International Journal for Housing Science and Its Applications
Publish August 3, 2025. Volume 46, Issue 3 Pages 1064-1075

https://doi.org/10.70517/ijhsa46382

Analysis of the interaction mechanism between regional economic growth and eco-agricultural benefits under water resource constraints based on structural equation modeling

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Abstract This study focuses on the interaction mechanism between regional economic growth and eco-agricultural benefits under water resource constraints, and takes County Yunyang as a typical case for empirical analysis. Based on the SEM method of structural equation modeling, the complex relationship between latent variables is quantified by integrating multi-source data, and the path of water resource constraints on the synergistic development of the system is revealed. The results show that the direct effect of agricultural resource endowment on the coupled state is significant, with a path coefficient = 0.731, P = 0.011, and indirectly drives the standardized impact coefficient of economic benefits η through the coupled state of 3.722. The negative effect of industrial posture on economic benefits, with a path coefficient = -4.683, P = 0.020, suggests that an over-reliance on the traditional agricultural model may inhibit the ecological benefits. The model fitness test showed that the chi-square degrees of freedom ratio $x^2/df=1.384$, goodness-of-fit index GFI=0.947, and root mean square of approximation error RMSEA=0.057 met the statistical standard, verifying the reliability of the theoretical framework. The degree of coupling and coordination of ecological-agricultural-economic systems in Yunyang County continued to increase from 0.578 in 2015 to 0.694 in 2024, with an annual average growth rate of 1.2%, reflecting the synergistic effect of policy optimization and resource integration. This study provides a quantitative basis for the synergistic development of regional economy and eco-agriculture under water resource constraints, and realizes the coupled optimization of eco-agriculture with resources and economy.

Index Terms structural equation modeling, water resource constraints, agroecology, coupling coordination degree, regional economy

I. Introduction

Agriculture plays an important role in the development of national economy, and China, as a large agricultural country, pays extra attention to agricultural development. At the present stage, the agricultural production mode has gradually shifted from the traditional high-input, high-energy-consumption and high-pollution mode to the ecologically friendly, resource-saving and environmentally friendly mode [1], [2]. Eco-agriculture improves the function of farmland ecosystems, reduces environmental pollution, realizes the benign interaction between farmland and natural ecosystems, and improves the eco-efficiency and sustainability of agriculture by means of eco-environmental construction, protection measures and agro-ecological engineering [3]-[5]. The implementation of sustainable agriculture not only needs to follow some core principles, such as resource conservation, ecosystem protection and improvement, and transformation of agricultural production methods, but also requires policy support and financial investment [6]-[8]. As an ecologically friendly agricultural production method, sustainable agriculture has great significance and potential, and has a positive impact on regional economic development [9], [10]. The prosperity of regional economy provides market demand and investment opportunities for sustainable eco-agriculture, as well as broad market space and infrastructure development [11], [12]. Through these aspects, sustainable agriculture is expected to make a greater contribution to regional economic development and sustainable social development.

As water resource management is an important component of sustainable agriculture, its goal is to improve the efficiency of water use and reduce waste and excessive discharge [13], [14]. Scientific water resource management and scheduling techniques can reduce water evaporation and loss, improve irrigation efficiency, and thus promote high-quality development of eco-agriculture [15], [16]. Therefore, taking water resources as a constraint and exploring the interaction effect between regional economic development and sustainable eco-agriculture is of great theoretical and practical significance for realizing the long-term sustainable development of agriculture and economy.

This study combines theoretical analysis and empirical tests to reveal the dynamic relationship between economy and ecological agriculture under water resource constraints. At the theoretical level, the driving role of regional economy is reflected in the dual dynamics of exogenous and endogenous: the exogenous dynamics rely on policy support and regional collaboration to optimize resource allocation, while the endogenous dynamics originate from ecological resource endowment and the deepening of the marketization process. Taking County Yunyang as a typical case, we analyze the economic environment and sustainability characteristics of its eco-agriculture development to provide data support for the model construction. Structural equation modeling (SEM), as the core of the methodology of this study, can effectively integrate multivariate and multilevel data, and deal with the complex relationship between explicit variables and latent variables at the same time. Through the combination of measurement modeling and structural modeling, the direct and indirect effects between latent variables, such as regional economy, eco-agricultural efficiency and water resource constraints, are quantified. Measurement error terms are introduced to minimize the impact of observational data bias on the conclusions. The model correction and fitness test ensure that the theoretical framework fits the empirical data.

II. Theoretical framework for the interaction between regional economic growth and eco-agricultural benefits under water resource constraints

II. A. Analysis of the contribution of the regional economy to agroecology

II. A. 1) External driving forces

Regional cooperation is one of the external driving forces for agricultural development, and seeking to carry out multi-regional cooperation has become an effective way for economic development in many regions, while the agricultural economy of the regions in the Three Gorges Reservoir Area Basin has strong complementarities, and there is a strong potential for development in the regional economic division of labor and cooperation and the optimization of resource allocation.

The Three Gorges Reservoir Area (Basin) has unique location advantages, and its agricultural industry is characterized by a large proportion of agriculture, a vast rural area, a large agricultural population and a relatively fragile ecological environment. Chongqing, for example, is the economic center of the upper reaches of the Yangtze River, a national logistics hub, and an important link between the “One Belt, One Road” and the Yangtze River Economic Belt, which has a broad space for development and can provide strong comprehensive support for eco-agriculturalization as well as the coordinated development of the regional economy. At the same time, Chongqing as the core to establish a logistics system with a wide coverage, for the agricultural industry and the market and even international standards to provide regional logistics services, thus reducing the cost of agricultural products, to obtain more market competitiveness.

Years of market development have allowed the Three Gorges Reservoir Area (Basin) to figure out the basic features of the characteristic industrial structure, and to participate in the regional economic development with characteristic products. At present, the citrus economy in the Three Gorges Reservoir Area (Basin) has begun to take shape, and the citrus development model of “Leading Enterprise + Base + Farmers” has become the key to expanding the citrus sales market, and the “Three Gorges Tangerine Township” national idyllic complex is an effective manifestation of the promotion of eco-agriculture by the regional economy. At the same time, the Three Gorges Reservoir Area (watershed) has built the largest squash production base in the country, relying on two national key enterprises, namely Fuling squash and Wanzhou Yuquan squash. With the development of the market, the scale of vegetable bases in the region is also developing, promoting the farmers' income while also continuously strengthening the construction of agricultural infrastructure and rural ecological environment in the region, and promoting the development of the agricultural industry in the region.

II. A. 2) Endogenous drivers

The Three Gorges Reservoir Area (watershed) has a good ecological environment, rich natural resources, plants, medicinal herbs, water energy, land, tourism and other resources, whether it is natural tourism, humanistic tourism or city sightseeing, there are a lot of natural landscapes, humanistic landscapes and ethnic customs to choose from. For example, the tertiary industry formed on the basis of the model of ecological agriculture for tourism and supporting technology, strengthening the functional characteristics of agricultural tourism, leisure, education and nature, such as high-tech eco-agricultural parks, eco-tourism villages, eco-farms and so on, are all ecological development brought about by the regional characteristics.

Agricultural infrastructure and science and technology are constantly improving, including the construction and management of water conservancy facilities, the construction and renovation of mechanized roads and farming roads, and the improvement of public services in rural areas, so as to improve the basic living and production security of farmers in order to effectively promote the development of farmers to the natural ecological development. At the same time, the national and provincial and municipal demonstration zones, scientific research units continue to add, in driving the transformation of agricultural research and results at the same time, but also the ecological promotion of agricultural technology. In addition, the perfect agricultural industry service system has effectively strengthened the coverage of modern production network in rural areas, and broadened the corresponding channels in agricultural law enforcement and supervision, agricultural product logistics, and agricultural resource development.

The process of agricultural marketization is accelerating, and agricultural market players are gradually growing, which promotes the development of agricultural industrialization, restricts the ecological protection and resource utilization of related enterprises, and gradually influences the ecological development direction of the agricultural industry itself. For example, green ecological products, pollution-free products and other market restrictions, both to regulate the direction of market operation, but also to restrain the poor agricultural industry behavior.

II. B.Analysis of the current situation of ecological agriculture in County Yunyang

The double driving force of regional economy provides theoretical support for ecological agriculturalization, but it needs to be combined with specific regional practice to verify its actual effect. For this reason, this study selects County Yunyang as a typical research object, and analyzes its economic environment and the current situation of eco-agriculture to reveal the reality of the interaction between economy and ecology under the constraints of water resources.

II. B. 1) Economic environment

Table 1 shows the agricultural output of County Yunyang in 2015 and 2024.

Table 1: Agricultural output value of County Yunyang in 2015 and 2024

Index	2015	2024	Amount of growth	Rate of increase
Area under cultivation/ha.	114369	110836	-3533	-3.09%
Grain crop yield /ton	749262	720374	-28888	-3.86%
Total output value of agriculture, forestry, animal husbandry and fishery / 100,000,000 yuan	46.17	62.88	16.71	36.19%

Driven by eco-agriculture and agricultural industrialization, the rural economy of County Yunyang as been developing rapidly, and according to the data of 2015 and 2024, the cultivated land area of the two years is 114,369 hectares and 110,836 hectares respectively, with a decrease ratio of 3.09%. Grain crop production was 749,262 tons and 720,374 tons respectively, with a decrease of 3.86%, but the total output value of agriculture, forestry, animal husbandry and fishery increased from 4.617 billion yuan to 6.288 billion yuan, an increase of 1.671 billion yuan, a growth rate of 36.19%, which can be seen that the development of the rural economy has been greatly promoted through the development of the model of eco-agriculture.

II. B. 2) Shape of sustainable agroecological development

In recent years, County Yunyang adheres to the road of sustainable development of eco-agriculture, combines the ecological needs of agricultural development with the local agricultural production situation, focuses on the road of integrated agricultural development, promotes the development of local agriculture on a large scale, promotes the development of local agriculture with high quality, and ultimately makes the agricultural production ecologically, efficiently, and branded, and embarks on the road of green and ecological development of agriculture.

The production of major agricultural products in County Yunyang from 2015 to 2024 is shown in Table 2.

The total output of grain crops in Yunyang county exceeded 700,000 tons for ten consecutive years, and the output of aquatic products exceeded 100,000 tons for seven years, with the “three increases” in yield, total output and benefits. Longping Seed Industry Innovation Base was completed. The new high-standard farmland of 62,000 mu, Gaozuo town comprehensive land improvement of the whole area of the comprehensive progress, Yunyang county was named the provincial arable land protection incentive units. The proportion of green and high-quality agricultural products reached 86.29%, the first in the city.

Table 2: The output of major agricultural products in Yunyang county from 2015 to 2024

	Output of aquatic products/10,000 tons	Grain crop yield/10,000 tons
2015	9.78	74.92
2016	9.83	74.86
2017	9.97	73.14
2018	10.06	73.47
2019	10.15	73.13
2020	10.18	73.15
2021	10.26	72.19
2022	10.38	72.53
2023	10.31	71.88
2024	10.42	72.04

II. C. Structural equation modeling concepts

The data on eco-agricultural development in County Yunyang suggest that the synergy between economic and ecological benefits needs to rely on scientific quantitative analysis tools. Structural equation modeling is the key methodology of this study because of its ability to resolve complex variable relationships. In the following, the theoretical framework and core components of the model are described from the basic concepts of the model.

Structural equation modeling is mainly composed of two core components: measurement equations and structural equations. The structural equation model is shown in Figure 1. Among them, the structural equations are used to describe the interactions between different latent variables, and the measurement equations are mainly used to explain the relationship between observed variables and latent variables. In the graphical representation of the model, the observed variables are usually identified by rectangles or rectangles, while the latent variables are represented by circles or ovals. Bidirectional curved arrows are used in the model to indicate correlations between variables, and unidirectional arrows are used to indicate unidirectional effects between variables. For observed variables, unidirectional arrows pointing to them indicate measurement error; for latent variables, unidirectional arrows pointing to them indicate that the potential endogenous component has not yet been accounted for. Observed variables may encompass both random and systematic errors, but these errors usually do not affect latent variables.

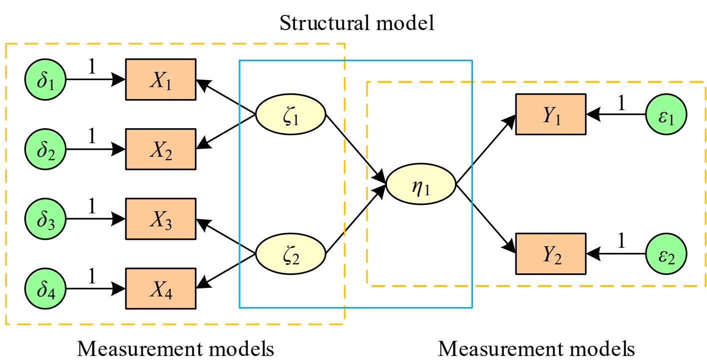

Figure 1: Structural equation model

II. C. 1) Measurement models

In validated factor analysis, the relationship between measured and latent variables is used to test the validity of the measurement model. The mathematical expression formula is as follows:

$$x = A_x \xi + \delta \tag{1}$$

$$y = A_y \eta + \varepsilon \tag{2}$$

X and Y denote exogenous and endogenous indicators; δ and ε denote the measurement error of X and Y; ξ and η are exogenous and endogenous variables, respectively; A_x and A_y describe the association of the X metric with the exogenous latent variable ξ and the Y metric with the endogenous latent variable η, respectively.

II. C. 2) Structural models

In the structural modeling section, the path analysis between potential variables is used primarily to test the fitness of the structural model. The mathematical expression for this analysis is as follows:

$$\eta = \beta\eta + \Gamma\xi + \zeta \tag{3}$$

β describes the link between endogenous latent variables; ζ represents the unexplained part of the model; and Γ denotes the effect of exogenous latent variables on endogenous latent variables.

II. D.Modeling steps for structural equation modeling

The theoretical composition of structural equation modeling lays the foundation for empirical analysis, while the scientificity and reliability of the model need to be realized through a standardized modeling process. The following section describes in detail the specific steps of modeling, including model setting, fitness testing and correction strategies, to ensure the rigor of the research conclusions.

Modeling steps: First, the basic framework of the model should be established to lay the foundation for subsequent analysis. Second, ensure the recognizability of the model, followed by model fitting to make the model fit the data and reveal the internal logic of the data. After that, the model is corrected as necessary to improve its accuracy and explanatory power. Finally, the corrected model is explained and interpreted in depth to uncover the deeper meaning behind it. The process of structural equation modeling analysis is shown in Figure 2.

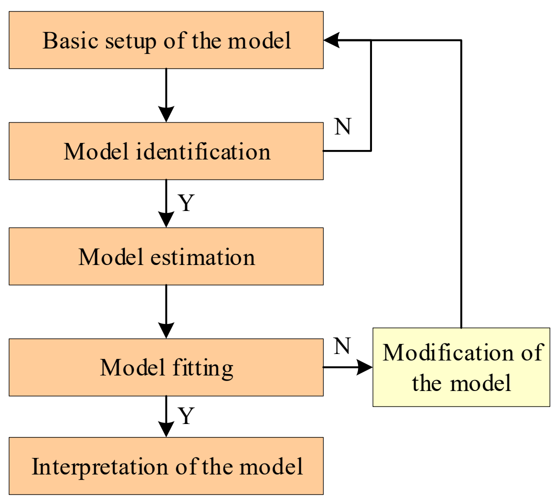

Figure 2: Structural equation model analysis process

II. D. 1) Modeling steps for structural equation modeling

When using structural equation modeling to analyze the data, the first step is to set up the model based on the relevant theories. Based on the relevant theories, it is first necessary to screen out the variables that are closely related to the topic of this study. Then, based on the possible correlation between these variables, the path diagram of the model is drawn, so as to clearly show the connection between the variables and the direction of influence, and to reveal the intrinsic connection between the latent variables, specifically in the following aspects: to explore the subtle connection between the observed variables and the latent variables, to analyze the interactions and influences between the latent variables, and to set the relevant parameters in a reasonable way.

II. D. 2) Fitting of the model

In practice, the evaluation of the fitness of structural equation modeling is centered on two core points. The first is to scrutinize the significance and reasonableness of the parameter estimates to ensure that the error terms follow statistical principles, such as preventing the errors from being negative or the correlation coefficients from exceeding a reasonable range (e.g., greater than 1), with particular attention to the significance of the path coefficients. Second, we comprehensively assessed model fit using a range of commonly used metrics, including but not limited to the chi-square degrees of freedom ratio (χ^2/df), a key metric of model fit, as well as the goodness-of-fit index (GFI), the comparative fit index (CFI), the incremental fit index (IFI), the unspecified fit index (TLI), and the root mean square of the approximation error (RMSEA), etc.

II. D. 3) Modifications to the model

If the parameter estimation of the structural equation model shows poor model fit, model correction is needed to improve its fit. Specific correction strategies include: adjusting the assumed path relationships, regrouping the observed variables, and resetting the correlation coefficients. After each correction, the fit of the new model should be re-estimated and tested using the original data. This process should be repeated until the model fitness reaches a satisfactory standard to ensure that the model can more accurately reflect the actual situation and provide a reliable basis for subsequent analysis. However, in the process of modifying the structural equation model, it is important to consider both the parameters in the model fit and the actual situation. This means that adjustments to the model should not be made solely to improve the fitness index, but should be based on the actual theoretical basis and research background. Whether a path is added or subtracted, or a parameter is restricted or released, it should be based on sufficient realistic considerations to be able to explain or predict the actual phenomenon.

III. Structural modeling results

By analyzing the theoretical framework of the interaction between regional economic growth and eco-agriculture under water resource constraints and the empirical study of the current situation of eco-agriculture in County Yunyang, this chapter preliminarily reveals the intrinsic mechanism of synergistic development of economy and ecology. To further quantify the complex relationships among variables, this paper will introduce the Structural Equation (SEM) model. Through data modeling and parameter verification, it will systematically analyze the multi-dimensional impact of water resource constraints on ecological agricultural systems.

III. A. Determination of model variables

In this paper, agricultural resources, the state of green development, ecological resources, and economic benefits are chosen to characterize the ecological-agricultural economic coupling system. In the process of constructing the conceptual model of structural equations, agricultural resources and industrial posture are identified as exogenous latent variables, and economic benefits and coupling status are endogenous latent variables. To highlight the impact of water resource constraints on the system, the structural model variables in this paper are shown in Table 3.

Table 3: Structural model variable

Latent variable	Observed variable
Agricultural resources(ξ1)	Per capita forest and grass areas(X1)
	Per capita basic cropland(X2)
	Per capita water resources (X3)
	Irrigation efficiency (X4)
The state of green development (ξ2)	Rate of grassland utilization(X5)
	Rate of marketable farm product(X6)
	Proportion of industrial and all kinds of sideline to total income of peasants(X7)
	Water consumption per unit of agricultural output (X8)
Ecological resources (ξ3)	Landuse structure of agriculture, forestry and animal husband(X9)
	Rate of resource utilization(X10)
	Correlation degree of agricultural industrial chain and resources(X11)
	Water resource utilization efficiency (X12)
Economic benefit (η)	Average annual net income of peasants (Y1)
	per capita grain production(Y2)
	Ecological benefit index (Y3)

Basic farmland per capita, forest and grassland per capita, water resources per capita and irrigation efficiency are the observation variables of agricultural resources; pasture utilization rate, industrial and sideline contribution rate, commodity rate of agricultural products and water consumption per unit of agricultural output value are the observation variables of the state of green development; the relevance of watershed industry chain and resources, resource utilization rate of eco-agricultural economic system, agricultural, forestry and animal husbandry land-use structure and water resource use efficiency are the observation variables of the ecological resources. The economic benefits include per capita net income, per capita food production and eco-efficiency index to comprehensively assess the ecological protection effect under water resource constraints.

III. B. Model fitting results

After identifying the model variables and their theoretical relationships, this section will further verify the statistical significance between latent and observed variables through model fitting and correction to reveal the direct and indirect paths of water resource constraints on the economic efficiency of eco-agriculture.

III. B. 1) Initial estimation of model parameters

Model parameter estimation is actually the quantification of the relationship between latent variables and latent variables, latent variables and observed variables and related observed variables, and two methods are commonly used: great likelihood estimation and generalized least squares. Since the data used in this study originated from simple random sampling, and these data information conforms to the multivariate normal distribution overall, this paper applies the great likelihood estimation method to estimate the model parameters.

Based on the sample data of 6932 households in County Yunyang, the software AMOS 7.0 was applied to obtain the initial conceptual model and the throughput coefficients among its variables. The fitting results of the initial conceptual model of the coupled ecological-agricultural-economic system in County Yunyang are shown in Table 4.

Table 4: The fitting results of the initial conceptual structure model of County Yunyang

Variable path	Estimate	SE	Critical ratio	P
ξ3←ξ2	0.073	0.088	1.544	0.273
ξ3←ξ1	0.693	0.314	5.287	0.000
η←ξ1	0.011	0.272	-0.773	0.852
η←ξ2	-0.899	0.099	-2.101	0.386
η←ξ3	0.838	0.197	4.824	0.000
x1←ξ1	1.841	0.137	2.547	0.001
x2←ξ1	0.891	0.051	6.942	0.000
x3←ξ1	0.926	0.201	3.614	0.003
x4←ξ1	1.939	0.276	6.006	0.000
x5←ξ2	1.000	0.248	3.338	0.000
x6←ξ2	0.824	0.083	3.201	0.000
x7←ξ2	1.000	0.081	5.135	0.000
x8←ξ2	1.000	0.026	3.882	0.016
x9←ξ3	0.943	0.110	3.496	0.000
x10←ξ3	1.000	0.083	5.680	0.000
x11←ξ3	0.838	0.126	0.646	0.172
x12←ξ3	2.271	0.212	6.677	0.000
y1←η	1.000	0.063	4.444	0.261
y2←η	0.943	0.077	6.058	0.000
y3←η	1.000	0.136	0.698	0.000

From the P-values in the fitting results of the initial conceptual model, the P-values between the latent variables agricultural resources and ecological resources, the state of green development and economic benefits, and coupling status and economic benefits are greater than the requirement of significance level of 0.05, and the model fitting effect is generally good, i.e., the estimated relevant parameters do not truly reflect the relationship between the variables, and it is necessary to revise the initial conceptual model.

III. B. 2) Model evaluation, modification and parameterization

The test of the rationality of the structural equation model includes the rationality test and significance test of each parameter as well as the suitability test of the whole model. The test can not only provide a quantitative basis for the rationality of the model, but also provide a direction for further research and model improvement. In general, the model can be evaluated in terms of the overall goodness-of-fit and the estimated values of single parameters. The closer the elements in the residual matrix are to 0, the better the model fits the data and the more valid the model constructed. The overall goodness-of-fit evaluation of the model is mainly evaluated in three categories: absolute fit effect indicators, relative fit effect indicators and alternative indicators.

The results of the first model fitting show that the model fitting effect is general, with reference to the suggestion of correcting the indexes, at the same time, according to the theoretical and practical significance of establishing the model, the model is corrected several times, and finally the model parameters with a more ideal fitting process are formed. Table 5 shows the fitting results of the revised model of the coupled relationship of ecological agricultural economic system in County Yunyang.

Table 5: The fitting results of the modified model of eco-agriculture in Yunyang county

Variable path	Estimate	SE	Critical ratio	P
ξ3←ξ2	0.086	0.125	2.335	0.000
ξ3←ξ1	0.731	0.071	4.489	0.011
η←ξ1	0.307	0.094	2.180	0.000
η←ξ2	-4.683	2.115	-2.081	0.020
η←ξ3	0.976	3.099	4.821	0.003
x1←ξ1	1.000	0.047	4.873	0.000
x2←ξ1	0.794	0.106	5.665	0.000
x3←ξ1	1.000	0.114	0.109	0.000
x4←ξ1	1.000	0.121	4.207	0.000
x5←ξ2	1.000	0.019	0.603	0.000
x6←ξ2	1.000	0.032	1.538	0.000
x7←ξ2	0.816	0.055	1.267	0.000
x8←ξ2	1.000	0.128	1.988	0.000
x9←ξ3	0.561	0.084	4.381	0.000
x10←ξ3	1.761	0.062	6.703	0.008
x11←ξ3	1.000	0.034	5.711	0.000
x12←ξ3	1.000	0.071	6.945	0.000
y1←η	1.000	0.107	6.849	0.000
y2←η	1.000	0.132	1.554	0.000
y3←η	1.000	0.046	0.569	0.000

The results of the modified model fitting showed that the modified model parameter estimates were significantly improved, and the P-values of most paths reached the statistical significance level of $P<0.05$, indicating that the relationship between the variables was statistically reliable. The path coefficient of agricultural resources ξ1 on coupling state ξ3 is 0.731, P=0.011, the path coefficient of industry posture ξ2 on economic efficiency η is -4.683, P=0.020, and the coefficient of coupling state ξ3 on economic efficiency η is 0.976, P=0.003, all of which pass the significance test. Notably, the direct impact coefficient of agricultural resources ξ1 on economic efficiency η is 0.307, P=0.000, indicating a stronger indirect effect through coupled states. In addition, the relationship between observed variables and latent variables is further optimized, such as the factor loadings of per capita water resources X3 and irrigation efficiency X4 are both standardized to 1.000, indicating their stronger explanatory power on the latent variables of agricultural resources.

Table 6 shows the total standardized impact coefficients of the coupled relationship model of ecological and agricultural economic systems in County Yunyang.

The standardized impact coefficients reveal the combined impact of each latent variable on the observed variables. The economic efficiency η is most directly affected by the coupled state ξ3 at 3.722, followed by the industrial posture ξ2 at 0.456, suggesting that the synergistic state of ecology and economy is the core factor driving the efficiency under the water resource constraint. The indirect impact coefficient of agricultural resources ξ1 on per capita food production Y2 is 0.387, while the impact coefficient on ecological efficiency index Y3 reaches 0.548, highlighting the fundamental role of resource endowment in ecological protection. In addition, the standardized coefficient of industrial posture ξ2 on pasture utilization rate X5 is 0.951, indicating that the marketization process promotes resource utilization efficiency significantly.

The fit indices obtained from the analysis of the structural equation model using AMOS 7.0 include: the cardinal freedom ratio (x2/df), the mean value of the difference between each constituent element of the regeneration matrix and the initial data (RMR), the degree of dispersion of the data profile that can be explained by the variance and covariance obtained from the model fit (GFI), the GFI indexes adjusted with the model degrees of freedom and the number of parameters (AGFI PGFI), the difference between the hypothesized model and the independent model (NFI), the degree of dispersion of the chi-square values of the hypothesized model from the theoretically expected central chi-square distribution (CFI), the NFI metrics adjusted by the degrees of freedom (PNFI, TLI), the degree of dispersion of the chi-square values obtained by the model estimation from the theoretically expected central chi-square distribution (NCP), the effect of adjusting the sample size on the NFI metrics (IFI), and the CFI index adjusted with degrees of freedom (PCFI), the fitting criteria for each index can be determined; GFI, PGFI, NFI, TLI, IFI, and CFI should all be >0.90 and the closer they are to 1, the better; PNFI, and PCFI should all be greater than 0.5; RMSEA is between 0 and 0.1, and <0.05 indicates that the model is well fitted; the smaller the NCP, the better; x2 /df>10 indicates that the model is very poor, <5 indicates that the model is acceptable, and <3 indicates that the model fits well.

Table 6: Overall standardized impact coefficient of agroecological economic model

Variable	ξ1	ξ2	ξ3	η
ξ3	0.253	0.938	0	0
η	0.302	0.456	3.722	0
x1	0.608	0.760	0.59	0
x2	0.482	0.711	1.347	0
x3	0.612	0.456	1.034	0
x4	0	0.289	0.689	0.
x5	0.241	0.951	0	0
x6	0.332	0.637	0	0
x7	0.589	0.244	0	0
x8	0.686	0.823	0	0
x9	0	0.765	0.937	0
x10	0.185	0.182	1.665	0
x11	0.482	0.546	0	0
x12	0	0.562	0.574	0
y1	0.069	0.645	2.776	0.882
y2	0.387	0.255	3.662	0.837
y3	0.548	0.683	1.112	0.903

The fitted indices of the ecological agricultural economic model under water resource constraints in County Yunyang are shown in Table 7.

Table 7: Yunyang county ecological agriculture economic model fitting index

Item	Evaluation index	Evaluation criteria	Model result
Index of absolute fitting effect	Chi-square degree of freedom ratio x^2/df	<3	1.384
	Goodness of fit index GFI	>0.9	0.947
	Reduced goodness of fit index PGFI	>0.5	0.510
Relative fitting effect index	Specification fit index NFI	>0.9	0.953
	Tuck-lewis index TLI		0.972
	Incremental fit index IFI		0.966
	Reduced gauge fit index PNFI	>0.5	0.588
Proxy index	The fitting index CFI was compared	>0.9	0.977
	Reduced comparison fit index PCFI	>0.5	0.624
	Approximate error root mean square RMSEA	<0.1,the smaller the better	0.057

The model fit indices show that the overall fit of the model is good. Among the absolute fit indices, the chi-square degrees of freedom ratio x^2/df=1.384 is much lower than 3, GFI0.947 and CFI0.977 are both greater than 0.9, and the RMSEA is 0.057, <0.06, which indicates that the model is highly fit to the data. The relative fit indices TLI0.972 and IFI0.966 are both close to 1, further validating the theoretical soundness of the model. However, some alternative indexes such as PGFI0.510 and PCFI0.624 still have room for optimization although they meet the minimum standard, >0.5, which may be affected by the sample size or variable complexity. Overall, the model passes the strict fitness test and provides a reliable theoretical framework for the analysis of economic and ecological interaction mechanisms under water resource constraints.

IV. Analysis of coupled and coordinated development of regional economic and ecological agricultural systems

Based on the arithmetic results of structural equation modeling, the interaction path between regional economy and ecological agriculture under water resource constraints has been empirically supported. In order to further explore the dynamic characteristics of the synergistic development of the two, the coupling degree model and coordination degree model will be constructed in Chapter 4 to analyze the coupling evolution process of the ecological-agricultural economic system by combining the time series data of County Yunyang.

IV. A. Coupling model

The change process of regional economic system and ecological agricultural system is a nonlinear process, and its evolution equation can be expressed as follows:

$$\frac{dx(t)}{dt} = f(x_1, x_2, \ldots x_n) \tag{4}$$

f is a nonlinear function of x_1, i=1,2,...,n, which can be approximated as:

$$\frac{dx(t)}{dt} = \sum_{i=1}^{n} a_i x_i \tag{5}$$

Therefore, the general function of the ecological agricultural system $en(t)$ and the regional economic system $el(t)$ at a point in time can be expressed as follows:

$$en(t) = \sum_{i=1}^{n} a_i(t) x_i(t) \tag{6}$$

$$el(t) = \sum_{i=1}^{m} b_i(t) y_i(t) \tag{7}$$

where, x, y are the elements of the two systems; a, b are the weights of each element. The $en(t)$, $el(t)$ of each time point are connected to become a smooth curve of the evolution process of the ecological agricultural system and the regional economic system in a certain period of time, which can be fitted by the historical data of its evolution process to establish a function of the time t, namely

$$en = f(en_1, en_2, \ldots, en_n) = f(t) \tag{8}$$

$$el = f_1(el_1, el_2, \ldots, en_m) = f_1(t) \tag{9}$$

Derivation of the above equation yields the system evolution equation as:

$$Ven = \frac{den}{dt} \tag{10}$$

$$Vel = \frac{del}{dt} \tag{11}$$

Ven, Vel are their evolutionary speeds respectively, so that the evolutionary speed (V) of the whole system can be expressed as

$$V = f(Ven, Vel) \tag{12}$$

The coupling between the whole system and the two subsystems is investigated by analyzing the variation of V

$$tg\ \alpha = \frac{Ven}{Vel} \tag{13}$$

$$\alpha = arctg \frac{Ven}{Vel} \tag{14}$$

In this way, the coupling degree α can be found by the above formula, the value of the coupling degree α is determined by Vel, Ven and their interrelationships, according to the value of α, the degree of coupling of the ecological agriculture and economic system evolutionary state can be determined, i.e., the ecological agriculture and economic system coupling posture.

IV. B. Analysis of the state of coupled and coordinated development of agroecological and economic systems

The coupling degree model portrays the nonlinear interaction between eco-agriculture and regional economic system from the theoretical level, while to further assess the actual level of synergistic development of the two, in this section, we will calculate the degree of coupling and coordination (D) based on the time-series data of County Yunyang, and quantitatively analyze the evolution trend and coordination level during the ten-year period.

In order to better analyze the comprehensive index changes of the watershed eco-agricultural system and the regional economic system, the two are regarded as two systems, and with the help of the theoretical model of coupling and coordination, the degree of coupling and coordination of the eco-agricultural system and the regional economic system (D) is calculated, with the purpose of better judging the synergistic degree of the coupling of the economic growth of agriculture and ecological interactions. The larger the value of D, the higher the degree of coupling and coordinated development of the eco-agricultural system and the agricultural economic system. The higher the degree of coupled and coordinated development. Figure 3 shows the coupled and coordinated evolution of ecological agriculture and economic system in County Yunyang from 2015 to 2024.

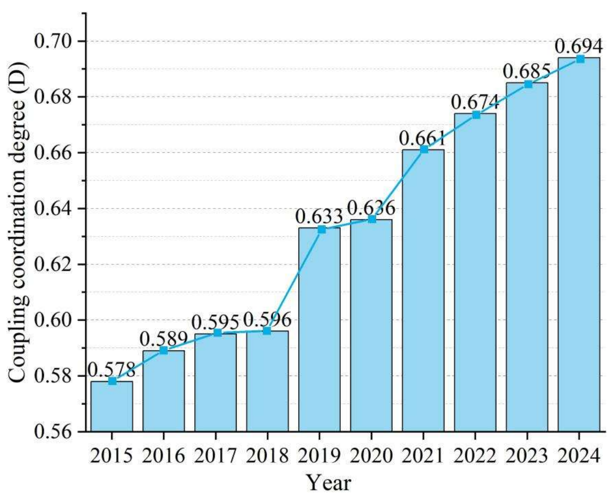

Figure 3: The coupling and coordination evolution of ecological agriculture and economic system

Figure 3 demonstrates the evolution of the coupling coordination degree (D) of the ecological agriculture and economic system in County Yunyang from 2015 to 2024. The data show that the coupling coordination degree gradually increased from 0.578 in 2015 to 0.694 in 2024, showing a continuous growth trend. Specifically, during the period from 2015 to 2018, the growth of D is relatively flat, with an average annual increase of about 0.006; the growth rate accelerates after 2019, and the average annual increase from 2019 to 2024 reaches 0.012. Among them, 2021 is the inflection point of growth, and the D value breaks through 0.66 for the first time, and then climbs year by year to 0.694 in 2024, with a cumulative compared to the base period of 2015 growth of about 20.1%. This trend indicates that the level of synergistic development between ecological agriculture and regional economic system in County Yunyang has gradually increased, especially under the impetus of policy support and optimal allocation of resources, the coupling and coordination between the systems has achieved significant improvement.

V. Conclusion

Based on structural equation modeling and coupled coordination theory, this study systematically analyzes the interaction mechanism between regional economic growth and ecological agricultural benefits under water resource constraints.

Agricultural resource endowment ξ1 indirectly drives economic efficiency η by enhancing the coupling state ξ3, with an indirect effect of 3.722, significantly higher than the direct effect of 0.307, indicating that the optimal allocation of resources is the core of sustainable development of eco-agriculture. The negative effect of industrial state ξ2 on economic efficiency is -4.683, revealing the potential conflict between the traditional agricultural model and ecological goals, which needs to be realized through technological innovation and market-oriented reform to achieve industrial upgrading.

The model fitting results showed that the absolute fit index $x^2/df=1.384$, RMSEA=0.057 and the relative fit index CFI=0.977, TLI=0.972 met the statistical standards, which verified the scientific validity of the theoretical framework of the “economy-ecology-resources” system. Among the observed variables, the factor loading of per capita water resources X3 and irrigation efficiency X4 is 1.000, which highlights the key role of water utilization efficiency.

From 2015 to 2024, the coupled coordination degree D of the ecological agriculture and economic system in County Yunyang steadily increased from 0.578 to 0.694, with an average annual growth rate of 1.2%. Among them, the growth rate accelerates after 2019, with an annual average of 0.012, confirming the feasibility of ecological and economic synergistic development.

Funding

This work was supported by Autonomous Region - Paradigm and Effectiveness Evaluation of Eco-agriculture Development in Modern Irrigation Districts in Dry Areas, (No. 2023A02002-6-1.).

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