Science of the Total Environment 658 (2019) 305–314

Contents lists available at ScienceDirect

Science of the Total Environment

journal homepage: www.elsevier.com/locate/scitotenv

Wetland ecosystem status and restoration using the Ecopath with Ecosim (EWE) model

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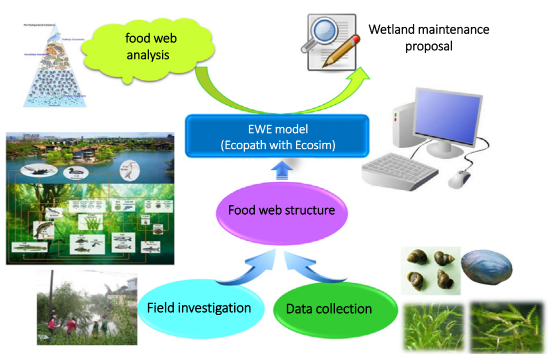
HIGHLIGHTS

- Optimizing wetland ecological function after restoration is a key issue in China.
- We use the EWE model to determine the ecosystem status of the Zhushanhu wetland.
- The model evaluates the current ecological regulations and biomass control measures.
- Manipulations improve wetland maturity and water purification capability.
- Our results provide guidance for wetland ecological maintenance after restoration.

GRAPHICAL ABSTRACT



ARTICLE INFO

Article history:
Received 10 October 2018
Received in revised form 9 December 2018
Accepted 9 December 2018
Available online 12 December 2018

Keywords:
Wetland ecosystem
EWE model
Lake Tai buffer zone
Wetland restoration
Wetland maintenance

ABSTRACT

With increasing awareness of the importance of wetlands, the number of new or restored wetlands in China is steadily growing; however, not all of them fulfill their expected ecological function. Maintaining wetlands in their optimal state is an urgent problem that requires research into the ecosystem evaluation, regulation, and biomass management of wetlands. The Ecopath with Ecosim (EWE) model, also known as the ecological channel model, is a balance model that can directly construct the ecological system structure and describe its energy flow and mass transfer through the principle of nutrition dynamics. Here, the EWE model is applied to determine the ecosystem status of a newly restored wetland, Zhushanhu wetland, in the Lake Tai buffer zone of Zhushan Bay, and evaluate the current ecological regulations and biomass control measures. Our results provide theoretical and scientific support for the management and maintenance of wetland ecological restorations.

1. Introduction

Wetlands are important ecological resources that provide valuable ecosystem services, including water purification, flood regulation or storm protection, biodiversity islands and corridors, climate regulation (carbon sequestration), leisure activities, and nature observation or education. Due to increasing awareness of the importance of wetlands, the number of new or restored wetlands in China has been increasing each year. The State Forestry Bureau of China reported in January 2016 that the protected area of wetlands increased by 2 million hectares during the 12th Five-Year Plan period, and the natural wetland protection rate increased to 46.80%. The aim of the 13th Five-Year Plan period is to increase the area of protected wetland to as large as 53 million hectares. However, a greater number of wetlands does not guarantee that

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https://doi.org/10.1016/j.scitotenv.2018.12.128
0048-9697/© 2018 Published by Elsevier B.V.

they fulfill their expected ecological function. Therefore, maintaining the optimal state of these wetland systems is an urgent problem that requires development of a set of wetland regulation and biomass management methods.

Wetland restoration belongs to the category of ecological engineering. At present, the follow-up management and maintenance of ecological projects in China is insufficient. Wetland ecosystem evaluation, regulation, and biomass management is a key objective of wetland protection and management (Wang et al., 2009a, 2009b). Substantial research has been conducted on wetland service function and hazardous plant management (Shukla, 1998; Alipiah, 2010; Cools et al., 2013a, 2013b; Johnston et al., 2013; Rebelo et al., 2013); however, research evaluating ecosystem status and guidance for regulating the wetland restoration process remains very inadequate. Wetlands contain complex biological networks; therefore, wetland research must find solutions to the following problems: how to evaluate the ecosystem status of restored wetland; how to optimize the biological structure of each trophic level, and how to establish a scientific management method to ensure that natural wetlands maintain long-term ecological health.

The wetland ecosystem is composed of a series of functional groups with ecological associations, which should cover the whole process of the ecosystem's energy flow. These groups mainly include detritus, plankton, fish, and hydrophytes (Tong, 1999). Due to their complex ecological interactions, traditional research methods can only study the behavior of individual organisms in simple habitats or competition between a few species. Thus, it is widely recognized that ecological models must be included in the study of complex natural ecosystem structures and functions (Jiang and Zhang, 1992).

The Ecopath with Ecosim (EWE) model, also known as the ecological channel model, is a balance model that can directly determine the structure of an ecological system and describe its energy flow and mass transfer through the principle of nutrition dynamics (Tong et al., 2000). It is not only a powerful ecosystem model, but also a encompassing ecological model based on the energy flow model. The model was originally created in 1984 (Polovina, 1984) and was followed by multiple ecological theories. After years of development, it has become a key tool for ecological system research. The model software has >6000 registered users in 164 countries and has produced >500 publications (Ainsworth and Walters, 2015). Specifically, it has become an important method for studying the structure and function of food webs (Christensen and Walters, 2004; Ainsworth and Walters, 2015). The EWE model can evaluate ecosystem status by using the system characteristic parameters of the model; it can also simulate and predict the development trend of an ecosystem using a time dynamic simulation module. The model can evaluate the economic, ecological, and social benefits of ecosystem management measures then propose appropriate ecosystem management measures (Song et al., 2007; Mi et al., 2012; Wu et al., 2012). Therefore, we employ the EWE model in this study to evaluate the ecosystem status of Zhushanhu wetland, China, and predict the different scenarios resulting from employing different regulation measures during the wetland restoration process.

The aims of this study are: (1) to study the general ecological characteristics of a wetland ecosystem immediately after restoration; (2) to evaluate the wetland ecosystem status using the EWE model; (3) to provide guidance for regulating the wetland restoration process; and (4) to provide strong theoretical support for the subsequent ecological control of wetland ecosystems.

2. Study area

Zhushanhu wetland, located in Yixing city, Jiangsu province, China, was chosen as the study area (Fig. 1), and lies within the buffer zone of Lake Tai. Its total area is 0.3 km^2 and its water area is 0.06 km^2. Zhushanhu wetland exhibits an irregular strip shape with a length of 1.8 km and an average width of 105 m (Fig. 2). Before restoration, Zhushanhu wetland was a swamp containing sediment dredged from Lake Tai and some waste construction materials. Restoration began in 2012 and was completed in 2014; the detailed design principle, restoration process, and water quality monitoring results are described in Ye and Li (2018). After restoration, water quality improved from inferior Class V to Class II, according to the National Surface Water Environmental Quality Standard (GB3838-2002). Wetland plant diversity also increased significantly; the Margalef richness index increased from almost zero in 2012 to 3.47 in 2014. This research focuses on the ecosystem status after restoration and its subsequent maintenance.

3. Material and methods

3.1. Data collection

Zhushanhu wetland was completely restored by 2014. A detailed ecological investigation of Zhushanhu wetland was conducted in 2015, obtaining all the data used for construction of the EWE model, including water quality, sediment quality, aquatic plants, plankton (phytoplankton and zooplankton), benthic animals, fishery resources, and bird and waterfowl resources. All data except bird and waterfowl

Fig. 1. Location of the Zhushanhu wetland study area.

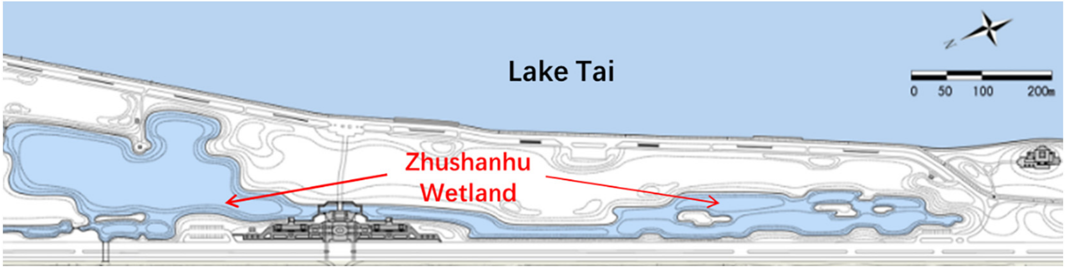

Fig. 2. Aerial view showing the shape of Zhushanhu wetland.

resources were sampled in all four seasons of 2015, while bird and waterfowl resources were surveyed monthly. The detailed sampling methods and analysis results are described in previous research (Xian, 2016).

3.2. Evaluation of ecosystem status after restoration

3.2.1. Basic principle of the EWE model

During modeling, it is assumed that all functional groups in the ecosystem are relatively stable; i.e., the total input of the ecosystem is equal to the total output, as follows:

$$Q = P + R + U \tag{1}$$

where Q is consumption; P is production; R is the respiratory volume; and U is the amount of undigested food. The model can be defined by a set of linear simultaneous equations, in which each equation represents a functional group in the ecosystem (Li et al., 2014):

$$B_i \cdot (P/B)_i \cdot EE_i = \sum_{j=1}^{n} B_j \cdot (Q/B)_j \cdot DC_{ji} + EX_i \tag{2}$$

where B_i is the biomass of functional group i; P_i is the production of functional group i; $(P/B)_i$ is the ratio of the production quantity to the biomass of functional group i; EE_i is the ecotrophic efficiency of functional group i; $(Q/B)_i$ is the ratio of digestion to the biomass of functional group i; DC_{ji} is the ratio by which the prey j accounts for the total predation of predator i; and EX_i is the output (including fishing and the amount of migration). The model requires six basic input parameters: B_i, $(P/B)_i$, $(Q/B)_i$, EE_i, DC_{ji}, and EX_i, respectively. The EE_i parameter is difficult to obtain; therefore, it is calculated using other parameters in the model.

3.2.2. Classifying functional groups

In the EWE model, the functional groups of an ecosystem can be divided into three categories: producers, consumers, and detritus. Producers are autotrophic organisms, such as algae and phytoplankton, consumers are heterotrophic organisms, such as fish and benthic animals, and detritus refers to the sum of all nonliving organic substances in the ecosystem, including the bodies of dead animals and plants, animal waste, food residue, and dissolved or solid particulate organic matters from outside the water (Chou et al., 2014).

The classification of functional groups in the EWE model of the Zhushanhu wetland ecosystem was conducted primarily according to the requirements of the whole ecosystem; species with a high degree of niche overlap were combined to simplify the food web. According to the functional groups partition principle (Liu et al., 2009): (1) it should include at least one combination of detritus; (2) populations with the same or similar niche should be placed within the same functional group; (3) classified functional groups must cover the entire process of the ecosystem's energy flows; dominant and keystone species must not be omitted; (4) considering the requirements of EWE software, the number of functional groups should range from 12 to 50. In addition, according to the availability of data, adjustments can made to the classification. Using this principle, the ecological survey results from 2015, and related research on the EWE model in the Lake Tai watershed, the functional groups of the Zhushanhu wetland ecosystem were divided into 16 groups (Table 1).

3.2.3. Source of biological parameters

In our survey data, the unit of plankton biomass was $mg \cdot L^{-1}$; biomass in units of $t \cdot km^{-2}$ was obtained by multiplying by the average depth of water. The unit of the biomass of benthic animals and aquatic plants was expressed in g/m^2, whose values are the same as that of $t \cdot km^{-2}$; thus, they were used directly in the model calculation. In this study, aquatic plants, plankton, benthic animals, fishery resources, and

Table 1
Species composition of the functional groups in the Zhushanhu wetland ecosystem EWE model.

No.	Group	Abbreviation	Composition
1	Waterfowl	WatF	Moorhen, *Ardea purpurea*, Kingfisher, White crane, etc.
2	Large culters	LarC	Topmouth culter, Redfin culter
3	Other piscivorous	OthP	Snakehead fish, Mandarin fish, *Odontobutis obscura*, Goby
4	Common carp	ComC	Common carp
5	Crucian carp	CruC	Crucian carp
6	Herbivorous fish	HerF	Bream fish
7	Other wild miscellaneous fish	OwmF	*Acheilognathus macropterus*, Rhodeus, *Pseudorasbora parva*, *Saurogobio dumerili* Bleeker, *Hemibarbus maculatus* Bleeker, etc.
8	Macrocrustaceans	MacC	Squilla, Procambarus clarkia, Sinensis sinensis
9	Molluscs	Moll	*Cipangopaludina chinensis*, Bellamya purificata, etc.
10	Other benthos	OthB	*Chironomus plumosus*, *Limnodrilus hoffmeisteri*, etc.
11	Cladocera	Clad	*Bosmina longirostris*, *Ceriodaphnia cornuta* Daphnia, etc.
12	Copepod	Cope	Sinocalanus dorrii, Mesocyclops leuckarti, etc.
13	Phytoplankton	Phyt	Diatom, Chrysophyta, Chlorophyta
14	Submerged macrophytes	SubM	*Hydrilla verticillata*, *Potamogeton crispus*, Potamogeton wrightii Morong
15	Other macrophytes	OthM	Cattai, *Zizania caduciflora*, Common cutgrass herb, *Alternanthera philoxeroides*
16	Detritus	Detritus	Detritus

Table 2
Basic inputs and estimated parameters of the Zhushanhu wetland ecosystem.

No.	Group name	Trophic level	Biomass ($t\cdot km^{-2}\cdot a^{-1}$)	P/B	Q/B	EE	P/Q
1	WatF	3.72	0.11	1.00	99.00	0.11	0.01
2	LarC	3.59	0.16	0.87	3.20	0.95	0.27
3	OthP	3.33	0.52	1.67	6.10	0.98	0.27
4	ComC	3.00	3.28	0.96	10.69	0.85	0.09
5	CruC	2.24	3.50	1.13	12.30	0.82	0.09
6	HerF	2.00	1.51	0.99	7.10	0.96	0.14
7	OwmF	2.79	3.47	2.16	11.00	0.98	0.20
8	MacC	2.45	2.42	3.09	41.22	0.49	0.08
9	Moll	2.05	4.37	1.33	10.60	0.54	0.13
10	OthB	2.02	2.52	4.13	206.50	0.80	0.02
11	Clad	2.00	2.00	25.00	500.00	0.90	0.05
12	Cope	2.00	3.55	25.00	500.00	0.86	0.05
13	Phyt	1.00	5.40	185.00	0.00	0.02	
14	SubM	1.00	357.00	2.25	0.00	0.63	
15	OthM	1.00	514.50	1.00	0.00	0.00	
16	Detritus	1.00	92.26			0.69	

Table 4
Trophic decomposition of groups in the Zhushanhu wetland ecosystem.

Group	Trophic level decomposition(%)						Effective trophic level
	I	II	III	IV	V	VI	
WatF			30.1	67.6	2.3	0.009	3.72
LarC		2.6	39.0	57.5	1.0	1	3.59
OthP		1.4	68.2	30.3	0.008		3.33
ComC		0.2	99.8				3.00
CruC		75.8	24.2				2.24
HerF		1.0					2.00
OwmF		21.8	77.9	0.3			2.79
MacC		55.5	44.5				2.44
Moll		94.9	5.13				2.05
OthB		98.4	1.57				2.02
Clad		1.0					2.00
Cope		1.0					2.00
Phyt	1.0						1.00
SubM	1.0						1.00
OthM	1.0						1.00
Detritus	1.0						1.00

other biomass data were derived from the ecological field survey in 2015.

For other biological parameters, the P/B and Q/B of fish resources were obtained from the website http://www.fishbase.org, the P/B of aquatic plants was obtained from Lake Tai watershed studies (Song, 2004), and the P/B and Q/B of zooplankton and benthic animals and their diet composition were derived from the results of various Lake Tai watershed studies (Liu et al., 2007; Li et al., 2009; Feng et al., 2011; Yang, 2003; Jia et al., 2013).

3.2.4. Data processing and model balancing

The collected data were entered into the EWE model for operational simulation. The model must be debugged in order to achieve the balance between inputs and outputs, with diet and other functional parameters as the main content, which are repeatedly adjusted until the basic model conditions are met; i.e. $0 < EE \leq 1$ and $P/Q < 0.3$ (Christensen and Walters, 2004). The basic input and output parameters and diet matrix of the balanced model are shown in Tables 2 and 3.

3.3. Determining wetland restoration regulations using the EWE model

EWE includes a time dynamic simulation module for policy exploration. Based on the above wetland ecosystem status analysis, any weaknesses or redundant production of the system structure were identified by applying the time dynamic simulation module. Accordingly, the corresponding control measures were determined, including adjustment of the community structure, restoration of biodiversity, improvement of the food chain structure, and management of aquatic plants. The purpose of ecosystem regulation is to coordinate the relationship between different populations and combine them in a reasonable manner to form a new complex population, ensuring that the structure and function of each component of the system is more coordinated and the energy flow and material circulation of the system is more reasonable. Wetland ecosystem regulation and biomass management measures involved the comprehensive application of the above points.

3.3.1. Biodiversity regulation method

According to the preliminary investigation and model results, low biodiversity was found in some plant or animal communities. A biodiversity improvement method was proposed and input into the EWE model to predict future wetland ecosystem status, which also tested the flow of material from primary producers to trophic level II.

3.3.2. Optimizing the biological community structure

The niche overlap in the EWE model reflects the combination of the predator overlap index and the prey overlap index. Analyzing the niche overlap allowed us to optimize the biological community structure.

3.3.3. Regulating the food chain structure

In the process of biomass management, the existing ecosystem for a specific species of ecological capacity is a key regulatory indicator. Regulation of the food chain structure by the EWE model was achieved by calculating the ecological capacity using the Ecopath model.

Table 3
Matrix of diet composition for the balanced Zhushanhu wetland ecosystem model.

No.	Prey/predator	1	2	3	4	5	6	7	8	9	10	11	12
1	WatF												
2	LarC	0.009	0.017										
3	OthP	0.051	0.027	0.041									
4	ComC	0.087	0.131	0.106									
5	CruC	0.098	0.218	0.190									
6	HerF	0.010	0.045					0.026					
7	OwmF	0.588	0.373	0.023									
8	MacC	0.157	0.164	0.229									
9	Moll			0.358				0.001					
10	OthB			0.039				0.214					
11	Clad				0.078	0.120		0.271	0.194	0.041	0.011		
12	Cope				0.920	0.122		0.271	0.251	0.010	0.005		
13	Phyt				0.002					0.375			
14	SubM		0.025			0.081	1.000	0.002			0.118	0.108	0.183
15	OthM			0.014									
16	Detritus					0.676		0.216	0.555	0.574	0.867	0.892	0.817
17	Sum	1.000	1.000	1.000	1.000	1.000	1.000	1.000	1.000	1.000	1.000	1.000	1.000

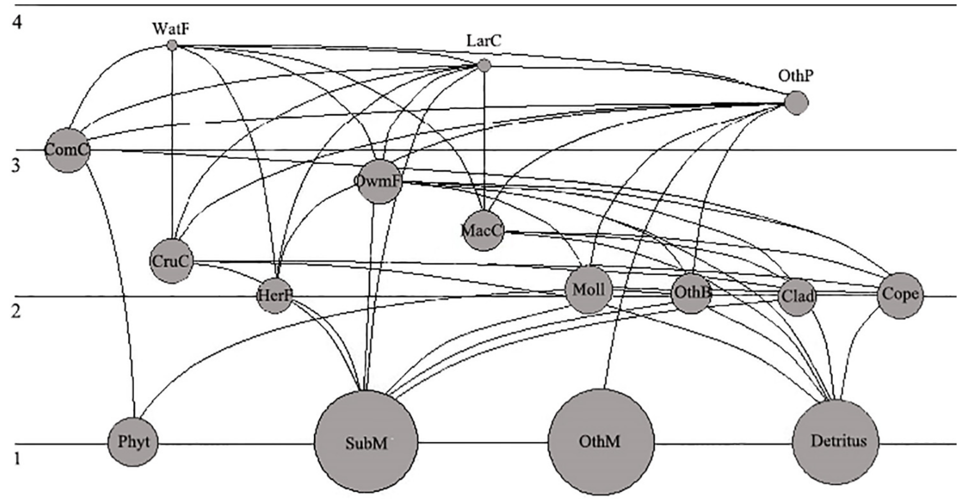

Fig. 3. Food web of the Zhushanhu wetland ecosystem (see Table 1 for group name definitions).

3.3.4. Determining biomass management measures

When unused primary production biomass enters wetland sediment, excessive deposition will accelerate aging of the ecosystem and increase the nutrient load of the system, which results in inefficient water purification. Therefore, unused primary production biomass was removed. The core aspect of the biomass management strategy was to use the EWE model to study the harvesting ratio of aquatic plants.

4. Results

4.1. Zhushanhu wetland ecosystem status after restoration

4.1.1. Food web and trophic structure

The trophic level structure of an ecosystem combines the nutrient flows from different functional groups for a number of trophic levels in order to simplify the complex food network (Feng, 2011). The EWE results are summarized in Table 4, which shows that the highest trophic level waterfowl functional group was 3.72; its food trophic levels in the III, IV, V, and VI integrated distribution ratio trophic levels were 30.1%, 67.6%, 2.28%, and 0.009%, respectively. The trophic levels of LarC and OthP functional groups were 3.59 and 3.33, respectively, and their food was mainly located in trophic level III and IV.

The ecosystem food web structure is shown in Fig. 3, which, combined with Table 4, indicates that the three functional groups from primary producers and the detritus functional group are dominant in the first trophic level; the HerF functional group and zooplankton (Clad and Cope functional groups) are dominant in trophic level II; and benthic animal groups (Moll and OthB functional groups) and function groups ComC, CruC, and MacC respectively occupy trophic level II and III. There are two main nutrient flows in the Zhushanhu wetland ecosystem. The first is the predatory food chain; i.e. aquatic organisms such as phytoplankton - carp - large piscivorous fish - waterfowl. The second is the detritus food chain; i.e. organic detritus such as detritus- molluscs - carp - waterfowl. In the food web of the Zhushanhu wetland, more food chains begin from submerged macrophytes and organic detritus, while fewer begin from phytoplankton and other vascular plants.

Table 5
Transfer efficiency between different trophic levels (%).

Source	Trophic level				
	II	III	IV	V	VI
Producer	4.3	9.1	3.5	0.6	
Detritus	4.0	8.5	3.8	0.6	
Total flow	4.1	8.6	3.7	0.6	0.1
Proportion of detritus to total flow			0.72		
From primary producers			5.2%		
From detritus			5.0%		
Ecosystem			5.1%		

4.1.2. Energy conversion efficiency of the Zhushanhu wetland ecosystem

The energy conversion efficiency between trophic levels in the ecosystem refers to the ratio between the output and feeding flow and total flow system of a trophic level; the efficiency reflects the level of nutrition used by the ecosystem (Jackson et al., 2001). The EWE model results are shown in Table 5. In the Zhushanhu wetland ecosystem, the energy conversion efficiency of primary producers and organic detritus to trophic level II is 4.3% and 4.0%, respectively; the total energy conversion efficiency is 4.1%; the total energy conversion efficiency of trophic level II to trophic level III is 8.6%; the comprehensive energy conversion efficiency of trophic level III to trophic level IV is 3.7%; and the energy conversion efficiency of trophic level IV to trophic level V and trophic level V to trophic level VI are both very low, 0.6% and 0.1%, respectively. The total system energy conversion efficiency is 5.1%, lower than the ecosystem average transmission efficiency (9.2%) reported by Christensen and Pauly (1993), and also far from the optimal "1/10 Law" of ecological pyramid energy conversion efficiency (Chen, 2010).

4.1.3. Mass transfer efficiency of the Zhushanhu wetland ecosystem

Throughput refers to flux of all nutrients flowing through a trophic level within a unit time. The total throughput of each trophic level includes the amount of output (the amount of catching and deposition from the ecosystem), feeding, respiration (not including the respiration from plants and detritus) and flow to detritus (Wu et al., 2012). Material transport efficiency (TE) for each nutrient level is the ratio of its output to its total intake, which is used to characterize the utilization efficiency of each nutrient level in the ecosystem.

Fig.4 shows that the primary producer's production was 2317.3 $t \cdot km^{-2} \cdot a^{-1}$, the amount of food intake was 526.3 $t \cdot km^{-2} \cdot a^{-1}$, the amount of inflow of detritus into the recycled was 1791 $t \cdot km^{-2} \cdot a^{-1}$, accounting for 77.3% of primary production. From each trophic level into the total flow of detritus group was 4243 $t \cdot km^{-2} \cdot a^{-1}$, the amount of detritus group being fed was 2913 $t \cdot km^{-2} \cdot a^{-1}$, the rest of the 1330 $t \cdot km^{-2} \cdot a^{-1}$ was separated from the ecological system due to mineralization. The throughput of trophic level I flowed to trophic level II was 526.3 $t \cdot km^{-2} \cdot a^{-1}$, the throughput from the trophic level II into trophic level III was 135.6 $t \cdot km^{-2} \cdot a^{-1}$ and the transfer efficiency was 4.1%. The throughput from trophic level III input to the trophic level IV, V and VI were less, respectively 8.66, 0.25, and 0.001 $t \cdot km^{-2} \cdot a^{-1}$, the transfer efficiency is

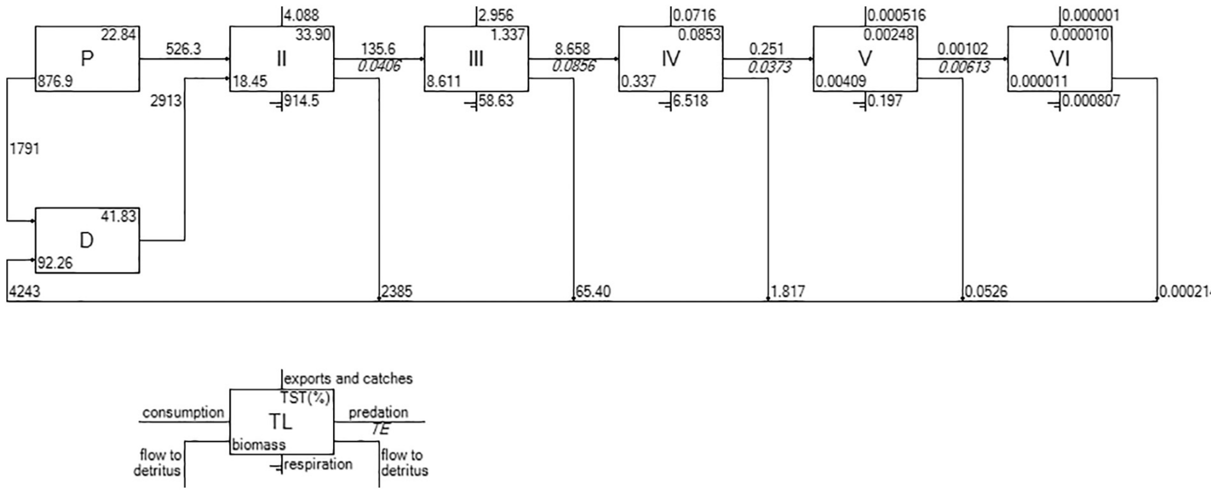

Fig. 4. Trophic flows transmitted through aggregated trophic levels in the Zhushanhu wetland ecosystem. P: producer; D: Detritus; TL: trophic levels; TST(%): total system throughput (%); TE: transfer efficiency.

also gradually reduced, respectively 8.6%, 3.7% and 0.6% and the average transmission efficiency was 4.3%.

4.1.4. Mixed trophic impacts of the Zhushanhu wetland ecosystem

The mixed trophic impact (MTI) is an effective way to analyze the direct and indirect effects of different populations in an ecosystem, which reflects the degree of mutual benefit or mutual harm between the various functional groups. It is one of the basic functions of the EWE model. The MTI can be used to evaluate the influence of changing the biomass of one functional group on other functional groups (Huang et al., 2012).

The MTI between various functional groups of the Zhushanhu wetland ecosystem was acquired through analysis of the Ecopath model (Fig. 5). Fishing has a negative impact on most fish resource functional groups, including WatF, OthP, ComC, CruC, HerF, MacC, Moll, OthB, Cope, and OthM, but a positive impact on LarC, OwmF, and Phyt groups. Most of the function groups of trophic level II face greater downward pressure because fishing reduces the biomass of piscivorous fish, decreases predation pressure, and promotes the growth of wild fish. The detritus group has a positive effect on functional groups, except for HerF and all aquatic plant functional groups, indicating that detritus can form part of the diet of these functional groups, promoting their growth. SubM plays a significant role in promoting growth of the HerF group. The OthB group, dominated by emergent plants, has neither a positive nor negative influence on other functional groups.

4.1.5. Total system properties of the Zhushanhu wetland ecosystem

The overall characteristics of the ecosystem are shown in Table 6. These characteristics indicate the size, stability, and maturity of the ecosystem. The ratio of total primary production and total respiration (TPP/TR) is an important index for describing the maturity of a system. A mature ecosystem has a TPP/TR value close to 1, and the difference between TPP and TR is close to 0 (Lin et al., 2009). The net primary production of the Zhushanhu wetland ecosystem is 2317.02 $t \cdot km^{-2} \cdot a^{-1}$ and the sum of all respiratory flows is 979.80 $t \cdot km^{-2} \cdot a^{-1}$. The difference between them is the net system production, 1337.23 $t \cdot km^{-2} \cdot a^{-1}$, which is far >0. Their ratio (TPP/TR) is 2.37, which does not reach the standard of a mature ecosystem.

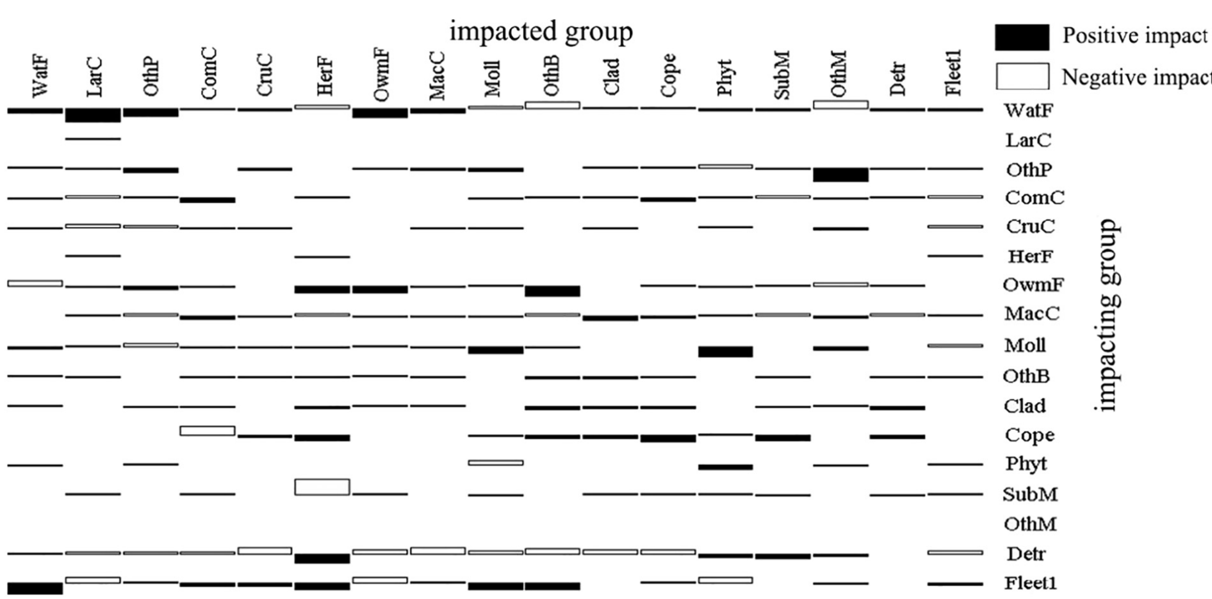

Fig. 5. Mixed trophic impacts of functional groups in the Zhushanhu wetland ecosystem.

Table 6
Total system properties of the Zhushanhu wetland ecosystem.

Parameter	Value	Units
Sum of all consumption	3583.88	$t \cdot km^{-2} \cdot a^{-1}$
Sum of all exports	1337.87	$t \cdot km^{-2} \cdot a^{-1}$
Sum of all respiratory flows	979.80	$t \cdot km^{-2} \cdot a^{-1}$
Sum of all flows into detritus	4243.66	$t \cdot km^{-2} \cdot a^{-1}$
Total system throughput	10,145.20	$t \cdot km^{-2} \cdot a^{-1}$
Sum of all production	2496.66	$t \cdot km^{-2} \cdot a^{-1}$
Mean trophic level of the catch	2.44	
Gross efficiency	0.003	
Net primary production (NPP)	2317.02	$t \cdot km^{-2} \cdot a^{-1}$
Total primary production/total respiration (TPP/TR)	2.37	
Net system production	1337.23	$t \cdot km^{-2} \cdot a^{-1}$
Total primary production/total biomass	2.56	
Total biomass/total throughput	0.09	a^{-1}
Total biomass (excluding detritus)	904.30	$t \cdot km^{-2}$
Connectance index (CI)	0.24	
System omnivory index (SOI)	0.07	
Finn's cycling index (FCI)	29.1	%
Finn's mean path length (FMPL)	4.38	

The connectance index (CI) and system omnivory index (SOI) reflect the degree of the ecosystem's internal complexity (Pauly et al., 2000). The more mature the ecosystem, the more complex the relationship between the functional groups, and the CI and SOI are closer to 1 (Li et al., 2010). For the Zhushanhu wetland ecosystem, CI is 0.24 and SOI is 0.07, which shows that the system is far from reaching maturity and the internal complexity is relatively low.

The maturity of the ecosystem can also be evaluated by Finn's cycling index (FCI) and Finn's mean path length (FMPL) (Liu et al., 2014). The circulation flow refers to the total amount of nutrients flows recycled in the ecosystem (Wang et al., 2009a, 2009b); FCI refers to the ratio of circulation flow and total flows; and FMPL refers to the average length of each cycle flow through the food chain (Chen and Qiu, 2010). One of the main characteristics of mature ecosystems is a higher proportion of material recycling and a longer food chain through which nutrients flow (Hannon, 1973). The FCI and FMPL values are 29.1% and 4.38 for the Zhushanhu wetland, which do not reach the standards of a mature system.

4.2. Regulating the wetland restoration process using the EWE model

4.2.1. Biodiversity regulation

According to the preliminary investigation and model results, there is only one species of herbivorous fish in the existing wetland ecosystem and its biomass is low. Therefore, the population of herbivorous fish, such as grass carp species, should be increased. When model simulations are used to increase the biomass of herbivorous fish by five times, the ecological nutrient efficiency of submerged plants changes from 0.633 to 0.686, an increase of 8.37%. When the biomass of herbivorous fish is increased by ten times, the ecological nutrient efficiency of submerged plants changes to 0.753, which is 19% higher than the current situation. The flow rate of substances from primary producers to nutrient level II also increases, from 526.31 $t \cdot km^{-2} \cdot a^{-1}$ (current status) to 569.1 $t \cdot km^{-2} \cdot a^{-1}$ (5 times) then 622.7 $t \cdot km^{-2} \cdot a^{-1}$ (10 times). The inflow to detritus for deposition decreased from 1791 $t \cdot km^{-2} \cdot a^{-1}$ (current status) to 1748 $t \cdot km^{-2} \cdot a^{-1}$ (5 times) then to 1587 $t \cdot km^{-2} \cdot a^{-1}$ (10 times). Therefore, according to the analysis of wetland species structure, the introduction of new species could not only improve biodiversity, but also solve the problem of excess primary production.

4.2.2. Optimization of biological community structure

Fig. 6 shows the niche overlap between different functional groups of the Zhushanhu wetland ecosystem. The higher predatory niche overlap indexes (predator niche overlap index) are mainly from omnivorous fish (carp, crucian carp, wild miscellaneous fish), shrimp, and crab. This indicates that the functional groups compete strongly against the same predator.

The current biomass of shrimp and crab (MacC) is 2.424 $t \cdot km^{-2} \cdot a^{-1}$ and its eco-nutrient efficiency is 0.489, which is much lower than that of most other fish functional groups. The ecological capacity of shrimp and crab is 3.05 $t \cdot km^{-2} \cdot a^{-1}$. These results show that the current stock of the ecosystem is close to system capacity. 51.1% of the biomass in the functional group is not used but deposited in the sediment. When the biomass of shrimp and crab decreases by 50%; i.e. to 1.212 $t \cdot km^{-2} \cdot a^{-1}$, the ecological nutrient efficiency of the functional group increases to 0.978, which is twice that of the current situation, and the corresponding inflow of debris decreases. By regulating the biomass of this functional group, the predator-prey relationship between this functional group and other functional groups can be reduced, the unused biomass can be reduced, the energy flow and material transfer

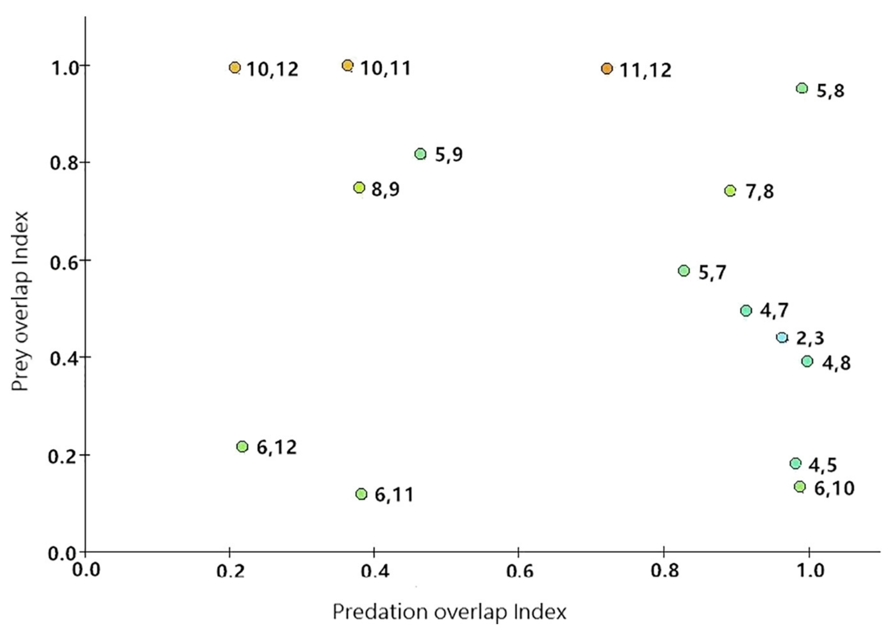

Fig. 6. Niche overlap status of the Zhushanhu wetland ecosystem.

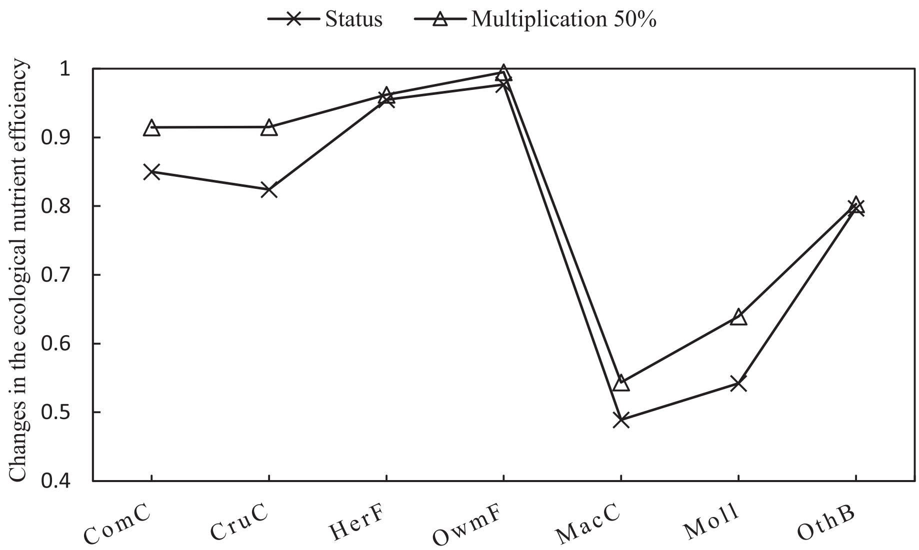

Fig. 7. Changes in the ecological nutrient efficiency of other functional groups with a 50% increase in piscivorous fish biomass.

efficiency can be improved, the species structure of the community can be enhanced, and the ecosystem can be stabilized.

4.2.3. Regulation of food chain structure

Among all fish functional groups in the Zhushanhu wetland ecosystem, the highest effective nutrient grade indexes are LarC and OthP, which occupy the top of the food chain and play important roles in supporting the structure of the food web. The Ecopath model was used to calculate the ecological capacity of these two species, which are 0.304 $t \cdot km^{-2} \cdot a^{-1}$ and 1.118 $t \cdot km^{-2} \cdot a^{-1}$, respectively. The current stocks of the system are 0.163 $t \cdot km^{-2} \cdot a^{-1}$ and 0.520 $t \cdot km^{-2} \cdot a^{-1}$, which represents 46.38% and 50.07% of the biomass proliferation space, respectively. This information will provide guidance for ensuring sustainable development of this ecosystem.

If the biomass of LarC and other fish-eating fish (OthP) is increased by 50%, the prediction results from the EWE model show good agreement with the classical biological manipulation theory, and the ecological nutrient efficiency of filter-feeding Cyprinidae and omnivorous fish increases correspondingly (Fig. 7).

Table 7
Changes in total system properties (35% of submerged plants harvested and 50% of emerged plants harvested).

Parameter	Status value	Simulated predicted value	Unit
Sum of all exports	1337.873	799.110	$t \cdot km^{-2} \cdot a^{-1}$
Sum of all flows into detritus	4243.656	3704.893	$t \cdot km^{-2} \cdot a^{-1}$
Total system throughput	10,145.200	9067.678	$t \cdot km^{-2} \cdot a^{-1}$
Sum of all production	2496.660	1957.678	$t \cdot km^{-2} \cdot a^{-1}$
Gross efficiency	0.003	0.004	
Net primary production (NPP)	2317.022	1778.260	$t \cdot km^{-2} \cdot a^{-1}$
Total primary production/total respiration (TPP/TR)	2.365	1.815	
Net system production	1337.227	798.465	$t \cdot km^{-2} \cdot a^{-1}$
Total biomass/total throughput	0.089	0.058	a^{-1}
Total biomass (excluding detritus)	904.302	522.102	$t \cdot km^{-2}$
Finn's cycling index (FCI)	29.100	34.69	%
Finn's mean path length (FMPL)	4.377	5.097	

4.2.4. Biomass management measures

According to the EWE model results, the productivity of primary producers in the Zhushanhu wetland ecosystem is 2317.3 $t \cdot km^{-2} \cdot a^{-1}$, of which 526.3 $t \cdot km^{-2} \cdot a^{-1}$ is consumed. The remaining 77.3% is not used by other predators but is instead deposited as debris, recycled, or deposited after mineralization. This result provides important guidance for aquatic plant harvesting measures; i.e., it is better to harvest 77.3% of the total plant biomass in the autumn season.

According to the ecological nutrient efficiency of existing aquatic plant functional groups in the wetland ecosystem, if the biomass of existing submerged plants is reduced by 35%; i.e. 124.95 $t \cdot km^{-2} \cdot a^{-1}$ is harvested, and 50% of emergent plants are harvested (257.25 $t \cdot km^{-2} \cdot a^{-1}$) the primary production will become optimal, according to the rebalancing analysis of the Ecopath model. The debris inflow from primary production of the system will change from 1791 $t \cdot km^{-2} \cdot a^{-1}$ to 1252 $t \cdot km^{-2} \cdot a^{-1}$, which is a decrease of 30%. The TPP/TR value decreases from 2.365 to 1.815, which is closer to the standard value of 1, indicating that the maturity of the ecosystem would be improved to a certain extent. The average Finn's path length; i.e. the length of the food chain through which nutrients flow, changes from 4.337 to 5.097, and the Finn's cycle index increases from 29.1% to 34.69%. The changes in these parameters indicate improved maturity of the ecosystem and a better water purification effect.

By calculating the total removal amount of aquatic plant biomass, the harvest amount and coverage rate are obtained. Thus, the coverage rate of emergent plants is reduced from 28.84% to 14.31% and the coverage rate of submergent plants is reduced from 23.4% to 15.21% (Table 7).

5. Discussion

The ecological channel model, based on ecosystem energy flow and food web structure, has integrated the basic theory of modern ecology and become a widely used and effective tool in water ecosystem management after 30 years of development. In this study, we used ecological survey data to successfully construct the EWE model for the Zhushanhu wetland. Our results showed that the effective trophic level distribution of the Zhushanhu wetland ecosystem ranged from 1 to 3.72. Among all functional groups, WatF had the highest trophic level of 3.72, followed by LarC and OthP, whose trophic levels were 3.59 and 3.33, respectively. The trophic level of the majority of remaining omnivorous and herbivorous fish ranged from 2–3, whereas primary producers and detritus firmly occupied trophic level I. The total energy conversion efficiency of the Zhushanhu wetland ecosystem was 5.1%, indicating that the current energy conversion efficiency was low. Along with the increase of trophic level, the mass transfer efficiency gradually decreased. Predators had a negative effect on other functional groups, while the functional groups at low trophic level played a very important role in the energy transfer process of the whole ecosystem. The Zhushanhu wetland ecosystem is in an immature state; ecosystem development is still far from reaching a mature standard, its internal complexity is very low, and the length of nutrient flows through the food chain is relatively short. The system's resistance is weak and extremely unstable.

According to the results of the EWE model, the proportion of primary production not being used by trophic level II but flowing into detritus was as high as 77.3%, which implies a blocked flow of nutrients in the Zhushanhu wetland ecosystem. In addition, 31.3% of the detritus functional group was not recycled but instead entered mineralization and deposition processes. Therefore, it is necessary to harvest aquatic plants in autumn and winter.

Achieving the long-term healthy development of wetland ecosystems, maintaining ecosystem stability, and achieving more efficient water purification are key issues that should be solved. Basing on our analysis of the existing species structure, grass carp species should be added to the wetland to improve biodiversity. The predator niche overlap and proliferating ecological capacity showed that the ecological carrying capacity of the MacC functional group was 3.05 $t \cdot km^{-2} \cdot a^{-1}$, indicating that the biomass of the MacC functional group in the current ecosystem is close to capacity. Approximately 51.1% of the group's material is not used by the ecosystem but is recycled and deposited. When the biomass of the MacC functional group was reduced to 50%, the group's ecotrophic efficiency doubled and the amount of detritus flows decreased. The LarC and OthP functional groups occupy the top of the food web, which play an important role in supporting the ecosystem's food web structure; their effective trophic levels were 3.587 and 3.333, respectively. The model calculations revealed that the ecological capacity of these two groups had space for an increase of 46.38% and 50.07%, respectively. The predicted simulation of proliferation conformed to the theory of classical biomanipulation; i.e., the ecotrophic efficiency of filter-feeding cyprinidae fish and omnivorous fish increased. Finally, the simulation and analysis of aquatic plant harvesting showed that, when the biomass of submerged and emerged macrophytes was reduced by 35% and 50%, respectively, the primary production decreased by 23% and parts that flowed into detritus decreased by 30%. Among the characteristic parameters of the ecosystem, the TPP/TR value reduced from 2.365 to 1.657, which was close to the standard value of 1, indicating that the maturity of the ecosystem had improved to a certain degree. The FCI value changed from 4.337 to 5.097 and the FMPL value changed from 29.1% to 34.69%. These variations in the characteristic parameters indicated that the ecosystem maturity had improved and was more conducive for achieving a water purification effect.

6. Conclusion

(1) The health status, maturity, and overall characteristics of the Zhushanhu wetland ecosystem were successfully evaluated by the EWE model. The nutrient level structure and energy flow efficiency between different nutrient levels were determined, which allowed us to clearly identify the deficiencies of the current wetland ecosystem.

(2) The total energy conversion efficiency of the wetland ecosystem was 5.1%, which did not reach the “1/10 law”. The average transmission efficiency of the material throughput in the ecosystem was 4.3%. The sum of all production was 2496.66 $t \cdot km^{-2} \cdot a^{-1}$ and total system throughput was 10,145.2 $t \cdot km^{-2} \cdot a^{-1}$. All these parameters showed that Zhushanhu wetland was in an immature stage in 2015 and would have to be artificially regulated.

(3) Through analysis of food chain species structure and biomass limitation measures, different scenarios were developed from different control measures, which led to improved wetland maturity and water purification capability. This provides scientific support for wetland regulation measures after restoration.

Acknowledgments

This work was jointly supported by the 13th-five National Water Pollution Control and Treatment Science and Technology Major Projects of China (2017ZX07203-005) and the China-German Cooperation on Monitoring and Risk Assessment of Toxic and Harmful Pollutants in Taihu Lake (S2016G1115).

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