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Case Study

SMaRT: a science-based tiered framework for common ravens

Seth J. Dettenmaier, U.S. Geological Survey, Western Ecological Research Center, Dixon Field Station, 800 Business Park Drive, Suite D, Dixon, CA 95620, USA
Peter S. Coates, U.S. Geological Survey, Western Ecological Research Center, Dixon Field Station, 800 Business Park Drive, Suite D, Dixon, CA 95620, USA *pcoates@usgs.gov*
Cali L. Roth, U.S. Geological Survey, Western Ecological Research Center, Dixon Field Station, 800 Business Park Drive, Suite D, Dixon, CA 95620, USA
Sarah C. Webster, U.S. Geological Survey, Western Ecological Research Center, Dixon Field Station, 800 Business Park Drive, Suite D, Dixon, CA 95620, USA
Shawn T. O'Neil, U.S. Geological Survey, Western Ecological Research Center, Dixon Field Station, 800 Business Park Drive, Suite D, Dixon, CA 95620, USA
Kerry L. Holcomb, U.S. Fish and Wildlife Service, Palm Spring Fish and Wildlife Office, 777 East Tahquitz Canyon Way, Suite 208, Palm Springs, CA 92262, USA
John C. Tull, U.S. Fish and Wildlife Service, Science Applications, 1340 Financial Boulevard, Reno, NV 89502, USA
Pat J. Jackson, Nevada Department of Wildlife, Reno, NV 89511, USA

Abstract: Large-scale increases and expansion of common raven (*Corvus corax*; raven) populations are occurring across much of North America, leading to increased negative consequences for livestock and agriculture, human health and safety, and sensitive species conservation. We describe a science-based adaptive management framework that incorporates recent quantitative analyses and mapping products for addressing areas with elevated raven numbers and minimizing potential adverse impacts to sensitive species, agricultural damage, and human safety. The framework comprises 5 steps: (1) desktop analysis; (2) field assessments; (3) comparison of raven density estimates to an ecological threshold (in terms of either density or density plus distance to nearest active or previous nest); (4) prescribing management options using a 3-tiered process (i.e., habitat improvements, subsidy reductions, and direct actions using StallPOPd.V4 software); and (5) post-management monitoring. The framework is integrated within the Science-based Management of Ravens Tool (SMaRT), a web-based application outfitted with a user-friendly interface that guides managers through each step to develop a fully customized adaptive plan for raven management. In the SMaRT interface, users can: (1) interact with pre-loaded maps of raven occurrence and density and define their own areas of interest within the Great Basin to delineate proposed survey or treatment sites; (2) enter site-level density estimates from distance sampling methods or perform estimation of raven densities using the rapid assessment protocol that we provide; (3) compare site-level density estimates to an identified ecological threshold; and (4) produce a list of potential management options for their consideration. The SMaRT supports decision-making by operationalizing scientific products for raven management and facilitates realization of diverse management goals including sensitive species conservation, protection of livestock and agriculture, safeguarding human health, and addressing raven overabundance and expansion. We illustrate the use of the framework through SMaRT using an example of greater sage-grouse (*Centrocercus urophasianus*) conservation efforts within the Great Basin, USA.

Key words: adaptive management**,** anthropogenic subsidies, *Centrocercus urophasianus,* common raven, *Corvus corax*, decision support tools, greater sage-grouse, science-based management, tiered management

In the past several decades, adaptive management has become a popular tool to better achieve management goals within complex systems (Holling 1978, Walters 1986, Williams and Brown 2014). Adaptive management, which combines repeated structured decision-making with continued learning to improve management outcomes over time (Holling 1978, Walters 1986), is a useful tool in managing complex, dynamic systems such as socialecological systems (Walters 1997, McCarthy and Possingham 2007, Fontaine 2011, Williams 2011*a*). By incorporating concepts from multiple fields (decision theory, systems theory, experimental science; Williams 2011*a*), adaptive management frameworks allow managers to make proactive decisions in the face of uncertainty to reach predetermined management goals (Walters and Holling 1990, Margoluis et al. 2009, Williams 2011*a*). While there are several adaptive management frameworks applied to natural resource management (e.g., active vs. passive; McCarthy and Possingham 2007), all frameworks are characterized by repeated decision-making over time to incorporate new information gained from monitoring (Walters 1997, Gregory et al. 2006, Williams 2011*b*).

The management of common raven (*Corvus corax*; raven) populations is one such complex system that has become a primary goal of managers in the western United States (Boarman 2003, Peebles et al. 2017, Shields et al. 2019). Large-scale increases in raven populations are occurring across much of western North America (Sauer et al. 2017, Harju et al. 2021), driven primarily by increases in availability of anthropogenic resource subsidies (Restani et al. 2001, Kristan and Boarman 2007, O'Neil et al. 2018). Throughout much of their distribution, increases in raven populations have adversely affected multiple sensitive species (Boarman 2003, Coates et al. 2020). In particular, lower trophic level nesting species may be especially vulnerable to effects of spillover- (Kristan and Boarman 2003, Oro et al. 2013) and hyper-predation (Smith and Quin 1996) because ravens are opportunistic foragers that prey-switch with ease (Boarman and Heinrich 1999). Current strategies for raven management have primarily focused on the lethal removal of individuals or eggs (Brussee and Coates 2018, Shields et al. 2019, O'Neil et al. 2021). However, such strategies have not prevented the growth of raven populations (Harju et al. 2021). Indeed, the generalist nature and behavioral plasticity of ravens make an adaptive management framework particularly well suited to the management of their populations because it emphasizes appropriate management options in response to environmental conditions and raven population parameters that change through time.

Managers can translate an adaptive management framework for ravens from conceptual to actionable by implementing science-based, tractable decision support tools that "operationalize," or quantify with measurable outcomes, well-studied ecological concepts to inform management plans (Ricca and Coates 2020). Advances in species distribution modeling promote the generation of spatially explicit, predictive surfaces (Guisan et al. 2013, Ricca and Coates 2020), such as the surfaces of raven occurrence and density developed by O'Neil et al. (2018) and Coates et al. (2020), respectively. These surfaces can be used to guide targeted management options by identifying high raven density areas. They can be further operationalized by overlapping with sensitive species distributions to identify areas of potential highest ecological impact (Coates et al. 2016, Doherty et al. 2016, O'Neil et al. 2018, Coates et al. 2020). Additionally, when species distributions are parameterized with metrics that link them to spatially explicit outcomes of disturbance and management actions, they can be used to predict the ecological or economical effectiveness of management outcomes following simulated actions (Ricca et al. 2018, Ricca and Coates 2020). Science-based tools support the iterative nature of adaptive management by operationalizing the accumulated knowledge of the system being managed. Repeatedly revisiting management decisions to consider alternative actions/outcomes based on continuous monitoring allows managers to assess progress toward meeting stakeholder goals, the state of different parts within a system, overall system function or resiliency, and target management resources to where they would be most effective (Argent 2009, Fontaine 2011, McFadden et al. 2011). Post-monitoring results can be used to update and reassess the potential outcomes of alternative management decisions and actions (Walters 1997, Johnson et al. 2002, Williams 2011*a*) to achieve repeatable outcomes.

Here, we develop and illustrate a science-based adaptive management framework and decision support tool that applies published empirical information to allow managers to reach multiple conservation goals concerning the management of overabundant raven populations. Our framework comprises 5 major steps: (1) desktop analysis; (2) site-level assessments of raven densities; (3) comparison of site-level raven density estimates to an ecological threshold;

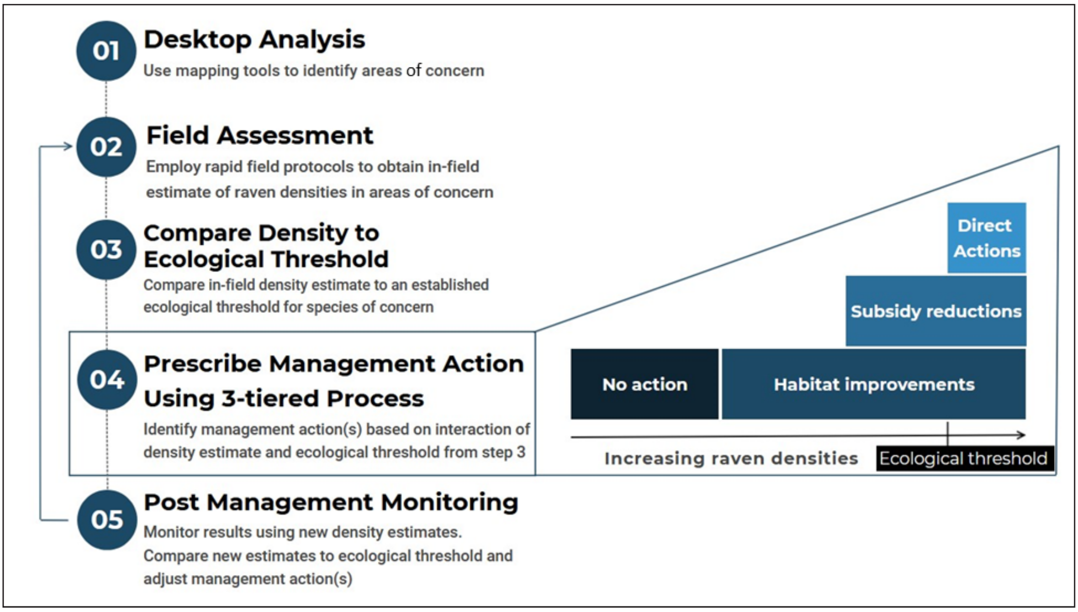


Figure 1. Diagram highlighting the 5-step, 3-tiered decision framework for the adaptive management of common ravens (*Corvus corax*) for sensitive species conservation.

(4) engagement of management options using a 3-tiered process; and (5) post-management monitoring (Figure 1). The framework is adaptive because these steps iterate with the post-management monitoring data that feed back into the learning process and provide a data-driven evaluation of management efforts. We also describe the 3 tiers of management options (i.e., habitat improvements, subsidy reductions, and direct actions using StallPOPd.V4 software) that are engaged based on the management objectives or the results of step 3 (comparison of site-level raven density estimates to an ecological threshold) and provide examples of management options that fit within each tier. To further illustrate how managers might implement the framework, we present a case study whereby it is applied to inform management of raven populations for the conservation of greater sage-grouse (*Centrocercus urophasianus*; sage-grouse). While our case study example focuses on the management of ravens for the conservation of sage-grouse, resource managers may also deem management warranted where conflicts with other sensitive species (Boarman 1993, 2003), livestock and agriculture (Larsen and Dietrich 1970), or human health and safety exist (Peebles and Spencer 2020).

Our objectives were to operationalize an adaptive management framework through the Science-based Management of Ravens Tool (SMaRT; https://usgs-werc-shinytools.shinyapps.io/SMaRT/), a web-based R Shiny (Chang et al. 2021) application, to assist managers in designing and comparing adaptive raven management strategies. The SMaRT is fully customizable, as the tool depends on user inputs such as site-specific field assessments and management goals to parameterize the framework and develop the management plan. The SMaRT is also flexible, allowing users to leverage existing science-based spatial layers or develop their own spatial layers. Within the SMaRT interface, users can populate steps of the framework with data, including (1) design proposed survey or treatment sites by interacting with and overlaying pre-loaded maps of raven occurrence and density (Coates et al. 2020) to delineate polygons representing areas of greatest impact on target species (Coates et al. 2016, Doherty et al. 2016, O'Neil et al. 2018, Coates et al. 2020) within the Great Basin, as well as import their own spatial layers of interest or directly import pre-defined GIS data representing survey or treatment sites; (2) directly input raven density estimates (e.g., distance sampling; Buckland et al. 2001) within their sites or generate a density value using a rapid assessment protocol (i.e., Brussee et al. 2021) by entering point count survey data, including the total number of ravens observed and the number of surveys conducted; (3) compare this density to their desired ecological threshold for a sensitive species (i.e., Coates et al. 2020 or Holcomb et al. 2021) or to another density such as a historic or previous value to determine the management options tier that a manager's site falls within; (4) produce a list of potential management options for the identified tier that can be refined by user input of known subsidies or a GIS evaluation of within-site subsidies. The SMaRT effectively operationalizes science specific to raven management and facilitates attainment of diverse management goals, from targeted sensitive species conservation to more general raven population management, by providing the flexibility for users to customize their plans with additional information such as relevant spatial extents and specific objectives regarding raven densities.

Science-based 5-step management framework

Step 1: desktop analysis

The management framework begins with the identification of areas of concern from relatively coarse-scale maps describing raven distribution and abundance. In this initial step, resource managers can make use of available raven density and raven occurrence surfaces to identify areas with the greatest potential concern. This is first achieved by overlaying the density and occurrence layers to create a separate layer that highlights areas with both high occurrence and high density of ravens. The availability of coarse-scale mapping products streamlines this initial step. Broad-scale mapping tools for estimating raven occurrence and density exist for the Great Basin (O'Neil et al. 2018, Coates et al. 2020), and the resulting spatial products from these tools are publicly available in the SMaRT (Roth et al. 2021) interface so users can visualize raven densities within their area of interest. These layers can be used to design a candidate survey or treatment area directly in the tool by drawing a polygon overlapping areas of high raven occurrence or density. However, such mapping tools may not be readily available in all areas where the management of ravens is a concern. For these areas, managers may choose to model and develop new raven occurrence or abundance layers. Where resources are limiting, managers may instead choose to leverage expert or local knowledge to identify candidate survey or treatment areas where raven populations may be problematic. The SMaRT allows users to alternatively target an area of interest by importing a geospatial polygon of the predefined area. However, there are advantages to using the currently available mapping products to predict areas of greatest concern. Robust models of raven occurrence and abundance will include multiple categories of covariates such as habitat measurements and anthropogenic features coinciding with management options discussed in step 4 below. This could help managers identify targeted management options that would be most effective at the local level. For example, if anthropogenic disturbance primarily drives the model estimation, then management options targeting modification to structures and reductions in access to food subsidies (e.g., trash, organic debris, and water) could be effective strategies at limiting raven numbers at those sites (Boarman 2003).

While these mapping products help managers identify areas of highest raven occurrence, the risk that ravens pose to sensitive prey species also depends on the distribution of that species. Because ravens mostly impact populations of sensitive species at the nesting or juvenile stage, the inclusion of sensitive species life-stage maps would further refine initial priority management areas. The SMaRT provides a targeted approach to delineate these areas within the Great Basin. Users can import polygons of species distributions and visualize raven impacts with a simple overlay of the raven density surfaces (O'Neil et al. 2018, Coates et al. 2020) or refine their priority area for their species of interest, assuming a density model is available, to represent highest raven impact by specifying a target density threshold and performing a spatial intersection with their species distribution. This feature is limited to species with distributions that fall within the Great Basin due to the extent of the raven density surface.

Inevitably, as these spatial products and associated models incorporate additional data and improve their predictive capability, resource managers will likewise improve their ability to identify areas of potential management action. Because the management framework includes the use of the best available science and the SMaRT is designed to be parameterized with user inputs, it increases management flexibility by engaging an adaptive process whereby improvements in our understanding of raven distribution and demographics are incorporated into raven management plans. With the conclusion of step 1, managers will have likely identified several areas of potential management action. In the following step, the process moves from coarse-scale to finer resolution site-level estimations of raven density necessary for determining local management options within the tiered framework.

Step 2: field assessment

While step 1 describes the methods managers could use to identify initial areas in need of raven management, more specific *in situ* estimates of raven densities obtained from surveys near the location of raven–prey conflicts are necessary to determine the relative threat of ravens to sensitive species at a site level. Traditionally, these estimates are derived through distance sampling, which model true abundances conditional on detection probabilities (Buckland et al. 2001). However, managers face challenges when trying to obtain estimates using this method, as it often requires sample sizes that may be infeasible. Tools such as the rapid assessment protocol described by Brussee et al. (2021) help managers overcome this problem. These protocols allow managers to obtain site-level estimates of raven density and their associated 95% prediction intervals using far fewer surveys than would be required otherwise with more traditional methods of distance sampling (Brussee et al. 2021). While best management practices dictate the use of distance sampling methods where feasible, managers may determine that the rapid assessment protocol (Brussee et al. 2021) is a reasonable alternative in instances where resources prevent the full implementation of distance sampling and surveys are conducted in open landscapes similar to those of the sagebrush steppe in the Great Basin. The SMaRT allows managers to populate the framework with distance sampling data when available but also offers the rapid assessment protocol (Brussee et al. 2021) to calculate densities by inputting summaries of raven data from surveys, such as total numbers of ravens and surveys conducted within a given sampling unit.

Step 3: compare density to an ecological threshold

We focused on 1 category likely to capture most management objectives, specific raven population densities, as the objective (e.g., a return to "background" or "historic" densities). With sensitive species, conservation management objectives reduce raven densities below an established ecological threshold needed to support species conservation efforts. Ecological thresholds likely vary by species. For example, in a study of sage-grouse within the Great Basin, Coates et al. (2020) measured negative impacts on sage-grouse nest survival when raven densities exceeded ~ 0.40 km$^{-2.}$ This density, therefore, represents the potential ecological threshold at which raven density is negatively affecting sage-grouse recruitment. In another study in the Mojave Desert of southern California, USA, Holcomb et al. (2021) found that juvenile (0–10-year-old) Mojave desert tortoise (*Gopherus agassizii*) survival was reduced below the threshold to sustain tortoise populations as raven densities exceeded ~ 0.89 km^{-2} within their study sites, at the observed median distance nearest previously active nest of 1.72 km. Managers may use values such as these to guide actions within the tiered framework. The SMaRT synthesizes and stores known thresholds for sensitive species (e.g., 0.40 km^{-2} , 0.89 km^{-2}) so they are readily available to managers working within the framework. Users select their species for conservation action, and the SMaRT automatically determines the targeted threshold for raven management—if a published value is available for the selected species. The SMaRT also provides the option for users to enter a custom density threshold and habitat distributions for a species not included in the tool. Where sensitive species management plans encompass multiple affected species, managers may choose to set raven density objectives to the minimum or average ecological threshold value identified among those species, thus taking a conservation approach that would benefit all target species.

Using the site-level raven density estimates obtained in step 2, managers could apply those values in context to the relative threat of ravens to sensitive prey species at that site (i.e., the ecological threshold). Categories of management options can be determined within a 3-tier

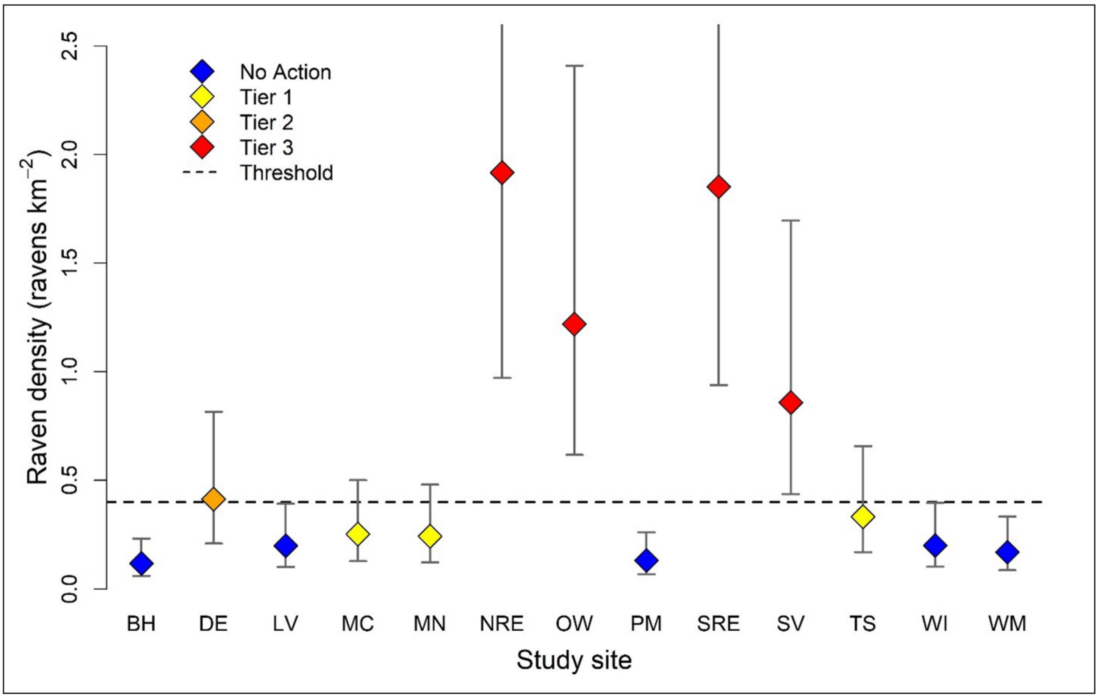


Figure 2. Identification of management action tier using the interaction of site-level common raven (*Corvus corax*; raven) density estimate with the ecological threshold. In the example here, the ecological threshold is represented as 0.40 ravens km^{-2}. This ecological threshold represents the site-level raven density at which ravens cause detectable impacts to greater sage-grouse (*Centrocercus urophasianus*). Tiers 1, 2, and 3 correspond to habitat improvement, anthropogenic resource subsidy reductions, and direct action, respectively. BH = Bodie Hills, California; DE = Desatoya Mountains, Nevada; LV = Long Valley, California; MC = McGinness Hills, Nevada; MN =Monitor Valley, Nevada; NRE = North Reese Valley, Nevada; OW = Owyhee, Idaho; PM = Parker Meadows, California; SRE = South Reese Valley, Nevada; SV = Susanville, California; TS = Tuscarora, Nevada; WI = Winecup-Gamble, Nevada; and WM = White Mountains, California, USA.

framework through comparisons of the site-level raven density estimates and the identified ecological threshold. In this process, the raven density estimates and associated 95% CIs can interact with the ecological threshold in 1 of 4 ways: (1) both the point estimate and 95% CI fall below the threshold (no action necessary); (2) the point estimate is below, but the 95% CI overlaps the threshold (tier 1 is engaged); (3) the point estimate exceeds the threshold, but the 95% CI overlaps the threshold (tier 2 is engaged); or (4) both the point estimate and 95% CI exceed the threshold (tier 3 is engaged; Figure 2). It is the specific interaction of the site-level raven density estimate and CIs with the ecological threshold that guides management amongst tiers and identifies predetermined management options that are discussed in step 4. The framework also accommodates flexibility within the types of ecological thresholds as new research investigates raven predator–prey dynamics. For example, in the Mojave Desert ecosystem, Holcomb et al. (2021) found distance to raven nests as an important factor in the predation risk of desert tortoises. Thus, thresholds that incorporate other factors such as distance to raven nest may be important for some prey species when identifying appropriate management option tiers.

Management objectives may not always be targeted toward reducing the impacts of ravens on other species. For example, resource managers may choose to set their principal management aim toward limiting raven population growth rates (Currylow et al. 2021, Rivera-Milán et al. 2021). The raven population dynamics model built from Breeding Bird Survey (BBS) data (Rivera-Milán et al. 2021) provides managers a method to estimate r_{max} (maximum intrinsic rate of population growth), which can be used to calculate potential take levels. Additionally, management objectives could involve reductions in raven populations to a predetermined "background" or "historic" density. Under this scenario, resource managers would need to objectively determine what density values may be appropriate for a particular management area and enter it as a custom threshold input within the SMaRT.

Managers may also obtain values by using several methods. For example, managers could leverage count data from the BBS to retrospectively determine historical raven densities from several decades ago. While this may represent one of the more rigorous methods available, it is not without issue. The BBS counts are based on a limited number of survey routes beginning in the eastern United States in 1966, with the number of routes increasing annually. In 1968, these routes had expanded to include the western United States. This means that managers may be relying on a progressively data-scarce resource the further back in time that they conduct assessments. Moreover, raven expansion in the western United States could have begun as early as the 1940s (USFWS 1990), before the initiation of BBS counts. Alternately, resource managers could use raven density models encompassing areas that represent various intensities of anthropogenic impacts. Values of modeled raven density outside of areas influenced by anthropogenic impacts may serve as a surrogate "background" or "natural" density for management purposes.

Step 4: prescribe management options using the 3-tiered process

Managers use this step to identify general management categories and specific options they can consider for implementation. Central to our science-based management framework are 3 tiers of management options for consideration: (1) habitat improvements that reduce the probability of prey species nest detection and depredation by ravens; (2) indirect actions, including reductions in access to anthropogenic resource subsidies that drive raven population expansion; and (3) direct actions such as hazing, taste aversion techniques, nest removal, egg-addling, and lethal removal options in areas where raven predation pressure is greatest and low reproductive rates of prey species jeopardizes population stability and thus persistence. The SMaRT synthesizes data provided by users to determine an appropriate tier, which suits the management plan and provides a list of associated management options, allowing managers to develop a plan with clearly defined actions that can be conducted concurrently. Managers can refine the management options to target subsidies within their sites in 2 ways: (1) they can select from a list of subsidies identified with on-the-ground knowledge of subsidies in their sites, or (2) they can use the GIS evaluation option within the SMaRT to map and quantify raven subsidies within their sites. The GIS evaluation produces a downloadable table containing subsidy information, such as presence of a subsidy or average distance to a subsidy, as well as a map of subsidies within the sites. The SMaRT provides the refined tiers data as a downloadable table that lists the general management category and the available options within that category. The options within each tier are detailed below.

Tier 1 management. Tier 1 targets improvements in prey species habitat quality. Predation is the proximate cause of local declines in many species populations, with habitat quality being the underlying distal cause (Silvy 1999). For example, game bird populations that are provided adequate amounts of suitable quality habitat proliferate despite the impacts of endemic predators (Bergerud 1988). However, habitat requirements vary between species, and managers will need to design habitat improvement efforts accordingly. For example, piping plover (*Charadrius melodus*; plover) nest success is known to increase when located in territories characterized by clumped vegetation within larger areas of interspace (Gaines and Ryan 1988). For plovers, managers may choose to target habitat improvement strategies that emulate a similar vegetation heterogeneity. In the case of the Mojave desert tortoise, restoration and augmentation of native perennial shrubs ameliorate protective cover, likely reducing the effects of predation by ravens (Abella and Berry 2016). Thus, habitat improvement efforts that increase native perennial shrub cover could be prioritized. The SMaRT includes a post-survey GIS evaluation option that allows managers to overlay their surveyed sites onto spatial layers of shrub and sagebrush percent cover and height provided by Rangeland Condition Monitoring Assessment and Projection data (Rigge

Table 1. Delineation and examples of anthropogenic subsidies, which aid in common raven (*Corvus corax*; raven) population growth. Also presented are tier 2 options that managers could implement to mitigate raven access to each type of subsidy.

Subsidy type	Subsidy examples	Tier 2 management option
Persistent food or water point source	Landfill – solid waste	Containment – bury or cover resource
	Livestock burial pits	Harassment devices – acoustic hazing, effigies
	Sewage pond	Chemical deterrents – nonlethal deterrents
	Livestock feedlots	
Ephemeral food or water sources	Roadkill	Regular disposal/collection
	Water troughs	Exclusion nets
	Residential/commercial garbage	Containment – cover and secure resource
	Agricultural crops	Harassment devices – acoustic hazing, effigies
Nesting	Communication towers	Deterrent structures
	Transmission line towers	Inactive nest removal
	Buildings	Harassment devices – effigies, acoustic hazing
		Exclusion nets
Perching	Tower structures	Perch deterrent structures
	Power lines	Harassment devices – effigies, acoustic hazing
	Transmission lines	Exclusion nets
	Buildings	
	Antenna structures	

et al. 2021), which can be used to visually identify areas where managers can target on-the-ground efforts to improve cover as protection from predation. The user-created map is available for download as an image file. The SMaRT also offers managers the ability to quantify habitat characteristics within their sites. In addition to quantifying shrub and sagebrush cover and heights, managers can also estimate the amount of core and priority sage-grouse habitat within their sites. These data are added as attributes to the uploaded site polygons and are available for download as a shapefile. Similar spatially explicit habitat layers for other sensitive species can be incorporated into SMaRT as they become available.

Tier 1 management does not address raven populations directly but aims to offset the impacts that ravens have on prey species. The ability of managers to mitigate the impacts of ravens through habitat improvements alone is likely limited to cases where density estimates are below the ecological threshold. Where raven densities exceed the ecological threshold, direct management of raven populations may be needed, as described in tiers 2 and 3. Furthermore, when management objectives are directed at limiting raven growth or reducing populations to a predetermined level, tier 1 options may not be necessary. Under those objectives, tier 2 and tier 3 management options would be applicable.

Tier 2 management. Tier 2 focuses on reducing resource subsidies, thereby removing the opportunity for inflated raven populations. Anthropogenic subsidies provide raven populations with resources that contribute to increases in density above the habitat's natural capacity (Marzluff and Neatherlin 2006, Kristan and Boarman 2007, O'Neil et al. 2018). Subsidies are typically alternative food resources (e.g., roadkill, landfills, livestock water troughs) or perching and nesting substrates (infrastructure such as power lines, buildings, and communication towers; Table 1). In areas where subsidies are prevalent and accessible, raven populations can increase to the point of becoming decoupled from natural carrying capacity (Restani et al. 2001, Peebles and Conover 2017). Anthropogenic subsidies can also influence raven distribution and demography (Peebles and Conover 2017) and are the greatest driving factor in the increase and expansion of raven populations across the western United States (Boarman 1993, Restani et al. 2001, Kristan and Boarman 2007). Reducing access to anthropogenic resources is a primary concern for a comprehensive raven management plan (Boarman 2003). By addressing these resource subsidies in areas where ravens are a concern (i.e., engaging tier 2), management addresses the inflated carrying capacity of these raven populations.

Restricting access to food, perching, and nesting subsidies can be accomplished with a variety of strategies and approaches. For example, sanitary landfills have been identified as an important food resource that can support ravens when natural food availability is low or during the breeding season when energetic demands of adults and nestlings are highest (Engel and Young 1992, Boarman and Berry 1995, Kristan and Boarman 2003). Access to landfills could be mitigated by covering solid waste with either substrate or tarps during processing (Boarman 2003). Similarly, solid waste in privately owned garbage bins/dumpsters (both residential and commercial) can attract and provide food subsidies to ravens (Boarman 2003). Access to these point subsidies could be reduced by encouraging businesses and residents to secure waste in closed containers or by modifying sanitation collection schedules in areas of concern to minimize the time waste is accessible to ravens before collection. Regarding the next generation of potential deterrent methods, tests of remotely fired 3-watt lasers are being conducted at a water treatment facility within the Mojave Desert. Depending on the efficacy of this novel method, lasers may represent another potential raven deterrent method.

Anthropogenic resource scavenging (e.g., roadkilled animals or livestock carcasses) is also an important subsidy source for ravens (Boarman and Heinrich 1999, Boarman 2003, Coates et al. 2016). Access to livestock carcasses could be reduced by encouraging landowners to bury or otherwise dispose of carcasses immediately after death so they are not available to ravens. Reducing vehicle collisions with wildlife that result in roadkill could be accomplished by creating wildlife crossing structures and by improving barrier fencing along highways (Boarman 2003, Kintsch et al. 2015). Importantly, creating safe wildlife road crossings might benefit multiple species of wildlife vulnerable to vehicle collisions, including sensitive species also affected by raven predation (e.g., desert tortoise; Boarman et al. 1997).

Agriculture and water resources are also important subsidies for ravens. Multiple studies have found crops (e.g., grains and nuts) are a frequent or substantial part of raven diet composition (Engel and Young 1989, Kristan et al. 2004). Current methods for reducing avian access to crops include using nets or other coverings to prevent landing in crop fields, hazing devices to deter ravens from remaining in an area, or chemical repellents on crops to prevent ingestion or damage (Avery et al. 2002, Peebles and Spencer 2020). Water resources, particularly those associated with commercial activities such as irrigation ponds, sewage treatment pools, or livestock troughs, are another subsidy for ravens (Boarman et al. 2006, Peebles and Spencer 2020). Managers could limit access to some of these anthropogenic sources of water by installing barriers around the edges, preventing ravens from accessing the water edge, or by partially covering water bodies to completely prevent access (Boarman 2003).

Finally, anthropogenic infrastructure subsidies provide perching or nesting substrates for ravens that drive raven population growth (Peebles and Conover 2017). Installing perch deterrents on structures like transmission lines, communication towers, and other vertical infrastructure is a strategy available for managers to reduce the use of vertical infrastructure by ravens. However, the efficacy of these devices has been mixed (Lammers and Collopy 2007, Slater and Smith 2010, Restani and Lueck 2020), with only a handful of studies reporting effective reductions in perching or nesting on vertical infrastructure at localized scales (Liebezeit and George 2002). Dismantling or removing defunct infrastructure and repairing or replacing perch/nest deterrent structures on active infrastructure are other important strategies to reduce the prevalence of anthropogenic perching/nesting substrate for ravens (Braun 1998, Dwyer et al. 2015). Importantly, several studies have suggested that reducing anthropogenic subsidies for ravens may be most effective when actions are carried out during late winter and spring when ravens are nesting (Boarman 2003, Shields et al. 2019). However, additional research on the ecology of ravens (Boarman 2003) and the effectiveness of subsidy reductions in reducing populations is recommended to help inform and develop long-term management strategies.

The SMaRT allows users to develop a list of subsidy management options that are customized to their sites. If they are already familiar with subsidies within or adjacent to their sites, they can select subsidies to target from a checklist and the tool will refine management options that address the selected subsidies. Managers can also use the post-survey GIS evaluation to identify additional subsidies within their sites. The GIS evaluation includes several spatial layers that capture important raven subsidies such as distance to road, water sources such as springs and streams, and point-source subsidies such as landfills, towers, and transmission lines. Managers can overlay their sites onto these layers to visually estimate the amount and location of potential targeted subsidies to download as a map image. The SMaRT also provides the option to quantify these subsidies within sites by calculating summaries such as mean distance to subsidies, counts of point-source subsidies, and total footprint of point-source subsidies. As with the tier 1 habitat data, these data are available for download as a shapefile.

Tier 3 management. For sites where raven impacts are directly limiting recovery of sensitive species populations or resource managers otherwise deem necessary for achieving management objectives, direct actions (i.e., lethal removal) may be necessary to mitigate predator–prey conflicts that eliminate or substantially limit prey species ability to maintain stable populations within conservation areas as well as corridors. Removal techniques can target breeding and non-breeding adult ravens or unhatched eggs. Strategies that target the unhatched eggs in raven nests include various methods of egg addling (hyperthermia, hypothermia, and suffocation) frequently achieved through egg oiling (Shields et al. 2019, Sanchez et al. 2021) and, to a lesser extent, the removal of active nests (Sanchez et al. 2021).

Egg addling leaves treated eggs intact while preventing hatching and increasing the likelihood that breeding adults will continue to incubate the nest and defend their breeding territory from other ravens (Shields et al. 2019). Nest removal destroys the eggs, which may lead adults to either disperse from the nesting area or attempt to re-nest (Harju et al. 2018). Importantly, ravens often nest in high, hard-to-access sites, increasing the difficulty of implementing such techniques. Fortunately, several novel techniques, including the use of telescoping poles and unmanned aerial vehicles (drones), have emerged in recent years to help facilitate the implementation of these removal techniques at previously inaccessible nests (Shields et al. 2019, Peebles and Spencer 2020). Both nest removal and egg addling have been demonstrated to positively affect the vital rates of target prey species under certain conditions (Sanchez et al. 2021). Egg addling or destruction at a rate of 0.80 is capable of reducing raven population expansion to 0.999, but egg addling at a rate of 1 only increases the rate of raven population decline by 4% annually, assuming density independence and no immigration (Shields et al. 2019). Consequently, current conditions my dictate that a more immediate reduction in raven density (raven km^{-2}) is necessary or that the removal of problem individuals and active nests located within a certain distance of conservation areas is necessary to meet management objectives.

Several direct methods have been studied to determine their effectiveness at reducing raven numbers, including the use of toxicants (i.e., DRC-1339; Larsen and Dietrich 1970, Coates and Delehanty 2004, Coates et al. 2007, O'Neil et al. 2021), trapping, and culling via shooting (Liebezeit and George 2002, Boarman 2003, Peebles and Spencer 2020). However, the effectiveness of these techniques has been limited to small areas and over short periods of time. Because removal actions must be implemented repeatedly to affect long-term raven population abundance or growth and because they are expensive to implement effectively (Boarman 2003, Dinkins et al. 2016), they may not be considered an efficient long-term solution to mitigate raven impacts on sensitive prey species. For example, StallPOPd.V4 (https://cwhl2.shinyapps.io/StallPOPdV4/) suggests that resetting raven densities to the 0.40 raven km^{-2} sage-grouse threshold would require the removal of ≥2,569 ravens (920 eggs or hatchlings, 329 non-breeders, and 1,320 breeders), assuming the management area has a geographical expanse equal to 2,215 km^2, current density of 1.56 raven km^{-2}, and vitality rate values that are similar to those reported in Kristan et al. (2005; Currylow et al. 2021).

Although our adaptive management framework has focused mainly on targeting areas for treatment and identification of potential management options, these can be combined with other information to produce potential take levels (PTL) when circumstances point to the application of tier 3 strategies. For example, Rivera-Milán et al. (2021) combined BBS route-level count data and harvest theory in a Bayesian modeling framework to predict raven abundance under varying hypothetical PTL scenarios. In a different approach, Shields et al. (2019) packaged a population matrix model within an interactive software tool (StallPOPd) to simulate the management outcomes under various egg-oiling scenarios. Currylow et al. (2021) expanded on this approach further (StallPOPd. V2-4) to facilitate the investigation of multiple scenarios that combine multiple tier 3 strategies with the overarching goal of reducing and then maintaining reduced raven abundance. Users can visually assess spatial variation in predicted raven densities within their sites using the SMaRT's post-survey GIS evaluation. These densities are provided at a 30-m^2 resolution for sites within the Great Basin (Coates et al. 2020).

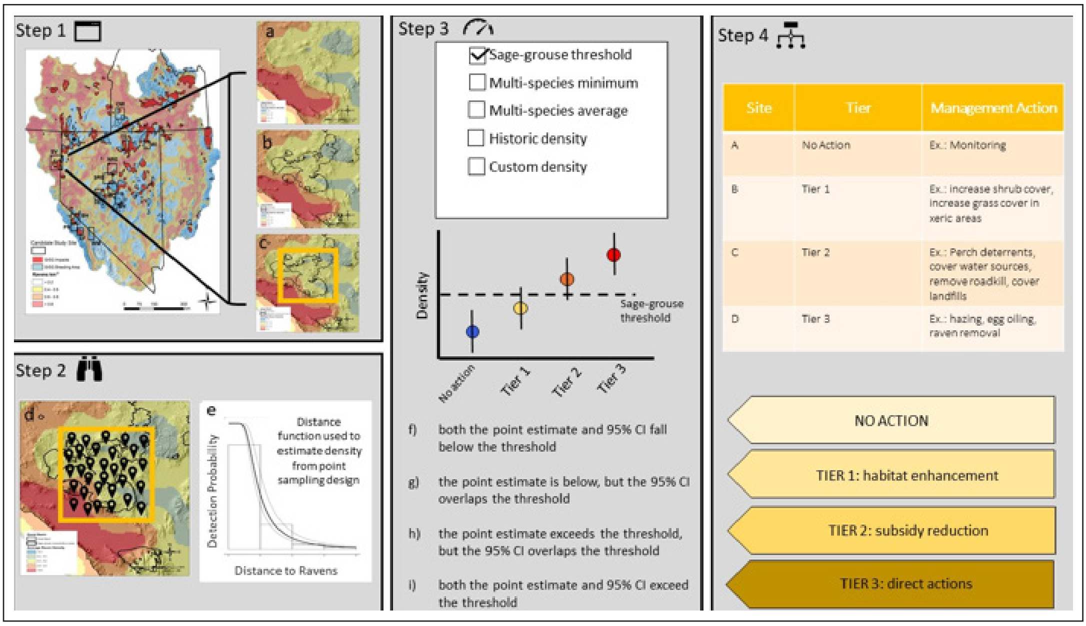
A crucial point for the successful implementation of the framework is the concomitance of management action among tiers. In short, a management strategy is likely to be most effective if any management tier identified in step 3 is carried out in concert with all lower tiers. For example, if the objective was prey species conservation and tier 2 (subsidy reductions) management options were identified for a treatment site, then the management plan could also include efforts to increase sensitive species habitat quality (i.e., tier 1). Similarly, sites identified for tier 3 (direct actions) management options would include actions for addressing local anthropogenic subsidies, if present, and habitat improvement efforts if the overall goal is sensitive species protection.

Currently, the SMaRT does not quantify the predicted outcome of management actions. For example, the SMaRT does not estimate how removal of subsidies will reduce raven numbers, nor does it project the benefit of these actions on sensitive species populations. Separate tools and models estimate the required raven reductions to affect significant improvements to sensitive species populations or other raven management goals (see Currylow et al. 2021, Rivera-Milán et al. 2021). In the future, similar models can be incorporated into the SMaRT so managers are not only able to develop adaptive management plans, but are also able to quantify the impact of management options and compare the potential success of different strategies.

Step 5: post-management monitoring

Achieving management goals can be challenging given the complexity of ecological stressors (Eviner and Hawkes 2008) and the uncertainty of management outcomes because of natural variation within a system. One of the central tenets of adaptive management is understanding uncertainty within a system (Regan et al. 2002, Halpern et al. 2006, McCarthy and Possingham 2007). Implementing adaptive management can reduce uncertainty as additional information is collected and used to improve the efficacy of management actions to reach the desired outcomes and goals (Runge 2011, Williams 2011*a*). Adaptive management strategies satisfy calls for more rigorous monitoring of management outcomes (Suding 2011) by targeting repeatable outcomes with post-treatment assessments. Additionally, post-action monitoring enables the comparison of expected outcomes and observed outcomes, which is useful for identifying prudent model refinements or the potential need for additional inputs (e.g., emigration-immigration).

The last step in the framework involves monitoring the management action outcomes to assess management plan effectiveness. Similar to an adaptive management strategy, the post-action monitoring conducted at each site provides managers the ability to reassess the risk ravens pose to sensitive species and evaluate management action efficacy. This can be accomplished by attaining post-action raven densities using the rapid assessment protocols from step 2 within each treatment site. Managers can then compare these new density estimates to the ecological threshold value using the methods outlined in step 3 and so forth. Such post-action monitoring allows for changes in management actions



☑ Sage-grouse threshold
☐ Multi-species minimum
☐ Multi-species average
☐ Historic density
☐ Custom density

f) both the point estimate and 95% CI fall below the threshold

g) the point estimate is below, but the 95% CI overlaps the threshold

h) the point estimate exceeds the threshold, but the 95% CI overlaps the threshold

i) both the point estimate and 95% CI exceed the threshold

Site	Tier	Management Action
A	No Action	Ex.: Monitoring
B	Tier 1	Ex.: increase shrub cover, increase grass cover in xeric areas
C	Tier 2	Ex.: Perch deterrents, cover water sources, remove roadkill, cover landfills
D	Tier 3	Ex.: hazing, egg oiling, raven removal

Figure 3. Diagram of the adaptive management framework for common raven (*Corvus corax*; raven) populations, operationalized through the Science-based Management for Ravens Tool (SMaRT) and applied to the sage-grouse case study. Inset boxes in steps 1 and 2 (A–D) highlight one of the candidate sites (labeled SV). In step 1, we intersected maps of raven density (A) and greater sage-grouse (*Centrocercus urophasianus*) breeding areas (B) to identify candidate sites across the Great Basin, USA (C). In step 2, we conducted point count surveys (D) and used the number of surveys conducted and the number of ravens surveyed to calculate raven densities within our candidate sites (E). In step 3, we selected the sage-grouse ecological threshold of 0.40 ravens km^{-2} to compare to our raven densities. In step 4, we used the criteria outlined in step 3 (F–I) to identify the management tier and associated prescribed management actions for each site.

dependent on the response of raven densities to the prescribed management actions. Managers can also cease management actions at sites when objectives have been met and they are determined to be low risk, thus freeing resources for management elsewhere. Step 5 of the adaptive management framework is inherently operationalized by the SMaRT as managers can use the post-monitoring reassessments to refine the parameters of the SMaRT and adjust their management plan. The tool facilitates truly adaptive management, as it can be updated with new data that adjust strategies accordingly or identify when a site can be graduated out of the tiered approach and into monitoring. Currently, the tool provides a method of incorporating post-monitoring information on ravens only. It does not have a method to address post-monitoring information on tier 1 habitat recovery actions or changes in sensitive species population dynamics. In the future, the SMaRT could draw from post-restoration monitoring databases such as the Land Treatment Digital Library (Pilliod et al. 2019) to include habitat restoration outcomes, or it could incorporate a feature to collect spatial post-monitoring information on habitat restoration to account for success of tier 1 actions.

Ultimately, to address the threat that increasing raven populations pose to sensitive species, managers may choose to adopt science-driven decision frameworks such as ours. Such frameworks have the advantage of incorporating both long- (i.e., tiers 1 and 2) and short-term (i.e., tier 3) strategies while allowing for adjustments in management actions based on the response of raven densities. This management framework prioritizes underlying issues of habitat quality and anthropogenic resource subsidies but provides managers the flexibility to employ raven removal in areas where impacts are egregious and may require immediate relief to conserve sensitive species.

Example case study for adaptive management of ravens for the conservation of sage-grouse

The impacts of ravens on sage-grouse populations have been well documented (Coates 2007, Lockyer et al. 2013, Dinkins et al. 2016, Peebles et al. 2017, O'Neil et al. 2018, Coates

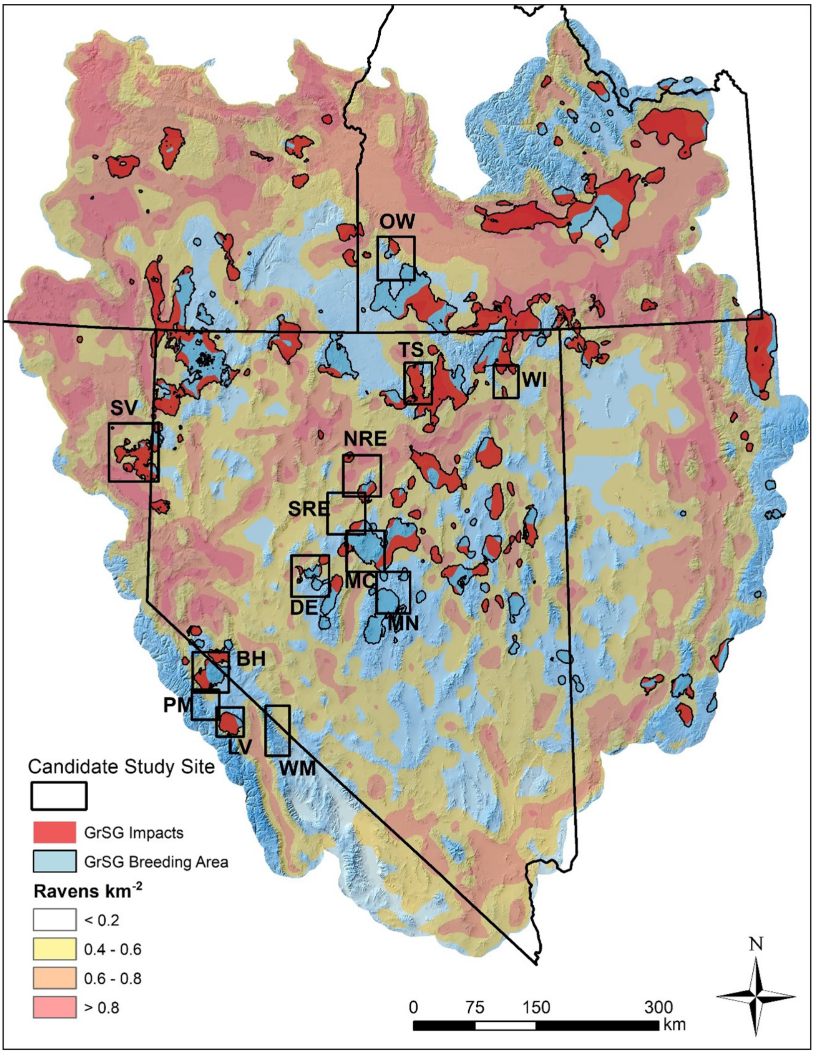


Figure 4. Sites identified within the Great Basin, USA, for in-field assessments of local common raven (Corvus corax; raven) abundance. Site selection was based in areas where potentially "high" raven density areas (i.e., >0.40 ravens km-2) and greater sage-grouse (Centrocercus urophasianus) breeding areas overlapped or occurred near the potential impact areas identified in step 1 of the raven adaptive management framework. BH = Bodie Hills, California; DE = Desatoya Mountains, Nevada; LV = Long Valley, California; MC = McGinness Hills, Nevada; MN =Monitor Valley, Nevada; NRE = North Reese Valley, Nevada; OW = Owyhee, Idaho; PM = Parker Meadows, California; SRE = South Reese Valley, Nevada; SV = Susanville, California; TS = Tuscarora, Nevada; WI = Winecup-Gamble, Nevada; and WM = White Mountains, California, USA.

et al. 2020). Specifically, if sage-grouse cannot compensate for low nest survival through increases in other demographic rates, nest predation effects could limit overall population growth rates. Here, we provide an example that illustrates the application of the science-based management framework through the SMaRT (Figure 3) for assessing raven population abundance and prescribing appropriate management options depending on estimated raven densities. We applied the framework in this example to reduce impacts to local sage-grouse populations (Figures 3 and 4), but the steps are transferable to any species or problem where raven impacts have been evaluated. Here we show steps 1–4 using study site locations in California, Nevada, and Idaho, USA (Figure 4), where field data have been collected for long-

Table 2. Common raven (*Corvus corax*; raven) monitoring occurring at field sites in Nevada, California, and Idaho, USA, including the total number of ravens observed, number of surveys with ravens present, and a raven index (RI) density estimate based on the number of ravens occurring per survey for each field site. The RI serves as a tool to rapidly evaluate raven densities based on predictive relationships with distance sampling models and can be used to identify raven management tiers given established ecological thresholds.

Site[a]	No. of surveys	Ravens present	Ravens observed	P (raven)	Raven count per survey	Raven index (RI)	RI lower	RI upper
BH	494	43	61	0.087	0.123	0.118	0.060	0.232
DE	268	47	131	0.175	0.489	0.413	0.209	0.816
LV	341	42	75	0.123	0.220	0.199	0.101	0.393
MC	234	39	67	0.167	0.286	0.253	0.128	0.500
MN	245	35	67	0.143	0.273	0.243	0.123	0.480
NRE	185	68	483	0.368	2.611	1.917	0.972	3.783
OW	416	139	663	0.334	1.594	1.220	0.618	2.410
PM	292	25	41	0.086	0.140	0.132	0.067	0.261
SRE	177	55	445	0.311	2.514	1.852	0.939	3.654
SV	274	74	298	0.270	1.088	0.859	0.436	1.696
TS	326	62	126	0.190	0.387	0.333	0.169	0.658
WI	270	35	60	0.130	0.222	0.201	0.102	0.397
WM	283	30	52	0.106	0.184	0.169	0.086	0.334

[a] BH = Bodie Hills, California; DE = Desatoya Mountains, Nevada; LV = Long Valley, California; MC = McGinness Hills, Nevada; MN =Monitor Valley, Nevada; NRE = North Reese Valley, Nevada; OW = Owyhee, Idaho; PM = Parker Meadows, California; SRE = South Reese Valley, Nevada; SV = Susanville, California; TS = Tuscarora, Nevada; WI = Winecup-Gamble, Nevada; and WM = White Mountains, California, USA.

term monitoring of sage-grouse populations. At these study sites, we have also conducted avian point-count surveys to assess avian predator populations. Because ravens are a top predator of sage-grouse nests, the point-count surveys have been used to develop density and distribution maps that can serve as baseline estimates indicating where impacts to sage-grouse are likely given distributional overlaps with delineated breeding concentration areas (Coates et al. 2016, Doherty et al. 2016, O'Neil et al. 2018, Coates et al. 2020).

Case study step 1: identifying candidate locations from desktop analysis

In step 1, we identified areas that could benefit from potential management actions within the Great Basin region based on the overlap of potentially "high" raven density areas (e.g., >0.40/km^{-2}) with sage-grouse breeding areas based on broad-scale distribution maps of raven occurrence and density (representing years 2007–2016; Coates et al. 2020; Figure 3). The potential raven conflict areas for sage-grouse in this region have been described and are publicly available (O'Neil et al. 2018, Coates et al. 2020). For reference, we show these data layers in Figure 5. These layers are available for visualization within the SMaRT, where users can intersect the layers to delineate the same areas of interest. The SMaRT also allows users to import their sensitive species boundaries to generate novel impact maps from which to delineate assessment sites or bring in the boundary of predetermined assessment sites. Therefore, managing agencies could further limit their areas based on potential raven impacts, logistical constraints (e.g., land ownership), and overlap with other species or known problem areas.

Case study step 2: field assessment

Once candidate sites have been identified in step 1, estimates of raven density can be obtained from any valid survey design and statis-

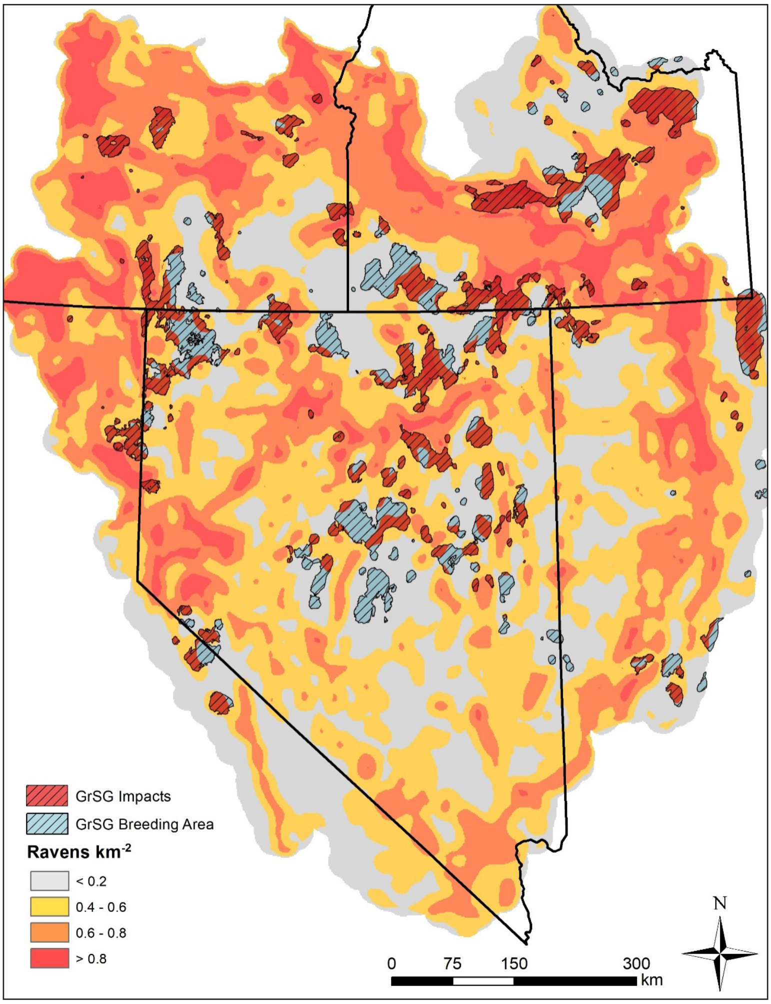


Figure 5. Identified areas of potential management actions within the Great Basin, USA, region based on the overlap of potentially "high" common raven (*Corvus corax*; raven) density areas (e.g., >0.40 ravens km-2) with greater sage-grouse (*Centrocercus urophasianus*) breeding areas based on broad-scale distribution maps of raven occurrence and density within the Great Basin, USA (representing years 2007–2016; Coates et al. 2020).

tical model of abundance like those proposed by Brussee et al. (2021). In step 2, we performed field assessments of local raven abundance. For demonstration, we applied survey data from 2019, conducted by the U.S. Geological Survey and its partners using the methods reported in Coates et al. (2016), to estimate localized raven densities at specific sites that overlapped or occurred near the potential impact areas identified in step 1 (Figure 4; O'Neil et al. 2018). We also included sites where potential impacts appeared low to show how steps 3–4 would apply across a range of scenarios for low, moderate, and high raven densities. We input the number of ravens observed and the number of surveys within the rapid assessment protocol (Brussee et al. 2021) available within the SMaRT to generate the index values at our sites of interest (Table 2; Figure 3).

Case study step 3: compare density to an ecological threshold

As mentioned, resource managers may have different objectives based on desired management response. For our sage-grouse example, the management objectives were directed at species conservation. To that end, we used an ecological threshold as the management objective.

Table 3. Examples of management options for each of 13 candidate sites within the Great Basin, USA, based on the framework as applied to a case study of greater sage-grouse (*Centrocercus urophasianus*). This table represents an example of the final output of the Science-based Management of Ravens Tool (SMaRT).

Field site[a]	Tier	Proposed raven management action
BH	0	None
DE	2	Habitat improvements and Subsidy reductions
LV	0	None
MC	1	Habitat improvements
MN	1	Habitat improvements
NRE	3	Habitat improvements, subsidy reductions, and direct action
OW	3	Habitat improvements, subsidy reductions, and direct action
PM	0	None
SRE	3	Habitat improvements, subsidy reductions, and direct action
SV	3	Habitat improvements, subsidy reductions, and direct action
TS	1	Habitat improvements
WI	0	None
WM	0	None

[a] BH = Bodie Hills, California; DE = Desatoya Mountains, Nevada; LV = Long Valley, California; MC = McGinness Hills, Nevada; MN =Monitor Valley, Nevada; NRE = North Reese Valley, Nevada; OW = Owyhee, Idaho; PM = Parker Meadows, California; SRE = South Reese Valley, Nevada; SV = Susanville, California; TS = Tuscarora, Nevada; WI = Winecup-Gamble, Nevada; and WM = White Mountains, California, USA.

In step 3, we related estimates of raven density to the threshold value of 0.40 ravens km^{-2} at 13 different field site locations identified in the previous steps. This threshold is identified by the SMaRT when the user selects the "sage-grouse" ecological threshold (Figure 3). The SMaRT then provided potential management options according to the 3-tiered framework (Table 3; Figure 3). We identified 4 sites where no action was deemed necessary, 3 sites where tier 1 would apply, 1 site where tier 2 would apply, and 4 sites where tier 3 would apply (Figure 2). Raven densities among the different sites ranged from 0.118–1.917, and the raven index values reflected a similar range and tiers of proposed options.

Case study step 4: prescribe management options using the 3-tiered process

Reductions in sage-grouse reproductive success have been documented in areas of high raven densities and linked to the increase of sage-grouse nest depredations by ravens(Bui et al. 2010, Coates and Delehanty 2010, Dinkins et al. 2016, Conover and Roberts 2017, Coates et al. 2020). The likelihood of a sage-grouse nest being depredated is an inverse function of the shrub canopy cover, where sage-grouse in areas of low shrub canopy cover experience higher rates of nest depredation (Coates and Delehanty 2010). Improvements in habitat quality and increases in shrub canopy cover specifically may reduce the ability of predators to detect nests and therefore the likelihood of depredation. It is with this understanding that resource managers may choose to implement targeted management actions for habitat improvement to increase shrub canopy cover within critical breeding habitats in response to raven depredation concerns. For sage-grouse, target ranges for habitat suitability characteristics within breeding habitats are well established and management targets have been identified (Connelly et al. 2000, Sather-Blair et al. 2000, Hagen 2011, Stiver et al. 2015). Management actions that address breeding habitat quality lay the foundation for the other tiers in the framework.

Lethal removal programs have been demonstrated as a potentially effective management option to bolster flagging populations of sage-grouse exhibiting low reproductive rates (Dinkins et al. 2016). Studies have documented that sage-grouse nest success was higher in areas where raven densities were decreased under a raven removal program compared to sites without raven removal (Dinkins et al. 2016, Peebles et al. 2017). However, while removal of ravens may be effective at providing short-term relief from nest depredation in the interim, the framework emphasizes consideration of possible underlying factors described in tier 1 and tier 2 as root sources for raven impacts from overabundance.

Case study step 5: post-management monitoring

The sites identified in previous steps, particularly those associated with prescribed management options in tiers 2 and 3, will continue to be monitored to evaluate whether (1) raven densities are effectively reduced by management action over time; (2) sage-grouse populations demonstrate noticeable, positive responses to those actions (e.g., increased nest survival and/or population growth); and (3) further actions are necessary. Continued monitoring at sites that did not fall into tiers 2 or 3 could determine whether raven population densities are increasing or stable to determine the potential need for future management.

Summary and conclusions

Successful raven management programs depend on the program's ability to continuously characterize and reduce uncertainty in management outcomes. By developing quantifiable metrics of success with spatially explicit surfaces of raven abundance, modeled impacts, and monitoring progress, management programs can effectively operationalize, or quantify with measurable outcomes, ecological processes that influence management results to develop predictable, repeatable management strategies. The tiered framework presented guides the development of adaptive management strategies for raven populations. Each tier provides effective raven management recommendations based on data within a proposed site. The framework can be applied using the SMaRT, which provides the web-based interface designed to develop customized, science-based management strategies that are driven by the best available data at proposed sites. The tool operationalizes the ecological concepts surrounding raven management through empirical inputs, such as spatially explicit maps of raven density and occurrence and survey data to develop data-driven outputs. These outputs represent a range of options that, when taken into consideration with other factors, help better inform management decisions.

The SMaRT specifically facilitates adaptive raven management in several ways. The SMaRT helps managers identify and prioritize site-specific management options based on the tier their sites fall within, as defined by their management goals. It improves access to scientific products by centralizing ecological and spatial data on raven dynamics and the impact on sensitive species. Further, the SMaRT fully integrates these data into a single tool, automatically synthesizing data in the most meaningful way for raven management and guiding managers through the steps of the adaptive management framework. It is flexible, prioritizing on-the-ground knowledge but augmenting with modeled data to fill information gaps such as estimates of raven density, sensitive species thresholds, or within-site subsidies that may be missing from management plans.

The SMaRT is fully customizable. Managers can design their treatment sites using the interactive map within the tool by leveraging raven density and occurrence maps as well as breeding areas for sage-grouse as reference layers, or they can import other critical boundaries for additional sensitive species. The SMaRT enables managers to delineate treatment sites that represent areas where management actions are required and will also be most effective. The tool also allows managers to refine their management options by targeting important habitat metrics and subsidies within their sites. After conducting field assessments within these sites, managers can input site-specific survey data to characterize raven density at their sites using the option for distance sampling techniques or the rapid assessment protocol (Brussee et al. 2021) provided in the SMaRT. These densities can be continually updated within the SMaRT as informed post-treatment monitoring. Furthermore, managers can identify the target raven density based on an ecological threshold for a sensitive species, raven population dynamics, or a historic population value within the SMaRT, facilitating multiple or shifting management goals.

Coupling SMaRT with the StallPOPd.V4 (https://cwhl2.shinyapps.io/StallPOPdV4/) software package could help managers identify estimates of ravens that may be removed to achieve intended density or maintain a threshold density target. StallPOPd.V4 leverages stage structured Lefkovitch population matrices to recommend the most efficient (i.e., fewest raven removals) combination of age-class specific removal targets necessary to achieve a 1-time density "reset" to a threshold density or maintenance of a threshold density (Currylow et al. 2021).

The SMaRT enables managers to customize management options to reflect on-the-ground knowledge of subsidies within a site or use the GIS evaluation to identify additional subsidies. They can also visualize and quantify raven subsidies within their sites to identify areas within their sites to target planned raven management actions. The SMaRT synthesizes the data inputs to provide customized, effective management options within a fully adaptive, actionable framework for raven management.

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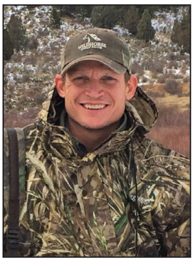
Associate Editor: S. Nicole Frey

SETH J. DETTENMAIER is a noteworthy wildlife biologist with the U.S. Geological Survey. He earned his B.S. degree in conservation ecology and a Ph.D. degree in wildlife ecology from Utah State University. He is passionate about conservation of our natural resources and providing tools to help others achieve the same. He recently discovered statistics that show 47% of people are pedantic. Well, 46.8%.

PETER S. COATES is a research wildlife biologist for the U.S. Geological Survey, Western Ecological Research Center. He obtained a Ph.D. degree from Idaho State University and an M.S. degree from University of Nevada Reno. His research currently focuses on population ecology of greater sage-grouse and other sensitive prey species. Specifically, he investigates relationships between species' habitat, predators, and climate. His studies also focus on how anthropogenic-resource subsidies influence changes in raven and other predator populations. His research findings are intended to help inform management practices and guide resource policies using quantitative decision support tools.



CALI L. ROTH is a biologist with the U.S. Geological Survey Western Ecological Research Center. Much of her research centers on operationalizing spatial data to quantify and simulate the impacts of disturbance and the outcomes of management actions in sagebrush ecosystems and subsequent effects on greater sage-grouse populations. She specializes in GIS, and her primary focus is the development of spatially explicit decision support tools that improve the accessibility and utility of timely best science for management applications. She received her B.S. degree in biology from the University of Akron and her M.S. degree in ecology and evolution from Kent State University.

SARAH C. WEBSTER is a wildlife biologist with the U.S. Geological Survey, Western Ecological Research Center and is based in Reno, Nevada. She received her doctorate and M.S. degrees in wildlife ecology and management from the University of Georgia and holds a B.S. degree in wildlife science and a B.S. degree in biology from Virginia Tech. Her professional interests include population ecology, spatial ecology, movement ecology, and the application of ecological analyses to inform conservation and management.

SHAWN T. O'NEIL is a biologist for the U.S. Geological Survey Western Ecological Research Center. He obtained his Master of Environmental Management degree from the University of North Dakota (2011) and later completed a Ph.D. degree at Michigan Technological University (2017), where he studied the spatial ecology of gray wolves in the Upper Peninsula of Michigan, USA. His work focuses on wildlife spatial and quantitative ecology with emphasis on greater sage-grouse habitat, population trends, and interactions with other overlapping species such as common ravens.

KERRY L. HOLCOMB is currently a fish and wildlife biologist in the Palm Springs, California U.S. Fish and Wildlife office. He is interested in restoring and conserving natural ecosystems faced with the myriad threats posed by climate change, fragmentation, and human subsidized predators to species and ecosystem function stability and thus persistence. Specifically, he seeks to understand the impacts that roads (from interstates to single-tracks) and subsidized predators have on the demography of extant tortoise and turtle populations. He currently leads or advises road mortality and common raven depredation mitigation programs throughout the Mojave desert tortoise's (*Gopherus agassizii*) 4-state distribution (Arizona, California, Nevada, and Utah), where he leverages adaptive management, statistical decision theory, and prioritization strategies to ensure program efficiencies. For fun, he and his wife and daughter recreate in one of California's greatest outdoor spaces.

JOHN C. TULL is the Nevada science coordinator for the U.S. Fish and Wildlife Service. He has been working in the Great Basin and sagebrush communities since 1997. After earning his B.S. degree in forest wildlife management from Stephen F. Austin University, he worked in the Sonoran Desert studying desert mule deer for his master's degree before moving to Reno, Nevada and completing his Ph.D. degree at the University of Nevada, Reno. He has been directly involved in collaborative conservation of wildlife resources in the Great Basin since 2007. He has a strong interest in the production and use of science-based management tools for conserving wildlife habitats and populations in desert landscapes.

PAT J. JACKSON graduated from the University of Missouri in 2007 with a bachelor's degree in forestry and another bachelor's degree in fisheries and wildlife. After graduation, he enjoyed a short stint of wildlife field work in southeast Alaska, transitioned to full-time trapping in Missouri, and then moved to Hawaii in 2008. In Hawaii, he spent 2 years doing vertebrate pest work focusing on feral cats, rats, and feral swine removal. In 2010, he moved to Utah and began work on a Ph.D. degree focusing on coyote biology, diet, and home ranges in central Nevada. He is currently the predator management staff specialist for Nevada Department of Wildlife. His professional interests include wildlife damage management, animal capture techniques, best management practices for furbearer trapping, public outreach, and predator management. He is an avid trapper, fisherman, and hunter, primarily focusing on big game in the west. One of his favorite aspects involves teaching others to big game hunt and trap. He also thoroughly enjoys sharing and teaching others to butcher and prepare wild game.