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Umbrella, keystone, or flagship? An integrated framework for identifying effective surrogate species

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ABSTRACT

The global biodiversity crisis demands targeted conservation strategies that maximize impact despite limited resources. Surrogate species approaches, particularly using umbrella, keystone, and flagship species, offer practical targets for conservation planning that may indirectly benefit ecosystems. However, selecting target species is often hindered by conceptual ambiguities and inconsistent methodologies. To address these challenges, we present an integrative framework that systematically identifies effective surrogate species through Multi-Criteria Decision Analysis (MCDA) combined with big data. Our framework quantifies each species' conservation potential using three indices: an Umbrella index, a Keystone index, and a Flagship index. The Umbrella index assesses habitat overlap using Area of Habitat (AOH) data, the Keystone index is calculated through a network analysis of predator-prey relationships, and the Flagship index analyzes public interest via Google Trends and Baidu Index. These indices are integrated into a composite Effectiveness index using the Multi-Attribute Utility Theory (MAUT) model, with sensitivity analysis to evaluate the robustness of species rankings. We applied this framework to Three-River-Source National Park in the Qinghai-Tibetan Plateau. Our results identified the snow leopard (*Panthera uncia*) as the most effective surrogate species among mammals, ranking first in both the Flagship and Keystone indices, and tenth in the Umbrella index, leading to its top position in the composite Effectiveness index. This data-driven, transparent approach enhances objectivity in surrogate species selection, promising more strategic and impactful biodiversity conservation efforts worldwide.

1. Introduction

The ongoing global biodiversity crisis, marked by alarmingly high extinction rates, demands effective conservation strategies to protect threatened species and ecosystems (Ceballos et al., 2017). Due to limited funding and the complexity of nature, conservation biologists and

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wildlife managers often use surrogate species as a proxy representing other species or aspects of the environment in conservation planning (Wiens et al., 2008; Caro, 2010). Three commonly used categories of surrogate species are umbrella, keystone, and flagship species, each emphasizing different but important aspects of conservation (Caro, 2010; Tälle et al., 2023). Umbrella species are typically wide-ranging species or species with broad niche breath whose protection can indirectly benefit many other co-occurring species. The key elements to identify an umbrella species are its distribution range and habitat requirements (Noss, 1990; Caro, 2003). Keystone species, on the other hand, are those that have a disproportionately large effect on their environment relative to their abundance, emphasizing species' ecological roles and functions (Power et al., 1996; Caro, 2010). Flagship species are usually charismatic species chosen to raise public awareness of conservation issues and funds for conservation actions, emphasizing the public popularity of a species (Leader-Williams and Dublin, 2000). There have been successful applications of surrogate species in different regions, and individual species may simultaneously serve with dual or even multiple surrogate roles. For example, jaguars (*Panthera onca*), an umbrella species in Latin America, have been proven to shelter a substantial portion of high-quality habitat for co-occurring mammals (Thornton et al., 2016) and are currently the flagship of rewilding projects in South America (Donadio et al., 2022); the giant panda (*Ailuropoda melanoleuca*), considered as both umbrella species and flagship species, has indirectly contributed to the conservation of numerous co-occurring endemic vertebrates, such as takin (*Budorcas taxicolor*) and red panda (*Ailurus fulgens*), by maintaining high-quality forest ecosystems (Li and Pimm, 2016). The gray wolf (*Canis lupus*) is considered a keystone species and its reintroduction in Yellowstone Park in the United States has produced several significant impacts on local biodiversity (Beschta and Ripple, 2009).

While these surrogate categories provide valuable tools for conservation planning, their selection and application are often hindered by conceptual ambiguity and a lack of systematic, quantitative approaches (Home et al., 2009; Tälle et al., 2023). The umbrella, keystone, and flagship categories, while valuable, are frequently conflated or applied inconsistently (Caro, 2010; Kalinkat et al., 2017), leading to uncertainty about their effectiveness in achieving conservation goals (Simberloff, 1998; Home et al., 2009). For example, keystone species, primarily selected for their ecological roles, have been proposed as criteria for umbrella species, despite their differing conservation focus (Andelman and Fagan, 2000). Similarly, charismatic vertebrates are often assumed to serve as umbrellas for other species (Breckheimer et al., 2014), although this relationship between the concepts is rarely tested. This blurring of the limits and overlap between categories can lead to the selection of inappropriate and ineffective surrogate species, potentially misdirecting conservation efforts and undermining their intended impact.

To address these challenges, we propose an integrative framework that combines Multi-Criteria Decision Analysis (MCDA) with the power of big data to systematically identify effective surrogate species (Fig. 1), providing quantitative indices for umbrella, keystone, and flagship potential based on habitat overlap, food web centrality, and public interest metrics, respectively. Our framework explicitly separates the processes of identification and combination of umbrella, keystone and flagship species to clarify the concept of each surrogacy term (Fig. 1). Multi-Criteria Decision Analysis (MCDA), a widely-used decision-making approach in conservation planning, allows for the evaluation of multiple, sometimes conflicting criteria (Adem Esmail and Geneletti, 2018).

We illustrate the utility of our framework by applying it to the selection of surrogate species for the Three-River-Source National Park, a region central to the Qinghai-Tibetan Plateau in China. The Three-River-Source region, known as the 'Water Tower of Asia,' harbors exceptional biodiversity and provides vital ecosystem services (Cao et al., 2020). However, this region faces increasing threats from climate change, overgrazing, and infrastructure development (Zhang et al., 2011; Han et al., 2018), making it a crucial area for conservation efforts. Through this case study we demonstrate the practical application of our framework in a complex, ecologically significant region, aiming to identify the most effective surrogate species for conservation in the Three-River-Source National Park. Our objectives were to (1) develop and apply quantitative indices to assess the potential of various candidate species as conservation umbrellas, keystones and flagships; (2) integrate these assessments to identify the most effective surrogate species; and (3) evaluate the robustness of our selections through sensitivity analysis. This study demonstrates the robustness and broad applicability of our framework for identifying effective surrogate species that could be adopted across diverse ecosystems worldwide.

2. Materials and methods

2.1. Study area and species selection

The Three-River-Source National Park, located in the heart of the Qinghai-Tibetan Plateau in China (Fig. 2), is a globally significant ecological asset which encompasses an area of 123,100 km^2 (Cao et al., 2020). Situated at an average elevation of over 4500 m above sea level, the park serves as the headwaters of three major Asian rivers: the Yellow, Yangtze, and Mekong, playing a critical role in regulating hydrological cycles for downstream ecosystems and human populations (Li et al., 2023). The park's diverse landscape, comprising alpine grasslands, wetlands, and permafrost ecosystems supports exceptional biodiversity adapted to the harsh high-altitude environment (Jiang and Zhang, 2016). However, this ecological integrity has been facing increasing threats from climate change, overgrazing, and infrastructure development (Zhang et al., 2011; Han et al., 2018). In response to these challenges, China designated Three-River-Source as one of the first pilot projects of its national park system, aiming to safeguard its vital ecosystem services and rich biodiversity (Cao et al., 2020; Li et al., 2023).

We compiled a comprehensive species list for Three-River-Source National Park based on field investigation research conducted by Cai et al. (2019) between 2015 and 2017. We then cross-referenced this initial list with "Taxonomy and Distribution of Mammals in China" (Wei et al., 2022) and the "China Checklist of Animals" (Ji et al., 2024) to ensure accurate species identification and obtain synonyms, scientific names, and common names (English and Chinese). To maintain precision in the dataset, we carefully excluded common names shared by multiple species. This rigorous process resulted in an initial list of 62 mammal species known to inhabit the park.

For this study, we focused on mammals as the focal taxa due to their well-documented ecological roles, broader availability of ecological data compared to other taxa in terrestrial ecosystems (Zhang et al., 2020), and their relevance in conservation planning. Notably, while birds are often a well-studied group, the lack of high-resolution data on ecological interactions (e.g., predator-prey relationships) required for our keystone index analysis, made them less suitable for inclusion in this case study. Among mammals, we prioritized endemic species, resulting in a final list of 29 candidates (Table S1). Although surrogates do not have to be endemic, we chose to focus on this subset of species for two primary reasons. First, endemic species contribute disproportionately to regional biodiversity and often represent unique evolutionary lineages (Lambeck, 1997), making their conservation crucial for safeguarding evolutionary history and ecological uniqueness. Second, endemic species are inherently linked to the park's specific environment, aiding in prioritizing conservation efforts within this newly established national park, where management plans are still under development. This approach is particularly relevant given the Tibetan Plateau's status as a significant evolutionary junction for biodiversity, with endemic species playing a key role in its ecological and evolutionary history (Deng et al., 2020).

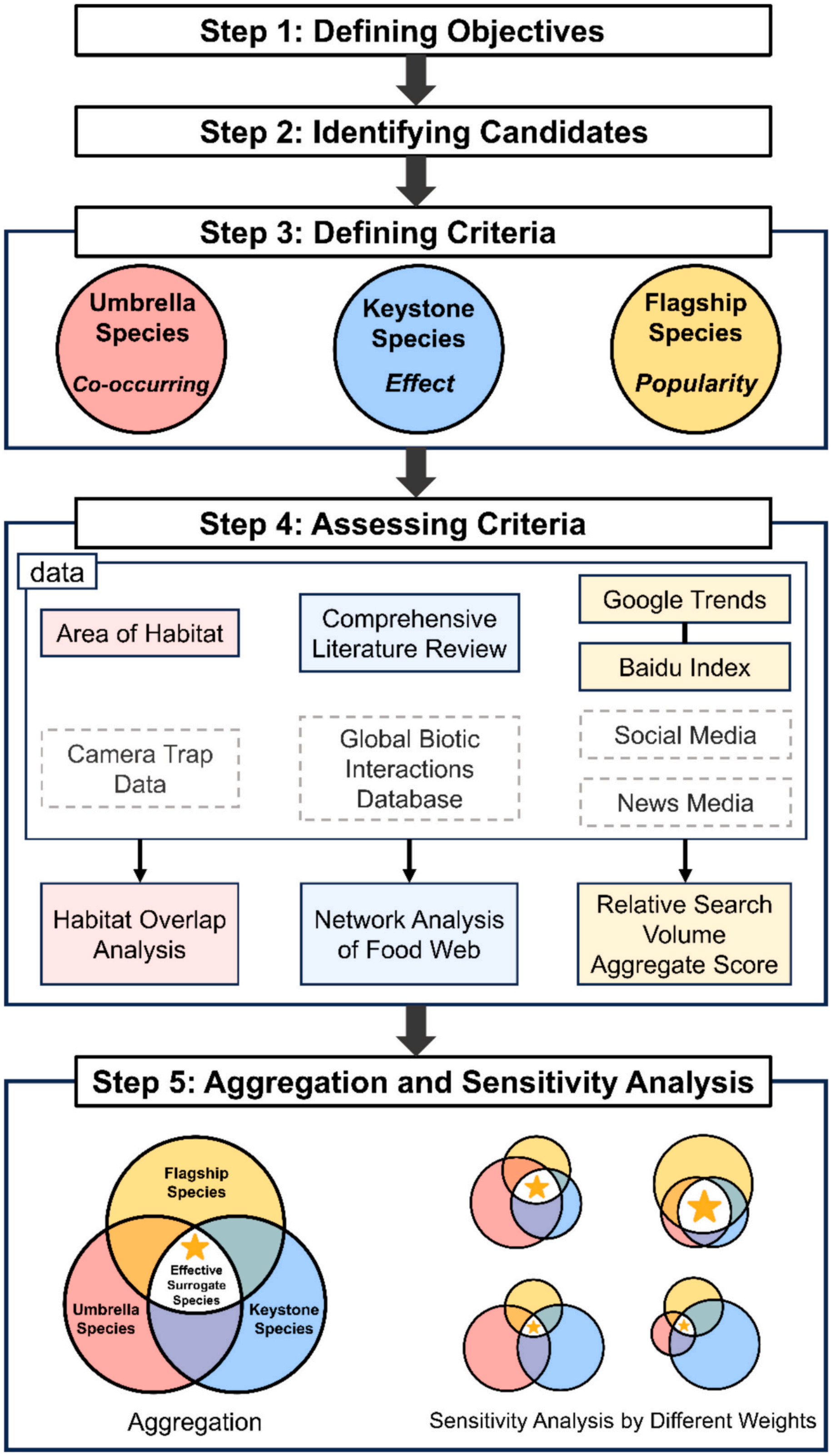

Fig. 1. Integrated Multi-Criteria Decision Analysis (MCDA) Framework for Identifying Effective Surrogate Species. The framework incorporates three key indices reflecting a species' potential as umbrella, keystone, and flagship species. These indices are evaluated and integrated using a weighted sum approach to produce a composite Effectiveness index, guiding the selection of the most effective surrogate species for conservation. Sensitivity analysis assesses the robustness of species rankings across varying conservation priorities by simulations with randomly assigned weights to the three indices. The gray dashed boxes indicate data types or information that could strengthen the framework but were not used in the current study.

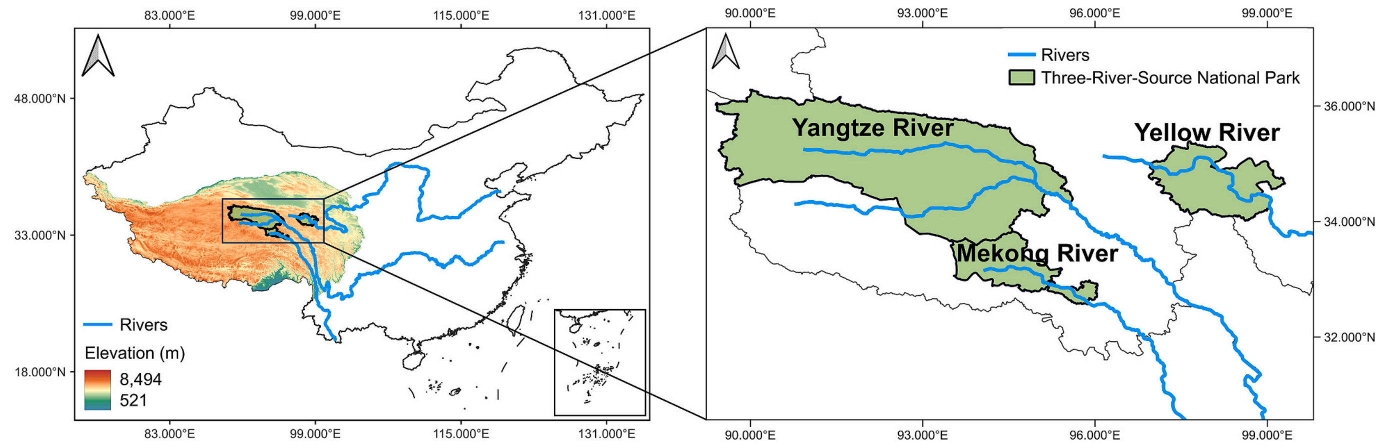

Fig. 2. Geographical location and boundaries of the Three-River-Source National Park, China. The first panel shows the park's position within the larger Qinghai-Tibetan Plateau region, while the second panel zooms in on the park's boundaries. The park is the source region for three major Asian rivers: the Yellow, Yangtze, and Mekong, and encompasses diverse ecosystems, including alpine grasslands, wetlands, and permafrost areas that support a rich array of endemic flora and fauna. The numbers on the axes represent geographic coordinates (latitude and longitude). (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

2.2. Multi-criteria decision analysis framework

We employed a MCDA framework to integrate the Umbrella, Keystone, and Flagship indices and assess their overall effectiveness in identifying suitable surrogate species. Specifically, we used a Multi-Attribute Utility Theory (MAUT) approach within the MCDA framework to achieve this integration. MCDA was chosen for its ability to systematically combine multiple, potentially conflicting criteria into a single decision framework, making it particularly suitable for complex conservation planning scenarios (Adem Esmail and Geneletti, 2018).

Our MCDA framework incorporated three indices reflecting distinct facets of a species' conservation value:

1) Umbrella index: Captures a species' potential to protect habitat for other co-occurring species, based on habitat overlap.
2) Keystone index: Quantifies a species' importance in maintaining ecosystem structure and function, based on its role in the food web.
3) Flagship index: Measures a species' ability to attract public support for conservation efforts, based on public interest.

These indices were selected to comprehensively assess each species' potential as a surrogate species, covering ecological, functional, and social aspects of conservation.

To ensure equal contribution of each index to the final composite Effectiveness index, we normalized all indices using min-max normalization (Eq. 1), which scales the values between 0 and 1.

$$Normalized\ index = \frac{x - min(x)}{max(x) - min(x)} \tag{1}$$

Our MCDA process involved five key stages:

1) Defining objectives: Conservation program goals are determined by decision-makers or stakeholders.
2) Identifying candidates: Species with potential being surrogate species are selected.
3) Defining criteria: In our framework, the Umbrella, Keystone, and Flagship indices serve as three criteria. We applied equal weighting to represent a balanced approach to surrogate species selection, in the absence of specific stakeholder input.
4) Assessing criteria: The three indices are evaluated for each candidate species.
5) Aggregation and sensitivity analysis: The indices are integrated into a composite Effectiveness index using the weighted sum method. Sensitivity analysis is conducted to test the robustness of the results, considering uncertainties in each step of the process.

Species ranking high according to the composite Effectiveness index are considered the most effective surrogate species for conservation programs. This integrated approach aims to provide a comprehensive assessment of each candidate species' overall contribution to multidimensional conservation goals.

2.3. Quantifying surrogate indices

We developed three indices to quantify the potential of each species as an Umbrella, Keystone, and Flagship species, respectively. Each index was calculated using specific methodologies and data sources, as detailed below.

2.3.1. Umbrella index

The Umbrella index assesses a species' potential to indirectly protect other species through habitat conservation. We used Area of Habitat (AOH) data from Lumbierres et al. (2022a, 2022b) to assess the umbrella potential of each candidate species. AOH data integrates species distribution models, habitat preferences, and elevation ranges, providing a more refined representation of potential species' habitats compared to simple range maps.

We obtained the boundary data for Three-River-Source National Park from the Ecological Data Center of Three-River-Source National Park (https://sjynp.tpdc.ac.cn/zh-hans/). AOH files and the park boundary file were aligned to the same coordinate reference system (EPSG:4326) using the *project* function in the R package *terra* (version 1.7.46; Hijmans, 2023). AOH files were then cropped and masked by the boundary data to fit within the park using the *crop* function.

For species lacking AOH data or with AOHs not overlapping the park boundaries, we generated alternative AOHs, produced following the method outlined by (Lumbierres et al., 2022a), associating IUCN's distribution range with a global habitat classification (Jung et al., 2020) and a habitat type translation table (Lumbierres et al., 2022b), but excluding elevation constraints. This process involved overlaying the IUCN range maps with suitable habitat types within the park boundaries, allowing us to include these species in our analysis while acknowledging potential data limitations. Species without overlapping IUCN ranges were excluded from the umbrella assessment (Table S3).

The Umbrella index (U_i) for each candidate species (i) was calculated as the median of each candidate species' habitat overlap percentages with other species' habitats. The overlap analysis was conducted using the *intersect* function in the R package *terra*. The equation of the Umbrella index calculation is shown as follow:

$$U_i = median\left\{\frac{\text{Area}(i\cap j_1)}{\text{Area}(j_1)}, \frac{\text{Area}(i\cap j_2)}{\text{Area}(j_2)}, \ldots, \frac{\text{Area}(i\cap j_n)}{\text{Area}(j_n)}\right\} \quad (2)$$

where:

- U_i is the Umbrella index of candidate species *i*.
- *j* is any other mammal species within the Three-River-Source National Park, excluding species *i*.
- Area($i\cap j$) is the intersection of the habitats area of species *i* and species *j*
- Area(*j*) is the habitat area of species *j*.

2.3.2. Keystone index

The Keystone index evaluates a species' importance in maintaining ecosystem structure and function. We constructed a food web network for all mammal species within the Three-River-Source National Park by compiling predator-prey pairs from a long-term natural history study (Schaller, 2000), and a comprehensive literature review. We searched both English and Chinese literature databases at Web of Science Core Collection (https://www.webofscience.com) and WanFang Data (http://www.wanfangdata.com.cn), respectively using species names and relevant keywords (e.g., ("(English common name)" OR "(scientific name)") AND (diet* OR prey OR predat* OR "food habit*" OR consume*) and ("(Chinese common name)" OR "(scientific name)") AND (食? OR 猎物 OR 捕食)). To ensure a comprehensive review, we did not limit the search by publication date.

The collected predator-prey pairs, their methods of determination (e.g., fecal DNA metabarcoding, microscopic examination), and study locations are recorded in Table S5. Species not recorded as either predator or prey were excluded from the keystone assessment. Due to the limitations of taxonomic resolution in diet analysis, eight pika species (*Ochotona* spp.), two musk deer species (*Moschus* spp.), and two hamster species (*Cricetulus* spp.) were considered at the genus level (Table S4).

Using the information on pairwise interactions we built a binary food web depicting the most likely predator-prey interactions and used the R package *igraph* (version 1.5.1; Csárdi et al., 2024) to conduct the network analysis (Banerjee et al., 2019; Xiao et al., 2022). We calculated three centrality indices:

1) Degree centrality: represents the direct interactions a species has with others;
2) Closeness centrality: indicates a species' influence on the entire network;
3) Betweenness centrality: represents the ability of one species that acts as a crucial bridge, controlling the flow of interactions in the network.

We chose these centrality indices because they capture different aspects of a species' importance in the food web, providing a more comprehensive understanding of its potential keystone role (Risdiyanto et al., 2024). Degree centrality highlights species with many direct connections, closeness centrality identifies species with broad influence across the food web, and betweenness centrality pinpoints species that link different parts of the food web.

The Keystone index (K_i) for each species (*i*) was calculated by combing normalized degree centrality, closeness centrality, and the betweenness centrality, the equation is shown as follow:

$$K_i = D_i + C_i + B_i \quad (3)$$

where:

- K_i is the Keystone index of species *i*.
- D_i is the normalized degree centrality of species *i*.
- C_i is the normalized closeness centrality of species *i*.
- B_i is the normalized betweenness centrality of species *i*.

For species considered at the genus level, their Keystone index was divided by the number of species within the genus to account for potential overestimation. This approach assumes that the ecological roles and interaction strengths are evenly distributed among the species within a genus, which may not always hold true. Therefore, the Keystone index values for these genera should be interpreted with caution.

2.3.3. Flagship index

The Flagship index assesses public interest in and recognition of a species, which can be leveraged for conservation efforts. We used Google Trends (https://trends.google.com/trends/) and Baidu Index (https://index.baidu.com/v2/index.html#/) to assess global and China-specific public interest in each candidate species, respectively. We opted to use both platforms to capture a more comprehensive picture of public interest, recognizing that Google Trends provides a global perspective while Baidu Index offers insights into China-specific trends (Vaughan and Chen, 2015).

For Google Trends, we searched for a matching "search topic" for each species (Table S2), which integrates related search keywords, including common and scientific names in any languages. Search topics were prioritized over individual search terms to capture a broader range of relevant queries and account for variations in species names used by the public. For Baidu Index, we searched for Chinese search keywords for each species (Table S2) since Baidu Index does not support search topic function.

We downloaded weekly relative search volume data for each search topic from Google Trends and daily search volume data for each species from Baidu Index, both covering the period from 2019/04/01 to 2024/03/31. This five-year period was chosen to represent general public interest, balancing short-term fluctuations with long-term trends (Segev and Baram-Tsabari, 2012). We used the aggregate scores from both platforms, calculated as the sum of the weekly relative search volumes, to quantify public interest. Species without a matching search topic in Google Trends or available data in Baidu Index were assigned a score of 0.

To combine the data from both platforms, we first aggregated the daily Baidu Index data to a weekly scale. We then normalized Baidu Index data to a 0–100 scale, where 100 represents the highest search volume in the dataset and 0 represents no search volume. This normalization ensures that both Google Trends and Baidu Index data are on the same scale and can be combined meaningfully.

The Flagship index (F_i) for each species (*i*) was calculated by combining the Google Trends aggregate score and the Baidu Index aggregate score. The equation for the Flagship index calculation is shown as follows:

$$F_i = \text{GT}_i + \text{BI}_i \quad (4)$$

where:

- F_i is the Flagship index of species *i*.
- GT_i is the Google Trends aggregate score of species *i*.
- BI_i is the Baidu Index aggregate score of species *i*.

This approach gives equal weight to global and China-specific public interest, recognizing the importance of both international and local perspectives in conservation efforts.

2.4. Surrogate species effectiveness and sensitivity analysis

To assess the overall effectiveness of each species as a potential surrogate species, we integrated the normalized Umbrella, Keystone, and Flagship indices into a composite Effectiveness index (E_i) using a MAUT model. This approach allows us to combine multiple attributes into a single measure of utility or effectiveness.

We used the *Eval.Utilities* function in the R package *mau* (version 0.1.2; Guarderas, 2018) to construct the MAUT model. The composite Effectiveness index was calculated as the weighted average of the three normalized indices:

$$E_i = \frac{W_U U_i + W_K K_i + W_F F_i}{W_U + W_K + W_F} \quad (5)$$

where:

- E_i is the Effectiveness index of species *i*.
- W_U is the weight of the normalized Umbrella index.
- U_i is the normalized Umbrella index of species *i*.
- W_K is the weight of the normalized Keystone index.
- K_i is the normalized Keystone index of species *i*.
- W_F is the weight of the normalized Flagship index.
- F_i is the normalized Flagship index of species *i*.

For our baseline assessment, we assigned equal weights (1/3 each) to the three indices. This balanced approach provides an unbiased evaluation of each species' overall potential as a surrogate species, recognizing the potential importance of each role in conservation efforts.

To account for varying conservation priorities among stakeholders and to assess the robustness of our Effectiveness index rankings, we conducted a sensitivity analysis using the *Sim.Weights* function in the R package *mau*. This analysis involved 500 simulations with randomly generated weights for each index. In each simulation, random weights were generated for the three indices (W_U, W_K, W_F), summing to 1. We then calculated the Effectiveness index (E_i) for each species using these weights and ranked the species based on their median E_i values among 500 simulations.

This sensitivity analysis provides insights into the consistency of species rankings across different weight combinations, identifies species that perform well regardless of index prioritization, and highlights species whose rankings are sensitive to weight changes. These results can guide decision-makers in selecting robust surrogate species that align with various conservation objectives and scenarios.

All data analyses were performed using R (4.3.3) (R Core Team, 2024). Visualizations were created using R packages *cheddar* (version 0.1–638; Hudson et al., 2013) and *ggplot2* (version 3.5.1; Wickham, 2016).

3. Results

A total of 62 mammal species are known to inhabit the Three-River-Source National Park. Of these, 29 are endemic species, and thus selected as surrogate species candidates (Table S1).

3.1. Umbrella species assessment

Our analysis of habitat overlap, using Area of Habitat (AOH) data, revealed substantial variation in the umbrella potential of the 29 endemic mammal species in the Three-River-Source National Park (Comprehensive Umbrella index values for all candidate species are provided in Table S6). The blue sheep (*Pseudois nayaur*) exhibited the highest Umbrella index (1.000), indicating significant habitat overlap with numerous other species (Fig. 3). Following closely were the woolly

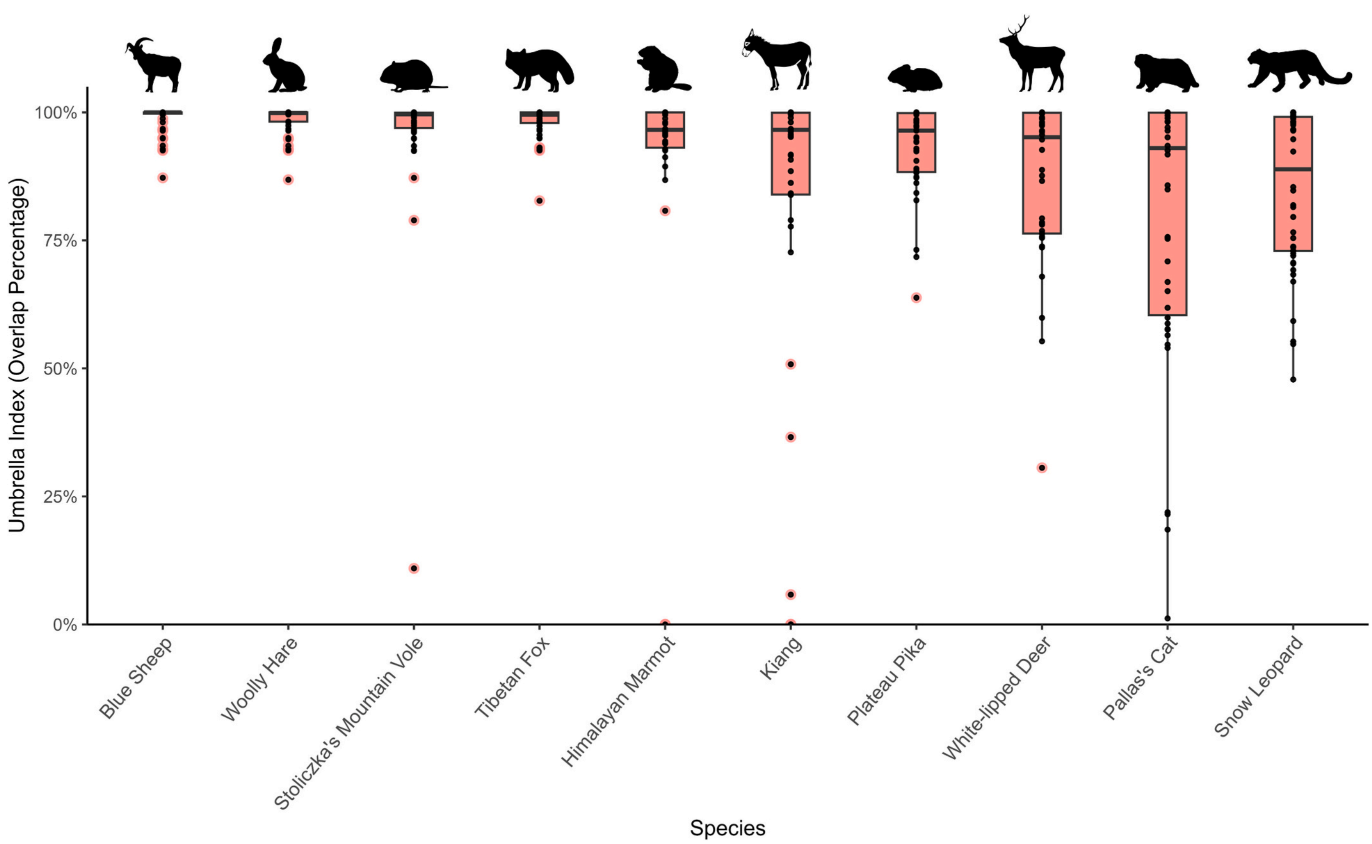

Fig. 3. Top ten candidate species ranked by Umbrella index in Three-River-Source National Park. The Umbrella index represents the median percentage of each candidate species' habitat that overlaps with the habitats of other species in the park. A higher Umbrella index indicates greater potential to protect the habitat requirements of co-occurring species. Box plots show the interquartile range (Q1 and Q3) and median (Umbrella index), with whiskers extending to the minimum and maximum values within 1.5 times the interquartile range. Species are ordered by decreasing median Umbrella index.

hare (*Lepus oiostolus*), Stoiczka's mountain vole (*Alticola stoliczkanus*), and Tibetan fox (*Vulpes ferrilata*) with high Umbrella indices (0.999, 0.996, and 0.995, respectively). These findings suggest that protecting the habitats of these species is likely to benefit a wide range of co-occurring species in the park.

The remaining species displayed a more varied distribution of habitat overlap percentages, reflecting the diverse habitat requirements and ecological associations within the park's mammal community. For instance, Pallas's cat (*Otocolobus manul*) exhibited a relatively wide interquartile range in its Umbrella index, suggesting that its habitat overlaps with some species more extensively than others.

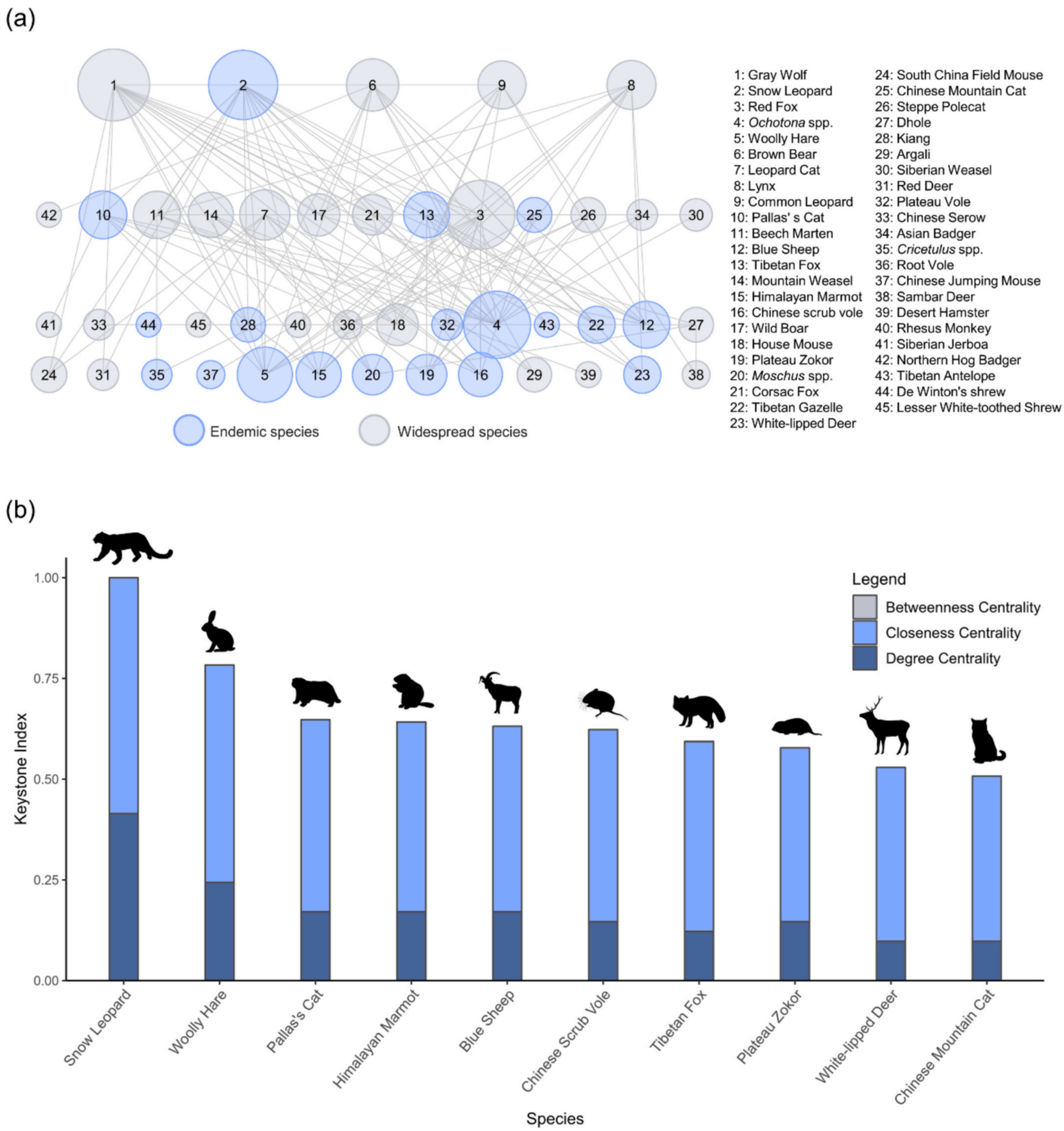

Fig. 4. Food web network and keystone species assessment for Three-River-Source National Park. (a) Constructed food web network from predator-prey pairs of mammal species identified through a comprehensive literature review. Node size is proportional to the Keystone index, with larger nodes indicating higher keystone potential. Species are labeled with ID numbers corresponding to their Keystone index ranking. (b) Top ten candidate species ranked by Keystone index. The Keystone index incorporates degree centrality (number of direct interactions), closeness centrality (average distance to other species in the network), and betweenness centrality (number of times a species lies on the shortest path between two other species) to quantify each species' importance in maintaining food web structure and function. Due to the low betweenness centrality values across species, this centrality is barely visible in the figure.

3.2. Keystone species assessment

The food web constructed for the Three-River-Source National Park, comprising 42 species and 3 genus groups (Table S4) and 123 predator-prey interactions (Table S5), revealed distinct patterns of trophic interactions and highlighted the importance of certain species in maintaining ecosystem structure and function (Fig. 4a) (Comprehensive Keystone index values for all candidate species are provided in Table S6). The snow leopard (*Panthera uncia*) emerged as the top-ranking keystone species among candidate species, exhibiting the highest Keystone index (1.000) based on its degree centrality, closeness centrality, and betweenness centrality (Fig. 4b). This finding underscores the snow leopard's pivotal role as an apex predator in the ecosystem, with its interactions influencing a wide range of species.

The woolly hare (0.783) also exhibited a relatively high Keystone index, suggesting its importance as a prey species supporting higher trophic levels. Other species, including Pallas's cat (0.647), Himalayan marmot (*Marmota himalayana*) (0.641), blue sheep (0.631), and Chinese scrub vole (*Neodon irene*) (0.623), had more moderate Keystone indices, indicating their less pronounced but still significant roles in the food web. Individual pika species showed relatively low Keystone indices of 0.126, based on dividing the genus group's Keystone index.

The low betweenness centrality of most species (Fig. 4b), suggests a relatively simple food web structure with few intermediary species. This pattern is consistent with the harsh environmental conditions and limited resources typical of high-altitude ecosystems, which can constrain trophic complexity.

3.3. Flagship species assessment

Our analysis of public interest, using Google Trends and Baidu Index data, revealed a wide variation in public interest across species, signaling the potential flagships for conservation in the Three-River-Source National Park (Comprehensive Flagship index values for all candidate species are provided in Table S6). The snow leopard stood out with the highest Flagship index (1.000), indicating substantial public interest both globally and within China (Fig. 5). The Tibetan antelope (*Pantholops hodgsonii*) (0.773), blue sheep (0.684), Tibetan gazelle (*Procapra picticaudata*) (0.619), and kiang (*Equus kiang*) (0.533) also exhibited relatively high Flagship indices.

Interestingly, we observed variations in species' popularity across different regions. For example, the blue sheep, Chinese mountain cat (*Felis bieti*), and Pallas's cat received more public interest globally than regionally, whereas the Tibetan antelope and kiang were more popular within China. These differences highlight the importance of considering both global and regional perspectives when assessing a species' flagship potential.

3.4. Effectiveness assessment and sensitivity analysis

Integrating the normalized Umbrella, Keystone, and Flagship indices into a composite Effectiveness index, using equal weighting for each component, allowed us to identify the most promising surrogate species candidates (Fig. 6a) (Comprehensive Effectiveness index values for all candidate species are provided in Table S6). The snow leopard ranked highest (0.963), followed by the blue sheep (0.772) and Tibetan fox (0.681). Notably, the woolly hare, despite its low Flagship index, achieved a relatively high overall Effectiveness index (ranking 9th), highlighting the importance of considering multiple dimensions of surrogate species potential.

The sensitivity analysis, involving 500 simulations with randomly assigned weights to the three indices, revealed varying degrees of

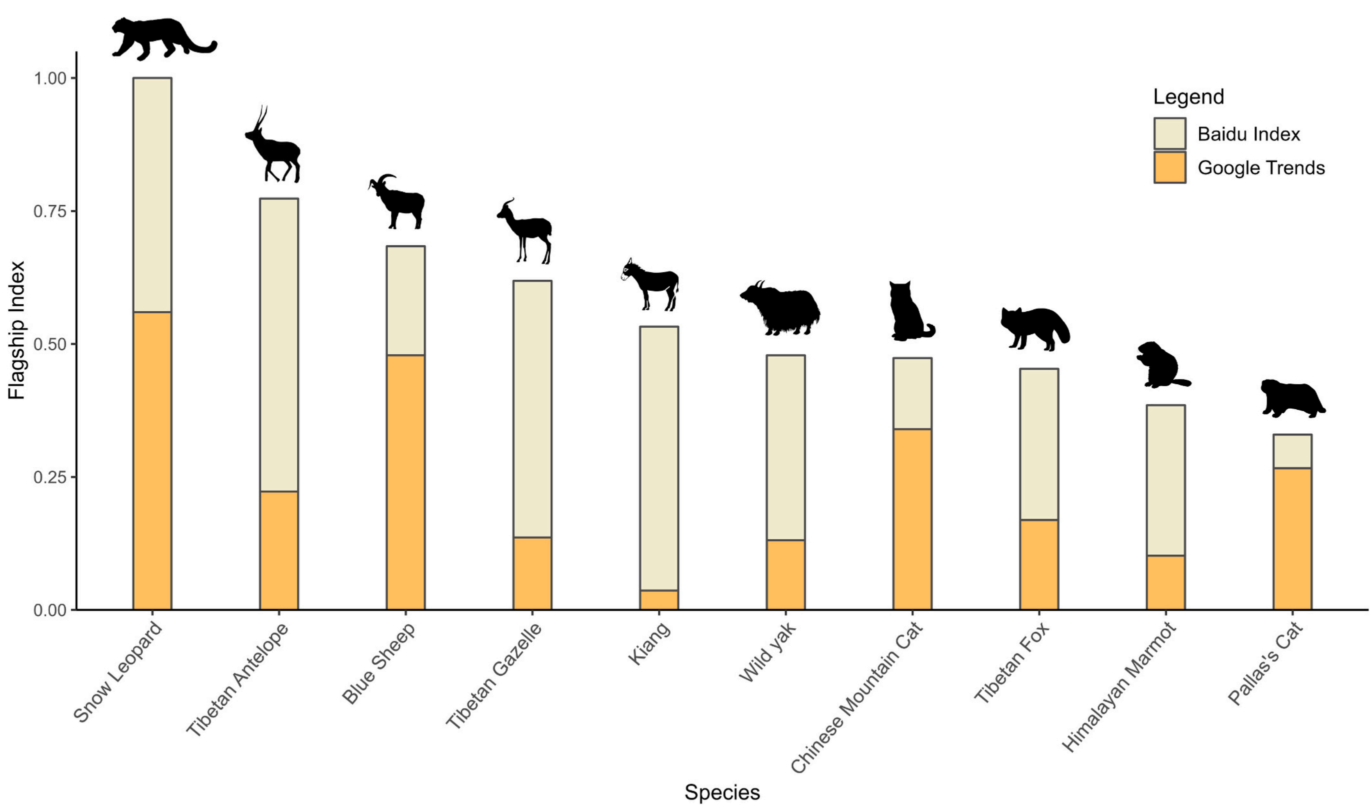

Fig. 5. Top ten candidate species ranked by Flagship index in the Three-River-Source National Park. The Flagship index combines global public interest data (from Google Trends) and regional public interest data in China (from Baidu Index) to assess each species' potential as a flagship for conservation. A higher Flagship index indicates greater public awareness and potential to garner support for conservation efforts. Stacked bars show the relative contributions of global and regional interest to the overall Flagship index.

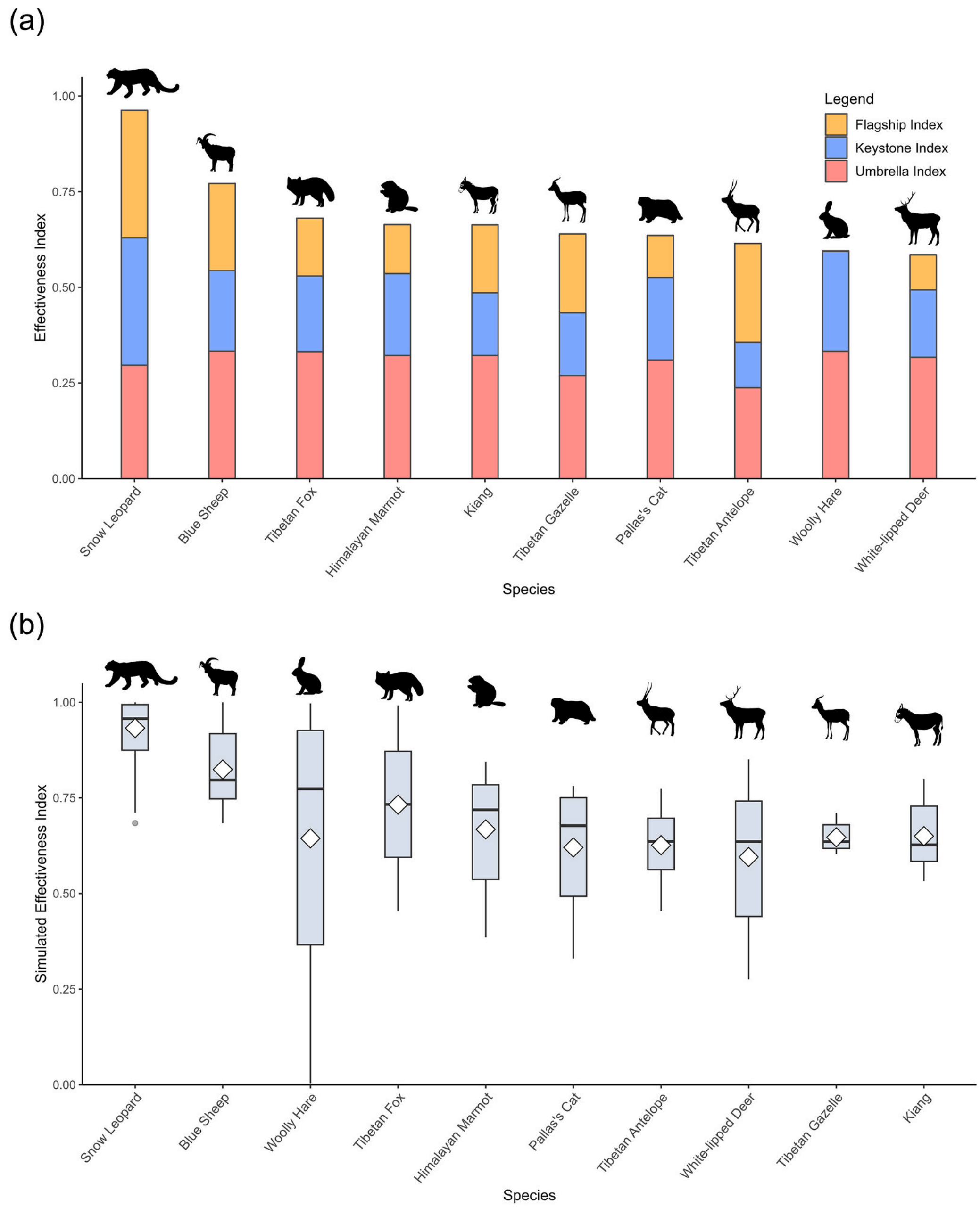

Fig. 6. Effectiveness assessment and sensitivity analysis of surrogate species candidates for the Three-River-Source National Park. (a) Top ten candidate species ranked by Effectiveness index, which integrates the normalized Umbrella, Keystone, and Flagship indices with equal weighting. The Effectiveness index represents the overall conservation potential of each species, considering its ability to function as an umbrella, keystone, and flagship species. (b) Sensitivity analysis results for the top ten species, showing the distribution of Effectiveness index values across 500 simulations with randomly assigned weights to the three component indices. Box plots show the interquartile range (Q1 and Q3) and median, with whiskers extending to the minimum and maximum values within 1.5 times the interquartile range. Diamond shapes represent mean values. Species with narrower interquartile ranges are less sensitive to changes in index weighting, indicating more robust surrogate potential across a range of conservation priorities.

robustness in the effectiveness rankings. The median values of sensitivity analysis of all candidates are provided in Table S6. The snow leopard consistently ranked the highest across all simulations, demonstrating its robust suitability as a surrogate species regardless of the relative weighting of the indices. The blue sheep also exhibited relatively consistent rankings, while the woolly hare displayed a wider interquartile range, indicating greater sensitivity to index weighting due to its contrasting index scores (high Umbrella and Keystone, low Flagship).

4. Discussion

4.1. Using the MCDA framework to incorporate multiple objectives

Our case study in the Three-River-Source National Park demonstrates the utility of using an integrative MCDA framework for selecting surrogate species. This framework is based on a quantitative analysis of each candidate species' capacity as an umbrella, keystone, and flagship species. This approach addresses a significant gap in conservation planning by providing a systematic, transparent, and replicable method for surrogate species selection. Notably, our framework balances multiple conservation objectives, unlike previous studies that recognized the potential benefits of combining different surrogate species concepts (Kalinkat et al., 2017; Wang et al., 2023), but often lacked a unified framework for doing so systematically. Our framework directly tackles this challenge by explicitly disentangling and quantifying the often-conflated concepts of umbrella, keystone, and flagship species, allowing for a more holistic and nuanced evaluation of each candidate's conservation potential.

The strength of our MCDA framework lies in its integrated approach. First, it disentangles the concepts of umbrella, keystone, and flagship species, establishing clear, quantifiable criteria for each: habitat overlap for umbrellas, food web importance for keystones, and public interest for flagships. Second, the framework combines these distinct surrogacy types into a composite Effectiveness index, allowing for a more comprehensive assessment of each species' overall contribution to conservation goals. This integration allows us to move beyond previous approaches that often-assumed interchangeability between surrogate roles (e.g., conflating charisma with umbrella value, as noted by Breckheimer et al., 2014). Instead, our framework provides a structured system to evaluate species based on their specific strengths in each surrogate role. This clear delineation enhances the precision of species selection and facilitates more targeted conservation strategies, allowing decision-makers to align their actions more closely with intended outcomes, whether leveraging a species' habitat requirements, ecological influence, or public appeal.

The framework's flexibility is another key feature, as it allows for the explicit consideration and weighting of multiple, sometimes conflicting, criteria (Adem Esmail and Geneletti, 2018). This adaptability ensures that the framework can be applied across various contexts, aligning with the growing recognition in conservation science that effective biodiversity protection requires balancing ecological, social, and economic factors (Mace et al., 2012). Moreover, the framework's transparency in its criteria selection and weighting facilitates stakeholder engagement and consensus-building in conservation planning processes, fostering greater ownership and support for conservation actions.

4.2. Leveraging big data for rapid surrogate species assessment

Our framework innovates by integrating traditional MCDA with the power of big data – specifically, the wealth of fast-growing, publicly available, and frequently updated social, ecological, and spatial datasets – for a more comprehensive and objective assessment of surrogate species criteria. By leveraging big data, we can quantify umbrella potential, keystone importance, and flagship appeal with greater precision and efficiency than traditional methods, which often rely on expert opinion or limited datasets.

For identifying potential flagship species, online platforms like Google Trends and Baidu Index provide valuable insights into public interest, complementing traditional methods such as surveys and media analyses (Correia et al., 2021). This approach can be enriched by incorporating data from news media databases (e.g., LexisNexis, Wisers) and social media platforms (e.g., Twitter, Instagram) to capture a more comprehensive picture of public perception and engagement (Correia et al., 2021). Analyzing search volume trends, as demonstrated in our case study, offers a quantifiable measure of a species' presence in the public consciousness. However, it's important to acknowledge that online data might not fully represent the perspectives of local communities, especially in regions with limited internet access. Therefore, incorporating local knowledge through published literature, interviews, and community consultations remains crucial for a nuanced understanding of a species' cultural significance and potential as a flagship species (Waylen et al., 2010).

Assessing a species' umbrella potential involves evaluating its ability to protect the habitat requirements of co-occurring species. Large-scale datasets like the Area of Habitat (AOH) data and the Global Biodiversity Information Facility (GBIF) occurrence records provide valuable resources for this purpose. However, the resolution and accuracy of these datasets can vary, and it's crucial to consider their limitations when interpreting the results. For smaller-scale projects, focusing on site-level occurrences from sources like camera trap data can be more appropriate.

Identifying keystone species, those with disproportionately strong influences on their ecosystems, often relies on understanding species interaction networks. The "Global Biotic Interactions" (GloBI) project (Poelen et al., 2014) offers a valuable resource for accessing a large collection of species interaction data. However, interaction data can be incomplete or biased, and it's important to acknowledge these limitations. In cases where direct interaction data are limited, ecological proxies, such as body mass, abundance, and morphological traits, can be used to infer interaction probabilities (Morales-Castilla et al., 2015; Pires, 2017).

By combining the structured decision-making process of MCDA with the rich information provided by big data, our framework offers a powerful tool for identifying effective surrogate species. This data-driven approach not only enhances the robustness and objectivity of the assessment but also allows for a rapid preliminary screening of potential candidates, enabling conservationists to efficiently prioritize their efforts and make more informed conservation decisions.

4.3. Surrogate species for Three-River-source National Park

The application of our framework to the Three-River-Source National Park demonstrates its practical utility in a real-world conservation context. Our results not only provide valuable insights for conservation planning in this ecologically crucial region, but also validate and refine existing conservation strategies. For example, the snow leopard consistently ranks the highest across all simulations, which has already been selected as an official surrogate species of the park (The Management Bureau of Three-River-Source National Park, 2023). Furthermore, the blue sheep consistently ranks high in our composite Effectiveness index, albeit with different strengths, suggesting its potential as another effective surrogate species. Conversely, our framework suggests that other previously proposed surrogate species, such as the Tibetan antelope, wild yak (*Bos mutus*), and kiang (The Management Bureau of Three-River-Source National Park, 2023), may not be as effective in this context.

The snow leopard's high public popularity, both globally and in China, is evidenced by Google Trends and Baidu Index data. This global recognition is complemented by strong local support from Tibetan herders based on local interviews, who generally express positive attitudes towards snow leopards (Gao et al., 2023; Piaopiao et al., 2023). This combination of global recognition and local acceptance creates a powerful foundation for its flagship role, potentially enhancing the effectiveness of conservation efforts within the park and beyond.

Our food web analysis further reveals the snow leopard's high Keystone index, indicating its central role in the ecosystem. This finding is corroborated by field studies that have identified the snow leopard as a key active top predator, with its kills providing carrion that benefits a range of sympatric species including red foxes and brown bears (Samelius et al., 2022), while also exerting top-down control on prey populations such as blue sheep (Xiao et al., 2018).

While the snow leopard's Umbrella index ranks 10th in our analysis, its conservation importance extends beyond direct habitat protection. The mountain ranges it inhabits coincide with areas of exceptionally high species richness and encompass the headwaters of Asia's major rivers, providing vital water resources for billions of people downstream (Li et al., 2023). Therefore, conservation efforts focused on the snow leopard are likely to have cascading benefits for a wide range of species and crucial ecosystem services.

Our findings highlight the snow leopard as a highly effective surrogate species for mammals in the Three-River-Source National Park, demonstrating the value of our multi-criteria approach in identifying species that can fulfill multiple conservation roles. Its combined strengths as a flagship, keystone, and, to a lesser extent, umbrella species, make it an ideal focal point for conservation efforts. By prioritizing snow leopard conservation, managers can leverage its wide-ranging influence to protect biodiversity, maintain ecosystem function, engage the public, and safeguard vital ecosystem services for both local communities and downstream populations.

4.4. Limitations and future directions

While our study provides a robust framework for surrogate species selection, several limitations warrant acknowledgment and point to directions for future research. First, our focus on mammals, while justified by data availability and their frequent use in surrogate studies, may limit the applicability of our findings to other taxa. This limitation is particularly relevant for the snow leopard, which is identified as the most effective surrogate species for mammals in the park but may not serve as an effective surrogate for birds, reptiles, amphibians, or invertebrates. Future research should aim to incorporate a broader range of taxa, such as birds, plants, and invertebrates, to provide a more comprehensive assessment of biodiversity.

Second, the use of global-scale datasets, while currently the best available option for some criteria, may not fully capture the nuances of species distributions or ecological interactions at finer spatial scales. Developing region-specific and high-resolution datasets would further enhance the accuracy of surrogate species assessments.

Third, our reliance on online search data as a proxy for public interest, while offering valuable insights, has limitations. Online data may not fully represent the perspectives of all stakeholders, particularly those with limited internet access. Future research could incorporate sentiment analysis and thematic modeling based on social media discussions, enabling deeper insights into public perception and its direction. However, to provide a more comprehensive understanding of a species' cultural significance and potential as a flagship species, it is crucial to incorporate local knowledge and values through more diverse methods, such as community consultations and ethnographic studies.

Finally, our current framework primarily focuses on identifying a single, highly effective surrogate species. However, relying solely on a single species may not always be sufficient to represent the full complexity of an ecosystem or address all conservation objectives (Lindenmayer and Likens, 2011). Future research should explore the potential of multi-species surrogacy, investigating optimal combinations of species that can collectively represent a broader range of conservation priorities. Our framework, with its ability to quantify and integrate multiple surrogate criteria, provides a valuable tool for exploring these multi-species approaches and developing more comprehensive conservation strategies.

5. Conclusion

Our study presents a novel and robust framework that integrates MCDA with big data to systematically identify effective surrogate species for conservation. By combining Umbrella, Keystone, and Flagship indices into a composite Effectiveness index, our approach provides a comprehensive assessment of a species' conservation potential, moving beyond single-dimensional evaluations. The application to the Three-River-Source National Park demonstrates the framework's practical utility, highlighting the snow leopard as a highly suitable surrogate species capable of fulfilling multiple conservation roles for other mammals. This integrated, data-driven, and transparent approach not only enhances the robustness and objectivity of surrogate species selection, but also enables rapid preliminary screening of potential candidates, thereby holding significant promise for enhancing the effectiveness of surrogate species selection and, ultimately, contributing to more strategic and impactful biodiversity conservation efforts worldwide.

CRediT authorship contribution statement

Minyi Kau: Writing – review & editing, Writing – original draft, Visualization, Software, Methodology, Formal analysis, Data curation. **Byron V. Weckworth:** Writing – review & editing. **Sheng Li:** Writing – review & editing, Validation, Data curation. **Mathias M. Pires:** Writing – review & editing, Validation. **Daiying Jin:** Writing – review & editing. **Michela Pacifici:** Writing – review & editing, Validation, Data curation. **Carlo Rondinini:** Writing – review & editing. **Luigi Boitani:** Writing – review & editing. **Thomas M. McCarthy:** Writing – review & editing, Funding acquisition. **Zhi Lu:** Writing – review & editing, Funding acquisition. **George B. Schaller:** Writing – review & editing. **Steven R. Beissinger:** Writing – review & editing, Supervision. **Juan Li:** Writing – review & editing, Writing – original draft, Supervision, Resources, Project administration, Funding acquisition, Conceptualization.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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Appendix A. Supplementary data

Supplementary data to this article can be found online at https://doi.org/10.1016/j.biocon.2025.111025.

Data availability

Most data is available from the original source or linked in the manuscript.

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