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Population-level effects of wildlife rehabilitation and release vary with life-history strategy

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A B S T R A C T

Wildlife rehabilitation is the treatment and subsequent release of injured wildlife. Wildlife rehabilitation benefits individual animals receiving care, but also supports Conservation Medicine approaches by providing opportunities to monitor wildlife health, contaminant loads, and disease prevalence. However, it is typically considered to have negligible effects on population growth, and has not traditionally been acknowledged as an effective tool for wildlife conservation. To explore whether rehabilitation and release could directly support population recovery in some cases (*i.e.,* increase population growth rates), we considered five case study species along a spectrum of life-history strategies (Raccoon, Painted Turtle, Blanding's Turtle, Snapping Turtle, and Little Brown Bat). We simulated populations over 200 years, while varying two parameters: 1) the rate of severe injury (0, 1, 2, or 5 % of the population); and 2) how many of these injured animals are successfully rehabilitated (0, 10, 25, or 50 %). The effect of the rehabilitation scenarios was largest when additive severe injury rates were highest (5 %). Species that were most sensitive to increased adult injury rates (turtles and bats) also exhibited the greatest population-level responses to rehabilitation and release interventions. We conclude that wildlife rehabilitation can support *in situ* recovery and help stabilize declining populations when 1) injury is an ongoing source of high additive mortality, 2) the target population is small, 3) the species exhibits a *K*-selected life-history strategy, 4) rehabilitation can be combined with other interventions, including *in situ* threat mitigations, and 5) rehabilitation efforts do not jeopardize or limit *in situ* conservation interventions.

1. Introduction

Wildlife rehabilitation is "the treatment and temporary care of injured, diseased, and displaced indigenous animals, and the subsequent release of healthy animals to appropriate habitats in the wild" (Miller, 2012). Treating injured wildlife often focuses on common and wide-spread species, and human-wildlife interactions are typically the main cause of admission (Grogan & Kelly, 2013; Molina-López, Mañosa, Torres-Riera, Pomarol, & Darwich, 2017; Tribe & Brown, 2000). Wildlife rehabilitation has traditionally been viewed as a field run by extremely dedicated laypeople, but veterinarians are increasingly involved with its oversight (Manire et al., 2017). Wildlife rehabilitation and wildlife veterinarians are essential components of Conservation Medicine, an interdisciplinary field that recognizes and integrates the links between human health, wildlife health, and ecosystem health (Jakob-Hoff & Warren, 2012; Tabor, 2002). Under the umbrella of Conservation Medicine (or One Health; Cleaveland, Borner, & Gislason, 2014), rehabilitation work targeting individual animals can be leveraged to monitor indicators of health in a population (Carstairs, 2019; Randall, Blitvich, & Blanchong, 2012; Trocini, Pacioni, Warren, Butcher, & Robertson, 2008). While these efforts can directly inform *in situ* management, it is unclear whether rehabilitation and release efforts themselves can have population-level impacts (Sleeman & Clark, 2003).

Conservation scientists typically focus their efforts on protection at the level of populations, species, and ecosystems, using tool sets such as population translocations and threat mitigation. Where wildlife rehabilitation and release efforts are represented in ecological and conservation research, studies have focused on evaluating rehabilitation

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methods (Molony, Dowding, Baker, Cuthill, & Harris, 2006), or on identifying potential pitfalls, such as the inconsistent application of protocols or the inadvertent transmission of disease through relocation of rehabilitated individuals (Deem, Karesh, & Weisman, 2001). Wildlife rehabilitation has also been portrayed as an indefensible use of resources that should be directed instead towards *in situ* biodiversity conservation and maintenance of landscape connectivity (Albrecht, 1998). This argument persists, although it is unclear whether (or how) funds currently used to rehabilitate wildlife could be directly diverted to *in situ* interventions (Sikarskie, 1992). A conservation science perspective might prioritize resource allocation towards population-level interventions, not the care of individual animals. In contrast, the work performed by wildlife rehabilitators is focused at the level of the individual, even when their ultimate goal is the recovery of a population or species (Aitken, 2018).

Wildlife rehabilitation practitioners are typically motivated by a sense of compassion, and by strong beliefs in the importance of animal welfare and environmental stewardship (Dubois, 2003; Englefield, Candy, Starling, & McGreevy, 2019; Stauber, 2002; Tribe & Brown, 2000). These values are shared with most conservation scientists, and many rehabilitators explicitly want their work to benefit wildlife conservation (Aitken, 2018; Guy, Curnoe, & Banks, 2013). Nevertheless, rehabilitators themselves must prioritize resource allocation at the individual level because that is where their work is focused (Mullineaux, 2014). The disparity between the "typical" perspectives of conservation scientists and wildlife rehabilitators may be further exacerbated by financial stress experienced by many rehabilitators, who are often self-funded or heavily subsidizing their own rehabilitation work (Dubois, 2003; Englefield et al., 2019; Stauber, 2002).

Some academic case studies have identified conservation value in the release of rehabilitated wildlife. For example, rehabilitation had conservation value in owls (Fajardo, Babiloni, & Miranda, 2000), bats (Kelly, Goodwin, Grogan, & Mathews, 2012) and wombats (Saran, Parker, Parker, & Dickman, 2011), but these studies focused on individual outcomes rather than population effects. The potential for rehabilitation to contribute to population stabilization or reinforcement deserves further exploration (Caillouet et al., 2016; Pyke & Szabo, 2018). Release of rehabilitated individuals back to their population of origin are unlikely to have population-level effects in large populations, but in small, threatened populations even small increases in mortality rate can lead to extinction (Mounce, Warren, McGowan, Paxton, & Groombridge, 2018; Taylor et al., 2017). The logical extension of this is that a small reduction in mortality in these populations (for example, through rehabilitation and release of injured individuals) might reduce the probability of extinction.

Species' life-history strategies also affect their response to increased mortality rates. Classic *r*-selected species that exhibit rapid maturity, short generation times, and high fecundity can recover relatively quickly from population declines (Hutchings, Myers, Garcia, Lucifora, & Kuparinen, 2012; Longson, Brejaart, Baber, & Babbitt, 2017; Vredenburg, 2004). In contrast, *K*-selected species (slow growth, long generation times, low fecundity) are vulnerable to population declines following increased mortality of adults (Congdon, Dunham, & Van Loben Sels, 1993; Enneson & Litzgus, 2008; Hayes, Gardner, Garrison, Henry, & Leandro, 2018; Heppell, 2007; Keevil, Brooks, & Litzgus, 2018; Whiterod, Zukowski, Asmus, Todd, & Gwinn, 2018). Thus, the potential population-level benefits of wildlife rehabilitation may vary with the target population's size and with the life-history traits of the species.

In this study, we ask whether there are some circumstances under which rehabilitation and release of injured wildlife may aid population recovery. Specifically, we attempted to identify circumstances where rehabilitate-and-release efforts could impact the growth rate of a threatened population. We simulated populations of five case study species to test how a range of adult mortality and wildlife rehabilitation scenarios could affect population growth for species with a range of life-history strategies.

2. Methods

We conducted population viability analyses (PVA) of five species that varied in their longevity, fecundity, and density-dependent responses (Fig. 1), and that are commonly treated at wildlife rehabilitation centres in northeastern North America. We chose these species because they are ones with which we are familiar through our work. However, the results of our modelling can be extrapolated globally to other regions, where other species with similar life-history strategies occur and are also treated in rehabilitation centres.

At one end of the life-history spectrum, we considered Raccoons (*Procyon lotor*), which are commonly admitted to North American wildlife rehabilitation centres and have many characteristics of *r*-selected species (high reproductive rates, young age of maturity, capable of rapid exponential growth). We also chose three turtle species affected by wildlife-vehicle collisions: Painted Turtles (*Chyrsemys picta*), Blanding's Turtles (*Emydoidea blandingii*) and Snapping Turtles (*Chelydra serpentina*). These turtle species vary substantially in their reproductive rates and age at maturity. Female Painted Turtles reach sexual maturity at 7 years, Snapping Turtles at 13 years, and Blanding's Turtles at 17 years (Congdon et al., 1993; Congdon, Dunham, & van Loben Sels, 1994; Wilbur, 1975). Finally, we included Little Brown Bats (*Myotis lucifugus*) because they are often admitted to wildlife rehabilitation centres, mature early (at one year old), but are long-lived (recaptures of wild *M. lucifugus* demonstrate longevity $\geq$ 34 years), and have low reproductive rates, producing only one pup per year (Davy & Whitear, 2016; Frick, Reynolds, & Kunz, 2010; Maslo & Fefferman, 2015).

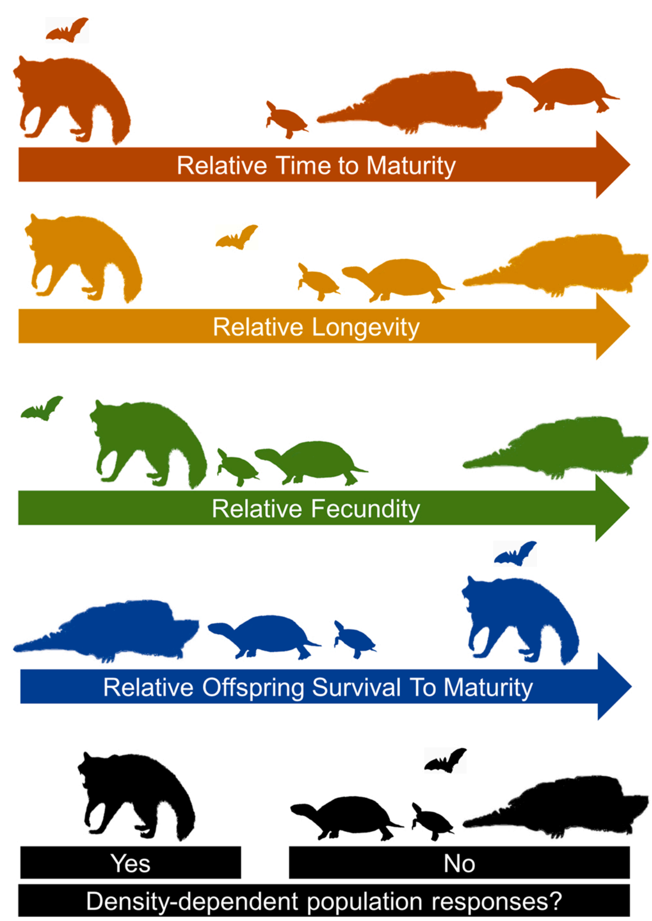

Fig. 1. Variation in key life-history traits of the five case-study species used to explore the potential population-level impacts of rehabilitation and release efforts. In order from left to right in the top row: Racoon (*Procyon lotor),* Little Brown Bat (*Myotis lucifugus),* Painted Turtle (*Chrysemys picta*), Blanding's Turtle (*Emydoidea blandingii*), and Snapping Turtle (*Chelydra serpentina*).

2.1. Simulation scenarios

We ran all PVA simulations in Vortex v10.0 (Lacy, 1993) and started with an adult population of 50 (25 adult males, 25 adult females) and a stable age distribution. We set the carrying capacity at 1000 individuals for all simulations. This is arguably low, but reasonable for the purpose of our conservation-focused research question because wildlife populations that need applied conservation interventions are typically much below their carrying capacity. The total starting population size for each species was different because the stable age distribution depends on demographic factors that vary across species (Raccoon: 50 individuals, Painted Turtle: 170 individuals, Blanding's Turtles: 355 individuals, Snapping Turtle: 600 individuals, Little Brown Bat: 50 individuals). We ran all scenarios for 200 simulated years, which was 67.11 generations for raccoons, 29.98 generations for Little Brown Bats, 17.26 generations for Painted Turtles, 7.67 generations for Snapping Turtles, and 5.70 generations for Blanding's Turtles (generation times in Appendix Table A.1 in Supplementary material).

Our simulated scenarios manipulated two parameters: 1) additional severe injury rates for adults, simulating injuries that would be fatal if not treated, and 2) the proportion of these injured adults subsequently saved by wildlife rehabilitation. Our base scenario used long-term demographic estimates for each species (Appendix Table A.1 in Supplementary material). Additive injury rates for adults were set to either 1, 2, or 5 %, representing injuries (such as collisions with vehicles or wind turbines) that would be fatal if not treated by wildlife rehabilitators. The simulations represent realistic scenarios for turtles based on turtle movement patterns, road density, and traffic volume (Gibbs & Shriver, 2002). The simulations represent feasible scenarios for Raccoons (Gehrt & Fritzell, 1999), and for Little Brown Bats based on mortality from roads and wind turbines (Zimmerling & Francis, 2016).

For each injury rate scenario (1, 2, and 5 %), we modelled how different rates of wildlife rehabilitation affected population size and probability of population persistence. Wildlife rehabilitation was modelled as a decrease in additive adult fatal injury rate for a year. Therefore, the number of animals rehabilitated and released in a year could never be greater than the number of animals that would have otherwise died in a year from untreated injuries. We simulated rehabilitation scenarios where 10, 25, and 50 % of animals injured per year were rehabilitated and released back into the wild, and assumed that injured, untreated animals died. We assumed rehabilitated and released animals had similar survival and reproductive rates as uninjured animals.

3. Results

3.1. Effects of additive severe injuries

Under the baseline scenario (*i.e.*, no added severe injury rate and no rehabilitation), population sizes of all species except Snapping Turtle increased over the 200-year simulations towards the carrying capacity of 1000. Increasing adult injuries decreased mean population size at the end of the 200 simulated years for all species (Fig. 2). Raccoon populations were resilient, only having a substantially lower final population size in the scenario with a 5 % per year adult severe injury rate. Blanding's Turtle and Snapping Turtle populations were most sensitive to increases in adult mortality rates and populations declined with a 1 % per year severe injury rate. Painted Turtle and Little Brown Bat populations still increased towards the carrying capacity of 1000 with an increase in adult severe injury rate of 2 %, but populations of both species declined when experiencing a 5 % per year adult severe injury rate.

Increases in adult mortality from injuries were associated with decreased probability of population persistence. Without additive severe injuries, populations of all species were likely to persist to the end of the 200-year simulation (>99.9 %). Increasing adult mortality to 5 % per year from severe injuries decreased probability of persistence within 200 years to 64 % for Painted Turtles, 12 % for Snapping Turtles, 8 % for Blanding's Turtles, and 7 % for Little Brown Bats.

3.2. Effects of wildlife rehabilitation

Reducing adult mortality *via* wildlife rehabilitation partially mitigated simulated extinction risks for turtles and bats (Figs. 3 and 4). Raccoon populations were largely unaffected by wildlife rehabilitation scenarios, because populations were fairly insensitive to the range of increased adult severe injury rates we simulated.

For scenarios with 1 % and 2 % adult severe injury rates, rehabilitating 10 % of injured wildlife slightly increased the final population size (Fig. 3). Rehabilitating higher proportions of injured individuals (25 % or 50 % of injured individuals) further mitigated population declines (Fig. 3) and increased the probability of persistence (Fig. 4).

The effect of wildlife rehabilitation on populations was largest when additive adult mortality from severe injuries was highest (5 %). Rehabilitating a high proportion of severely injured individuals (25 %–50 %) led otherwise declining Painted Turtle and Little Brown Bat populations to increase (Fig. 3). Rehabilitation increased probability of persistence for Snapping Turtle and Blanding's Turtle populations under scenarios with 2 and 5 % additive adult severe injury rates.

Species that were more sensitive to increases in adult mortality (Snapping Turtle, Blanding's Turtle, and Little Brown Bat) were more likely to have population-level effects from wildlife rehabilitation (Fig. 4). However, while the range of simulated rehabilitation rates slowed declines in these scenarios, it did not reverse them for Snapping Turtle and Blanding's Turtle (Fig. 3).

4. Discussion

Saving individuals can benefit wildlife populations, in certain scenarios. Our results illustrate that wildlife rehabilitation and release can be a tool for wildlife conservation in some scenarios, because intensive rehabilitation efforts can stabilize some endangered populations or at least reduce their chance of extirpation. Rehabilitation efforts are most likely to benefit species with slow life-history strategies, and the population-level benefit of rehabilitation interventions in our simulations was negligible for species that are capable of rapid exponential population growth. Whether rehabilitation of injured wildlife is performed from an individual-focused or population-focused perspective, the result is a reduction in mortality rates. Thus, the effect should approximate that of a population reinforcement program, albeit with potential reductions in the fitness of rehabilitated individuals (Kelly et al., 2011; Mullineaux, 2014). Population reinforcement efforts have prevented a number of extinctions over the past century (Jachowski & Lockhart, 2009; Jones et al., 2008; Walters et al., 2010), and rehabilitation efforts can in theory have a similar effect when practiced on a scale sufficient to offset the key threats to a species. Rehabilitation of individual animals is clearly not always an effective tool for population stabilization, but neither are most other available conservation interventions (translocations, captive breeding and release, *etc.* Dodd & Seigel, 1991; Magdalena Wolf, Garland, & Griffith, 1998). If wildlife rehabilitation can be an effective tool in some cases then it should be explicitly included in the conservation science toolbox, and the contributions of wildlife rehabilitators should be recognized and encouraged.

In the small populations we modelled in our scenarios, rehabilitation of a small number of adult individuals had the greatest effect on the population persistence in species that were long-lived, slow to mature, and had relatively low fecundity. This result is not surprising, as increased adult mortality rates have the greatest impact on population growth in species with slow life-history strategies (Heppell, 1998; Heppell, Caswell, & Crowder, 2000; Wang, Fujiwara, Gao, & Liu, 2019). Rehabilitation of injured individuals effectively reduces the rate of mortality in cases where the source of injury and potential mortality is

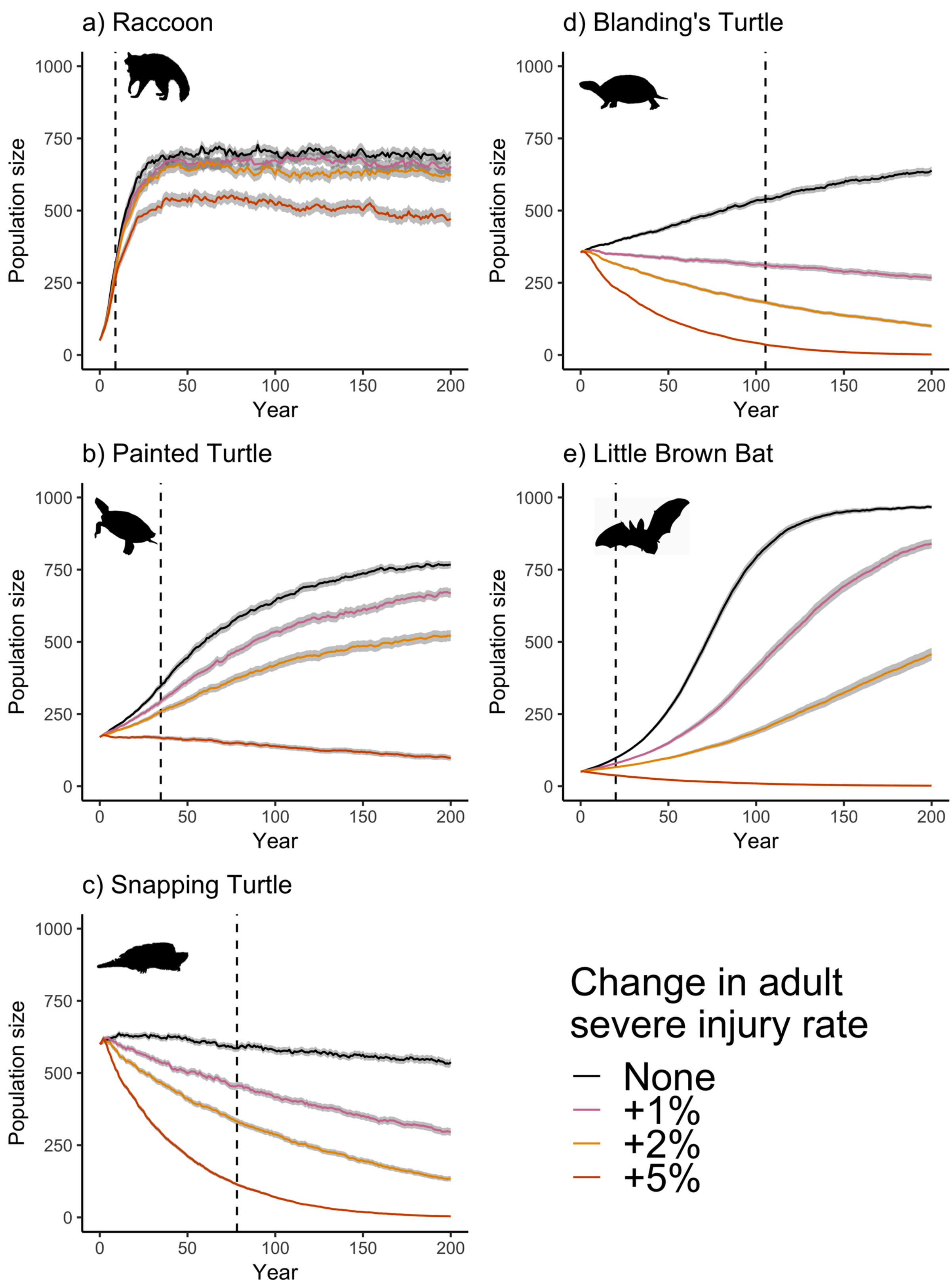

Fig. 2. The effect of adult severe injury rate on a) Raccoons (*Procyon lotor*), b) Painted Turtle (*Chrysemys picta*), c) Snapping Turtles (*Chelydra serpentina*), d) Blanding's Turtles (*Emydoidea blandingii*), and e) Little Brown Bats (*Myotis lucifugus*). Coloured lines are mean simulation values and grey ribbons encompass the 95 % confidence interval from 1000 replicates. All species started with a stable age distribution and 50 adults. Vertical dashed lines represent three generations for each species.

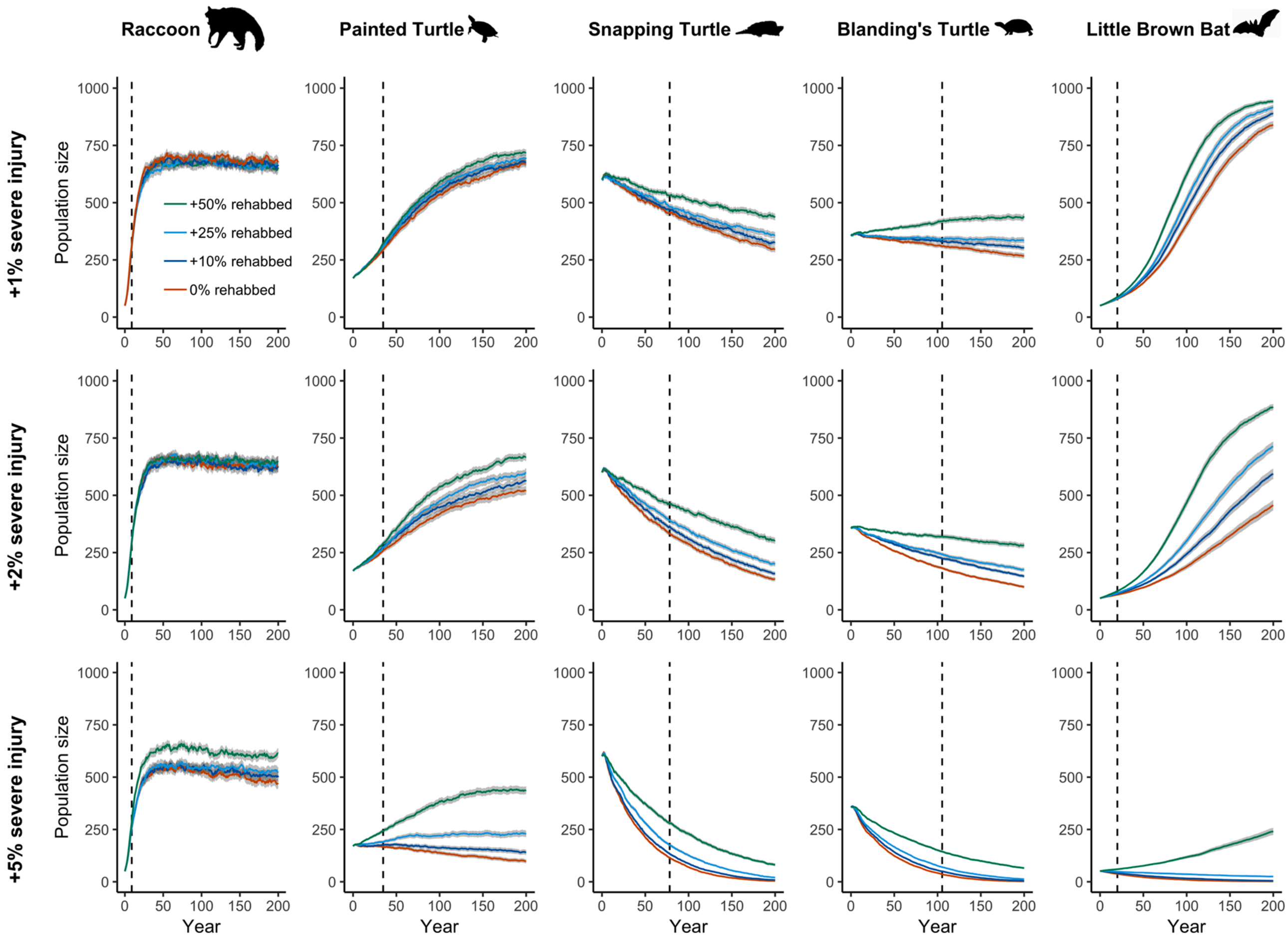

Fig. 3. The relationship between year and population size for population viability analyses with increase rates of severe injury of 1 %, 2 %, or 5 % and four different scenarios of rehabilitation of animals (0 %, 10 %, 25 %, or 50 % of individuals that would have died) for five species: Raccoon (*Procyon lotor*), Painted Turtle (*Chrysemys picta*), Snapping Turtle (*Chelydra serpentina*), Blanding's Turtle (*Emydoidea blandingii*), and Little Brown Bat (*Myotis lucifugus*). Coloured lines are mean simulation values and grey ribbons encompass the 95 % confidence interval from 1000 replicates. Vertical dashed lines represent three generations for each species.

difficult to mitigate directly. In species where rehabilitation efforts can have population-level effects, we would expect these effects to increase as the population size decreases, because the effect of removing or replacing an individual is larger in very small populations. Rehabilitation of individuals can therefore have population-level impacts and be considered as a conservation tool when population size is low (compared to carrying capacity) and species are long-lived.

Our scenarios considered a relatively long time-frame (200 years) and the magnitude of the effect of rehabilitation increased with time, indicating that sustained rehabilitation efforts would be required to have the maximum effect on a threatened population. Nevertheless, population sizes after three generations (as indicated by the dashed lines on Figs. 2 and 3) were already higher under the rehabilitation scenarios. Finally, we did not consider the potential population-level effects of intensive, large-scale rehabilitation efforts in response to mass injury (for example, exposure to oil spill). However, these can also mitigate population-level impacts of sudden spikes in adult mortality (Saba & Spotila, 2003; Underhill et al., 1999). We encourage conservation scientists to recognize wildlife rehabilitation as a potential tool for stabilizing very small populations of long-lived species that are threatened by sources of injury that are difficult to mitigate.

Our estimates of the population-level benefits of rehabilitation are optimistic because we assumed the rehabilitated individuals would exhibit comparable fitness (reproduction and survival) to other individuals in the population. While best practice for wildlife rehabilitation is to release animals that exhibit this level of fitness (Miller, 2012), this is challenging to assess in practice. Treating wildlife in captivity is a form of wildlife translocation (IUCN/SSC, 2013) and may affect the behaviour and fitness outcomes in animals temporarily or permanently. However, rehabilitation differs from other types of translocation because animals are released at their capture site instead of an unfamiliar location. Post-release monitoring of rehabilitated individuals is required to evaluate the relative fitness of rehabilitated and wild individuals (Gaydos et al., 2013; Kelly, Scrivens, & Grogan, 2010; McWilliams & Wilson, 2015; Saba & Spotila, 2003). Time in captivity for rehabilitation can affect movement and dispersal by increasing displacement (Lyn et al., 2012), which can affect how released animals contribute to local or meta- population dynamics. Fitness of rehabilitated individuals may also vary depending on the protocols used during care in captivity (Davy & Whitear, 2016; Holz, Naisbitt, & Mansell, 2006). It may be challenging to achieve sufficient sample sizes of comparable rehabilitated individuals treated with different methods, and of comparable rehabilitated and non-rehabilitated, wild individuals, to enable statistically robust comparisons (Grogan & Kelly, 2013; Hughes, Kennedy, & Litzgus, 2019; Kelly et al., 2011). Nevertheless, building principles of experimental design into evaluations of rehabilitation or other conservation interventions is critical to informing best practices (Bennett, Steiner, Carstairs, Gielens, & Davy, 2017; Carstairs et al., 2019; Pyke & Szabo, 2018). Our models present a simplified illustration of the potential population-level effects of wildlife rehabilitation under various scenarios. We acknowledge that the fitness of released, rehabilitated individuals may not always equal that of untreated individuals,

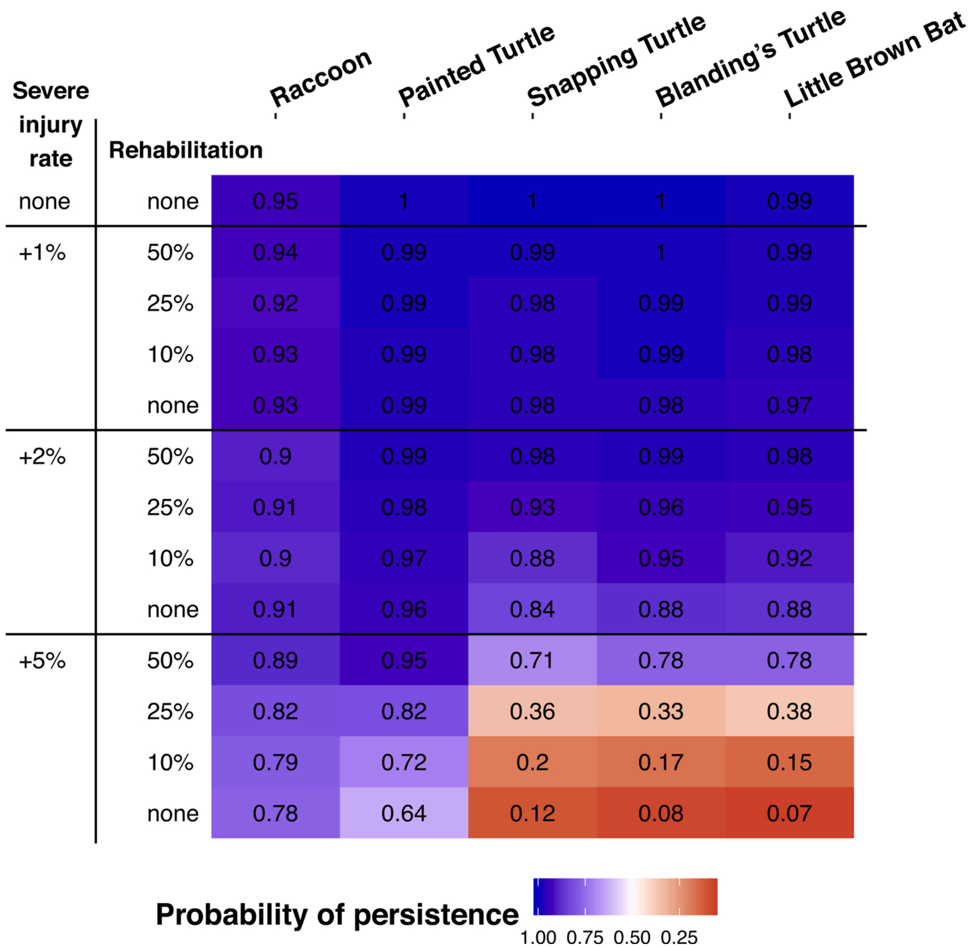

Fig. 4. The relationship between probability of persistence after 200 years), the amount of additive severe injury of adults (none, 1, 2, or 5 %), and the proportion of injured adults successfully rehabilitated (0, 10, 25, or 50 % of individuals that would otherwise have died) for simulated populations of Raccoons (*Procyon lotor*), Painted Turtles (*Chrysemys picta*), Snapping Turtles (*Chelydra serpentina*), Blanding's Turtles (*Emydoidea blandingii*), and Little Brown Bats (*Myotis lucifugus*). Each scenario was simulated 1000 times and populations started at a stable age distribution, with 50 adults. More *r*-selected species on the left, and more *K*-selected species are in the centre and right-hand columns.

and that more complex models and empirical data are required to understand how rehabilitation impacts particular target populations.

We are not suggesting that there is no value in rehabilitating Raccoons or other species with similar life-history strategies, only that rehabilitation and release efforts are unlikely to alter population trajectories in those species. Rehabilitation of wildlife serves other purposes, such as encouraging stewardship and meeting an ethical obligation to provide compassionate care to other living things (Henkel & Ziccardi, 2018; Stauber, 2002). Wildlife rehabilitation also provides opportunities for biomonitoring in partnership with veterinarians and academic researchers. Data collected at rehabilitation centres can identify anthropogenic sources of injury and cryptic threats such as environmental contaminants and novel diseases (Browning, Gulland, Hammond, Colegrove, & Hall, 2015; Orós, Montesdeoca, Camacho, Arencibia, & Calabuig, 2016; Randall et al., 2012; Trocini et al., 2008). Many rehabilitation centres are also involved in public outreach and education, attempting to directly mitigate threats to wildlife by reducing the human-wildlife interactions that lead to injury. These outreach programs may have positive effects, although these are challenging to quantify (Mullineaux, 2014). Given these benefits, we see no logical reason why conservation scientists should oppose wildlife rehabilitation, provided that rehabilitators follow best practices, and that rehabilitation efforts do not hamper conservation of wild populations (for example, by increasing risk of disease introduction, or diverting resources that could be redirected to *in situ* conservation work; Miller, 2012; Wimberger, Downs, & Boyes, 2010).

We conclude that wildlife rehabilitation and release efforts can slow declines in small populations of long-lived species, 'buying time' for *in situ* interventions to be implemented. We are not suggesting that conservation resources should be diverted from direct threat mitigation to fund wildlife rehabilitation. Evidence-based, *in situ* conservation interventions should always be prioritized when allocating resources. Nevertheless, wildlife rehabilitation is an undervalued and potentially useful tool for stabilizing some declining populations, and could be targeted to support *in situ* interventions. Under a Conservation Medicine framework, future collaborations between veterinarians, rehabilitators and ecologists should explore how rehabilitation can be combined most effectively with other conservation interventions to support the recovery of endangered populations.

Data statement

The data and code used in our analyses are available in an Open Science Framework project: https://osf.io/cwdqg/?view_only=19dcce100f37438298a06bbb56eb55dc.

Declaration of Competing Interest

The authors report no declarations of interest.

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Appendix A. Supplementary data

Supplementary material related to this article can be found, in the online version, at doi:https://doi.org/10.1016/j.jnc.2021.125983.

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