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Population viability management: ecological standards to guide adaptive management for rare species

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Victoria J Bakker[1*] and Daniel F Doak[2]

Many approaches to rare species management formulated by academics lack practicality and meaning for managers. Here, we propose an approach, which we refer to as population viability management (PVM), that is based on linking monitoring and management models with population models. By closely coordinating biological analyses with the range of decisions and actions considered by managers, the PVM approach ensures that population models reflect realistic management options and risk tolerances, and that adaptive conservation systems remain focused on population viability rather than statistical targets indirectly tied to population persistence. We summarize our use of PVM to formulate draft recovery criteria for the endangered island fox and to generate specific guidance for conserving this species. We argue that PVM can be widely adapted to provide more biologically justified and focused management and monitoring recommendations than those typically emerging from conventional population viability analyses. Overall, PVM represents an effective and understandable tool that enables managers to optimize monitoring effort and better control risk for species of concern.

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A universal goal for managers of rare populations is to identify and reduce threats to population viability. Because threats change through time – as does a manager's ability to counteract them – effective stewardship requires ongoing evaluation of population status and management strategy. There is widespread agreement that the success of this type of adaptive management hinges on the collection and careful analysis of monitoring data, and monitoring is required by almost all conservation plans. Rarely, however, do conservation plans convey a clear strategy for using monitoring data to guide decisions about population status or management actions, making the design, implementation, and analysis of monitoring programs an intellectual afterthought (Morris *et al.* 2002). Stewards of rare species thus continue to expend substantial resources collecting data that do not yield commensurate conservation benefits. Here, our goal is to provide a roadmap for strengthening the linkages between monitoring, management, and analysis of population dynamics in order to improve this regrettable situation.

In a nutshell:

- Population viability management (PVM) incorporates monitoring and subsequent management actions directly into population viability analyses
- PVM uses extinction risk as a common currency for comparing widely varying management options
- By simulating management responses to monitoring data, PVM produces roadmaps for future adaptive management
- PVM makes it easier to update management plans based on evolving information on population status and threats

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In terrestrial conservation, both population viability analysis (PVA) and monitoring planning are typically only withered appendages of the adaptive management cycle (Figure 1a). Typically, PVAs identify general foci for management action based on sensitivity analyses that identify life stages having the greatest impact on long-term population growth rates (λ). However, they usually fail to evaluate how data from feasible monitoring plans can best be used to gauge population health or optimize responses to short-term or recurring threats (Caughley 1994; Krebs 2002). Similarly, monitoring plans typically detail the effort needed to obtain statistically robust estimates of demographic parameters, but do not evaluate how to allocate logistically and financially constrained resources to obtain the most information about population risk or management effectiveness. Most strikingly, both types of analyses are usually one-time exercises that are left behind after conservation plans are written and implemented. As a result, conservation biologists often abandon on the planning table valuable tools capable of generating biological assessments of population status through time and of the likely outcomes of decisions about monitoring and management plans.

A more powerful use of these statistical and modeling tools is to integrate them directly into the chain of adaptive monitoring and management decisions that really

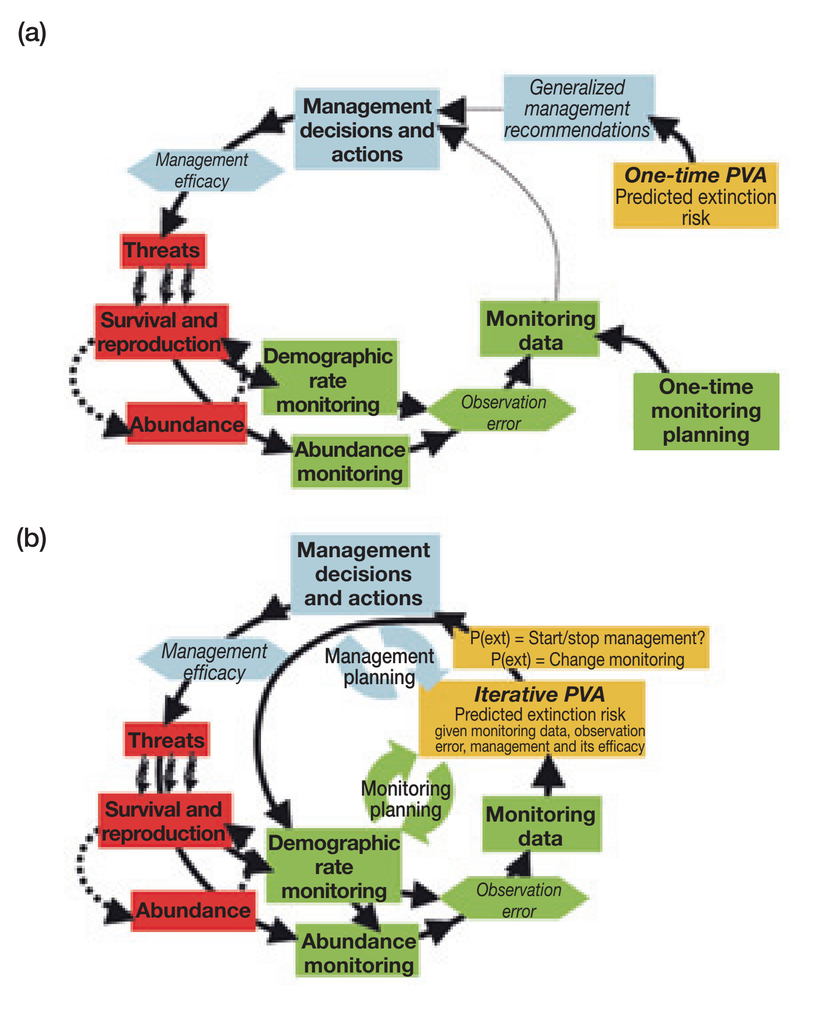

Figure 1. *Population viability management (PVM) versus population viability analysis (PVA). (a) Adaptive management consists of management decisions (blue) based on monitoring data (green) to reduce threats to at-risk populations and to ensure their long-term viability (red). PVA (yellow) has conventionally been a one-time exercise, yielding generalized recommendations without explicitly accounting for the influences of data uncertainties and management actions on viability predictions, and management decisions are typically based on statistical trends in abundance or demographic rates. (b) In PVM, PVA is integrated into the adaptive management cycle. Ongoing population status is assessed using viability predictions based on monitoring data (eg Figure 2). PVM can also guide the development of conservation plans by predicting risks associated with different monitoring and management scenarios (ie planning feedback loops; Figure 3 offers an example). All risk predictions account for uncertainty, monitoring precision, and, where appropriate, management effectiveness.*

occurs in conservation (Figure 1b). Here, we propose that the development and iterative use of models that simulate and link population dynamics, monitoring, and management activities can broaden traditional PVA into a tool capable of guiding detailed management and monitoring decisions, making adaptive management more rigorous and effective. We call this conservation tool Population Viability Management (PVM).

We illustrate PVM with the case of the island fox (*Urocyon littoralis*), an endangered species found only on the Channel Islands of California, which recently experienced catastrophic declines due to golden eagle (*Aquila chrysaetos*) predation (Figure 4) and exotic disease (Roemer *et al.* 2001; USFWS 2004). Managers had developed a PVA (Coonan 2003) for foxes that provided guidance on the demographic rate most important to population growth rate (adult survival) and the maximum allowable mortality rate for maintaining population stability (~ 20% for adults). However, it was unclear how to translate these general results into the specific guidance needed for detailed recovery planning. In response to these needs, we developed a PVM system to provide guidance on a broad range of questions, including what type of monitoring data should be collected (and with what precision) to assess recovery status, what level of monitoring was needed to detect and effectively respond to eagle predation and disease threats, and, more broadly, how adequate existing management tactics were for controlling threats to fox viability.

Our PVM approach builds on recent developments in the management of marine harvesting, in which population models are linked to models of the stock assessment process and of alternative harvest quota systems (Butterworth and Punt 1999; Punt and Donovan 2007). Some fisheries are now being managed using this approach (eg Plaganyi *et al.* 2007), and several authors (eg Harwood and Stokes 2003; Halpern *et al.* 2006) have argued that this framework, including its focus on comprehensive consideration of uncertainty, should be extended to terrestrial species management. While it has begun to play a role in evaluations of terrestrial harvest strategies (eg Milner-Gulland *et al.* 2001; Bradshaw *et al.* 2006; Nichols and Williams 2006), for which the links between management, monitoring, and population dynamics are clear and direct, there are few or no examples of the use of this type of adaptive management framework for the conservation of unexploited species. In PVM, we adapt this framework to the dominant tools and goals of managing rare species, which revolve around assessing and counteracting threats to population viability.

PVM: monitoring and managing for viability within an adaptive management cycle

In contrast to standard PVAs, PVM models describe not only population processes, but also alternative management actions, including their estimated uncertainties, their efficacy at reducing specific impacts, and the range of conditions under which they might be implemented. Just as critically, PVM models also simulate the monitoring systems that generate the data upon which decisions about population status and management actions are made, including the intensity of monitoring, and thus, expected observation error. Several authors have recently suggested that monitoring and management should be tied more closely to population models when developing conservation plans (Harwood and Stokes 2003; Gerber *et al.* 2005; Halpern *et al.* 2006; see also Thompson *et al.* 2000; Yokomizo *et al.* 2004; Staples *et al.* 2005; Hauser *et al.* 2006; Moore and Conroy 2006), but a clear approach for doing so has not yet been presented or tested on the ground.

PVM's strengths arise from its use of extinction risk, or other closely related measures of viability, as a clear, consistent, and biologically relevant measure of changing population status. Conventionally, monitoring data are analyzed statistically, yielding, for example, estimates of trends in abundance or adult survival rates – numbers that are obviously important for population health, but that are not directly interpretable in terms of viability or easily merged together to form a single, consistent measure of progress or endangerment. In contrast, when monitoring systems are simulated along with population dynamics, the results can be used to tie monitoring data directly to viability, while accounting for both natural variation in population parameters and uncertainty in monitoring information. Thus, monitoring systems rooted in PVM should yield fewer false alarms or premature celebrations. For example, Staples *et al.* (2005) showed that assessing monitoring data using a count-based PVA and comparing risk predictions through time was a more powerful way to detect worrisome or encouraging population behavior than even the most liberal criteria for statistical trends. While some have criticized the quantitative accuracy of risk predictions from PVA models (Fieberg and Ellner 2000; Coulson *et al.* 2001), by comparing risks relative to each other, PVM draws on the documented strengths of PVA (Lindenmayer and Possingham 1996; McCarthy *et al.* 2003).

Predictions of extinction risk from these linked population, monitoring, and management models can allow evaluations of alternative monitoring and management plans, and also of short-term decisions in response to new threats. For example, using this approach, managers can decide how to allocate resources to each of several monitoring efforts, based not on the statistical precision in individual point estimates, but on the precision of extinction risk estimates derived from joint analysis of all monitoring information. Similarly, alternative management actions, including their timing and intensity, can be compared, based on the predicted risk of extinction for each. A substantial marine harvest literature argues that this type of whole-system modeling is the best way to implement a precautionary approach to resource management (Punt 2006). To evaluate monitoring and management plans in this way, modelers and managers must explicitly tie what is really seen – monitoring data – to alternative management actions. That is, they must develop scenarios in which monitoring data of a given precision triggers a management action of an expected efficacy. We have found that this process of considering the entire management–monitoring system via PVM is itself beneficial, as it clarifies the thinking of both modelers and managers. Ultimately, this evaluation produces a justifiable roadmap for adaptive management. While this forecasting role of PVM models assists with planning future actions, risk predictions from each year's monitoring data also allow continual reassessment of the effectiveness of implemented management actions.

An integrated PVM approach synthesizes our best understanding of the conservation system, including its uncertainty, and facilitates updates to this understanding with the acquisition of new data on population demography and threats, and with changes in management approaches. This updating feature is essential to interpreting monitoring data optimally for status evaluations and decision making (Butterworth 2007). It is also critical to tailoring the goals and procedures of monitoring programs to real, on-the-ground, biological management issues, rather than attainment of generalized statistical goals (Dimond and Armstrong 2007).

PVM for the island fox

To illustrate the PVM approach, we summarize some of the analyses we have performed for the island fox. To date, the PVM system we have developed for the fox has been used to set draft recovery criteria for delisting and to inform a long series of management and monitoring decisions (Spencer *et al.* 2006; Island Fox Recovery Coordination Group 2007; Rubin *et al.* 2007).

The island fox occurs as six distinct subspecies, each endemic to one of the Channel Islands off the coast of southern California. We based our models on a detailed analysis of mark–recapture data from fox populations on four of the islands, along with data on reproductive success, movement, and environmental variables. Using these analyses, we built an age-structured demographic model that features: negative density dependence, environmental stochasticity in survival due both to weather-induced variation and to unexplained process variance, and full consideration of both model and parameter uncertainty (Bakker *et al.* in press).

Setting recovery goals

One of the simplest uses of the PVM framework is to establish criteria for evaluation of monitoring data and, thus, population status. Working with the island fox recovery team, we have used such an approach to define recovery standards that are directly linked to extinction risk (Figure 2). Like all conservation decisions, the selec-

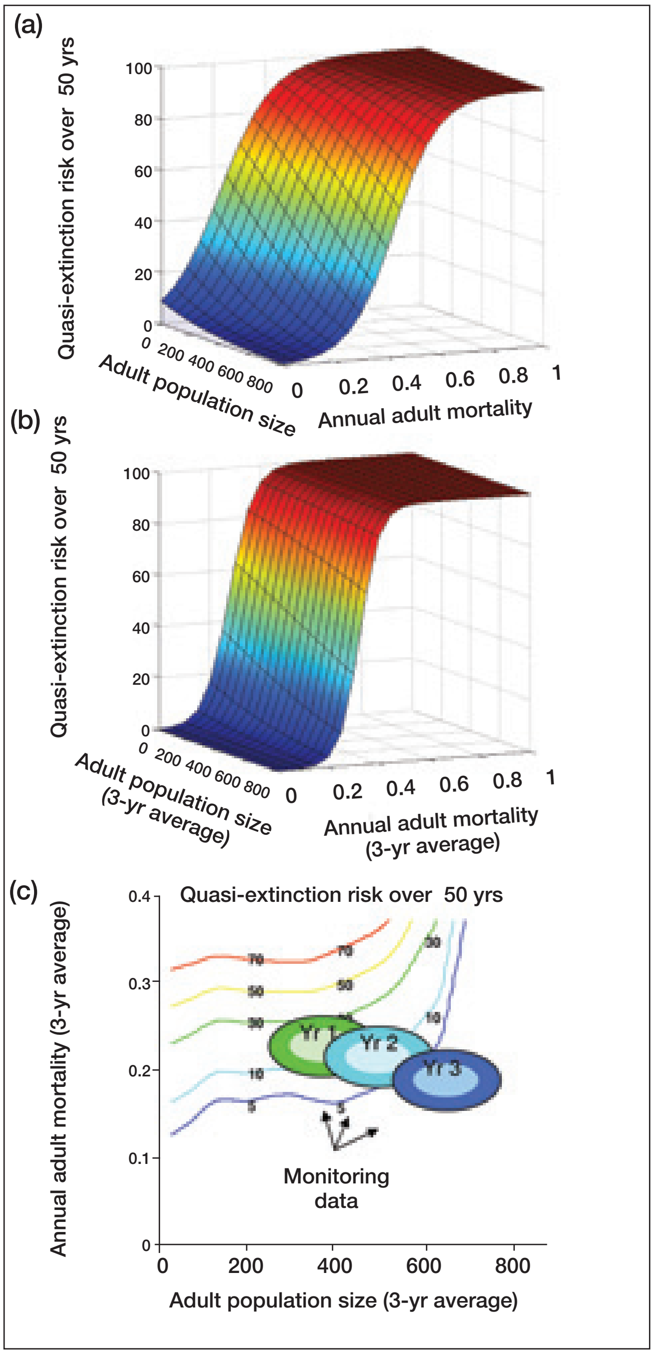

Figure 2. *PVM for assessing endangered species recovery. Relationship between 50-year risk of quasi-extinction and (a) annual or (b) 3-year-averaged demographic conditions of adult island foxes on Santa Cruz Island. The steeper rise in risk for time-averaged data indicates a greater ability to distinguish safe versus risky conditions. The recovery criterion chosen by island fox managers, in partnership with model developers, was 3-year averaged adult mortality and adult population size consistent with a 5% risk of quasi-extinction over 50 years. This was depicted as (c) an isocline figure showing extinction risk as a function of monitoring data. To control for uncertainty in monitoring data, managers required that 80% confidence regions fall below the risk criterion. In the hypothetical monitoring data shown, notice that, for the same underlying demographic conditions, managers employing a more precise monitoring system will meet the delisting criterion before those opting for less precise and less expensive monitoring. Nonetheless, both approaches would eventually lead to delisting of a recovering population.*

tion of recovery criteria is informed by complex sociopolitical and biological processes. In the case of the fox, recovery criteria were chosen during a 2-day workshop that allowed communication among model developers, biologists, and managers, and ensured mutual understanding of the general workings of the models, the ecology of the fox, and the needs and constraints of managers.

We considered criteria that have a strong influence on population viability and that are readily monitored – specifically, mortality rates and fox densities (Bakker *et al.* in press). We established a relationship between extinction risk and these parameters by performing a series of stochastic population simulations and then assessing the degree to which current survival rates and population sizes (island-wide population sizes were used because models assumed homogeneous densities) could predict the probability of quasi-extinction in 50 years. Specifically, for each island we simulated 1000 50-year trajectories under a range of eagle-driven mortality rates and starting population sizes. We then performed logistic regressions ($n \geq 85\,000$) using observed starting demographic parameters to predict whether a population would hit the defined quasi-extinction threshold of 30 individuals within within 50 years.

We investigated a variety of ways to increase the power of monitoring data to predict extinction risk, including use of annual or time-averaged data (2-year, 3-year, or 5-year averaged data) and the use of single or multiple monitoring parameters for specific age groups (adults or all ages). Examination of support for these model forms (eg Table 1) and discussions concerning the feasibility of accurately monitoring pups led our group to settle on the use of adult mortality rates and adult population size, each averaged over 3 years. Averaging reduces the effect of strong annual variance in rates to better extract signal from noise (compare Figure 2a and 2b), and adults are easier to monitor without bias, both logistically and economically. Uncertainty in the monitoring system was addressed simply, by requiring that measured parameters, including their entire 80% confidence intervals, fall below the 5% risk isocline to qualify for delisting (Figure 2c). Managers further required that this criterion be met for 5 years to ensure sustained progress towards recovery.

This approach provided a uniform and objective biological criterion, but also allowed for flexibility to accommodate the different priorities and budgets of individual land managers. For example, some managers could implement lower intensity, and thus less expensive, monitoring programs, but the reduced precision could delay the time to delisting (Figure 2c). We initially preferred a more direct and elegant way of incorporating monitoring uncertainty into recovery contours by simulating monitoring systems of varying precision and using the "observed" demographic parameters to define extinction risk contours. However, managers strongly preferred plotting each year's monitoring data and associated uncertainty themselves, using a single set of contours for each population that were not themselves a function of monitoring effort. This is one example of how the close communication inherent to PVM yields approaches that work best for the managers who must then implement them.

Table 1. Comparison of models used to predict extinction risk based on demographic rates

Model	*AIC*	*△AIC*	*k*	*Deviance*
$N_{ad} + M_{ad} + N_{ad}*M_{ad}$	95 992.3	0.0	4	95 984.3
$N_{ad} + M_{ad}$	96 038.3	46.0	3	96 032.3
M_{ad}	96 790.8	798.5	2	96 786.8
N_{ad}	147 886.9	51894.7	2	147 882.9
N_{tot}	158 573.8	62581.5	2	158 569.8

Notes: Here, we considered 3-year averages of: adult population size (N_{ad}), total population size (N_{tot}), and adult mortality (M_{ad}). We disregarded total mortality as a potential predictor because it is not currently feasible to obtain an unbiased measure of pup mortality. k = number of parameters.

Monitoring and managing ongoing threats

We next used the PVM approach to model the interacting influences of monitoring and management of golden eagle predation on fox viability, taking into account the efficacy and uncertainty of threat abatement options. In these analyses, we simultaneously evaluated several components of the eagle management system, which consists of attempting to capture and remove eagles after eagle predation of radiocollared foxes is detected. Given the potential for continued arrival of new eagles to the islands, balancing future population safety with monitoring and management costs is a key concern of managers. Because mobilizing and sustaining equipment and personnel is costly, eagle control efforts are only initiated when eagle predation rates are deemed "unsafe", and they are continued until threats are reduced to a level assumed to be "safe". Risk of extinction provides a biological metric of population safety, and thus serves as a planning tool for evaluating potential trigger points for management action and for comparing the relative efficacy of different allocations to monitoring and management effort.

To address these issues, we simulated the demography of fox populations as influenced by changing eagle numbers, with monthly eagle colonization or recruitment probabilities treated as a Poisson variate and based on the estimated pattern of annual eagle increases prior to eagle control from 1991 to 1998 (ie 1 1 1 2 5 2 2 7; Latta 2005), with up to a maximum of 30 eagles supported on the northern islands. On top of this process, we simulated known fate mortality monitoring using 40 or 80 radiocollars, with and without the additional monitoring of annual population size (with 20% coefficient of variation; Rubin *et al.* 2007). "Observed" demographic conditions were converted to predicted extinction risk, based on the logistic regressions developed for recovery criteria (above). In each simulation, we used these results to trigger eagle removal efforts at predicted extinction risks of 0.25, 0.20, 0.15, 0.10, 0.05, or 0, coupled with different triggers to stop removal efforts. Finally, we simulated three eagle management intensities based on a logistic regression relationship between hours of effort and probability of eagle capture. Given the historically poor capture success, we simulated eagle control equal to the highest effort expended to date, as well as efforts 50% and 100% greater than this. Eagle colonization, collection of monitored mortality data, start–stop management decisions, and eagle capture success were all summarized monthly. For each of the 216 scenarios, we simulated 2000 replicate runs, with each run consisting of a 50-year population trajectory.

Sparse or poorly targeted monitoring may fail to detect true population declines and delay threat abatement actions, making inadequate monitoring efforts inherently risky. We found that use of abundance monitoring, in addition to radiocollar mortality monitoring, substantially increased the precision of risk predictions (thereby allowing managers to initiate eagle control later and end eagle control sooner), but that increasing the intensity of mortality monitoring was somewhat less effective in this regard (Figure 3). For the conditions considered here, however, no amount of increased vigilance could offset the gains of enhanced management efficacy. The clearest message from our analyses was that more intense or more effective eagle control methods are needed to reduce extinction risks to acceptable levels (Figures 3, 4). Current levels of effort always result in extinction risks $\geq$ 50%, regardless of the monitoring system or the triggers for management action. The PVM results predicted that reasonable safety was only achieved when current efforts were doubled. While it is hardly surprising that increasing management efficacy reduces extinction risk, the message that existing capture efforts are simply insufficient for long-term safety was unexpected and of direct management importance.

Based in part on these analyses, managers of the island fox recently brought in a helicopter net-gunner to attempt eagle capture; this qualitatively different – and potentially far more effective – method of eagle capture has met with early success. These results have also helped to convince managers to continue abundance monitoring in addition to radiocollaring of individual foxes.

Expansion and improvement of PVM

The basic concepts of PVM are applicable to a wide variety of monitoring and management problems. We have presented just a few examples of the ways in which we have used PVM approaches to aid planning for the island fox. We used similar techniques to assess the value of captive breeding programs for island fox viability and, in par-

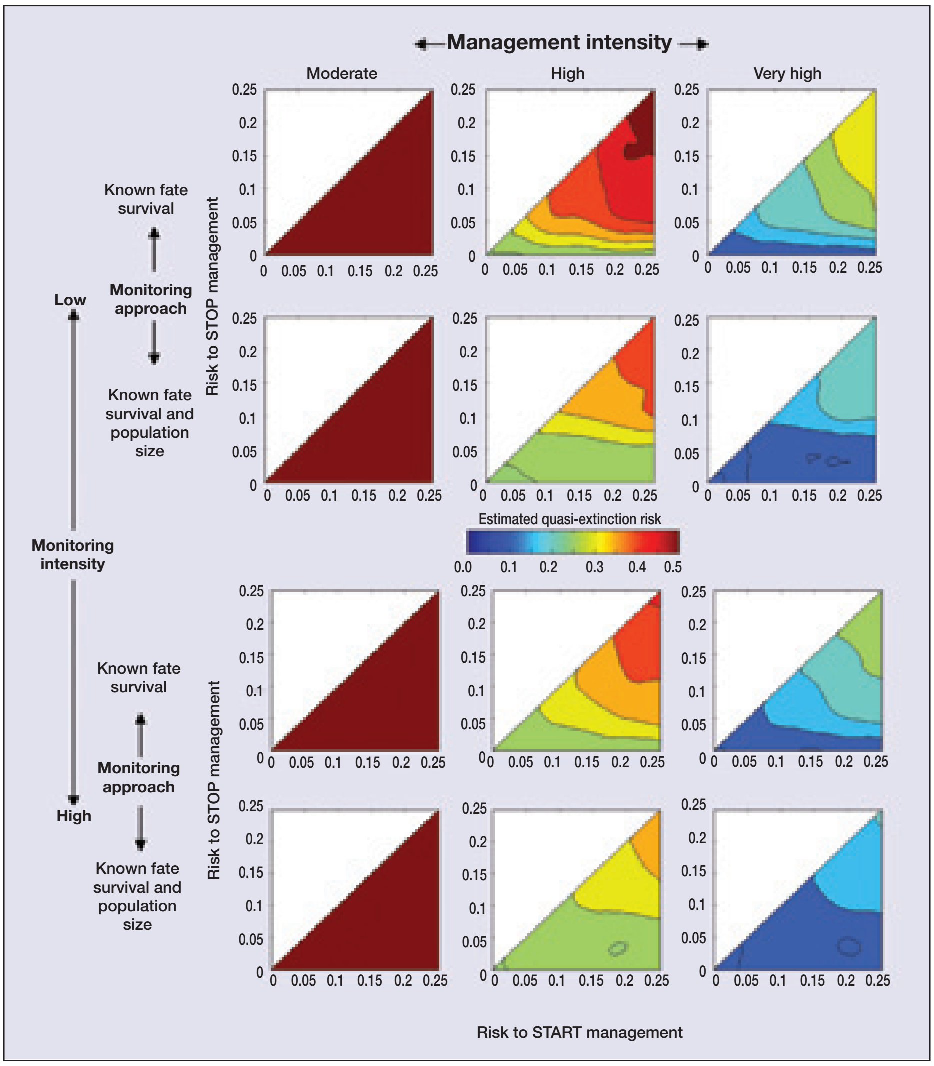

Figure 3. *PVM can be used to compare monitoring and management options relative to their effects on population viability. Here, PVM was used to compare approaches for detecting and abating golden eagle predation on island foxes, using predicted 50-year quasi-extinction risks under a range of scenarios: 18 start–stop management risk triggers, three levels of management intensity (equal to, 50% greater than, or 100% greater than the highest effort expended to date, labeled moderate, high, and very high, respectively), two monitoring approaches, and two monitoring intensities (40 or 80 radiocollars, plus annual population size estimates with CV = 20%). The 12 panels compare the simulated extinction risks associated with initiating eagle control when observed demographic conditions predict extinction risks ranging from 0.25 to < 0.05 and continuing control until risk is reduced to a lower level, using 2000 replicate runs for each scenario. Uncertainties in fox demography, eagle arrival numbers, monitoring, and management efficacy are incorporated into ultimate risk predictions. Colors in the lower left corner of each graph indicate the risk attainable when eagle control at the specified intensity occurs continuously (ie start management when risk > 0 and stop when risk = 0).*

ticular, to identify optimal release strategies and demographic conditions favoring closure of captive breeding programs, an issue of particular concern to managers, due to high operational costs. Similarly, we have used PVM to compare disease management approaches as disparate as surveillance and response and prophylactic vaccination, again using extinction risk as a common metric of management efficacy.

Future work is needed to expand these ideas to other modeling approaches, including census-based models (Staples *et al.* 2005), metapopulation models, and spatial models with individual movement. New technologies, such as MODIS satellite data and GPS collars, provide nearly continuous updates of changing environmental conditions and the status and habitat-use patterns of monitored individuals. By modeling predicted responses to changing conditions and updating these models with monitoring data, PVM techniques can take advantage of this rich data stream to refine system knowledge and test hypotheses about species management in an adaptive framework.

While PVM allows the use of varied data types and amounts to make well-justified management decisions, it also requires careful use of contemporary statistical techniques to fully utilize incoming data, in particular to make valid estimates of observation uncertainty, as well as of the mean and variance of biological processes (eg Kendall 1998; Millar and Meyer 2000; White 2000; Burnham and Anderson 2002). Like any other adaptive management approach, PVM requires a consistent monitoring program, and although it can use low-intensity monitoring data (eg simple count data), it will be most effective when paired with a high-quality monitoring program. For species with extremely limited data, the PVM approach will have to be modified to better utilize data collected on related species or other indirect monitoring efforts. Although these situations are certainly more challenging than those with better-funded monitoring programs, thinking about them in a PVM framework can nonetheless help to clarify the degree of uncertainty in the expected biological outcomes of conservation decisions and to identify the best allocation of limited monitoring resources.

Another key issue in conservation management – cost trade-offs – is not an explicit feature of our PVM analyses, except in the exclusion of management and monitoring options that were financially prohibitive. While considering costs in trade-off decisions is vital to managers, cost is distinct from, and generally subordinate to, extinction risk as a primary criterion with which to judge priorities for managing rare species. Cost evaluations are most meaningful after PVM analyses have defined ecologically relevant and defensible monitoring and management combinations. Even then, the different sources of funds available for specific management or monitoring activities argue against a one-size-fits-all analysis of costs. Nonetheless, the ability of PVM to define clear, bottom-line viability needs can be blended with realistic cost analyses to better integrate economic needs with the requirements of a successful conservation strategy.

Figure 4. *Golden eagle predation is one of the primary threats to foxes that managers on the northern Channel Islands seek to control. Here, a golden eagle chick that was captured from a nest on Santa Cruz Island is surrounded by the remains of numerous radiocollared and uncollared foxes.*

Overall, PVM can provide a platform for adaptive decision making, so that, as knowledge increases and conservation and management challenges change, key decisions can be updated to better reflect the newest realities. Although we have emphasized the integration of models of population dynamics, monitoring, and management, the PVM approach also relies on effective communication among field biologists, managers, and modelers. This is needed partly to help modelers lacking field experience in a particular system to appreciate key issues – biological, logistical, or otherwise – and partly to allow decision makers the time and training to understand the outputs of sometimes complex analyses. Increased communication also allows analysts to adapt PVM to rapidly changing conservation situations, in which results that were of extreme importance 6 months ago are often completely irrelevant in the present, and new results are required. Finally, biological and political judgment will always be needed to interpret PVM results, frequently requiring multiple rounds of explanation and refinement to integrate results into decision-making frameworks. PVM's requirement for strengthened communication between practitioners and scientists through the "handshake approach" (Bormann *et al.* 2007) is one of its key advantages. Forging these partnerships will allow us to improve conservation planning for rare species, reducing our failures and allowing us to better understand our successes.

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WebTable 1. Comparison of models used to predict extinction risk based on demographic rates

Model	*AIC*	*△AIC*	*k*	*Deviance*
Nad + Mad + Nad*Mad	95992.3	0.0	4	95984.3
Nad + Mad	96038.3	46.0	3	96032.3
Mad	96790.8	798.5	2	96786.8
Nad	147886.9	51894.7	2	147882.9
Ntot	158573.8	62581.5	2	158569.8

Notes: We considered 3-year averages of adult population size (Nad), total population size (Ntot), and adult mortality (Mad). We disregarded total mortality as a potential predictor because it is not currently feasible to obtain an unbiased measure of pup mortality. k is number of parameters.

