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Review

Evaluating the efficacy of predator removal in a conflict-prone world

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A B S T R A C T

Predators shape ecosystem structure and function through their direct and indirect effects on prey, which permeate through ecological communities. Predators are often perceived as competitors or threats to human values or well-being. This conflict has persisted for centuries, often resulting in predator removal (i.e. killing) via targeted culling, trapping, poisoning, and/or public hunts. Predator removal persists as a management strategy but requires scientific evaluation to assess the impacts of these actions, and to develop a way forward in a world where human-predator conflict may intensify due to predator reintroduction and rewilding, alongside an expanding human population. We reviewed literature investigating predator removal and focused on identifying instances of successes and failures. We found that predator removal was generally intended to protect domestic animals from depredation, to preserve prey species, or to mitigate risks of direct human conflict, corresponding to being conducted in farmland, wild land, or urban areas. Because of the different motivations for predator removal, there was no consistent definition of what success entailed so we developed one with which to assess studies we reviewed. Research tended to be retrospective and correlative and there were few controlled experimental approaches that evaluated whether predator removal met our definition of success, making formal meta-analysis impossible. Predator removal appeared to only be effective for the short-term, failing in the absence of sustained predator suppression. This means predator removal was typically an ineffective and costly approach to conflicts between humans and predators. Management must consider the role of the predator within the ecosystem and the potential consequences of removal on competitors and prey. Simulations or models can be generated to predict responses prior to removing predators. We also suggest that alternatives to predator removal be further developed and researched. Ultimately, humans must coexist with predators and learning how best to do so may resolve many conflicts.

1. Introduction

Predators can influence ecosystems through top-down control of the distribution and abundance of other species (Estes et al., 2011; Mills et al., 1993; Newsome et al., 2017; Pace et al., 1999). The loss of predators can therefore have profound ecological effects in certain contexts, including disease outbreaks, biodiversity loss, and ecosystem state changes (Myers et al., 2007; Ripple et al., 2014). There is evidence to suggest that ecological communities can exhibit dramatic shifts following the loss of predators (Crooks and Soulé, 1999; Pech et al., 1992; Ritchie and Johnson, 2009; Wallach et al., 2010), including changes at other trophic levels (Anthony et al., 2008; Atwood et al., 2015; Suraci et al., 2016). Although predators occur among diverse animal taxa (e.g., arthropods, molluscs, teleosts, raptors, canids, mustelids, etc.), vertebrate predators frequently conflict with humans, and many species are threatened (Ripple et al., 2014); they are therefore the focus of this paper.

Many predatory vertebrates are vulnerable to disturbances because they generally have slower life histories, higher investment in parental care, lower abundances, and patchy distributions (Purvis et al., 2000). Yet, predators are challenged by a perception of being a threat to human interests or safety. Indeed, predators can be considered hazardous to domesticated animals (Gusset et al., 2009; Mishra, 1997; Oli et al., 1994), prey species of economic importance (Dalla Rosa and Secchi, 2007; Henschel et al., 2011; Weise and Harvey, 2005), or human safety via direct conflict (Dickman, 2010; Gore et al., 2005; Löe and Röskaft, 2004; Penteriani et al., 2016). Consequently, predators are often negatively perceived and persecution of vertebrate predators has a long a history (Bergstrom et al., 2014; Kruuk, 2002; Reynolds and Tapper, 1996; Treves and Naughton-Treves, 1999). Competition with

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predators yielded many institutionalized campaigns against them dating back to ancient Greece and Rome, a trend that pervaded through medieval Europe and was exported to North America with emigrants in the 1700s (Reynolds and Tapper, 1996 and references therein). Today, state, regional, and agency-led programs to systematically control predator populations exist. Predator removal is carried out systematically via a number of methods and across various geographic scales (Bergstrom et al., 2014; Reynolds and Tapper, 1996), including poison baiting, trapping, hunting, and culling or via bounty or reward systems in public hunting or fishing events, but may also be more haphazard as retaliation for encroachment or interaction with humans or their property (e.g., farmer killing a wolf encroaching on their herds; e.g. Bergstrom et al., 2014; Treves and Karanth, 2003).

The significance of predators in ecosystems is well established yet their removal remains a component of the management toolbox. Owing to a lack of clarity pertaining to how and when removal can be expected to be successful, it may be difficult for management agencies to decide whether to proceed with predator removal when confronted with a problem. Furthermore, there is mounting opposition from advocacy groups (especially animal rights) and conservation-aware citizens that provide social inertia and pressure on animal control (van Eeden et al., 2017), which may complicate and influence decision-making (see Wallach et al., 2015). The science of predator removal therefore could benefit from an objective evaluation to identify successes and failures to both inform decision-making and identify lingering research gaps across multiple taxa (Treves et al., 2016; Eklund et al., 2017). Syntheses of this topic have focused on using meta-analysis, particularly for nesting birds (Côté and Sutherland, 1997; Smith et al., 2010, 2011), but it is challenging to apply such an approach across taxa and research paradigms (i.e., motivations). In this review, we evaluated these two competing hypotheses by considering of the available evidence for predator removal to determine whether predator removal is successful for wildlife conservation and management. We reviewed relevant literature and evaluated outcomes. In doing so, we propose a definition of success that can be applied to predator removal programs and we provide examples of success and failure in predator removals based on the following motivations 1) protection of domestic species, 2) preservation of prey species (e.g. economically important species or species at risk), and 3) mitigating risks of direct human-wildlife conflict. We conclude by considering evidence for the costs of failure in predator removal and a discussion of alternatives to predator removal. Although there are social and economic motivations associated with predator removal (Reynolds and Tapper, 1996; Engeman et al., 2002; Eklund et al., 2017; Swan et al., 2017), we focus on the ecological motivations aiming to synthesize perspectives on this practice. In this context, we refer to removal interchangeably with killing or lethal control. Removal may also refer to translocation, however, translocating predators has generally been demonstrated as ineffective for reducing conflicts (Athreya et al., 2011; Linnell et al., 1997; but see Hazin and Afonso, 2014). We focus on examples of aquatic and terrestrial vertebrate predators and ecosystems that include urban and rural areas. Moreover, we restrict the scope of this review to native predators. Invasive species are a global threat to biodiversity (Doherty et al., 2016) and the problems associated with biological invasions, although not necessarily unique or distinct from the problems that create nuisance predator conflict, are sufficiently different from a conservation and management perspective (see Doherty and Ritchie, 2016). Specifically, we incorporated evidence from published and gray literature on a variety of predatory taxa and from studies with varied predator removal motivations.

2. Approach

Based on preliminary searches and our perceptions regarding the quality of the evidence base (i.e., most studies had replication or included appropriate controls) we opted to conduct a qualitative literature review rather than a systematic review. Because the scope of our paper was broad, we used general search terms of the title, keywords, and abstract of papers in the Scopus search engine: "predator remov*", "cull", and "predator control" to identify relevant literature (asterisks are wildcards in the Scopus search engine). Reference lists in identified literature were consulted for additional resources and searches were repeated in Google Scholar. Articles were appraised at the title and then abstract level for inclusion in a synthetic table. Referring to our definition of success (see below), we sorted literature into successful and failed applications of predator removal and by the objective of the study in removing predators. All searches, filtering and analysis were conducted by the same individual (RJL) following input from coauthors. Bibliometric analyses were conducted in R (R Core Team, 2017). Figure plotted using the ggplot2 package (Wickham, 2009). Included studies were stored in a table (Supplementary material) with the predator species, motivation for removal, study duration, experimental method, our evaluation of success or failure (or equivocality), the removal method, a description of the study, and a citation (if not included in main text).

2.1. Defining successful predator removal

Success is a difficult outcome to define in predator removal because the motivations may be variable and idiosyncratic. Although we define success in the context of ecological responses, we acknowledge that successful predator removal must also consider the socioeconomic dimensions. For governments, the decision to implement predator removal may be a balance between satisfying demands of constituents for safety or prosperity against national or international agreements to protect species and economic externalities associated with wildlife, particularly ecological integrity. Nonetheless, we approach it from a conservation perspective insofar as removal must not cause long-term change or damage to the ecosystem while demonstrably benefiting the prey species, be they domestic animals (e.g. reduced rates of depredation), species at risk (e.g. increased local abundance or population growth rate) or of economic concern (e.g. increased harvest yield), or humans (e.g. reduced conflict or fear from predators). From an ecological and management perspective, we propose that successful predator removal would *reduce predator population to a size (or demographic state) that would not negatively impact the persistence of that population or its competitive status relative to mesopredators, but still provide demonstrable benefits to the prey species following predator removal* (Table 2).

Correlative methods used to evaluate success broadly match population trends of predator and prey species and ascribe outcomes (in terms of predator or prey densities) to the removal. Correlative approaches may lack the power to identify mechanisms (at least in the short term) driving population dynamics (Grubbs et al., 2016; Marcström et al., 1988) but can still provide insight into processes underlying prey population dynamics, particularly where experiments are infeasible. This can be observed in open marine systems where marine mammal culling programs may be tested by measuring correlations with fishery yields (Bax, 1998; Morissette et al., 2012). Shortcomings of retrospective analyses and correlational studies render it difficult to identify evidence supporting any positive effects accrued from predator removal, particularly in the context of different problems that arise where predator removal is being considered as a management strategy.

Experimental approaches to predator removal have more power to detect main effects on livestock depredation or species recovery. Controlled experiments using reference sites may be necessary but before-after-control-impact (BACI) studies can be useful to relate demographic trends to predator removal; however, BACI cannot account for changes to the environment that occur over time (e.g. Hervieux et al., 2014). Marcström et al. (1988) monitored grouse (*Bonasa bonasia*, *Lagopus lagopus*, *Tetrao tetri*) and capercaillie (*Tetrao urogallus*) populations across eight years, the first four with fox (*Vulpes vulpes*) and