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PERSPECTIVES AND PARADIGMS

The unaddressed threat of invasive animals in U.S. National Parks

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Abstract Invasive species, both plants and animals, are a long-standing threat to the National Parks of the United States. For nearly two decades the National Park Service has implemented a service-wide invasive plant management program without a commensurate program focusing on invasive animals. While individual park units are struggling to sufficiently address the threat of invasive terrestrial and aquatic animal species, a system-wide effort could bring the resources and capacity needed to address a challenge of this magnitude. We present our key findings from a detailed review about invasive animal species and their management by the National Park Service. We assert that the global threat of invasive animals substantially undermines the National Park Service mission. Coordinated action could improve the ability for the National Park Service to meet the challenge, and partnering with neighboring agencies and invasive species networks outside of the National Park Service is essential for success. Public engagement, cooperation and support is also critical and can be accomplished through strategic engagement efforts. Finally, the National Park Service would benefit from the development of an invasive animal program that includes structured decision support, adaptive man-

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agement and monitoring, the organizational structure to meet the highest needs, and capitalizing on the significant opportunities that exist through the appropriate use of emerging technologies.

Keywords Invasive species · Public lands · Protected areas · Land management · Introductions

Introduction

The National Parks of the United States of America (U.S.) are national and global treasures. They conserve natural and cultural resources and American values that are an irreplaceable part of the national fabric, and hence are managed to preserve these resources unimpaired for the enjoyment of this and future generations. This mission is under a deep and immediate threat as a consequence of invasive animal species (Dorcas et al. 2012; Lawrence et al. 2012; Ma et al. 2007). Over half of all U.S. National Parks report the presence of invasive animal species (Resnick 2018). The species plaguing the parks include the most costly invasive animals in the U.S. (Pimentel et al. 2005), such as rats (*Rattus* spp.) and cats (*Felis catus*). Additionally, feral hogs (*Sus scrofa*) (Aplet et al. 1991), Burmese pythons (*Python bivittatus*) (Dorcas et al. 2012), red lionfish (*Pterois volitans*) (Whitfield et al. 2002) and a host of freshwater aquatic invertebrates, such as quagga mussel (*Dreissena bugensis*) (Hickey 2010), have been documented to directly undermine the potential ofU.S. National Parks to deliver on their mission to preserve unimpaired systems. Although the U.S. National Park Service (NPS) has taken service-wide action to address invasive plant species since 2000 (NPS 2016) through the Exotic Plant Management Team (Resnick 2018), animal species have not received the same service-wide programmatic attention.

Despite recognition for nearly 100 years that invasive animals are a threat to parks (Simberloff 2017), the NPS lacks both a comprehensive understanding of the costs and impacts of invasive animals and integrated coordinated strategies for managing the system-wide threat that they pose. Yet, there are successful examples where individual parks are managing invasive species challenges (Hughes et al. 2014), as well as opportunities for the NPS to take a lead in addressing regional threats (Brown et al. 2016). Successfully maintaining the nationally and globally significant values of the National Park System would benefit from a coordinated and innovative service-wide strategy to manage invasive animal species that is fully integrated with park-specific management plans and stewardship strategies.

As part of a 3-year project "NPS Strategic Invasive Animals Management" initiated in 2016, our team was tasked with interpreting a recent draft report documenting the pervasiveness of invasive animals in parks (Resnick 2018) and assessing what the NPS might do to respond to invasive animals as a broad ecosystem stressor. We framed our task, then met on several occasions, by teleconference and in person, to derive a set of conclusions based on documented evidence of invasive species in the U.S. National Parks and our collective professional experience with invasive animals.

Based on our review, we believe the threat of invasive animal species is of sufficient magnitude and urgency that it would be appropriate for the NPS to formally declare invasive animals as a service-wide priority. Invasive animals, from pythons and other invasive herpetofauna in the Everglades to emerging diseases in wildlife, represent a parks crisis on par with prior crises that have resulted in transformative management in the NPS. In particular, three previous crises have represented touchstones that rallied the NPS into bureau-transforming action. First, an overabundance of ungulates due to aggressive NPS predator control led to the *Leopold Report* in the 1960s (NPSAB 2012), which re-framed how the NPS fulfilled its mission to protect unimpaired systems. Second, the 1988 Yellowstone fire crisis led to a new age of wildfire awareness and treatment nationwide; including the embrace of natural wildfire in parks. Third, recent recognition of the importance of climate

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change led to a report revisiting the 1960s Leopold report to create a vision for park stewardship under climate change (NPSAB 2012).

Engagement by NPS leadership to create a system-wide approach to address the challenge of managing invasive animals can magnify existing individual cases of success into a program of much broader scale success. The integrity of U.S. National Parks depends on it. To support this assertion, we present from our review six key findings (Fig. 1) about invasive animal species and their management by the NPS, along with associated evidence:

1. The ubiquitous presence of invasive animals in parks undermines the NPS mission.
2. Coordinated action is required to meet the challenge.
3. Partnering is essential for success.
4. Public engagement, cooperation and support is critical.
5. Decision support across all levels is strategic.
6. NPS would benefit from applying emerging technologies.

Our focus, throughout, remains on the park system as a whole with the goal of improving efficient delivery of solutions to park units; we do not discuss strategies for specific park units.

The ubiquitous presence of invasive animals in parks undermines the NPS mission

The NPS manages 419 national park units, located in each of the 50 states and many U.S. territories. Encompassing over 84 million acres, all units follow a mission "to preserve unimpaired the natural and cultural resources and values of the National Park System for the enjoyment, education, and inspiration of this and future generations." From American Samoa to Guam, the northernmost reaches of Alaska, the southwestern deserts, and the Virgin Islands, National Parks protect some of the nation's most important ecosystems, native iconic plant and animal species, cultural resources, and the stories and values that define America. A diversity of invasive animal species in numerous parks are already significantly diminishing the value of parks to park visitors (Resnick 2018) by constraining recreational activities. For example, invasive lake trout (*Salvelinus namaycush*) in Yellowstone National Park have concerned visitors largely due to the indirect impact their presence could have on birds and grizzly bears and associated wildlife viewing opportunities (Cherry and Shogren 2001). Species such as domestic cats (*Felis catus*) have significant potential to cause a loss of park wildlife and, in turn, the value that visitors derive from wildlife

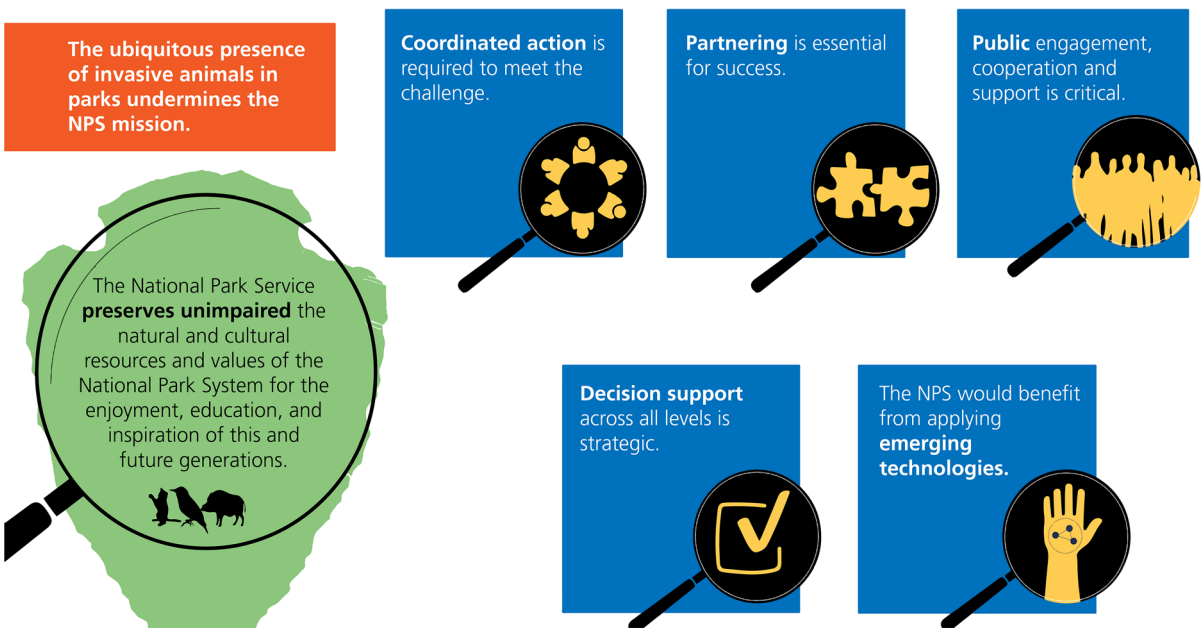

Fig. 1 Six key findings about the National Park Service's (NPS) management of invasive animal species

viewing. Aquatic invasive species such as quagga mussels (*Dreissena bugensis*) have presented a unique challenge for parks such as Lake Mead National Recreation Area, as they attempt to manage the problem while still fulfilling the park's mission of protecting nature and providing recreation (Hickey 2010).

Beyond the impacts of invasive animals themselves, there are a plethora of issues that are associated with invasive animals carrying novel zoonotic diseases that spread to native species. Well-recognized examples include toxoplasmosis [caused by *Toxoplasma gondii* spread by domestic cats (Aguirre et al. 2019)], tickborne diseases (ISAC 2019), white-nose syndrome in bats (Frick et al. 2010), chytridiomycosis in amphibians (Kilpatrick et al. 2010), and West Nile Virus in birds (LaDeau et al. 2007). These diseases present serious risks to the fauna and ecosystems of National Parks that often exceed the impact of their hosts that are introduced.

Invasive animals are not simply a problem for parks within the U.S. Invasive animals are a global issue, impacting nearly all aquatic and terrestrial ecosystems and reducing the natural value of those ecosystems on both protected areas and working landscapes and seascapes. Recent estimates indicate that invasive species negatively affect almost 2300 threatened or near-threatened sensitive species worldwide (26.5% of all species that have been adequately assessed), and have contributed to the extinction of many others (Maxwell et al. 2016). As an example, it is estimated that free-ranging domestic cats kill over a billion birds per year in the U.S. alone (Loss et al. 2013). Estimates of the economic costs of invasive animals vary, but are substantial (Pimentel et al. 2005). In U.S. National Parks alone, millions of dollars are spent each year controlling invasive animal species. Although data are only available from 2008 through 2012, expenditures on invasive animal control in parks nearly doubled over that 5-year period, from $5 million in 2008 to $9.6 million in 2012 (Resnick 2018). Notably, this figure is for expenditures only, not costs of damages.

These widespread problems are adversely impacting U.S. National Parks. Of the 1409 reported populations of 311 invasive animal species in U.S. National Parks, 23% have management plans at the park unit level, and only 11% are reported as being "under control" (Resnick 2018; Table 1). Uncontrolled invasive species are often demonstrably obstructing National Parks from fulfilling their mission (e.g., Burmese python in the Everglades: Dorcas et al. 2012), and the threat caused by invasive animals has long been acknowledged by the NPS (Dennis 1980; Shafer 2012).

Coordinated action is required to meet the challenge

Given the wide-ranging impacts caused by invasive animals, the NPS could consider developing a service-wide organizational approach for their management. Some highly effective park-specific actions are notable highlights within the system (Campbell and Donlan 2005; Krajick 2005; Witmer et al. 2007), but overall there is no strategic, coordinated service-wide program to control invasive animal threats. Parks are at risk from invasive animal threats that are under-prioritized and under-funded (Resnick 2018). Addressing this challenge must begin at the highest levels within the NPS, engage all levels of management, and will require investments from the NPS leadership. Resnik (2018) presents constraints to achieving NPS-wide effective action on invasive animals including (1) lack of focused leadership and NPS-wide coordination; (2) lack of capacity; and (3) lack of resources. In this section we address how these three items could be addressed, at least in part, through coordinated action. The findings below additionally contribute further to building capacity and resources through partnering.

The lack of service-wide initiatives limits both the support of individual parks' efforts and coordination among parks facing similar problems. Park staff report that it is a struggle to communicate the importance of invasive animal control efforts to their park leadership (Resnick 2018). Lacking national prioritization, park units may not prioritize invasive species management because other challenges are more pressing or because they want to avoid the bureaucratic obstacles to meeting compliance requirements for management efforts (Resnick 2018). A further challenge is that staff capacity in most parks is not adequate for invasive animal species management. This assertion is evidenced both by the lack of planning and management documents that try and control harmful invasive animals (Resnick 2018) as well as the stated backlog of infrastructure that overwhelms existing budgets

Table 1 Summary findings of the impact of invasive species on National Parks as reported from a survey of parks with 326 of 404 (81%) queried parks reporting. (Resnick 2018)

A. Invasive animal populations are a common problem
1409 populations
331 species
B. Invasive animal species within parks are taxonomically diverse
Vertebrates: amphibian (8), bird (36), fish (103), mammal (37), reptile (17)
Invertebrates (130)
C. Impacts reported in all major biomes
Terrestrial: forests, grasslands, shrublands, and deserts
Freshwater: lakes, rivers, wetlands
Marine: reefs, estuaries
D. Management and successful control is lacking
23% of invasive animal species populations in parks have NPS management plan
11% of invasive animal species populations are under control

(NPS 2018). Many parks have no specific natural resource staff, or anyone knowledgeable and well-trained on invasive animal management or compliance measures associated with lethal treatment of animals (Resnick 2018). In any management decision, parks must balance many competing demands for their limited staff and funding resources. This issue is likely to be even more acute for invasive animal species because there are often substantial time lags between when an invasive species establishes itself and when its effects are felt, making management action more difficult (USDOI 2016). Prevention, early detection and immediate eradication are preferred strategies for effective management (Leung et al. 2002; Lodge et al. 2006). Yet, it is possible that park staff are often overloaded and react to issues that are most urgent at the moment. At that time that invasive animals become widespread and unavoidable though, it is extremely challenging and costly to address them. Under budget constraints that often demand attention to immediate threats, the absence of an effort to incentivize proactive park unit attention to chronic and emerging problems of invasive species means the problems will continue unabated.

The National Invasive Species Council [NISC (https://www.doi.gov/invasivespecies/aboutnisc); NISC 2018] and its subsidiary, the Invasive Species Advisory Committee [ISAC (https://www.doi.gov/invasivespecies/about-isac)], are housed within the Department of Interior and provide high level strategic planning and advise on inter-agency challenges with invasive species [e.g., NISC 2016–2018 Management Plan (NISC 2016)]. These bodies provide over-arching guidance federal priorities with respect to invasive species as well as topic-specific reports on pressing issues (e.g., ISAC 2019). Because the role of these bodies is strictly advisory, they lack the authority to compel agencies to action and to allocate the resources to implement recommended actions. The NPS, however, might make better use of these coordinating bodies to specifically address and implement recommendations and best practices regarding the issue of invasive animals on federal lands.

Achieving a potential future state where invasive animals are given a system-wide priority that befits the threat that they pose requires systematic efforts to increase operational efficiencies and on-the-ground effectiveness of natural resource management programs, including those for invasive animals. These steps may include establishing a coordination mechanism that enables ongoing and timely information sharing among park units. For example, creating a system-wide capacity to engage in strategic horizon scanning for potential new invaders and then dissemination of that information to potentially impacted parks would help increase the timeliness and effectiveness of monitoring and rapid response once the invasive animals actually invade the park (Ricciardi et al. 2017). An increase in NPS capacity for forecasting threats and alerting parks could contribute significantly to effective prevention and early detection and rapid response programs, if paired with

increased capacity to address the invasion.

Providing national coordination of invasive animal management,[1] paralleling the current program for plants (NPS 2016), allows mainstreaming the invasive species issue across the NPS branches from interpretation to resource management to human and financial resources. Creating a cross-cutting invasive species initiative among the Biological Resources Division, Water Resources Division, Inventory and Monitoring Division, Climate Change Response Program, and the regional offices would further facilitate national coordination and better information exchange. This service-wide initiative could also tackle insufficient monitoring of invasive animals. The existing NPS Inventory and Monitoring efforts focus on long-term monitoring and were not designed for detection and recognition of potentially harmful invading animals. While the NPS Inventory and Monitoring has some targeted monitoring protocols designed to yield data on occurrence and distribution of invasive species, detection of invasive species during monitoring relies primarily on detection during other biological monitoring protocols, where detection of invasive species is ancillary data. The national level of the NPS could also (1) lead development of partnerships with other federal, state, and local agencies' national-level programs that share similar management concerns and (2) create public–private partnerships for invasive species management (see finding 3) and technology innovation (see finding 6). Further, a goal of national coordination could be to build service-wide capacity and support individual parks in (1) effectively engaging the public on invasive species issues (see finding 4), (2) adopting socially engaged decision support (see finding 5), and (3) appropriately applying emerging technologies (see finding 6).

Partnering is essential for success

Globalization in trade, transport, and travel is the major factor driving the increase in invasive species (Hulme 2009). While in the past what became invasive species were sometimes introduced directly in parks by managers (e.g., sportfish; Simberloff 2017), since 1968 introductions of non-native species have been banned completely by NPS policy (Drees 2004). Even as early as 1933, introductions of non-native species were banned "except for the occasional stocking of an otherwise barren body of water with some species of game fish…" (Dennis 1980, citing Albright 1933). Now, invasions do not usually begin in parks, but instead invasive species become resident in parks through spread from outside the park. As a result, the NPS must work with resource managers beyond park boundaries to detect and manage species before they arrive in parks (Brown et al. 2016). NPS policy provides authority for spending funds for such cooperative work to prevent, control, or eradicate invasive exotic species adjacent to a park unit.

Effective communication and coordination with neighbors is critically important for prevention, detection and control (Epanchin-Niell et al. 2010). Many of the invasive species reported by the greatest number of park units are broadly distributed in the U.S., including emerald ash borer (*Agrilus planipennis*), gypsy moth (*Lymantria dispar*), feral hog, hemlock woolly adelgid (*Adelges tsugae*), Asian longhorned beetle (*Anoplophora glabripennis)*, and quagga mussel (*Dreissena bugensis*) (Resnick 2018). These regionally invasive species are problems outside of parks as well as inside parks. Neighboring resource managers may have shared priorities; yet, if NPS is not collaborating with neighbors, then continuing within-park treatment will likely be necessary as invasive animals re-spread into parks. Some parks have developed robust inter-agency, transboundary partnerships that have been effective at leveraging resources and addressing resource management challenges (Krysko et al. 2016; Hallac et al. 2014). Parks can find great value, and ultimately increased effectiveness at a lower cost, by engaging collaboratively and broadly in invasive species problems. In many cases this need for collaboration is learned after parks initially launch into programs in isolation and struggle to achieve success until they partner (Hallac et al. 2014). Cooperative Invasive Species Management Areas or Cooperative Weed Management Areas are partnerships that can include governmental agencies, tribes, and private parties with a goal to invest in long-term cooperation to address weed management within a geographically defined boundary (North American Invasive Species Network 2018). Examples such as the Florida Everglades Cooperative Invasive Species Management Area (EvergladesRestoration.gov, n.d.),

[1] Since sharing our findings with NPS, they have now created an invasive animal initiative and hired a coordinator.

where they enabled the effective control of the invasive sacred ibis (*Threskiornis aethiopicusserve*), serve as models for effective park engagement in regional invasive animal challenges.

Partnering can be a challenge because different stakeholder groups and communities bring both different values and knowledge to the table. While individual parks may invest the time and cost required to build robust, systematic programs of stakeholder engagement on the issue of invasive animals, there can also be great value in adopting a system-wide approach to this collaborative decision making and garnering of evidence. Organizations and partnerships such as the National Invasive Species Council (described in finding 2 above), invasive species partnerships (e.g., Florida Invasive Species Partnership, www.floridainvasives.org; IUCN Invasive Species Specialist Group, https://www.iucn.org/theme/species/our-work/invasive-species), councils (e.g., Illinois Invasive Species Council, www.dnr.illinois.gov/programs/Pages/InvasiveSpeciesCouncil.aspx), and public policy organizations (e.g., Public Policy Institute of California, www.ppic.org; Association for Fish and Wildlife Agencies, www.fishwildlife.org) exist to foster such collaboration. Some of these partnerships the NPS is already part of and could consider how to strategically leverage benefits at the service-wide and park unit-level. In some cases, the networks addressing invasive species in a region have a broader mission than invasive species (e.g., Great Lakes Commission, www.glc.org), and there may be need for regional coordination with the NPS. Other organizations seek to be information repositories for strategies. Managing information on invasive animals, for example, would be greatly improved by building knowledge management systems about potential impacts and management options, possibly utilizing existing databases (e.g., Global Invasive Species Database). Alternatively, Collaboration for Environmental Evidence (www/environmentalevidence.com) and Conservation Evidence (www.conservationevidence.com) specifically seek to identify what does and does not work in conservation based on empirical evidence. All of these organizations are potential partners in the quest to acquire and share state of the art knowledge on invasive species management.

Public engagement, cooperation and support is critical

The public's perceptions of invasive species are complex and dependent on a variety of factors [e.g., characteristics and experiences of the individual person, the species and its effects, socio-cultural context (Shackleton et al. b)]. Similarly, invasive species impacts on human livelihoods can be highly variable, both positive (e.g., firewood, food products) and negative (e.g., reducing agricultural production or land access) (Shackleton et al. 2019a). Our understanding of both components of the human dimensions of invasive species and their management is limited by a field of social science research still in its infancy (Kapitza et al. 2019). These factors pose challenges to invasive animal control because nearly every program of prevention, eradication, and containment can only be effective with public support. Conflict over whether and how a species should be managed can become highly contested and political (Crowley et al. 2017). For example, an attempt to control lake trout (*Salvelinus namaycush*) in Yellowstone Lake was met with resistance from fishing advocacy groups. When the focus shifted from invasive species removal to ecosystem recovery, public support for the program grew (Hallac et al. 2014; Wilcox 2014; Johnson 2011). The NPS has a strong and highly regarded public outreach and interpretation program (Rasmussen Report 2016), which could be strengthened to the benefit of parks management through consistent messaging, such as in the lake trout example, and system-wide facilitation of programs that educate the public about stressors and threats to parks management. These programs will be most effective if based on a solid understanding of human perceptions towards invasive species (Shackleton et al. 2019b). Yet, an institutional challenge remains to building the capacity for interpretive programs to engage in a partnering role with resource management; such a partnership could focus on raising awareness of the resource values achieved in successfully deploying invasive species programs.

To address issues of public support for invasive species management, parks can develop a strategic communications and engagement strategy to proactively: (1) identify the current and potential stakeholders (i.e., persons who may affect or may be affected by management decisions); (2) employ social

science methods (e.g., focus groups, surveys, social feasibility assessments) or stakeholder engagement methods (e.g., public meetings, solicitation of comments) to better understand stakeholders and whether an invasive species management project would be accepted; and (3) involve stakeholders (e.g., task forces, large group decision-making processes, negotiated agreements) throughout the entire process to build relationships and trust and find more effective solutions. Some of the predominant NPS invasive animal problems (e.g., feral horses, feral cats, feral hogs) have advocacy groups, and this approach can guide careful coordinated engagement with these groups. Employing participatory approaches is perceived to be democratic, and thus, more appropriate for federal agencies managing in the interests of people. Further, projects that result from such engagement approaches are more likely to garner and maintain social support (Crowley et al. 2017).

Simply improving public education may not be sufficient when changes in visitor behavior are required to address invasive animal species challenges. Extensive research has shown that human action is driven by multiple factors involving values, attitudes, skills, and norms (Heberlein 2012). The consequence is that filling a knowledge gap through education often does not translate into action (Heberlein 2012). Social marketing and behavior change strategies (Mckenzie-Mohr and Schultz 2014) may work well when the goal is fostering pro-conservation behaviors. Parks can also join in efforts that that encourage people to prevent releases of invasive species into the wild. For example, Everglades National Park has been part of the "Don't let it loose! Be a responsible pet owner" bumper sticker campaigns (Armour 2006) to address intentional introductions. Other campaigns and educational resources are available from the Invasive Species Action Network, including those focused on unintentional introductions (e.g., "Clean, Drain, Dry"). Coordinated support can foster a culture of broad engagement, rather than a piecemeal suite of individual parks engaging in a narrow suite of problems.

Parks could also better engage stakeholders and the public at large through the implementation of "citizen science" or "community science" programs. Deploying community scientists can help a park address invasive issues through volunteer work as well as increasing public buy-in of invasive species management through hands-on learning. Partnering with national programs for citizen science, such as eBird (an extensive online database for bird observations) or iNaturalist (a program frequently used for BioBlitz events; Lundmark 2003) has been useful for some park units. These examples are bright spots of innovative action within the NPS; yet, a service-wide invasive animals program could further foster and grow this kind of innovation. Further, volunteer programs require financial resources and staff capacity to coordinate them, both of which are currently lacking (Resnick 2018).

Decision support across all levels is strategic

Natural resource management, generally, is in the midst of significant change involving the adoption of formal decision support tactics to better engage partners and stakeholders, increase decision transparency, and increase efficient use of limited resources (Schwartz et al. 2018). The key attribute of decision support is that it asks the decision-makers to consider the full spectrum of resource objectives, threats to those objectives, and all of the potential actions that could be used to meet those objectives, to provide logical support for a suite of actions taken (Groves and Game 2015). In contrast, the NPS has largely addressed major national challenges (e.g., the distribution of invasive species in parks) and created problem-specific programs (e.g., Inventory & Monitoring, Exotic Plant Management Team, Natural Conditions Assessments and Vulnerability Assessments through the climate change program). In fact, we make the recommendation to create such national coordination for invasive animals (finding 2). While recognizing that creating programs is an effective way to dedicate resources to specific threats, it also creates challenges for making sound decisions that balance potentially competing objectives (e.g., aging infrastructure versus managing wildland fuels). An alternative approach is to reduce investment in these issue-specific bodies in favor of increasing investment in cross-issue decision making. We acknowledge that this alternative approach would require institutional change in NPS far beyond invasive animals and may be more of a long-term goal.

The emerging field of decision support for natural resources management borrows from the disciplines of

resource economics, decision science, geospatial analysis and project planning to create a set of frameworks and tools for decision support (Schwartz et al. 2018). This decision support emphasizes the establishment of clear objectives that balance competing objectives. Invasive species management decisions exemplify the complex challenge of deploying limited resources among challenges that overwhelm those resources. Recently developed decision support frameworks can help increase accountability, define performance measures to evaluate outcomes, and build social support as the NPS makes difficult decisions.

Given that restoring native ecosystem functions and services that have been degraded by invasive animals is often expensive and may include actions that are socially unpopular (e.g., lethal control of non-native vertebrates), adopting structured decision support frameworks, especially if stakeholders are engaged in their design, is also likely to considerably increase effectiveness. The NPS has the capacity and opportunity to systematically adopt socially engaged decision support that may allow the bureau to tackle difficult management issues with public support. A persistent challenge is to place management support and action at the appropriate scale for effective action. The NPS must find the opportunity to elevate invasive animal management to its appropriate level of importance while also developing approaches that foster structured decision support that integrates across all (e.g., ecological, hydrological, historical, and infrastructural) resource management challenges. Maintaining and improving the state of natural ecosystems is dependent upon addressing interacting stressors (e.g., invasive species, fire) and management levers (e.g., invasive species eradication/suppression, prescribed fire). Although it is logical to deploy resources controlling invasive species assessed to degrade ecosystems, improving ecosystem health and resilience is often a more complex problem than simply eradication. Other changes in the ecosystem may, or may not, result in intended outcomes. As a specific example, the invasive plant pest teams eradicate weeds, but are not responsible for follow-up monitoring or restoration work. Park managers are left with burden of follow-up, and they may or may not be able to prioritize it. Treatment without follow-up restoration and assessment is likely to lead to inefficient expenditures and unknown outcomes. The result is a need to simultaneously address multiple pressing issues facing parks to foster integrated resource management that focuses on enhancing the fundamental values provided by ecosystems, rather than on targets for invasive animal removal.

NPS would benefit from developing and appropriately applying emerging technologies

Emerging technologies at varying stages of development may prove to be useful for managing invasive species that are impacting National Parks. There is a significant opportunity for the NPS to become a leader in developing and testing innovations to detect and prevent (e.g., eDNA for surveillance of quagga and zebra mussels, in tandem with boat inspections), eradicate (e.g., biocontrol by a mass-produced plant pathogen) and control invasive animals (e.g., gene drives to control spread of vector-borne disease). Technology innovation can increase the efficacy of traditional methods for invasive species prevention, eradication, and control, as well as develop new approaches that enable more cost-efficient and effective outcomes. The NPS can foster technology innovation by engaging in partnerships with NGOs, universities, other government agencies, and for-profit entities to develop, test, and implement technologies. Additionally, the NPS can provide case studies and articulate challenges for improving invasive animal management in U.S. National Parks, neighboring lands and waters. A collaborative approach of co-production between NPS staff and outside researchers can also help create a culture of support for innovation and testing.

One of the most difficult, but often the most cost effective, means of managing invasive species is prevention. Methods including eDNA and metabarcoding can detect and alert managers to the presence of new invaders where they might not yet be detectable with standard methods (Brown et al. 2016). For example, Yellowstone National Park has used eDNA for detection of aquatic invasive species since about 2014. Improving methods for early detection will increasingly lead to earlier and thus more effective rapid responses to new invaders.

Tools and technologies for cost-effective management are constantly changing. Learning about effective management methods can be challenging, since

actors engaged in efforts face resource limits for both learning and sharing information (Bekkers et al. 2013). These emerging tools include new genetic methods (e.g., CRISPR) which allow creation and insertion of genes that would disable invaders (Johnson et al. 2016; Gurr and You 2016). Such tools could potentially be used with gene drive manipulation that allows the rapid movement of these useful genes throughout invading populations of, for example, rodents and mosquitoes where they are invasive (Piaggio et al. 2017). Consideration of genetic tools such as these should follow recommended approaches as developed by the US National Academy of Sciences (NASEM 2016) and more recently the International Union for the Conservation of Nature (Redford et al. 2019). To date, as indicated by publications in *Park Science*, the NPS's engagement with invasion genetics and evolution has lagged behind their attention to ecosystem impacts (Simberloff 2017). A national effort by NPS could incentivize knowledge sharing and reduce barriers to technology transfer, building the capacity of parks through learning from each other.

Conclusion

National Parks have long been cherished as natural representations of valued ecosystems. The mandate of the NPS has been to steward natural ecosystems, favoring the use of natural processes, to remain unimpaired, with unimpaired being viewed through an historical lens. Multiple case studies suggest that the publicly valued resources of our National Parks are under a deep and immediate threat from invasive animals. NPS has, itself, documented a diversity of invasive animals impacting parks across the NPS system that represent serious threats to the maintenance of unimpaired park ecosystems. While some parks have responded in effective ways that should draw the attention of other parks, the threat posed by invasive animals cannot only be addressed on a park-by-park basis. Managing invasive animals requires system-wide change, coordinated management with adjacent landowners, and a willingness to embrace new ideas and technologies for resource management. Some of these new technologies are likely to test the NPS, as well as its constituents, with regard to risks that parks will bear to fight impairment by invasive animals. Engaging the public in discussions about these technologies and management of invasive animal species generally will be essential to garner social support.

Coordination of management approaches starting at the highest levels of NPS and involving all parts of the organization offers the best opportunity for success in addressing the problem of invasive animals. Management that crosses park boundaries to operate at the landscape scale can contribute to ensuring the ecological integrity of parks into the future. Active resource stewardship is already recognized as a duty of park management. Our six findings offer the NPS a roadmap to work across boundaries, across disciplines, and apply decision-making tools to work with the American public to manage invasive animals and ensure the persistence of the treasured values of our National Parks.

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Compliance with ethical standards

Conflicts of interest Three of the co-authors (DH, EL, and LR) are employed by the National Park Service. The lead author and other co-authors received travel funding from the National Park Service to attend a worksession that informed this manuscript. One of the co-authors (KR) was also funded to coordinate this project.

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