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A novel approach to determining umbrella species using quantitative food web: A case study from fresh-water lake

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ABSTRACT

To formulate practical strategies that maximise conservation benefits, it's essential to identify the most critical players in conservation efforts. As the conservation of umbrella species can benefit other co-occurring species, it has emerged as a pivotal tool for improving the effectiveness of biodiversity conservation. In this study, from the perspective of the food web, we carried out a case study in Xingkai Lake region by regarding species with predator-prey relationships as co-occurring, and proposed a novel concept of "umbrella species strength" for the first time after quantifying the concept of "top vertebrate predators" as umbrella species. On the one hand, we assessed whether the oriental white stork (*Ciconia boyciana*), a candidate umbrella species, could be an effective umbrella species in Xingkai Lake region; on the other hand, we further studied which ecosystem was more suitable for managing by using umbrella species. It is found that the oriental white stork enjoyed the highest umbrella species strength (1.00) and degree centrality (1.00), indicating that the oriental white stork was the most suitable umbrella species in Xingkai Lake region. Moreover, the feeding rate of the oriental white stork was significantly higher in the marsh ecosystem (82.10 %) than in the lake ecosystem (18.00 %); the mean clustering coefficient of the marsh food web (0.65) was also higher than lake (0.57), indicating that marsh ecosystem was more suitable for managing by using umbrella species. This research aims to provide a novel method for biodiversity conservation based on selecting umbrella species from the perspective of food web.

1. Introduction

On 13th October 2021, the United Nations convened the 15th Conference of the Parties (COP15) to the Convention on Biological Diversity (CBD), the first global conference on the theme of ecological civilisation, which launched the initiative of "Building a Global Ecological Civilisation and Conserving Global Biodiversity". However, in the context of the current era, conservation biologists have been forced to focus on "shortcuts" (Jean and Per, 2010) due to limited funding and management resources to maximise conservation benefits while maintaining a balanced and stable development of the entire ecosystem (Rozylowicz et al., 2011). The emergence of the concept of "umbrella species" has made the protection of a wide-ranging co-occurring species a shortcut (Fleishman et al., 2000; Seddon and Leech, 2008), and has been proposed as an efficient way to guide ecosystem management by using species requirements (Jean and Per, 2010).

The umbrella species is defined as "a species whose conservation confers protection to a great number of naturally co-occurring species and the ecosystems in which they live" (Jean and Per, 2010; Seddon and Leech, 2008). The concept of umbrella species primarily reflects notions of protection. From this concept, protect umbrella species can protect other species, those in their home range and foodchain. As Barua (2011) said, from the perspective of food web, protecting umbrella species protects species below them in the foodchain.

As an important "buzzword" in the field of conservation, the concept, method of selection, and umbrella potential of umbrella species have always been the focus in the conservation research. It is often challenging to select appropriate study designs and scientific methods for

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these types of selection and assessment (Sattler et al., 2014; Seddon and Leech, 2008; Wang et al., 2021), which also lead to debates in the field of conservation biology (Caro and O'Doherty, 1999; Leader-Williams and Dublin, 2000). Seddon and Leech (2008) suggested that conservation planners should follow seven criteria. Sattler et al. (2014) suggested the species selected as umbrella species are usually the so-called "flagship species". Some scholars have shown that top predators are often seen as suitable umbrella species to participate in biodiversity conservation programs because they usually have large area requirements for foraging and breeding (Sergio et al., 2006; Jean and Per, 2010; Suter et al., 2002). As top predators link entire communities through trophic cascades, they often provide a "protective umbrella of enemy-free space" exploited by the associated species in such cases (Haemig, 2001; Quinn and Kokorev, 2002). Although scholars have shown trophic level have an influence on a species' potential to serve as an umbrella species. However, there is no consensus on what trophic level is best (Caro et al., 2004; Roth and Weber, 2008; Sergio et al., 2008).

In this context, faced with the controversy and uncertainty about trophic level in the selection of umbrella species, we creatively put forward a new concept, umbrella species strength, and test it in a case study, the Xingkai lake region. It is an index that incorporates the trophic level measurement on the basis of the node strength (Opsahl et al., 2010), a traditional measurement of node importance of network. Of course, the premise of applying this index is to quantify the species in the ecosystem. The combination of the food web constructed by carbon and nitrogen stable isotope and the centrality index which have been successfully applied to identify keystone species (Xing et al., 2021) and indicator species (Perez-Garcia et al., 2016) makes this possible. We break with the traditional way to select umbrella species, like monitoring habitat distribution ranges, niche modeling (Wilson et al., 2022; Maslo et al., 2016). One consensus we can reach from the perspective of the food web is that as long as there is a predator-prey relationship among species, their habitats overlap in the same area. Based on this characteristic, we use a quantitative method, in light of the food web, to determine whether the oriental white stork (*Ciconia boyciana*), which is often regarded as the flagship species in wetland conservation (Wang and Lv, 2007; Liu et al., 2022), is suitable as an umbrella species for conservation in the Xingkai Lake region.

On the whole, inspired by the controversy of trophic level in the selection of umbrella species, we connect species with different spatial needs through predator-prey relationships from the food web perspective and construct a quantitative food web structure model with stable isotope, based on which, we innovatively propose the index of "umbrella species strength" integrating the concept of "trophic level". The main purpose of our study is to answer the following two questions: 1) From a new perspective of the food web, can we use the quantitative method and the umbrella species strength index, to determine whether the oriental white stork is suitable as an umbrella species in Xingkai Lake region? 2) Which ecosystem is more suitable managed with the oriental white stork as an umbrella species among the lake and marsh ecosystems in Xingkai Lake region? It is expected that this study will provide a novel and efficient method for the quantitative selection of umbrella species to form a more scientific basis for wetland ecosystem management and biodiversity conservation from the food web perspective.

2. Methods

2.1. Candidate umbrella species

The oriental white stork is a large wading bird, with its population declining dramatically in the last decade due to habitat loss and disturbance caused by human activities (Cheng et al., 2019; Fan et al., 2020). It is classified as "Endangered" on the IUCN Red List of Threatened Species (BirdLife International, 2018) and has attracted widespread attention as a common indicator species and flagship species for wetland conservation in northeastern China. It has also been considered as a suitable umbrella species in some studies (Wang and Lv, 2007; Liu et al., 2022). As the top predator in the entire wetland ecosystem, the oriental white stork prefer to choose open lakes and marsh habitats with abundant food resources where they can consume various prey species, such as fish, shrimp, frogs, insects, etc. during the breeding period (Tawa and Sagawa, 2021; Zhou et al., 2013). It mainly breeds in northeast China and southeastern Russia (Zan et al., 2008; Yamada et al., 2019; Wu et al., 2021). As its vital migration and breeding place, the Xingkai Lake region is crucial to the protection of the oriental white stork (Liu et al., 2021).

2.2. Study area

Xingkai Lake (Khanka Lake), located on the Sino-Russian border, is the largest freshwater lake in northeast Asia (Liu et al., 2021) (Fig. 1). The lake is relatively shallow with an average water depth of 4.5 m and a catchment area of 16,890 km^2 (Sun et al., 2018; Zhu et al., 2018). The climate here features a temperate continental monsoon. As a rare lake-forest-wetland ecosystem, it plays a vital role in climate regulation and water conservation (Ma, 2017).

The Xingkai Lake, separated by a 1 km wide natural dam, is named Large Xingkai Lake and Small Xingkai Lake by Chinese people, respectively. Hydrological connectivity between them is achieved via two sluices (Yu et al., 2021). Large Xingkai Lake is a semi-enclosed shallow lake with a mean water depth of 3.5 m; Small Xingkai Lake is also a shallow lake with a mean water depth of 1.8 m, surrounded by swamps and farmland (Yuan et al., 2018). Previous studies have shown that some part of Small Xingkai Lake has been turned into a marshland in recent years (Yu et al., 2016). It is a suitable breeding area for wildlife living in shallow water and marsh ecosystem (Xing et al., 2021).

2.3. Sample collection and pre-treatment

According to the objective fact and relevant data that the oriental white stork prefer to choose open lakes and marsh habitats for foraging, we selected the open lakes of Large Xingkai Lake (lake ecosystem) and the marsh area of Small Xingkai Lake (marsh ecosystem) for representative sampling. We collected 132 samples of 24 species in Xingkai Lake region in June 2018 and July 2020. Species collected from two ecosystems includes fishes and shrimps, amphibians, insects, snails, and chicks' feathers of the oriental white stork obtained from the natural shedding of the chicks' feathers during bird banding in the Xingkai Lake National Nature Reserve. Samples were placed in sealed bags, with detailed information on sampling time, location, and species recorded, before they were stored in a $-20\,^{\circ}C$ incubator for further analysis in the laboratory. Previous literature has confirmed that the fish communities of the Large and the Small Xingkai Lakes are diverse due to different water environments, water connectivity, and artificial breeding conditions (Li, 2014). The samples collected in this study were primarily consistent with the main fish species reported in the survey of fish resources in the Xingkai Lake by Li (2014) and Yang et al. (2012), indicating a representative sample of typical species in this study.

Species identification was carried out in the laboratory first, followed by sample pre-treatment. After identification, for fish samples, we took 2 g back muscles for analysis; for shrimp samples, we removed the head, shell muscles, gastrointestinal tract and then took the muscle tissue; for amphibian samples, leg muscles were removed for analysis; for insect samples, surfaces of insects were rinsed with deionised water and then blotted with filter paper; for snail samples, gastropod muscles were removed from the shells of snail samples after being washed with deionised water and evacuated of the intestinal contents; for feather samples of the oriental white stork, they were treated in the same way as Wang (Wang, 2015), acidified (Jaschinski et al., 2008), defatted (Post et al., 2007) and then tested. The treated samples were oven-dried at $60\,^{\circ}C$ for 12–24 h to a constant weight, ground to a fine powder using a mortar and pestle, passed through a 100 mesh sieve, and placed in a

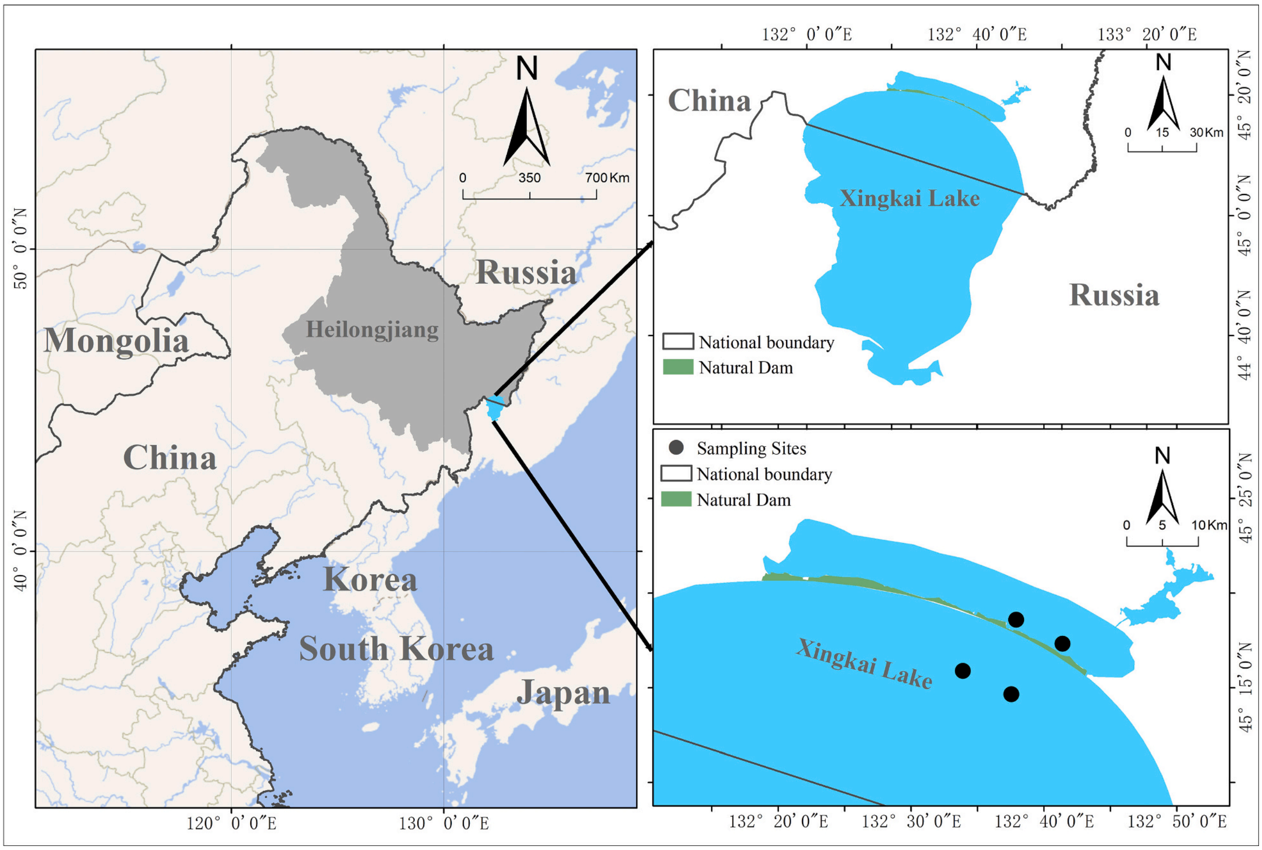


Fig. 1. Sampling sites in Xingkai Lake region.

centrifuge tube in a desiccator for testing. The Northeast Forestry University Ethics Committee provided ethics approval for this research (2022032).

2.4. Stable isotope analysis

The pre-treated samples were sent to the Public Technology Service Center of the Northeast Institute of Geography and Agroecology, Chinese Academy of Sciences. The $\delta^{13}C$ and $\delta^{15}N$ stable isotopes were determined by using an elemental analyser (Flash 2000, Thermo Fisher Scientific, USA) and a stable isotope mass spectrometer (Thermo Scientific MAT 253, Finnigan, Germany).

Stable isotope ratios were expressed in standard δ unit notation ($\delta^{13}C$ and $\delta^{15}N$), which is defined by the following Eq. (1):

$$\delta X(‰) = \left[\left(R_{sample}/R_{standard}\right) - 1\right] \times 1000 \quad (1)$$

In this Eq., X indicates ^{13}C or ^{15}N; R is the corresponding $^{13}C\,/\,^{12}C$ or $^{15}N\,/\,^{14}N$ ratio.

2.5. Date processing and analysis

2.5.1. Division of food web nodes

To reflect the relationship between species in the food web more clearly, we referred to the classification of species by Yuan (2018) based on the similarity of their dietary composition, which grouped one or more species with similar dietary habits and ecological characteristics in the same habitat into one food web node described in Table 1.

In the model construction, the white shrimp (*Exopalaemon modestus*), as a common species in both lake and marsh ecosystems, was treated as two separate nodes of the food web because the nitrogen isotope values of the white shrimp in these two ecosystems were significantly different ($p < 0.05$); Mudsnail (*Cipangopaludina chinensis*), also a common species in both ecosystems, was regarded as one node in the food web model because it has similar feeding habits and no significant difference in isotopic values in the two ecosystems ($p > 0.05$).

2.5.2. Calculation of trophic level

The trophic levels of each species in the food web were calculated by Eq. (2):

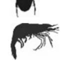
$$TL = \frac{\left(\delta^{15}N_{consumer} - \delta^{15}N_{baseline}\right)}{\Delta^{15}N} + \lambda \quad (2)$$

$\delta^{15}N_{consumer}$ represents the nitrogen isotope values of consumers and $\delta^{15}N_{baseline}$ indicates the nitrogen isotope values of baseline organisms. In this study, we chose the mudsnail, a common, stable, and perennial primary consumer in the Xingkai Lake region, as the baseline species (Post, 2002; Vander Zanden et al., 2005; Vander Zanden et al., 2003; Li et al., 2019; Chen et al., 2017), following the method of Post (2002), with a trophic level of 2 ($\lambda = 2$); $\Delta^{15}N$ is the mean trophic enrichment factor of $\delta^{15}N$, which takes an average value of 3.4 ‰ (Post, 2002; Michener and Lajtha, 2007).

2.5.3. Construction of the food web model

To assess the relative contributions of each food source in the food web to its consumers, the isotope mixing model MixSIAR 3.1.12 in R 4.1.2 was used for this study, which takes into account of the uncertainty, variability of isotopic values and trophic enrichment factors (TEFs), can significantly improve the accuracy of the contribution ratio estimation (Stock and Semmens, 2016). Here, we collected different TEFs and standard deviations from the literature, and we also used different TEFs for different diet types. Fractionation factors of 2.16 ± 0.35 ‰; 3.84 ± 0.26 ‰ were applied for $\delta^{13}C$ and $\delta^{15}N$ respectively (Caut et al., 2009) in the analysis of bird consumers, and 1 ± 0.2 ‰ ($\delta^{13}C$); 3.4 ± 0.68 ‰ ($\delta^{15}N$) were applied for other aquatic organism

Table 1
Basic information of each node in the oriental white stork habitat typical food web in the Xingkai Lake region.

Ecosystem	Scientific name	Food web node	Abbreviation	Pattern
Lake (Large Xingkai Lake)	*Ciconia boyciana*	Oriental white stork	Ows	
	Culter dabryi *Culter alburnus* *Culter mongolicus* *Silurus asotus* *Sander lucioperca*	Large carnivorous fish	Lcf	
	Protosalanx chinensis	Clearhead icefish	Ci	
	Hemibarbus maculatus *Pelteobagrus fulvidraco*	Small carnivorous fish	Scf	
	Cyprinus carpio	Common crap	Cc	
	Carassius auratus *Hemiculter leucisculus*	Lake small omnivorous fish	Lsof	
	Exopalaemon modestus	Lake white shrimp	Lws	
	Macrobrachium nipponensis	Oriental river prawn	Orp	
	Perccottus glenii	Amur sleeper	As	
Marsh (Small Xinkai Lake)	*Carassius auratus* *Pseudorasbora parva* *Phoxinus lagowskii* *Phoxinus percnurus* *Rhodeus sericeus*	Marsh small omnivorous fish	Msof	
	Rana amurensis	Siberian wood frog	Swf	
	Misgurnus mohoity	Amur weatherfish	Aw	
	Dytiscidae Leach *Corixidae*	Insects	Is	
	Exopalaemon modestus	Marsh white shrimp	Mws	
Lake/Marsh	*Cipangopaludina chinensis*	Mudsnail (Baseline species)	Ms	

consumers (Vander Zanden and Rasmussen, 2001; Fry, 2006; McCutchan et al., 2003; Holmerin et al., 2022). The model was run with 3 chains, 500 thin, 500,000 burn-in period, and 1,000,000 iterations for Markov chain Monte Carlo (MCMC), and the error structure was set as "Residual Only"; we also used the Gelman-Rubin and Geweke diagnostic tests to assess whether the model was close to convergence (Stock and Semmens, 2013). The results are expressed as mean values (Ward et al., 2010; Li et al., 2022).

2.5.4. *Quantitative evaluation of umbrella species selection and application*

2.5.4.1. Degree centrality. The degree of a node is the number of edges connected to that node (Freeman, 1978). In a directed network, the degree is the sum of the in-degree and the out-degree. Degree centrality can be expressed as Eq. (3):

$$\mathrm{D}_i = \sum_i a_i \tag{3}$$

D_i denotes the degree centrality of node i and a_i denotes the total number of links passing through node i (i.e. the sum of inflows and outflows).

2.5.4.2. "Umbrella species strength". In weighted networks, degree has been extended to the sum of weights (Barrat et al., 2004; Newman, 2004; Opsahl et al., 2008), labeled node strength. In an attempt to combine both degree and strength. Opsahl et al. (2010) used a tuning parameter, α, and proposed the following measure:

$$C_D^{w\alpha}(i) = \mathrm{k}_i \times (\mathrm{s}_i/\mathrm{k}_i)^{\alpha} = \mathrm{k}_i^{(1-\alpha)} \times \mathrm{s}_i^{\alpha} \tag{4}$$

In Eq. (4), S_i is the sum of the weights of the edges connected to node i, and k_i is the number of neighbouring nodes of i. Where α is a positive tuning parameter, referring to Opsahl et al. (2010) the empirical value of α is 0.5 in this study.

Top vertebrate predators that generally have a large range of activity are preferentially defined as effective umbrella species for ecosystem conservation, including large mammalian carnivores (Rozylowicz et al., 2011; Carroll et al., 2001) and even avian predators with migratory characteristics (Ozaki et al., 2006; Suter et al., 2002). Therefore, in order to balance the description of both the concept of trophic level (TL) in the selection of umbrella species and the degree, strength of its association with other species, we proposed an index of "umbrella species strength" in this study for the first time, which is defined by the following Eq. (5):

$$\mathit{Umbrella\ species\ strength}(i) = \mathrm{k}_i^{(1-\alpha)} \times \mathrm{s}_i^{\alpha} \times \mathrm{TL} \tag{5}$$

In the Eq. (5), TL is the trophic level of each food web node, S_i is the sum of the weights of the edges connected to node i (%). Species are regarded as nodes of the food web. The species (nodes) with a higher index means that the species is related to more other species (degree), also means the intensity of the connection is higher and closer (strength), the species with a higher trophic level also has a higher score. Therefore, from these three aspects, the umbrella species strength index conforms to the definition of umbrella species and can meet the conditions for quantitative determination of umbrella species.

2.5.4.3. Application evaluation of umbrella species. The clustering coefficient (C) describes the degree of aggregation of food web nodes in a food web (Watts and Strogatz, 1998), which can be expressed in the following Eq. (6):

$$\mathrm{C}_{i=}\frac{\mathrm{A}_i}{\mathrm{k}_i(\mathrm{k}_i-1)/2} \tag{6}$$

In Eq. (6), C_i is the clustering coefficient of each node; k_i is the number of neighbours of node i; A_i is the actual number of edges generated between the neighbours of node i.

The degree of node clustering of the whole network can be observed by the average of the local clustering coefficients of all nodes in the network, i.e. the average clustering coefficient (Watts and Strogatz, 1998), which is defined in the following Eq. (7):

$$\mathrm{C} = \frac{1}{\mathrm{n}}\sum_i C_i \tag{7}$$

2.5.5. *Others*

One-way ANOVA was conducted using SPSS 18.0 for carbon and nitrogen stable isotopes at each food web node in the Xingkai Lake food web, with $p < 0.05$ as the level of significant difference. In order to compare the effectiveness of different indicators for the evaluation of umbrella species, the indices were normalised together with the following Eq. (8):

$$x' = \frac{\mathrm{x}-\mathrm{x}_{\min}}{\mathrm{x}_{\max}-\mathrm{x}_{\min}} \tag{8}$$

The sampling points were mapped using ArcGis 10.2; all other images were drawn using Origin 2018, CorelDRAW 2021.

3. Results

3.1. Carbon and nitrogen stable isotopes characteristics of each food web node

We analyzed a total of 24 species and 15 food web nodes for carbon and nitrogen stable isotope values in this study (Fig. 2). One-way ANOVA results showed that the $\delta^{13}C$ and $\delta^{15}N$ stable isotope values were significantly different ($p < 0.05$) at each node. Carbon isotope values fluctuated between −20.12 ‰ and − 34.26 ‰ and nitrogen isotope values fluctuated between 1.19 ‰ and 14.61 ‰ at each node, with an overall wide span. Large carnivorous fish had the highest $\delta^{15}N$, with a mean value of 12.45 ‰; mudsnail, the baseline species, had the lowest nitrogen isotope value, with a mean value of 2.30 ‰; the highest $\delta^{13}C$ value of −20.12 ‰ recorded was the oriental river prawn; the marsh small omnivorous fish had the lowest $\delta^{13}C$ value at −34.26 ‰.

3.2. Trophic level characteristics of each food web node

The results of the calculation of trophic levels at each node are shown in Fig. 3. The trophic level at each node fluctuated between 2 and 4.99. The trophic level of large carnivorous fish in the lake ecosystem was the highest at 4.99, followed by the clearhead icefish at 4.85 and the oriental white stork at 3.76.

3.3. Construction of the oriental white stork habitat typical food web model in the Xingkai Lake region

The construction of the oriental white stork habitat typical food web model was shown in Fig. 4. According to the results, the oriental white stork primarily fed on amur weatherfish (38.70 %), while marsh small omnivorous fish (11.70 %) and amur sleeper (10.90 %) were also favored; among the food sources of large carnivorous fish, common carp (47.30 %) and small carnivorous fish (22.10 %) accounted for the highest proportions; the highest feeding rate of intake of small carnivorous fish was lake small omnivorous fish (52.30 %); as for common carp, mudsnail (66.50 %) had the highest contribution. Overall, the feeding rate of the oriental white stork was significantly higher in the marsh ecosystem (82.10 %) than in the lake ecosystem (18.00 %).

3.4. Selection of umbrella species

After normalization, the index of "umbrella species strength" and "degree centrality" values of each node were shown in Fig. 5. It could be found that the highest degree of connectivity indicated by two indices among the nodes was for the oriental white stork (1.00). From the results of the degree centrality, amur sleeper (0.50) was second only to the oriental white stork; the index of umbrella species strength indicated that lake small omnivorous fish (0.96) ranked second, followed by small carnivorous fish (0.82), while the lowest was amur weatherfish (0).

3.5. Applicating evaluation of umbrella species based on clustering coefficient

The mean clustering coefficient of the food webs of the lake and marsh ecosystems was calculated separately by considering them as two separate food webs (Fig. 6). The results showed that the mean clustering coefficient of the marsh ecosystem food web (0.65) was significantly higher than that of the lake ecosystem food web (0.57), indicating that the nodes in the marsh food web were more aggregated and more connected compared with lake ecosystem.

4. Discussions

Monitoring and managing all aspects of biodiversity is a huge challenge (Itakura et al., 2020) because of the sheer scale of conservation efforts and constrained resources to meet the needs of all species (Donal et al., 2012). The concept of umbrella species provides a framework to improve the efficiency of conservation actions while reducing the complexity of quantifying specific species outcomes (Macpherson et al., 2018). In this study, we creatively put forward a new concept, umbrella species strength and tested it in a case study in the Xingkai lake region. We start from the food web perspective, centrality indices were used to determine whether the oriental white stork was a suitable umbrella

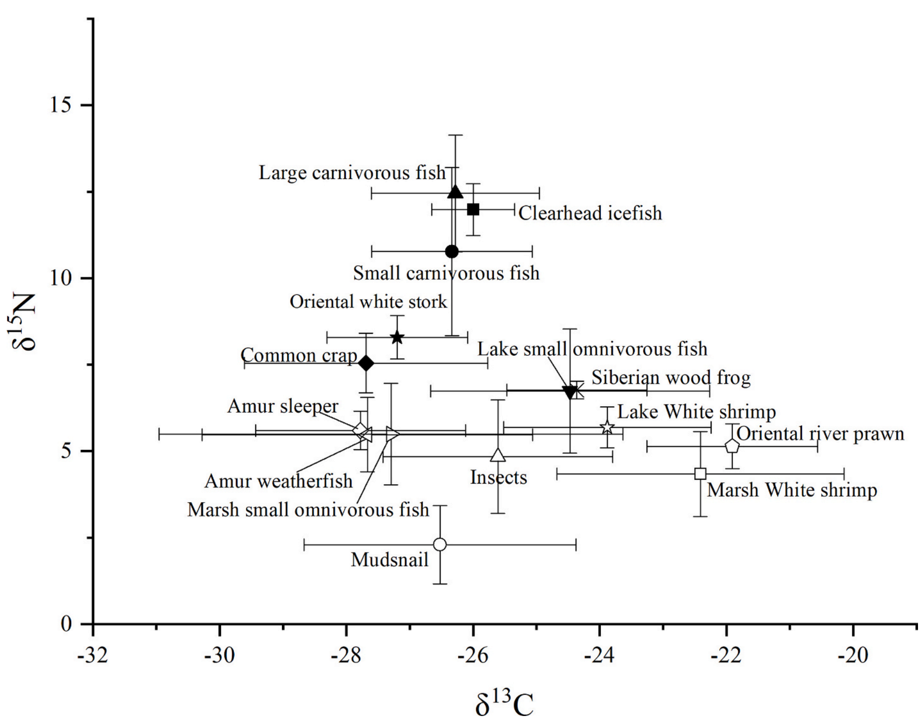


Fig. 2. Characteristics of carbon and nitrogen stable isotopes at each food web node in the oriental white stork habitat typical food web in the Xingkai Lake region.

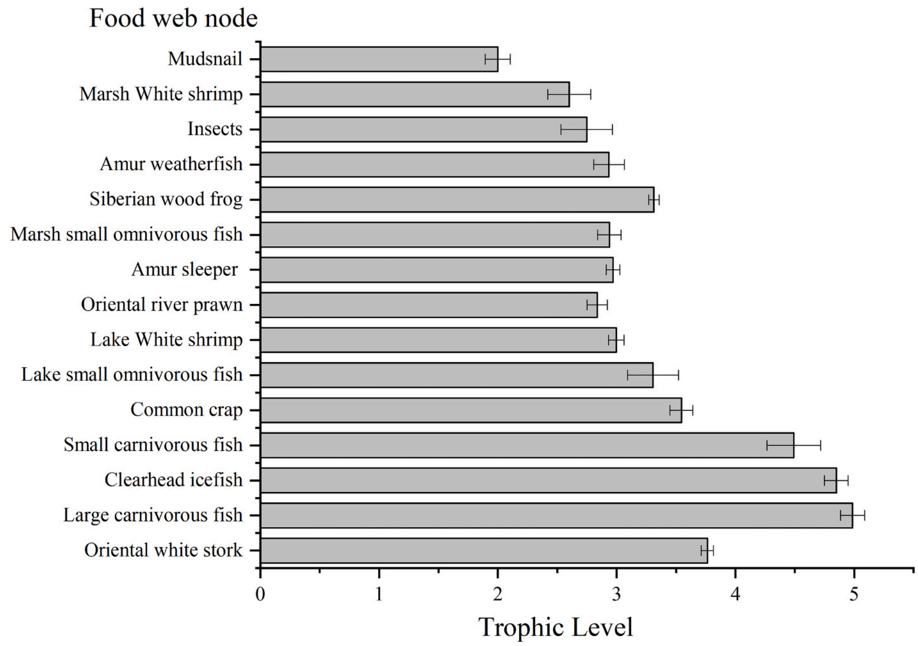


Fig. 3. The trophic level characteristics (mean ± standard error) of each food web node in the oriental white stork habitat typical food web in the Xingkai Lake region (Error bars represent standard errors of trophic levels within each food web node, with 95 % confidence intervals).

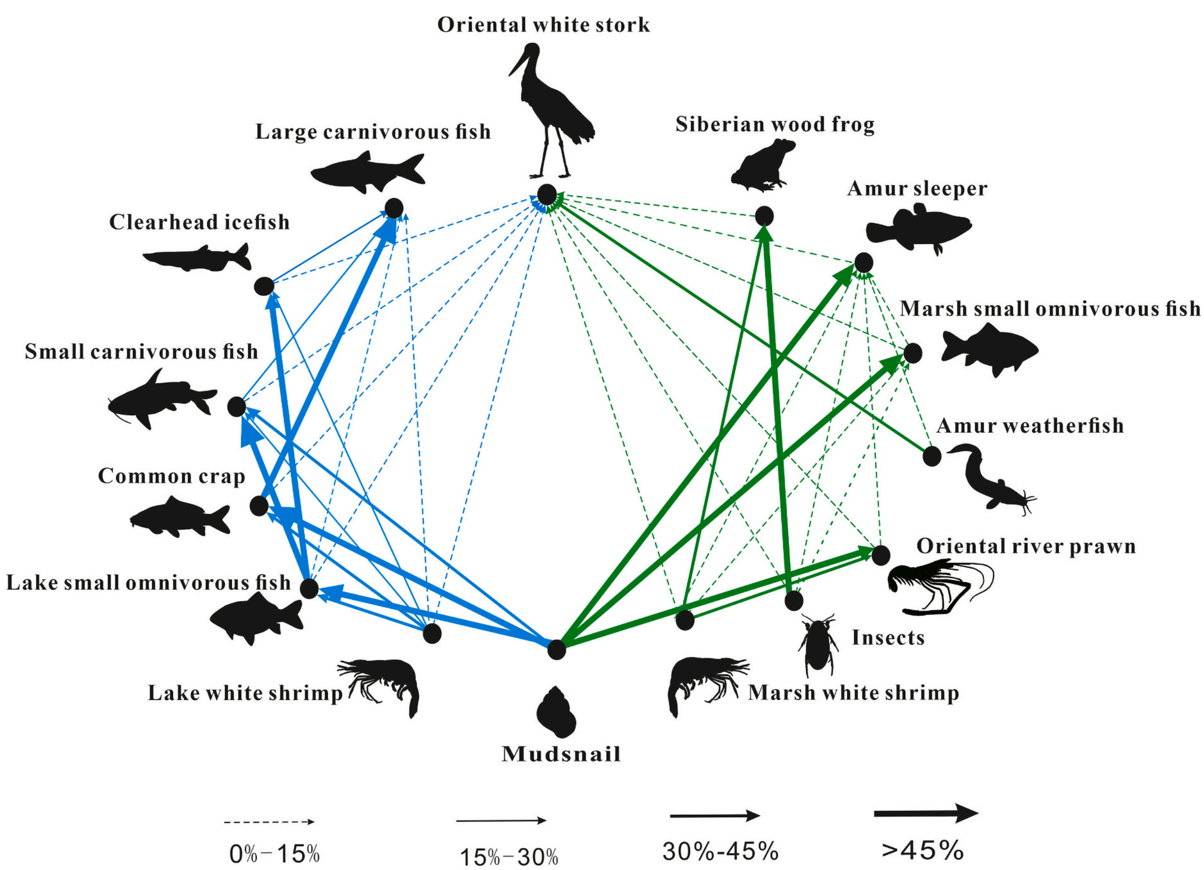


Fig. 4. The oriental white stork habitat typical food web model in the Xingkai Lake region. (The thickness of the line represents the different feeding ratio between consumers and their food sources. In the figure, blue represents predator-prey relationships in the lake ecosystem; green represents marsh ecosystem). (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

species in the Xingkai Lake region, and which ecosystem, lake or marsh, was more suitable for management by using umbrella species. Our results confirm the effectiveness of this new approach in selecting umbrella species from the food web perspective.

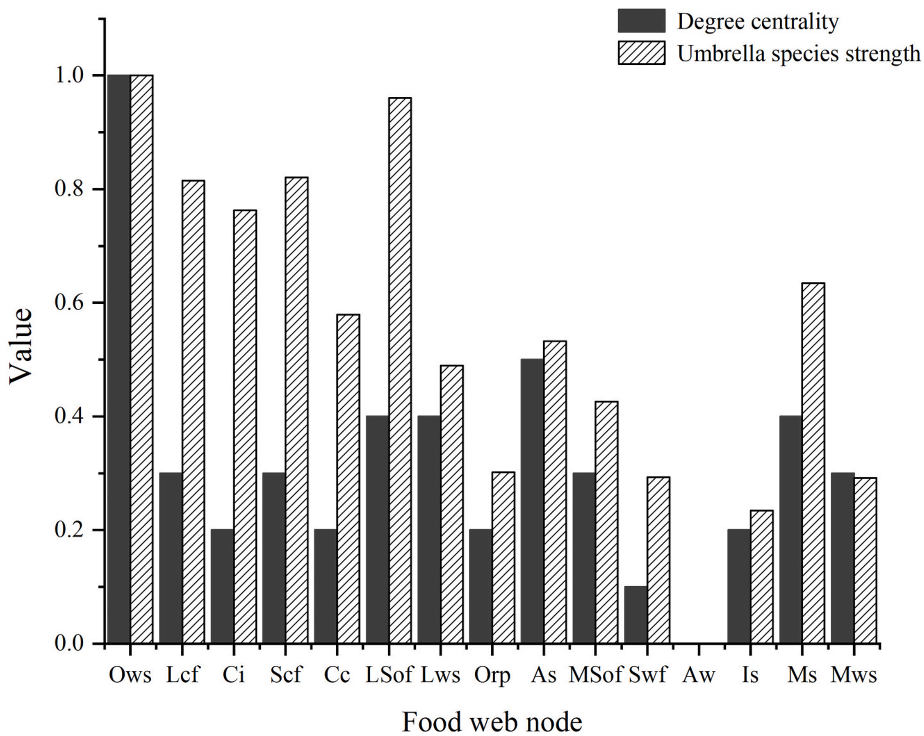


Fig. 5. The index of "Umbrella species strength" and "Degree centrality" values of each food web node (In the Fig. 5, different abbreviations represent "Ows: Oriental white stork; Lcf: Large carnivorous fish; Ci: Clearhead icefish; Scf: Small carnivorous fish; Cc: Common crap; Lsof: Lake small omnivorous fish; Lws: Lake white shrimp; Orp: Oriental river prawn; As: Amur sleeper; Msof: Marsh small omnivorous fish; Swf: Siberian wood frog; Aw: Amur weatherfish; Is: Insects; Ms: Mudsnail; Mws: Marsh white shrimp").

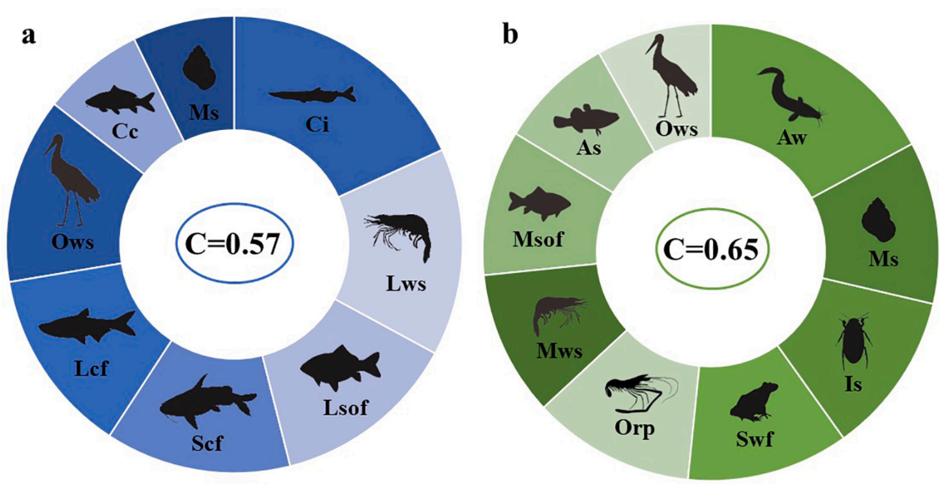


Fig. 6. The clustering coefficient of the two food webs (a represents the lake ecosystem, b represents the marsh ecosystem; different abbreviations represent "Ows: Oriental white stork; Lcf: Large carnivorous fish; Ci: Clearhead icefish; Scf: Small carnivorous fish; Cc: Common crap; Lsof: Lake small omnivorous fish; Lws: Lake white shrimp; Orp: Oriental river prawn; As: Amur sleeper; Msof: Marsh small omnivorous fish; Swf: Siberian wood frog; Aw: Amur weatherfish; Is: Insects; Ms: Mudsnail; Mws: Marsh white shrimp").

4.1. Determination umbrella species based on quantitative food web

The method of selecting umbrella species is often diversified, but the premise is that the requirements of the demanded species encapsulate the needs of many co-occurring species with less demand (Lambeck, 1997). Many methods have been used to select umbrella species in previous studies, including using species traits, which is often too subjective and one-sided, and relying on co-occurrence within a species range to indicate appropriate umbrella species, which requires intensive ground surveys to assess (Crosby et al., 2015; Dunk et al., 2006; Whiteman and Sites, 2008; Weng et al., 2015), etc. Given the complexity of natural food webs and the practical problems that managers face in developing conservation plans, as well as the complexity of ecosystems and the difficulty of determining the equilibrium between species (Wu et al., 2020), we urgently need a quantitative approach to help us visualise the position and role of species in the ecosystem (Bauer et al., 2010). The application of the quantitative food web makes this vision possible. In this study, from the food web perspective, we eliminated the difficulty and hassle of monitoring the distribution of all species, and regarded species with predator-prey relationships as co-occurring connected by food web. The fundamental reason is that from the food web perspective, as long as there is predation between species, there must be some degree of overlap in their habitats.

The oriental white stork has been known as the flagship species and umbrella species in previous studies (Wang and Lv, 2007; Liu et al., 2022). However, there has been a lack of effective quantitative evaluation of its role as umbrella species. Our study aims to quantitatively assess whether it is a suitable umbrella species in the Xingkai Lake region. On the premise of connecting species with the same spatial requirements through the food web, that is, all species in the food web have a certain degree of co-occurrence, we selected the appropriate umbrella species by calculating the degree centrality and the novel umbrella species strength index. From the results of the degree centrality, the oriental white stork had the highest degree of connectivity with other species in the network as it inhabits both the lake and marsh ecosystems, which means that it can co-occur with more species, indicating its strong potential as an umbrella species (Osgood et al., 2020). Besides, the degree of the lake small omnivorous fish, the lake white shrimp, and the mudsnail were also high, which can be explained by the level of their out-degree. In relevant studies of umbrella species, top vertebrate predators are often considered to be effective umbrella species because they confer protection to other co-occurring species in their habitat (Fleishman et al., 2000; Suter et al., 2002; Sergio et al., 2008). However, primary consumers and basal feeders at the bottom of food webs do not effectively umbrella the habitats of their co-occurring species due to their smaller living space and lower trophic levels, suggesting that trophic level also needs to be considered in the selection of umbrella species.

Trophic levels have become one of the ecological indicators to accurately assess the interactions between species in food webs (Lindeman, 1942; Vander Zanden and Rasmussen, 1996). At present, studies on top predators as umbrella species are mostly descriptive, while effective quantitative research on top predators as umbrella species is scarce, and the results available are mixed (Fabrizio et al., 2008). In this study, the traditional concept of "top vertebrates" as umbrella species is quantified, and the index of "umbrella species strength" is innovatively introduced by taking into account trophic level and link strength, which has been used to reflect the strength of connectivity between nodes and other nodes in the network to test the candidate umbrella species in the Xingkai Lake region. After calculation, it can be found that when only inter-species predation ratios were considered, nodes of the mudsnail, the lake small omnivorous fish, and the oriental white stork were the three in food web with the highest node strength due to the large number of links involved and the high link weights. If we only considered the trophic level, the nodes of the large carnivorous fish would surpass the oriental white stork. However, if we comprehensively considered both the node strength and trophic level, nodes of the oriental white stork far exceeded the other nodes. Under the premise that each species already has a co-occurrence relationship, it indicates the strong potential of the oriental white stork as an umbrella species. The reason is that the oriental white stork spans two ecosystems and has a wide range of predation, covering almost all species in the food web. It coexists with more species and has a higher trophic level, which is consistent with the original description of umbrella species. Therefore, it is considered to be a suitable umbrella species in the Xingkai Lake region. This study verifies that a quantitative food web constructed by relying on predator-prey relationships is an important basis for selecting umbrella species. It also shows that the index of "umbrella species strength", which considers trophic level and link strength, can determine the umbrella species effectively.

4.2. Use umbrella species for better conservation and management

It is necessary to apply quantitatively selected umbrella species in the actual management of the nature reserve. In the Xingkai Lake, oriental white storks mainly breed and forage in the marsh and submerged lake habitats (Lu et al., 2003). The oriental white stock habitat typical food web model in this study indicates that the oriental white stork primarily preyed on fish and shrimps (87.60 %), while other insects (8.90 %) and amphibians (3.60 %) were also regarded as food but at a lower rate, in line with the analysis of the feeding habits of the oriental white stork in studies of Ge and Sun (2020).

Our analysis of the diet of the oriental white stork not only provides insight into its dietary preferences but also proves its umbrella potential as an umbrella species. Previous studies have shown that the oriental white stork mainly feeds on aquatic organisms in shallow water (Zhou et al., 2013), with swamp minnow (*Phoxinus percnurus*), amur weatherfish, and amur sleeper accounting for about 70 % of its total food source based on the investigation of the food types and feces of the oriental white stork in the feeding area combined with telescopic observation (Lu et al., 2003). The results of our study also show that the oriental white stork has the highest feeding ratio for amur weatherfish, small omnivorous fish (including swamp minnow), and amur sleeper, which mostly inhabit lakes, marshes, etc. A survey of the habitat of the oriental white stork shows that it prefers open wetland marsh habitats with few trees or small islands of forest, where human disturbance is few, and food resources are relatively abundant so that it can effectively avoid disturbance and ensure safety during the breeding period (Xie, 2018). The food preference of the oriental white stork in this study is in line with previous studies. The diversity of its habitat indicates the great advantage of the oriental white stork as an umbrella species, and its high foraging rate for food in the marsh ecosystem also shows its preference for the marsh ecosystem.

We also consider the clustering coefficient in topological networks in our study. The clustering coefficient refers to the proportion of the network occupied by closed double chains (Dunne et al., 2013), which is one of the vital indicators of the aggregation characteristics of the network structure (Hu et al., 2013). Compared to other food web studies of streams (Sánchez-Carmona et al., 2013), and polar regions (De Santana et al., 2013), the clustering coefficient in this study is significantly higher. A greater clustering coefficient means a greater closeness of connections (Chen and Zhang, 2020). Our results suggest that species in the marsh food web are more closely connected compared to the lake food web. In another word, more closely connected food webs are more easily managed through umbrella species, indicating that the marsh ecosystem is better suited to management with the oriental white stork offering umbrella protection.

The selection of umbrella species has been highly subjective due to limited quantitative research in the past. To assess whether the oriental white stork has the potential to become an effective umbrella species for biodiversity conservation in the Xingkai Lake region, this study quantifies its umbrella effect based on a quantitative food web structure model and a "trophic level" weighted network characteristic index, as well as the umbrella species strength index. As conservation action is often constrained by cost, this study can largely improve biodiversity conservation efficiency by protecting an umbrella species that clearly knows its coverage and strength of links with other species. Based on the current manuscript, we proposed a new index from the original concept and made a case study in the Xingkai Lake region. For future research, on the one hand, we think it is necessary to integrate this approach with species habitat distribution data and models. By comparing and integrating with other different methods, we can more accurately determine the umbrella species and provide a practical method for the management of nature reserves. On the other hand, although it is an interesting attempt to select the appropriate umbrella species based on the quantitative food web, in order to better test the umbrella potential of the oriental white stork, we believe that it is necessary to carry out relevant dynamic food web simulation research, which will be the direction of next efforts.

CRediT authorship contribution statement

Xingchun Li: Writing – original draft, Methodology, Investigation, Writing – review & editing. **Qiang Wang:** Conceptualization, Writing – original draft, Methodology, Writing – review & editing. **Minyan Xing:** Writing – review & editing, Investigation, Formal analysis. **Yike Li:** Writing – review & editing, Visualization. **Xuehong Zhou:** Conceptualization, Methodology, Writing – review & editing, Supervision, Project administration, Funding acquisition. **Chengxue Ma:** Methodology, Writing – review & editing, Supervision, Investigation.

Declaration of competing interest

The authors declare that they have no conflict of interest.

Data availability

The data that support the findings of this study are available on reasonable request from the corresponding author.

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