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Integrated analysis for population estimation, management impact evaluation, and decision-making for a declining species

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ABSTRACT

A challenge for making conservation decisions is predicting how wildlife populations respond to multiple, concurrent threats and potential management strategies, usually under substantial uncertainty. Integrated modeling approaches can improve estimation of demographic rates necessary for making predictions, even for rare or cryptic species with sparse data, but their use in management applications is limited. We developed integrated models for a population of diamondback terrapins (*Malaclemys terrapin*) impacted by road-associated threats to (i) jointly estimate demographic rates from two mark-recapture datasets, while directly estimating road mortality and the impact of management actions deployed during the study; and (ii) project the population using population viability analysis under simulated management strategies to inform decision-making. Without management, population extirpation was nearly certain due to demographic impacts of road mortality, predators, and vegetation. Installation of novel flashing signage increased survival of terrapins that crossed roads by 30%. Signage, along with small roadside barriers installed during the study, increased population persistence probability, but the population was still predicted to decline. Management strategies that included actions targeting multiple threats and demographic rates resulted in the highest persistence probability, and roadside barriers, which increased adult survival, were predicted to increase persistence more than other actions. Our results support earlier findings showing mitigation of multiple threats is likely required to increase the viability of declining populations. Our approach illustrates how integrated models may be adapted to use limited data efficiently, represent system complexity, evaluate impacts of threats and management actions, and provide decision-relevant information for conservation of at-risk populations.

1. Introduction

Conservation management requires addressing problems involving complex interactions between social and ecological systems; multiple, concurrent threats to natural resources; and potential strategies whose outcomes are uncertain (Game et al., 2014). Concomitantly, ecological modeling can help infer and forecast system dynamics, upon which management decisions can be based. Modeling approaches that are realistic in the representation of context-specific processes and transparent in the treatment of key uncertainties are a means to robust conservation decisions (Schmolke et al., 2010).

Population viability analysis (PVA) is an effective tool for predicting outcomes of interest (e.g., population abundance, growth, persistence) for wildlife species, (Akçakaya and Sjögren-Gulve, 2000; Morris and Doak, 2002). PVAs are highly customizable to a species' life history (e.g., life stages, behavioral states) and context-specific factors that affect demographic rates on which predictions are based (Akçakaya and Sjögren-Gulve, 2000; Morris and Doak, 2002; Rhodes et al., 2011; Wilson et al., 2016). Modeling multiple, concurrent threats within a single PVA is crucial for decision-making, since factors not addressed may render targeted management actions ineffective (Heppell et al., 1996; Rhodes et al., 2011; Crawford et al., 2014a). PVAs also provide decision-relevant information via efficient evaluation of the sensitivity of model outcomes to changes in parameter values, including values estimated by expert opinion (Wade, 2002). Still, obtaining reliable predictions from PVAs remains challenging within many conservation

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contexts given multiple sources of parameter uncertainty. These issues magnify as PVAs are commonly applied to rare, declining, and cryptic species with sparse datasets. Population parameters (e.g., abundance, survival, productivity) are estimated from observation data; thus, uncertainty around parameter estimates inherently includes variation of demographic process as well as observation error that should be separated before making inferences (Clark and Bjørnstad, 2004). Overestimation of demographic rates and increases in uncertainty can occur for species with limited data or low detection (e.g., Zipkin et al., 2014). In some cases, there may be no current data on which to estimate parameters, such as for rare species or novel management actions, and PVAs may rely on expert elicitation associated with higher degrees of uncertainty (Krueger et al., 2012). Finally, the effectiveness of management strategies may be difficult to estimate for cryptic species or those with low productivity or delayed maturity because longer post-management periods are necessary to detect changes in population growth (Heppell et al., 1996; Moore et al., 2012; Tempel et al., 2014).

Novel modeling approaches have been developed to improve the accuracy of parameter estimates and population predictions associated with PVAs. First, an integrated model is a unified analysis that can leverage information contained in multiple, partial datasets to estimate shared demographic processes for a population (e.g., Wilson et al., 2016). Integrated models increase precision, ensure consistency of estimates across datasets, and reduce effects of potential bias of individual datasets (Schaub and Abadi, 2011). Examples of these frameworks include the joint live-dead encounter model for mark-recapture and dead-recovery data developed by Burnham (1993) and, more recently, integrated population models (IPMs) for the unified analysis of mark-recapture, population count, and other datasets (Schaub and Abadi, 2011). Second, recent PVA formulations have been developed to improve the accuracy of population predictions by formally incorporating uncertainty around parameter estimates while separately modeling annual stochasticity in population simulations (e.g., Moore et al., 2012; Shoemaker et al., 2013). These models have been constructed in Bayesian (e.g., Bayesian PVAs: Wade, 2002, Kéry and Schaub, 2012) and frequentist frameworks (e.g., McGowan et al., 2011), and we refer to this general class of models as robust PVAs. Robust PVAs reduce the risk of overestimating population outcomes, such as probability of persistence (McGowan et al., 2011), and have also been used to explicitly evaluate effects of management alternatives on population outcomes (Moore et al., 2012; Hegg et al., 2013; Servanty et al., 2014; Green and Bailey, 2015). To date, the application of integrated models to conservation issues is limited (Schaub and Abadi, 2011; Zipkin and Saunders, 2018). The application of robust PVAs to evaluate management actions is growing, but these efforts have not been coupled with integrated models for improved parameter estimation in the context of conservation decision-making (but see Hoyle and Maunder, 2004, Maunder, 2004, Lieury et al., 2015, Saunders et al., 2018). Here, we use integrated models and robust PVAs to estimate context-specific demographic rates, evaluate management actions, and predict population outcomes to inform decision-making for a declining species of conservation concern, the diamondback terrapin (*Malaclemys terrapin*).

Diamondback terrapins inhabit salt marshes along the Eastern and Gulf Coasts of the United States – regions experiencing the fastest annual increases in developed area, road density, and traffic loads (Baird, 2009). Multiple anthropogenic threats contribute to terrapin population declines, which has prompted many states to list the species as "of special concern" or a higher protection status (Roosenburg, 1991; Gibbons et al., 2001; Grosse et al., 2011; Crawford et al., 2014a; Chambers and Maerz, in press; Maerz et al. in press). Terrapins are frequent bycatch in commercial and recreational crab pot fisheries (Roosenburg et al., 1997; Grosse et al., 2011; Chambers and Maerz, in press), and in areas where roads fragment salt marsh, adult females are struck by vehicles while searching for elevated nesting habitat (Butler et al., 2006; Szerlag-Egger and McRobert, 2007; Crawford et al., 2014b). Terrapins share characteristics with the majority of turtles (e.g., long-lived, delayed maturity, naturally high adult survival) that are likely to make populations susceptible to even low rates (3–10%) of additive mortality due to roads (Gibbs and Shriver, 2002; Steen and Gibbs, 2004; Butler et al., 2006; Maerz et al. in press). Human-subsidized predators, such as raccoons (*Procyon lotor*), contribute to high rates (50–90%) of nest mortality on roadsides and other developed areas (Crawford, 2015; Maerz et al. in press). The density of roadside vegetation can also influence terrapin demographic rates. Grosse et al. (2015) observed higher predation rates and higher proportions of male hatchlings for nests laid in planted hedgerows (commonly cedar and wax myrtle *Myrica cerifera*), relative to cleared, open areas along roadsides. Like many reptiles, terrapins exhibit environmental sex determination (ESD) where warmer incubation temperatures produce greater proportions of female offspring (Ewert et al., 1994). While existing management practices have targeted road mortality (Aresco, 2005) and predation (Munscher et al., 2012), vegetation management practices also have the potential to increase population growth (Maerz et al. in press).

The aim of this research was to apply an integrated analysis to evaluate the consequences of management strategies to inform decision-making within the context of road impacts on wildlife. We used a population of terrapins that nest on the causeway to Jekyll Island, Georgia, USA as a model system. Our specific objectives were (i) to develop an integrated model to jointly estimate demographic rates from two mark-recapture datasets, (ii) to directly estimate impacts of road mortality and management actions deployed during the study on demographic rates, and (iii) to incorporate estimates from this and other studies, as well as expert opinion, in a robust PVA to project population persistence under simulated management strategies. This work builds on previous research that estimated the effects of road-associated threats and identified management targets (Crawford et al., 2014a; Crawford et al., 2014b; Crawford et al., 2017; Grosse et al., 2015). It precedes research that will incorporate population persistence outcomes for each strategy in the context of other socioeconomic objectives for road management on Jekyll Island. Our approach, linking integrated models and robust PVAs in a unified analysis, is applicable across conservation contexts for using limited data efficiently, tailoring models to represent system complexity, and prioritizing threats and management actions that impact at-risk populations.

2. Methods

2.1. Study area and population

We conducted research in conjunction with long-term monitoring efforts of the Georgia Sea Turtle Center (GSTC) on the 8.7-km Downing-Musgrove Causeway (aka Jekyll Island Causeway: JIC) to Jekyll Island, GA, USA (31.08°N, 81.47°W; Fig. 1). The JIC bisects a salt marsh peninsula consisting of a network of intertidal creeks and high marsh dominated by *Spartina* spp. We defined the population of interest for this study as terrapins inhabiting this peninsula and using JIC roadsides for nesting. The JIC represents a regional road mortality hot spot where 100–400 adult female terrapins are killed each summer while searching for roadside nesting habitat (Crawford et al., 2014b; GSTC, unpubl. data). Previous monitoring during terrapin nesting seasons revealed that crossing activity was concentrated spatially on road sections (hot spots) and temporally within a daily 3-h period around the scheduled diurnal high tide (Crawford et al., 2014b), and we exploited these peaks with two management actions. In 2011, we constructed a 22-m hybrid barrier composed of fencing and nest boxes at one hot spot and evaluated its effects on preventing terrapins from accessing the road (Crawford et al., 2017). Nest boxes consisted of elevated artificial mounds of sand with electrified cages on top, which were designed to allow terrapins access to the box while excluding mammalian and avian predators (see Buhlmann and Osborn, 2011; Quinn et al., 2015) and