



A Strategy for Monitoring and Managing Declines in an Amphibian Community

EVAN H. CAMPBELL GRANT,* ELISE F. ZIPKIN,† JAMES D. NICHOLS,†
AND J. PATRICK CAMPBELL‡

*U.S. Geological Survey, Silvio O. Conte Anadromous Fish Laboratory, 1 Migratory Way, Turners Falls, MA, U.S.A., email ehgrant@usgs.gov

†U.S. Geological Survey, Patuxent Wildlife Research Center, 12100 Beech Forest Road, Laurel, MD 20708, U.S.A.

‡Center for Urban Ecology, National Park Service, 4598 MacArthur Boulevard NW, Washington, D.C. 20007, U.S.A.

Abstract: *Although many taxa have declined globally, conservation actions are inherently local. Ecosystems degrade even in protected areas, and maintaining natural systems in a desired condition may require active management. Implementing management decisions under uncertainty requires a logical and transparent process to identify objectives, develop management actions, formulate system models to link actions with objectives, monitor to reduce uncertainty and identify system state (i.e., resource condition), and determine an optimal management strategy. We applied one such structured decision-making approach that incorporates these critical elements to inform management of amphibian populations in a protected area managed by the U.S. National Park Service. Climate change is expected to affect amphibian occupancy of wetlands and to increase uncertainty in management decision making. We used the tools of structured decision making to identify short-term management solutions that incorporate our current understanding of the effect of climate change on amphibians, emphasizing how management can be undertaken even with incomplete information.*

Keywords: climate change, management, monitoring, structured decision making, uncertainty

Estrategia para Monitorear y Manejar Disminuciones en una Comunidad de Anfibios

Resumen: *Aunque muchos taxones han declinado globalmente, las acciones de conservación son inherentemente locales. Los ecosistemas se degradan aún en áreas protegidas, y mantener sistemas naturales en una condición deseada puede requerir de un manejo activo. Implementar decisiones de manejo bajo incertidumbres requiere un proceso lógico y transparente para identificar objetivos, desarrollar acciones de manejo, formular modelos de sistemas enlazando acciones con objetivos, monitorear para reducir la incertidumbre e identificar estados de sistema (p. ej.: condición del recurso) y determinar una estrategia óptima de manejo. Aplicamos una aproximación de toma de decisiones estructurada de esa manera, que incorpora estos elementos críticos para informar al manejo de poblaciones de anfibios en un área protegida manejada por el Servicio de Parques Nacionales de Estados Unidos. Se espera que el cambio climático afecte la ocupación anfibia de humedales y que incremente la incertidumbre en el manejo de la toma de decisiones. Usamos las herramientas de la toma de decisiones estructurada para identificar las soluciones del manejo a corto plazo que incorporen nuestro entendimiento actual del efecto del cambio climático sobre los anfibios, enfatizando cómo el manejo puede sobrellevarse incluso con información incompleta.*

Palabras Clave: cambio climático, incertidumbre, manejo, monitoreo, toma estructurada de decisiones

Introduction

Faced with complex conservation problems, limited resources, and multiple sources of uncertainty, managers

need a means to select appropriate management actions. It is widely recognized that increased information about a system can lead to better management decisions, where information may be obtained via monitoring. However,

all information and monitoring programs are not equal with respect to their contributions to either resolve scientific uncertainty or inform conservation decisions. Monitoring is most useful to conservation when it is designed for, and embedded within, a larger program of action-oriented management (Yoccoz et al. 2001; Nichols & Williams 2006; Lyons et al. 2008). Unfortunately, few examples of the deliberate incorporation of monitoring into management decisions exist, especially for management programs focused on local resources. Instead, a common approach to conservation is uncertainty-induced inaction in which managers rightly identify important sources of uncertainty associated with conservation decisions and wrongly (in our opinion) conclude that new or additional monitoring will eventually cause such uncertainty to fall away from the decision. The expectation is that more information will identify a single action that, when implemented, will advance conservation or reverse degradation in resource conditions. In reality, uncertainty is never eliminated completely, so the decision to wait and collect more information is itself a management decision that delays implementation of other actions that could improve conditions of local resources.

Structured decision making (Clemens & Reilly 2001; Martin et al. 2009) offers a logical means by which to develop decisions under uncertainty. In providing a transparent and objective approach to decision making, this approach clarifies what kinds of information are most useful to the decision (Runge et al. 2011), which then provides clear guidance for the development of a monitoring program. Here, we relate our experiences working on a community of wetland-breeding amphibians in the Washington, D.C. area of the United States (hereafter National Capital Region), where we anticipate that the amphibian community may be affected by both landscape and climate change. We emphasize that management can be undertaken even with incomplete information on the system and show how the steps of structured decision making can be used to develop effective monitoring that meets the information needs of management.

Management of Amphibians in National Capital Region Parks

Lands managed by the U.S. National Park Service (NPS) in the heavily urbanized Washington, D.C. area are becoming increasingly isolated from other natural areas, such that factors internal and external to park boundaries may threaten park resources (Carter et al. 2006). National park managers are directed by federal law and NPS policies to determine the status and trends of natural resources under their stewardship. Accordingly, the NPS developed an Inventory and Monitoring Program for selected indicators of the condition of park ecosystems (Fancy et al. 2009).

Explicit in the goals of the NPS Inventory and Monitoring Program is to provide information useful for improving park management (Oakley et al. 2003).

The National Capital Region network, and specifically the Chesapeake and Ohio Canal National Historical Park (CHOH), identifies amphibians as a priority taxonomic group for monitoring (National Park Service 2005). Managers of CHOH were concerned that amphibians in the park were at risk of extirpation because of increasing urbanization adjacent to the park boundary and the potential for additional climate change-induced ecosystem degradation. Although habitat loss is generally cited as a leading cause of decline in amphibian populations (Cushman 2006), even populations in protected areas have declined (Corn & Fogleman 1984; Drost & Fellers 1996; Halliday 2005; Adams et al. 2013). Forecasts of climate change across the region (Hayhoe et al. 2007; Huntington et al. 2009) lead to the prediction that amphibians will face multiple interacting climate stressors, such as decreased and more variable summer precipitation, that may limit their persistence even in protected areas. In response to these concerns, an amphibian monitoring program was implemented in 2005 to develop an understanding of the distribution and occupancy dynamics of amphibians in wetlands across the park and to inform management decisions (National Park Service 2007).

Use of a Structured Approach to Decision Making

Structured decision making has 5 basic elements: clearly defined management objectives; a set of management actions that may be used to achieve stated objectives; a model or models linking management actions to outcomes and objectives; a monitoring program to estimate system state and reduce uncertainty; and a decision algorithm (e.g., an optimization method) to derive state-specific decisions (Williams et al. 2002). The foundations for these elements were developed during a workshop that brought together park managers, researchers from the U.S. Geological Survey Amphibian Research and Monitoring Initiative (ARMI), The Nature Conservancy staff, and the National Capital Region network coordinator and staff. During this workshop, participants identified ecosystem stressors to the CHOC, developed management objectives for amphibian populations within the park, identified a set of potential management options, and began to develop conceptual models linking the management actions to the objectives. In addition, participants discussed the effectiveness of the amphibian monitoring program initiated in 2005, and adaptation of this monitoring program to better inform the specific decisions of this structured decision making process. Under the existing monitoring program, 2 independent observers sampled 33 randomly chosen wetlands on

4 occasions annually through 2009, between March and July, and recorded each species encountered at each wetland. In 2010 and 2011, an additional 30 wetlands were sampled. These data were useful in developing models of system response to management actions. This workshop provided a framework for informing conservation decisions and formed the basis for continued interaction among participants.

Clear Management Objectives

The first step is to identify objectives that are of fundamental importance to the decision maker. Development of objectives is necessarily informed by values of the decision maker and relevant stakeholders. During the workshop, the resource manager acknowledged that amphibians are under global threat of decline and that CHOH represents an isolated system of wetlands in an otherwise urbanized region. Accordingly, he decided that the maintenance of amphibian species in CHOH, measured in terms of species richness (number of species occupying wetlands), was of fundamental importance. Multiple objectives may be identified if additional components of a system are fundamentally important. For example, we discussed including a separate objective for maximizing diversity in wetland characteristics (e.g., hydroperiod, vegetation, and size), but ultimately the decision maker decided that the desire to achieve this objective was more appropriately a means to maximize amphibian species richness; thus, we did not consider this objective further.

We discussed 2 ways of specifying the NPS objectives, which included both management costs and metrics reflecting amphibian well-being. The first approach specified that some threshold of average species richness has been exceeded (Martin et al. 2009). We focused on specifying a utility threshold (i.e., the manager's satisfaction with the outcome). For example, we might specify a desired number of amphibian species in the system as a utility threshold. The management objective over the long term might be to maximize the number of years for which the system contained at least this number of species. Under this utility threshold approach, we specified the objective as minimizing management cost or effort, conditional on maintaining this specified level of species richness. The richness level selected as the utility threshold was developed on the basis of 2005 estimates of wetland-specific species' richness (the first year for which this information is known). Use of such a utility threshold generally leads to management strategies that keep the state variable (in our case, species richness) at levels that ensure a relatively low probability of it dropping below the threshold in the next time step. Thus, greater uncertainty leads to larger distances between richness and the threshold. Alternatively, one might attempt to maximize amphibian species richness of wetland habi-

tats within the park conditional on available funds. We decided against this second specification because limited resources can be devoted to other projects in years where the system state does not suggest management actions are necessary.

The focus on species richness means that all species have the same value in the community. This was reasonable for our decision because there are no rare, threatened, or endangered species at CHOH, and thus the manager valued each species equally. The objective may change as more monitoring data are collected. For example, species may decline at different rates, and this information may affect the relative importance of one or more species. Differences in the relative value of each species can be accommodated by adding weights to the occupancy probabilities for each species in proportion to their value to resource managers (Yoccoz et al. 2001).

Identify Potential Management Actions

Management alternatives should be developed after the objective(s) are identified, as they are focused directly on achieving the fundamental concerns of a resource manager. A number of techniques are available to aid identification of appropriate management options (e.g., Gregory et al. 2012). All of them focus on generating alternatives that address the fundamental objective or objectives, challenge perceived constraints, and are distinct, such that trade-offs may be assessed with respect to the ability to achieve the objectives. During the workshop, participants identified several potential management actions they based on existing hypotheses of the relation between amphibian occupancy and landscape features, including create new wetlands, change hydroperiod (i.e., duration a wetland has surface water) of existing wetlands, translocate animals among wetlands, manage forested areas including removing invasive plant species surrounding wetlands to increase potential juvenile and adult survival and connectivity among wetlands, or take no action.

Of the 274 wetlands in the Potomac Gorge region of the park (focal area for management and the southernmost 16 miles of the park), approximately 78% are temporary and dry every year during the late summer, 8% are semipermanent, drying every few years on average, and the remaining 14% are permanent and never dry. Climate predictions for the region show that precipitation may become increasingly variable, especially during the amphibian breeding season (Hayhoe et al. 2007; Huntington et al. 2009); thus, semipermanent wetlands in particular may become more temporary. Hydroperiod is one of the primary wetland characteristics associated with amphibian species occupancy (Skelly et al. 1999; Snodgrass et al. 2000; Babbitt 2005), and different species' assemblages are associated with particular hydroperiods (Wellborn

et al. 1996), in part because of variations in life-history characteristics. This association suggests species richness is maximized in landscapes with a diversity of wetland hydroperiods (Snodgrass et al. 2000).

Because the park has limitations on disturbance of forest (mainly because of the density of cultural resources) and few wetlands exist in the heavily urbanized region outside of the park, resource managers chose to capitalize on natural topography and water flow by modifying existing wetlands. This naturally led to a decision process with 2 potential management actions: manipulate hydroperiod of existing wetlands conditional on available funds or take no action.

Management Models

Successful management requires the ability to predict consequences of each action with respect to the objectives, under models dictated by the a priori hypotheses of the investigator. In structured decision making, relevant hypotheses and their models focus on the selected management actions and other potentially important environmental covariates. Thus, we developed a model that predicted species richness (our objective) as a function of key variables that may be affected via management. We also sought to include key covariates that are not controlled by management but that are nonetheless considered important for predicting amphibian occupancy. Although there are many potentially important covariates not considered in our model, we focused on what we thought were dominant controls on amphibian species richness and on variables that may be affected by management. In our case, the decision to take management actions to manipulate hydroperiod was based on hypotheses about the potential relevance of this factor and on the ability of managers to manipulate this wetland feature. We used our monitoring data to develop our initial models that linked hydroperiod to occupancy dynamics.

To determine species richness in wetlands, we used a hierarchical modeling approach that estimates community-level attributes through annual, wetland-specific estimates of species' occupancy and detection. Under this framework, species-occurrence models that account for detection errors are linked under the assumption that species' parameters come from a common distribution in a hierarchical model (Dorazio et al. 2006; Kéry & Royle 2008). Sharing information among species leads to increased precision of parameter estimates and enhanced understanding of both species-specific occupancy dynamics and the dynamics of the entire community. This approach is especially useful for infrequently observed species for which estimates of occupancy and detection would otherwise be unattainable (Mattfeldt et al. 2009; Zipkin et al. 2009).

Our multispecies occupancy model explicitly estimates how occupancy of every species in the community is related to wetland characteristics, including hydroperiod, area, and connectivity. Therefore, the estimate of the effect of each of these variables (parameters in our occupancy models) describes the relation between occupancy and a change in each covariate. The key uncertainties relevant to management decisions involved these parameter estimates. Learning about species responses to management actions thus entails obtaining increasingly precise estimates of these relations and then using those estimates to make predictions about species occupancy, and hence richness, that results from the management alternatives. Using these estimates, we predicted how species richness would change if we changed the hydroperiod of a given wetland from temporary to semipermanent (Table 1). In addition to incorporating the wetland-specific covariates, we also explored how annual occupancy probabilities have varied and whether or not an increasing or declining trend in occupancy probability and wetland richness has been observed over the duration of sampling. Model details are available in Supporting Information. A validation of model performance is in Zipkin et al. (2012).

Monitoring Program

The shift of emphasis to active management sharpens the focus on 4 specific uses of monitoring data. The first is estimation of system state variables (i.e., species richness) in order to inform state-specific decisions. The appropriate action usually depends on the current status of the system. The second is simply to assess the degree of management success. The third is in the development of management-oriented models, which make predictions about the future state of the system. The final use of monitoring data is to facilitate learning, a role that requires further explanation. Monitoring is a critical part of adaptive resource management, a subset of structured decision making that is useful when decisions are made iteratively over time (e.g., when a management decision is made each year) and when there is uncertainty about the manner in which the system responds to management actions (Walters 1986; Williams et al. 2007). We viewed our management problem as iterative in the sense that management actions would be considered at multiple times as the program proceeded. In addition, our management model was characterized by uncertainty. For example, the key parameters of our management model were the parameters relating multispecies occupancy to the hydrological variables affected by management actions. These parameters were characterized by a sampling variance-covariance matrix that reflected our uncertainty about their exact values. Monitoring can be used to obtain updated, more precise estimates of these model parameters each year. If uncertainty about the basic form of the

Table 1. Priority ranking for management of the 214 temporary wetlands in CHOH. Wetlands were ranked by the expected gain in mean species richness (last column with SD) should the management action to increase hydroperiod (i.e., turn them into semi-permanent) be implemented for each wetland.

<i>Wetland rank</i>	<i>Average richness</i>	<i>Projected richness with proposed management action</i>	<i>Expected increase in richness due to management</i>
1	3.61 (1.49)	6.22 (1.50)	2.62 (2.05)
2	3.99 (1.51)	6.60 (1.48)	2.61 (2.04)
3	2.47 (1.33)	5.05 (1.52)	2.58 (2.00)
4	3.13 (1.45)	5.71 (1.56)	2.57 (2.07)
•	•	•	•
99	7.74 (1.55)	9.20 (1.28)	1.46 (1.78)
100	0.91 (0.88)	2.36 (1.33)	1.46 (1.61)
•	•	•	•
213	11.75 (0.52)	11.78 (0.49)	0.03 (0.25)
214	11.76 (0.51)	11.78 (0.49)	0.02 (0.25)

model arises, then these ecological hypotheses can be incorporated into the management process via the use of competing models (Williams et al. 2007). It is therefore important that the monitoring program be designed to provide information to meet the 4 purposes specified here.

The use of monitoring data to improve estimates that define relations between key environmental variables (e.g., hydroperiod, area, and connectivity) and multi-species occupancy will reduce uncertainty and thus lead to an increased ability to meet management objectives. Of secondary interest is the relation between occupancy and other key environmental variables not under management control. Better knowledge of these relations is also useful in predicting community responses to management actions and predicting future occupancy under various environmental conditions.

Decision Algorithm to Evaluate Trade-Offs

When this management program is formally implemented, the annual decision will have 2 parts. First, should wetlands be managed in the focal year or not? Second, if management is required, then conditional on available funds, how many and which wetlands should be manipulated? Optimal decisions can be derived from approaches such as stochastic dynamic programming. Other less-formal approaches are possible. For example, we may base the first decision (to manage or not) on the probability distribution of expected species richness in the next year (from the system model) in the absence of management. If there is a sufficiently high probability that richness will not exceed the utility threshold, wetland management would be warranted. In terms of the actions, we would then select wetlands to manipulate, starting with the wetlands most likely to produce increases in species richness and proceeding until we either attained a specified probability of achieving the desired richness or expended all available funds, whichever occurred first.

Program Implementation and the Price of Delay

Using existing monitoring data, we estimated a $\geq 95\%$ probability of a negative trend in occupancy for 5 out of 12 species (an additional 3 species had a probability $> 75\%$) from 2005 to 2011 (Fig. 1). We also found that average amphibian species richness in wetlands in CHOH was most affected by hydroperiod (Fig. 2) (consistent with Snodgrass et al. [2000] and Babbitt [2005]) and has declined since implementation of the monitoring program in 2005 (Fig. 3). This finding indicates support for the initiation of active management. In this case, the optimal management action is to increase the hydroperiod of a set of temporary wetlands so that manipulated wetlands retain sufficiently long hydroperiods for multiple years. This management strategy is optimal for 2 reasons. First, wetland hydroperiod was estimated to have the largest effect on richness relative to the other landscape features (e.g., wetland area or connectivity). Second, existing predictions suggest that spring and summer precipitation is likely to decrease in the CHOH region as climate changes (Hayhoe et al. 2007), which could lead temporary wetlands to become increasingly unsuitable for amphibians. We used our model to rank the 214 temporary wetlands within the park by the expected gain in species richness if the wetland were managed to increase hydroperiod to a semipermanent state (Table 1 & Supporting Information). These rankings will be used to make annual decisions on which wetlands to manipulate.

Once a decision is made to embark on a management program for a system, it is generally appropriate to initiate the program immediately. This does not mean management actions that manipulate the system (as opposed to the no-action alternative) are warranted right away, but this should be an active decision rather than tacitly assumed (as when programs are delayed). Initiation of a new management program may depend on, for example, current levels of funding and reluctance of agencies to embark on new programs. Although a formal analysis can be conducted across the range of potential time horizons

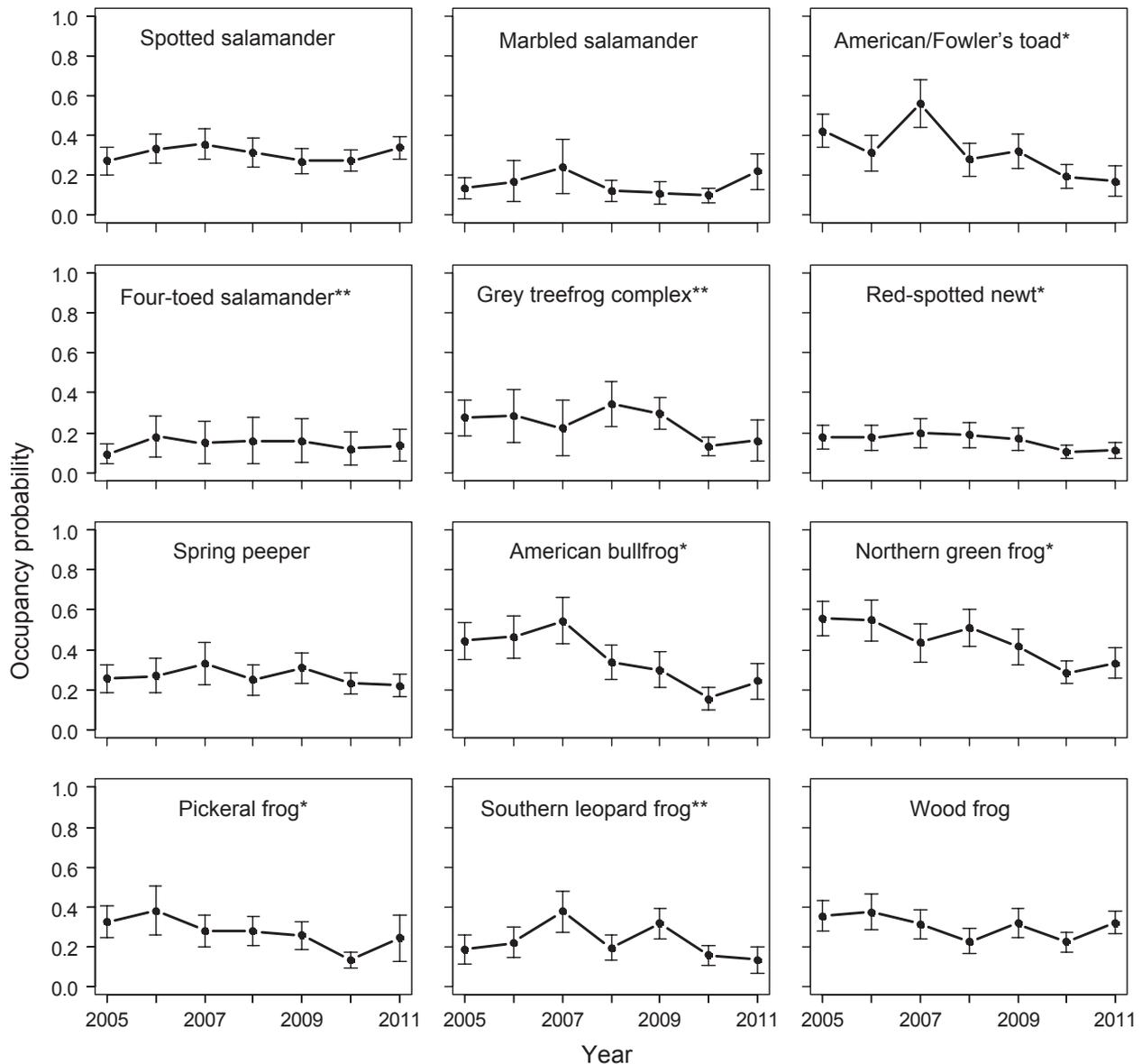


Figure 1. Average species-specific occupancy (and 1 SD) from all monitored sites as estimated from a model with no ecosystem covariates (*, species estimated to have a $\geq 95\%$ probability of a negative trend; **, species estimated to have a $\geq 75\%$ probability of a negative trend). See Supporting Information for model details.

(Martin et al. 2011), we used the species-specific trend and covariate estimates and assumptions about ranges in system response to management to illustrate the potential variation in future species richness given a management decision was implemented 1, 5, or 10 years in the future (Fig. 4). We assumed effects are realized immediately when a management action is implemented and that the state of the system is not changing over time as a result of factors other than those affected by management. In other words, we assumed no effect of climate change on the hydroperiod of each wetland. On a longer timescale, we would expect an increase in the number of temporary

wetlands and a corresponding decrease in the suitability of existing temporary wetlands for amphibian occupancy and persistence.

If management is delayed, an increasing fraction of the existing wetlands must be managed in order to meet the objective (e.g., compare the marginal benefit of implementing management in year 1 vs. year 5 relative to the utility threshold [Fig. 4]). Increasing the number of wetlands managed increases costs; thus, the objective cannot be fully realized. Monitoring will help elucidate which trajectory the system is taking (i.e., given a management action is taken in year t , what is the

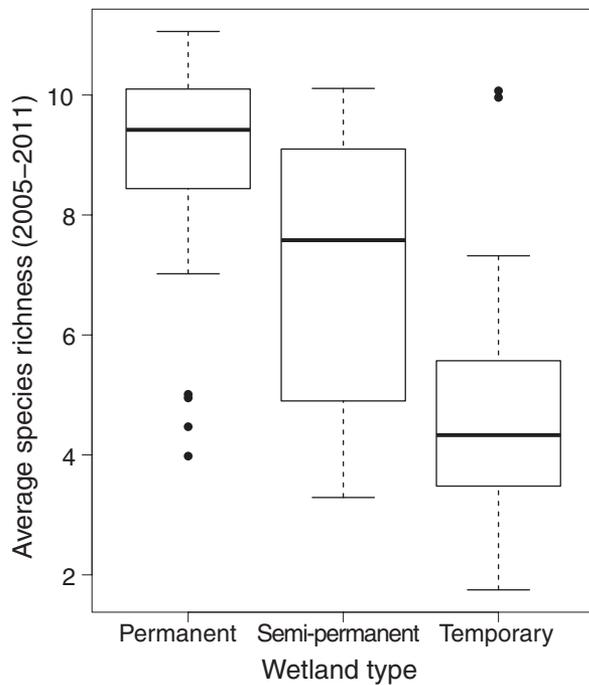


Figure 2. Variation in species richness (total number of species estimated to occur over all sampling years) in individual wetlands by hydroperiod as estimated on the basis of wetland-specific habitat variables (hydroperiod, area, and connectivity) (heavy lines in bars, median richness; top line and bottom line, middle 50% range; whiskers, 95% range; circles, outliers).

predicted response of system state) (Fig. 4). Monitoring in an adaptive-management program will help elucidate the true trajectory of the system and reduce uncertainty about the effectiveness of management actions and the responses to environmental covariates not affected by management.

Future Amphibian Conservation

Concern for natural resources, especially in protected areas such as national parks in the United States, has resulted in a general call for monitoring data on the status of animal populations at broad scales (e.g., Marsh & Trenham 2008). Although the motivations for such programs typically emphasize management utility, only rarely are these monitoring programs designed to directly inform resource management decisions; thus, these programs ultimately do not provide data that are as useful as they could be in making management decisions (Cook et al. 2009).

One approach to management is to monitor until a decline is detected and then to consider management alternatives. However, if a set of species is designated

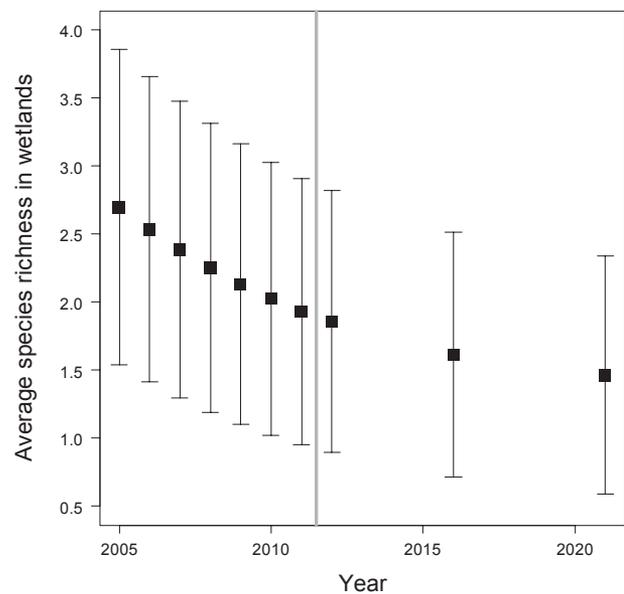


Figure 3. Average annual species richness (and 1 SD) in the Potomac Gorge region of the Chesapeake and Ohio Canal National Historical Park, Maryland (U.S.A.), projected for all 274 wetlands that occur on the landscape (see Supporting Information for details of estimation model). Points to the left of the vertical line are determined by using the estimated species-specific habitat effects (wetland hydroperiod, area, and connectivity) and the estimated trend effect and projecting occupancy probabilities to all unsampled wetlands in the region. Points to the right of the vertical line are similarly projected but under the assumption that the estimated trends in species-specific occupancy continues past the end of the sampling period.

as worthy of monitoring, then a preferable approach is to develop a management program immediately rather than wait for strong evidence of a decline. This proactive approach still incorporates the potential decision of no action at any decision point but minimizes the possibility of delaying action until it is too late for management to be of much use (Green & Hirons 1991; Nichols & Williams 2006; Martin et al. 2012). For example, a 50% decline (typically cited as a target for monitoring [Mattfeldt et al. 2009]) is a substantial decrease in occupancy for any given species, and our results suggest that by waiting to observe a decline of this magnitude, the objective of maintaining species richness may become unachievable, at least in the short term, given the management options the decision maker considered feasible.

Our monitoring program was designed to provide unbiased estimates of the status of wetland-breeding amphibian populations in the Potomac Gorge region of CHO. We used the monitoring data to identify a declining trend in occupancy of most species and to develop

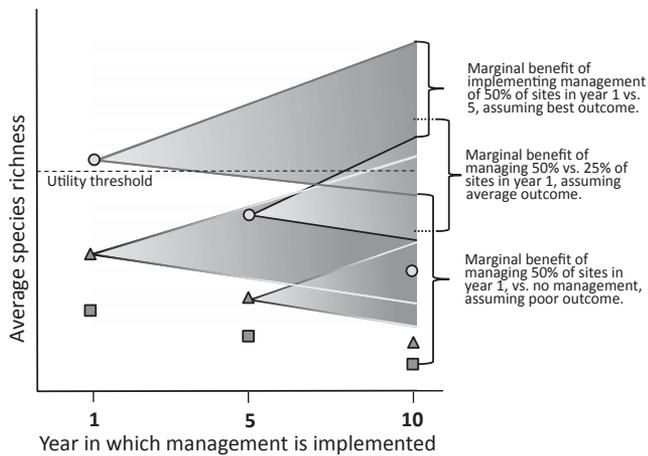


Figure 4. Expected change in average species richness, given management of 0% of wetlands (squares), 25% of wetlands (triangles), and 50% of wetlands (circles) in a given year t (where $t = 1, 5,$ or 10 years from the present). The utility threshold is the desired system state. The shaded triangles are the potential future outcomes, the true value of which depends on whether managed sites perform differently than natural semipermanent sites, effectiveness of the management action, and degree to which species richness in each wetland hydroperiod category declines at the same or different rates. For illustration, we show 3 potential outcomes.

management-oriented models to assess the efficacy of actions to halt or reverse declines. Despite uncertainties in the relation between our covariates and observed declines in occupancy and richness, we have an expectation that future climate change may exacerbate declines. Although resource managers cannot directly mitigate this long-term threat, managers can modify critical hydrological variables that are predicted to change under climate change; thus, they can provide a measure of protection.

We recognize that climate change has the potential to alter natural processes and systems, is largely outside the control of resource managers, and is characterized by uncertainty. More positively, the results of our decision analysis suggest that despite the potential for a disproportionately large effect of external stressors on park resources, managers may still be able to conserve park resources. We suggest that a proactive approach to resource management can result in more rapid learning than monitoring alone (Lyons et al. 2008) and thus increase the potential for success in meeting objectives with less management effort (Fig. 4). In the face of critical uncertainty about climate change, a focus on short-term management solutions in an adaptive-management program may provide advantages over inaction.

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Supporting Information

Details on construction of our community occupancy models (Appendix S1) are available online. The authors are solely responsible for the content and functionality of these materials. Queries (other than absence of the material) should be directed to the corresponding author.

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