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Research article

A conceptual framework to inform conservation status assessments of non-charismatic species

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ABSTRACT

The conservation of at-risk species is rooted in the ability of natural resource agencies to recognize when a species is imperiled and in need of regulatory action, which can be a difficult task due to incomplete information. Freshwater mussels (Bivalvia: Unionidae), are a highly imperiled group of aquatic organisms and conservation tools such as the NatureServe Conservation Methodology provide a framework to determine whether a species is in decline and in need of potential management. For data deficient species like mussels this method relies heavily on expert opinion, which can lead to biased estimates of conservation status that may not reflect the true nature of their conservation need. To address these concerns, we developed a standardized and repeatable conservation ranking framework that builds upon the established NatureServe methodology. We compiled a data set of 12,018 species occurrence records of 48 freshwater mussel species, 17 geospatial layers representing environmental threats, and life history information to estimate their response to those threats. Estimated ranks were compared to previous status ranking metrics from IUCN, NatureServe, USFWS and Texas Parks and Wildlife Department. Of the 48 species we evaluated, three were classified as critically imperiled, 16 were imperiled, 15 were vulnerable, 13 were apparently secure, and one was secure. We found 48% of species assessed were less imperiled than NatureServe estimates and found 10% of species assessed to have a higher conservation status than previous evaluations. Our approach can be applied to other species in other regions and should be useful for managers and scientists interested in reducing uncertainty and improving reproducibility in assignment of conservation ranks, particularly for those with limited information.

1. Introduction

The conservation of at-risk species is rooted in the ability of natural resource agencies to recognize when a species is imperiled and in need of regulatory action (Male and Bean, 2005). This is a difficult task because of incomplete information (life history traits, population estimates, age structure, response to environmental stressors, etc.), and reliance on expert knowledge that may not accurately reflect the status of given species (Humphries and Winemiller, 2009; Popejoy et al., 2018). Ideally, a species status should represent the likelihood of extinction or extirpation (Ripple et al., 2017), which can be estimated using a combination of quantitative and qualitative methods. Unfortunately, data needed to quantitatively assess extinction risk is often lacking, particularly for non-charismatic species (Bland et al., 2017; IUCN, 2022). Bland et al. (2017) reviewing species loss and data gaps of imperiled species noted that ~16% species on the International Union for the Conservation of (IUCN) Red List were considered data deficient. This varied by taxonomic group such that freshwater invertebrate species (crabs, mollusks, snails) were the most data deficient. These estimates only consider species for which some limited information was available and so the percentage of data-deficient species is likely much higher than reported estimates (Cowie et al., 2017, 2022).

The pervasiveness of data-deficient species among non-charismatic species such as mollusks is a concern, and managers often rely on qualitative assessments to help diagnose extinction risk for species that would otherwise be overlooked. These assessments can be broadly

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categorized as either subjective or objective (i.e., ranking criteria). Subjective assessments utilize expert opinion to estimate extinction risk, which is useful in cases where species occurrences and life history information are poorly understood, but this approach can poorly estimate extinction risk (McCarthy et al., 2004; Cardoso et al., 2011). Assignment to an unwarranted in need ranking can tie up resources that may be better spent on species in greater need of conservation and management (Martín-López et al., 2011; Lind-Riehl et al., 2016). Additionally, mismanagement of limited resources can erode political and public trust leading to decreased management effectiveness and increased pushback on regulatory policy (Waples et al., 2013; McCune et al., 2017; Connelly et al., 2022). To reduce potential bias, objective methods address these issues by using a ranking method that utilizes standardization across all species conservation rankings. The IUCN and the NatureServe are examples of objective assessments and are widely used to evaluate the conservation status of terrestrial and aquatic species. These methods use estimates of rarity, distribution, population trends, and threats to estimate extinction risk (IUCN, 2001; Master et al., 2012). The United States Fish and Wildlife Service (USFWS) uses a process known as a Species Status Assessment (SSA) for evaluating whether a species warrants listing under the United States Endangered Species Act (ESA). The SSA process is also an objective method and uses information on the ecology, current, and future conditions of a species to estimate extinction rate (Smith et al., 2018).

Freshwater mussels (Bivalvia: Unionidae), although globally distributed are among the most imperiled aquatic fauna worldwide (Lydeard et al., 2004; Aldridge et al., 2023; Sousa et al., 2023). In North America, where they reach their greatest diversity, at least 30 of 297 species are now considered extinct, and 65% of the remaining species are considered imperiled (Ricciardi and Rasmussen, 1999; Haag and Williams, 2014). These declines stem from a combination of human mediated impacts to water quality and quantity combined with the inability of mussels to cope or avoid them (Vaughn and Taylor, 1999; Haag and Williams, 2014; Chase et al., 2020; Bakshi et al., 2023). Within Texas, located in the southwestern United States, almost 34% of the mussel fauna (17 of 50 species) are listed as state threatened, seven are currently listed under the ESA, and four others are proposed for listing under the ESA (USFWS, 2018; USFWS, 2023a; USFWS, 2023b; USFWS, 2024). Due to the unique biogeography of Texas, many of these species are basin endemics or occur only in spring dominated systems, which are vulnerable to environmental change.

Previous efforts to evaluate the conservation status of mussels in Texas have relied solely on subjective assessments (Winemiller et al., 2010). More recently the NatureServe ranking tool has been used to estimate conservation ranks for the 17 state-threatened species (Birdsong et al., 2020), leaving the remaining 33 species unranked. Questions have since been raised on the accuracy of these assessments given the development of a web-based mussel database called the Mussels of Texas (MoTX; https://mussels.nri.tamu.edu; Randklev et al., 2023), along with revisions to mussel taxonomy in the state (e.g., Pfeiffer III et al., 2016; Johnson et al., 2018; Pieri et al., 2018; Smith et al., 2019). The NatureServe ranking tool is based on two broad factors, rarity (i.e., range of extent, area of occupancy, number of occurrences, and percent area occupied) and threats (i.e., scope and severity). The NatureServe more heavily weights rarity in its ranking criteria with rarity comprising 70% and threat magnitude making up 30% of the final scores (Master et al., 2012). Because of this, biased or incomplete species distribution information could lead to scenarios where a species estimated rank is incongruent with its actual status. Similarly, taxonomy that does not reflect actual species boundaries can lead to scenarios where cryptic species are overlooked or those recently elevated out of synonymy have yet to be evaluated.

In addition to these issues, quantifying threats and their impacts on mussels continues to be a challenge due to lack of information. Land use and land use change (LULC) is considered a main driver of biodiversity loss (Sala et al., 2000; Alkemade et al., 2009; Pereira et al., 2010), yet conservation assessments that evaluate extinction risk like the NatureServe ranking tool do not use quantitative data in their assessments. This means the scope and severity of species-stressor relationships and relevance to extinction risk could be speculative. Incorporating LULC data can address these issues by providing quantitative metrics (e.g., points, percentages, statistics) on current and future conditions such as percent land use or number of wastewater outfalls, among others, which are included as potential threats in the NatureServe ranking tool. Species trait information, which are adaptive responses to environmental variation (Stearns, 1989, 1992), has the potential to improve species rankings by providing insight on how species will likely cope with environmental threats (Poff, 1997; Winemiller, 2005; Winemiller et al., 2015). The NatureServe ranking tool does not explicitly consider species trait information in the calculation of a conservation status rank, though it is likely some of this information is implicit in expert opinion. However, expert opinion can vary based on experience, which may result in generalizations that do not accurately characterize species-threat relationships (Humphries and Winemiller, 2009), which, in turn, could affect how severity for a given threat is determined in the ranking tool. This bias could lead to scenarios where threats are not properly accounted for either through omission or overestimation, leading to ranks that do not accurately reflect the true status of a species.

To begin addressing these issues, we created a standardized and repeatable aquatic conservation ranking framework, which incorporates quantified LULC and species trait data, to estimate conservation ranks for mussel species in Texas. The specific objectives of this study were to: (1) develop a standardized methodology that builds on the existing NatureServe framework and addresses issues pertaining to aquatic species; (2) identify conservation rank discrepancies between existing frameworks; (3) determine mussel species of greatest conservation need and geographic areas where management would be most beneficial to their survival.

2. Methods

2.1. Study area

Texas is the largest state within the continental United States spanning 695,662 km^2, hosts 15 river basins, and 8 coastal basins that drain directly into the Gulf of Mexico or the Mississippi Embayment (TWDB, 2022). Climate across the state varies such that precipitation is highest in the eastern part (up to 1475 mm annually) and lowest in the western part (200–350 mm annually; Griffith et al., 2007). Precipitation is seasonally pronounced with greater rainfall in the spring and fall compared to summer and winter (Wong and Breecker, 2015), but heavy precipitation events can occur in summer and early fall in association with tropical storms and hurricanes. Similarly, air temperature varies significantly from season to season, with northern latitudes typically much cooler than southern latitudes due to the influence of the Great Plains and Gulf of Mexico respectively, with mean annual temperatures in the north averaging 14.4 °C while those in the south average 24.1 °C (NOAA, 2021). These differences in climatic regimes combined with past geological processes have shaped patterns of mussel biodiversity across the state such that species richness is maximized in east Texas, whereas endemism is highest in central and west Texas (de Moulpied et al., 2022).

2.2. Mussel records

We obtained occurrence records of freshwater mussels from the MoTX, an online repository of over 28,000 validated records from historic and contemporary mussel collections within Texas (Randklev et al., 2023). Following the NatureServe methodology, we excluded records prior to 2011 because historical data may overestimate current species distribution, which could bias species ranks (Master et al., 2012). We excluded records of *Arcidens wheeleri*, Ouachita Rock Pocketbook, *Lampsilis sietmani*, Canary Kingshell, *Lampsilis cardium*, Plain Pocketbook, and *Quadrula couchiana*, Rio Grande Monkeyface, because of uncertainties regarding their distribution or occurrence within Texas. We compiled records of live mussels with associated geospatial information spanning 2011–2021. More recent data collections have yet to be uploaded to MoTX and this time period matches the temporal range of current LULC threats.

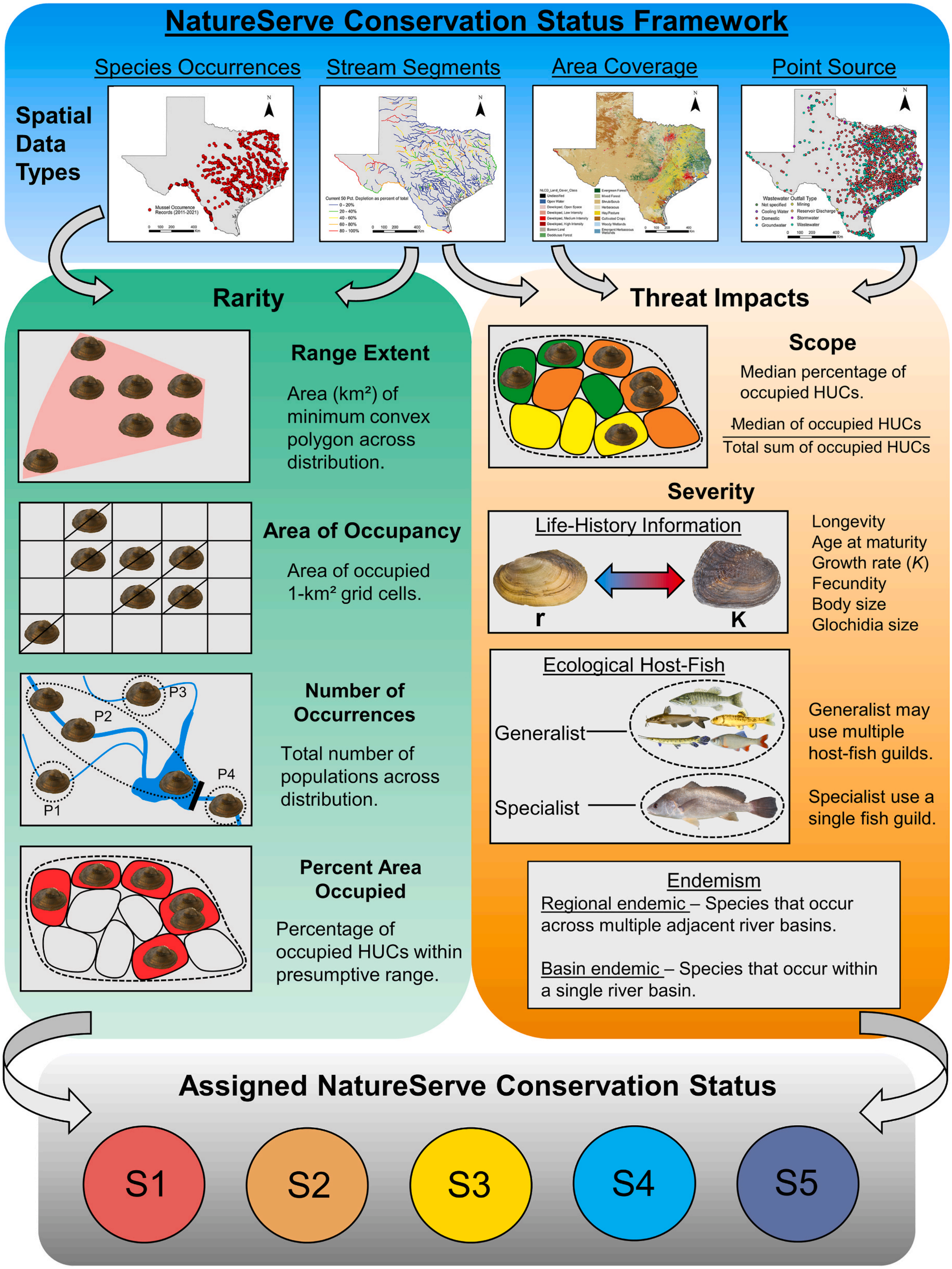

Fig. 1. Conceptual framework for proposed NatureServe conservation status assessment outlining sources of data and the subsequent criteria used to calculate each metric of rarity and threat impact. Bold headings in Rarity and Threat Impacts section of figure represent the major metrics used in calculating species rankings.

2.3. Spatial information

To quantify landscape level threats, we obtained publicly available spatial data from several sources including land cover data (i.e., vegetation type, urbanization level, roads, etc.) which was obtained from the Multi-Resolution Land Characteristics (MRLC) consortium, National Land Cover database (Homer and Dewitz, 2016; Yang et al., 2018) (details in Table S1). River segment data relating to hydrology, impairment, invasive species, watershed development, and pollution were obtained from Texas Water Explorer dataset through The Nature Conservancy (https://texaswaterexplorer.tnc.org/). Pollution assessments for domestic, industrial, and energy production sites, water management, and stream flow (perennial vs intermittent) were obtained from the Texas Commission on Environmental Quality (TCEQ, 2022). Road and railroad data were obtained from the Texas Department of Transportation (https://gis-txdot.opendata.arcgis.com/). Oil and gas well data were obtained from the Railroad Commission of Texas (https://www.rrc.texas.gov/). Hydrologic unit code 8s, hereafter HUC, were used as the spatial measure to quantify and estimate the prevalence (i.e., scope) of these threats to mussel populations. HUCs were obtained from the National Hydrography Dataset (NHD) and were overlaid with species occurrences to identify which HUC-8s each species occupied prior to spatial threat impact analyses (McKay et al., 2013). All spatial data was scored as either number of points within watershed (i.e., oil wells, dams, etc.) or as percent coverage of total basin area (i.e., % forested, % of stream impacted, etc.). The scope metric is used to calculate threat impacts and is assessed by applying one of five categorical percentile ranges (pervasive [71–100%], large [31–70%], restricted [11–30%], small [1–10%]; Master et al., 2012).

2.4. NatureServe methodology

The NatureServe conservation assessment calculator is a quantitative tool which aims to evaluate species extinction risk of species and elimination risk of ecosystems at the national and subnational level. The NatureServe methodology measures two broad categorical factors: rarity and threats which are calculated using a point-and-rule based approach (Fig. 1). The subsequent components are weighted and summed with rarity comprising 70% and threat magnitude making up 30% of the final scores (Master et al., 2012). Calculated scores corresponding to one of five conservation status ranks ranging from S1 (critically imperiled) to S5 (secure) (Fig. 1).

2.5. Rarity

To calculate rarity, we assessed range of extent, area of occupancy, number of occurrences, and percent area occupied. Range extent is defined as the minimum area that can be delimited to encompass all present occurrences and area of occupancy is defined as the area within the range extent that a species occupies (Master et al., 2012). To estimate both, we used the GeoCat Geospatial Conservation Assessment Tool (geocat.kew.org), developed by the IUCN (Bachman et al., 2011). For area of occupancy, 1 km^2 grid cells were used following recommendations by Master et al. (2012) for aquatic species, which have a linear distribution within stream systems. The number of occurrences, which estimates total number of populations across a species distribution, was determined based on reproductive connectivity. Specifically, populations separated by manmade barriers (i.e., major dams) or located in tributaries, and thus isolated from mainstem populations, were considered unique because of potential disruption to geneflow (see Fig. S1 for example). Finally, percent area occupied is defined as the extent of a species range where favorable characteristics with respect to population size and/or quality and quantity of occupied habitat will likely persist for the foreseeable future (Hammerson et al., 2008; Master et al., 2012). To calculate this metric, we quantified the number of occupied HUC-10s and divided it by the total number of HUC-10s containing perennial flow based on the idea that perennial flows are fundamental habitat requirement for mussels (Vaughn et al., 2015; Randklev et al., 2018). Results for range of extent, area of occupancy, number of occurrences, and percent area occupied were then inputted into the appropriate categorical range of the Nature Serve Calculator.

2.6. Threats

To calculate the effect of threats on a given species requires information on its scope, which is defined by NatureServe as the proportion of the species population that could be expected to be impacted by the threat within 10–20 years. Additionally, threat impacts are assessed by severity, explained as the level of impact of a given threat to a species (Master et al., 2012). We utilized spatial data to measure the scope for 9 of the 11 possible threat categories (level-1 threats) at the HUC-8 level to capture reach to catchment point and non-point stressors. For polygon data, we calculated the median percentage of a given stressor for every occupied HUC-8 within a species range. We then divided those values by the total sum for that stressor across occupied HUC-8s to provide a mean value. We quantified point data as the proportion of the median count of occupied HUC-8s divided by the total number of points within the occupied HUC-8s. We chose HUC-8s instead of HUC-10s because the coverage of HUC-8s captures a wider upstream area that may host impactful threats to downstream populations that would not be covered at the more localized HUC-10 level. Furthermore, we inputted the median values instead of mean because median values are rank ordered which allows for better comparison across narrowly distributed and common species as normal distributions required in parametric statistics are likely unachievable in rare taxa (Siegel, 1957). Therefore, a median value from all occupied HUCs allows for greater comparability across a wide range of taxa and provides a similar baseline for the prevalence of each threat in a species distribution. Once the median HUC value (i.e., percentage) was calculated based on its layer type, it was inputted into the corresponding range of percentages available in the NatureServe calculator.

2.7. Severity

To more accurately evaluate how mussels may cope with a given threat we first polled the state malacologist for Texas Parks and Wildlife to rank the assessed threats based on the perceived impact to mussels from a categorical and rank-order standpoint. Threats were categorized as having either high (3), medium (2), and low (1) perceived impacts to mussels and rank order from highest (1) to lowest (17) threat impact. The subsequent weightings of each threat impact were used in calculating a baseline score that all species would start with in each threat category. Specifically, the baseline score was calculated by multiplying categorical impacts scores by the rank-order score of each threat which produced a range of unique values based on the perceived impacts of mussels.

To quantify how a given species may respond to a specific threat we determined its life history strategy, number of host fish, and degree of endemism (Haag, 2012). To determine life history, we ordinated all species using information on longevity, average fecundity, age at maturity, growth rate (measured by the von Bertalanffy parameter, K), maximum length, and average glochidia size. If no information was available for a species, we used information from closely related congeners. Species scores were extracted from the first principal component (PC) axis of a principal component analysis (PCA), which contrasted species along a r/K continuum based on their ability to cope with density and environmental effects (MacArthur and Wilson, 1967; Pianka, 1970). Species possessing r-selected suite of attributes (e.g., short lifespans, small-bodies, and high fecundity) are expected to have higher fitness under density-independent influences (disturbance), whereas species possessing K-selected suite of attributes (e.g., large bodied, long lifespan, low fecundity) are expected to have higher fitness under density-dependent influences (e.g., competition, predation) (Winemiller, 2005). We then assigned weights starting at 0.5 and ending at 1.0 based on their position along the *r*/*K* gradient, respectively (Tables S3 and S4).

Successful mussel reproduction requires a fish to briefly host their parasitic larvae (glochidia; Watters and O'Dee, 1998) and imperilment has been linked with host specificity (Haag, 2012; Modesto et al., 2018). Mussel species were designated as specialist (2), generalist (1), and unknown (1.5), based on whether a species or congener employed an infection strategy that targeted a specific guild of fishes or not (Fig. 1; Table S2) (Barnhart et al., 2008; Haag, 2012). Species with unknown host fish affiliation were given a higher score than generalist to be cautious of undervaluing their response to environmental disturbances while highlighting knowledge gaps of certain species with missing life history information. Lastly, species with limited geographical ranges tend to be more susceptible to landscape level threats (Bland et al., 2017). Species that occur within a single major river basin were categorized as a basin endemic (3) species occurring in multiple adjacent river basins, but not outside of Texas were classified as regional endemic (2), species occurring in multiple basins outside of Texas were classified as wide ranging (0) (Tables S3 and S5). Scores of endemism, host fish strategies, and baseline threat scores were then summed and multiplied by the corresponding life history weight generated from the PCA. This generated a final species-specific severity score that was used to determine the severity ranking that was then applied into the calculator. (e.g., extreme, serious, moderate, slight, negligible). Threat impact data summaries, species loadings, and calculations are available at Mendeley Data (https://dx.doi.org/10.17632/8589ysv6kn.1).

2.8. Assessment of proposed conservation ranks

Based on the results from the NatureServe calculator, we then evaluated the relationships between species rankings, rarity metrics, and threat impacts. Scores of four rarity metrics and threat impacts were exported and weighted based on the contribution to the final rankings (Table S3). These data were then used to construct a species-ranking matrix which was analyzed using a PCA. We used a correlation matrix in our PCA because of its ability to handle assorted data types. We considered only the first two components as significant based on the broken stick rule (Legendre and Anderson, 1999). PCA's were calculated and visualized using the 'vegan' package in R (Oksanen et al., 2020; R Core Team, 2021). We then compared the species ranks from our assessment with those conducted by other conservation entities. For this analysis, we ranked species status listings on the following scale of 1–4; 1) for species listed as S1 (NSS), critically imperiled (NSG), or endangered (IUCN, TPWD, USFWS); 2) for species listed as S2 (NSS), imperiled (NSG), vulnerable (IUCN), or threatened (TPWD, USFWS); 3) for species listed as S3 (NSS),vulnerable (NSG), near-threatened (IUCN) or species of greatest conservation need (SGCN; TPWD) or under review (USFWS); and 4) for species listed as S4 (NSS), secure (NSG), least concern (IUCN) or not listed (TPWD, USFWS) (Table S4). The mean and standard error of ranks were calculated across for each species to quantify meta-status (i.e., status of statues) which measures uncertainty between listing entities (Perkin et al., 2021) (Table S5). Lastly, using R we visualized species meta-statuses in order of conservation need (i.e., most imperiled to lowest concern).

3. Results

We compiled 12,018 species occurrence records of 48 freshwater mussel species from MoTX from 2011 to 2021. *Pustulosa pustulosa* comprised the most individual records for a species (1,222) and *Lasmigona complanata* the lowest (6) (Table S6). Of the 48 species analyzed in our NatureServe conservation assessment, three (6%) had final rankings as critically imperiled (S1), 16 (33%) were imperiled (S2), 15 (31%) ranked vulnerable (S3), 13 (28%) ranked apparently secure (S4), and one species was secure (S5) (Fig. 2; Table S7).

3.1. Evaluating proposed NatureServe rankings

Principal component analysis axes 1 and 2 explained 83.55% of the variation in species rarity metrics and threat impacts. Of this variation, PCA axis 1 (PCA 1) explained 58.53% and PCA axis 2 (PCA 2) comprising 25.02% of the variation (Fig. 3; Table S8). Number of occurrences (−1.60) had the greatest negative loadings onto PCA 1, followed by range extent (−1.59), area of occupancy (−1.55), area with good ecological integrity (−0.91), and threat impacts (−0.77; Fig. 3). Area with good ecological integrity (−1.22) had the greatest negative loading onto PCA 2, followed by area of occupancy (−0.51). Threat impacts (1.38) had the greatest positive loading on PCA 2, followed by number of occurrences (0.41), and range extent (0.12; Fig. 3; Table S8). Species with the highest imperilment were found positively along PCA 1 and those considered secure are ordinated negatively across PCA 1 (Fig. 3; Table S9).

3.2. Sensitivity analysis of proposed NatureServe rankings

Meta-status evaluation of conservation ranks revealed examples of convergence and dissimilarity across the different rankings (Fig. 4). Our proposed rankings found 14 (29%) and 13 (27%) of the 48 species with the same ranking as the existing NSS and NSG assessments, respectively (Table S2). Our species rankings were congruent with other organizational assessments including the IUCN with 11 (23%) similar species, TPWD 33 (57%) similar species, and the USFWS converged with 17 (35%) (Table S2). Our quantitative method found 48% of species assessed were less imperiled than NSS estimates and that estimates were 6–20% less imperiled for the other ranking methods. Our methods also found 10% of species assessed to have a higher conservation need than that of NSS and 20–49% of species had a more conservative ranking than the other methods. Finally, 47% of the species assessed in this study did not have a comparative ranking from the IUCN and 2–16% of species did not have a comparative analysis among the other analyses (Table S2).

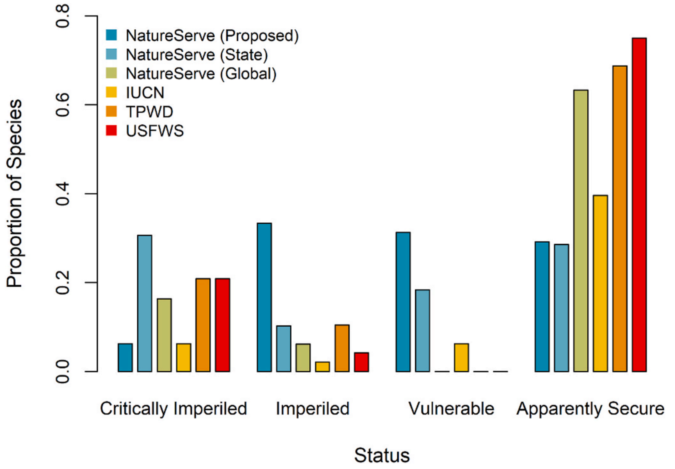

Fig. 2. Proportion of Texas freshwater mussel species in each status type for six conservation status assessments; including the proposed NatureServe status assessment, current NatureServe State and Global rankings, the International Union for the Conservation of Nature (IUCN), Texas Parks and Wildlife Department (TPWD), and United States Fish and Wildlife Service (USFWS). Status titles shown from left to right follow the NatureServe categories but differ slightly for IUCN (Critically Endangered and Endangered, Vulnerable, Near Threatened, Least Concern), TPWD (Endangered, Threatened, Species of Greatest Conservation Need [SGCN], Not Listed) and USFWS (Endangered, Threatened, SGCN/Under Review, Not Listed).

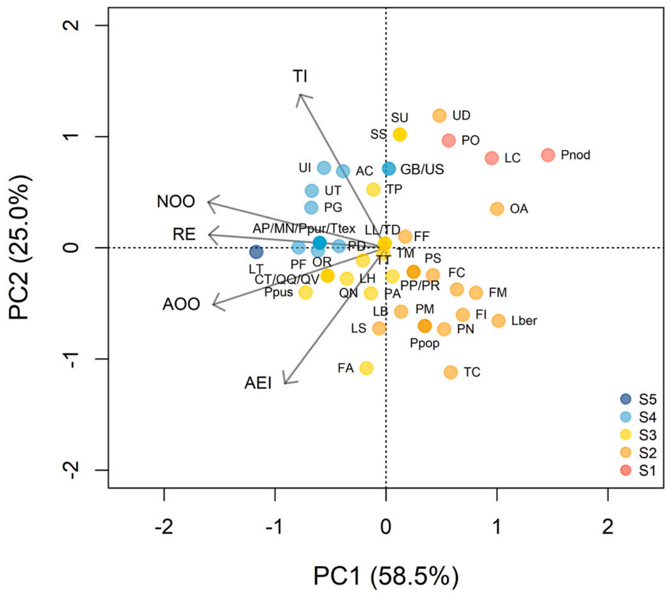

Fig. 3. Principal components analysis (PCA) results illustrating ordination of 48 freshwater mussel species based on calculated NatureServe scores for range extent (RE), area of occupancy (AOO), number of occurrences (NOO), area of good ecological integrity (AEI), and threat impact (TI). Each point represents a species, points are colored according to calculated rank and does not include adjusted ranks. The percentage of variation in criteria scores explained by each PC axis are given in parentheses and arrows represent the direction of species scores from all major criteria used to calculate conservation status.

4. Discussion

We were able to successfully estimate the conservation status of 48 mussel species, including 19 species of high conservation concern using approximately 12,018 species records and adapting the NatureServe calculator to include LULC data and life history information. By using a large species occurrence database along with quantitative LULC data, we were able to reduce uncertainty and improve reproducibility and transparency in assignment of conservation ranks for mussels in Texas. By using life history theory to infer how a species will respond to environmental disturbances, we provide a framework for assessing species sensitivity towards threat impacts when physiological thresholds and demographic rates are still poorly understood. This also improves reproducibly and reduces uncertainty. Taken together, the approach used in this study can serve to guide similar efforts focused on data-deficient species, in cases where expert opinion is lacking, or where bias is suspected.

Land use and land change is considered a primary driver of biodiversity loss (Thomas et al., 2004; Pereira et al., 2010), yet conservation assessments rarely include this type of information when estimating extinction risk (de Baan et al., 2013). In this study, we quantified LULC and environmental characteristics within a given species range to improve estimation of scope and severity for various environmental stressors in the NatureServe calculator. With these metrics included, we were able to quantify threat impacts to individual populations from drought impacts, urbanization, pollution metrics (oil, gas, wastewater, mining effluent), and the impact of invasive/exotic species. This approach is likely more accurate compared to attributing the impact of these threats across the entire species population or using best professional judgement. Quantifying these threats also helped to improve reproducibility and transparency so that researchers and practitioners interested in auditing our findings or replicating our study can do so quite easily.

The LULC data used in this study is widely available at both the US and Global scale, thus allowing for use in the analysis of other faunal groups beyond the present study. Also, using LULC data can serve to guide recovery efforts by identifying suites of environmental stressors that may be contributing to imperilment and areas within a species range where those stressors are likely problematic (Gao et al., 2020). In our analysis we identified several threat metrics (i.e., habitat shifting alterations, water management, commercial industrial areas, etc.) for

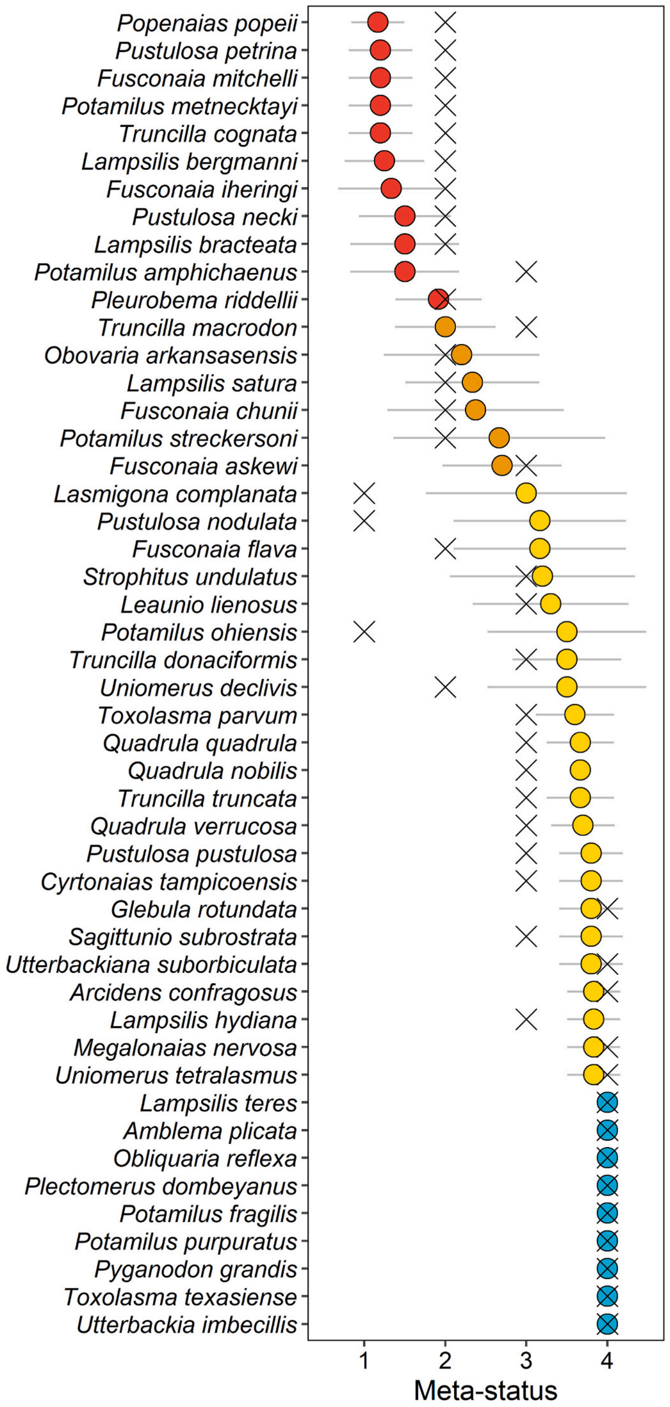

Fig. 4. Conservation meta-status rankings of Texas freshwater mussel derived from calculating the average (circles) and standard error (error bars) across ranked statuses listed by conservation organizations, and state and federal agencies. Colors denoted meta-status values 1–1.9 (red), 2–2.9 (orange), 3–3.9 (yellow), and 4 (blue). Statuses from the proposed NatureServe conservation assessment are demarcated by an “X” for reference. (For interpretation of the references to color in this figure legend, the reader is referred to the Web version of this article.)

Pustulosa necki that were disproportionately higher than other threats (i.e., roads & railroads and boat ramps). Recovery efforts for this species could use this information to focus mitigation efforts on threats that are likely contributing to imperilment instead of those perceived to be causing imperilment. Our approach also provides a flexible method that is transferable to other species, regions and data types. For example, utilizing available online georeferenced databases like the Global Biodiversity Information Facility (GBIF), iNaturalist, or obtaining spatially referenced historical museum collections would allow for analysis of other taxa or multiple faunal groups within or outside of Texas.

Using Land Use Land Cover (LULC) data in conservation planning for imperiled species, such as freshwater mussels, presents challenges due to biological uncertainties and assumptions around specific stressors. To mitigate overestimations, we weighted impacts based on expert knowledge. However, some stressors remain difficult to assess at a landscape level, despite expert input. For example, dreissenids are well-studied invaders compared to newer introductions like *Melanoides tuberculata* (Red-rimmed Melania) and spatially explicit models may offer more detailed insights into potential impacts on mussels than coarser-scale measures like point counts or HUC-based averaging (Sousa et al., 2014; McClure, 2021; Zurell et al., 2022). Nonetheless, these models have limitations, as they are often specific to particular water bodies or regions. Additionally, even for well-studied unionids, the mechanistic links between population dynamics (e.g., growth, survival, and reproduction) and landscape-level stressors are still poorly understood (Ferreira-Rodríguez et al., 2019). Thus, strengthening connections between stressors and landscape data is essential to improve threat assessment accuracy and precision.

We were also successful with incorporating life history information to predict how a given species will likely respond to threat impacts. Life history theory predicts that organisms will evolve suites of traits to optimize their survival and reproduction in response to environmental change (Stearns, 1989, 1992; Winemiller et al., 2015). This idea has led to several conceptual frameworks, most notably the *r/K* selection theory, which contrasts species along a continuum based on their ability to cope with density and environmental effects (Pianka, 1970). Species possessing *r*-selected suite of attributes (short lifespans, small-bodies, and high fecundity) are expected to have higher fitness under density-independent influences (disturbance), whereas species possessing *K*-selected suite of attributes (large bodied, long lifespan, low fecundity) are expected to have higher fitness under density-dependent influences (competition, predation) (Winemiller, 2005). In our study, we successfully used *r/K* selection theory to ordinate mussels in Texas based on demographic information and then used that information to improve estimation of scope and severity. Similar to using LULC data, incorporating life-history information improves reproducibility and transparency. It also serves to better connect threat occurrence with explicit predictions of a species' response to those threats, which has been a general criticism of past efforts focused on assessing species risk (Andelman et al., 2004).

Comparing our rankings with those of the IUCN, NatureServe, TPWD, and USFWS, we found that our estimates for threatened and endangered species were generally more conservative. Specifically, no state or federally listed species were assigned as critically imperiled (S1), instead most were assigned as imperiled (S2). The likely reason for these differences is because our assessment does not forecast future condition, which plays a significant role in USFWS Species Status Assessments (Smith et al., 2018), and to a lesser extent ranks estimated by NatureServe or TPWD. The NatureServe Calculator includes an option for evaluating future conditions, but because we did not have environmental data for those threats projected into the future, we instead focused on the present status condition of each species. Another likely reason for differences between rankings is that accepted norms for the condition of a given species may not reflect ecological reality. Unionid mussels in Texas have been largely ignored by stakeholders and scientists until state listings in 2010 (Howells et al., 1996; Winemiller et al., 2010), and so much of what is known is based on inferences drawn from a small number of field and laboratory studies, though this is changing. Moreover, given the geographic size of Texas very few mussel experts are familiar with the entire mussel fauna of the state. Thus, best professional judgment provided in previous assessments may be overly conservative, particularly in scenarios where significant knowledge gaps exist for a given species.

We also found incongruence for widely distributed species with ranges in Texas. For example, *L. complanata, Potamilus ohiensis* and *Pustulosa nodulata* were assigned as critically imperiled (S1), but these species reach their southwestern range limits in Texas, which means they have a very restricted distribution in the state. Because of this, their calculated status reflects issues with estimating conservation status for species whose ranges overlap political boundaries rather than their true status, which is a common issue for state-wide focused assessments (Richardson and Whittaker, 2010). Finally, misidentification may also play a factor in *P. nodulata*'s assignment as a S1. This is because *P. nodulata* is often confused with *P. pustulosa,* which it co-occurs with in east Texas. It is unknown how prevalent misidentification is for other species, but it is an important consideration for interpreting whether or not estimated ranks reflect actual conservation status. This underscores the importance of not only rooting these types of analyses in data, but also ensuring those data are as accurate as possible and then validating with experts who are familiar with the species in question to raise questions when estimated ranks do not align with general expectations for that species.

Comparing estimated ranks for species presently considered common, we found that over half of species assessed indicated a greater level of imperilment than previously recognized. This would suggest that preconceived notions based on expert knowledge about these species are incorrect and the only way to have recognized this was by conducting an assessment and rooting it in data and ecological theory. This finding raises a larger issue, which is only species perceived as rare are often identified as "at-risk" and often only those species are the focus of conservation efforts (Lindenmayer et al., 2011). However, because these species were not evaluated in prior conservation assessments, it is unclear how they would have been ranked, but based on our findings for rare taxa (see previous discussion), we suspect they would have been given a rank of most secure. These findings should serve as a clarion call for other regions like Texas that have only focused on species presumed to be rare. As pointed out by Lindenmayer et al. (2011), if a key aim of conservation biology is to prevent species from declining or becoming extinct, then there needs to be steps to recognize and detect changes in status before species become rare. To do this requires evaluating all species not just those considered rare. It also requires rooting conservation assessments in data that will allow for identification of threats, reductions in abundance and changes in distribution. Finally, there needs to be a paradigm shift from focusing only on rare species to including common species, which help conserve ecosystem function and structure (Lindenmayer et al., 2011; Chase et al., 2020). To do this requires their recognition and inclusion in conservation assessments (Lopes-Lima et al., 2021).

5. Conclusions

The conservation of at-risk species is a difficult task because of incomplete information, and reliance on expert knowledge that may not accurately reflect the status of given species (Humphries and Winemiller, 2009; Popejoy et al., 2018). In this study, we provide an approach that addresses these issues and can serve as a framework to guide similar assessments for other species and regions. Our approach establishes a standardized set of rules before the analysis, which provides an unbiased lens to reduce researcher bias. Additionally, our approach provides a method for handling quantitative information, which allows for the incorporation of other types of environmental data.

Also, because we adapted the NatureServe tool, which is widely used and publicly available, instead of developing an entirely new method, ensures transparency and transferability of our estimates for use in ongoing and future conservation planning rooted in findings from previous NatureServe assessments. Finally, our approach will be a valuable tool for managers and scientists interested in reducing uncertainty and improving reproducibility in assignment of conservation ranks for other aquatic species.

CRediT authorship contribution statement

Michael de Moulpied: Writing – review & editing, Writing – original draft, Visualization, Validation, Project administration, Methodology, Investigation, Formal analysis, Data curation, Conceptualization. **Alexander H. Kiser:** Writing – review & editing, Writing – original draft, Validation, Software, Methodology, Investigation, Formal analysis, Data curation, Conceptualization. **Clinton R. Robertson:** Writing – review & editing, Validation, Supervision, Resources, Project administration, Methodology, Investigation, Funding acquisition, Conceptualization. **Roel Lopez:** Writing – review & editing, Supervision, Resources, Project administration. **Charles R. Randklev:** Writing – review & editing, Writing – original draft, Validation, Supervision, Resources, Project administration, Methodology, Investigation, Funding acquisition, Formal analysis, 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.jenvman.2024.123423.

Data availability

Data will be made available on request.

Texas Mussel Threat Impact Analysis (Reference data) (Mendeley Data)

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