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Study on the environmental efficiency of agricultural water resources about typical cropping patterns around the Dongting Lake area

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ABSTRACT

This paper aims to evaluate the environmental efficiency of agricultural water resources utilization in different cropping patterns in the Dongting Lake area. To achieve that, the following materials are used: (1) study area: 16 counties (cities and districts) of Yueyang, Changde, and Yiyang around the Dongting Lake area; (2) data: relevant indicators of economic and environmental benefits of agricultural water resources utilization from 2011 to 2020; and (3) model: the Luenberger productivity model based on the directional distance function. With all the materials above, this paper calculates the environmental efficiency of typical cropping patterns in the Dongting Lake ecological zone and explores the spatial and temporal evolution patterns of typical cropping patterns in the lake area. The results show that (1) the environmental efficiency (LEI) of four typical cropping patterns in 16 counties (cities and districts) around Dongting Lake shows an overall increasing trend from 2011 to 2020, especially the environmental efficiency of four cropping patterns has increased significantly since 2014. (2) Among the four typical cropping patterns, the environmental efficiency of one-season rice + lobster is higher, and the environmental efficiency value of two-season rice + winter leisure is lower but most significantly improved. (3) The environmental efficiency of agricultural water resources in the hilly areas around the lake is higher than that in the Dongting Plain. Finally, some countermeasures and suggestions were put forward, such as implementing the reduction and efficiency of pesticide and chemical fertilizer in the planting industry in the lake area, optimizing the rice + planting mode, strengthening the construction of water conservation projects in the four river basins, and promoting high-standard farmland water-saving irrigation.

Key words: agricultural water resources, Dongting Lake area, environmental efficiency, Luenberger environmental indicators, planting mode

HIGHLIGHTS

- To improve the efficiency of agricultural water resources and environmental use, establish an index system for the economic and environmental benefits of agricultural water resources use in the lake area.
- Application of the Luenberger productivity model based on the directional distance function to calculate the environmental efficiency of typical cropping patterns in the ecological zone around Dongting Lake.
- To explore the spatial and temporal evolution of the environmental efficiency of typical cropping patterns in the lake area, and to propose a series of countermeasures for the cropping industry in the lake area.

INTRODUCTION

The National Water Conservation Action Plan which was issued by the National Development and Reform Commission and the Ministry of Water Resources in 2019 emphasizes the vigorous promotion of agricultural water-saving irrigation and optimal adjustment of crop planting patterns as key measures to promote agricultural water conservation, increase efficiency, and improve the use of agricultural water resources (Fu *et al.* 2012). Affected by the water regulation and storage of the Three Gorges Project in the upper reaches of the Yangtze River, in recent years, the Dongting Lake basin has the problems of lake shrinkage, water sediment imbalance, and decline of regulation and storage function, and the problems of water ecology and water environment. As an important rice producing area in China, the Dongting Lake area used 19.58 billion cubic meters of grain irrigation water in 2020, accounting for 64.2% of the total annual water consumption. The total nitrogen (121,900 tons) and total phosphorus (9,500 tons) of agricultural wastewater were the main sources of water environmental pollution in the Dongting Lake area. Due to the differences in economic efficiency, water resources utilization, wetland or forest ecological resources of main agricultural land types around Dongting Lake, there were spatial differences in the environmental efficiency of different agricultural land types (Hu *et al.* 2017). Therefore, under the condition of ensuring effective food supply and appropriate economic return in the Dongting Lake area, improving the environmental efficiency of agricultural water resources utilization of food production was an urgent problem to be solved. The Luenberger productivity index model based on directional distance function was selected to study the relationship between economic return and environmental pressure of agricultural water resources utilization of the four planting modes in counties around Dongting Lake: (1) one-season rice + oilseed rape; (2) one-season rice + lobster; (3) one-season rice + vegetables; and (4) double-season rice + winter fallow. Besides, it also deeply explored the spatial differences of environmental efficiency of agricultural water resources utilization in different regions, so as to provide a reference for the adjustment of planting structure in the Dongting Lake area. Therefore, the utilization of agricultural water resources can provide a decision-making basis, which had practical guiding significance for maintaining food security and water ecological security in the Dongting Lake area (Hsiao *et al.* 2007).

The research on environmental efficiency was first proposed by Schaltegger and Sturm in 1990. Environmental efficiency includes two dimensions: economy and environment. Its core idea is to maximize economic value and minimize environmental impact. Chambers and Chung *et al.* creatively developed the Malmquist productivity index into the Malmquist-Luenberger productivity index by introducing the directional distance function based on the Shepard distance function (Chambers *et al.* 1996; Chung *et al.* 1997). At this stage, the measurement of domestic agricultural water use efficiency mainly includes single factor productivity evaluation and total factor productivity evaluation; the single factor productivity evaluation mainly includes water consumption per unit of agricultural output value, agricultural irrigation water use coefficient, and water use intensity coefficient (Hong *et al.* 2017); and the total factor productivity mainly includes the DEA-Malmquist index method (Liao & Dong 2011; Li, & Zhang 2016; Lu & Xu 2017; Gu *et al.* 2021), the super-efficient SBM-DEA model (Li 2014; Liu *et al.* 2022), and the Luenberger index method (Azad & Ancev 2014). In terms of the selection of the study area, Deng, etc., used 31 Chinese provinces as the study area to study the efficiency of water resources utilization in each province (Deng *et al.* 2016; Wang *et al.* 2019; Zhu & Lu 2022); Liu *et al.* used 17 cities and states under the jurisdiction of Hubei province as the samples, and used the DEA to calculate the efficiency evaluation index of water resources utilization in each city and state, and Luo *et al.* used the Yangtze River Economic Belt as the research objective and analyzed the spatial and temporal differences in the efficiency of agricultural water resources in the Yangtze River Economic Belt and its influencing factors (Liu *et al.* 2007); Zhang *et al.* used 68 prefecture-level administrative units in the Yellow River Basin as the research object and measured their water resources efficiency (Zhang & Sun 2021). For water resources development and utilization in arid regions, Zhang *et al.* took the Hotan region in Xinjiang as the research object and studied the development and utilization of regional water resources (Zhang *et al.* 2022).

Under the framework of total factor productivity, scholars use the DEA-Malmquist-Luenberger model to study the change of environmental efficiency, bring the relationship between ecological and economic systems into a unified analysis framework, and reveal the development law of the composite system composed of agricultural resource utilization, agricultural development, and ecological environment. The Malmquist-Luenberger model is a ratio-based index, which is mainly applied to evaluate the change of environmental efficiency in production units. The Luenberger productivity index can be applied not only to estimate the change of environmental efficiency of production units over a period, but also to evaluate the difference of environmental efficiency of a series of production units alone. It is a difference-based index. Due to the differences in water resources supply, planting pattern, and total pollution emission in various regions, there may be great differences in agricultural economic efficiency and environmental efficiency in various regions. In summary, most of the current studies are focused on one particular province, and relatively few studies have used the Luenberger index model to study the efficiency of agricultural water use in the Dongting Lake area, especially for cities within a province.

In this paper, the total water resources input and production cost (excluding water) of different planting modes around Dongting Lake during 2011–2020 are selected as input indicators, and the Gross revenue of each planting mode and the total amount of nitrogen and phosphorus discharge of agricultural wastewater are selected as output indicators. The Luenberger environmental productivity index (LEI) model based on the directional distance function is applied to calculate the environmental efficiency of the four typical planting patterns in 16 counties around Dongting Lake during 2011–2020. With all conditions above, this paper explores the spatial and temporal evolution patterns of environmental efficiency of four typical cropping patterns in 16 counties around Dongting Lake from 2011 to 2020 and proposes countermeasures for the cropping patterns in 16 counties around Dongting Lake.

MATERIALS AND METHODS

Study area

Dongting Lake is the second largest freshwater lake in China, the largest inland wetland in Asia, and a nationally important commodity grain, cotton, oil, livestock, poultry, and aquatic products production base, bears the great responsibility of guaranteeing national food security and water ecological safety in the Yangtze River basin. The Dongting Lake area is in the north of Hunan Province and the south bank of Jingjiang River in the middle reaches of the Yangtze River, which is the ecotone of southeast monsoon and southwest monsoon. The total drainage area is 257,200 km^2. There is plenty of rain, a dense river network, and an annual average rainfall of 1,200–1,450 mm.

This paper takes 16 counties in Yueyang, Changde, and Yiyang of Hunan Province as the research area. In 2011, the grain crops planting area of the 16 counties around Dongting Lake was 1,153,000 hm^2, accounting for 23.6% of the total planting area of grain crops in Hunan Province, and the total grain output is 6.68 million tons, accounting for 23.8% of the total grain output in Hunan Province. In 2020, the grain crops planting area of the 16 counties was 1,572,000 hm^2, accounting for 31.3% of the total planting area of grain crops in Hunan Province, and the total grain output is 8.20 million tons, accounting for 33% of the total grain output in Hunan Province. One-season rice + oilseed rape, one-season rice + lobster, one-season rice + vegetables, and double-season rice + winter fallow are the main planting modes around Dongting Lake. Typical agricultural counties (cities and districts) around the Dongting Lake area are shown in Figure 1.

Data sources, indexes selection, and data description

The basic input–output data of the planting industry around the Dongting Lake area are from 2011 to 2020 Hunan Rural Statistical Yearbook, Hunan water resources bulletin, and the water resources bulletin of Yueyang City, Yiyang City, and Changde City, respectively.

In October 2021, Hunan Yueyang Rural Development Research Center widely collected the land use types, main planting modes, agricultural production, geology, hydrology, and agricultural non-point source pollution around the Dongting Lake area through expert discussion and field investigation.

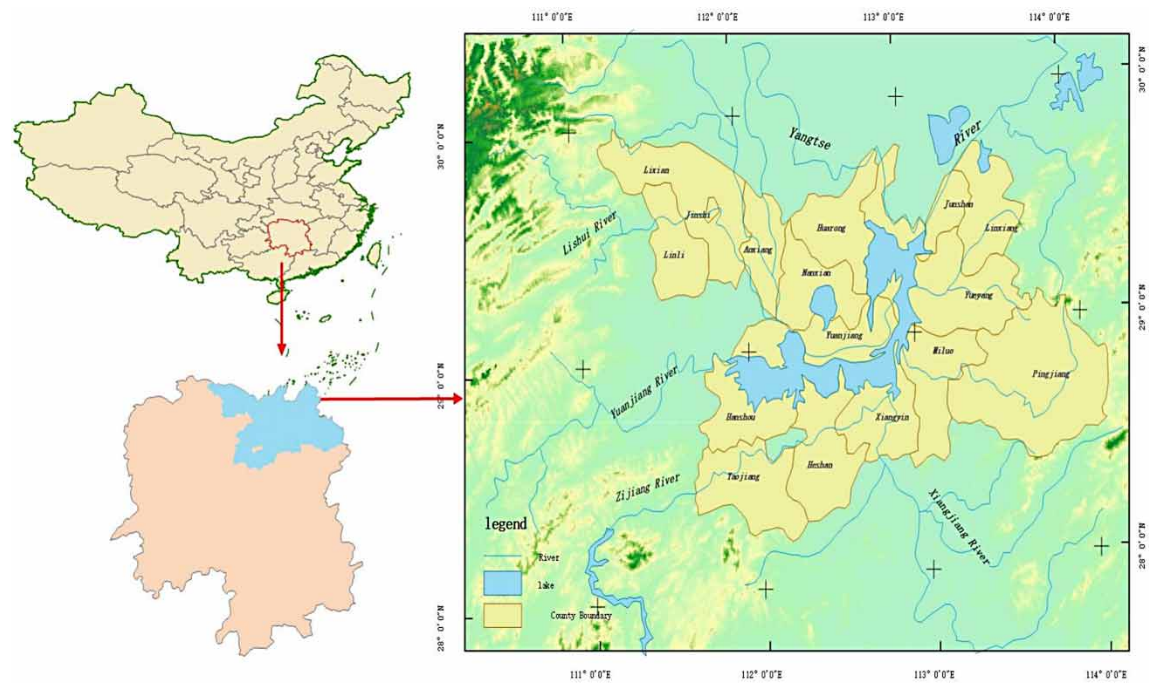

Figure 1 | Typical agricultural counties (cities, districts) around the Dongting Lake area.

According to the situation of agricultural water use, input–output of different planting modes and agricultural non-point source pollution around the Dongting Lake area, and following the principles of data availability and operability, the model selects the utilization of water resources and production cost excluding water as the main input indicators, the gross revenue as the desirable output, and the total nitrogen and phosphorus discharge of agricultural wastewater as the undesirable output. The main input indicators select the agricultural water consumption of counties around the Dongting Lake area under four main planting modes per unit area, and other inputs excluding irrigation water cost as production cost input (production cost includes land transfer fee, labor fee, electricity fee, land consolidation, harvesting machinery, drying fee, seed, pesticide, fertilizer, and other means of production). According to the Dongting Lake water, an environment detection report provided by Hunan Dongting Lake Ecological Environment Monitoring Center, the agricultural water environment pollution of Dongting Lake is mainly reflected in the excessive total nitrogen and phosphorus emission. Therefore, the unexpected output indicators in this paper mainly select the total nitrogen and phosphorus emissions of agricultural wastewater per unit area, and use the nitrogen and phosphorus emissions indicators to measure the pressure of agricultural non-point source pollution on the water environment. The input–output indicators of the main cropping patterns in the Dongting Lake area from 2011 to 2020 and their average values are shown in Table 1.

Productivity model with the regional directional environmental distance function (DEDF model)

The data envelopment analysis method (DEA) does not need to determine the function relationship in advance and adopts the non-subjective weighting method, so as to avoid the influence of the distance factor of subjective decision-making unit (DMU). It can realize the multi-input and multi-output water resources utilization efficiency measurement without considering the dimensions of input and output.

Directional distance function

The Luenberger productivity index is constructed based on the directional distance function. The use of the directional distance function in the efficiency model enables us to measure the efficiency of production units, considering the desirable output and the undesirable output of production technology.

Suppose a DMU uses input vectors $x = (x_1, \ldots, x_N) \in R_+^N$, the desired output is $d = (d_1, \ldots, d_M) \in R_+^M$, and the undesired output is $u = (u_1, \ldots, u_j) \in R_+^J$, so that $P(x)$ is the set of production possibilities for a given input vector x. The set of outputs can be described as:

$$P(x) = \{(d, u)|x \text{can produce} (d, u)\},\ x \in R_+^N \tag{1}$$

and a good environmental technology must satisfy the following four conditions: closed and convex sets, input and 'good' outputs can be free disposal, joint weak disposability, and zero combination of good and bad outputs. The DEA model satisfying the above conditions is set up as follows. In this paper, let each sample region be a decision unit, then there are k regions $k \in (1 - 16)$ around Dongting Lake, and the time period is 2011–2020, and assume that the input and output vectors of K decision units in the period $t = 1, \ldots T$ are $(x^{k,t}, d^{k,t}, u^{k,t})$, using these data, we can construct an output set that satisfies

Table 1 | Average value of economic and environmental variables of the main planting patterns in 2011–2020

Planting patterns	Water resources utilization (m^3 ha^{-1})	Production costs (Excluding water) Yuan (ha^{-1})	Gross revenue Yuan (ha^{-1})	Total N, P discharge of agricultural wastewater (kg ha^{-1})
One-season rice + oilseed rape	3,967.5	14,259	29,883	196.9
One-season rice + vegetable	4,513.75	18,933.75	58,331.25	201.3
One-season rice + lobster	5,405	40,006	79,348	105.6
Double cropping rice + winter fallow	6,555	9,569.34	32,886	254.1

the above four conditions and (1):

$$\begin{aligned} P^t(x^t) = \{(d^t, u^t)\colon &\sum_{k=1}^{K} z_k^t d_{mk}^t \geq d_m^t \quad m = 1, \ldots, M \\ &\sum_{k=1}^{K} z_k^t d_{jk}^t = d_j^t \quad j = 1, \ldots, J \\ &\sum_{k=1}^{K} z_k^t x_{nk}^t \leq x_n^t \quad n = 1, \ldots, N \\ &z_k^t \geq 0, \quad k = 1, \ldots K\} \end{aligned} \tag{2}$$

In the above constraint, z_k^t are the weight variables set for each observation in order to construct the production possibility frontier, and they represent the weights assigned to individual observations in the construction of the production possibility frontier. So the directional distance function can be written as follows:

$$\vec{D}_o(x, d, u; g_d, -g_u) = \sup\{\beta\colon (d + \beta, g_d, u - \beta, g_u) \in P(x)\} \tag{3}$$

where g is the directional vector of expansion, indicating that the desired output is increasing and the undesired output is decreasing. β indicates the maximum possible value of the desired output and undesired output, and its smaller value indicates that the observation is closer to the production frontier surface, which is equal to 0, indicating that the decision unit is located on the production frontier surface and is fully efficient.

Under the above setting of the possible set of environmentally efficient production, combined with the directional distance function, four directional distance functions can be constructed. $D_o^t(x^t, d^t, u^t; g_d^t, -g_u^t)$ denotes the number of times that output d^t and u^t can be expanded given x^t in the case of period t technology, $D_o^{t+1}(x^t, d^t, u^t; g_d^t, -g_u^t)$ denotes the number of times that output d^t and u^t can be expanded given x^t in the case of period $t+1$ technology, $D_o^t(x^{t+1}, d^{t+1}, u^{t+1}; g_d^{t+1}, -g_u^{t+1})$ denotes the number of times that output d^{t+1} and u^{t+1} can be expanded given x^{t+1} in the case of period t technology, $D_o^{t+1}(x^{t+1}, d^{t+1}, u^{t+1}; g_d^{t+1}, -g_u^{t+1})$ denotes the number of times that output d^{t+1} and u^{t+1} can be expanded given x^{t+1} in the case of period $t+1$ technology. Therefore, the expression for the Luenberger productivity index from period t to period $t+1$ is:

$$\begin{aligned} \mathrm{LPI}_t^{(t+1)} = &\frac{1}{2}[\vec{D}_o^{t+1}(x^t, d^t, u^t; g_d^t, -g_u^t) - \vec{D}_o^{t+1}(x^{t+1}, d^{t+1}, u^{t+1}; g_d^{t+1}, -g_u^{t+1}) \\ &+ \vec{D}_o^t(x^t, d^t, u^t; g_d^t, -g_u^t) - \vec{D}_o^t(x^{t+1}, d^{t+1}, u^{t+1}; g_d^{t+1} - g_u^{t+1})] \end{aligned} \tag{4}$$

Here the subscript o of the distance function indicates constant payoffs to scale, and LPI greater (less) than 0 indicates environmental productivity growth (decline), respectively. The four directional distance functions involved in Equation (4) above can be obtained by solving the following linear program:

$$\begin{aligned} &D_o^t(x^t, d^t, u^t; g_d^t, -g_u^t) = \max \beta \\ &\text{s.t.} \\ &\sum_{k=1}^{K} z_k^t d_{mk}^t \geq (1+\beta) d_m^t, \quad m = 1, \ldots, M \\ &\sum_{k=1}^{K} z_k^t d_{jk}^t = (1-\beta) d_j^t, \quad j = 1, \ldots, J \\ &\sum_{k=1}^{K} z_k^t x_{nk}^t \leq x_n^t, \quad n = 1, \ldots, N \\ &\sum_{k=1}^{K} z_k^t x_{nk}^t \leq x_n^t, \quad n = 1, \ldots, N \\ &z_k^t \geq 0, \quad k = 1, \ldots, K \end{aligned} \tag{5}$$

Regional directional environmental distance function

In the measurement of environmental efficiency in 2020, the directional distance function is taken as *a* region, and the cross-sectional data of 16 counties (cities and districts) around Dongting Lake in 2020 are used instead of time-series data. Combining the above conditions as well as assumptions, the directional distance function of region *a* can be written as follows:

$$\vec{D}_o^a(x^a, d^a, u^a; g_d, -g_u) = \sup\{\beta:(d^a + \beta, g_d, u^a - \beta, g_u) \in p^a(x^a)\} \tag{6}$$

Taking region *a* as the reference, the output-oriented Luenberger environmental index in region *b* can be expressed as:

$$\begin{aligned} \mathrm{LEI}_a^b = \frac{1}{2}[&\vec{D}_o^b(x^a, d^a, u^a; g_d, -g_u) \\ &-\vec{D}_o^b(x^b, d^b, u^b; g_d, -g_u) \\ &+\vec{D}_o^a(x^a, d^a, u^a; g_d, -g_u) \\ &-\vec{D}_o^a(x^b, d^b, u^b; g_d, -g_u)] \end{aligned} \tag{7}$$

where $D_o^a(x^a, d^a, u^a; g_d^a, -g_u^a)$ denotes the number of times that output d^a and u^a can expand given x^a, given the production technology in region *a*; $D_o^b(x^a, d^a, u^a; g_d^a, -g_u^a)$ denotes the number of times that output d^a and u^a can expand given x^a, given the production technology in region *b*; $D_o^a(x^b, d^b, u^b; g_d^b, -g_u^b)$ denotes the number of times that output d^b and u^b can expand given x^b, given the production technology in region *a*; $D_o^b(x^b, d^b, u^b; g_d^b, -g_u^b)$ denotes the number of times that output d^b and u^b can expand given x^b, given the production technology in region *b*. Therefore, the four components of the Luenberger environmental index are calculated as follows:

$$\begin{aligned} &\vec{D}_o^b(x^{k',a}, d^{k',a}, u^{k',a}, g_d, -g_u) = \max\beta \\ \text{s.t.} &\sum_{k=1}^{k} z_k^b d_{km}^b \geq d_{k'm}^a + \beta g_{dm}, \quad m = 1, \ldots, M \\ &\sum_{k=1}^{4} z_k^b u_{kj}^b = u_{k'j}^a - \beta g_{uj}, \quad j = 1, \ldots J \\ &\sum_{k=1}^{4} z_k^b x_{kn}^b \leq x_{k'n'}^a, \quad n = 1, \ldots, N \\ &z_k^b \geq 0, \quad k = 1, \ldots, K \end{aligned} \tag{8}$$

$$\begin{aligned} &\vec{D}_o^b(x^{k',b}, d^{k',b}, u^{k',b}, g_d, -g_u) = \max\beta \\ \text{s.t.} &\sum_{k=1}^{k} z_k^b d_{km}^b \geq d_{k'm}^b + \beta g_{dm}, \quad m = 1, \ldots, M \\ &\sum_{k=1}^{4} z_k^b u_{kj}^b = u_{k'j}^b - \beta g_{uj}, \quad j = 1, \ldots J \\ &\sum_{k=1}^{4} z_k^b x_{kn}^b \leq x_{k'n'}^b, \quad n = 1, \ldots, N \\ &z_k^b \geq 0, \quad k = 1, \ldots, K \end{aligned} \tag{9}$$

$$\vec{D}_o^a(x^{k',a}, d^{k',a}, u^{k',a}, g_d, -g_u) = \max\beta$$

$$\begin{aligned}
\text{s.t.} \sum_{k=1}^{k} z_k^a d_{km}^a &\geq d_{k'm}^a + \beta g_{dm}, \quad m = 1, \ldots, M \\
\sum_{k=1}^{4} z_k^a u_{kj}^a &= u_{k'j}^a - \beta g_{uj}, \quad j = 1, \ldots J \\
\sum_{k=1}^{4} z_k^a x_{kn}^a &\leq x_{k'n'}^a, \quad n = 1, \ldots, N \\
z_k^a &\geq 0, \quad k = 1, \ldots, K
\end{aligned} \tag{10}$$

$$\vec{D}_o^a(x^{k',b}, d^{k',b}, u^{k',b}, g_d, -g_u) = \max\beta$$

$$\begin{aligned}
\text{s.t.} \sum_{k=1}^{k} z_k^a d_{km}^a &\geq d_{k'm}^b + \beta g_{dm}, \quad m = 1, \ldots, M \\
\sum_{k=1}^{4} z_k^a u_{kj}^a &= u_{k'j}^b - \beta g_{uj}, \quad j = 1, \ldots J \\
\sum_{k=1}^{4} z_k^a x_{kn}^a &\leq x_{k'n'}^b \quad n = 1, \ldots, N \\
z_k^a &\geq 0, \quad k = 1, \ldots, K
\end{aligned} \tag{11}$$

The relative environmental efficiency of the four main cropping patterns in the typical ecological zone around Dongting Lake can be calculated by the above equation. The environmental efficiency scores of the major cropping patterns around the Dongting Lake area are estimated using the Luenberger environmental indicator (LEI) method and the efficiency scores are calculated using data envelopment analysis DEA. The results estimated using the traditional Luenberger productivity indicator can be either positive or negative, with positive signs indicating productivity increases and most efficiency increases, and negative signs indicating productivity and efficiency decreasing over time. Unlike the traditional Luenberger productivity indicator, the Luenberger environmental indicator in this paper does not produce negative values because it uses a positive value of the Luenberger environmental indicator for a different region to compare with the worst performing region in this area, which means that the environmental efficiency of irrigated firms in the given region is bigger than that of the reference region. By using DEA and DEA software to calculate the efficiency values of four typical cropping patterns in each region and the environmental efficiency of each cropping pattern in 16 counties, the calculation results and analysis are as follows.

RESULTS AND DISCUSSION

The Luenberger environmental productivity index model based on the directional distance function is used to calculate the environmental efficiency of four typical cropping patterns in 16 counties (cities and districts) around Dongting Lake from 2011 to 2020 by Equations (2)–(5). The environmental efficiency in 2020 is calculated by Equations (6)–(11). To analyze the spatial and temporal evolution of the four typical cropping patterns from 2011 to 2020, and to further investigate the spatial differences in the environmental efficiency of 16 counties (cities and districts) around Dongting Lake in 2020, the conclusions of the empirical study are as follows.

The overall environmental efficiency (LEI) of four typical cropping patterns in 16 counties (cities and districts) around Dongting Lake from 2011 to 2020 showed an upward trend

As shown in Figure 2, the overall ranking of the environmental efficiency of water resources of four typical cropping patterns in 16 counties (cities and districts) around Dongting Lake from 2011 to 2020 is one-season rice + lobster > one-season rice + oilseed rape > one-season rice + vegetables > double-season rice + winter leisure. Specifically, (1) from 2011 to 2014, the environmental efficiency values of the four cropping patterns were low and fluctuated unstably. Since 2014, when the ecological economic zone of Dongting Lake was elevated to a national strategy, the lake area began to focus on green food

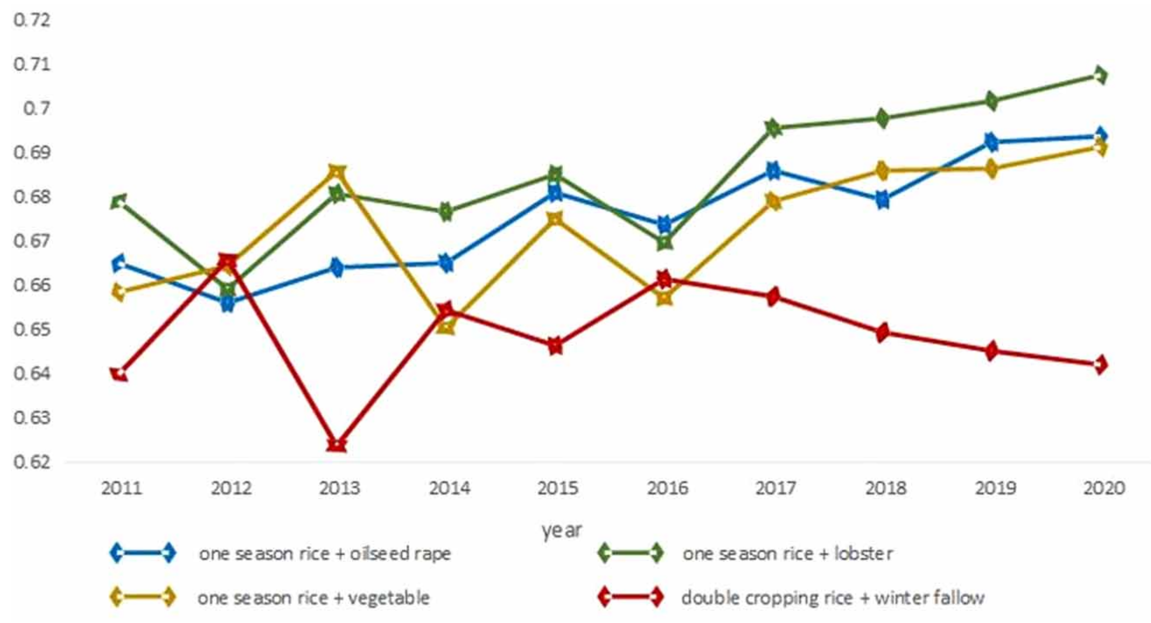

Figure 2 | Trend of environmental efficiency of four typical cropping patterns in the Ring of Dongting Lake from 2011 to 2020.

production and water resource utilization efficiency to strengthen the production of food crops and the development, utilization, and protection of water resources, so the environmental efficiency values of the four planting patterns in the lake area have been improved to some extent since 2014. In 2016, Hunan Province issued the Regulations on Comprehensive Agricultural Development in Hunan Province, and the counties and urban areas around Dongting Lake, and began to fully promote four typical planting models for intensive use of water resources and land, which improved land utilization in the lake area. Therefore, the overall environmental efficiency of the four planting patterns has increased significantly since 2016, especially the one-season rice + lobster planting pattern. From 2016 to 2020, the environmental efficiency of the remaining three cropping patterns showed a steady upward trend, except for double-season rice + winter leisure. (2) In order to reflect the spatial and temporal evolutionary trends of four typical cropping patterns more intuitively in 16 counties (cities and districts) around Dongting Lake, this paper used ArcGIS10.5 software to plot the spatial distribution trends of four typical cropping patterns in 16 counties (cities and districts) around Dongting Lake in 2011 and 2020, respectively. As shown in Figure 3, the environmental efficiency in 2020 is significantly improved compared with 2011. From 2011 to 2020, comparing the four cropping patterns, the environmental efficiency of the double-season rice + winter leisure pattern has improved the most significantly. It indicates that although the environmental efficiency value of double-season rice + winter leisure is lower among the four cropping patterns, combined with the policies and rectification efforts in the lake area in recent years, the results above show that the lake area has been actively improving and adjusting the cropping pattern, and the effect is remarkable.

Significant differences in environmental efficiency (LEI) of four typical cropping patterns in 16 counties (cities and districts) around Dongting Lake in 2020

As shown in Table 2, the better relative environmental efficiency of the one-season rice + rape cultivation model is in Pingjiang County and Xiangyin County, with environmental efficiency scores of 0.946 and 0.92, respectively, and the worst is in Huarong County, with an environmental efficiency value of 0.423. The better relative environmental efficiency of the one-season rice + lobster cultivation model is in Xiangyin County and Nan County, with environmental efficiency scores of 0.975 and 0.915, respectively, and the worst is in Hanshou County, with an environmental efficiency value of 0.414. The better relative environmental efficiency of the one-season rice + vegetable cultivation model is in Junshan and Xiangyin counties, with environmental efficiency scores of 0.926 and 0.91, respectively, and the worst is in Taojiang County, with an environmental efficiency score of 0.405. The better relative environmental efficiency of the two-season rice + winter leisure cultivation model is in Li County and Linxiang City, with environmental efficiency scores of 0.765 and 0.765, respectively. Overall, among the 16 counties (cities and districts) around Dongting Lake, those with better environmental efficiency are

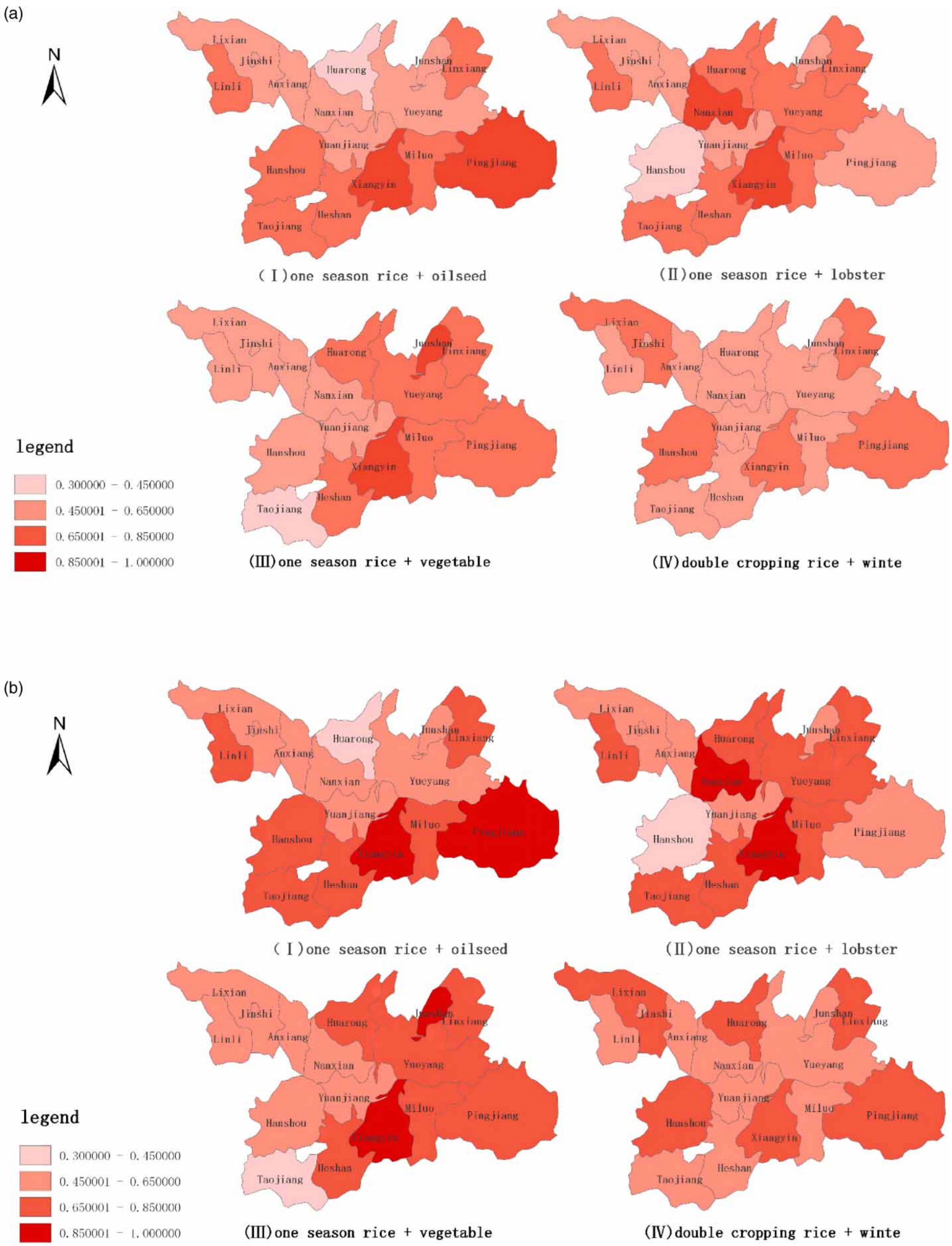

Figure 3 | Distribution of environmental efficiency of four typical cropping patterns in the circular Dongting Lake area in 2011 (a); distribution of environmental efficiency of four typical cropping patterns in the Ring of Dongting Lake in 2020 (b).

Table 2 | Score value of the Luenberger environmental index of four typical planting patterns

Regions	One-season rice + oilseed rape	One-season rice + lobster	One-season rice + vegetable	Double cropping rice + winter fallow
Pingjiang County	0.946	0.636	0.82	0.75
Xiangyin County	0.92	0.975	0.91	0.715
Huarong County	0.423	0.677	0.715	0.66
Yueyang County	0.631	0.75	0.766	0.64
Miluo City	0.795	0.729	0.811	0.634
Linxiang City	0.789	0.825	0.775	0.728
Junshan District	0.609	0.643	0.926	0.606
Lixian County	0.535	0.644	0.52	0.765
Hanshou County	0.788	0.414	0.644	0.7
Linli County	0.754	0.705	0.635	0.6
Anxiang County	0.62	0.601	0.509	0.549
Jinshi City	0.536	0.604	0.623	0.609
Taojiang County	0.732	0.765	0.405	0.647
Nanxian County	0.621	0.915	0.608	0.545
Yuanjiang City	0.645	0.626	0.636	0.579
Heshan District	0.755	0.812	0.758	0.545

Xiangyin County, Linxiang City, Pingjiang County, and Miluo City. It can be concluded that a certain cropping pattern has a high LEI value in a specific county and a relatively low LEI value in other counties, and counties with high LEI scores can obtain considerable economic returns by expanding the cropping scale without causing larger-scale environmental damage, while counties with low LEI scores cause relatively large environmental pressure or produce relatively low economic returns. Under the condition of ensuring food types and yields, each county can adjust its cultivation structure appropriately according to its own strengths and weaknesses.

Spatial variation analysis of four typical cropping patterns in hilly and plain areas around Dongting Lake

Influenced by factors like the Three Gorges Reservoir storage reservoir dam clear water discharge, the whole of the middle and lower reaches of the Yangtze River flushing, the upper Jingjiang River bed undercut water level reduction, and four mouth basin into the lake runoff flow significantly reduced, etc., the Dongting Plain area agricultural water resources relative environmental efficiency is low, and the agricultural water supply and demand contradictions are more prominent. In recent years, there has been no significant change in the amount of runoff water into the lake in the basins of Xiang, Zizhi, Yuan, Li, and Buru River. The ecological assets and total water resources in Linxiang City, Yueyang County, Pingjiang County, Miluo City, Heshan District, Taojiang County, and Linli County are richer than those in the Dongting Plain area, the overall agricultural water environment is under less pressure and the relative environmental efficiency (LEI) is higher. Combining Table 1 and Figure 4, among the four typical cropping patterns, the environmental efficiency value of one-season rice + oilseed rape is the highest and the environmental efficiency value of double-season rice + winter leisure is the lowest in the hilly areas around the lake, while the water resources utilization of double-season rice + winter leisure is the highest and its agricultural wastewater nitrogen and phosphorus emissions are the highest, as can be seen from Table 1. Therefore, in the hilly areas around the lake, under the condition of ensuring grain production, the one-season rice + oilseed rape can be promoted appropriately, and the double-season rice + winter leisure planting pattern can be reduced appropriately. The environmental efficiency value of one-season rice + lobster in the Dongting Plain area is the highest, while the environmental efficiency value of one-season rice + oilseed rape is the lowest, and the one-season rice + lobster cropping pattern has high income, high cost, and low nitrogen and phosphorus emissions from agricultural wastewater. Therefore, the one-season rice + lobster planting model can be promoted appropriately in the Dongting Plain area while ensuring certain yields of other crops, so as to achieve maximum benefits. As a result, the environmental efficiency value of one-season rice + rape is the highest and that of double-season rice + winter leisure is the lowest in the hilly areas around the lake, while the environmental efficiency value of

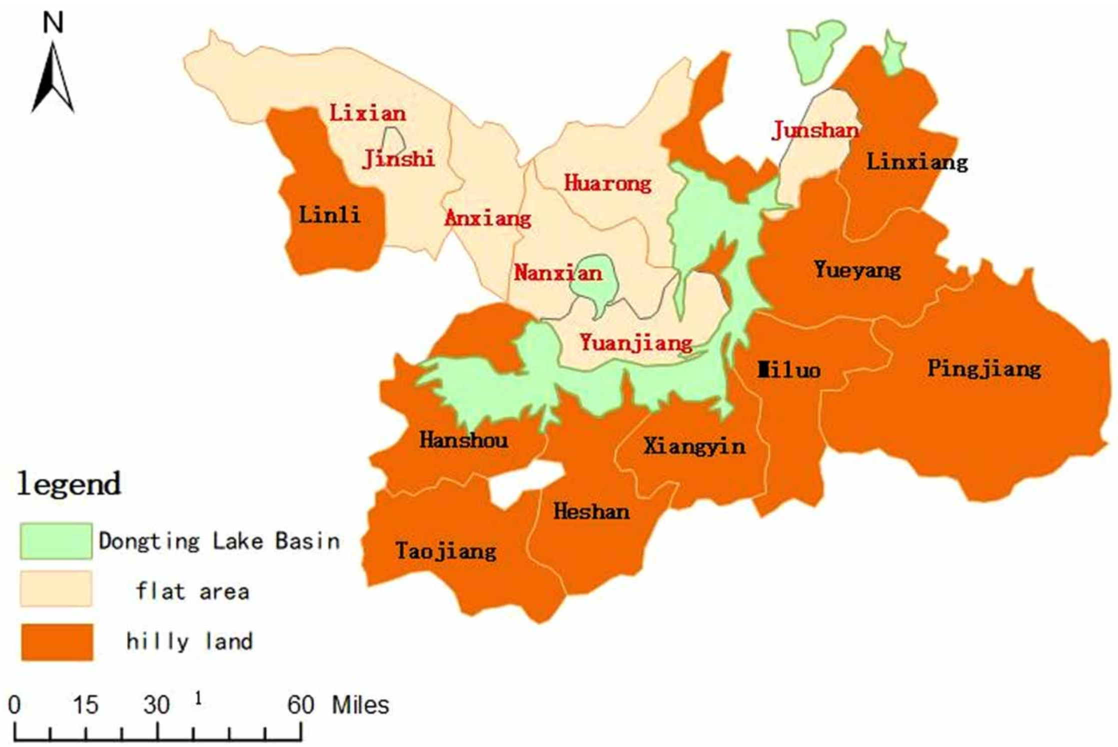

Figure 4 | Comparison of environmental efficiency (LEI) between the hilly area around the lake and the Dongting Plain area.

one-season rice + lobster is the highest and that of one-season rice + rape is the lowest in the Dongting Plain area. Overall, the hilly area around the lake has a higher environmental efficiency value (LEI) and the Dongting plain area has a lower environmental efficiency value (LEI). Their comparisons are shown in Figure 4.

CONCLUSION AND SUGGESTION

To analyze the spatial and temporal evolution patterns of environmental efficiency of typical cropping patterns in the Dongting Lake area from 2011 to 2020, this paper selects the total water resources input and production cost (excluding water) of four typical cropping patterns in the Dongting Lake area from 2011 to 2020 as input indicators; it takes the total income, total nitrogen, and phosphorus discharge of agricultural wastewater of the four typical cropping patterns as output indicators; it applies the Luenberger environmental productivity index model based on the directional distance function; and estimates the environmental efficiency of typical cropping patterns in the Dongting Lake area and environmental efficiency of agricultural water resources in each county (urban area). The results show that (1) the environmental efficiency (LEI) of four typical cropping patterns in 16 counties (cities and districts) in the Dongting Lake area showed an overall increasing trend from 2011 to 2020, and the environmental efficiency of the one-season rice + lobster cropping pattern was significantly higher than that of the other three cropping patterns, while the environmental efficiency of the double-season rice + winter leisure cropping pattern was low, but the rate of increase was relatively the fastest. (2) The environmental efficiency of typical cropping patterns in the Dongting Lake area is significantly different. The relative environmental efficiency of the one-season rice + rape planting pattern is better in Pingjiang County and Xiangyin County, the relative environmental efficiency of the one-season rice + lobster planting pattern is better in Xiangyin County and Nan County, the relative environmental efficiency of the one-season rice + vegetable planting pattern is better in Junshan District and Xiangyin County, and the relative environmental efficiency of the double-season rice + winter leisure planting pattern is better in Li County and Linxiang City. Overall, the counties (cities and districts) with better relative environmental efficiency are Xiangyin County, Linxiang City, Pingjiang County, and Miluo City. (3) There are large spatial differences in the environmental efficiency values (LEI) of typical cropping patterns in the hilly and plain areas around Dongting Lake. The highest environmental efficiency values are found for one-season rice + oilseed rape and the lowest environmental efficiency values are found for double-season rice + winter leisure in the hilly areas around the lake, while the highest environmental efficiency values are found for one-season rice + lobster and the lowest environmental efficiency values are found for one-season rice + oilseed rape in the Dongting Plain. Overall, the areas in the hills around the lake (Linxiang City, Yueyang County, Pingjiang County, Miluo City, Heshan District, Taojiang County, and Linli County) had higher environmental efficiency values (LEI), and the areas in the Dongting Plain (Junshan District, Xiangyin County, Yuanjiang City, Hanshou County, Nan County, Anxiang County, Huarong County, Jin City, and Li County) had lower environmental efficiency values (LEI).

According to the above results, this paper puts forward the following policy suggestions:

1. Implement the reduction and efficiency increase of pesticides and chemical fertilizers in the planting industry around the lake area. The provincial competent agricultural and commercial departments shall strictly enforce the use quality standards of pesticides and fertilizers in the main grain producing areas of Dongting Lake and jointly formulate the market access list of pesticides and fertilizers. The municipal agricultural departments take the lead in implementing soil testing and formula fertilization, unified controlling of crop diseases and insect pests, and whole process of green prevention and control. On the other hand, the county-level agricultural departments actively guide new agricultural business entities such as large farmers, agricultural cooperatives, and family farms around Dongting Lake to adopt green and efficient agricultural production methods.
2. Optimize the rice + planting mode in the lake area. According to the requirements of green, high-quality, and eco-efficient modern agricultural development, in the counties and urban areas with prominent contradiction between supply and demand of water resources and low score of LEI in the four river basins, clarify the priority of land use in basic farmland areas, appropriately control the rice + fishery planting mode, and continue to promote the rice + oilseed rape, rice + vegetable, double cropping rice + winter fallow planting mode. In the hilly area around Dongting Lake, we should actively carry out pilot projects of paddy and drought rotation and dry miscellaneous grain production.
3. Strengthen the construction of water conservancy projects in the four river basins. We should strive to bring the special rectification of water conservancy in the four river basins into the national comprehensive treatment project of water resources and water environment in the Yangtze River basin, dredge the main rivers of Songzi River, Hudu River, Ouchi River, and Huarong River, increase and restore the runoff into the lake in the four river basins, and reduce the cut-off time of the main rivers. The dredging project of ditches in the lake area should be implemented to restore the connectivity and water delivery capacity of rivers and lakes, open the capillaries, and solve the problems of immobile flow, poor flow, and serious sedimentation.
4. Promote water-saving irrigation of high standard farmland. Adhere to the construction principle of 'centralized connection, perfect facilities, supporting rural electricity, and good ecology', adhere to the construction guided by planning, achieve the combination of planning, and design of high-standard farmland construction projects in the lake area with large-scale operation, adjustment of planting structure, industrial transformation and development and beautiful rural construction, and enlarge the construction benefits of high-standard farmland projects. In accordance with the local standards of the general principles for the construction of high standard farmland in Hunan Province, increase the inclination and financial support for the construction projects of high standard farmland and water-saving irrigation facilities around the Dongting Lake area, make full and rational use of water resources, and realize the standardization and ecology of high standard farmland construction in the Dongting Lake River Network Plain.

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DATA AVAILABILITY STATEMENT

All relevant data are included in the paper or its Supplementary Information.

CONFLICT OF INTEREST

The authors declare there is no conflict.

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