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Quantifying the relative importance of survival threats to a long-lived reptile using expert elicitation

Jennifer F. Moore[1,*], J. Hardin Waddle[2], Fred Johnson[3], Julien Martin[4], Evan H. Campbell Grant[5], Jill Fleming[5], Thomas S. Akre[6], Donald J. Brown[7], Yu Man Lee[8], Jonathan Drescher-Lehman[6], John Kleopfer[9], Jessica Meck[10], Kevin Oxenrider[11], Jeff Tamplin[12], Anthony Tur[13], Lisabeth Willey[13]

[1]Moore Ecological Analysis and Management, LLC, St. Petersburg, FL 33702, USA
[2]US Geological Survey, Wetland and Aquatic Research Center, Gainesville, FL 32653, USA
[3]Department of Ecoscience, Aarhus University, C.F. Møllers Allé 8, 8000 Aarhus C, Denmark
[4]US Geological Survey, Eastern Ecological Science Center, Laurel, MD 20708, USA
[5]US Geological Survey, Eastern Ecological Science Center, Turners Falls, MA 01376, USA
[6]Conservation Ecology Center, Smithsonian National Zoo and Conservation Biology Institute, Front Royal, VA 22630, USA
[7]USDA Forest Service, Pacific Northwest Research Station, 42218 NE Yale Bridge Road, Amboy, WA 98601, USA
[8]Michigan Natural Features Inventory, Michigan State University, Lansing, MI 48901, USA
[9]Virginia Department of Wildlife Resources, 3801 John Tyler Highway, Charles City, VA 23030, USA
[10]Amphibian and Reptile Conservancy, 6844 Bardstown Road, STE 677, Louisville, KY 40291, USA
[11]Wildlife Resources, West Virginia Division of Natural Resources, Romney, WV 26757, USA
[12]Department of Biology, University of Northern Iowa, 1227 W. 27th Street, Cedar Falls, IA 50614, USA
[13]US Fish and Wildlife Service, Science Applications Program, Hadley, MA 01035, USA

ABSTRACT: Long-term survival of a conservation-reliant species requires understanding the impact of threats on population growth rate and the management actions that can help mitigate these threats. We used a threat assessment with expert-elicited estimates to determine the relative effect of each stage-specific threat on the population growth rate of the wood turtle *Glyptemys insculpta*. In addition, we offered potential management actions that could mitigate these threats and examined the relative cost and benefit of each. The experts responded that predators had the largest effect on hatchling and juvenile survival and that road mortality had the largest effect on adult survival. The population growth rate of the simulated turtle population increased the most when predators were removed from the system, though the population trajectory remained negative. Finally, we found that predator control had the lowest cost:benefit ratio of the proposed management actions. The process used in this analysis of expert elicitation combined with modeling that accounts for uncertainty proved to be a useful technique that is less expensive and labor intensive than empirical studies and quicker to implement, although it relies on sufficient empirical studies to inform expert responses. This process could be replicated for other species to inform species status assessments.

KEY WORDS: Expert elicitation · Threat analysis · *Glyptemys insculpta* · Wood turtles · Population growth rate

1. INTRODUCTION

Threat assessments can advance understanding of the impact of various threats to persistence of a species or group of species and for implementing the most efficient and cost-effective management actions to ensure protection of populations (Salafsky et al. 2002, 2008, Carwardine et al. 2012, Croxall et al. 2012, Adhikari et al. 2018). These decisions often need to be made in a timely manner, and thus it is not always possible to conduct empirical studies on the influence of every possible threat on demographic rates, or the

*Corresponding author: jenn.f.moore@gmail.com

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utility of each management action in reducing these threats (Fitzgerald et al. 2021). In these situations, expert elicitation can be used to help identify the expected threats to population persistence, quantify the impact of each threat on the trajectory of the population, and predict the effect of different management actions on survival of the species (Robbins et al. 2017, Runge et al. 2017, Riskas et al. 2018, Lintermans et al. 2020). This process can be completed quickly and allows a decision to be supported based on the current state of knowledge about a species (Kuhnert et al. 2010, Martin et al. 2012, Drescher et al. 2013). Previous studies and species assessments have used this process across a wide range of species and ecosystems (Battisti et al. 2008, Donlan et al. 2010, Doubleday et al. 2017, Singh et al. 2017, Swan et al. 2017).

Species face many threats to survival, which may include predation, climate change, poaching, habitat destruction and fragmentation, road mortality, and the introduction of invasive species (Brown et al. 2018, Fletcher et al. 2018, Howell & Seigel 2019, Polak et al. 2019, Falaschi et al. 2020, Peers et al. 2020, Vetter et al. 2020, LeDee et al. 2021, Moore et al. 2021, Parker et al. 2021). Turtles in particular may be especially vulnerable to these threats given aspects of their life histories (Rhodin et al. 2018). Long-lived species are often disproportionately affected by threats because they have low reproductive rates, delayed sexual maturity, and slow growth rates (Krebs 2001). These traits prevent a population from being able to rebound quickly, as the threats can affect multiple life stages and demographic rates with impacts often felt across multiple generations (Bennett & Owens 1997, Owens & Bennett 2000, Rowe 2008, Karraker & Gibbs 2011, Margalida et al. 2014). Threats may affect species throughout their life or during particular life stages, such as eggs which could be affected by nest predation (Leighton et al. 2011, Holopainen et al. 2020) or adult survival, which could be affected by illegal collection, especially when larger or older specimens are often more desirable (Allendorf & Hard 2009, Jones et al. 2018, Corlatti et al. 2019).

Some threats to wildlife populations can be mitigated through management actions. For example, for freshwater turtles, some common management actions include headstarting (i.e. raising hatchling turtles in a controlled environment and then releasing them into the wild), nest protection, creation of artificial nesting areas, removal of invasive species, restrictions on agricultural practices, alternative passageways for turtles to avoid road crossings, or a combination of these actions (Frazer 1992, Saumure et al. 2007, Erb & Jones 2011, Spencer et al. 2017, Heaven et al. 2019, Wallace et al. 2020, Vlk et al. 2021, Bougie et al. 2022). However, all of these mitigation actions for protecting a species have an associated monetary cost. Therefore, evaluating the effect of each threat on the population growth rate for a species and evaluating the efficiency of each management action for reducing this threat can help in developing effective management plans to ensure the long-term survival of a species (Carwardine et al. 2012).

In this paper, we conducted a threat analysis (Runge et al. 2017) for the wood turtle *Glyptemys insculpta*. The wood turtle is a freshwater turtle species of high conservation concern because of multiple realized and expected threats (van Dijk & Harding 2011). Specifically, we describe threats to the survival of hatchling, juvenile, and adult wood turtles generated through a formal process of expert elicitation. Using expert-elicited estimates for a set of threats, we determined the relative effect of each stage-specific threat on the population growth rate of the species using a matrix population model for wood turtles (Moore et al. 2022), and offer potential management actions that could mitigate important threats to this species.

2. MATERIALS AND METHODS

2.1. Study species

The wood turtle is a long-lived turtle species found throughout the eastern USA and Canada (Powell et al. 2016). Survival in freshwater turtle species, like the wood turtle, is typically size-related, with higher survival in larger and older individuals (Bodie & Semlitsch 2000). Wood turtles are a semi-aquatic species, with expected losses of at least one-third of their river, stream, and riparian habitats over the next 50 yr due principally to a changing climate (Mothes et al. 2020). The wood turtle is a species considered to be of special concern, vulnerable, threatened, or endangered at the state and provincial level across its range, as well as Endangered based on the International Union for the Conservation of Nature (IUCN) Red list (van Dijk & Harding 2011). Currently, the species is under review by the US Fish and Wildlife Service (USFWS) to determine whether it should be listed as threatened or endangered, and if critical habitat should be designated under the Endangered Species Act (USFWS 2015).

2.2. Expert elicitation

We conducted expert elicitation during a full-day workshop in Berkeley Springs, West Virginia (USA), on 6 November 2019 with experts from multiple states within the wood turtle range using a modified version of the Investigate—Discuss—Estimate—Aggregate (IDEA) protocol (Hanea et al. 2017, Moore et al. 2022). This workshop followed the Spotted, Blanding's & Wood Turtle Conservation Symposium on 4—5 November 2019, and 9 wood turtle experts were available and willing to participate in the elicitation. Most of the workshop was focused on eliciting demographic rates for wood turtles for constructing a matrix population model for the species as explained in detail by Moore et al. (2022). The group of experts was asked to consider a population in the eastern portion of the range near the middle of the latitudinal gradient for the elicitation of the demographic rates (Moore et al. 2022).

To identify the threats facing the survival of wood turtles, we conducted an additional expert elicitation specifically about the hypothesized causes of wood turtle mortality. We began by asking the experts to list all significant sources of mortality they could think of for wood turtles. The experts were then asked to work together to form a consensus on the list of major threats to wood turtle populations. We then asked each expert to independently provide their best estimate of the proportion of mortality that is attributed to each threat at each life stage (hatchling, juvenile, and adult), as well as the 95% confidence intervals around these estimates (Waddle et al. 2025). For each life stage, total mortality across all threats plus an 'other' category must add up to 100%. The 'other' category was any mortality not attributed to one of the other listed threats.

2.3. Effect of threats

First, we fit a beta distribution to the estimate and 95% confidence intervals from the experts for each of the threat categories using the mean-based aggregation method (Colson & Cooke 2018). We used the mean-based aggregation method because we could not fit beta distributions using the median-based approach due to an excess of zeros within the estimates and lower 95% confidence intervals. Next, we fit a Dirichlet distribution to the set of beta distributions for each threat category, which scales the Dirichlet parameters so that the expectations across all threats sum to 1 for each age class (i.e. the total proportion of mortality across all threats was 100%; the methodology was obtained from Zapata-Vázquez et al. 2014). Distributions were fit using the packages 'rriskDistributions' v.2.1.2 (Belgorodski et al. 2017), 'gamlss' v.5.4-12 (Rigby & Stasinopoulos 2005), 'gamlss.dist' v.6.0-5 (Stasinopoulos & Rigby 2020), and 'SHELF' v.1.9.0 (Oakley 2021) in the statistical software R (v.4.3.3, R Development Core Team 2019).

Next, we simulated 100 000 matrices pulling values independently from the Dirichlet distribution for each threat. We used a post-breeding age-structured matrix model based on the life history of the wood turtle (Moore et al. 2022). Parameter estimates for the rest of the demographic parameters (e.g. survival probabilities, age at first reproduction, and clutch size) were pulled from the 'A4' aggregation method as described by Moore et al. (2022). This method fits a unimodal distribution to the quantiles of the distributions fit for each expert. By pulling values from each distribution for all the population parameters and threats, we took into account uncertainty both within and among experts. First, we calculated updated survival values for hatchling, juvenile, and adult turtles by removing mortality associated with each threat for each age class, and then used these new survival values to simulate matrices with each threat independently removed, as well as a baseline set of matrices where no threats were removed.

We calculated the deterministic population growth rate (λ) as the dominant eigenvalue of each of the matrices. We present the mean λ as well as the 95% confidence intervals around this mean based on the set of 100 000 matrices generated with each threat independently removed. Lastly, we projected the population over 20 years to calculate the change in population size over time when each threat is removed. This follows an approach similar to the one described by Runge et al. (2017) on the effect of threats on the probability of quasi-extinction. For demonstrative purposes, we started with an initial population of 100 individuals divided into age classes by the stable age distribution resulting from the initial (all threats included) population projection matrix. Population projections and growth rate calculations were conducted using the 'popbio' package v2.7 in R (Stubben & Milligan 2007).

2.4. Stochastic dominance of management actions

To illustrate a method of identifying the optimal management action for reducing threats with expert-elicited threat data, we used the concept of stochastic dominance with hypothetical management actions (Canessa et al. 2016, Levy 2016). The stochastic-dominance approach utilizes the cumulative distribution function (CDF) of each objective function for each of the management actions. The optimal action is the one associated with the lowermost CDF if this CDF does not cross the CDF from any other action — an action with this property is 'first-order dominant.' The action meeting this criterion is the optimal choice for a decision maker (given the objective function and set of actions considered) regardless of their risk attitude. If the CDFs cross, then 'second-order dominance' is examined using the integral of the CDFs, with again the lowermost integral being optimal so long as its integral does not cross another. Second-order dominance assumes a decision maker who is averse to variability in predicted outcomes. If there is no first- or second-order dominance, the double integral of the CDF can be used to examine third-order dominance, in which the decision maker is also averse to skewness that allows the possibility of very poor outcomes, even if they are associated with small probabilities.

To calculate the CDF for each action, we chose 6 hypothetical management actions that are commonly used for freshwater turtles, and postulated the percentage of each threat that would be reduced if the management action was implemented (Table 1). We then assumed a relative cost for each of the actions, based on which actions would cost the most to employ compared to one another. Finally, we created an objective function that combined the desire to minimize relative cost with the desire to maximize population growth rate due to threat reduction:

$$V(a) = w\lambda_a^{std} + (1-w)c_a^{std} \quad (1)$$

where V = objective value, a = management action, λ_a^{std} and c_a^{std} are standardized population growth rate and cost associated with action a, respectively, and $w = 0.9$ is the relative weight on the population objective. This equation reflects a trade-off between population growth rate and associated cost for a management action, with a higher value for V representing a lower cost and a larger increase in population growth rate. We chose a weight of 0.9 in this hypothetical example because we valued an increase in population growth rate as more important than a lower cost. This weight could be adjusted depending on the specific scenario and importance of each component. Growth rate was standardized on the interval [0, 1], with 1 being the best as:

$$\lambda_a^{std} = \frac{\left(\lambda_a - \min_a \lambda_a\right)}{\left(\max_a \lambda_a - \min_a \lambda_a\right)} \quad (2)$$

and cost was standardized on [0, 1], with 1 being the best (lowest cost) as:

$$c_a^{std} = 1 - \frac{\left(c_a - \min_a c_a\right)}{\left(\max_a c_a - \min_a c_a\right)} \quad (3)$$

3. RESULTS

3.1. Description of threats

The experts came to a consensus and identified 9 threats as having the largest effect on survival of hatchling, juvenile, and adult wood turtles including both natural and anthropogenic threats. Natural threats include drought, flood severity, invasive species (e.g. Japanese knotweed *Fallopia japonica*), predators, and habitat succession. Anthropogenic threats included mowing on agricultural fields,

Table 1. Hypothetical management action scenarios, their effect on survival and the relative cost. Relative cost is represented using the uniform distribution from the given minimum and maximum values, respectively

Scenario	Management action	Effect on survival	Relative cost
1	Moratorium on agricultural machinery	Reduce mowing threat to adults by 80%	(1,3)
2	Nest protection	Reduce predator and invasive species threat to hatchlings by 80%	(0.5,1.5)
3	Headstarting	Reduce predator, flood, and invasive species threat to hatchlings by 100%	(4,6)
4	Predator control	Reduce predator threat to hatchlings and juveniles by 80%	(2,4)
5	Seasonal road closures/culverts/ other diversions	Reduce road mortality threat to juveniles and adults by 80%	(3,5)
6	Increased law enforcement protected	Reduce poaching threat to hatchlings, juveniles, and adults by 80%	(4,6)

poaching, road mortality, and upland habitat development. A 10th category of 'other' was included for any mortality attributed to other threats not included in the analysis (Fig. 1).

Overall, we found that predators were expected to have the largest effect on hatchling survival, followed by drought and flood severity. Similarly, predators were expected to have the largest effect on juvenile survival, followed by road mortality, and mowing of agricultural fields. Lastly, road mortality and mowing of agricultural fields were expected to have the largest effect on adult survival (Fig. 1).

3.2. Effect of threats on survival rates

When evaluating the effect of threat removal by each age class separately, hatchling survival is expected to increase the most when predators are removed from the system. This was an increase from the baseline hatchling survival of 0.185 (95% CI: 0.059–0.362) to 0.664 (95% CI: 0.535–0.780). For juveniles, the largest increase in survival is expected when mortality from predators is removed, with survival increasing from the baseline of 0.664 (95% CI: 0.473–0.829) to 0.800 (95% CI: 0.673–0.903). For adults, removing road mortality is expected to have the largest effect, increasing adult survival from 0.914 (95% CI: 0.789–0.985) to 0.934 (95% CI: 0.838–0.989; Fig. 2).

3.3. Effect of threats on population growth rate

We found that on average when each threat was individually removed, the population growth rate increased by between 0.001 and 0.057 (Fig. 3). Scenarios were not evaluated when multiple threats were removed simultaneously. The baseline population

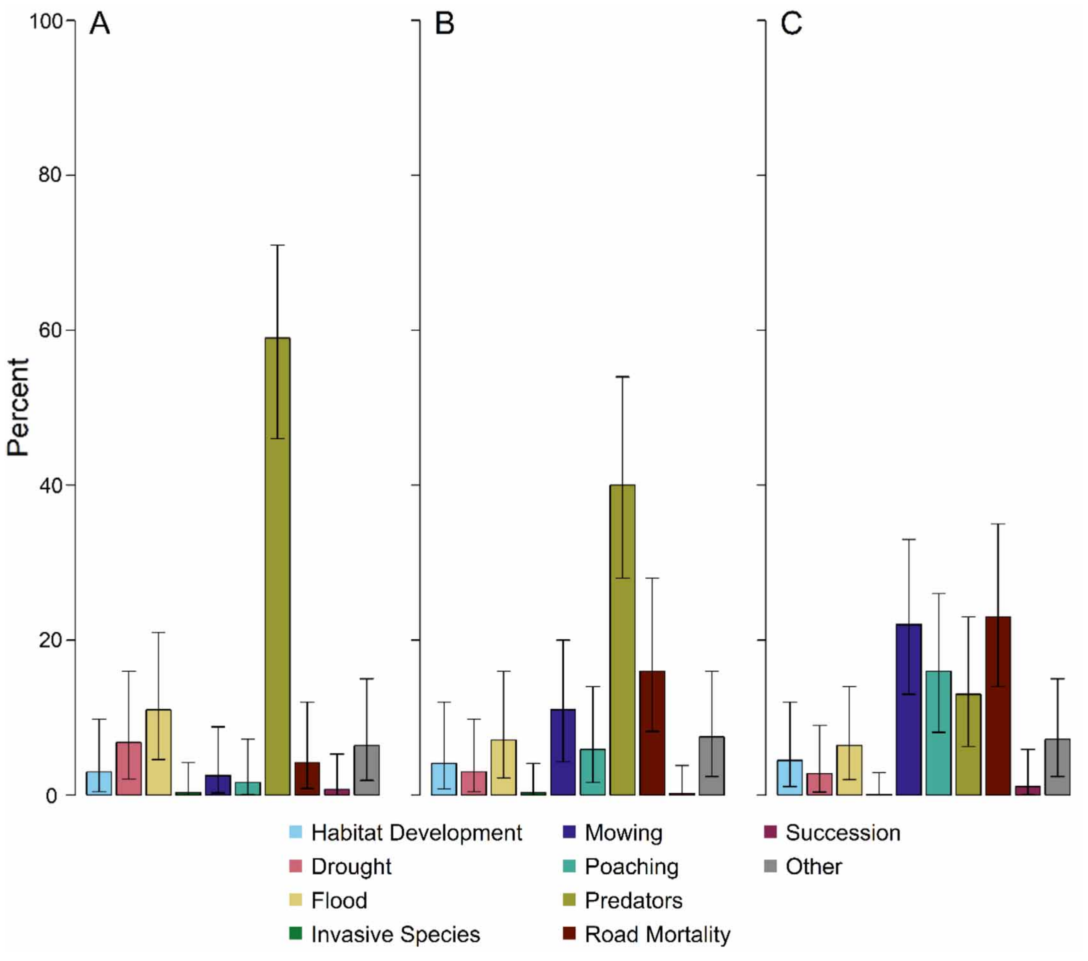

Fig. 1. Percent of mortality attributed to each threat for (A) hatchling, (B) juvenile, and (C) adult wood turtles based on expert elicitation. Elicited values were fit to a Dirichlet distribution to ensure that all threats for each age class added together equaled 100% of mortality. Error bars: 95% CI

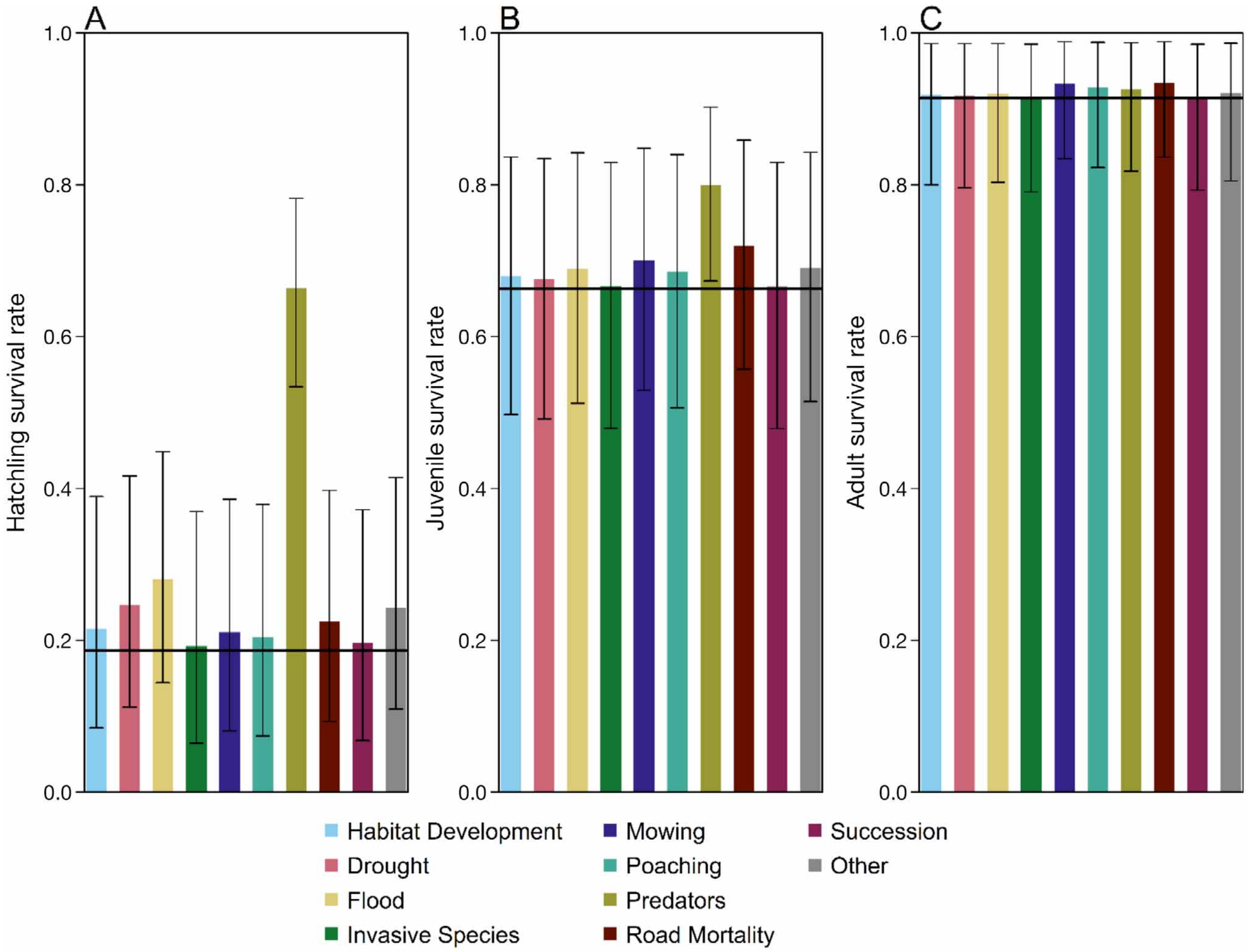

Fig. 2. Estimated survival rates of wood turtles with each individual threat removed by life stages: (A) hatchling, (B) juvenile, and (C) adult. The horizontal line represents the baseline survival rate for each age class when all threats are included, based on the average value elicited from the experts. Error bars: 95% CI

growth rate with all threats included was 0.922 (95% CI: 0.807–0.990) but increased to as high as 0.979 (95% CI: 0.889–1.056) when predators were removed. After removing predators, the population growth rate increased the most by removing road mortality and then mowing of agricultural fields. All scenarios resulted in a declining population growth rate (i.e. $\lambda < 1$); however, the upper bound of the 95% confidence interval was >1 when either predators or road mortality were removed.

3.4. Effect of threats on population projections

If we start with a population size of 100 individuals, all population projections result in a decline in population size, with a baseline of 30 (95% CI: 2–83) individuals remaining after 20 yr if no threats are removed. If mortality from predators is removed, the final remaining population size after 20 yr is estimated to be 89 individuals (95% CI: 11–281). The next best scenario would be a remaining population size of 44 individuals (95% CI: 5–103) when road mortality is eliminated (Fig. 4).

3.5. Stochastic dominance: management actions

We compared 6 hypothetical management action scenarios to assess the optimal scenario based on a combination of objectives related to relative cost versus an increase in population growth rate (i.e. λ; Table 1).

We found that there was no first-order dominance, as the CDFs overlap among management action scenarios, meaning that there is no clear preference for a decision maker (Fig. 5). However, according to the second-order dominance, the optimal management

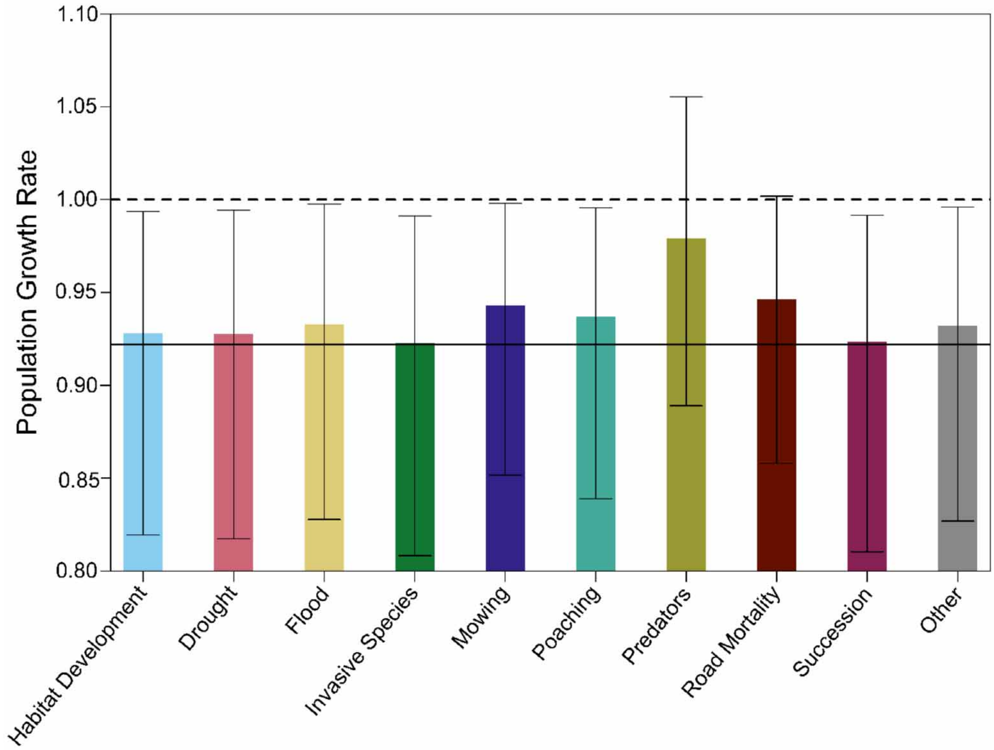

Fig. 3. Estimated population growth rate (λ) with each threat removed from wood turtle hatchling, juvenile, and adult mortality. Matrices were constructed using average values for population parameters from the expert elicitation as well as the average values for each threat from the Dirichlet distribution for each age class. The horizontal solid line represents the baseline population growth rate with no threats removed, and the dashed line represents lambda = 1, or a stable population. Error bars: 95% CI

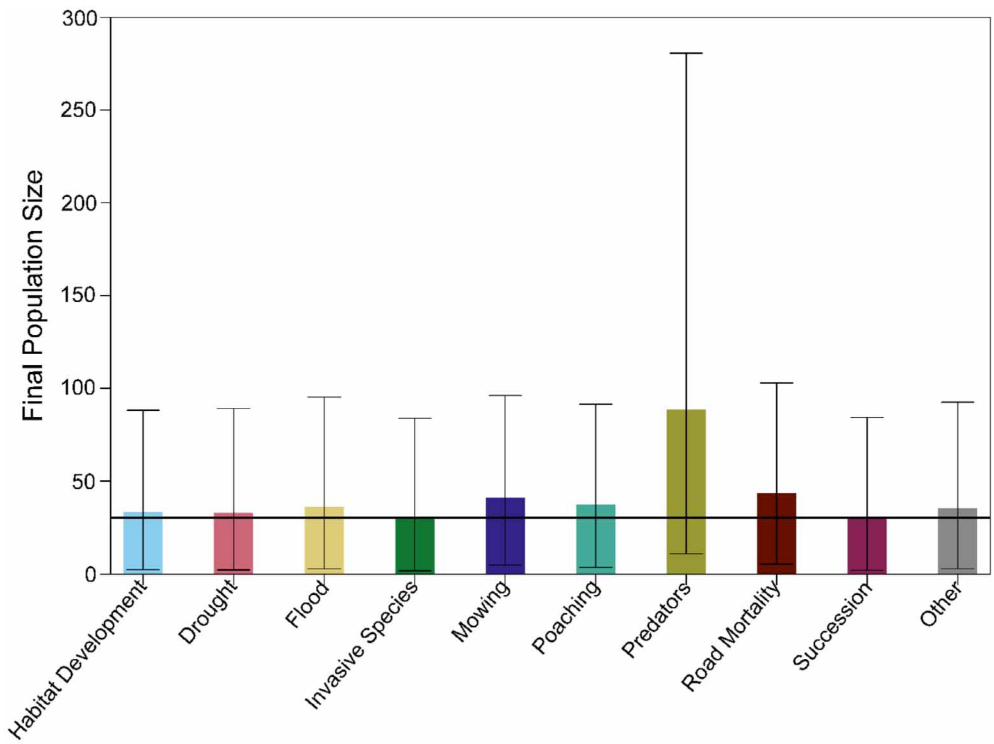

Fig. 4. Final wood turtle population size after 20 yr when each threat is removed. Starting population size is 100 individuals divided up into age classes based on the stable age distribution. Error bars are the 95% confidence intervals, and the black line denotes the baseline values with no threats removed

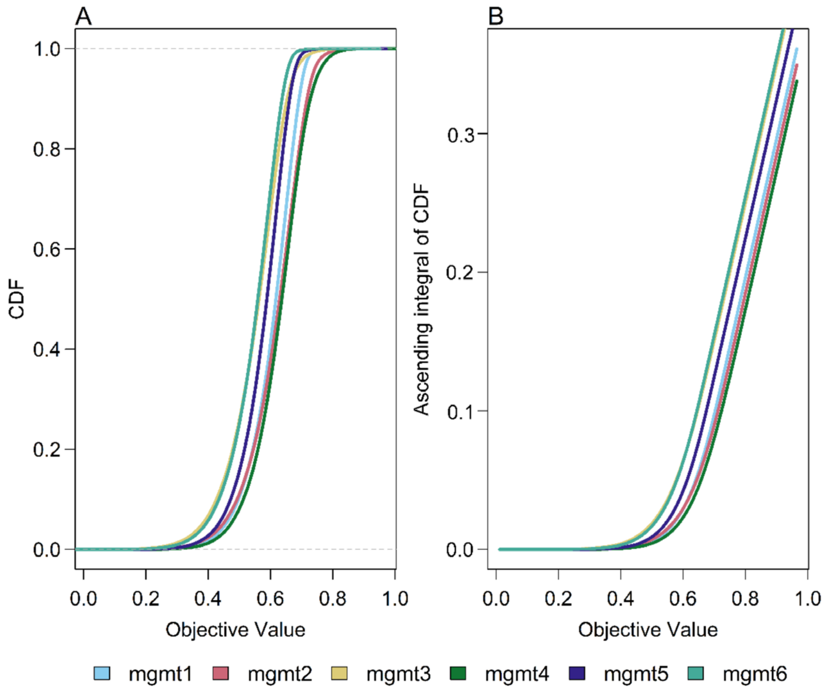

Fig. 5. Cumulative distribution function (CDF), or (A) first-order stochastic dominance and the ascending integrals of the values of management actions or (B) second-order stochastic dominance for 6 hypothetical management action scenarios (Table 1). These plots show no first-order stochastic dominance and management action 4 (mgmt4) as the optimal management action according to second-order dominance

action if the decision-maker is risk-averse would be management action 4, predator control (Fig. 5). This management scenario has a moderate cost but is very effective at increasing λ (i.e. it has a high return on investment).

4. DISCUSSION

Expert elicitation of threat effects allows for an alternative to empirical studies when management decisions about the conservation of a species need to be made on a rapid timeline (Regan et al. 2005, Wilcox et al. 2016). This is often the case in species status assessments, when decisions need to be made even when few or no empirical studies exist (USFWS 2016, Cummings et al. 2020). Additionally, empirical studies for threat assessments can be labor-intensive, expensive, or simply not feasible for some species based on their distribution or ecology (e.g. Donlan et al. 2010). Therefore, by conducting an expert elicitation, results can be used to inform how funds should be spent to better mitigate and understand specific threats, define priorities in terms of threat reduction, and choose optimal management actions for reducing threats.

For turtles, age structure is a consideration when evaluating threats and management actions, as populations are more sensitive to changes in survival of certain life stages (e.g. Heppel et al. 1996, Richards et al. 2024). Therefore, it is not only the size of the effect of a threat that affects population growth rate, but also which parts of the population the threat affects. Our results show differences in key threats to different age classes. Interestingly, there was also a difference in that natural threats (e.g. predators) had larger effects on the survival of hatchling and juvenile age classes, while anthropogenic threats (e.g. road mortality) had the largest effect on the survival of adult turtles (Fig. 1). Because hatchling and juvenile survival rates are lower initially, removing the largest threat increases survival rates more than for adult turtles, which already have high survival rates. For example, removing predators increases hatchling survival by 48% and juvenile survival by 14%. In adults, removing road mortality increases adult survival by 2% (Fig. 2). In terms of their effect on population growth rate, removing predators increased population growth rate by 0.057, while removing road mortality increased population growth rate by 0.024 (Fig. 3). The high end of the 95% CI included a growing population in both of these scenarios, but the mean estimate still indicated a declining population. Understanding threats and forecasting their effects on different age classes is still important regardless of whether the final population is still declining, because reducing these threats can still slow the rate of population decline and time to extinction.

For a population starting at 100 individuals, after 20 yr the final population size would be 89 with predators removed, and 44 with road mortality removed. The upper 95% CI indicates an increase of 218 individuals with no predators and 103 individuals with no road mortality (Fig. 4). The elasticity analysis suggests that increasing adult survival would have the largest effect on population growth rate, with growth rate reaching 1 (i.e. growing population) when adult survival is 100%, keeping juvenile and hatchling survival constant (Moore et al. 2022). However, in this scenario, the increase in hatchling and juvenile survival due to removing predators is large enough compared to the increase in adult survival due to removing road mortality that eliminating predators causes the largest increase in overall population growth rate, even though this is not what would be expected based on the elasticity analysis alone.

Our process identified several threats that experts considered to have the largest expected effects on the survival of wood turtles. These results were corroborated by empirical studies. For example, in Iowa, egg incubation and headstarting, both management actions that reduce predation on turtle eggs, had positive outcomes on turtle survival (Tamplin 2016, 2019). The creation of artificial nesting mounds with predator protection in New Jersey also proved beneficial for survival (Buhlmann & Osborn 2011). Additionally, in the upper Midwest of the USA, predation was found to be the cause of the majority of mortalities, again supporting the notion that predator control would have the largest effect on survival of the species (Lapin et al. 2019). In a long-term study in Michigan, the closure of roads, which would reduce road mortality, was found to increase survival (Schneider et al. 2018); this was also the case in New Hampshire (Hillman & Jones 2022). Finally, a study in Wisconsin found that both nest protection and fewer roads increased survival, corroborating both of our findings (Bougie et al. 2020). Focal populations in Wisconsin are currently being monitored to determine if the conservation actions being implemented influence wood turtle population trends (Badje et al. 2024).

Management actions can be used to mitigate threats specifically for a particular age class or for the species across all ages. However, there may be a difference in cost and effort required to implement each action. Using the concept of stochastic dominance, it was possible to examine the trade-offs among different management actions in terms of how the actions are expected to affect population growth rate as well as their relative cost. In our analysis, predator control was found to be the optimal management action — this action had the largest effect both in terms of efficacy and cost-effectiveness compared to other management actions, provided that predator control is able to reduce the predator threat by 80%. Although this was only a hypothetical example (i.e. we did not frame a specific management decision), we provide a relatively simple framework that could be used to compare management actions for a specific species management decision. In our example, we show an example with no first-order dominance (i.e. actions are not differentiable at the first-order CDF), but with second-order dominance. In some scenarios, it might be necessary to progress to higher-order dominance to choose the optimal management action. In third-order dominance, the optimal management action would be the lowermost double integral of the CDF, and would be important if the managers are concerned with highly skewed distributions, or even a small chance of small values (Levy 2016). In this scenario, it is useful to have a specific decision to understand the context and tradeoffs between different actions.

The modeling approach that we used accounts for uncertainty within and among experts for both the estimates of population parameters and the effects of various threats on demographic rates. For the population parameters, we fit a distribution to the values across experts for each parameter (following Moore et al. 2022). For the threat data, we used a mean-based approach to aggregate estimates across experts for each threat for each age class (Colson & Cooke 2018). For this threat assessment, accounting for uncertainty is important because all experts did not agree on which threat is expected to be most influential on the various demographic rates, and thus what management may best lead to improvements in the population growth rate for the species. By examining the point estimates in addition to the confidence intervals around these estimates, we account for the range of potential values associated with each threat across all experts that could then affect which management actions are optimal. The direct estimation of cause-specific mortality from empirical studies could greatly increase the reliability of the estimates, and therefore should be considered when possible. Approaches combining fraction of mortality analysis from necropsies combined with capture—mark—recapture modeling have been successfully applied to wildlife (e.g. Runge et al. 2017).

Overall, using expert elicitation to conduct a threat assessment can be a useful technique when empirical studies are lacking, though it is important to note that experts rely on empirical studies to inform their responses. This can be especially beneficial for wide-ranging species, where new empirical studies are not always feasible (Froese et al. 2017, Pearman-Gillman et al. 2020), and when decisions have to be made quickly in the face of large uncertainty. This process could be a first step for informing future research and for evaluating potential management actions for reducing threats to a species in the context of species status assessments, after which more detailed empirical studies can be conducted.

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