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Evaluating Agricultural Sustainability Based on the Water–Energy–Food Nexus in the Chenmengquan Irrigation District of China

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Abstract: Agriculture is one of the largest consumers of water and energy. This paper evaluated the agricultural sustainability of the Chenmengquan irrigation district of China based on the water–energy–food nexus. One objective weighting method and one subjective weighting method were integrated, based on game theory, and a matter–element model was constructed to evaluate agricultural sustainability for the research region. The sensitivity of each index to the evaluation class was also analyzed. The results showed that agricultural sustainability was moderate in 2006–2012 and high in 2012–2015. The indexes, which represent water-use efficiency and yield per unit area of crops, had higher sensitivities in the context of the present case study. The results also indicated that agricultural sustainability had a comparatively positive trend between 2012 and 2015, and that pesticide utilization was the most important issue for agricultural sustainability. The approach of using the combination of a weighting method, based upon game theory, and the use of the matter–element model provides a guide for the evaluation of agricultural sustainability.

Keywords: agricultural sustainability; water–energy–food nexus; combination weighting method; the matter–element model

1. Introduction

The issue of agricultural sustainability has received considerable critical attention in the world with the changing environment and the growing population [1]. In the case of limited arable land resources, in order to satisfy the expected demands for food, agriculture must be transformed, in order to feed a growing global population and provide the basis for economic growth and poverty reduction [2]. More than 80% of agricultural production growth by 2050 is expected to come from increased productivity on presently cultivated land [3]. However, intensive agricultural practices have resulted in serious environmental degradation, including groundwater level decline, the loss of biodiversity, and soil and water pollution [4]. Improving agricultural sustainability is the inevitable choice for agricultural development in the future. Operationalizing the assessment of agricultural sustainability is an important premise in order to promote it. The assessment of agricultural sustainability aims to provide an efficient tool for decision-makers to determine which actions should be preferentially taken in an attempt to promote agricultural sustainability [5].

Studies over the past two decades have developed a wide variety of methodologies for evaluating agricultural sustainability. Most of methodologies have a similar structure constructed by index selection and data gathering, reference values definition, weighting indexes, and index aggregation [6–12]. However, there are huge differences between selections of indexes. Some methods take three dimensions, accounting for economic, social, and environmental issues in the frame of a holistic vision of agricultural sustainability [6,7]. These methods select more quantitative indexes to define a methodology, but some indexes of economic and social dimensions (e.g., the income of agricultural producers) cannot sufficiently reflect the agricultural sustainability; those indexes depend more on the economic situation in the specific region and at the specific time. Some methods establish the index system based on general attributes (e.g., the productivity, stability, and compatibility) of agricultural sustainability. Those kinds of index systems have a good thinking structure regarding the agricultural sustainability as a whole [8]. Due to the highly complex nature of systemic indicators, those indexes remain qualitative rather than quantitative parameters [13]. These qualitative indexes must be artificially assigned numerical values for any quantitative evaluation of agricultural sustainability. In this paper, indexes were selected from the perspective of agricultural intensity based on the concept of the water–energy–food nexus (WEFN).

The Bonn conference of 2011 promoted the concept of the water–energy–food nexus (WEFN) in the international discussion of sustainable development [14,15]. Water, energy, and food are closely linked in agricultural practices. Agriculture has accounted for 70% of the world’s total freshwater extraction, making it the largest water user. Food production and supply chains consume about 30% of global energy [16]. The WEFN has emerged as a new perspective to agricultural sustainability, with its conceptual relevance, and pragmatic potential emphasized by many policymakers [17]. The aim of this research is not to analyze the impact of water resources and energy consumption on agricultural production, but to evaluate the status of agricultural sustainability from an integrated perspective. Based on the WEFN, the level of agricultural water use, the intensity of agricultural energy use and food productivity are regarded as evaluation objectives. Taking advantage of “degree” instead of “quantity” to select indexes provides a useful approach for sustainability assessment across different scales.

Many mathematical models were applied to quantitative evaluation of sustainability, such as the matter–element model [18], the artificial neural network model [19], and the gray correlation model [20]. Agricultural sustainability as the evaluation object can be regarded as a composite whole with different aspects. The attribute diversity of agricultural sustainability can be assumed as an incompatibility problem. Therefore, the matter–element model is an appropriate mathematical tool for assessing agricultural sustainability. Considering that different indexes have different impacts on agricultural sustainability, this paper also adopts a comprehensive weighting method which combines the G1 method and the entropy method to determine the weights of indexes. The G1 method is a subjective method. It is improved according to the analytic hierarchy process (AHP). That method overcomes the large amount of calculations and consistency checks [21]. The entropy method was proposed by Shannon and Weaver [22]. The entropy method is a method to determine the weight of the index according to the amount of information provided by the observational values of each index. The comprehensive weighting method can reach consistency or compromise between the subjective weights and the objective weights [23].

The purpose of this study was to develop a methodology to evaluate agricultural sustainability in a given region with intensive agricultural practice. The index system was established based on the WEFN. A comprehensive weighting method was used to weight indexes. The matter–element model was applied to reference values’ definitions and indexes’ aggregations. Through the analysis of the results calculated by the matter–element model, the key information affecting agricultural sustainability can be identified.

2. Case Study

The Chenmengquan irrigation district (117.17°–117.34° E, 36.70°–36.89° N) is located in Jinan City, the capital of Shandong province in China (Figure 1). The study area is important for agricultural

production in Jinan City. The total population of the irrigation district is 223,000, of which the agricultural population is 185,000. The total area of the irrigation district is approximately 20,000 ha. The main crops in the irrigation district are wheat, maize, and vegetables. With the continuous adjustment of the proportion of different crop acreages, the vegetable planting area has increased substantially. The study area is located in the mid-latitude zone and belongs to the warm, temperate, semi-humid monsoon climate. Rainfall varies greatly in different seasons. The average annual precipitation is 673 mm (1956–2016) and 70% of the annual precipitation is concentrated between June and September [24].

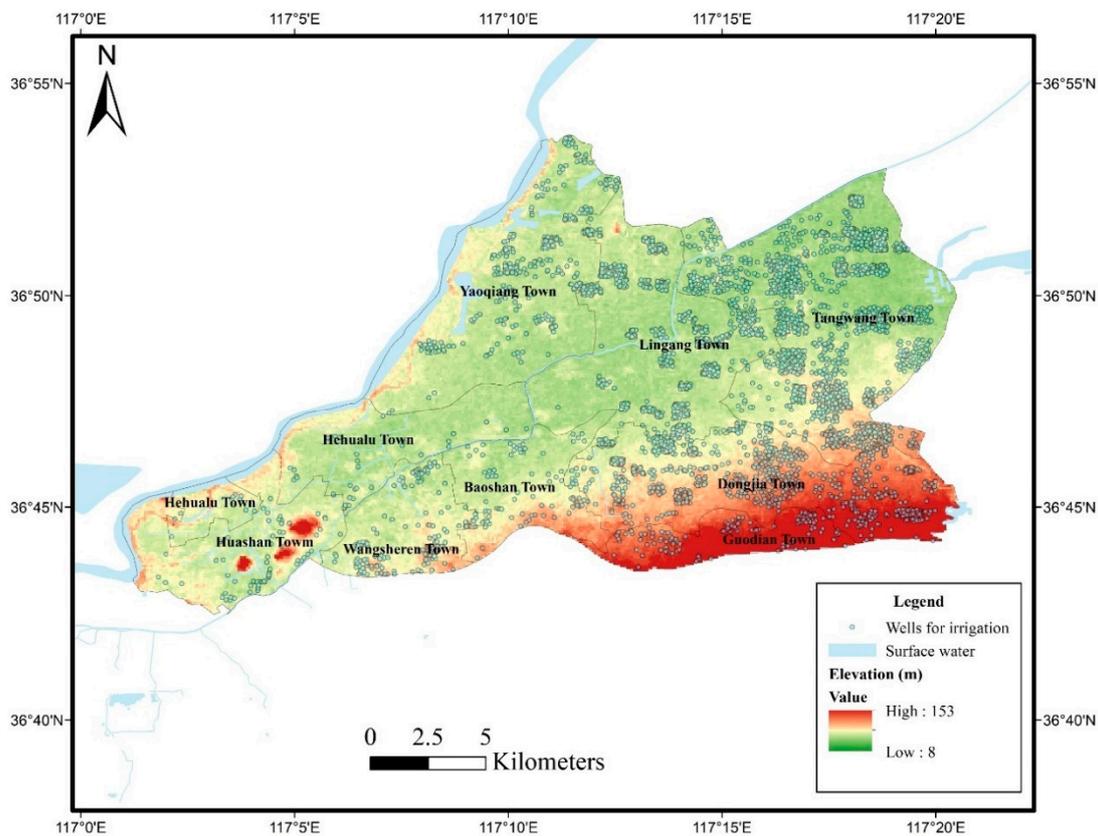


Figure 1. A location map of the Chenmengquan irrigation district.

Irrigation plays an important role for agriculture in the study area. Irrigation water is mainly supplied by the Yellow River and groundwater. With increased use of water for agriculture the exploitation of groundwater gradually exceeded the recharge, resulting in the continuous decline of the groundwater level in 2000–2006. Since 2006, the administrative department has promoted the protection of groundwater. However, there are still other problems like soil and water pollution caused by the excessive application of fertilizer and pesticide.

3. Methods

Based on the above introduction, the steps of the proposed methodology are shown in Figure 2.

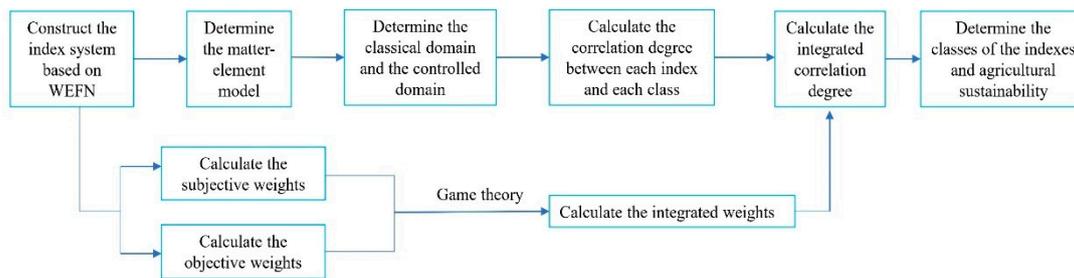


Figure 2. The steps of the methodology.

3.1. Index System

To assess agricultural sustainability, representative indexes are identified in Table 1 through a comprehensive perspective based on WEFN (c_i represents index number, $i = 1, 2, \dots, 10$).

Table 1. The index system based on water–energy–food nexus.

Sector	Index (unit)
Water	c_1 Agricultural blue water proportion
	c_2 Water-use efficiency
	c_3 Irrigation proportion of arable land
Energy	c_4 Energy utilization for irrigation amount per arable land (kWh/ha)
	c_5 Agricultural machinery power per arable land (kW/ha)
	c_6 Fertilizer utilization amount per arable land(kg/ha)
	c_7 Pesticide utilization amount per arable land(kg/ha)
Food	c_8 Yield per unit area of Wheat(t/ha)
	c_9 Yield per unit area of Maize(t/ha)
	c_{10} Yield per unit area of Vegetable(t/ha)

3.1.1. Water

Irrigation plays an important role in increasing the output of agricultural products. However, it also faces the practical problems of improving the efficiency of agricultural water use and controlling the total amount of water used. Cao et al. proposed an evaluation index for agricultural water use effect based on water footprint (WF) and irrigation development [25]. The indexes c_1 (agricultural blue water proportion), c_2 (water-use efficiency), and c_3 (irrigation proportion of arable land), which represent agricultural water use effects, were used as indexes in the water sector.

The index c_1 (agricultural blue water proportion) is based on the concept of WF proposed by Hoekstra [26]. It indicates the dependence of agriculture on irrigation water. The index expression for c_1 is given in Equation (1), as the ratio between agricultural blue water footprint (AWF_b) and the agricultural water footprint (AWF).

$$c_1 = AWF_b / AWF \tag{1}$$

AWF_b and AWF are calculated as in Equations (2) and (3)

$$AWF_b[m^3] = \sum_{cr=1}^{cm} ET_{b,cr} \times 10 \times S_{cr} \tag{2}$$

$$AWF[m^3] = \sum_{cr=1}^{cm} (ET_{b,cr} + ET_{g,cr}) \times 10 \times S_{cr} \tag{3}$$

$ET_{b,cr}$ and $ET_{g,cr}$ (in mm) are the blue and green evapotranspiration components of a given crop, which are computed by the CropWat® software. S_{cr} (in ha) is the total area cultivated of a given crop.

The index c_2 (water-use efficiency) is essential regarding the water consumption. It has a high correlation with the infrastructural performance of the irrigation network, the farm management

techniques, and irrigation methods. The index c_3 (irrigation proportion of arable land) is the ratio of effective irrigated area to arable land area. The effective irrigated area is the area of farmland which is relatively flat, has a certain water source and irrigation facilities, and can be irrigated normally in an average year. The data of c_2 (water-use efficiency) and c_3 (irrigation proportion of arable land) were derived from the Statistical Yearbook of Jinan City.

3.1.2. Energy

The energy consumed by agriculture can be divided into direct energy and indirect energy [27]. Direct energy includes fuel and electricity mainly used for irrigation and agricultural machinery's operation. Indirect energy refers to the energy used to produce fertilizers and pesticides. In this research, energy consumption intensity is expressed by four indicators: c_4 (energy utilization for irrigation amount per arable land), c_5 (agricultural machinery power per arable land), c_6 (fertilizer utilization amount per arable land), and c_7 (pesticide utilization amount per arable land).

The index c_4 (energy utilization for irrigation amount per arable land) is given in Equation (4)

$$c_4 = E_{ir}/S \quad (4)$$

where S represents the area of the arable land and E_{ir} represents energy utilization for irrigation, which refers to the energy requirement from-source-to-field. It not only depends on the specific water source, but also on the distribution of irrigation systems, the characteristics of the conveyance with their respective water losses and operational pressures [28]. For simplicity, the energy requirement for conveyance was not included, hence the water source was assumed to be on-farm [29]. For surface irrigation, the energy for surface water transport was mainly driven by gravity. Consequently, energy used for groundwater abstraction was computed as E_{ir} , shown in Equation (5)

$$E_{ir} = Volume_g \times H_t / (367 \times \eta) \quad (5)$$

$$H_t = H_{lift} + H_{pr} \quad (6)$$

where $Volume_g$ represents the gross amount of water from a groundwater source. η represents the pump efficiency; and H_t , H_{lift} , and H_{pr} represent the total hydraulic head, the elevation head, and the nominal operating pressure of the irrigation system, respectively. The data of c_5 (agricultural machinery power per arable land), c_6 (fertilizer utilization amount per arable land), and c_7 (pesticide utilization amount per arable land) were derived from the Statistical Yearbook of Jinan City.

3.1.3. Food

The indexes of the food sector were formulated according to the actual agriculture production in the given area. Wheat, maize, and vegetables make up more than 90% of the arable land at the study site. Because different crops have different attributes, it is not rigorous to use the total output value or total yield of all crops as the index. In this research, the index c_8 (yield per unit area of wheat), c_9 (yield per unit area of maize), and c_{10} (yield per unit area of vegetables) were used to represent the food productivities of the arable land. The data of these indexes were calculated from data on gross yields and planting areas given in the Statistical Yearbook of Jinan City.

3.2. Calculation of the Weights

In a comprehensive evaluation, the weight reflects the significant performance of each basic indicator or dimension criterion [30,31]. Major factors act on sustainability in different degrees. Thus, each major factor must be assigned with a weight. Selecting the appropriate weight determination method is the key step of the comprehensive evaluation work. Weight calculation methods primarily include objective weighting methods and subjective evaluation methods. Objective weighting methods are represented by the entropy method [32] and the coefficient of variation (CV) method [33]. Subjective

weighting methods are represented by the analytic hierarchy process (AHP) method [34] and the Delphi method [35].

Each type of those methods has its own advantages and disadvantages. Objective weighting methods depend on objective data completely, whereas subjective weighting methods are influenced by human-subjective experience inevitably. The combination weighting method [36] combines the subjective weighting method with the objective method based on game theory, so that the weight can reflect the subjective and objective information simultaneously. The central idea is to minimize the deviations of different weights calculated by different methods. In this study, subjective weights were determined by the G1 method, whereas objective weights were acquired by the entropy method.

3.2.1. The G1 Method

The G1 method (order relation analysis) is an improved method based on the analytic hierarchy process (AHP) [21]. This method does not require a consistency check, so a large amount of calculations can be avoided. The method consists of three steps:

Firstly, the order of the evaluation indexes has to be determined

$$c_1 > c_2 > \dots > c_n \quad (7)$$

The number of the evaluation indexes is n . “>” indicates that the index on the left side of the symbol is more important.

Secondly, the importance ratio assignments of adjacent evaluation indexes are determined.

$$\frac{w_{i-1}^1}{w_i^1} = r_i (i = 2, 3, \dots, n) \quad (8)$$

The reference assignments for r_i are shown in Table 2.

Table 2. The importance ratio assignments of adjacent evaluation indexes.

r_i	Instruction
1.0	The index c_{i-1} and index c_i are equally important
1.2	The index c_{i-1} is slightly more important than index c_i
1.4	The index c_{i-1} is fairly more important than index c_i
1.6	The index c_{i-1} is strongly more important than index c_i
2.0	The index c_{i-1} is extremely more important than index c_i

Finally, the weights of indexes are calculated

$$w_i^1 = (1 + \sum_{i=2}^n \prod_{k=i}^n r_k)^{-1} \quad (9)$$

$$w_{i-1}^1 = w_i^1 \cdot r_i (i = n, n-1, \dots, 2) \quad (10)$$

where w_n^1 , w_i^1 , and w_{i-1}^1 represent the weights of the indexes c_n , c_{i-1} , and c_i using the G1 method, respectively.

3.2.2. The Entropy Method

The entropy method is based on objective data. Therefore, it can avoid personal subjective interference. Supposing the number of evaluation objects is m and the number of evaluation indexes is n , the original data matrix can be expressed as: $X = \{x_{ij}\}_{m \times n}$ ($j = 1, 2, 3, \dots, m; i = 1, 2, 3, \dots, n$).

In the process of the calculation, negative and extreme values cannot be used directly because of the concept of logarithm and entropy. Thus, the index data needs to be normalized in advance.

The normalized indexes can be divided into positive type and negative type, as shown in Equations (11) and (12):

$$y_{ij} = \frac{x_{ij} - \min(x_{ij})}{\max(x_{ij}) - \min(x_{ij})} \quad (11)$$

$$y_{ij} = \frac{\max(x_{ij}) - x_{ij}}{\max(x_{ij}) - \min(x_{ij})} \quad (12)$$

The entropy measure is calculated using the following equation:

$$E_i = -\ln(m)^{-1} \sum_{j=1}^m p_{ij} \times \ln p_{ij} \quad (13)$$

where $p_{ij} = \frac{y_{ij}}{\sum_{j=1}^m y_{ij}}$, E_i is the entropy of the i th index. It is supposed that when $p_{ij} = 0$, $\ln p_{ij} = 0$.

The weights of indexes are obtained as:

$$w_i^2 = \frac{1 - E_i}{n - \sum_{i=1}^n E_i} \quad (14)$$

where w_i^2 denotes the weight of the index x_i using entropy method.

3.2.3. Combination Weighting Rule

If L types of methods are used to assign weights to an index; a weight vector set can be constructed: $w_k^T = \{w_{k1}, w_{k2}, \dots, w_{kn}\}$, $k = 1, 2, \dots, L$. The linear combination of L weight vectors can be represented by Equation (15):

$$w = \sum_{k=1}^L \alpha_k w_k^T \quad (15)$$

where w is a possible weight vector obtained through L types of methods, and α_k is the coefficient of the k th method.

Searching for the most ideal weight vector can be aided by optimizing the coefficients α_k in the Formula (15). Based on game theory [37,38], the goal of the optimization is to minimize the deviation between w and the various w_k^T :

$$\min \left\| \sum_{k=1}^L \alpha_k w_k^T - w \right\| \quad u = 1, 2, \dots, L \quad (16)$$

The optimal first-order derivative conditions can be converted to the following linear system of equations:

$$\begin{bmatrix} w_1 \cdot w_1^T & w_1 \cdot w_2^T & \dots & w_1 \cdot w_L^T \\ w_2 \cdot w_1^T & w_2 \cdot w_2^T & \dots & w_2 \cdot w_L^T \\ \vdots & \vdots & \dots & \vdots \\ w_L \cdot w_1^T & w_L \cdot w_2^T & \dots & w_L \cdot w_L^T \end{bmatrix} \begin{bmatrix} \alpha_1 \\ \alpha_2 \\ \alpha_3 \\ \alpha_4 \end{bmatrix} = \begin{bmatrix} w_1 \cdot w_1^T \\ w_2 \cdot w_2^T \\ \vdots \\ w_L \cdot w_L^T \end{bmatrix} \quad (17)$$

$\alpha_1, \alpha_2, \dots, \alpha_L$ can be computed mathematically and normalized, as in Equation (18):

$$\alpha_k^* = \alpha_k / \sum_{k=1}^L \alpha_k \quad (18)$$

The combination weights of indexes can be obtained as:

$$w = \sum_{k=1}^L \alpha_k^* w_k^T \tag{19}$$

where w represents $(w_1, w_2, \dots, w_i, \dots, w_n)$.

3.3. Matter–Element Model

The matter–element theory has been widely applied to mathematics and system theory [39]. The matter–element model consists of objects, characteristics, and values [40]. Therefore, agricultural sustainability as the evaluation object can be regarded as a composite whole with different characteristics and corresponding values. The attribute diversity of agricultural sustainability can be assumed as an incompatibility problem. The extension method aims to solve this type of problem by combining indexes with different attributes to deduce a comprehensive result [36].

3.3.1. Determining the Matter–Element

The matter–element is the basic element to describe objects (\mathbf{R}), which is constituted of a given object (N), a characteristic (C), and the value of the characteristic (V). The matter–element is defined according to by Equation (20):

$$\mathbf{R} = (N, C, V) = \begin{bmatrix} N & c_1 & v_1 \\ & c_2 & v_2 \\ & \vdots & \vdots \\ & c_i & v_i \\ & \vdots & \vdots \\ & c_n & v_n \end{bmatrix} \quad (i = 1, 2, \dots, n) \tag{20}$$

3.3.2. Determining the Classical Domain and the Controlled Domain Matter–Element Matrix

The classical domain matter–element matrix can be expressed as Equation (21):

$$\mathbf{R}_t = (N_t, C, V_{ti}) = \begin{bmatrix} N_t & c_1 & \langle a_{t1}, b_{t1} \rangle \\ & c_2 & \langle a_{t2}, b_{t2} \rangle \\ & \vdots & \vdots \\ & c_i & \langle a_{ti}, b_{ti} \rangle \\ & \vdots & \vdots \\ & c_n & \langle a_{tn}, b_{tn} \rangle \end{bmatrix} \tag{21}$$

where t represents the t th class of agricultural sustainability. \mathbf{R}_t is the matrix of the classical domain in the t th class. N_t is the agricultural sustainability in t th class. V_{ti} is the value range of the i th index in the t th class, with the lower bound of a_{ti} and the upper bound of b_{ti} .

The controlled domain matter–element matrix can be expressed as Equation (22):

$$\mathbf{R}_p = (N, C, V_{pi}) = \begin{bmatrix} N_p & c_1 & \langle a_{p1}, b_{p1} \rangle \\ & c_2 & \langle a_{p2}, b_{p2} \rangle \\ & \vdots & \vdots \\ & c_i & \langle a_{pi}, b_{pi} \rangle \\ & \vdots & \vdots \\ & c_n & \langle a_{pn}, b_{pn} \rangle \end{bmatrix} \tag{22}$$

where R_p represents the matter–element of the controlled domain. V_{pi} is the value range of the i th index in all classes, with the lower bound of a_{pi} and the upper bound of b_{pi} .

3.3.3. Correlation Degree between Each Index and Each Class

The correlation degree determines whether one index belongs to a sustainability class and how much it belongs there. The value of the correlation degree was calculated according to the following functions.

$$K_t(x_{ij}) = \begin{cases} \frac{-\rho(x_{ij}, V_{ti})}{|V_{ti}|}, & x_{ij} \in V_{ti} \\ \frac{\rho(x_{ij}, V_{ti})}{\rho(x_i, V_{pi}) - \rho(x_i, V_{ti})}, & x_{ij} \notin V_{ti} \end{cases} \quad (23)$$

where

$$\rho(x_{ij}, V_{ti}) = \left| x_{ij} - \frac{1}{2}(a_{ti} + b_{ti}) \right| - \frac{1}{2}(b_{ti} - a_{ti}) \quad (24)$$

$$\rho(x_{ij}, V_{pi}) = \left| x_{ij} - \frac{1}{2}(a_{pi} + b_{pi}) \right| - \frac{1}{2}(b_{pi} - a_{pi}) \quad (25)$$

where x_{ij} is the value of the i th index of the j th object. $K_t(x_{ij})$ is the value of correlation degree between the i th index of the j th object and the t th class. c_{ij} belongs to the t th class if $K_t(x_{ij}) = \max [K_t(x_{ij})]$ ($t = 1, 2, \dots, o$).

Combined with the corresponding weights according to Section 3.2, the integrated correlation degree $K_t(N_j)$ between N_j and the t th class is shown in Equation (26).

$$K_t(N_j) = \sum_{i=1}^n w_i K_t(x_{ij}) \quad (t = 1, 2, \dots, o) \quad (26)$$

where N_j is the j th object and o represents the number of all the classes. In conclusion, N_j belongs to the t th class if $K_t(N_j) = \max [K_t(N_j)]$ ($t = 1, 2, \dots, o$).

4. Results

4.1. The Weights of Indexes

Subjective weights were calculated by the G1 method, as stated in Section 3.2.1. The order of the evaluation indexes is $c_4, c_2, c_7, c_6, c_1, c_{10}, c_8, c_9, c_5$, and finally, c_3 . The importance ratio assignments of the adjacent evaluations are $c_4/c_2 = 1.2$; $c_2/c_7 = 1$; $c_7/c_6 = 1$; $c_6/c_1 = 1.2$; $c_1/c_{10} = 1$; $c_{10}/c_8 = 1$; $c_8/c_9 = 1.2$; $c_9/c_5 = 1$; $c_5/c_3 = 1$. It should be noted that the G1 method is a subjective method, so that the order and ratios of the indexes have to be defined according to study site characteristics and research objectives on a case-by-case basis.

Objective weights were calculated by the entropy method, as stated in Section 3.2.2. According to the combination weighting rule, $\alpha_1 = 0.915$ and $\alpha_2 = 0.085$. Subjective weights, objective weights, and synthetic weights of indexes are shown in Table 3.

Table 3. The weights of indexes.

Index	c_1	c_2	c_3	c_4	c_5	c_6	c_7	c_8	c_9	c_{10}
w_i^1	0.095	0.114	0.079	0.137	0.079	0.114	0.114	0.095	0.079	0.095
w_i^2	0.133	0.084	0.142	0.193	0.055	0.072	0.005	0.153	0.096	0.068
w_i	0.13	0.087	0.137	0.188	0.057	0.075	0.014	0.148	0.094	0.07

4.2. The Classical Domain and the Controlled Domain

Agricultural sustainability classes reflect the degree of agricultural sustainability [41]. The degree of agricultural sustainability was divided into five classes: very low, low, moderate, high, and very high. Thus, as described in Section 3.3.2, the classical domain and the controlled domain are listed

in Table 4. The classical domain of each index was determined by data from Jinan over the past 30 years. The controlled domain was determined by minimum or maximum values of the indexes of the research site.

Table 4. The classical domain and the controlled domain.

Index	The Classical Domain					The Controlled Domain
	Very Low	Low	Moderate	High	Very High	
c_1	[0.8, 1]	[0.6, 0.8]	[0.4, 0.6]	[0.2, 0.4]	[0, 0.2]	[0, 1]
c_2	[0, 0.2]	[0.2, 0.4]	[0.4, 0.6]	[0.6, 0.8]	[0.8, 1]	[0, 1]
c_3	[0, 0.2]	[0.2, 0.4]	[0.4, 0.6]	[0.6, 0.8]	[0.8, 1]	[0, 1]
c_4	[1.6, 2]	[1.2, 1.6]	[0.8, 1.2]	[0.4, 0.8]	[0, 0.4]	[0, 2]
c_5	[25, 30]	[20, 25]	[15, 20]	[10, 15]	[0, 10]	[0, 30]
c_6	[800, 1000]	[600, 800]	[400, 600]	[200, 400]	[0, 200]	[0, 1000]
c_7	[16, 20]	[12, 16]	[8, 12]	[4, 8]	[0, 4]	[0, 20]
c_8	[2, 3]	[3, 4]	[4, 5]	[5, 6]	[6, 7]	[2, 7]
c_9	[3, 4]	[4, 5]	[5, 6]	[6, 7]	[7, 8]	[3, 8]
c_{10}	[30, 42]	[42, 54]	[54, 66]	[66, 78]	[78, 90]	[30, 90]

4.3. Determination of the Sustainability Class

For each object to be evaluated, the correlation between each index and each evaluation class can be calculated by Equations (23)–(25). For example, Table 5 shows the correlation degree and evaluation class of each index in 2015. $K_1(c_1) = -0.050$, $K_2(c_1) = -0.023$, $K_3(c_1) = 0.062$, $K_4(c_1) = -0.021$, and $K_5(c_1) = -0.038$. Thus, c_1 belongs to the moderate class because $K_3(c_1)$ is the maximum of all of the classes.

Table 5. The correlation degree and evaluation class of each index in 2015.

Index	Very Low	Low	Moderate	High	Very High	CLASSES
c_1	-0.050	-0.023	0.062	-0.021	-0.038	moderate
c_2	-0.038	-0.022	0.022	-0.009	-0.022	moderate
c_3	-0.090	-0.074	-0.043	0.050	-0.010	high
c_4	-0.111	-0.085	-0.034	0.069	-0.024	high
c_5	-0.020	-0.006	0.015	-0.014	-0.017	moderate
c_6	-0.028	-0.011	0.032	-0.014	-0.024	moderate
c_7	-0.004	0.005	-0.003	-0.007	-0.007	low
c_8	-0.100	-0.085	-0.053	0.042	-0.008	high
c_9	-0.035	-0.014	0.039	-0.018	-0.030	moderate
c_{10}	-0.044	-0.036	-0.019	0.032	-0.006	high

The correlation degree between each index and evaluation class is shown in Figure 3. Evaluation results of each index from 2006 to 2015 are shown in Table 6. For simplicity, I, II, III, IV, and V represent very low, low, moderate, high, and very high, respectively.

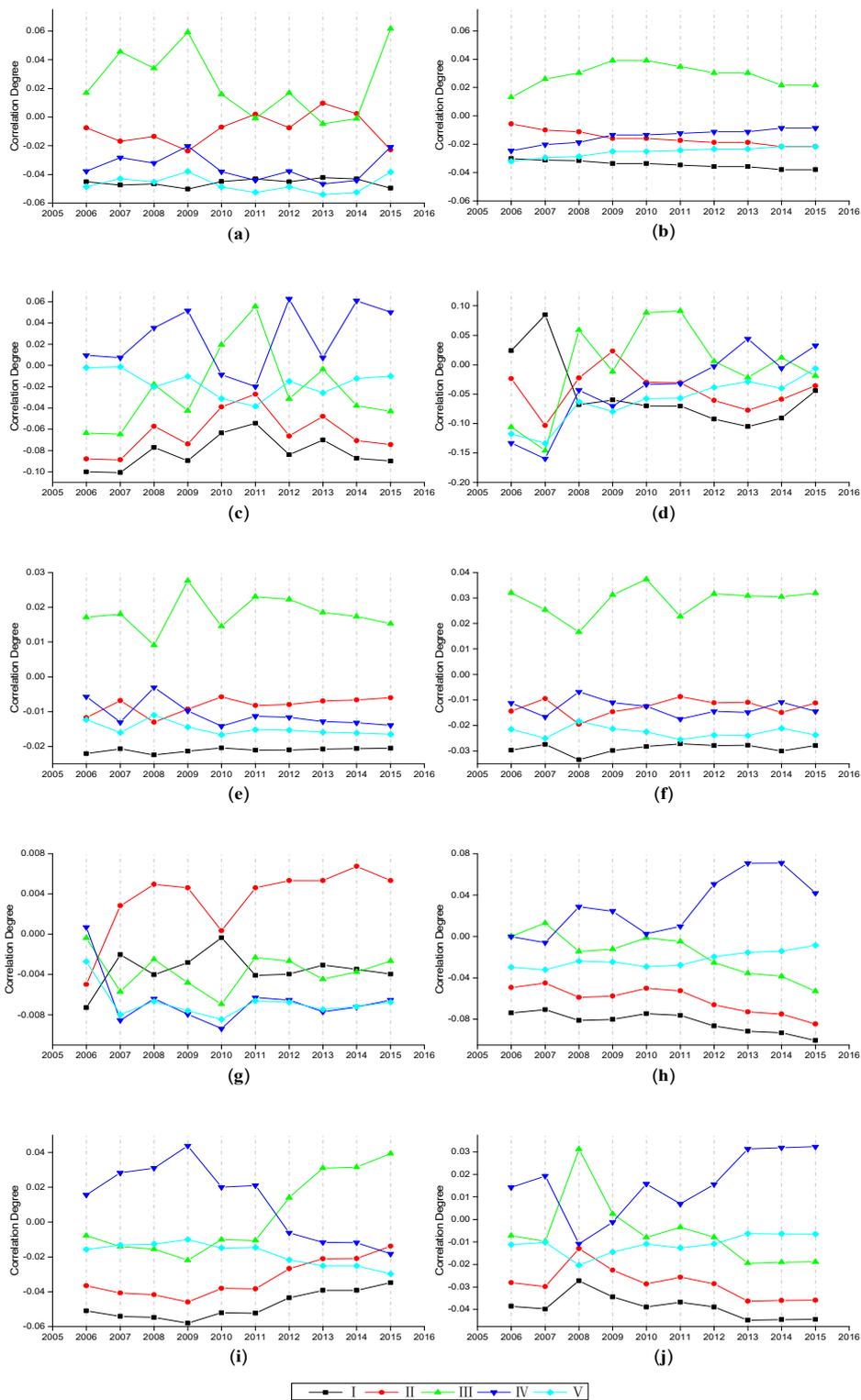


Figure 3. The correlation degree between each index and each evaluation class. (a) The correlation degree between c_1 and each class; (b) the correlation degree between c_2 and each class; (c) the correlation degree between c_3 and each class; (d) the correlation degree between c_4 and each class; (e) the correlation degree between c_5 and each class; (f) the correlation degree between c_6 and each class; (g) the correlation degree between c_7 and each class; (h) the correlation degree between c_8 and each class; (i) the correlation degree between c_9 and each class; (j) the correlation degree between c_{10} and each class.

Table 6. The evaluation class of each index in 2006–2015.

Index	2006	2007	2008	2009	2010	2011	2012	2013	2014	2015
c_1	III	III	III	III	III	II	III	II	II	III
c_2	III									
c_3	IV	IV	IV	IV	III	III	IV	IV	IV	IV
c_4	I	I	III	II	III	III	III	IV	III	IV
c_5	III									
c_6	III									
c_7	IV	II								
c_8	III	III	IV							
c_9	IV	IV	IV	IV	IV	IV	III	III	III	III
c_{10}	IV	IV	III	III	IV	IV	IV	IV	IV	IV

Combined with the corresponding weights in Table 3, the integrated correlation degree between each year and evaluation class was calculated by Equation (26), as shown in Figure 4. Thus, the final evaluation results of every year were obtained as shown in Table 7.

Table 7. The integrated correlation degree and evaluation class of 2006–2015.

Object	Very Low	Low	Moderate	High	Very High	Classes
2006	−0.374	−0.270	−0.105	−0.172	−0.293	moderate
2007	−0.310	−0.348	−0.112	−0.197	−0.312	moderate
2008	−0.447	−0.246	0.130	−0.026	−0.250	moderate
2009	−0.460	−0.236	0.067	−0.014	−0.246	moderate
2010	−0.427	−0.227	0.189	−0.091	−0.265	moderate
2011	−0.420	−0.202	0.205	−0.106	−0.274	moderate
2012	−0.477	−0.28	0.0363	0.032	−0.227	moderate
2013	−0.480	−0.277	0.021	0.049	−0.226	high
2014	−0.490	−0.295	0.013	0.062	−0.217	high
2015	−0.521	−0.351	0.018	0.110	−0.186	high

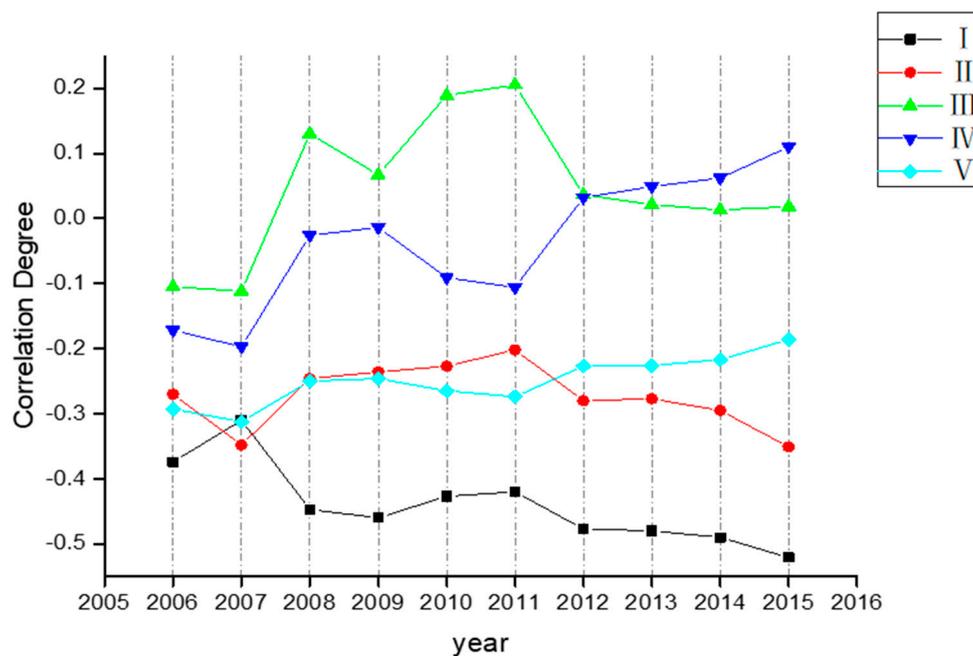


Figure 4. The integrated correlation degree between each year and evaluation class.

5. Analysis and Discussion

The level of agricultural sustainability was promoted from class III to class IV in 2013 (Table 7), and the level was steady in class III before 2013. A higher degree of correlation to a given class indicates that the state in a given evaluation class is more stable, or that there is a greater tendency to convert to this class. Thus, it is worth noting that the integrated correlation degree of class IV was continuously increasing in 2013–2015 (Figure 2). It indicates that the state of agricultural sustainability in class IV was more and more stable. In the meantime, in regard to the other classes, the integrated correlation degree of class V was also growing, whereas the integrated correlation degree of class III was constant. Cumulatively, reflecting that agricultural sustainability was in a comparatively positive trend.

The above-mentioned analysis path can be extended to analyze the sustainable development of each index. The index c_1 (agricultural blue water proportion) was switching back and forth between class II and class III. Besides, there was no obvious upward trend for the correlation degree of class IV. The evaluation result of c_3 (irrigation proportion of arable land) was one class higher than that of c_1 . The trends of those two indexes were similar. This shows that the dependencies of agriculture on irrigation and irrigation intensity have not been effectively alleviated in recent years. The index c_2 (water-use efficiency) ranked class IV in all the years and the correlation degree to class V kept increasing. This shows that water-use efficiency was improved. The improvement of water-use efficiency benefited from the renovation of irrigation infrastructure and the optimization of irrigation methods (i.e., sprinkler or drip irrigation) in the Chenmengquan irrigation district. The index c_4 (energy utilization for irrigation amount per arable land) experienced a leap from class I to class IV in 10 years, which can be attributed to the increase of the groundwater table caused by the regional groundwater protection by the administrative department [42]. The indexes c_5 (agricultural machinery power per arable land) and c_6 (fertilizer utilization amount per arable land) were both in class III all the time and their correlation degrees to class III were significantly higher than those to other classes. This suggests that the sustainability classes of c_5 and c_6 will not change in the short term. The amount of fertilizer utilization did not decrease effectively. Except for 2006, c_7 (pesticide utilization amount per arable land) was always in class II and the correlations to the two adjacent classes were still much lower than class II. It performed the worst of all the indexes. Regarding the use of pesticide, adequate attention should be paid by the administrative department. In the period 2010–2015, c_8 (yield per unit area of wheat) and c_{10} (yield per unit area of vegetable) were both in class IV, and both of their correlation degrees with class IV, were getting close to the correlation degrees of class V. Those results showed that the productivity of wheat and vegetables was gradually increasing. However, the productivity of maize was getting worse, which can be demonstrated by the fact that c_9 (yield per unit area of maize) dropped down from class IV to class III after 2012.

In addition, the sensitivity of the indexes was analyzed in this research. The simplest form of sensitivity analysis includes varying one index by a given amount at a time in the model and examining the impact of such change on the result of the model [43]. Consider that agricultural sustainability consists of multiple indexes which have different attributes. Each index value was given certain changes (−5%, −10%, +5%, and +10%) in double-directions [44]. The evaluation result of agricultural sustainability in 2015 did not change with the variations of the indexes. However, the evaluation results of c_2 , c_8 , c_9 , and c_{10} were changed, as shown in Table 8. Compared with other indexes, these four indexes had higher sensitivities. The variations of c_8 (yield per unit area of wheat), c_9 (yield per unit area of maize), c_{10} (yield per unit area of vegetable), and c_2 (water-use efficiency) had a strong influence on the evaluation results of corresponding indexes.

It is worth noting that the proposed procedure cannot be generalized to other contexts and should be considered site-specific. The indexes need to be selected according to the characteristics of the agriculture in other research regions.

Table 8. Evaluation results with index variations in 2015.

Index	Variation Range				
	−5%	−10%	+5%	+10%	0
c_2	III	III	III	IV	III
c_8	IV	IV	V	V	IV
c_9	III	II	III	III	III
c_{10}	IV	III	IV	V	IV

6. Conclusions

This paper proposes an index-based approach to evaluate agricultural sustainability in a given area based on the concept of the WEFN. The index system was established in the dimensions of agricultural water use, the intensity of agricultural energy use, and food productivity. The index system can not only reflect the agricultural sustainability comprehensively, but also avoid the influence of scale variation. In this premise, the evaluation approach integrated the combination weighting method and the matter–element model. The matter–element model was applied to quantify the fuzzy concept of agricultural sustainability. The combination weighting method gave each index a more scientific weight. The methodology was implemented in a case research, on an irrigation district in Jinan City of China, which is characterized by highly intensive agricultural practices. The results show the evaluation classes of agricultural sustainability in the study area. From 2006 to 2012, the level of agricultural sustainability was class III (moderate). From 2013 to 2015, the level of agricultural sustainability was class IV (high). At the same time, the results indicate the trend of the state change and the single index information. The agricultural sustainability was in a comparatively positive trend after 2012. Excessive use of pesticides was a shortcoming of agricultural practices in the study area. The results derived from the sensitivity analysis indicated that c_2 (water-use efficiency), c_8 (yield per unit area of wheat), c_9 (yield per unit area of maize), and c_{10} (yield per unit area of vegetable) had higher sensitivities. The research results could be applied both for scientific and decision-making purposes. The methodology is suitable to evaluate agricultural sustainability.

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