Analysis of the Ecosystem Characteristics and Ecological Carrying Capacity of the Main Commercial Fish in the Artificial Reef Ecosystem in Laizhou Bay Using the Ecopath Model

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Abstract: In this study, we constructed an Ecopath model of the artificial reef ecosystem in Laizhou Bay, with special emphasis on the stock enhancement opportunities. Laizhou Bay is the largest semi-enclosed bay in the Bohai Sea, China, where multiple factors, especially overfishing, have led to the decline of many commercial marine fish stocks. Artificial oyster reefs were developed in 2011 in this region, providing shelter, feeding, and breeding sites for marine organisms. Additionally, stock enhancement by release can be used to replenish fishery species resources. Ad hoc stock enhancement, however, can fail to bring economic benefits and may impact ecosystem stability. Therefore, we estimated the ecological carrying capacity of the three main economic fish species in Laizhou Bay, including black rockfish (Sebastes schlegelii), fat greening (Hexagrammos otakii), and Chinese seabass (Lateolabrax maculatus) before release to ensure the sustainable use of fishery resources. The Ecopath model in Laizhou Bay was divided into 17 functional groups based on commercial relevance, dietary similarity, and habitat needs of the species present in the area. The ecological parameters, such as the ratio of total primary productivity to total respiration (1.205), connectance index (0.207), and system omnivory index (0.090) indicated that the artificial reef ecosystem in Laizhou Bay has a relatively simple food web structure. The ecological carrying capacities of S. schlegelii, H. otakii, and L. maculatus were assessed at 0.4676 t/km², 0.5472 t/km², and 0.3275 t/km², respectively. This study provides a reference for the formulation of fishery strategies to maintain ecosystem stability and biodiversity and to maximize fishery returns and sustainability in Laizhou Bay.

Keywords: fishery resource; ecosystem maturity; trophic structure; stock enhancement

1. Introduction

Overfishing, water pollution, climate change, and other factors have a significant impact on marine fishery resources [1]. At a global scale, fishery resources have substantially declined. Large fish from the dominant species that occupy a high trophic level have been replaced gradually by low trophic level invertebrates and planktivorous pelagic fish [2]. Many inshore fish populations have been depleted or even collapsed, owing to overexploitation [3]. Therefore, appropriate management measures need to be taken to protect and restore fishery resources.

Marine ranching is a new type of marine economy that plays an important role in enhancing fishery stocks and restoring marine ecosystems [4]. Ocean ranching is an artificial fishery approach based on the principles of marine ecology and modern ocean engineering technology. It makes full use of natural productivity and cultivates and manages fishery resources in specific marine areas [5]. Ocean ranching focuses on artificial reefs and fish releases [6]. Artificial reefs can restore the ecological environment and protect fishery resources by providing shelter, feeding, and breeding sites for marine organisms [7].
Stock enhancement by release is also an important way to restore biological resources. Enhancement refers to the replenishment of species resources and the improvement of the biodiversity of marine areas by releasing the fry of various fish species into the marine ecosystem [8,9].

Although such releases are often implemented to restore fishery resources, a range of potential ecological problems may be associated with this practice [10]. Releases are driven by a production imperative rather than by a fisheries management perspective in many cases [11,12]. As a result, many release activities are ineffective [13]. To ensure the sustainable development of fishery resources, it is necessary to formulate a proper release strategy that balances the economic and ecological benefits. This requires an evaluation of the breeding potential and the ecological carrying capacity of the target species before release [14,15].

The Ecopath model is used to construct the structure of aquatic ecosystems by inputting the ecological parameters of each functional group based on the principle of trophic dynamics. The model quantifies the characteristic parameters of the ecosystem to describe the process of energy flows and nutrient relationships between species and to assess the maturity and stability of the ecosystem [16–19]. The Ecopath model can also be used to estimate the ecological carrying capacity for a species to maintain a balanced ecosystem [20,21].

Laizhou Bay is as the largest semi-enclosed bay in the Bohai Sea, located on the northwest of the Shandong Peninsula in the southern Bohai Sea, China. The Yellow River is the largest river entering the bay. The river carries a large quantity of nutrients and regulates the salinity and temperature of the sea around its mouth, forming the nearshore water mass of Laizhou Bay, which is characterized by low salinity, plentiful nutrients and moderate water temperatures. This distinctive marine environment makes Laizhou Bay the spawning, breeding, and feeding ground for important fishery resources. The bay is among the most productive fishery areas in China. Many of the fish, cephalopod and large crustacean species occupy a high trophic level in the marine ecosystem and are also the targets of fishing [22]. However, in recent years, multiple factors have caused substantial changes in fishery resources and the ecosystem structure, with a shift from higher to lower trophic levels, and to small-sized and low-quality individual catches, which have reduced fishery productivity [23].

At present, Ecopath-based studies in Laizhou Bay are mainly used to evaluate the ecological carrying capacity of oysters, sea cucumbers, and crustaceans [24–27]. Few studies have assessed the ecological carrying capacity of fish. Therefore, in the current study, the Ecopath model was used to describe the structure and function of the artificial reef ecosystem in Laizhou Bay, and to evaluate the ecological carrying capacity of three common economic fish species (Sebastes schlegelii, Hexagrammos otakii, and Lateolabrax maculatus).

2. Materials and Methods
2.1. Study Area

The study area was located in the China ocean ranching demonstration zone of Laizhou Bay (Figure 1). Laizhou Bay covers 6966 km² and has a coastline of 319.6 km. The bay borders the mouth of the Yellow River and receives a large sediment flow from the river. This sediment accumulates rapidly on the seabed, causing the water to become shallower. The sediment of the marine area is muddy sand facies. The current velocity is generally between 0.1 m/s and 0.4 m/s and flows from southwest to northeast. The mean tidal range is 0.89 m. The water depth is 6–8 m, and the average water temperature in spring, summer and autumn is 17.8 °C, 27.2 °C, and 22.0 °C, respectively. There is little difference between the surface and bottom water temperature.
The region’s fish stocks are dwindling because of excessive and illegal fishing. The destruction of the zoobenthos has led to a decrease in the income from the fishery. In 2011, Blue Ocean Ltd. launched artificial reefs in the east of Laizhou Bay, and fishing boats in the area were managed with the aim of protecting and restoring the marine ecological functions of Laizhou Bay [24].

In this study, the water quality and marine fishery resources in the artificial reef area of Laizhou Bay were investigated in July 2020 (summer), November 2020 (autumn), and March 2021 (spring). The modeled artificial reef area was 3333 ha. The survey site (37°14′-37°20′ N, 119°34′-119°42′ E) is shown in Figure 1.

2.2. Ecopath Approach

The food web model was built using EwE, version 6.5. The Ecopath model defines an ecosystem through the similar bioecological characteristics of functional groups. Because all the functional groups in the system should reflect the energy flows of the entire ecosystem [28], the contribution of each functional group to the energy balance model can be established using the formula:

\[ B_i \times (P/B)_i \times EE_i - \sum_{j=1}^{n} B_j \times (Q/B)_j \times DC_{ij} - Y_i - E_i - BA_i = 0 \] (1)

where \( B_i \) is the biomass of functional group \( i \); \( (P/B)_i \) is the ratio of production to the biomass of functional group \( i \); \( EE_i \) is the ecotrophic efficiency of functional group \( i \), which refers to...
the extent to which the productivity of a functional group is used by the ecosystem and represents the proportion of the total amount of captured food intake, fish catch, biomass accumulation, and migration, to total productivity. \( B_j \) is the biomass of predator \( j \); \( (Q/B)_j \) represents the ratio of predator \( j \)'s consumption to biomass; \( DC_{ji} \) represents the proportion of prey \( i \) in the food composition of predator \( j \); \( Y_i \) is the fishery catch rate of group \( i \); \( E_i \) is the net migration rate of group \( i \); and \( BA_i \) is the biomass accumulation of group \( i \).

To construct the Ecopath model, the basic parameters required are \( B_i \), \( (P/B)_i \), \( (Q/B)_i \), \( EE_i \), \( DC_{ji} \), and catch data. Any one of the first four parameters can be unknown and can be calculated by the model through the other parameters. The last two parameters, namely the food composition matrix \( DC_{ij} \) and catch data, must be known.

The Ecopath software solves the linear equation shown above, so that the energy flow represented by the equation maintains a balance between each functional group in the ecosystem, and it quantifies the biological parameters of each component of the ecosystem [19].

2.3. Structure of the Model

On the basis of the commercial relevance, dietary similarity, and habitat of the species present in the area, the Ecopath model of the artificial reef ecosystem in Laizhou Bay was divided into 17 functional groups consisting of six fish groups, eight invertebrate groups, phytoplankton, zooplankton, and a detritus group. The main economic fishes in Laizhou Bay (\( S. \) schlegelii, \( H. \) otakii, and \( L. \) maculatus) and other valuable species (e.g., \( R. \) venosa, \( A. \) japonicus) were set as separate functional groups. We combined oysters (Lamellibranchia) and other mollusks into one group because the biomass of oysters amounted to 99.6% of the total mollusk biomass based on our survey. We did not observe any macrophytes in the study area. The 17 functional groups covered the whole process of ecosystem energy flows (Table 1).
Table 1. Functional groups included in the trophic model in Laizhou Bay.

| Number | Functional Group | Group Description with Main Species |
|--------|------------------|-------------------------------------|
| 1      | Sebastes schlegeli | Sebastes schlegeli                   |
| 2      | Hexagrammos otakii | Hexagrammos otakii                  |
| 3      | Lateolabrax maculatus | Lateolabrax maculatus               |
| 4      | Gobiidae          | Chaemrichthys stigmatias, Synechogobius omnimaturus, Odontamblyopus rubicundus, Amblychaeturichthys hexanema, Acanthogobius flavimanes |
| 5      | Other pelagic fishes | Thryssa kammalensis, Scomberomorus niphonius, Konosirus punctatus, Sardinella zunasi, Sillago sihama, Setipinnia tenuifilis, Argyrosomus argentatus, Johnius |
| 6      | Other demersal fishes | Paralichthys olivaceus, Einedrias fangi, Platichthys bicoloratus, Cynoglossus joyneri, Cynoglossus semilaevis, Platicephalus indicus, Platicephalus indicus, Sparus macrocephalus |
| 7      | Charybdis japonica | Charybdis japonica                 |
| 8      | Oratosquilla oratoria | Oratosquilla oratoria             |
| 9      | Rapana venosa      | Rapana venosa                     |
| 10     | Octopodidae       | Octopus variabilis, Octopus ocellatus |
| 11     | Apostichopus japonicus | Apostichopus japonicus         |
| 12     | Mollusca           | Lamellibranchia, Gastropoda       |
| 13     | Large crustaceans  | Prionospio pgymma, Glyceraulba, Sthenopus scutata, Neptys polybranchia, Chone infundibuliformis, Corophium, Neanthes succinea, Eledersilenuria izensis, Magelona cincta, Scoloplos armiger, Ophela acuminata, Ostracpa unid., Ophiura kinki, Pinnosyris compacta, Ampelisca miharonisi, Melina cristata, Ampelisca, Lumbrineris, Cleanus planicuda, Hemigrapsus pericillatus, Cosmocera dimorpha, etc. |
| 14     | Zoobenthos        | Noctiluca miliaris, Pleurobrachia globosa, Paracalanus parvus, Paracalanus crassirostris, Centropages abdominalis, Centropages tenuiremis, Centropages doris, Labidocera bipinnata, Acartia pacifica, Corvaceus affinis, Caprella, Sagitta crassa, Oikopleura dioica, Polychaeta larvae, Copepoda larvae, Benthic Amphipoda, Caenorhabditis elegans, Acartia hongi, etc. |

Table 1. Cont.

| Number | Functional Group | Group Description with Main Species |
|--------|------------------|-------------------------------------|
| 15     | Zooplankon       | Noctiluca milliarii, Pleurobrachia globosa, Paracalanus parvus, Paracalanus crassirostris, Centropages abdominalis, Centropages tenuiremis, Centropages doris, Labidocera bipinnata, Acartia pacifica, Corvaceus affinis, Caprella, Sagitta crassa, Oikopleura dioica, Polychaeta larvae, Copepoda larvae, Benthic Amphipoda, Caenorhabditis elegans, Acartia hongi, etc. |
| 16     | Phytoplanton     | Bacillariophyta, Dinoflagellates, Chrysophyta |
| 17     | Detritus         | Detritus                           |

2.4. Input Parameters of Functional Groups

The biomass data of most functional groups in this study were obtained through ocean surveys. Fish and crustaceans were investigated by trawling, gill netting, and ground cage fishing. The trawl mouth had a width of 4 m, the ship speed was 2 knots, and each tow lasted 15 min. Because trawling is prohibited in some areas of the artificial reef, we used ground cages and gill nets in those areas. The ground cage mesh size was 2 cm, a string of cages had 24 sections, and there were three strings of ground cages in a group. The gill nets were connected together with mesh sizes of 40 mm, 50 mm, and 60 mm, a total length of 150 m and a net height of 1.2 m. Both the ground cages and gill nets were left in place for 48 h (the calculation method can be seen in Supplementary Materials). The biomass and abundance of A. japonicus and R. venosa were estimated by SCUBA grasping and videos combined with net operations and the area size of quadrats was 0.5 m × 0.5 m. The regional biomass was inferred from the results of the quadrat survey. A shallow
water type I plankton net was used to investigate the biomass of zooplankton, and the concentration of chlorophyll a in the phytoplankton was measured in accordance with a standard Turner Fluorometer procedure [29]. The biomass of phytoplankton was calculated using the ratio of chlorophyll content to phytoplankton wet weight [30]. The detritus biomass was calculated as a function of primary production and euphotic depth [28]:

\[
\log(D) = -2.41 + 0.954 \log(PP) + 0.863 \log(E) \tag{2}
\]

where \( D \) is the detrital biomass (g cm\(^{-2}\)); \( PP \) is the primary production (in g cm\(^{-2}\) year\(^{-1}\)); and \( E \) represents the euphotic depth in meters.

Owing to the lack of data on diet composition and catch (fishing data for \( S. \) \( schlegelii \), \( Charybdis \) \( japonica \), \( R. \) \( venosa \) and \( A. \) \( japonicus \) were provided by Blue Ocean Ltd.), we referred to relevant studies in the same marine area when entering these parameters [24,31] (Table 2). We used the equation proposed by Banse and Mosher [33] to estimate the value of P/B:

\[
\log(P/B) = \log a + b \log(M) \tag{3}
\]

where \( \log a = 0.38 \), \( b = -0.26 \), and \( M \) is in g wet weight [33].

\[
\log (Q/B) = 7.964 - 0.204 \log W_{\infty} - 1.965 T' + 0.083 A + 0.532 h + 0.398 d \tag{4}
\]

where \( W_{\infty} \) = asymptotic fish weight (g), \( T' = 1000/(\circ C + 273) \), \( A \) = aspect ratio of the caudal fin (H\(^2\)/S, H is the tail height and S is the surface area of the tail), \( h \) is a dummy variable expressing food type (1 for herbivores, and 0 for detritivores and carnivores), and \( d \) is also a dummy variable expressing food type (1 for detritivores, and 0 for herbivores and carnivores) [20].

In this study, we estimated the P/B and Q/B values for \( S. \) \( schlegelii \), and \( H. \) \( otakii \) using the above equations (details of the calculations can be seen in the Supplementary Materials).

| Num | Group | Trophic Level | Biomass | P\(\text{\textbackslash}B\) | Q\(\text{\textbackslash}B\) | EE | Landing | Unassim Consumption | P\(\text{\textbackslash}Q\) |
|-----|-------|--------------|---------|----------------|----------------|---|---------|---------------------|-----------|
| 1   | \(S. \)\( schlegelii\) | 4.067 | 0.280 * | 0.558 | 5.980 | 0.747 | 0.093 * | 0.2 | 0.093 |
| 2   | \(H. \)\( otakii\) | 3.893 | 0.322 | 0.785 | 8.190 | 0.225 | 0.033 [24] | 0.2 | 0.096 |
| 3   | \(L. \)\( maculatus\) | 4.134 | 0.206 | 1.058 [31] | 4.000 [31] | 0.005 | 0.001 [31] | 0.2 | 0.264 |
| 4   | \(Gobiidae\) | 3.445 | 0.224 * | 3.600 [24] | 14.000 [24] | 0.856 | 0.032 [24] | 0.2 | 0.257 |
| 5   | Other pelagic fishes | 3.414 | 0.452 | 3.500 [24] | 22.10 [24] | 0.95 | 0.035 [31] | 0.2 | 0.158 |
| 6   | Other demersal fishes | 2.793 | 0.568 | 2.750 [34] | 12.50 [34] | 0.882 | 0.007 [31] | 0.2 | 0.220 |
| 7   | \(C. \)\( japonica\) | 3.007 | 1.635 | 1.500 [24] | 11.60 [24] | 0.789 | 0.695 | 0.2 | 0.129 |
| 8   | \(O. \)\( oratoria\) | 3.063 | 0.227 | 8.000 [24] | 30.00 [24] | 0.654 | 0.005 [24] | 0.2 | 0.267 |
| 9   | \(R. \)\( venosa\) | 3.000 | 71.67 | 0.800 [24] | 2.820 [24] | 0.023 | 1.297 | 0.2 | 0.284 |
| 10  | Octopodidae | 4.071 | 0.308 | 2.000 [24] | 7.000 [24] | 0.796 | 0.196 [24] | 0.2 | 0.286 |
| 11  | \(A. \)\( japonicus\) | 2.000 | 40.00 | 0.600 [24] | 3.360 [24] | 0.021 | 0.510 | 0.2 | 0.179 |
| 12  | Mollusca | 2.000 | 266.2 * | 6.000 [25] | 27.00 [25] | 0.127 | 0.7 | 0.222 |
| 13  | Large crustaceans | 3.030 | 3.040 * | 4.000 [24] | 20.00 [24] | 0.558 | 0.780 [31] | 0.7 | 0.200 |
| 14  | Zoobenthos | 2.000 | 13.38 * | 9.000 [31] | 33.00 [31] | 0.681 | 0.7 | 0.273 |
| 15  | Zooplankton | 2.250 | 5.757 | 25.00 [31] | 104.20 * [31] | 0.946 | 0.65 | 0.240 |
| 16  | Phytoplankton | 1.000 | 5.784 | 180.00 * [24] | 0.807 |
| 17  | Detritus | 1.000 | 25.35 | 0.977 |
The P/B and Q/B values of other functional groups referred to relevant studies in the same marine area [24,25,31,34] (Table 2).

2.5. Model Balancing and Uncertainty

The Pedigree Index is used to evaluate model quality and parameter sources. This index categorizes the origin of each parameter and specifies the likely uncertainty associated with these parameters. The quality value ranges between 0 (low) and 1 (high) for each parameter according to the source. After confirming the source, the model averages the quality values of all parameters in all groups to obtain a general synthetic index of data quality [21].

PREBAL diagnostics were performed on the model before debugging to check for potential problems [35]. The PREBAL diagnostics checks the slopes of B, P/B, and Q/B across trophic levels based on ecological principles and some “rules of thumb” [36]. We used the logarithms of B, P/B, and Q/B, using a line with a slope of 10% as a reference (Figure 2). The accuracy and integrity of the data for groups above or below the sloped line were considered [37]. The information in Figure 2a shows that the biomass of *R. venosa*, *A. japonicus* and Mollusca might be overestimated in our model, while the biomass data of other functional groups were likely to be underestimated to varying degrees (except the *S.schlegelii* functional group). The information in Figure 2b shows that annual P/B ratios for *L. maculatus*, *S. schlegelii*, *H. otakii*, *C. japonica*, *R. venosa*, other demersal fishes, and sea cucumber (*A. japonicus*) seemed low, while that of phytoplankton was high. Similarly, annual Q/B ratios (Figure 2c) of *R.venosa*, other demersal fishes, and *A. japonicus* seemed low, while those of other fish functional groups, Octopodidae, *Oratosquilla oratoria*, large crustaceans, and zooplankton seemed high. These estimates were examined before constructing the model to determine whether further analyses and reparameterization were necessary [37]. For some functional groups that deviated significantly from the reference value, parameters were corrected to improve ecological integrity and validity.
When the Ecopath model is run for the first time, the functional group estimate will give an eventuality of \( EE > 1 \), which shows that the energy flow in the ecosystem is out of balance. Thus, the model needs to be debugged by adjusting the input parameter values and eliminating the factors that do not contribute to the model until the model satisfies all the functional groups \( 0 < EE \leq 1 \). This indicates that the balance of the whole system energy flow has been maintained. In addition, the gross food conversion efficiency, which is the ratio of production to consumption \( (P/Q) \), should range from 0.05 to 0.3 [19].
2.6. Ecosystem Attributes

Ecopath contains a number of indicators that objectively reflect the current stability and maturity of the ecosystem. Some representative indicators, such as total system throughput (TST), which represents the overall size of the ecosystem flows, are the sum of total consumption, total exports, total respiration, and energy flowing to detritus [19].

Other indicators can reflect ecosystem maturity. For example, the ratio of total primary production to total respiration (TPP/TR) is considered to be an important indicator of ecosystem maturity [16,18]. Values of TPP/TR that are closer to 1 show that the ecosystem is more mature [19]. The ratio of total biomass to total throughput of the system also reflects the maturity of the system to a certain extent. For this ratio, larger values equate to a more mature ecosystem.

The connectance index (CI) and the system omnivory index (SOI) are measures of the complexity of the relationships within the food web. They represent the ratio of actual connections to possible connections in the food web and the log-weighted average of food consumption by all consumers, respectively. More developed ecosystems have a more complex internal food web relationship, which is manifested by CI and SOI values close to 1 [19].

Finn’s cycling index (FCI), and Finn’s mean path length (FML) are also closely related to the maturity and stability of the system [38]. They represent the ratio of the total flow of nutrients re-entering the system for recycling to the total flow of the system and the average length of each cycle through the food chain, respectively. More mature and stable systems usually have a high degree of recycling [18].

Mixed trophic impact (MTI) analysis can measure the impact of changes in the biomass of one functional group on other functional groups [39]. This parameter reflects the direct or indirect interaction between functional groups [19]. If there is a positive effect between the two functional groups, the value is greater than 0, otherwise it is negative. The value ranges from $-1$ to 1.

2.7. Ecological Carrying Capacity Assessments

In this study, we developed an Ecopath model for the Laizhou Bay ecosystem, and then perturbed it by increasing fish biomass until the model produced unfeasible values for other model components. As additional biomass enters the model, it rebalances the energy accordingly. When the system fails to compensate for any additional biomass, the response shown is usually a value of a functional group of ecological efficiency parameters exceeding 1, which means that there is not enough production to support the increased biomass. This method is analogous to approaches used for estimating shellfish carrying capacity [20], whereby artificially increasing the biomass of farmed mussels represents an increase in farmed scale until the ecological efficiency of any functional group in the system becomes unbalanced [21].

3. Results

3.1. Balancing the Model and Trophic Structure

The food web structure of the artificial reef ecosystem in Laizhou Bay was composed of 17 functional groups and five trophic levels (Figure 3). The trophic levels ranged from 1 (primary producers and detritus) to 4.134 ($L.\ maculatus$). The major economic species—$S.\ schlegelii$, $H.\ otakii$, and $L.\ maculatus$—had trophic levels of 4.067, 3.893, and 4.134, respectively. Together, they constituted the top predators in the ecosystem. The EE ranged from 0.005 to 0.977 for all functional groups and the P/Q ratio ranged from 0.093 to 0.286 (Table 2).
3.2. Transfer Efficiencies

The artificial reef ecosystem in Laizhou Bay consisted of five main aggregated trophic levels (Figure 4). Most of the energy flow was between trophic levels I and II. The total primary production of ecosystem primary producers was 1041.120 t·km\(^{-2}\)·year\(^{-1}\). Approximately 839.8 t·km\(^{-2}\)·year\(^{-1}\) was ingested by consumers and flowed into trophic level II and 201.3 t·km\(^{-2}\)·year\(^{-1}\) flowed into the detrital pool. The energy inflow into trophic levels II, III, IV, and V accounted for 48.004%, 1.752%, 0.057%, and 0.004% of the total flow of the ecosystem, respectively.

We obtained a mean transfer efficiency of 5.307% from detritus and 6.224% from primary producers within the ecosystem. The geometric mean of the trophic transfer efficiencies for the system as a whole was 5.419% (Table 3).
Table 3. Transfer efficiency of different trophic levels in Laizhou Bay artificial reef ecosystem.

| Energy Source | Trophic Level |
|---------------|---------------|
|               | II  | III | IV  | V   |
| Producer      | 3.141 | 6.825 | 11.25 | 9.335 |
| Detritus      | 3.713 | 3.959 | 10.17 | 9.709 |
| All flows     | 3.655 | 4.210 | 10.34 | 9.627 |

- Proportion of total flow originating from detritus (%): 89.0
- Transfer efficiencies from primary producers (%): 6.224
- Transfer efficiencies from detritus (%): 5.307
- Total transfer efficiencies (%): 5.419

3.3. Mixed Trophic Impacts

The analysis of the mixed trophic impacts among different trophic levels in the ecosystem is shown in Figure 5. All functional groups (except for the detritus group) had some negative effects within the group. For instance, an increase in zooplankton biomass had the greatest negative impact on zooplankton. Predators had a negative effect on the functional group of their prey, while some prey had a positive effect on the functional group of their predators. For example, other demersal fishes had a positive impact on their predators (S. schlegelii, H. otakii, and L. maculatus). Phytoplankton and detritus had positive effects on most functional groups. Phytoplankton had positive effects on other demersal fishes, zooplankton, and other pelagic fishes, and detritus had positive effects on Mollusca, A. japonicus, and zoobenthos. In addition, fishing practices had a negative effect on some economic species, especially S. schlegelii, H. otakii, and R. venosa, but they had a significant positive effect on Mollusca.

Figure 5. Mixed trophic impact assessment of the Laizhou Bay.
3.4. Niche Overlap Analysis

Prey and predator overlap indices reflected the niche overlap between functional groups to a certain extent (Figure 6). Among all the functional groups, *O. oratoria* and large crustaceans had the highest prey overlap index (0.977), followed by *S. schlegelii* and *H. otakii* (0.948). This suggested that the food preferences of these functional groups were similar and that interspecific competition among the groups would be more intense than among other functional groups. The functional group with the highest predator overlap index was *S. schlegelii* and *H. otakii* (1.000); these fish were targeted by the fleet. Other pelagic fish and *O. oratoria* also had a high predator overlap index (0.815) because they were hunted by the same predators as *L. maculatus*, other pelagic fishes, and other demersal fishes.

![Figure 6](image_url)

**Figure 6.** The niche overlap analysis of the Laizhou Bay ecosystem. The numbers on the diagram represent the numbers of the functional groups.

3.5. Ecosystem Analysis and Indicators

Of the total system throughput of 17,300.57 t·km$^{-2}$·year$^{-1}$, 50.2% was due to consumption (8679.232 t·km$^{-2}$·year$^{-1}$); 4.99% was due to the respiratory process (864.160 t·km$^{-2}$·year$^{-1}$); 43.8% originated in backflows to detritus (7580.222 t·km$^{-2}$·year$^{-1}$); and 1.02% was due to export (176.955 t·km$^{-2}$·year$^{-1}$). The sum of all production was 3005.624 t·km$^{-2}$·year$^{-1}$ (Table 4).

The TPP/TR ratio was 1.205, the TPP/Total biomass ratio was 2.539, and the Total biomass/Total system throughput ratio was 0.024. The FCI and the FML were 76.15 and 16.62, respectively, in the artificial reef ecosystem. The total number of pathways and the mean length of pathways were 188 and 5.330, respectively. The CI was 0.207 and the SOI was 0.090 (Table 4).
Table 4. The overall system statistics of the Laizhou Bay artificial reef ecosystem.

| Attribute Parameters                                      | Value     | V1         | V2         | V3         |
|-----------------------------------------------------------|-----------|------------|------------|------------|
| Ecosystem properties                                      |           |            |            |            |
| Total consumption (CT)/t·km⁻²·year⁻¹                      | 8679.232  | 8681.018   | 8681.076   | 8680.367   |
| Total exports (TEX)/t·km⁻²·year⁻¹                         | 176.955   | 175.736    | 175.657    | 176.278    |
| Total respiratory flows (TR)/t·km⁻²·year⁻¹                | 864.160   | 865.379    | 865.458    | 864.837    |
| Total flows into detritus (TDET)/t·km⁻²·year⁻¹            | 7580.222  | 7579.003   | 7578.924   | 7579.545   |
| Total system throughput (TST)/t·km⁻²·year⁻¹               | 17,300.57 | 17,301.14  | 17,301.12  | 17,301.029 |
| Net system production (NSP)/t·km⁻²·year⁻¹                 | 176.960   | 175.741    | 175.662    | 176.283    |
| Total production (TP)/t·km⁻²·year⁻¹                       | 3005.624  | 3005.833   | 3005.800   | 3005.855   |
| Total biomass (TB), excluding detritus/t·km⁻²              | 410.054   | 410.272    | 410.279    | 410.204    |
| Calculated total net primary production (TPP)/t·km⁻²·year⁻¹| 1041.120  | 1041.120   | 1041.120   | 1041.120   |
| Total catch/t·km⁻²·year⁻¹                                 | 3.682     | 3.682      | 3.682      | 3.682      |
| Gross efficiency (catch/net p.p.)                         | 0.004     | 0.004      | 0.004      | 0.004      |
| Mean trophic level of the catch (TLc)                     | 2.969     | 2.969      | 2.969      | 2.969      |
| Ecosystem maturity                                        |           |            |            |            |
| Total primary production/total respiration (TPP/TR)       | 1.205     | 1.203      | 1.203      | 1.204      |
| Total primary production/total biomass (TPP/TB)           | 2.539     | 2.538      | 2.538      | 2.538      |
| Food web structure                                        |           |            |            |            |
| Connectance index (CI)                                    | 0.207     | 0.207      | 0.208      | 0.208      |
| System omnivory index (SOI)                               | 0.090     | 0.090      | 0.090      | 0.085      |
| Finn’s cycling index (FCI)                                | 76.15     | 76.14      | 76.14      | 76.14      |
| Finn’s mean path length (FML)                             | 16.62     | 16.62      | 16.62      | 16.62      |
| Ascendancy (A)/%                                          | 45.18     | 45.18      | 45.18      | 45.18      |
| System overhead (O)/%                                      | 54.82     | 54.82      | 54.82      | 54.82      |
| Pedigree Index                                            | 0.432     | 0.432      | 0.432      | 0.432      |

Value: The current status of the system; V1: The status at ecological carrying capacity of *Sebastes schlegelii*. V2: The status at ecological carrying capacity of *Hexagrammos otakii*. V3: The status at ecological carrying capacity of *Lateolabrax maculatus*.

3.6. Ecological Carrying Capacity Assessment

*S. schlegelii*, *H. otakii*, and *L. maculatus* are common economic species in Laizhou Bay artificial reef areas, and they are also important fishing targets. At present, the biomass of *S. schlegelii*, *H. otakii*, and *L. maculatus* is 0.280 t/km², 0.322 t/km², and 0.206 t/km², respectively. We modeled the effect of increasing the biomass of *S. schlegelii*, *H. otakii*, and *L. maculatus* by 1% based on the current biomass, while the biomass of other functional groups remained unchanged. Increasing the biomass of the three functional groups changed the ecological efficiency of each functional group. When the biomass of *S. schlegelii*, *H. otakii*, and *L. maculatus* increased by 1.67 times, 1.71 times, and 1.59 times, respectively, the EE of the functional groups of Gobiidae and other demersal fish, which form the prey of these three predators, rose above 1 owing to excessive predation pressure. This showed that the model was out of balance, indicating that the reef ecosystem area had reached its ecological carrying capacity (Table 5).

Table 5. Effects of increased biomass of *Sebastes schlegelii*, *Hexagrammos otakii*, and *Lateolabrax maculatus* on functional groups.

| The Target Species | *Sebastes schlegelii* | *Hexagrammos otakii* | *Lateolabrax maculatus* |
|--------------------|-----------------------|----------------------|-------------------------|
| Current biomass (t·km⁻²) | 0.280                | 0.322                | 0.206                   |
| Multiples of ecological carrying capacity | 1.67                   | 1.71                   | 1.59                   |
| Ecological carrying capacity (t·km⁻²) | 0.468                | 0.547                | 0.327                  |
| Functional group with EE of 1 | Gobiidae               | demersal fishes       | demersal fishes         |

Table 4 shows the state of the ecosystem when the three top predators—*S. schlegelii*, *H. otakii*, and *L. maculatus*—reached their ecological carrying capacity. The total consumption...
and total system throughput of the ecosystem increased slightly, while the total exports, total flows into detritus, and net system production decreased slightly. In general, most of the ecological characteristics did not change substantially and there was no significant effect on the stability of the artificial reef ecosystem in Laizhou Bay.

4. Discussion

In this study, the Ecopath model was used to characterize the structure and function of the food web of the artificial reef ecosystem in Laizhou Bay and show the ecological carrying capacity of various economic fish species. By analyzing the simulation results, we provide a reference for the enhancement of fish stock through artificial release activities.

In the study area, most fish groups had high EE values, indicating that the utilization rate of fish groups was high. Detritus and phytoplankton serve as food sources for other functional groups, and had high EE values, closely linked to the characteristics of the Laizhou Bay ecosystem. The artificial reef ecosystem in Laizhou Bay is dominated by the filter-feeding oyster species *Crassostrea gigas* (Mollusca). Owing to the shallow depth of Laizhou Bay and its geographical location, the seawater exchange capacity is low, and accumulation of nutrients can cause persistent pollution [1] and eutrophication of seawater. These factors might explain the frequent occurrence of red tides in Laizhou Bay [40]. However, the deployment of oyster reefs had improved the utilization rate of detritus, delayed the accumulation of organic substances, and allowed more substances to circulate within the system. In this way, the artificial reef played a key role in maintaining the ecosystem stability.

In the ecosystem studied here, 89.0% of the total flow came from detritus, while 11.0% came from primary producers, indicating that the main energy flow of the ecosystem was the detrital food chain. Thus, many primary producers were not immediately used by higher trophic level predators and were able to flow into the detrital pool, which led to low transfer efficiencies in the ecosystem (Table 3). The utilization rate of detritus was high because almost all the organisms in the second trophic level fed on detritus, and the biomass of the second trophic level accounted for 79% of the total biomass. This had a great influence on the ecosystem.

The ecological parameter TST is the sum of all flows in a system, including the sum of all consumption; sum of all exports; sum of all respiration flows; and sum of all flows into detritus. In this study, the functional group of Mollusca made a significant contribution to the TST of the ecosystem. The large number of oysters in the artificial reef ecosystem of Laizhou Bay accounted for a substantial proportion of the consumption, respiration, and flows into the detritus of the whole ecosystem. Compared with previous research [24], the present status of Laizhou Bay ecosystem has been significantly improved (Table 6). This is mainly related to the higher current biomass of oysters (2651 t·km⁻²), compared with that in 2016 (974 t·km⁻²). By comparing the simulation results with other artificial Gulf ecosystems along the coast of China, [24], which are important economic locations for fishing and aquaculture (Table 6), the TST of the artificial reef ecosystem in Laizhou Bay was found to be higher than Beibu Gulf [41], Jiaozhou Bay [42] and the Haizhou Bay [43], but lower than Hangzhou Bay [44].

According to Odum [16], among the 24 parameters for assessing ecosystem maturity, the ratio of TPP/TR is considered an important indicator of ecosystem maturity. When the ratio is closer to 1, the ecosystem is more stable and more able to resist external disturbance. In 2016, the TPP/TR value of the artificial reef ecosystem in Laizhou Bay was 0.52 (Table 6) because only a short time had passed since the construction of the reef ecosystem, and the ecosystem was still in an early development stage [24]. The value of TPP/TR assessed in this study was 1.205. This showed that the ecosystem had matured and stabilized over the 4 years. The value of TPP/TR obtained in this study was closer to 1 than in other Gulf ecosystems, suggesting that the ecosystem was close to a mature status.
Table 6. Comparison of system attributes of Laizhou Bay artificial reef model with other Gulf ecosystems.

| Ecological Indicator | This Work | Laizhou Bay (2016) [24] | Hangzhou Bay [44] | Beibu Gulf [41] | Haizhou Bay [43] | Jiaozhou Bay [42] |
|----------------------|-----------|-------------------------|-------------------|----------------|----------------|-----------------|
| TST                  | 17,300.57 | 4697.276                | 19,323.00         | 8520.01        | 9549.47        | 12,917.10       |
| TPP/TR               | 1.205     | 0.52                    | 2.560             | 1.710          | 1.370          | 3.18            |
| CI                   | 0.207     | 0.208                   | 0.310             | 0.333          | 0.39           | 0.310           |
| SOI                  | 0.09      | 0.164                   | 0.350             | 0.198          | 0.18           | 0.160           |
| FCI                  | 76.15     | 22.52                   | 25.00             | 9.73           | 10.96          | 2.47            |
| FML                  | 16.62     | 4.090                   | 2.174             | 1.821          | 2.800          | 2.300           |

The FCI refers to the ratio of recycled energy to total flow in an ecosystem, while the FML refers to the average length of each cycle through the food chain. Longer nutrient flows through the food chain led to a higher proportion of energy being recycled [38]. In this study, the FCI was 76.15%, indicating that 76.15% of the energy in the ecosystem was recycled. The FML was 16.62, and the energy recycling efficiency was higher than that of other artificial reef ecosystems. We consider that this is due to the large number of oysters in the Laizhou Bay ecosystem. Because oysters are filter feeders, they use a substantial proportion of detritus, which then re-enters the system, resulting in a high recycling rate.

The CI and SOI are indicators that reflect the complexity of the internal connections in the ecosystem. More mature ecosystems that have closely related functional groups and a more complex food web structure will have a CI and SOI values that are closer to 1. This indicates that the ecosystem is relatively stable. In this study, the CI and SOI of the artificial reef ecosystem in Laizhou Bay were 0.207 and 0.090, respectively. These values were much less than 1, indicating that the functional groups of the ecosystem were not closely related, and the food web structure was relatively simple. This may increase volatility in response to environmental disturbances and can lead to large fluctuations in fish abundance and catches. The increased volatility also can greatly affect the recovery and conservation of fish species [45].

According to a previous study [23], the fishery resources in Laizhou Bay were dominated by hair tail and small yellow croaker in 1959. Since 1982, small pelagic species, such as half-fin anchovy and anchovy, have become the dominant species, and this trend became more pronounced after 1992. The biomass of some of the more common and economically valuable species at that time is now significantly reduced, or they are not harvested at all. The mean trophic level of catch in the Laizhou Bay ecosystem was estimated to be 2.969, which was significantly lower than the Bohai ecosystem in 1982 (3.69) and 1992 (3.41) [17]. This finding confirms that the fishery resources in Laizhou Bay have been destroyed. In addition, the fish tend to be miniaturized and younger than in previous studies. To this end, the Chinese authorities have introduced a series of policies to restore marine fishery resources, including setting up trawl-prohibition zones, seasonal fishing moratoriums, enhancement and release, and mesh-size control. However, many of these management measures are narrowly focused on the yield of individual species while ignoring the integrity of the ecosystem [45]. It is important to consider the interactions among functional groups, rather than focusing on the production of target species, because the ecosystem reflects dynamic trade-offs within a whole.

MTI analysis may be a useful method to illustrate the effects of interventions among functional groups. It shows how changes in species can affect other species in an ecosystem. Almost all functional groups had some negative effects within the group. This might be related to intraspecific competition for habitat space and food, reflecting density-dependency within functional groups. The MTI indicated that both detritus and phytoplankton had positive effects on most other functional groups because they were at lower trophic levels and provided a food source for other functional groups. As for the top predators of the artificial reef ecosystem in Laizhou Bay, fishing effect had the greatest negative impact on *S. schlegelii*, and *H. otakii* because they were the main economic species in the system. The negative effects of fishing on the biomass of top predators resulted in positive effects on
their prey, such as, Gobiidae, other demersal fishes, and O. oratoria. In addition, as one of the main economic species, R. venosa, is under great fishing pressure. Increasing the fishing pressure would reduce the pressure of predation of Mollusca by R. venosa, which may explain the positive effect of fishing on Mollusca. As the main reef species in the Laizhou Bay artificial reef area, increasing mollusk biomass will lead to a decrease in the biomass of their food source (detritus) and their competitors (e.g., A. japonicus, zoobenthos). This indicates that mollusks can not only provide habitats for organisms, but also re-recruit organic matter in debris into the system to participate in recycling through feeding. This explains the high EE value of detritus that we obtained in the Ecopath model.

In this study, we estimated the ecological carrying capacities of S. schlegelii, H. otakii, and L. maculatus in the artificial reef area of Laizhou Bay (Table 5). The existing stocks of these three species were shown to be close to the assessed ecological carrying capacities, indicating that the stocks were sufficient. Compared with the ecosystem of Laizhou Bay in 2016 [24], the biomass of fish species has significantly improved, which reflects the effects of enhancement and the attraction of fish to artificial reef areas [46]. The above results are only predicted limits, and decisions should be made based on the actual situation on-site, considering economic, social, and other factors. A suggested precautionary approach is to limit stock enhancement to half the calculated carrying capacity. This value is equivalent to the maximum sustainable yield where the growth rate is high and is an accepted management target for many fin fisheries [47].

5. Conclusions

We assessed the artificial reef ecosystem in Laizhou Bay using the Ecopath model and evaluated the nutrient interactions, energy flows, and ecosystem characteristics among species. We calculated the ecological carrying capacity of S. schlegelii, H. otakii, and L. maculatus. This study showed that (1) the establishment of artificial reefs contributed to the stability and maturation of the ecosystem; (2) artificial reefs had a positive effect on the restoration of biological resources; and (3) at present, the resources of economic fish—S. schlegelii, H. otakii, and L. maculatus—are sufficient in Laizhou Bay. However, the ecological carrying capacity estimated by the Ecopath model is only a predicted upper limit, and the economic and social benefits should be considered as well as the ecological benefits.

Supplementary Materials: The following supporting information can be downloaded at: https://www.mdpi.com/article/10.3390/su142113933/s1, Section S1. Biomass data. Table S1. Diet composition of functional groups in Laizhou Bay. The values in parentheses were modified to fit the mass-balance model. Horizontal groups correspond to the vertical group names. Refs. [19,20,24,25,28,30,31,33,34,48–52] are cited in Supplementary Materials.

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