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Assessment of Ecosystem Characteristics and Fishery Carbon Sink Potential of Qianxiahu Reservoir Based on Trophic Level and Carbon Content Methods

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Abstract: Optimizing biological carbon sequestration has become a primary strategy in global low-carbon-emission initiatives. Freshwater fisheries in reservoirs play an important role in aquatic biological carbon sequestration. However, a standard method for evaluating the carbon sink capacity of inland fisheries has not been developed. Therefore, this study aimed to assess and compare the carbon sequestration potential of the Qianxiahu Reservoir's fisheries using the trophic level and mass-balance methodologies. The Ecopath model was employed to determine the trophic levels of aquatic organisms within the Qianxiahu Reservoir ecosystem, with input parameters sourced from in situ surveys and the literature on reservoirs. The model includes 21 functional groups, with trophic levels ranging from 1.000 to 3.281. The key species identified are silver carp, bighead carp, and crucian carp. The indices of Finn's cycling index (FCI), connectivity index (CI), system omnivory index (SOI), and total primary production/total respiration (TPP/TR) for the Qianxiahu Reservoir are 11.35, 0.27, 0.196, and 1.540, respectively. These values indicate a high degree of material recycling and complex interconnections among functional groups. The fishery carbon sink potential of the Qianxiahu Reservoir, calculated using the trophic level and carbon content methods, yielded values of 261.8362 tons/km^2 and 66.6818 tons/km^2, respectively. The trophic level method showed a notable increase of 195,1544 tons/km^2 compared to the carbon content method, underscoring significant differences in results between the two methods. The study concludes with recommendations for research on methods to assess the carbon sink capacity of freshwater fisheries, aiming to establish a scientific framework for this evaluation.

Keywords: Qianxiahu reservoir; ecosystem characteristics; fishery carbon sink; trophic level; carbon content

Key Contribution: This study was the first to construct the Ecopath model to analyze the trophic levels, energy flows, and ecosystem characteristics among the species of the Qianxiahu Reservoir. Then, the carbon sink capacity was evaluated by the "trophic level" and "carbon content" methods. This significant variations in carbon sink capacity between the two calculation methods, indicating that the evaluation framework requires further exploration from a methodological perspective. The results suggest that the Qianxiahu Reservoir holds significant potential for carbon sink fisheries, and the composition of fishery species should be further refined based on the results from the Ecopath model to maximize its carbon sink functionality. The study aimed to provide references for assessing the fisheries carbon sink capacity within the reservoir, maximizing its carbon sink functionality based on the results from the Ecopath model.

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1. Introduction

Through international agreements like the Paris Climate Accord, society has expressed its commitment to curbing the increase in atmospheric carbon dioxide (CO_2) concentrations. While reducing emissions remains a critical priority, there is also a pressing need to improve the uptake and storage of CO_2 throughout various ecosystems [1]. Biological carbon sequestration, recognized as a key method due to its safety and cost-effectiveness [2], is poised to become a significant focus for the future expansion of carbon sinks, encompassing areas such as forestry [3], oceans [4], grasslands [5], and agriculture [6,7]. Notably, fishery carbon sinks, integral to aquatic ecosystems, also play a vital role [8]. These sinks include "removable carbon sinks", "storable carbon sinks", and "industrialized blue carbon pools" in both seawater and freshwater ecosystems [9–11].

As a crucial component of marine and freshwater ecosystems, carbon sink fisheries pertain to the activities within fisheries that facilitate carbon sequestration and can either directly or indirectly reduce atmospheric CO_2 concentrations through the biological carbon pump process. This process involves organisms absorbing carbon from water and transferring it to sediments or other organisms [12]. Depending on the type of activity, this can include algae cultivation, shellfish farming, and the cultivation of filter-feeding fish, among others [13]. These practices are instrumental in regulating the global carbon cycle and mitigating climate change. Currently, the focus of carbon sink fisheries is primarily on the cultivation of marine algae and shellfish [8]. Research on freshwater fishery carbon sinks is also emerging; for instance, Chen et al. [14] estimated that in 2009, the annual carbon sink from freshwater filter-feeding fish farming in China was about 2.58 million tons, and Xie et al. [9] reported that the carbon removal from freshwater bodies in China in the same year was approximately 278,000 tons. Given its potential to significantly reduce greenhouse gas emissions, fishery carbon sinks are drawing increasing attention globally [13].

Reservoir fishery cultivation occupies about 40% of the national freshwater aquaculture area, marking it as a significant component of China's carbon sink fisheries (China Fishery Statistics Yearbook 2021). This process primarily involves the absorption and storage of carbon and inorganic nutrient salts by algae and aquatic plants through photosynthesis. Aquatic organisms accumulate carbon in their bodies by consuming various natural nutrients, such as zooplankton and aquatic plants, which then contribute to "removable carbon sinks" through fishery harvests. Notably, this entire process avoids baiting, aligning with the core principles of carbon sink fisheries [15]. Fishery resources depend on the food chain (or network) to acquire energy and transfer it efficiently to higher trophic levels [16]. This approach is pivotal in advancing green and carbon sink fisheries, garnering significant interest from academic circles, management departments, and other sectors [17]. Yet, a standardized method for assessing the carbon sink capacity of inland fisheries has yet to be developed. The primary research methods include the trophic level method and the carbon content method [9]. The trophic level method evaluates the carbon sink capacity based on organisms' positions in the food chain [9]. Within a reservoir ecosystem, various species of fish and other aquatic organisms occupy different trophic levels. By assessing the energy flow and material cycling among them, the overall carbon sink potential of the fishery system can be gauged [8]. Conversely, the mass law focuses on the carbon content and biomass of the organisms themselves. By measuring and calculating the carbon content and biomass of different aquatic species, the carbon sink capacity of the fishery system can be directly determined [13]. This method is both highly accurate and practical for assessing the effectiveness of carbon sinks in reservoir fisheries. However, comparative studies evaluating these two methodologies in the context of reservoirs are still lacking.

Therefore, this study was to evaluate and compare the carbon sequestration potential of Qianxiahu Reservoir's fisheries, employing both trophic level and carbon content methodologies. The findings provide substantial referential value for assessing the ecological significance of reservoir carbon sink capacity. This, in turn, establishes a foundation for enhancing the progress of freshwater fishery carbon sinks not only in China but also globally.

2. Materials and Methods

2.1. Study Area

Qianxiahu Reservoir is situated in Lishui City, Zhejiang Province, Southeast China (27°99′91″ N, 119°96′21.36″ E). It forms part of the middle section of a tributary of the Xiaoxi River in the Oujiang River Basin (Figure 1). Classified as a typical canyon-type reservoir, it stretches over 80 km, covers a water surface area of approximately 70 km^2, and has a total storage capacity of 4.15 billion m^3, with a typical water storage elevation of 160 m. Construction of the reservoir commenced in 2004 and it became operational in 2008. Positioned within the subtropical monsoon climate zone, the reservoir experiences warm and humid conditions year-round. The average annual temperature and precipitation are 19.3 °C and 1390 mm, respectively. However, precipitation distribution throughout the year is uneven, with marked seasonal variations. About 70% to 77% of the annual rainfall occurs from April to September. Qianxiahu Reservoir stretches from the Jingning Hexi district to the dam of the Qingtian Tiankeng hydropower station, exhibiting relatively stable temperature variations year-round. Water temperature fluctuations are more pronounced during the summer, with the average thermocline ranging between 20 and 40 m.

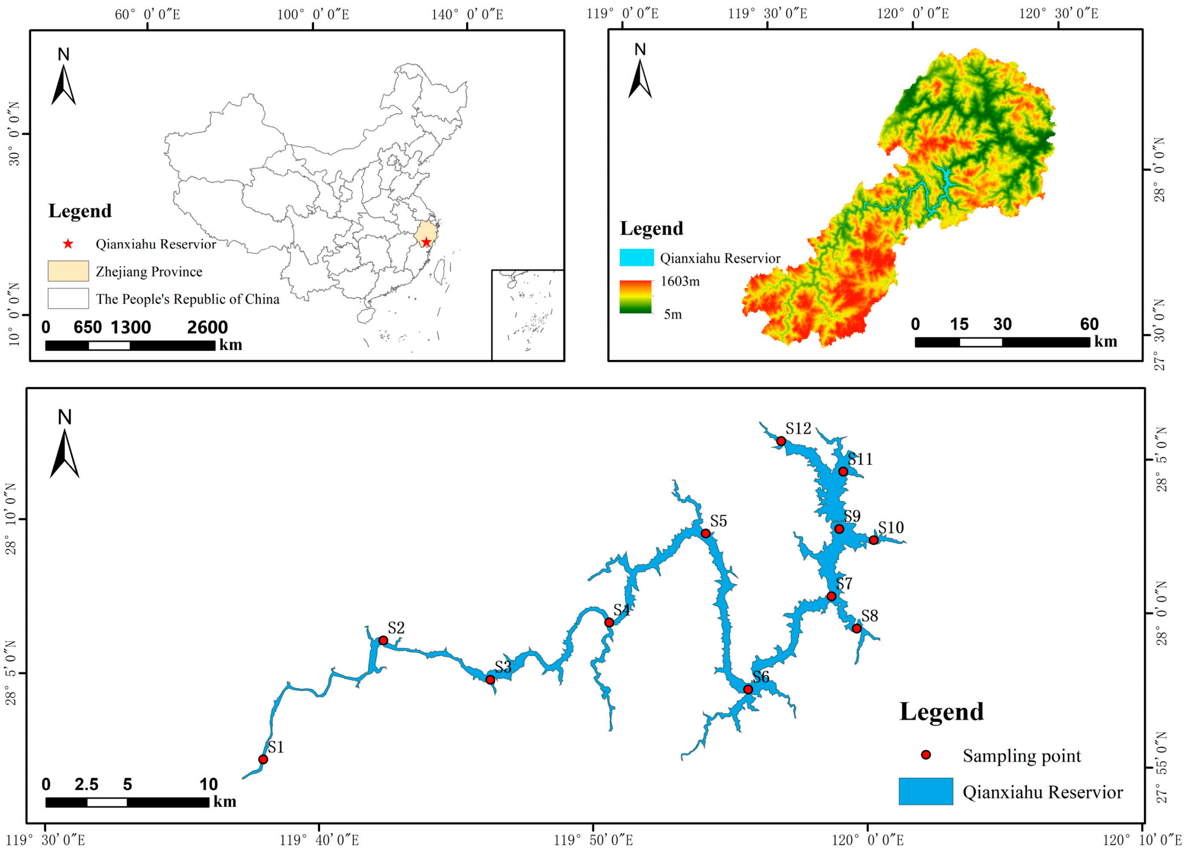

Figure 1. Geographical location and sample sites of the Qianxiahu Reservoir.

2.2. Ecopath Modeling Method

This static mass-balance trophic models for Qianxiahu reservoir were developed utilizing the freely accessible Ecopath with Ecosim (EwE) software, specifically version 6.5. The comprehensive models encompass the entire breadth of the trophic spectrum, comprehensively accounting for all ecological niches and interactions. This makes them ideally suited for conducting quantitative, systematic assessments of ecosystem structures and functions. This approach is grounded in two fundamental equations: one outlining the production component and the other elucidating the consumption aspect. Within Ecopath, the production term encompasses the sum of fishery catches, predation-induced mortality, biomass accumulation, net migration, and additional mortality factors. Christensen et al. [18] have formally articulated this concept as follows:

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

For the predator–prey interaction between prey i and predator j, let B_i represent the biomass of functional group i. P denotes the production, with $(P/B)_i$ signifying the production-to-biomass ratio specific to functional group i. Furthermore, EE_i is the ecotrophic efficiency of functional group i. The term (Q/B), meanwhile, represents the consumption-to-biomass ratio. DC_{ji} quantifies the proportion of prey i in the diet of predator j, while EX refers to the export value, accounting for factors like fishing activities and migration volumes. To formulate a comprehensive mass-balance model for each functional group, essential inputs encompass DC_{ji}, EX, and at least three of the four key parameters: B (biomass), P/B (production-to-biomass ratio), EE (ecotrophic efficiency), and Q/B (consumption-to-biomass ratio). Notably, acquiring the EE value often poses a challenge; therefore, it is commonly estimated based on other model parameters.

2.3. Classifying Functional Groups

In the Ecopath framework, an ecosystem is typically organized into three fundamental categories: detritus, producers, and consumers. These categories are further refined into distinct functional groups, each categorized primarily based on their biological and ecological attributes, alongside their abundance levels. To enhance the clarity and efficiency of the food web representation, species displaying considerable niche overlap were consolidated. As a result, a comprehensive delineation of 21 functional groups was established for the Qianxiahu Reservoir ecosystem, underpinning the development of its Ecopath models. This detailed classification is outlined in Supplementary Material Table S1.

2.4. Input Parameters

In the model, every functional group necessitates fundamental input parameters, including B, P/B, and Q/B. Furthermore, to establish a comprehensive diet matrix that interconnects all model compartments, it is imperative to ascertain the dietary composition of each group. For the specified fisheries within the system, catch (Y) emerges as an additional vital input. In scenarios where any of these core parameters is absent, the model possesses the capability to estimate the missing parameter, contingent upon the availability or assumption of EE [18,19]. The model employs a temporal unit of year^{-1} for various rates and t/km^2 for quantifying biomass.

In 2022, comprehensive data on biomass and catches across all biotic groups, in addition to the importation of detritus, were collected through seasonal field investigations conducted in January, April, July, and October. These investigations were designed to represent the annual mean values of the data across the entire year. Seasonal sampling was conducted at all sites, encompassing zoobenthos, plankton, and aquatic plants, which were subsequently identified and quantified to ascertain biomass utilizing standardized methodologies. Additionally, detritus was categorized into dissolved organic carbon (DOC), particulate organic carbon (POC), and bacteria, following the classification framework established by Heymans et al. [20].

The total quantity and biomass of fish within this reservoir were evaluated utilizing hydroacoustics, specifically employing a DT-X split-beam echosounder functioning at a frequency of 120 kHz. The device boasts a beam width of $7^\circ \times 7^\circ$ at the -3 dB level, a pulse duration of 0.128 milliseconds, and a ping rate of 5 pings per second. The precise composition and relative abundance of fish species were assessed through the utilization of multi-mesh gillnet samples, each 30 m in height and 180 m in length, divided into 24 segments with varying mesh sizes ranging from 1.0 cm to 26.0 cm. The carbon content of each fish species was analyzed using an elemental analyzer (Elementar vario Max). The biomass of each species within the Qianxiahu Reservoir was calculated through a multi-step process. Firstly, the total fish count, estimated utilizing hydroacoustic techniques, was multiplied by the quantitative proportion of each species, which was precisely determined via gillnet sampling. This was further multiplied by the average weight of each species, also derived from gillnet sampling. Additionally, to enhance the comprehensiveness of our analysis, fish catch data were gathered from commercial landings and augmented with insights from the local fishery bureau. From January to December 2022, fishers recorded the species composition of both daily and annual catches, ensuring a detailed account of the fishery's diversity and dynamics.

P/*B* and *Q*/*B* ratios of functional groups for phytoplankton, zooplankton, benthos, and aquatic plants were primarily derived from the parameter values used in the Ecopath models of the Qiandaohu Reservoir [21] and Changtan Reservoir [22], which share similar latitude and ecosystem function characteristics with the Qianxiahu Reservoir. The other necessary biological parameters for the models were sourced from existing literature [20].

P/*B* and *Q*/*B* coefficients for each fish group are calculated using empirical estimation formulas developed by Pauly [23] and Palomares [24]. These calculations are grounded in comprehensive data sourced from fishery resource surveys in this study, further enriched by information retrieved from FishBase (http://www.fishbase.org), ensuring a robust and well-informed analysis.

Food matrix of diet composition (DC) for the Qianxiahu Reservoir primarily references the Ecopath models of the Qiandao and Changtan Reservoirs [21,22], which exhibit similar ecological systems (Supplementary Material Table S2). The trophic levels of each functional group, determined through stable isotope analysis in the Qianxiahu Reservoir, are utilized to refine the model's food matrix, thereby ensuring a tight congruence between the trophic levels predicted by the model and those empirically validated through stable isotope analysis.

2.5. Data Processing and Model Balancing

Model debugging encompasses adjusting system balance and analyzing the sensitivity of functional groups. By entering collected parameters, such as *B*, *P*/*B*, *Q*/*B*, etc., into EwW6.6.5, the initial model often reveals some functional groups with *EE* values of 1 or higher. This indicates an imbalance among the functional groups, suggesting that the ecosystem may be on the brink of collapse. To rectify this, the study begins by fine-tuning the parameter values within the food matrix. By meticulously adjusting these values in the input food matrix, a balanced Ecopath model is achieved when *EE* values are less than or equal to 1 for all functional groups.

2.6. Calculating Fishery Carbon Sink Potential Based on Trophic Level and Carbon Content Methods

2.6.1. Trophic Level Method

Utilizing the reverse principle of the energy transfer model, the biomass of ingested phytoplankton is calculated through indicators such as fishing catch, corresponding trophic levels, and energy transfer efficiency between different trophic levels. Subsequently, using the carbon content of phytoplankton, the carbon sink attributable to the fishing industry is estimated. The specific equation is detailed below [14]:

$$C_2 = \sum_i \frac{y_i}{E(\gamma_i - 1)} \times \omega \tag{2}$$

In this equation, C_2 represents the carbon sink assessed by the trophic level method, y_i represents the fishing yield of species i, E is the average energy transfer efficiency between organisms at different trophic levels, γ_i indicates the trophic level of species i, and ω stands for the average carbon content of phytoplankton.

2.6.2. Carbon Content Method

Currently, the method of evaluating the carbon sink of freshwater fisheries based on carbon content is widely used. This approach concentrates on determining the "carbon content" of the subject under evaluation. The principle behind the carbon content evaluation method is as follows [15]:

$$C_1 = \sum_j p_j \times c_j \quad (3)$$

In the equation, C_1 represents the carbon sink evaluated by the carbon content method; P_j denotes the yield of freshwater fishing species j; C_j indicates the carbon content of freshwater fishing species j, where j ranges from 1 to n (with n representing the total number of freshwater fishing species).

3. Results

3.1. Food Web Structure and Trophic Analysis

3.1.1. Trophic Structure

As shown in Table 1, the *EE* values of eight ecological groups exceeded 0.5. These groups are heterotrophic bacteria (0.927), crabs (0.787), siniperca (0.709), zoobenthos (0.607), yellow catfish (0.600), sweetfish (0.569), phytoplankton (0.512), and shrimps (0.508). Notably, the *EE* values for culter fish were recorded as 0 due to the absence of predators and catches, while the *EE* values for silver carp and bighead carp were relatively low at 0.009 and 0.008, respectively.

Table 1. Input and output (bold) parameters of the Ecopath model for the Qianxiahu Reservoir.

Number	Functional Group	Trophic Level	*B* (t/km^2)	*P*/*B* (a^{-1})	*Q*/*B* (a^{-1})	*EE*	*P*/*Q* (a^{-1})
1	Sliver carp	**2.190**	8.345	1.534	8.65	**0.009**	**0.177**
2	Bighead carp	**2.560**	6.879	1.325	7.239	**0.008**	**0.183**
3	Crucian carp	**2.413**	3.876	1.231	8.967	**0.012**	**0.137**
4	Common carp	**2.361**	0.25	1.212	6.789	**0.089**	**0.179**
5	Herbivorous fish	**2.169**	0.65	1.789	12.13	**0.036**	**0.147**
6	Snail carp	**2.651**	0.523	1.845	8.154	**0.028**	**0.226**
7	Culter	**3.281**	0.187	1.546	7.895	**0**	**0.196**
8	Sharpbelly	**2.342**	0.26	2.15	10.145	**0.396**	**0.212**
9	Xenocypris	**2.160**	0.15	2.45	13.478	**0.222**	**0.182**
10	Siniperca	**2.813**	0.28	1.56	9.678	**0.709**	**0.161**
11	Yellow catfish	**2.312**	0.08	1.89	9.452	**0.600**	**0.200**
12	Sweetfish	**2.360**	0.136	1.859	9.98	**0.569**	**0.186**
13	Other fishes	**2.483**	5.879	1.22	8.678	**0.154**	**0.141**
14	Crab	**2.300**	0.652	3.092	38.95	**0.787**	**0.079**
15	Shimps	**2.247**	1.63	3.092	39.95	**0.508**	**0.077**
16	Zoobenthos	**2.240**	2.897	8.88	195.85	**0.607**	**0.045**
17	Zooplankton	**2.000**	30.028	18.84	120	**0.394**	**0.157**
18	Macrophyte	**1.000**	15.987	15.87		**0.040**	
19	Phytoplankton	**1.000**	32.875	93.89		**0.512**	
20	Heterotrophic bacteria	**1.000**	28.532	42.6		**0.927**	
21	Detritus	**1.000**	52.672			**0.246**	

B: biomass; *P*/*B*: production/biomass; *Q*/*B*: consumption/biomass; *EE*: ecotrophic efficiency; *P*/*Q*: production/consumption.

Trophic levels (TLs) of all ecological groups in the Qianxiahu Reservoir varied from 1.0 to 3.281, as shown in Figure 2. The lowest TLs were observed in detritus, heterotrophic bacteria, and primary producers, primarily comprising submerged macrophytes and phytoplankton (Table 1). Culter fish, including *Culter alburnus* and *Culter mongolicus*, had the highest TLs in the ecosystem. The TLs for the primary economic fish species, silver carp and bighead carp, are 2.190 and 2.560, respectively. The main food source for silver carp in the Qianxiahu Reservoir is zooplankton, while bighead carp primarily feed on plankton, as illustrated in Figure 2.

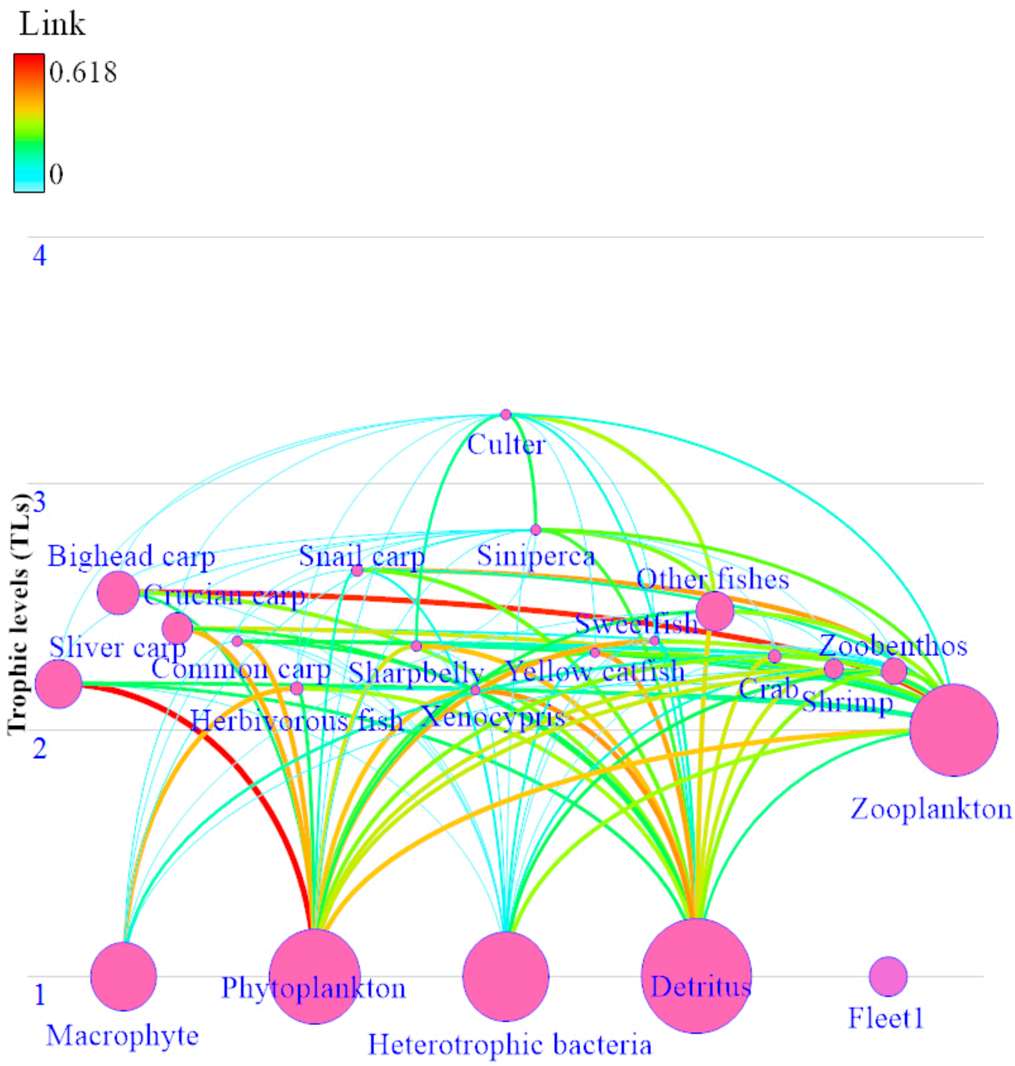

Figure 2. Structure of the Qianxiahu Reservoir's food web. (The thickness of the curve is determined by the quantity of material flow. The size of the circles is logarithmically scaled to be proportional to the biomass, while TLs are clearly denoted on the left side of the diagram.)

3.1.2. Transfer Efficiencies

The net production of primary producers in the entire Qianxiahu Reservoir ecosystem amounts to 5192.69 $t/(\text{km}^2 \cdot \text{a})$, of which 2719 $t/(\text{km}^2 \cdot \text{a})$ is consumed by primary consumers. The bulk of energy is concentrated at trophic level I, with energy decreasing significantly as the trophic level increases. The biomass of primary producers not consumed by higher levels is channeled into the detritus functional group for material recycling. In the upward transmission of trophic levels across the entire food chain, trophic levels II, III, IV, and V account for 34.2%, 1.65%, 0.038%, and 0.0012% of the total system flux, respectively (as shown in Figure 3). In the Ecopath model of the Qianxiahu Reservoir, the ecological energy conversion efficiencies of heterotrophic bacteria and phytoplankton in primary production are the highest, reaching 0.927 and 0.512, respectively, while that of organic detritus is relatively low, at 0.246 (as indicated in Table 1). This suggests that the "grazing food chain" comprises a larger share of the system compared to the "detrital-based food chain" in the Qianxiahu Reservoir ecosystem, thus establishing it as the dominant food chain in this thriving aquatic environment, a notable characteristic of reservoir ecosystems dominated by silver carp and bighead carp.

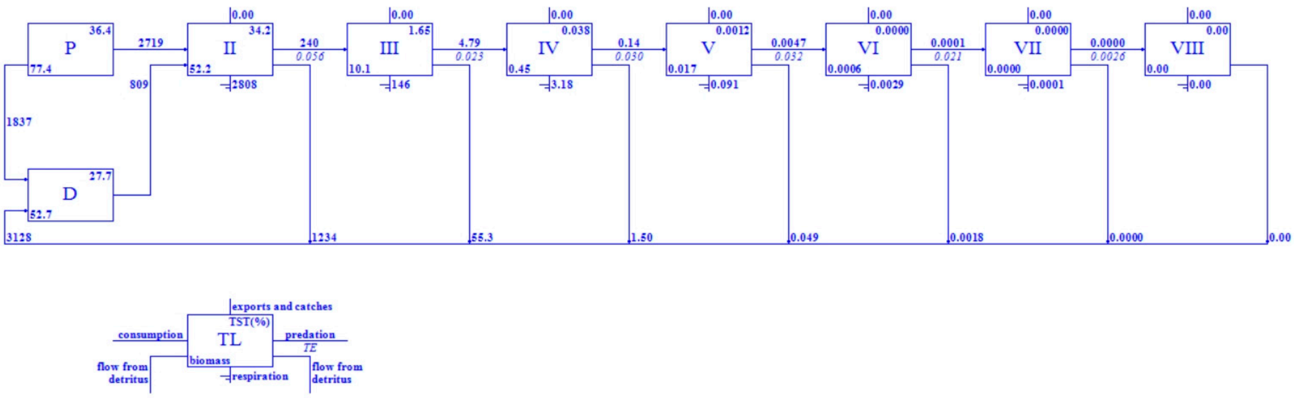

Figure 3. Energy flow dynamics within the Qianxiahu Reservoir ecosystem, encompassing various trophic levels (P: primary production; D: detritus; TL: trophic level; TE: transfer efficiency; TST: total system throughput).

3.1.3. Mixed Trophic Impacts

Mixed trophic impact (MTI) describes the mutual trophic impacts among various functional groups within an ecosystem. The MTI analysis of the Qianxiahu Reservoir ecosystem (as shown in Figure 4) reveals several insights: (1) increases in biomass across all functional groups generally exhibit varying degrees of negative correlation with the zooplankton functional groups and varying degrees of positive correlation with organic debris functional groups; (2) the primary economic fish species, namely silver carp and bighead carp, show a certain degree of negative correlation with the zooplankton functional group, but also display a level of positive correlation with the phytoplankton functional group; and (3) detritus and producers, including phytoplankton and heterotrophic bacteria, exert positive effects on nearly all functional groups.

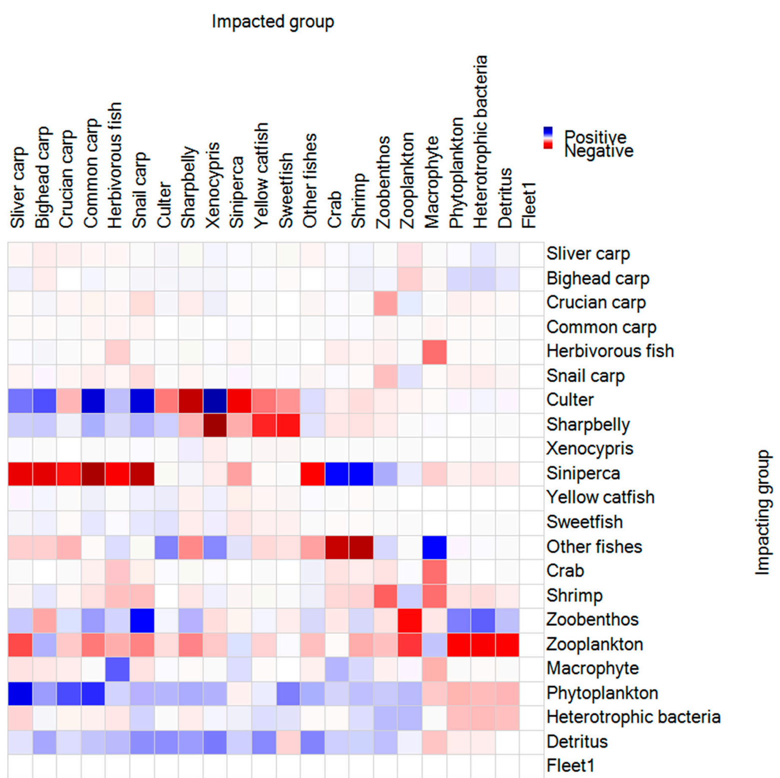

Figure 4. Mixed trophic impact (MTI) analysis of groups in the Qianxiahu Reservoir ecosystem. Blue and red colors in the graph indicate positive and negative correlation effects, respectively, and deeper color indicates stronger correlation effect.

3.1.4. Niche Overlap

Figure 5 illustrates the distribution of niche overlap among various fish functional groups in the Ecopath model of the Qianxiahu Reservoir. The results reveal that the highest prey overlap index, reaching 0.98, is observed between the crucian carp and sweetfish functional groups (points 3 and 12), followed by crucian carp and common carp at 0.95. This suggests that these functional groups share similar food preferences, leading to more intense interspecies competition compared to other groups. The functional group with the highest predator overlap index includes crab and shrimp at 0.98, common carp and herbivorous fish at 0.98, and yellow catfish and sweetfish at 0.96, as they are preyed upon by the same predators, such as *Culter alburnus* and other pelagic fishes.

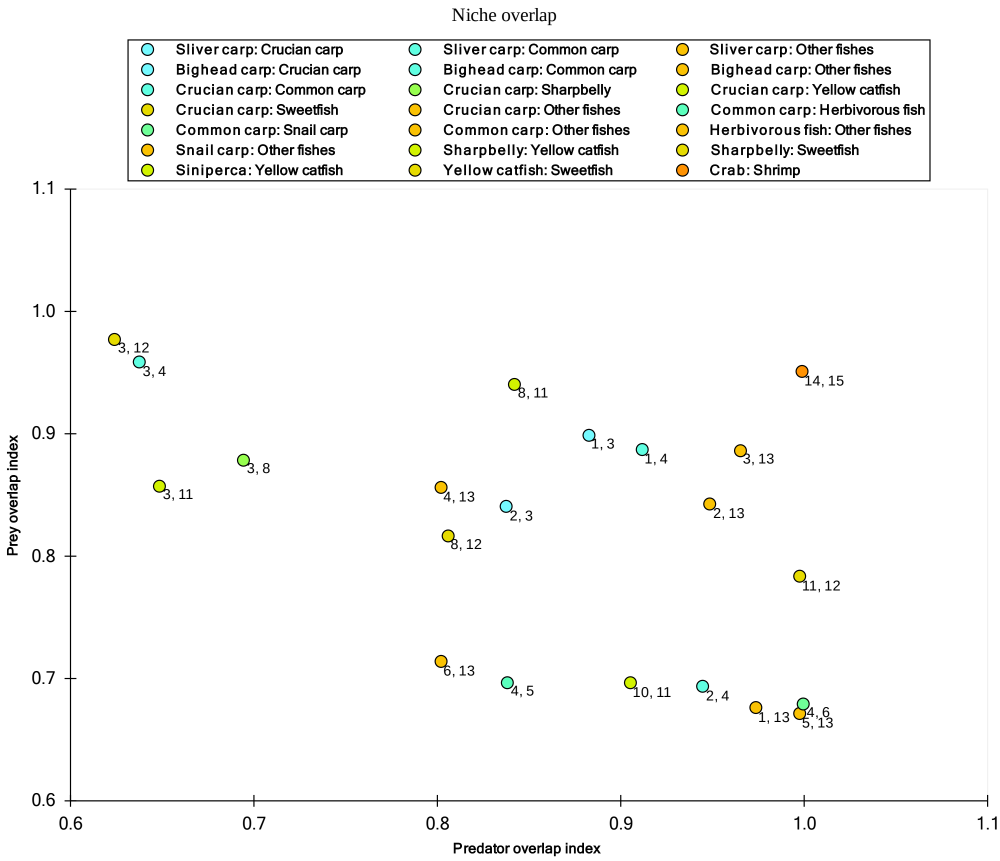

Figure 5. Analysis of niche overlap within the Qianxiahu Reservoir ecosystem. The numerical labels on the diagram correspond to the specific functional groups detailed in Table 1.

3.2. *Ecosystem Properties and Indicators*

The summary statistics and characteristic parameter values presented in Table 2 provide insightful information on the Qianxiahu Reservoir ecosystem. Notably, the total detritus influx into the reservoir's ecological fishery water system is substantial, reaching 3295.221 $t/(km^2 \cdot a)$, with a net production of 1597.638 $t/(km^2 \cdot a)$. Moreover, the ratio of total net primary productivity to the total respiratory volume, at 1.540072, indicates a robust balance between energy production and consumption within the ecosystem. Flow indices such as the ecosystem connectivity index (CI) and system omnivory index (SOI) play pivotal roles. Specifically, the CI and SOI values of 0.27 and 0.1963563, respectively, reveal an intricate interplay between the various components and TLs of the Qianxiahu Reservoir. Furthermore, the Finn's cycling index (FCI), with a value of 11.35%, underscores the efficient cycling of matter and energy within the system.

Table 2. Comprehensive summary of the ecosystem attributes of the Qianxiahu Reservoir.

Attribute Parameter [19]	Unit	State of the Ecosystem
Total system throughput (TST)	$t/(km^2 \cdot a)$	13232.99
Sum of all production (P)	$t/(km^2 \cdot a)$	5192.688
Sum of all consumption (C)	$t/(km^2 \cdot a)$	4493.812
Sum of all exports (E)	$t/(km^2 \cdot a)$	2485.766
Sum of all respiratory (R)	$t/(km^2 \cdot a)$	2958.194
Sum of all flows into detritus (D)	$t/(km^2 \cdot a)$	3295.221
Net primary production (NPP)	$t/(km^2 \cdot a)$	4555.832
Ratio of total primary production to total respiration (TPP/TR)	/	1.540072
Net system production (NSP)	$t/(km^2 \cdot a)$	1597.638
Ratio of total primary production to total biomass (TPP/TB)		32.51924
Ratio of total biomass to total throughput (TB/TP)		0.01058691
Connectance index (CI)		0.27
System omnivory index (SOI)		0.1963563
Finn's cycling index (FCI, %)		11.35
Shannon diversity index (Shannon)		2.06

3.3. Calculating Fishery Carbon Sink Potential

The evaluation of the carbon sinks of freshwater fisheries using the trophic level method and carbon content method reveals significant differences (Table 3). The carbon sink calculated by the trophic level method (267.8362 tons/km^2) is 4.02 times greater than that calculated by the carbon content method (66.6818 tons/km^2), with an absolute difference of 201.1544 tons/km^2. The three categories with the largest ratios—zoobenthos, phytoplankton and detritus—show significant proportions regardless of the method used, accounting for 22.42%, 12.27%, and 19.67% by the trophic level method and 17.97%, 19.01%, and 28.18% by the carbon content method, respectively. Furthermore, the ratios of carbon sink derived from silver carp, when calculated using the trophic level method, are 6.82% and 6.57%, while the same ratios calculated via the carbon content method are 2.03% and 1.38%, respectively.

Table 3. Carbon sink potential assessment results of Qianxiahu Reservoir based on trophic level and carbon content methods.

Dominant Species Composition	Biomass (tons/km^2)	Trophic Level	Carbon Sink Calculated by Trophic Level Method (tons/km^2)	Carbon Content (%)	Carbon Sink Calculated by Carbon Content (tons/km^2)
Sliver carp	2.19	8.345	18.27555	16.19	1.351056
Bighead carp	2.56	6.879	17.61024	13.4	0.921786
Crucian carp	2.413	3.876	9.352788	11.36	0.440314
Common carp	2.361	0.25	0.59025	12.14	0.03035
Herbivorous fish	2.169	0.65	1.40985	13.15	0.085475
Snail carp	2.651	0.523	1.386473	13.26	0.06935
Culter	3.281	0.187	0.613547	16.78	0.031379
Sharpbelly	2.342	0.26	0.60892	14.56	0.037856
Xenocypris	2.16	0.15	0.324	13.21	0.019815
Siniperca	2.813	0.28	0.78764	12.34	0.034552
Yellow catfish	2.312	0.08	0.18496	14.51	0.011608
Sweetfish	2.36	0.136	0.32096	13.67	0.018591
Other fishes	2.483	5.879	14.59756	14.12	0.830115
Crab	2.3	0.652	1.4996	12.34	0.080457

Table 3. *Cont.*

Dominant Species Composition	Biomass (tons/km^2)	Trophic Level	Carbon Sink Calculated by Trophic Level Method (tons/km^2)	Carbon Content (%)	Carbon Sink Calculated by Carbon Content (tons/km^2)
Shimps	2.247	1.63	3.66261	14.26	0.232438
Zoobenthos	2.24	2.897	6.48928	39.78	1.152427
Zooplankton	2	30.028	60.056	42.23	12.68082
Macrophyte	1	15.987	15.987	5.968947	41.22
Phytoplankton	1	32.875	32.875	12.27429	36.45
Heterotrophic bacteria	1	28.532	28.532	10.65278	39.56
Detritus	1	52.672	52.672	19.66575	35.68
Total	44.882		267.8362		66.6818

4. Discussion

4.1. Analysis of Energy Fluxes and Trophic Structure

The niche overlap index reflects the interspecies relationships among fish species within aquatic ecosystems. As the niche overlap index increases, the competitive interaction between the two species intensifies [20]. Notably, in the Qianxiahu Reservoir, the economically valuable species—silver carp and bighead carp, along with crucian carp, common carp, and other smaller fish species—exhibit the highest niche overlap indices, suggesting intense competition between these groups. Therefore, to optimize the economic returns from silver carp and bighead carp, increasing the fishing pressure or grazing on populations of crucian carp, common carp, and other minor fish species in the Qianxiahu Reservoir is recommended [25].

The mixed trophic impact revealed that biomass variations in the key species, *Siniperca chuatsi*, significantly affect the *EE* value of the herbivorous fish functional group. Similarly, changes in the biomass of *Culter alburnus* profoundly influence the *EE* value of the *Hemiculter leucisculus* functional group. Additionally, when the biomass of the principal economic species, *Aristichthys nobilis*, fluctuates, the most noticeable effect is seen in the *EE* value of zooplankton. Variations in the biomass of zooplankton within the forage organism functional group markedly impact phytoplankton levels.

Based on the analysis of ecosystem characteristic values, parameters such as TPP/TR, FCI, CI, and SOI in the Ecopath model are effective indicators of ecosystem status [20]. The establishment of the ecological channel model for the Qianxiahu Reservoir revealed that the FCI, CI, and SOI values for this reservoir were 11.35, 0.27, and 0.196, respectively. These indices suggest a higher aggregation degree of functional groups, tighter connectivity, and a higher proportion of material recycling in the Qianxiahu Reservoir compared to other reservoirs, indicating a more mature ecosystem. For instance, the FCI of the Qianxiahu Reservoir exceeds those of the Ecopath models for Qiandao Lake in 2016 (5.15) [26] and the Jinshahe Reservoir in 2013 (6.73) [27], demonstrating a higher proportion of material recycling than those ecosystems. The CI of the Qianxiahu Reservoir is slightly higher than that of Qiandao Lake in 2016 (0.263) [26] but substantially lower than that of the Changtan Reservoir (0.349) [22], showing that connectivity among the 20 functional groups in the Qianxiahu Reservoir is comparable to Qiandao Lake but significantly lower than the Changtan Reservoir. Unlike the FCI and CI, the SOI of the Qianxiahu Reservoir is markedly higher than the Ecopath model of the Jinshahe Reservoir in 2013 (0.087) [25] and Qiandao Lake in 2016 (0.13) [18], indicating a significantly more complex ecosystem in the Qianxiahu Reservoir than in the other two. These indices collectively reflect a more mature ecosystem in the Qianxiahu Reservoir, where TPP/TR has a pronounced influence on system maturity. The closer the TPP/TR ratio is to 1 (greater than 1), the more mature the ecosystem. The TPP/TR ratio of the Qianxiahu Reservoir, at 1.54, is closer to 1 compared to the ecosystems of Qiandao Lake (6.509) [18], the Jinshahe Reservoir (6.735) [27], and the Changtan Reservoir (2.445) [22], indicating a more mature stage for the Qianxiahu Reservoir, which is nearly fully mature.

4.2. Comparative Analysis of Fishery Carbon Sink Potential

At present, various studies have assessed the carbon sink capacity of freshwater fisheries among different regions and species, achieving progress in both the evaluation results and methodologies, especially in China [28]. This study employs the "trophic level" evaluation method, which uses the theory of energy transfer to estimate the total mass of aquatic organisms in the Qianxiahu Reservoir that can be converted into plankton along the food chain. The calculated carbon sink capacity for the reservoir's fisheries is 261.8362 tons. In contrast, the "carbon content" method estimates only 25.47% of this value, resulting in significantly different conclusions. The disparities between these methods stem from various factors, including the average transfer efficiency among organisms at different energy flows, the trophic levels of distinct aquatic species [29,30], and their carbon metabolism [31,32].

As a critical component and focus of China's strategy to optimize biological carbon sequestration, fishery carbon sequestration holds substantial importance for advancing the development of a low-carbon economy [33]. Accurate assessments of fishery carbon sequestration are essential for effectively implementing the strategy for amplifying aquatic biological carbon sequestration. Currently, however, there is no standardized method or framework for evaluating carbon sequestration in freshwater and marine fisheries [34]. Based on existing research, the "carbon content" method is predominantly utilized for freshwater fisheries, whereas the "trophic level" method is preferred for assessing marine fisheries [35]. It is advisable to develop an evaluation framework for fishery carbon sequestration from a methodological standpoint.

4.3. Management Implications and Future Outlook

The concept of a "clean water fishery" in reservoirs primarily involves strengthening the aquatic environment by introducing water-purifying species, such as silver carp and bighead carp. This intervention allows for the transformation of waterborne nitrogen and phosphorus through trophic levels, thereby bolstering the self-purification capabilities of the water bodies. The objective of a "clean water fishery" is to concurrently achieve fishery production and environmental restoration. Conversely, a "carbon sink fishery" is designed to effectively sequester carbon and nitrogen within water bodies, increasing the utilization rates of carbon and nitrogen and reducing emissions of greenhouse gases such as CO_2, CH_4, and N_2O. This approach aligns with the principles of low-carbon environmental protection and lays the groundwork for the sustainable development of freshwater fisheries [36]. A "carbon sink fishery" can be established through non-bait fishing activities, such as the use of filter-feeding fish like silver carp and bighead carp, along with stocking and releasing practices [37]. By strategically managing the quantity and types of fish released, integrating the objectives of both "clean water fisheries" and "carbon sink fisheries" can not only secure economic benefits but also revitalize both aqueous and atmospheric environments, thereby promoting the healthy and sustainable growth of freshwater fisheries [38]. In this vein, the silver carp and bighead carp released in the Qianxiahu Reservoir or other similar reservoirs are pivotal to advancing both "clean water fisheries" and "carbon sink fisheries".

Secondly, owing to the ubiquitous deceleration of biological metabolism associated with species aging, there exists an optimal harvest period for silver carp and bighead carp in reservoirs, as highlighted in [11]. This harvest timing is crucial for maximizing the carbon sequestration and food supply benefits derived from these fish species. Unfortunately, in the present study, the fish from Qianxiahu Reservoir were selected without taking into account this optimal harvest time. Nevertheless, the chosen species are representative, and the findings, albeit limited, still hold some valuable insights. Consequently, there is a pressing need for comprehensive and standardized fundamental research on the carbon sequestration mechanisms of filter-feeding fish, integrating their biological growth and metabolic traits.

Thirdly, for an extended period, factors such as water pollution, the construction of reservoir dams, and overfishing have led to a marked decline in the fishery resources of China's inland waters [39]. To counteract this trend, long-term fishing bans have been introduced in critical areas including the Yangtze River Basin, the Pearl River Basin, and Taihu Lake [40,41]. Thus, from the viewpoint of water ecosystem services, it is imperative to provide a solid scientific foundation for decision-making and management to balance the impacts of fishing bans and fishery carbon sinks.

Finally, while freshwater fisheries contribute to carbon sequestration, they also emit greenhouse gases such as N_2O and CO_2 during growth and metabolic processes [42]. Consequently, freshwater fisheries serve dual roles as both carbon sinks and carbon sources. Therefore, by examining the carbon balance [30,43], we must scientifically determine whether freshwater fisheries act primarily as carbon sinks or sources, or exhibit dynamic characteristics. Furthermore, it is essential to integrate this with existing freshwater fishing yield databases, adopt carbon sink accounting methods, develop a national database for freshwater fishing carbon sinks, and perform carbon sink analyses based on the development of ecosystems over time, regional distribution of fisheries, and species composition. This will provide essential data for advancing studies on ecological conservation.

5. Conclusions

As an important part of carbon sink fisheries, freshwater fisheries in reservoirs are one of the important directions for the development of green fisheries and carbon sink fisheries, which have attracted wide range of concerns from academic fields, management departments, etc. However, at present, the evaluation method of carbon sink in inland freshwater fisheries has not yet formed a standard, and the specific methods and applications are still in the stage of academic discussion.

In this study, we constructed the Ecopath model to analyze the trophic levels, energy flows, and ecosystem characteristics among the species of the Qianxiahu Reservoir based on on-site field fishing and hydroacoustic detection. Then, the "trophic level" and "carbon content" methods were used to evaluate the potential of the Qianxiahu Reservoir for carbon sink fisheries. The results showed that the carbon sink capacity was estimated at 261.8362 tons/km^2 and 66.6818 tons/km^2 evaluated by the "trophic level" and "carbon content" methods, respectively, indicating that the Qianxiahu Reservoir or other similar reservoirs holds substantial potential for carbon sink fisheries.

The significant variations in the carbon sink capacity estimated by these two calculation methods indicate that the evaluation framework requires further exploration from a methodological perspective. Finally, measures such as stocking filter-feeding fish, implementing appropriate fishing practices, and enforcing seasonal fishing bans could improve energy utilization efficiency and the trophic structure, thus optimizing the ecological value of carbon sinks. Overall, the findings suggest that the Qianxiahu Reservoir holds significant potential for carbon sink fisheries, and the composition of fishery species should be further refined based on the results from the Ecopath model to maximize its carbon sink functionality in the future.

Supplementary Materials: The following supporting information can be downloaded at https://www.mdpi.com/article/10.3390/fishes9110438/s1, Table S1: Functional groups of Ecopath model for the Qianxiahu Reservoir; Table S2: Diet composition matrix for Ecopath model of the Qianxiahu Reservoir.

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References

1. IPCC. *Climate Change 2021: The Physical Science Basis. Contribution Of Working Group I to the Sixth Assessment Report of the Intergovernmental Panel on Climate Change*; Cambridge University Press: Cambridge, UK, 2021.
2. Gephart, J.A.; Henriksson, P.J.G.; Parker, R.W.R.; Shepon, A.; Gorospe, K.D.; Bergman, K.; Eshel, G.; Golden, C.D.; Halpern, B.S.; Hornborg, S.; et al. Environmental Performance of Blue Foods. *Nature* **2021**, *597*, 360–365. [CrossRef]
3. Alongi, D.M. Carbon Cycling and Storage in Mangrove Forests. *Ann. Rev. Mar. Sci.* **2014**, *6*, 195–219. [CrossRef]
4. Saba, G.K.; Burd, A.B.; Dunne, J.P.; Hernández-León, S.; Martin, A.H.; Rose, K.A.; Salisbury, J.; Trueman, C.N.; Wilson, R.W.; Wilson, S.E. Toward a Better Understanding of Fish-Based Contribution to Ocean Carbon Flux. *Limnol. Oceanogr.* **2021**, *66*, 1639–1664. [CrossRef]
5. Anderson, T.R.; Martin, A.P.; Lampitt, R.S.; Trueman, C.N.; Henson, S.A.; Mayor, D.J.; Link, J. Quantifying Carbon Fluxes from Primary Production to Mesopelagic Fish Using a Simple Food Web Model. *ICES J. Mar. Sci.* **2019**, *76*, 690–701. [CrossRef]
6. Jia, L.; Wang, M.; Yang, S.; Zhang, F.; Wang, Y.; Li, P.; Ma, W.; Sui, S.; Liu, T.; Wang, M. Analysis of Agricultural Carbon Emissions and Carbon Sinks in the Yellow River Basin Based on LMDI and Tapio Decoupling Models. *Sustainability* **2024**, *16*, 468. [CrossRef]
7. Liu, M.; Yang, L. Spatial Pattern of China's Agricultural Carbon Emission Performance. *Ecol. Indic.* **2021**, *133*, 108345. [CrossRef]
8. Lee, H.Z.L.; Davies, I.M.; Baxter, J.M.; Diele, K.; Sanderson, W.G. A Blue Carbon Model for the European Flat Oyster (*Ostrea Edulis*) and its Application in Environmental Restoration. *Mar. Freshw. Ecosyst.* **2024**, *34*, e4030. [CrossRef]
9. Bianchi, D.; Carozza, D.A.; Galbraith, E.D.; Guiet, J.; DeVries, T. Estimating Global Biomass and Biogeochemical Cycling of Marine Fish with and without Fishing. *Sci Adv.* **2021**, *7*, eabd7554. [CrossRef]
10. Cavan, E.L.; Hill, S.L. Commercial Fishery Disturbance of the Global Ocean Biological Carbon Sink. *Glob. Chang. Biol.* **2022**, *28*, 1212–1221. [CrossRef]
11. Le, C.; Feng, J.; Sun, L.; Yuan, W.; Wu, G.; Zhang, S.; Yang, Z. Co-benefits of Carbon Sink and Low Carbon Food Supply via Shellfish and Algae Farming in China from 2003 to 2020. *J. Clean. Prod.* **2023**, *414*, 137436. [CrossRef]
12. Feng, J.; Sun, L.; Yan, J. Carbon Sequestration via Shellfish Farming: A Potential Negative Emissions Technology. *Renew. Sustain. Energy Rev.* **2023**, *171*, 113018. [CrossRef]
13. Nowicki, M.; DeVries, T.; Siegel, D.A. Quantifying the Carbon Export and Sequestration Pathways of the Ocean'S Biological Carbon Pump. *Glob. Biogeochem. Cycles* **2022**, *36*, e2021GB007083. [CrossRef]
14. Chen, Z.X.; Mou, Z.B. Carbon Sink Function of Filter-Feeding Fish in Freshwater Fisheries. *Chin. J. Fish.* **2011**, *24*, 65–68. (In Chinese)
15. Yue, D.D.; Wang, L.M.; Fang, H. Development Strategy of Marine Fisheries in China Based on the Carbon Balance. *J. Agric. Sci. Technol.* **2016**, *18*, 1–8. (In Chinese)
16. Sethi, S.A.; Branch, T.A.; Watson, R. Global Fishery Development Patterns are Driven by Profit but Not Trophic Level. *Proc. Natl. Acad. Sci. USA* **2010**, *107*, 1216–12167. [CrossRef]
17. Jonathan, E.F.; Maria, G.; Andrew, J.P. Optimizing Fisheries for Blue Carbon Management: Why Size Matters. *Limnol. Oceanogr.* **2022**, *67*, S171–S179.
18. Christensen, V. Ecosystem Maturity-Towards Quantification. *Ecol. Model.* **1995**, *77*, 3–32. [CrossRef]
19. Christensen, V.; Pauly, D. Ecopath II—A Software for Balancing Steady-State Ecosystem Models and Calculating Network Characteristics. *Ecol. Model.* **1992**, *61*, 169–185. [CrossRef]
20. Heymans, J.J.; Coll, M.; Link, J.S.; Mackinson, S.; Steenbeek, J.; Walters, C.; Christensen, V. Best Practice in Ecopath with Ecosim Food-Web Models for Ecosystem-Based Management. *Ecol. Model.* **2016**, *331*, 173–184. [CrossRef]
21. Deng, Y.; Zheng, Y.C.; Chang, J.B. Evaluaion of the Elleet of Stocking Silver Carp and Bighead Carp on the Ecosystem of Qiandao Lake Using Ecopath Model. *Acta. Ecol. Sin.* **2022**, *42*, 6853–6862.
22. Shi, Z.Y.; Zhang, J.T.; Huo, S.L. Research on the Application of Ewe Model in Aquatic Ecosystems and a Case Study of Changtan Reservoir. *J. Environ. Engn. Technol.* **2023**, *13*, 567–577.
23. Pauly, D. On the Interrelationships between Natural Mortality, Growth Parameters, and Mean Environmental Temperature in 175 Fish Stocks. *ICES J. Mari. Sci.* **1980**, *39*, 175–192. [CrossRef]
24. Palomares, M.L.D.; Pauly, D. Predicting Food Consumption of Fish Populations as Functions of Mortality, Food Type, Morphometrics, Temperature and Salinity. *Mar. Freshw. Res.* **1998**, *49*, 447–453. [CrossRef]
25. Lorenzen, K.; Cowx, I.G.; Entsua-Mensah, R.; Lester, N.; Koehn, J.; Randall, R.; So, N.; Bonar, S.; Bunnell, D.; Venturelli, P.; et al. Stock Assessment in Inland Fisheries: A Foundation for Sustainable Use and Conservation. *Rev. Fish Biol. Fish.* **2016**, *26*, 405–440. [CrossRef]
26. Yu, J.; Liu, J.R.; Wang, L.; Wu, Z.; Yu, Z.; Liu, M.; Han, Y.; Xie, P. Analysis on the Ecosystem Structure and Function of Lake Qiandao Based on Ecopath Model. *Acta. Hydrobiol. Sin.* **2021**, *45*, 308–317. (In Chinese)
27. Zhang, Y. *The Study of Fishery Resources and Ecopath Model in Jinshahe Reservoir Ecosystem, Hubei Province*; Wuhan: Huazhong Agricultural University: Wuhan, China, 2015. (In Chinese)
28. Wu, B.; Wang, H.H.; Xi, H.B. The Carbon Sink Capacity of the Chinese Freshwater Aquaculture. *J. Biosafety.* **2016**, *25*, 308–312. (In Chinese)

29. Panikkar, P.; Khan, M.F.; Desai, V.R.; Shrivastava, N.; Sharma, A. Characterizing Trophic Interactions of a Catfish Dominated Tropical Reservoir Ecosystem to Assess the Effects of Management Practices. *Environ. Biol. Fishes* **2014**, *98*, 237–247. [CrossRef]
30. Zhang, Y.; Gu, K.; Wang, X.; Zhang, J.; Duan, J.; Hu, Z.; Liu, Q. Food Web Structure and Ecosystem Functions of the Water Source in the Middle Route of China's South-to-North Water Diversion Project. *Fishes* **2024**, *9*, 202. [CrossRef]
31. Konar, M.; Qiu, S.; Tougher, B.; Vause, J.; Tlusty, M.; Fitzsimmons, K.; Barrows, R.; Cao, L. Illustrating the Hidden Economic, Social and Ecological Values of Global Forage Fish Resources. *Resour. Conserv. Recycl.* **2019**, *151*, 104456. [CrossRef]
32. Ahmed, N.; Bunting, S.W.; Glaser, M.; Flaherty, M.S.; Diana, J.S. Can Greening of Aquaculture Sequester Blue Carbon? *Ambio* **2017**, *46*, 468–477. [CrossRef]
33. Hilborn, R.; Agostini, V.N.; Chaloupka, M.; Garcia, S.M.; Gerber, L.R.; Gilman, E.; Hanich, Q.; Himes-Cornell, A.; Hobday, A.J.; Itano, D. Area-based Management of Blue Water Fisheries: Current Knowledge and Research Needs. *Fish Fish.* **2021**, *23*, 492–518. [CrossRef]
34. Jihong, Z.; Yi, L.; Wenguang, W.; Xinmeng, W.; Yi, Z. Overview of the Marine Fishery Carbon Sink Project Methodology. *Prog. Fish. Sci.* **2022**, *43*, 151–159.
35. Gao, F.; Tian, Z.; Wang, Y.; Yang, Z.; Ding, G. Study on Carbon stock and Sequestration Potential of Typical Grasslands in Northern China: A Case Study of Wuchuan County. *Sustainability* **2024**, *16*, 4053. [CrossRef]
36. Czamanski, M.; Nugraha, P.; Lasbleiz, A.; Caroff, R.; Tréguer, P. Carbon, Nitrogen and Phosphorus Elemental Stoichiometry in Aquacultured and Wild-Caught Fish and Consequences for Pelagic Nutrient Dynamics. *Mar. Biol.* **2011**, *158*, 2847–2862. [CrossRef]
37. Mariani, G.; Cheung, W.W.L.; Lyet, A.; Sala, E.; Mayorga, J.; Velez, L.; Gaines, S.D.; Dejean, T.; Troussellier, M.; Mouillot, D. Let More Big Fish Sink: Fisheries Prevent Blue Carbon Sequestration—Half in Unprofitable Areas. *Sci. Adv.* **2020**, *6*, eabb4848. [CrossRef]
38. Hilborn, R. Future Directions in Ecosystem based Fisheries Management: A Personal Perspective. *Fish. Res.* **2011**, *108*, 235–239. [CrossRef]
39. Wang, H.; Wang, P.; Xu, C.; Shi, L.; Zhou, L.; Jeppesen, E.; Chen, J.; Xie, P. Can the "10-year Fishing Ban" Rescue Biodiversity of the Yangtze River? *Innovation* **2022**, *3*, 100235. [CrossRef]
40. Yang, T.; Li, D.; Xu, Q.; Zhu, Y.; Zhu, Z.; Leng, X.; Zhao, D.; An, S. Effects of A Fishing Ban on the Ecosystem Stability and Water Quality of A Plateau Lake: A Case Study of Caohai Lake, China. *Water* **2024**, *16*, 782. [CrossRef]
41. Cao, W. Ten-year Fishing Ban is An Important Step for the Protection of the Yangtze River. *J. Aquat. Biol.* **2022**, *46*, 1.
42. Parker, R.W.R.; Blanchard, J.L.; Gardner, C.G.; Green, B.S.; Hartmann, K.; Tyedmers, P.H.; Watson, R.A. Fuel Use and Greenhouse Gas Emissions of World Fisheries. *Nat. Clim. Chang.* **2018**, *8*, 333–337. [CrossRef]
43. Pikitch, E.K.; Santora, C.; Babcock, E.A.; Bakun, A.; Bonfil, R.; Conover, D.O.; Dayton, P.; Doukakis, P.; Fluharty, D.; Heneman, B.; et al. Ecosystem-based Fishery Management. *Science* **2004**, *305*, 346–347. [CrossRef] [PubMed]