Supplement B: Selecting Parameters for Ecological Monitoring Programs: A Case Study of Pima County

Supplement to the Pima County Ecological Monitoring Program: Phase II Plan Summary

September 2010

Robert J. Steidl, University of Arizona
Andrea R. Litt, Colorado State University[a]
Brian F. Powell, Pima County, Arizona
Sherry Mann, University of Arizona

[a] Current affiliation: Texas A&M at Kingsville

This page intentionally left blank

Table of Contents

List of Tables

List of Figures

List of Appendices

Executive Summary

Strategies to conserve endangered species are commonly focused on single species. Section 10 of the Endangered Species Act was developed to provide a strategy to protect multiple species through development of Habitat Conservation Plans (HCP). Early HCPs focused on conservation of a few species across narrow geographic areas, whereas more recently, many HCPs have expanded their focus to include dozens of species across much wider geographic areas. As HCPs increase in coverage and geographic extent, these plans have effectively become comprehensive conservation strategies for entire ecosystems, including provisions to conserve dozens of plant and animal species of conservation concern. These increasingly broad and complex conservation strategies require a more synthetic and comprehensive framework for monitoring than has been implemented previously if changes in populations of protected species are to be detected reliably, an important step in the process for ensuring conservation of covered species required by the Endangered Species Act.

Development of efficient broad-scale ecological monitoring programs is challenging, in part, because these must choose among a vast number of design-related alternatives, including a set of ecological parameters should be measured. As the number, breadth, and goals for ecological monitoring programs increase in scope and extent, the process of deciding which parameters to measure increases deeply in complexity, especially in light of practical limitations in funds available for monitoring.

In this report, we outline a step-by-step process to guide selection of parameters for monitoring based on considering explicitly four fundamental planning components important to conservation and many types of ecological monitoring: target species, environmental features important to habitat of target species, ecological processes, and anthropogenic threats that may affect target species and other aspects of ecosystems. We developed a process for collecting and organizing information about these components and their interrelationships that we capture in a series of two-dimensional matrices that we use as the basis for choosing an optimal set of parameters for monitoring.

We illustrate this process using information from Pima County, Arizona. Pima County is home of the Sonoran Desert Conservation Plan, an award-wining regional conservation strategy that involves a Section 10 permit application to allow incidental take of endangered species. To comply with the Endangered Species Act, the County is required to develop a robust monitoring program to ensure that species covered under the permit will be conserved.

The process we developed to identify parameters for monitoring focuses primarily on terrestrial vertebrates because their populations cover the landscape at a scale that is relevant to management and monitoring, and because vertebrates are common targets for conservation and management. To ensure the monitoring program being developed is effective for as many vertebrates in the region as possible, we developed a sampling process for selecting target species from all terrestrial vertebrate species that inhabit a planning area. We selected a random sample of resident species after first stratifying species based on taxonomy, vegetation association, trophic level, and body size to ensure the sample would be representative. The sample of target species we selected included 109 species to which we added 13 additional species that will be included for coverage in the County's application for a Section 10 permit.

Based on a review of the literature and input from experts, we identified a suite of environmental features that were important to each target species. This suite provides the foundation for incorporating threats, ecosystem processes, and management feasibility into selection of parameters for monitoring. We also incorporated information on the effort and cost required to measure each potential parameter.

We then developed an objective strategy based on principles of decision theory to use this information to prioritize among all possible sets of parameters and to identify sets of parameter that best meet an explicit set of monitoring objectives. We used this objective function to evaluate sets of parameters identified under four alternative weighting schemes that reflected different sets of monitoring and conservation priorities: (1) all planning components considered receiving equal weight, (2) target species prioritized with greater weight, (3) species of highest conservation concern prioritized with greater weight, and (4) costs associated with field measurement of parameters prioritized with greater weight. As expected, the set of parameters identified as most relevant reflected each weighting scheme, but some common themes emerged across schemes. Most notably, vegetation characteristics were among the most important regardless of weighting scheme because of their importance to habitat of vertebrates. We use the set of parameters we identified as the foundation for monitoring lands managed by Pima County.

The approach we develop has advantages over previous approaches because it is explicit, repeatable, and flexible, and offers the potential to inform development of a foundation for monitoring programs for a range of comprehensive conservation strategies.

1 Introduction

The term *monitoring* is used to represent a wide array environmental sampling efforts designed to provide information to evaluate the status or condition of natural resources at a single point in time or, more commonly, to evaluate trends in attributes of these resources through time (Noss 1990, Steidl and Thomas 2001, Noon 2003). Although monitoring programs are most effective when designed to evaluate the consequences of specific management actions (Nichols and Williams 2006), monitoring is often necessary to assess whether broad conservation and management goals are being met (Christensen et. al. 1996, Lindenmayer et. al. 2008). Designing monitoring programs to evaluate the effectiveness of these general efforts is substantially more challenging than designing monitoring programs to evaluate the effects of specific management actions because decisions as to which resources to measure as well as when and where to measure them are nearly limitless.

The degree of complexity involved in long-term monitoring programs designed to evaluate changes in attributes of natural resources though time will depend on many factors, including the specific objectives of the program, the spatial and temporal scale of interest, and the particular resources targeted for monitoring (Elzinga et. al. 2001). When the targets of a monitoring program include vertebrates, effective programs can be relatively complex because most vertebrates are cryptic, highly mobile, and their activity varies seasonally, which makes them more challenging to survey efficiently than other taxa or other potential monitoring targets (Landres et. al. 1988, Thompson et. al. 1998). Further, many attributes of vertebrate populations tend to have naturally high rates of variation over time, which requires sampling to be more intensive to reliably gauge temporal trends (Gibbs et. al. 1998) or responses to management manipulations. Consequently, most monitoring efforts that target vertebrates are designed for single species, especially species that are rare, threatened with extinction, or that are otherwise of conservation concern.

Designing programs to evaluate the effect of specific management manipulations on single species is relatively straightforward, in part because the number of relevant environmental parameters to sample is comparatively small. As the number of target species increases, however, the number of parameters and the number of alternative sampling designs increases greatly, making efficient program design a much more complex problem that requires careful planning to ensure that resources devoted to monitoring are used as efficiently and effectively as possible.

The need to develop efficient strategies for monitoring many species across large geographic areas and in response to a large number of potential stressors and threats has increased in recent years (Palmer and Mulder 1999). One increasingly common application for multi-species monitoring is the monitoring element required by U.S. Fish and Wildlife Service (USFWS) to support multi-species habitat conservation plans. Multi-species Habitat Conservation Plans (HCPs) seek to overcome some of the single-species limitations inherent in the Endangered Species Act, most notably the focus on conservation efforts relevant to meeting the habitat and life-history needs of a single species—efforts that may not serve other species in a region well. Over their history, multiple-species HCPs have increased in geographic scope and species coverage, from single species in a small geographic area to dozens of species that span entire ecoregions. There are currently over 500 HCPs in place. To ensure protection for all species covered by these complex plans, USFWS requires that a monitoring program be established to demonstrate that permitted species are being protected (U.S. Fish and Wildlife Service 1996, 2000). Unfortunately, as HCPs continue to increase in breadth and complexity, the monitoring element—the safeguard for the species being covered—has not kept pace, and the monitoring programs outlined in many HCPs have been criticized as ineffective (Kareiva et. al. 1999, Clark and Harvey 2002, Hoekstra et. al. 2002, Wilhere 2002). Therefore, it seems increasingly likely that declines in species targeted for protection through multi-species HCPs could go undetected unless the rigor of these monitoring elements is increased (Barrows et. al. 2005).

In this report, we describe a process that we developed to provide an explicit framework for choosing a suite of features—that we refer to as *Environmental Features*—to provide a foundation for monitoring programs that target vertebrates and span broad geographic scales. Specifically, the process we describe seeks to identify an optimal set of environmental features by balances a set of explicit objectives for a comprehensive suite of target species that inhabit the monitoring area and that helps to overcome limitations of efforts based solely on judgment of experts (e.g., Schmoldt et. al. 1994) or on more cursory analyses of selection criteria (e.g., Tegler 1999, Hilty and Merenlender 2000). The process we developed incorporates information about relationships among target species, environmental features important to habitat of those species, ecosystem processes, anthropogenic threats, and management feasibility in such a way that the set of features selected for monitoring satisfy an explicit set of criteria that optimize the information gained for a given effort and cost. The process is comprehensive, flexible, and explicit, and based principally on the habitat requirements of terrestrial vertebrates, which we believe offers advantages for informing development of efficient, general-purpose monitoring programs that span large spatial scales.

1.1 Case Study: Sonoran Desert Conservation Plan

We illustrate the process we developed to provide a framework for a regional-scale monitoring program for the Sonoran Desert in southern Arizona; specifically, the monitoring element of the Sonoran Desert Conservation Plan (SDCP) and associated HCP for Pima County, Arizona. The SDCP is an award-winning plan developed to conserve natural and cultural resources and inform land-use planning in rapidly urbanizing Pima County (Pima County 2000, Steidl et. al. 2009). The biological goal of the SDCP is to ensure the long-term persistence of all plants and animals indigenous to Pima County through maintaining or improving habitat condition and ecosystem function (Pima County 2000). To help ensure this goal is realized—and to provide regulatory certainty—Pima County drafted a multi-species HCP that embodies the scientific principles of the SDCP biological goal, specifies mechanisms for addressing legal conservation requirements of the Endangered Species Act, and identifies 48 species proposed for coverage in the County's forthcoming Section 10(a)(1)(B) permit application to the USFWS (Pima County 2009).

As part of the permit application, USFWS requires that applicants develop a monitoring program that evaluates the impact of the permitted action(s) and determines whether the HCP is achieving the biological goals and objectives of the HCP. Though most monitoring efforts associated with HCP tend to focus on the species covered under the permit, Pima County's approach has been to broaden the suite of potential monitoring parameters to include four levels of monitoring:

- *Species-level monitoring* to evaluate changes in status and trends of a select set of permitted or "covered" species.
- *Habitat-based monitoring* to evaluate changes in environmental features thought to affect the distribution and abundance of covered species and other species in the planning area.

- *Threats-based monitoring* to evaluate changes in factors that have the potential to affect species, their habitat, and other ecosystem elements.

- *Landscape-pattern monitoring* to evaluate changes in coverage, spatial configuration, and fragmentation of major land-cover types.

These four levels represent a mix of coarse and fine filters that are essential to effective long-term conservation (e.g., Noss 1990, Parrish et. al. 2003). In this report, we describe a process designed to optimize selection of environmental features appropriate for habitat-based monitoring and to provide the foundation on which species-level, threats-based, and landscape-pattern monitoring elements can be added (**Section 10**) to form a comprehensive, effective, and financially efficient monitoring program that can be implemented over time horizons spanning from 5 to 100 years.

2 Conceptual Framework

2.1 General Design Principles

A principal goal of many ecological monitoring programs is to assess changes in abundance, distribution, condition, or other attributes of natural resources through time. For monitoring programs with a goal of evaluating changes in a large number of natural resources or other conservation or management targets, one decision that has a powerful influence on program design and on the ultimate effectiveness of the program is the choice of which resource attributes or “parameters” should be measured from among the wide range of possibilities (National Research Council 2000). This decision will influence all aspects of the program, from design through implementation, and ultimately affect the likelihood that the program will successfully detect biologically meaningful changes. Choosing from among the hundreds of potential parameters is difficult (Noon 2003), and the basis for these choices is rarely well-justified for most general monitoring programs.

When the goal of a monitoring program focuses on one target, the number of potential parameters is small, and selection is typically guided by experts. When the goal of a monitoring program reflects many monitoring targets, such as many species of conservation concern or habitat features required by these species, however, no group of experts can effectively balance the advantages and disadvantages inherent in all possible combinations of potential parameters. In addition, each potential combination of parameters has higher-order consequences for the monitoring program, including advantages of sets of parameters that are most relevant to most monitoring targets, that provide sampling efficiencies, or that provide insight into other important planning targets, such as anthropogenic threats. In short, there are far too many combinations of parameters to consider for informing monitoring programs many targets for any set of experts to evaluate without the help of an explicit, objective strategy.

One approach for choosing parameters for programs where the monitoring targets are collections of species is to simply measure all parameters relevant to all target species. Although this approach has some advantages, when the number of species to monitor is large, this strategy will likely be prohibitively expensive to implement and will almost certainly be inefficient when resources used by target species overlap, which increases in likelihood as the number of target species increases. Further, by considering all target species in concert with other potential conservation and management targets, the costs associated with sampling can be reduced by considering the overlap in environmental features relevant to all planning targets, which will also serve to increase the amount of information gained by sampling when multiple environmental features can be measured concurrently in space and time (e.g., Manley et. al. 2005).

Our overarching goal was to develop a process for selecting monitoring targets and the environmental features (parameters) most relevant to those targets that is explicit, repeatable, and based on the best available information, from peer-reviewed scientific literature through expert knowledge. We sought to capitalize on the efficiencies gained by choosing sets of parameters that reflected the overlap among resources relevant to multiple monitoring targets to maximize sampling efficiency and minimize costs, and ultimately to maximize the amount of information to inform program goals.

We explored the range of methods available (**Appendix A**), but felt that none of the available methods or models was entirely appropriate for our goal. Therefore, we developed a new framework to optimize selection of parameters to provide the foundation for complex monitoring programs. We built the framework on four fundamental sets of components: monitoring targets, environmental features important to targets, ecological processes, and anthropogenic threats. We then established relationships among components (**Fig. 1.1**), relevance of components to management, and costs of data collection to optimize selection of a set of parameters that best meet a set of explicit objectives established to reflect objectives of specific monitoring programs. The framework is sufficiently flexible that the framework can be used to guide parameter selection for a wide range of potential monitoring efforts.

No framework can include every aspect of the biotic and abiotic environment relevant to the area to be monitored. We have sought, however, to incorporate information about all ecological structures and functions relevant to monitoring at spatial and scales most commonly considered for long-term monitoring programs. Below, we describe briefly each component of the framework that we explore in detail in subsequent sections of the report.

2.2 Components

We gathered information relevant to each component and to relationships among components (**Fig. 1.1**, solid lines). Although we considered several other relationships among components (**Fig. 1.1**, dashed lines), we did not find these to be especially useful for monitoring. We explore the approach we used to establish planning targets (**Section 3**), other monitoring targets, relationships among components of the framework (**Sections 4-8**), and the strategy we developed to use information about these components to identify sets of environmental features to monitor as parameters because they best met a set of specified objectives (**Section 9**).

2.2.1 Planning Targets

A critical step in any monitoring program is to identify a target or set of targets as the focus of the design and the basis for design-related decisions (Parrish et al. 2003). For monitoring programs with a narrow focus, selecting targets is straightforward, as these are usually the focus of monitoring program and the reason it is being developed. For example, the Northwest Forest Plan was initiated in part to conserve spotted owls (*Strix occidentalis*) and marbled murrelets (*Brachyramphus marmoratus*), therefore these species became the primary targets for these processes (Noon et. al. 1999). Because the goal for many ecoregional monitoring programs and HCPs are inherently broad and not linked explicitly to one or a few individual species, we explored a range of potential targets on which to base the development of this framework, including invertebrates, plants, and vertebrates. We compared each of these potential targets to the characteristics of good ecological indicators based on three general criteria: ecological relevance, feasibility of implementation, and management relevance and utility (**Table 2.1)**.

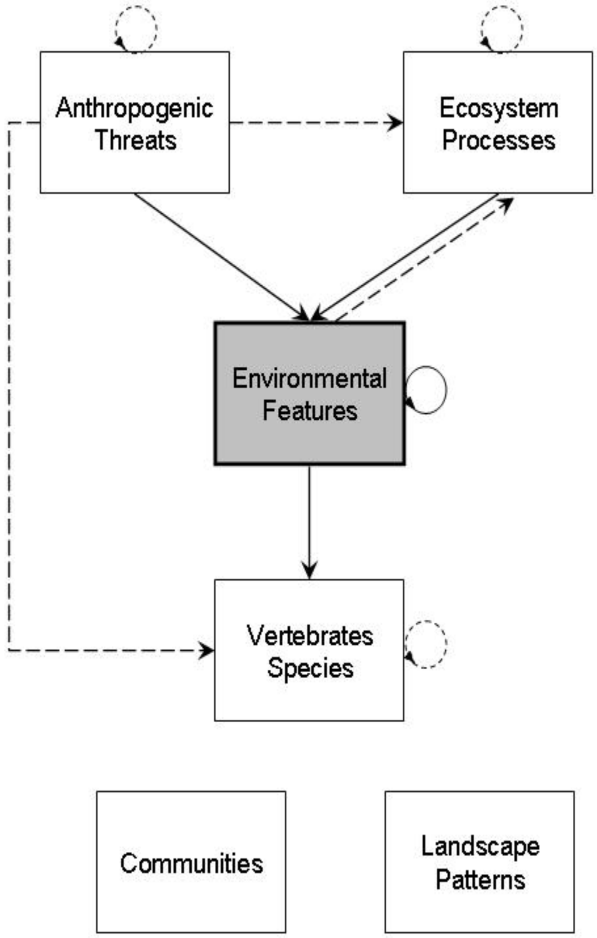

Figure 1.1. Conceptual representation of ecosystem components (boxes) and interconnections among components (lines and arrows). Communities and landscape patterns represent additional potential components of monitoring programs that are emergent properties of the four primary components. Solid lines represent relationships we included in the framework we describe, and dashed line represent relationships we considered, but did not include.

Table 2.1. Characteristics of ecological indicators categorized into three general classes of criteria (Morrison and Marcot 1995, Hilty and Merenlender 2000, Dale and Beyeler 2001).

General Class	Specific Criteria
Ecological Relevance	Adequate baseline information available
	Dynamics parallel those of ecosystem or component of interest
	Respond quickly and predictably to changes in ecosystem
	Distributed over wide geographical area and/or are numerous
	Relevant to a range of ecosystems
	Harvested, endemic, alien, of special interest, or protected
	Provides information about other parameters
	Recognized as scientifically valuable
Feasibility of Implementation	Inherently low natural temporal and spatial variability
	Low sampling error (can be estimated with high precision)
	Likelihood of detecting change is high
	Survey methods well established, have low observer bias, are cost effective
	Measurements have low impact
	Results are easy to interpret
Management Relevance and Utility	Inform management
	Predict changes that can be averted by management

We eliminated invertebrates as potential planning targets because taxonomic uncertainty exists for some groups, specific habitat information is often lacking, and they are difficult to quantify reliably. Likewise, we eliminated plants as potential planning targets because their responses to some types of environmental changes can be slow and their responses can be difficult to link to larger scale environmental changes. We chose terrestrial vertebrate species as the fundamental planning target because:

- Vertebrates respond to environmental change over temporal and spatial scales relevant to monitoring.
- Vertebrates are well studied, so their habitat requirements are generally well known and their taxonomy is stable.
- When examined across taxa, habitat requirements of vertebrates capture a wide breadth of environmental features on the landscape.
- Vertebrates hold broad public appeal.
- The biological goals of many ecoregional planning efforts, including many HCPs, are based on species-level assessments, primarily for vertebrates.

Although vertebrate species themselves may or may not be monitored directly, we used information about their habitat associations as a way to inform the environmental features that should be measured as parameters in a monitoring program. Therefore, our approach involved selecting a subset of terrestrial vertebrates that inhabit the planning area to use as the foundation for the process (**Section 3**).

2.3 A Focus on Environmental Features

The framework integrates an array of conservation targets, from individual species through broad-scale environmental threats, all of which we consider to be interconnected through their relationships with features of the environment. We define these features as *Environmental Features*, which collectively form the primary focus of our framework. Below, we describe why we chose to focus on environmental features rather than individual target species.

Single species are the currency by which the adequacies of HCPs are evaluated by U.S. Fish and Wildlife Service. As HCPs increase in scope, however, the focus on conservation of individual species becomes one element in a larger and more comprehensive conservation strategy that requires a more synthetic and comprehensive strategy for monitoring than has been proposed previously. This new strategy for monitoring is warranted because current monitoring efforts for HCPs have been criticized for not provided sufficient information to detect meaningful changes in populations of target species and for not adequately informing management, especially when HCPs cover multiple species (see critiques in Harding et. al. 2001, Wilhere 2002, Rahn et. al. 2006). Within the context of broad-scale, multi-species HCPs, monitoring programs for each target species have never been fully implemented, and if developed, would be prohibitively expensive; further, less intensive monitoring strategies, such as assess changes in land use, lack the power necessary to evaluate trends in populations of target species, especially for species whose populations are naturally variable. Populations of many vertebrates, for example, change markedly through time and in responses to environmental changes, so assessing trends can take years, even if the trend is biologically meaningful (Elzinga et al. 2001, Fleishman and Mac Nally 2003).

Consequently, habitat-based monitoring offers greater capacity to detect environmental changes that are likely to be important to a wide range of organisms, which is one of the reasons we chose it as the primary focus of our process. Habitat is a species-specific concept that represents the sum of the environmental features required by a species for survival and reproduction (Hall et. al. 1997). Therefore, changes to any of the environmental features that comprise habitat for species can predict changes to populations of those species, making them ideal leading indicators. Monitoring habitat features also provides a foundation for assessing changes to other important conservation targets, such as ecosystem process or threats.

A potential weakness of a habitat-based approach to monitoring is the need to be certain that there is a clear link between habitat features and attributes of the species themselves (e.g., Cushman et. al. 2008), although few would argue that habitat features do not affect species, their populations, and communities (Morrison et al. 2006). Ultimately, however, we do not suggest that habitat-based monitoring be considered to be a complete surrogate for the species they are especially important, but given the challenges to monitoring a large number of species across a large area, habitat-based monitoring program ultimately will be more informative, financially efficient, and more comprehensive and power for assessing assessment a wide array of potential trends.

Finally, guidance provided by U.S. Fish and Wildlife Service indicate that adopting a habitat-based approach to monitoring for HCP can be appropriate. Specifically, their five-point policy states that "goals and objectives may be stated in habitat terms" provided that there is a tie to target species (U.S. Fish and Wildlife Service 2000).

2.3.1 Environmental Features

With vertebrate species established as the principal target of the framework, we linked species to resources on the landscape by identifying environmental features that were important habitat elements for each species. Specifically, we identified the set of environmental features necessary for individuals of a species to inhabit an area. Identifying environmental features was a key step in the process because changes in composition, configuration, amount, or quality of key environmental features is often reflected in changes in species abundance and distribution (Wiens 1985). Therefore, environmental features important to habitat of target species provided the foundation for the strategy we developed to select parameters and therefore provides the foundation for the monitoring program (**Section 4**).

2.3.2 Anthropogenic Threats

We defined threats as human-caused disturbances to environmental features, species, and ecosystem processes (Salafsky et. al. 2008). We identified and assessed potential effects of current and future threats on environmental features in the plan area over the next 30 years, the timeframe of the Pima County Section 10 permit (**Section 5**).

2.3.3 Ecosystem Processes

We distinguished ecosystem process from anthropogenic threats by defining processes as natural functions of ecosystems, including cycling and flow of energy, elements, nutrients, and materials, as well as relationships among populations and communities of organisms. Processes influence ecosystem structure, including common targets for monitoring, and can also be affected by anthropogenic threats (Klein et. al. 2009). Therefore, we established a set of ecosystem processes as a component in our framework and linked these processes to environmental features (**Section 6**).

2.3.4 Management Feasibility

Monitoring efforts should be designed to provide practical information to inform conservation and management (Walters 1986, Lyons et. al. 2008). The ability and speed with which managers can affect change, however, varies considerably among environmental features. For example, managers may find that the effort required to change density of overstory vegetation is small relative to the effort required to alter the amount of available lentic waters. Therefore, we included management feasibility in our framework to reflect the relative complexity involved with changing attributes of environmental features (**Section 7**).

2.3.5 Effort, Sampling Variation, and Sample Units

The amount of effort necessary to measure each potential parameter figures prominently in the overall cost and efficiency of a monitoring program. The natural variation inherent in an environmental feature across space and over time affects the amount of effort necessary to measure the feature precisely (Gibbs et al. 1998, Urquhart et. al. 1998). Therefore, we estimated the relative amount of effort required to measure each environmental feature to provide insight into the relative efficiency of including different environmental features as part of a monitoring program (**Section 8**).

2.4 Relationships among Framework Components

We characterized relationships among components by scoring either the presence of a relationship or the relative strength of a relationship. We used two-dimensional matrices as a data structure for scores, which provided the basis for many of the analyses we describe (**Table 2.2**).

Table 2.2. Relationships among structural components of the framework developed for establishing a foundation for regional monitoring programs. Relationships are represented in two-dimensional matrices.

Matrix	Details
Species x Environmental Features	Quantifies importance of environmental features to target species Species determine importance of environmental features Foundation for framework 279 features identified, 22 used in analysis
Threats x Environmental Features	Quantifies severity and permanence of anthropogenic threats on environmental features Threats determine importance of environmental features 45 threats identified, 32 used in analysis
Processes x Environmental Features	Quantifies effects of natural process on environmental features Processes determine importance of environmental features 34 processes identified, 9 used in analysis
Management Feasibility x Environmental Features	Quantifies feasibility of management to avert changes in environmental features Feasibility determines importance of environmental features

2.5 Additional Planning Targets

Considering multiple components in the design of monitoring programs is not new (Odum 1985 see also Appendix A). However, we sought make the process of integrating multiple components straightforward and to develop an effective strategy for identifying an optimal sets of ecological parameters that could be measured efficiently and that would provide a reliable foundation for a comprehensive monitoring program. Importantly, additional monitoring targets or components could be added to this foundation as necessary to complete a program. These additional components could include single species that are regionally important and require intensive sampling, animal communities that provide a breadth of information informative and are cost-effective to monitor, and parameters that can be measured efficiently across the entire target landscape and do not require field sampling, such as information on land cover provided by remote sensing (**Section 10**). These components should be identified, evaluated, and integrated with the set of parameters established through the strategy we describe in this report.

2.6 Importance of Spatial and Temporal Scale

Scale affects the expression of both ecological structure and function within and across landscapes, the ability to measure those structures and functions, and their relevance to monitoring (Wiens 1989). Although our focus is on design of monitoring programs at regional scales, processes expressed at larger and smaller spatial scales influence how best to quantify the effects of those processes on the environmental features selected for monitoring. Therefore, we evaluated how scale influenced the temporal and spatial expression of change in each component we considered.

Effects of many large-scale processes and anthropogenic threats have clear and long-lasting implications for conservation and management, and are therefore important to measure as part of a monitoring program. One important example is evident as changes in land use, such as the proportion of the landscape classified as residential development (e.g., Theobald and Romme 2007). Some important threats express most clearly at different spatial scales that affects the most efficient way to measure their effects and to remediate their effects. Processes and threats that manifest at large scales are measured most easily across the entire target landscape and typically do not require field sampling as they can be measured directly from satellite images or indirectly by relevant indicators such as the number of new housing permits issued (see Fonseca et. al. 2009 for recommendations for Pima County). Although field-based sampling efforts could be used to measure changes in large-scale parameters over time, it would surely be inefficient and more expensive than alternative approaches. Ultimately, sampling is more appropriate for measuring environmental features and processes that are expressed at smaller scales and that are impossible or prohibitively expensive to measure in the field across an entire region, such as the number of cavities in trees or saguaros that are important habitat components for many animals.

Temporal scale is also an important in design of monitoring programs because an overarching objective of long-term monitoring efforts is to detect trends in natural resources over time periods of at least 10-20 years, but sometimes hundreds or even thousands of years (for a one thousand year example, see Stige et. al. 2007). The choice of an ideal set of parameters to measure is influenced by the temporal scale of likely future changes in those parameters. For example, environment features such as water temperature in perennial stream can be detectable on a time scale of as little as an hour, whereas cover of overstory vegetation in semi-desert grassland can be detectable on time scales measured in years or decades. These biological realities drive the choice of which features to monitor and the frequency with which those features should be measured.

Whenever there were several alternative scales at which a parameter could be measured, we focused on measurements appropriate for the smallest scale. Consequently, our strategy focuses on selecting a subset of environmental features and threats that are relevant for field-based sampling efforts because larger-scale elements can be assessed more efficiently across the entire target landscape or through relevant indicators (e.g., building permits).

3 Target Species

Many monitoring programs are established to assess changes in attributes of one or a few monitoring targets that are usually species. For monitoring programs that target many species and that span broader geographic scopes, the efficiency of monitoring each species individually decreases markedly as the number of species increases. If the habitat requirements of target species overlap, a species-by-species approach to monitoring does not leverage potential efficiencies that could be realized by capitalizing on the environmental features shared among species. Consequently, we sought to develop a strategy to identify environmental features to monitor by (1) identifying all terrestrial and semi-aquatic vertebrates that inhabit a planning area, (2) identifying all environmental features relevant to habitat for these vertebrates, and (3) identifying features to monitor that are relevant to the greatest number of vertebrate species. Environmental features that are important to many species provide a basis for prioritizing among parameters and developing sampling strategies that are cost effective and informative. Our first objective was to develop a strategy to identify a subset of vertebrate species that would represent well all terrestrial vertebrate species in the planning area.

3.1 Species in the Planning Area

This planning process began by compiling a list of terrestrial vertebrate species (amphibians, reptiles, birds, and mammals) that inhabit the planning area (Pima County) based on a list of species that was compiled for the Sonoran Desert Conservation Plan (Fonseca et. al. 1999). To refine this list, we searched available literature (e.g., Minckley 1973, Hoffmeister 1986, Rosen 2003, Corman and Wise-Gervais 2005, Powell et. al. 2006) and queried local experts. From an initial list of 656 potential species, we eliminated species that:

- Were extirpated from the planning area (e.g., grizzly bear [*Ursus arctos*] and wolf [*Canis lupus*]);
- Were introduced (e.g., American bullfrog [*Rana catesbeiana*]) or have expanded their range as a direct result of human activities (e.g., great-tailed grackle [*Quiscalus mexicanus*]);
- Inhabit areas beyond the elevational limits of the planning area, which for our case study excludes areas above 1250 m (4000 feet) (e.g., red-faced warbler [*Cardellina rubrifrons*] and Arizona black rattlesnake [*Crotalus molossus*]);
- Are distributed only in a very small portion of the planning area, such as species that only inhabit Organ Pipe Cactus National Monument or the Tohono O'odham Nation (e.g., LaConte's thrasher [*Toxostoma lecontei*]);
- Were birds that:
    - Are passage migrants (e.g., dusky flycatcher [*Empidonax oberholseri*]);
    - Breed only rarely within the elevations limits of the planning area (e.g., violet-crowned hummingbird [*Amazilia violicets*]);
- Were bats that:
    - Are not known to roost or breed in the planning area (e.g., western small-footed myotis [Myotis ciliolabrum]);

- Are not linked to specific environmental features that are anticipated to change at a temporal scale relevant to monitoring, such as mines or caves (e.g., insectivorous bats that are not year-round residents, such as Brazilian free-tailed bats [*Tadarida brasiliensis*]).

Based on the above criteria, we identified 228 candidate target species[1] to include as part of the planning process: 113 birds, 45 mammals, 10 amphibians, 3 turtles, 25 lizards, and 32 snakes (Appendix B). A list of all species that were evaluated for possible inclusion in the planning process is available on request from the authors.

3.2 Selecting Target Species

3.2.1 Selection Framework

We could have included information on all 228 candidate target species that met the criteria we described above; however this would have been more time-intensive and have included a considerable amount of redundancy because environmental features used by many species overlap considerably (see discussion in Wiens et. al. 2008). Therefore, we developed a strategy for selecting a sample of vertebrates based on shared life-history characteristics that provide a basis for selecting a subset of species to represent all terrestrial vertebrates that inhabit the planning area, which will represent well a broad array ecosystem structures and processes. The strategy for selecting this subset of species is important because the environmental features used by these species will determine the set of environmental features used to link species with other monitoring targets, such as anthropogenic threats and ecosystem processes. Consequently, we devised a strategy to classify species into groups based on attributes that will ensure the subset of species we select represent well all of the species that inhabit the planning area.

We considered 11 different life-history attributes as the basis for classifying species, four of which we selected as most valuable based on a review of scientific literature and the opinions of experts.

3.2.2 Classifying Candidate Target Species

Below, we list each attribute that we considered for classifying species and a brief rationale for accepting or rejecting each.

Attributes that we used:

> **Taxonomy**. Taxonomy captures evolutionary history and is therefore a prudent starting point to represent the diversity of life-history traits of vertebrates in an area. Classifying species by taxonomy will ensure that the full range of species diversity is represented in the sample of species selected.

---

[1] Scientific names of species mentioned in this report are found in Table B.1. For species not in Table B.1, the scientific name is included the text of the report.

Vegetation association. Vegetation represents biotic and abiotic features of an area and provides important habitat features for many vertebrates. Classifying vertebrates by their vegetation affinities will ensure that species that inhabit all vegetation associations are represented in the sample and that the entire planning area will be well represented.

Trophic level or guild. Represents functional position in food webs or ecosystems, reflecting key differences in life histories among species (Parker et. al. 2001).

Body size. Represents life-history traits related to allometric scaling, including spatial scale of habitat use and home-range size (Purvis et. al. 2000), population density, population turnover, and other demographic characteristics (see Appendix B for a more detailed description of this classification).

We generated a categorical classification for each of the four criteria we selected (**Table 3.1**). We considered seven other attributes of species for this planning process, but chose not to use them (see Appendix B for more information).

Table 3.1. Four criteria for selecting Target Species.

Criterion	Categories	Body-Size Classes (if applicable)
Taxonomy and Body-size	Amphibians	All sizes
	Birds	2.9-14.0 g
		14.1-40.0 g
		40.1-130.0 g
		130.1-5800.0 g
	Lizards	≤ 13 cm
		> 13 cm
	Mammals	4-209 g
		210-4950 g
		4951-152,000 g
	Snakes	≤ 48 cm
		48.01-88 cm
		> 88 cm
	Turtles	All sizes
Vegetation Association	Marsh/open water	
	Mesoriparian	
	Semi-desert Grassland	
	Sonoran Desert Upland	
	Xeroriparian	
Trophic Level	Carnivore	
	Herbivore	
	Omnivore	

3.2.3 Selection Process for Target Species

We classified each of the 228 candidate species identified by each criterion (**Table 3.1**), then created groups of species that shared all four criteria. For example, there were five species classified as Taxonomy = birds, Body Size = 2.9-14.0 g, Vegetation = xeroriparian, Trophic Level = omnivore: black-chinned hummingbird, broad-billed hummingbird, black-throated sparrow, Costa's hummingbird, varied bunting, and verdin. After grouping species, we determine that additional refinement of groups was warranted for small, herbaceous mammals (see Appendix B for additional information). Many candidate species were eligible to represent >1 group because of their presence in >1 vegetation association. For example, the Sonoran Desert toad is found in all five vegetation associations and therefore had multiple five chances to be chosen. By contrast, the desert box turtle occurs in only a single vegetation association and therefore had only one opportunity to be chosen.

We then selected one species at random from each group of species that shared the same classification to include in the final set of target species. This process yielded 109 Target Species (45 birds, 30 mammals, 8 amphibians, 3 turtles, 10 lizards, 13 snakes) that we used to represent all species in the planning area (**Appendix C**).

3.2.4 Inclusion of Additional Target Species

During development of a monitoring program, planners might choose to include species of special interest. For the SDCP, for example, 56 species that were identified as federally threatened or endangered or otherwise regionally important and were classified as Priority Vulnerable Species (PVS; Pima County 2001). Of the 56 PVS, 25 are terrestrial vertebrates that were candidate target species 228 Target Species. Twelve of the 25 PVS were selected in the sample of 109 target species used to represent terrestrial vertebrates in the planning area. With the addition of the 13 PVS, the total number of Target Species is 122, unless otherwise noted.

4 Environmental Features

4.1 Identifying Environmental Features

To identify environmental features (EFs) that function as important components of habitat for each of the 122 Target Species, we searched major scientific databases for relevant literature, including published journal articles, books, unpublished agency reports, and reliable websites. We developed a consistent searching protocol to ensure that we explored all information sources for all target species or for closely related species (see **Appendix C**). During searches, we sought sources that provided ecological and natural history information for each species—especially information on species/habitat relationships—and targeted environmental features described as relevant to each species. For species that were year-round residents in the planning area, we identified environmental features that pertained to both breeding and non-breeding periods; for species that were seasonal residents in the planning area and that migrated elsewhere during part of the year, we identified environmental features that pertained only to the breeding period. We identified 279 environmental features used by at least one species during its life cycle (the complete list of EFs is available upon request from the authors).

We reduced this detailed set of environmental features by combining features into supercategories by first arranging environmental features into a hierarchy (**Table 4.1**), then combining features that were nearly identical except for minor differences that were artifacts of resolution of measurement or description (see **Appendix D**). We represented groups of combined features with the feature that most closely reflected characteristics of good indicators (**Table 2.1**), especially when a feature was most likely to reflect changes in other ecosystem components, that had low levels of natural variation, or that could be measured most efficiently.

Some of the environmental features on this list were capable of exhibiting meaningful change over time scales relevant to ecological monitoring; others, however, were not likely to change on that time scale. Therefore, we eliminated environmental features that were not appropriate for ecological monitoring because they met one of the following criteria (see also **Appendix D**):

- *Change too slowly*. Environmental features that are expected to change measurably over time scales of hundreds to thousands of years, such as those related to topography and soil. Because many of these features are important habitat elements for conservation targets, they should be measured once at the start of field sampling to capture the ecological character of a sampling location, which is important but need not be measured repeatedly. Some of these features might be considered as strata within the sampling design.

- *Change too quickly*. Features that are expected to change too quickly for monitoring programs, perhaps over time horizons of hours, days, or weeks, such as water quality and soil moisture.

Table 4.1. A hierarchy for classifying environmental features important to habitat of vertebrates.

Class	Category	Subcategory
Physical	Topography	Relief
		Aspect
		Terrain
	Subterranean	Natural Shelters
		Human-made Shelters
	Soils	Type
		Condition
		Other
	Surface Water	Perennial
		Intermittent
		Quality
		Other
	Channels	Morphology
Biological	Terrestrial Vegetation	Structure
		Composition
		Other
	Aquatic Vegetation	Structure
		Composition
		Other
	Animal-made Features	Structures
		Habitat Alterations
		Waste
Anthropogenic	Human-made Features	Structures
		Waste
		Structures Provided for Wildlife
		Landscape Alterations

- *Anthropogenic features*. Features that are not natural components of ecosystems despite being important to habitat of some species, such as bridges, bird feeders, and debris piles. Many of these features, however, could be important elements in monitoring programs developed for individual species. We made exceptions for anthropogenic features developed to provide surface water, such as cattle tanks, ponds, and guzzlers, because these features were essential to many species in the desert environment of the planning area.

After excluding features that met those criteria, the remaining environmental features were retained only if they were identified as important to >5% of target species, which excluded features important to few species (see **Appendix D** for additional information on excluded environmental features). The final list included 22 environmental features (**Table 4.2**).

Table 4.2. Environmental features that we considered in development of a monitoring program.

Group	Environmental Feature
Aquatic	Large perennial lotic waters (rivers, streams, creeks)
	Small perennial lotic waters (springs, seeps)
	Perennially flooded vegetation (marsh, cienega)
	Perennial open lentic waters (ponds, lakes, stock tank)
	Large ephemeral lotic waters (rivers, streams, creeks)
	Ephemeral open lentic waters (pools, tinajas)
Structures	Burrows into substrate made by animals
	Cavities in trees made by animals
	Terrestrial coarse woody debris, snags, stumps
	Instream coarse woody debris
	Earthen banks
Vegetation: Overstory	Cover of overstory vegetation
	Density of overstory vegetation
	Composition of overstory vegetation by species
Midstory	Cover of midstory vegetation
	Density of midstory vegetation
	Composition of midstory vegetation by species
Understory	Cover of understory vegetation by class
	Composition of understory vegetation by species
Aquatic	Structure of emergent and submerged vegetation
	Composition of emergent and submerged vegetation
	Cover of algae

4.2 Prioritizing Environmental Features

Our goal was to score the relative importance of each environmental feature to each component included in the framework (**Section 2.1**), thereby creating a quantitative basis for evaluating environmental features for monitoring. Each set of scores was stored in a two-dimensional matrix for later analysis (see Example, **Table 4.3**).

For environmental features related to physical structure, we scored the relative importance of each feature to each species based on relationships established in the literature:

3 = Most important: a feature that almost always affects habitation of an area;
2 = Important: a feature that has an important influence on habitation;
1 = Least important: a feature that has some affect on habitation;
0 = Not important: a feature not known to affect habitation.

For example, burrows are considered to be essential features of habitat for Sonoran coral snakes (score = 3) but are not an important habitat feature for verdins (score = 0).

For environmental features related to vegetation composition, we scored the relative strength of floristic preferences for that species as:

3 = Most important: nearly essential; very few alternative species suitable;
2 = Important: strong, but not essential; several alternative species suitable;
1 = Least important: minor; many alternative species suitable;
0 = Not important: not used or not mentioned in the literature.

For example, composition of overstory vegetation, principally mesquite (*Prosopis*), is considered to be essential for habitat of the mesquite mouse (score = 3), but is not considered important for the western harvest mouse (score = 0).

Features could have either important positive or important negative effects on species, and both effects would merit that same score. For example, cover of overstory vegetation was scored most important (score = 3) to habitat of Merriam's kangaroo rat because the absence of overstory vegetation is necessary for this species to inhabit an area.

We organized scores relating species and environmental features in two-dimensional matrices that we asked four groups of experts to evaluate. When then met with each group to reconcile any differences between our original score and their scores to determine final scores (**Table 4.3**).

4.3 Data Realities

Although the data we synthesized were occasionally limited in quantity and quality for some species, and we cannot be certain that we located all references pertinent to characterizing habitat relationships for a species, we did not feel it necessary to eliminate any target species based on a lack of information. Although the relationships we scored were based on information we gathered from the scientific literature and from experts, steps in this process involved some use of judgment. Nonetheless, by making explicit the relationship scores between species and environmental features, results of this process can be evaluated by anyone and revised when new and better information become available, which we consider to be an advantage of the framework we describe.

Table 4.3. Example of the environmental-features-by-species matrix. Values in the matrix are scores derived from the literature and expert opinion; if there is no value indicated, it means that environmental feature is not important (i.e., "0"). The complete matrix is available on request from the authors.

Group	Environmental Feature	Lesser long-nosed bat	Prong-horn	Botta's pocket gopher	Great Plains toad	Desert spiny lizard	Sonoran coral snake	Sonoran mud turtle	Verdin	Black-tailed gnat-catcher	Gray hawk
Aquatic	Large perennial lotic waters (rivers, streams, creeks)		2		3			3			
	Small perennial lotic waters (springs, seeps)		2		3			3			
	Perennially flooded vegetation		2		3			2			
	Perennial open lentic waters (ponds, lakes, stock tank)		2		3			3			
	Large ephemeral lotic waters (rivers, streams, creeks)		2		3			3			
	Ephemeral open lentic waters (pools, tinajas)		2		3			3			
Structures	Burrows into substrate made by animals			1		3	3				
	Fractures in substrates not made by animals					3					
	Cavities										
	Terrestrial coarse woody debris, snags, stumps					3					
	Instream coarse woody debris										
	Earthen banks										
Vegetation: Overstory	Cover of overstory vegetation		2	2		1		2	1	1	3
	Density of overstory vegetation		2	2		1		2	1	1	3
	Composition of overstory vegetation by species	3				1	1	1	2	3	3
Midstory	Cover of midstory vegetation	1	2	2		2		2	2	2	2
	Density of midstory vegetation	1	2	2		2		2	2	2	2
	Composition of midstory vegetation by species	3		1		1		1	2	3	1
Understory	Cover of understory vegetation by class		2	3	2	1	2	2	2	2	2
	Composition of understory vegetation by species	2	3	2	1	1	1	2	2	3	1
Aquatic	Structure of emergent and submerged vegetation							2			
	Composition of emergent and submerged vegetation							2			
	Cover of algae				2			2			

5 Anthropogenic Threats

In contrast to natural ecosystem processes (**Section 6**), we defined threats as processes or activities that are driven primarily by the past, present, or likely future actions of humans, especially those with high potential to influence ecosystem structure, environmental features, species, or natural ecosystem processes. Many of the threats we identified resulted from past human activities that left a persistent legacy that will affect conservation targets long after the action that caused the threat was removed, such as introduction of non-native species.

Identifying threats is integral to conservation planning in general (e.g., Salafsky and Margoluis 1999, Theobald 2003, Wilson et. al. 2005) and in identifying parameters for monitoring (Hilty and Merenlender 2000, Tegler et. al. 2001). Quantifying patterns in threats through time may itself be a goal of many monitoring programs, such as assessing whether coverage of non-native plants changes over time. However, we identified threats as an additional way to inform which environmental features are most important to include as part of a monitoring program. For example, if cover of grasses is selected as a parameter important to conservation targets, then cover of nonnative grasses will be included as part of the field-based sampling strategy for the monitoring program.

5.15.1 Classifying Threats

Anthropogenic threats range widely in scope and intensity; in southern Arizona, threats mirror those in other rapidly developing areas of the United States (Steidl et al. 2009). To develop a classification scheme for threats, we first compiled a comprehensive list of known or potential threats in the planning area according to their groupings into the following seven categories (as suggested by Salafsky et al. 2008):

- <u>Land-use change</u>: Elimination of natural areas.
- <u>Transportation infrastructure</u>: Narrow corridors for transporting people, goods, and energy.
- <u>Consumption of abiotic resources</u>: Extraction of non-biological resources.
- <u>Consumption of biological resources</u>: Harvesting or other use of biological resources that removes resources from the ecosystem.
- <u>Non-consumptive biological use</u>: Use of biological resources that does not remove resources from the ecosystem.
- <u>Pollution</u>: Introduction and spread of unwanted matter and energy, including point source and non-point source releases of chemical, biochemical, thermal, radiation, and noise pollution.
- <u>Nonnative species</u>: Introduction of species novel to the planning area.

We then combined similar threats into 32 classes based on similarities in how they are likely to affect environmental features **(Appendix E)**. For example, we combined threats related to development into two general classes based on how they were likely to affect the landscape: one based on development-related that typically leave residual natural open space and one based on development-related threats that leave little or no open space. In Pima County, certain types of developments are required to set aside up to 80% of a parcel as natural open space (Steidl et al. 2009), whereas some developments in central Tucson are required to leave little or no open-space remaining. Combining threats eliminated some smaller-scale distinctions among threats with similar characteristics, but we sought a parsimonious classification that reflected the knowledge available to distinguish among the effects of different threats on conservation targets. As with all aspects of our framework, threats can be reclassified in the future as additional information about their effects on conservation targets becomes available.

5.2 Prioritizing Threats

Threats can affect environmental features important to target species in multiple ways (Salafsky et al. 2008), at different spatial scales, and for different periods of time. For example, primary highways do not have an especially large footprint relative to other land uses, nonetheless their effects are severe and long lasting (Trombulak and Frissell 2000, Riley et. al. 2006). Therefore, we prioritized threats by establishing the relationship between each threat and each environmental feature based on two attributes: *severity* and *permanence* in the immediate vicinity of the threat. As with other aspects of our approach, we sought a classification to reflect the amount of information available to establish meaningful distinctions among threats without being unrealistically complex. We considered other characteristics of threats, including (spatial extent, potential and cost for abatement, likelihood of a threat, and timing of a threat; for additional information on additional threat categories, see Salafsky and Margoluis 1999 , Low 2003, The Nature Conservancy 2007), but we believe that severity and permanence captured the most important differences among threats.

Severity. We defined severity as the degree to which a threat could alter the structure or function of an environmental feature in the planning area over the next 30 years. For many threats, such as invasive species and shallow-groundwater pumping, severity can vary; therefore, we established a threshold above which we considered the threat to be consequential. For example, adverse effects of pumping shallow groundwater will not affect conservation targets until it affects the amount of water available to plants and the amount of available surface water. We evaluated severity by considering the effects of threat manifested in a typical way across an area relevant to each threat. For example, rural development typically affects areas >10 hectares with different types of disturbances across the affected area, such as homes, corrals, and roads; therefore, the footprint of development was less (score = 1) as compared to development in the urban setting (score =3) that left little or no natural open space. We scored the potential effect of each threat on each environmental feature as:

3 = extreme degradation,
2 = high degradation,
1 = low degradation,
0 = no appreciable degradation.

For example, the impact on large perennial lotic waters differs significantly if the threat is urban core development (score = 3) as compared to motorized off-road vehicle use (score = 1) (**Table 5.1**).

Table 5.1. Example of environmental features and threats matrix. Each threat was evaluated for severity (Sev) and permanence (Per), with higher numbers indicating more severe or more permanent threats. A complete matrix is available on request from the authors.

		Urban-core development		Rural development		Shallow ground-water pumping		Motorized off-road vehicle use	
Group	**Environmental Feature**	**Sev**	**Per**	**Sev**	**Per**	**Sev**	**Per**	**Sev**	**Per**
Aquatic	Large perennial lotic waters (rivers, streams, creeks)	3	4	1	4	3	1	1	1
	Small perennial lotic waters (springs, seeps)	3	4	1	4	3	2	1	1
	Perennially flooded vegetation	3	4	1	4	3	1	1	1
	Perennial open lentic waters (ponds, lakes, stock tank)	3	4	1	4	3	3	1	1
	Large ephemeral lotic waters (rivers, streams, creeks)	2	4	1	4	1	1		
	Ephemeral open lentic waters (pools, tinajas)	2	4	1	4	1	1		
Structures	Burrows into substrate made by animals	3	4	2	4			2	2
	Fractures in substrates not made by animals	3	4	1	4	1	3	1	2
	Cavities	3	4	1	3				
	Earthen banks	3	4	1	4	1	4	1	2
	Terrestrial coarse woody debris, snags, stumps	3	4	1	4			1	2
	Instream coarse woody debris	3	4	1	3	3	2	1	1
Vegetation: Overstory	Cover of overstory vegetation	3	4	1	4	3	3	1	
	Density of overstory vegetation	3	4	1	4	3	3	1	
	Composition of overstory vegetation by species	3	4	1	4	3	2		
Midstory	Cover of midstory vegetation	3	4	1	4	3	2		
	Density of midstory vegetation	3	4	1	4	3	2		
	Composition of midstory vegetation by species	3	4	1	4	2	2		1
Understory	Cover of understory vegetation by class	3	4	2	4	3	2	2	2
	Composition of understory vegetation by species	3	4	1	4	3	2	1	2
Aquatic	Structure of emergent and submerged vegetation	3	4	1	4	3	2	1	1
	Composition of emergent and submerged vegetation	3	4	1	4	3	2		
	Cover of algae	2	4	1	4	3	2		

Permanence. We defined permanence as the amount of time required for a conservation target affected by a threat to recover to its pre-disturbance condition after the threat is eliminated. We scored permanence of threats based on the time period required for recovery for each environmental feature:

1 = <1 year,
2 = ≥1 to <10 years,
3 = ≥10 to <100 years,
4 = ≥100 years.

Extending the example of large perennial lotic waters to permanence, development in the urban core will last indefinitely (i.e., score = 4 on the assumption that once developed into urban core, it will remain in that state), whereas some effects from off-road vehicles could last less than a year (i.e., score = 1).

6 Ecosystem Processes

Ecosystems are comprised of structural elements that drive and are driven by processes that function and manifest at different spatial and temporal scales, from nutrient and energy flow through long- and short-term dynamics of plant and animal communities. Changes in the rate and intensity of these processes can alter ecosystem structure and other ecosystem processes. Because of their importance, incorporating ecosystem processes into regional conservation planning efforts has received increasing attention (e.g., Pima County 2000, Cowling and Pressey 2001, Pressey et. al. 2003, Rouget et. al. 2003, Klein et al. 2009). Therefore, we developed a strategy to incorporate the influence of important ecosystem processes into monitoring programs.

6.1 Selection of Processes

We initially identified a large number of ecosystem processes that we reduced to eight primary processes in four general categories for further consideration (**Table 6.1**). Although temperature is not a process, we included it here because of its influence on many other ecosystem processes. We excluded processes that were principally biotic, because such processes can be monitored indirectly by monitoring the biotic structures that drive these processes, such as pollination, where both plants and their pollinators could be monitored. We also excluded processes that manifest at scales that are either too small or too large to be relevant to monitoring at the regional scale or were captured in other processes (**Table 6.2**).

Table 6.1. Ecological processes that we included in development of a monitoring program.

Category	Ecological Process
Atmosphere	Solar radiation
	Temperature
Water	Precipitation
	Evaporation
Soils	Erosion
	Deposition
Materials Cycling	Nutrient transfer (e.g., C, N, P)
	Decomposition
	Fire

Table 6.2. Ecosystem processes that were considered but excluded.

	Reason for Exclusion		
Process/Condition	**Principally Biotic**	**Captured by another process**	**Too broad or fine**
Pollination	X		
Evolution	X		
Competition	X		
Dispersal	X		
Recruitment	X		
Respiration	X		
Transpiration	X		
Herbivory	X		
Defoliation	X		
Germination	X		
Predation	X		
Population dynamics	X		
Parasitism	X		
Primary production	X		
Plant succession	X		
Seasons		temperature, precipitation, and solar radiation	
El Niño southern oscillation		temperature, precipitation, and solar radiation	
Humidity		temperature and precipitation	
Wind			X
Atmospheric deposition		nutrient transfer	X
Humification of soil		nutrient transfer and decomposition	X
Mineralization of soil		nutrient transfer and decomposition	X
Water run-off		precipitation	X
Water infiltration/ percolation		precipitation	X
Groundwater recharge		precipitation	X

6.2 Processes and Other Components

As with threats (**Section 5**), we scored the relationship between each ecological process and each environmental feature, but here we used a simpler binary response; we noted whether or not the process had a direct effect on creation, elimination, persistence, alteration, state, or quality of an environmental feature (**Table 6.3**). Although there are many potential direct and indirect relationships among processes and environmental features, we considered only direct effects as we did when evaluating the effects of threats on environmental features (**Section 5**).

Table 6.3. Example of environmental features by processes matrix. A complete matrix is available from the authors.

Group	Environmental Feature	Temperature	Precipitation	Erosion	Nutrient transfer	Decomposition	Fire
Aquatic	Large perennial lotic waters (rivers, streams, creeks)	x	x	x	x		
	Small perennial lotic waters (springs, seeps)	x	x	x	x		
	Perennially flooded vegetation	x	x	x	x		
	Perennial open lentic waters (ponds, lakes, stock tank)	x	x	x	x		
	Large ephemeral lotic waters (rivers, streams, creeks)	x	x	x	x		
	Ephemeral open lentic waters (pools, tinajas)	x	x	x	x		
Structures	Burrows into substrate made by animals		x	x			
	Fractures in substrates not made by animals		x	x			
	Cavities						x
	Terrestrial coarse woody debris, snags, stumps					x	x
	Instream coarse woody debris					x	
	Earthen banks			x			
Vegetation:							
Overstory	Cover of overstory vegetation		x				x
	Density of overstory vegetation		x				x
	Composition of overstory vegetation by species	x	x		x		x
Midstory	Cover of midstory vegetation		x				x
	Density of midstory vegetation		x				x
	Composition of midstory vegetation by species	x	x		x		x
Understory	Cover of understory vegetation by class		x	x			x
	Composition of understory vegetation by species	x	x		x		x
Aquatic	Structure of emergent and submerged vegetation			x	x		
	Composition of emergent and submerged vegetation	x			x		
	Cover of algae	x			x		

7 Management Feasibility

All ecological monitoring programs exist to provide information on the status, condition, and trends of target resources so that if the selected attributes of resources change adversely, management strategies can be developed to reverse or ameliorate those changes. Parameters measured as part of a monitoring program advance that goal when they:

- Inform current and future management programs directly;
- Can be manipulated to affect attributes of target resources.

Therefore, environmental features are most relevant to monitoring when they can be manipulated by management actions designed to affect targets resources (Atkinson et. al. 2004, Nichols and Williams 2006). To evaluate the degree to which environmental features can affect target resources, we answered this question for each environmental feature:

> *As a natural-resource manager, you are informed of a meaningful change in an environmental feature important to at least one target species. Given sufficient resources to provide a reasonable chance for success, what are the chances that management actions can be implemented to reverse this change?*

We scored management feasibility as:

0 = No reasonable chance of affecting change through local management;
1 = Small chance of affecting change through local management;
2 = Moderate chance of affecting change through local management;
3 = High chance of affecting change though local management.

A few environmental features scored a “3”, including cavities and instream course woody debris (**Table 7.1**) and a few environmental features were deemed infeasible to manipulate (e.g., large ephemeral lotic waters).

A key challenge to evaluating management feasibility is incorporating the influence of spatial scale as some management actions are feasible at small scales and infeasible at larger scales. For example, building artificial burrows or installing nest boxes would be a relatively easy way to increase the number of cavities on a small scale, but if this required action across an entire region, management feasibility decreases. Therefore, we evaluated feasibility on a local scale by estimating the effectiveness of management actions at a scale of approximately 10-25 hectares. Though not all management can take place at this scale, it nevertheless provides a consistent and practical scale for evaluation.

Table 7.1. Management feasibility scores for environmental features organized by groups.

Group	Environmental Feature	Management Feasibility
Aquatic	Large perennial lotic waters (rivers, streams, creeks)	1
	Small perennial lotic waters (springs, seeps)	1
	Perennially flooded vegetation	1
	Perennial open lentic waters (ponds, lakes, stock tank)	3
	Large ephemeral lotic waters (rivers, streams, creeks)	0
	Ephemeral open lentic waters (pools, tinajas)	0
Structures	Burrows into substrate made by animals	2
	Fractures in substrates not made by animals	2
	Cavities	3
	Terrestrial coarse woody debris, snags, stumps	2
	Instream coarse woody debris	3
	Earthen banks	2
Vegetation: Overstory	Cover of overstory vegetation	2
	Density of overstory vegetation	2
	Composition of overstory vegetation by species	2
Midstory	Cover of midstory vegetation	2
	Density of midstory vegetation	2
	Composition of midstory vegetation by species	2
Understory	Cover of understory vegetation by class	2
	Composition of understory vegetation by species	2
Aquatic	Structure of emergent and submerged vegetation	2
	Composition of emergent and submerged vegetation	2
	Cover of algae	0

8 Sampling Effort

Monitoring efforts sometimes fail to provide sufficient information to reliably evaluate changes in target parameters over time because sampling designs and effort are insufficient (Legg and Nagy 2006, Field et. al. 2007). In recent years, however, there has been increased appreciation for the influence that sampling design has on the effectiveness of monitoring programs (e.g., Steidl et. al. 1997, Cauglan and Oakley 2001). In this section, we describe a process to incorporate sampling cost and sampling variation on selection of parameters for monitoring, which are important factors influencing decisions related to sampling design.

Any effort to quantify temporal changes in attributes of natural resources at all but the smallest scales requires sampling, which in the context of monitoring involves measuring ecological parameters on a subset of the larger area of interest (Thompson 2002). For some parameters, sampling is also necessary within the primary sampling units that form the sample. Sampling within primary sampling units, or "subsampling," increases the efficiency of measuring some natural resources because within a single sampling unit, it might be impossible or cost prohibitive to measure the resource across the entire unit. For example, to quantify composition of understory vegetation in a 1 x 1-m^2 quadrat is straightforward and time efficient; to quantify the same parameter in a 100 x 100-m^2 quadrat would be extremely time intensive—approximately 10,000 times the effort of quantifying composition on a single 1 x 1-m^2 quadrat. Consequently, the effort necessary to reliably quantify a resource on a primary sampling unit is an integral aspect of making sampling efficient, as resources that require less subsampling effort are likely to be more efficient to measure. The following sections highlight three important and inter-related issues related to on-the-ground field sampling.

8.1 Sampling Unit

After considering multiple alternatives for how to collect on-the-ground data for a regional monitoring program, we established the primary sampling unit as a circular plot with a radius of 200 m (12.6 ha), a size that will support measurement of all environmental features, plus additional biological parameters, such as community-based measures for vertebrates, that are likely to a part of many monitoring programs (**Fig. 1.1**). Sampling units of different sizes and shapes might be equally suitable for general monitoring at the ecoregional scale, but for our purposes, this size appears to provide a reasonable tradeoff between too large (i.e., too much variation within a plot), and too small (i.e., not suitable for measuring all potential environmental features).

8.2 Variation within a Sampling Unit

Understanding the natural variation in parameters over space and time (daily, seasonal, annual, etc.) is fundamental to design of any sampling effort because these patterns drive decisions as to where and when to sample; in general, the more a parameter varies naturally in time and space, the more sampling effort that is required to obtain precise estimates of that parameter. The precision of these estimates is central to being able to detect systematic temporal variation (that is, trends) that constitute common goal of monitoring programs. Coefficient of variation (CV = standard deviation/estimate * 100) is a relative measure of precision useful in evaluating parameter estimates, including those relevant to monitoring (Gibbs et al. 1998). Because CV is relative, it is useful to compare parameters measured on different scales. The smaller the CV, the less variation there is in estimates of a parameter.

For environmental features that are most conveniently measured at scales smaller than the sampling unit, such as composition of understory vegetation that is often measured on 1-m^2 plots, subsampling on smaller subplots within the larger sampling unit will reduce the amount of effort necessary and still yield reliable estimates of the parameter.

Many of the environmental features we are considering can be measured as proportions, such as cover of midstory vegetation, or can be measured as counts, such as density of overstory vegetation. Both types of environmental features can be represented well by statistical distributions whose variances are function of their means (Krebs 1999; p. 214), and we can use these distributions as a basis for establishing the approximate number of subplots that must be measured within the larger primary plot to achieve a target level of precision—a measure of how close estimates from subplots come to the true value of the parameter on the entire sampling unit. For proportions, we used the binomial distribution and for counts we used the Poisson distribution.

As a target level of precision, we established a coefficient of variation equal to 20% and used conservative values of the mean for each distribution. For proportions, we used a mean equal to 0.5, which is the level at which variation in estimates is highest. To achieve a CV = 20%, we must measure approximately 25 subplots per sampling unit. For counts, variation decreases as the mean number of objects per subplot increases; we used a mean equal to 3.0. To achieve a CV = 20%, we must measure approximately 10 subplots per sampling units. Consequently, for all proportions we set the number of subplots equal to 25 and for counts we set the number of subplots to 10.

8.3 Costs and Sampling Effort

To establish a basis for comparing the *relative* costs of measuring different sets of environmental features, we estimated the amount of effort in minutes necessary to measure each environmental feature on a plot. For environmental features measured on subplots, we multiplied effort per subplot times the number of subplots per plot (**Table 8.1**). Some environmental features will require multiple visits to a plot in a year when they are sampled, and features that are slow to change not need be measured every year. Therefore, we computed effort per primary sampling unit per year across a 10-year window (to account for variation among environmental features in required frequency of surveys) by combing these factors:

Effort = no. surveys /year x no. subplots/plot x no. visits/year x effort/subplot

To estimate abundance or amount of water in small perennial lotic waters, for example, plots should be surveyed twice every year, once pre- and once post-monsoon, and we estimated that each survey would take 15 minutes. Therefore, the estimated effort per primary plot per year for this environmental feature was computed as:

Annual Effort per Plot = 2 x 1 x 15 x 1 = 30 minutes.

Table 8.1. Estimates of annual amount of effort (in minutes) required to monitor each environmental feature on one sampling unit.

Group	Environmental Feature	Measure	Surveys: No. in 10 years	Surveys: No. / year	No. subplots/ plot	Effort: subplot	Effort: plot	Effort/ plot/year
Aquatic	Large perennial lotic waters (rivers, streams, creeks)	Amount or areal coverage	10	2	1	15	15	30
	Small perennial lotic waters (springs, seeps)	Abundance or aerial coverage	10	2	1	15	15	30
	Perennially flooded vegetation (marsh, cienega)	Aerial coverage	10	2	1	15	15	30
	Perennial open lentic waters (ponds, lakes, stock tank)	Aerial coverage	10	2	1	15	15	30
	Large ephemeral lotic waters (rivers, streams, creeks)	Aerial coverage	10	2	1	15	15	30
	Ephemeral open lentic waters (pools, tinajas)	Abundance or duration of presence	10	2	1	15	15	30
Structures	Burrows into substrate made by animals	Abundance	3	1	1	100	100	30
	Fractures in substrates not made by animals	Abundance	1	1	1	200	200	20
	Cavities	Abundance	2	1	1	50	50	10
	Earthen banks	Length	2	1	1	20	20	4
	Terrestrial coarse woody debris, snags, stumps	Density or Volume	1	1	5	15	75	8
	In-stream coarse woody debris	Density or Volume	1	1	3	15	45	5
Vegetation: Overstory	Cover of overstory vegetation	Cover	2	1	25	1	25	5
	Density of overstory vegetation	Density	2	1	10	5	50	10
	Composition of overstory vegetation by species	Density or cover x species	2	1	10	15	150	30
Midstory	Cover of midstory vegetation	Cover	2	1	25	1	25	5
	Density of midstory vegetation	Density	2	1	10	5	50	10
	Composition of midstory vegetation by species	Density or cover x species	2	1	10	20	200	40
Understory	Cover of understory vegetation by class	Cover x woody/herbaceous x native/nonnative	3	1	25	3	75	23
	Composition of understory vegetation by species	Density or cover x species	2	1	10	20	200	40
Aquatic	Structure of emergent and submerged vegetation	Cover	3	1	1	3	3	1
	Composition of emergent and submerged vegetation	Density x species	2	1	1	20	20	4
	Cover of algae	Areal coverage	10	1	1	3	3	3

Several environmental features can be characterized with several possible attributes, each of which would provide different information about the environmental feature and each of which might require a different amount of effort to measure. For example, the structure of a single tree can be characterized by its height, trunk diameter, canopy diameter, and so on. To estimate effort, we selected only one attribute of each environmental feature and considered the most appropriate survey methods for measuring this particular attribute. A more complex approach for features with multiple attributes would be to consider each attribute as an independent environmental feature, estimate the amount of effort necessary to measure each attribute, and include each attribute as an independent feature in the species x environmental feature matrix. We used this approach for several vegetation features where we considered cover and composition as separate features.

Although travel related to field sampling will comprise an appreciable portion of the budget of a monitoring program, this will depend largely on the specific sampling design that will be established later (**Section 10**). Therefore, we estimated effort required to measure each environmental feature on one sampling unit which will be largely independent of the design employed. Similarly, we did not estimate effort for data management, data analysis, or project management because these costs will be similar for all sampling designs and likely small relative to costs of data acquisition. Finally, we also did not include the cost savings associated with co-locating groups of environmental features that would be measure concurrently, such as midstory and overstory vegetation density, as the cost savings would come from reducing travel time among plots, not the amount of effort necessary to measure features within plots.

9 Prioritizing Environmental Features

Like all scientific endeavors, developing a monitoring program requires establishing well defined goals and objectives (Elzinga et al. 2001, Yoccoz et. al. 2001) that become the cornerstone of the creative process that is sampling design. To guide the complex process of identifying which environmental features to monitor, we developed a strategy based on principles of decision theory and informed by a set of explicit objectives relevant to monitoring programs. This process translates a set of objectives into quantitative criteria that are included in an equation called an *objective function*. The objective function provides a basis for score different subsets of environmental features based on how well they meet the objectives included in the function. This provides a quantitative basis for comparing among subsets of environmental features, with those scoring highest fulfilling best the objectives defined in the function. The main strengths of this process are that it is explicit, objective, and flexible, in that it can incorporate different sets of objectives and weight objectives to reflect local priorities, providing solutions that reflect different sets of objectives or monitoring priorities. Several subsets of environmental features may result in the same score from the function, but these subsets may differ with regards to how well they satisfy each individual monitoring objective, given that there will always be tradeoffs when attempting to meet multiple objectives simultaneously.

The objective function can be evaluated for all possible combinations of environmental features or, if the number of potential combination is too great, can be evaluated with a selection algorithm to improve efficiency of processing. Although selection algorithms such as simulated annealing (Possingham et. al. 2000) can be used to reach optimal solutions quickly without the need for exploring all possible combination of environmental features, we chose to evaluate all possible combinations of features.

9.1 Prioritizing Environmental Features

We established monitoring objectives to represent the ideas described in each major section of this report that provided the basis for comparing among different subsets of environmental features. Any number of objectives can be established, and we developed objective criteria for target species, anthropogenic threats, ecosystem processes, management feasibility, and sampling effort. We then established quantitative criteria to assess how well each subset of environmental features meets each monitoring objective. Below, we describe each objective, the quantitative criteria we developed, and potential alternatives or modifications that might be appropriate for these criteria in other circumstances.

9.1.1 Species-related criteria

9.1.1.1 Comprehensive coverage

Monitoring objective: Ensure that the largest number of species is represented by the subset of environmental features selected for monitoring.

Quantitative criterion: For each subset of environmental features, compute the proportion of species that use at least one of the selected environmental features based on information in the species-environmental feature matrix. Subsets of environmental features with the largest value for this criterion best meet this objective (range 0-1).

Comprehensive coverage for species =
no. species that use ≥ 1 environmental feature / total no. species

Potential modifications: Because we scored relative importance of each environmental feature for each species with a series of ranks (0-3), we can incorporate this information by changing the ranks in the matrix that are considered in this computation. We set ranks of 2 and 3 as equal and did not evaluate ranks of 1; that is, we included only the most important relationships between species and environmental features (ranks 2 and 3). We also had information on two sets of species: target species and the priority vulnerable species, which could be considered separately or collectively in this computation. We computed comprehensive coverage for the two sets of species separately.

9.1.1.2 Redundancy

Monitoring objective: This is an extension of comprehensive coverage designed to ensure that the largest number of species is represented by more than one environmental feature selected for monitoring.

Quantitative criterion: We computed the proportion of species that are represented by >X of the selected environmental features (where X = level of redundancy = 1, 2, … n) based on information in the species-environmental feature matrix. Those subsets of environmental features with the largest value for this criterion best meet this objective (range 0-1).

Redundancy for species =
no. species that use >X environmental features / total no. species

where X = 1, 2,…n

Potential modifications: This criterion could be modified by changing the level of redundancy desired and ranks in the matrix considered in this computation. We set X = 1, that is, species needed to be represented by more than one (at least two) environmental features. Further, we set ranks of 2 and 3 as equal and did not use ranks of 1, that is, we included only the most important relationships between species and environmental features (ranks 2 and 3). We also had information on two sets of species: 109 Target Species and 25 Covered Species (12 of which are also included in the list of target species), which could be considered separately or collectively in this computation. We computed redundancy for the two sets of species separately.

9.1.2 Threat-related criteria

9.1.2.1 Threat severity

Monitoring objective: Monitor environmental features most likely to be affected by the most severe anthropogenic threats.

Quantitative criterion: We summed severity scores for threats affecting each environmental feature in each subset based on information in the threats-environmental feature matrix, computing the average severity score for all threats that affect an environmental feature, and then scaled this average by dividing by the maximum average score. Those subsets of environmental features with the largest value for this criterion best meet this objective (range 0-1).

Depth for threat severity =
average severity score for threats that affect an environmental feature / maximum score

Potential modifications: Because we scored relative severity of threats on each environmental feature with ranks, we could compute this value with only certain ranks, such as those considered most severe. We chose to use all scores because the cumulative effects of many less severe threats could be as problematic as effects of one severe threat.

9.1.2.2 Threat permanence

Monitoring objective: Monitor environmental features most likely to be affected by the most permanent anthropogenic threats.

Quantitative criterion: We summed permanence scores for threats affecting each environmental feature in each subset based on information in the threats-environmental feature matrix, computing the average permanence score for all threats that affect an environmental feature, and then scaled this average by dividing by the maximum average score. Those subsets of environmental features with the largest value for this criterion best meet this objective (range 0-1).

Depth for threat permanence =
avg. permanence score for threats that affect an environmental feature / max. score

Potential modifications: Because we scored relative permanence of threats on each environmental feature with ranks, we could compute this value with only certain ranks, such as those considered most permanent. We chose to use all scores because the cumulative effects of many less permanent threats could be as problematic as the effects of one permanent threat.

9.1.3 Process-related criterion: Process Depth

Monitoring objective: Choose the subset of environmental features that are most likely to be affected by the largest number of natural ecosystem processes.

Quantitative criterion: We counted the number of processes that affect each environmental feature in the selected subset based on information in the process-environmental feature matrix, computed the average number of processes that affected an environmental feature, and then scaled this average by dividing by the maximum average score. Those subsets of environmental features with the largest value for this criterion best meet this objective (range 0-1).

Depth for processes = avg. no. of processes that affect an environmental feature */ max. score*

Potential modifications: Although we only indicated whether or not (i.e., 0 or 1) each process affected each environmental feature, some sort of ranking could be developed to represent the strength of these relationships.

9.1.4 Management-related criterion: Management Feasibility

Monitoring objective: Monitor environmental features that could be altered by management actions, such that detrimental changes could be abated.

Quantitative criterion: We computed average management-feasibility score for environmental features in each subset based on information in the management-environmental feature matrix. We scaled each management-feasibility score by dividing by 3 (the maximum score possible) then computing an average. Those subsets of environmental features with the largest value for this criterion best meet this objective (range 0-1).

Management feasibility =
scaled management feasibility score for each environmental feature /
no. environmental features in subset

Potential modifications: Because we scored management feasibility on each environmental feature with ranks, we could consider computing this value based on certain ranks.

9.1.5 Effort-related criteria: Relative effort/cost

Monitoring objective: Monitor environmental features that require low relative effort.

Quantitative criterion: We summed relative effort necessary for sampling each environmental feature in each subset based on information in the effort-environmental feature matrix. We scaled each effort score by dividing by the maximum cost for all subsets of environmental features considered. We subtracted this score from 1, such that more expensive and time-consuming subsets of environmental features would get the lowest score, therefore, those subsets of environmental features with the largest value for this criterion best meet this objective (range 0-1).

Relative effort =
1 – (sum of relative effort for a subset of environmental features /
maximum relative effort)

Potential modifications: More detailed effort and cost information would help to better evaluate trade-offs of meeting biological objectives and realities of cost and effort limits. Considerations of plot co-location and concurrent sampling and the inherent cost-savings should be considered as part of the overall sampling design.

9.2 Objective Functions for Selection Criteria

We incorporated all of the quantitative selection criteria into a single equation—the objective function—that we evaluated for all possible subsets of environmental features. Any or all of the individual selection criteria can be differentially weighted (wt_i) to reflect the relative importance of each criterion based on local priorities or perspectives (e.g., rare species, cost, etc.). Therefore, objective functions can be evaluated to explore the effects of varying priorities through different weighting schemes. Evaluating any objective function will ensure that the environmental features selected simultaneously satisfy all objectives optimally, whether the objectives are ecological, financial, or management-related. Because the objective function seeks to balance many objectives, the overall score reflects tradeoffs among these objectives.

The general form of the objective function (OF) is:

*OF score = (wt_1 * comprehensiveness for target species) + (wt_2 * redundancy for target species) +*
*(wt_3 * comprehensiveness for PVS) + (wt_4 * redundancy for PVS) +*
*(wt_5 * depth for processes) + (wt_6 * depth for threat severity) +*
*(wt_7 * depth for threat permanence) + (wt_8 * management feasibility) +*
*(wt_9 * relative effort)*

The maximum score for each individual criterion is 1. If all included criteria are equally weighted (wt_i = 1), the maximum score for a given objective function is simply the sum of the number of criteria used.

We developed computer code (in SAS, available on request from the authors) to evaluate this general objective function, which includes user-specified variables for the various weights, desired level of redundancy, and ranks in matrices targeted for inclusion. All combinations of environmental features were evaluated to generate an overall score, then ranked by scores. As mentioned previously, several subsets of environmental features may yield the same or similar scores; however, each subset will likely meet individual objectives differently.

9.3 Sensitivity of Objectives

To understand the relative influence of individual objectives on the objective function and therefore on the set of environmental features identified as optimal in top-ranked sets, we performed a type of sensitivity analysis to assess how well individual objectives were met when we altered the weight of other objectives in the function.

We established a scheme as the benchmark for comparison by weighting all criteria in the objective function equally (i.e., all wt_i = 1). We evaluated this weighting scheme for all combinations of environmental features, generated a score for each criterion as well as an overall score (a sum of all individual scores), sorted all combinations of environmental features by overall score, and retained the subset of environmental features that resulted in the highest overall score. We then increased the weight of each criterion individually from 2 through 10 by 1, re-evaluated all combinations of environmental features, and retained the set of environmental features that resulted in the highest score for each of weighting scheme. We then compared the scores for each individual criterion between the equal weighting scheme and where each criterion was maximally weighted (i.e., wt_i = 10) by computing the difference in scores for all criterion at weight = 10 minus the score at weight = 1.

If scores for individual criterion increased with changing weight, this suggests an improvement in the ability to meet that objective for a given change in priority in the objective function. If scores for individual criterion decreased with changing weights, this suggests a reduction in the ability to meet that objective as for a given change in priority in the objective function. If scores for individual criterion did not change with changing weights, the ability to meet that objective did not change with a given change in priorities.

Emphasizing target species – When weights were increased for species-related objectives–comprehensive coverage and redundancy–we were less likely to meet the objective of selecting a subset of environmental features with low sampling effort as was evident as scores for effort in **Fig. 9.1** fall below the reference line at zero for species-related objectives (comprehensive – species, comprehensive – PVS, redundancy – species, redundancy – PVS). As expected, increasing redundancy or coverage of species requires higher sampling effort. In general, scores for comprehensive coverage were high (>0.97) when all criteria were weighted equally, and increases in scores in response to changing the weighting for these criteria was relatively small compared to changing other criteria; that is, there was little to no change in scores for other components as values fall near the reference line at zero (**Fig. 9.1**). Scores for redundancy did increase when the priority (weight) for this component was increased as values fall above the reference line in **Fig. 9.1**.

Emphasizing processes – When weights were increased for processes, the amount of sampling effort required also increased and we were less likely to meet objectives related to redundancy and management feasibility (see decrease in scores for effort, redundancy, and management in **Fig. 9.1**, processes). When emphasizing processes, more aquatic features were selected for monitoring (e.g., ephemeral open lentic waters), as these features are tied to many ecological processes. Monitoring these features is effort-intensive and some of these aquatic features are difficult to affect through management action.

Emphasizing threats – When weights were increased for threat-related objectives, there was little change in the results from objective function, as scores for most criteria did not change (**Fig. 9.1**, threat severity and threat permanence).

Emphasizing management – When weights were increased for the management objective, we were more likely to meet that criterion as the score increased, but criteria related to processes and threat severity were less likely to be met as those scores decreased (**Fig. 9.1**, management). This again was related to aquatic features being important for species and processes, but difficult to affect through management action.

Emphasizing effort – When weights were increased for effort/cost, selecting a subset of environmental features that resulted in lower sampling effort/cost, other objectives related to species and processes were less likely to be met, especially redundancy (see decrease in score for comprehensive, redundancy, redundancy PVS, and processes in **Fig. 9.1**, effort). This is not a surprising result, as reducing cost and sampling effort could mean monitoring fewer environmental features or not monitoring features that are expensive to measure even when they are informative, which would reduce the chances of monitoring more than one environmental feature for each target species. By emphasizing environmental features that can be measured with less sampling effort, environmental features that are tied to processes were less likely to be selected for monitoring as their scores decreased (**Fig. 9.1**, effort), in part because various aquatic features (e.g., ephemeral open lentic waters) are both tied to many ecological processes and because monitoring these features is effort-intensive. Some of these aquatic features are also difficult to affect with management, therefore excluding these environmental features from the monitored subset can help to meet the management objective.

By emphasizing some objectives over others in the objective function, scores change to reflect the explicit change in priorities, ultimately resulting in different set of environmental features being selected. The most obvious of these changes is the tradeoffs involved in balancing sampling effort and cost of a monitoring program with biological-based objectives. Relative to other tradeoffs considered, emphasizing the redundancy criterion seems to provide a nearly ideal best compromise. Under this weighting scheme, redundancy objectives are more likely to be met without greatly decreasing the chance of meeting other objectives (see increases in scores for redundancy, little to no change in scores for most components, and only slight decreases in the score for effort in **Fig. 9.1, redundancy – species, redundancy – PVS**). This weighting would increase the number of species represented by more than one environmental feature selected for monitoring with only slight increases in relative sampling effort.

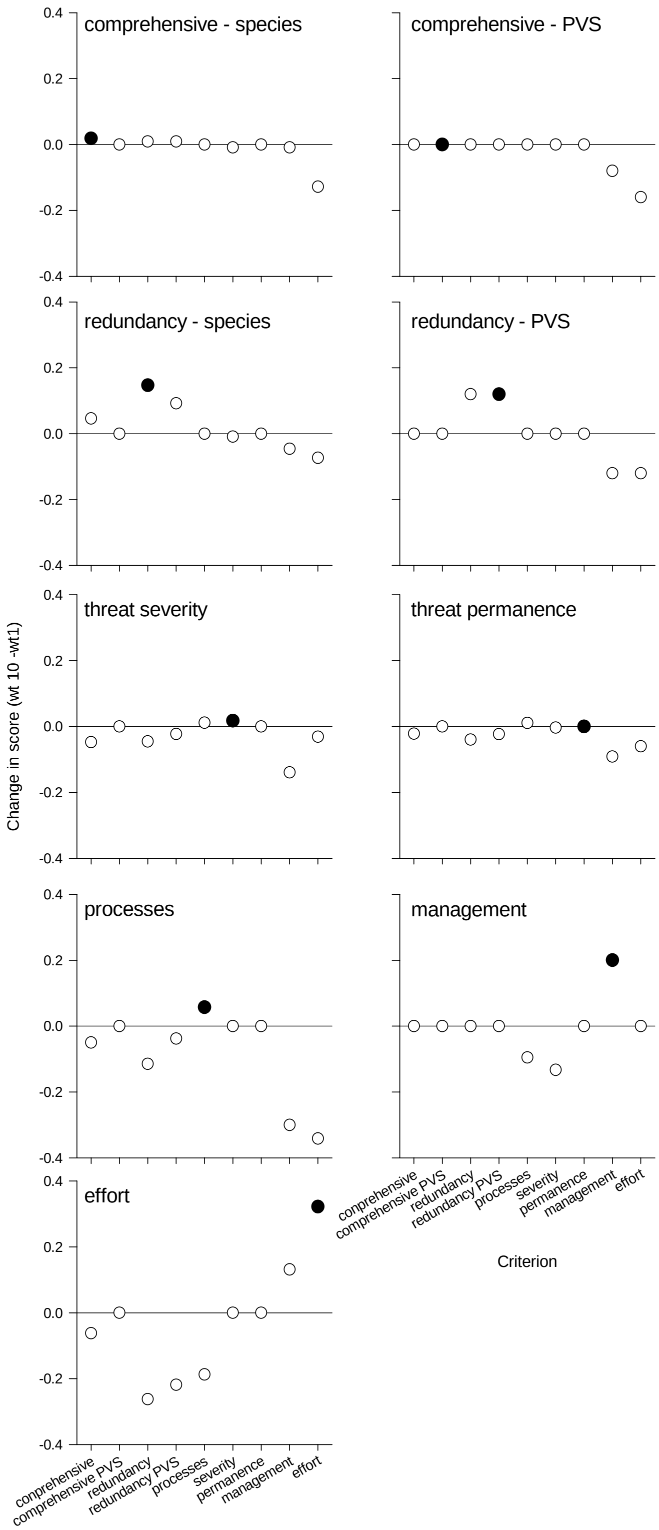

Figure 9.1. Changes in scores for each criterion in the objective function with changing weights, when compared to an objective function where all criteria are weighted equally. Each graph is labeled with the criterion that was emphasized by changing the weight to 10.

9.4 Prioritizing Environmental Features

We prioritized subsets of environmental features by evaluating the general objective function with four different weighting schemes that we selected to reflect different sets of priorities that seem likely for different monitoring programs.

<u>All equal</u>

Priority: None. All criteria are weighted equally.

*OF score = (1 * comprehensiveness for target species) + (1 * redundancy for target species) +*
*(1 * comprehensiveness for PVS) + (1 * redundancy for PVS) +*
*(1 * depth for processes) + (1 * depth for threat severity) +*
(1 depth for threat permanence) + (1 * management feasibility) +*
*(1 * relative effort)*

<u>Target species</u>

Priority: Comprehensive coverage and redundancy for target species.

*OF score = (**1 * comprehensiveness for target species**) + (**1 * redundancy for target species**) +*
*(0 * comprehensiveness for PVS) + (0 * redundancy for PVS) +*
*(1 * depth for processes) + (1 * depth for threat severity) +*
(1 depth for threat permanence) + (1 * management feasibility) +*
*(1 * relative effort)*

<u>Species of concern</u>

Priority: Comprehensive coverage and redundancy for priority vulnerable species (PVS).

*OF score = (1 * comprehensiveness for target species) + (1 * redundancy for target species) +*
*(**2 * comprehensiveness for PVS**) + (**2 * redundancy for PVS**) +*
*(1 * depth for processes) + (1 * depth for threat severity) +*
(1 depth for threat permanence) + (1 * management feasibility) +*
*(1 * relative effort)*

<u>Effort/Cost</u>

Priority: Minimum relative cost and effort.

*OF score = (1 * comprehensiveness for target species) + (1 * redundancy for target species) +*
*(1 * comprehensiveness for PVS) + (1 * redundancy for PVS) +*
*(1 * depth for processes) + (1 * depth for threat severity) +*
(1 depth for threat permanence) + (1 * management feasibility) +*
*(**3 * relative effort**)*

We evaluated these four objective functions for all possible combinations of 1-10 environmental features (2,842,225 possible subsets) and examined subsets of environmental features selected, which were those with highest scores because they best met the established objectives. Because there may be tradeoffs inherent in maximizing one criterion over another, scores for multiple subsets of environmental features were sometimes quite similar (e.g., to the 2nd and 3rd decimal place). As such, we considered scores (and the subsets of environmental features) to be essentially equivalent if they were within 1% of the highest score (range: 14-216 equivalent subsets of environmental features). We computed the proportion of times each environmental feature was included in one of these "best" subsets (**Table 9.1**).

Overall, cover of understory vegetation by class was included in all of the top-scoring subsets and perennial open lentic waters was always among the best subsets where effort/cost was not a priority (**Table 9.1**). Vegetation-related environmental features were common among the selected subsets, regardless of the weighting scheme. Conversely, several environmental features were never included in the top-scoring subsets: large ephemeral lotic waters, ephemeral open lentic waters, cavities, and cover of algae. Small perennial lotic waters and earthen banks were never included in more than 7% of the best subsets.

Selected environmental features often varied greatly when the priority was mainly species of concern (**Table 9.1**, PVS). Collecting information about burrows and additional data on vegetation at each location, such as composition of the understory and midstory, and density of the overstory, may be important for these species. Although there were some similarities between the general weighting scheme and the weighting scheme focused on species of concern (**Table 9.1**, General, PVS), this occurred because both sets of species are included in each scheme. The weighting scheme focused on target species, however, does not include any criteria specifically related to species of concern (i.e., weights are 0 for comprehensive coverage and redundancy).

Although cost/effort are certainly a large consideration in developing any long-term monitoring program, results from the sensitivity analysis (**Section 9.3**) indicated that biological objectives may be comprised with this cost/effort is the primary focus. As such, measuring only the subset of environmental features selected under this weighting scheme (**Table 9.1**, Cost) should be considered as a bare minimum, and the resulting tradeoffs considerable.

9.5 Conclusions

The choice of which environmental features to include in a monitoring program can vary depending on the priorities and weighting scheme used (**Table 9.1**). We used four different weighting schemes and, for all but one environmental features, the results differed by scheme. However, of the top five proportions in each weighting scheme, four were for vegetation categories regardless of weighting scheme. Because structure and composition of vegetation and their vertical location (i.e., under-, mid-, and overstory) are monitored concurrently, this conformity of results is encouraging and suggests that it developing a monitoring program to successfully meet multiple objectives without requiring that an undo number of parameters be monitored is a tenable proposition.

Table 9.1. Proportion of the equivalent subsets (scores within 1% of the largest value) that included each environmental feature under each of four weighting schemes: all equal (General), selected species (Species), species of concern (PVS), and cost/effort (Cost). Values in parentheses represent the number of equivalent subsets. Highlighted are the top five proportions for each weighting scheme.

Environmental Feature	General (216)	Species (16)	PVS (90)	Cost (14)
Large perennial lotic waters (rivers, streams, creeks)	0.14	0.13	0.10	0.00
Small perennial lotic waters (springs, seeps)	0.06	0.00	0.06	0.00
Perennially flooded vegetation (marsh, cienega)	0.12	0.06	0.10	0.00
Perennial open lentic waters (ponds, lakes, tanks)	**1.00**	**1.00**	**0.92**	0.36
Large ephemeral lotic waters (rivers, streams, creeks)	0.00	0.00	0.00	0.00
Ephemeral open lentic waters (pools, tinajas)	0.00	0.00	0.00	0.00
Burrows into substrate made by animals	0.44	0.00	0.82	0.00
Cavities in trees made by animals	0.00	0.00	0.00	0.00
Terrestrial coarse woody debris, snags, stumps	0.06	0.00	0.08	0.14
Instream coarse woody debris	0.00	0.00	0.20	0.00
Earthen banks	0.00	0.00	0.07	0.07
Cover of overstory vegetation	**0.80**	**0.50**	**0.93**	**0.86**
Density of overstory vegetation	**0.54**	0.13	0.88	0.29
Composition of overstory vegetation by species	0.20	0.19	0.14	0.00
Cover of midstory vegetation	**0.60**	**0.63**	0.34	**0.86**
Density of midstory vegetation	0.27	**0.31**	0.19	0.14
Composition of midstory vegetation by species	0.20	0.00	**0.89**	0.00
Cover of understory vegetation by class	**1.00**	**1.00**	**1.00**	**1.00**
Composition of understory vegetation by species	0.40	0.00	**0.96**	0.00
Structure of emergent and submerged vegetation	0.34	0.06	0.47	**0.79**
Composition of emergent and submerged vegetation	0.39	0.06	0.48	**0.57**
Cover of algae	0.00	0.00	0.00	0.00

10 Future Work

We developed the strategy described in this report as an explicit process for choosing a set of parameters to measure that balanced targets and goals of a framework program with the challenges and costs of field sampling required to estimate those parameters. As mentioned earlier, the set of parameters identified will provide a reliable foundation on which a more complete monitoring program can be built by adding additional parameters as required, such as single-species, community-, or landscape-level metrics. We sought to keep the strategy sufficiently general and flexible so that it could be used for developing monitoring efforts in other regions and tailored to meet different program-specific objectives.

Tailoring the strategy to best meet local needs is an important subsequent step. For example, goals established for the SDCP requires that the monitoring program address five specific elements:

1) Vegetation structure and composition
2) Water and riparian resources
3) Climate
4) Landscape pattern
5) Vertebrate species and communities

The strategy we developed addresses elements 1, 2, and part of 5. For the monitoring program to be fully operational, two important steps remain. First, we need to identify parameters to measure to address elements 3 and 4 and the community aspects of element 5. Second, we need to develop an overall sampling design for the suite of environmental features we identified and the remaining elements.

10.1 Monitoring Environmental Features

The strategy we developed provides an explicit basis for identifying a set of environmental features to measure for monitoring that reflect the goals and targets established through the set of objective functions. For the SDCP, goals and targets have been established in the biological goal of the SDCP and the monitoring needs of a Section 10 permit. These goals reflect the need to monitor the species covered by a Section 10 permit, other species that represent the diversity of life in Pima the County (**Section 3**), and factors that can affect persistence of these species, including anthropogenic threats (**Section 5**) and ecosystem processes (**Section 6**). Based on these goals, the equal weighting scheme (**Section 9**) provides the most appropriate starting place for establishing a long-term monitoring program for Pima County.

Results from this weighting scheme (**Table 9.1**) reveal an important pattern: monitoring attributes of vegetation will play a prominent role in the monitoring program. To this need, Pima County is in the process of developing a protocol to monitor vegetation that reflects these results which is being informed by field sampling from March through May, 2010. Results of this effort will be used to provide a basis for developing an overall sampling design, including an appropriate stratification scheme and information needed to establish the number of plots necessary to monitor vegetation and other environmental features effectively during the 30-year permit period.

10.1.1 Plot Design

We established the primary sampling unit as a circular plot with a radius of 200 m (12.6 ha) to support measurement of all environmental features and many other parameters that are likely to a part of ecological monitoring programs (**Section 8.1**). Consequently, we will establish plots on County-controlled mitigation lands (**Section 10.1.2**). As other parameters are added to the program, it will be important to locate them to maximize the amount of information gained. Therefore, we will measure additional parameters on the same set of plots where we are measuring vegetation to take advantage of the information gained at common locations to better understand interactions among parameters, processes, and threats.

Sampling for multiple parameters at the same location has two primary advantages over strategies that establish sampling locations for parameters independently. First, co-locating measurements will allow us to better assess interactions among parameters, changes in parameters in response to changes in process and threats, and to include information as covariates in analyses to increase the power of the program to detect trends in parameters. For example, changes in abundance of a target species can be explored to assess whether these changes are associated with other parameters, such as vegetation structure and composition. Second, costs are reduced when sampling sites are co-located because several parameters can be measured at a site during a single visit.

There are two primary disadvantages of co-location. First, parameters for uncommon resources may not be sampled sufficiently to generate estimates of sufficiently high prevision. This can be overcome by increasing the number of locations where those resources are sampled. Second, consistent surveys on a plot may damage some resources, and therefore careful attention must be paid to ensure protection of a site from trampling by surveyors.

10.1.2 Sampling Design: Where to Locate Plots, How Often to Visit Them?

A general goal of many monitoring efforts is to assess status and trend in resources over time, yet it is rarely possible to survey all resources of interest due to financial or logistical limitations. To increase the efficiency of monitoring, efforts must employ sampling, which is the process of selecting units from a larger population so as to draw inferences to it. We will establish monitoring sites using a *probability-based sampling* approach, which employs a component of randomization in selecting sampling units to ensure that inferences to the entire planning area are justified (Thompson 2002).

Spatial aspects of a sampling design define the framework for choosing sampling locations and temporal aspects of a design define when sites are measured. The most common strategies involve surveying sites at fixed intervals, which for vegetation monitoring typically occurs at 3-5 year intervals. Other options for temporal sampling involve the use of panel designs (McDonald 2003), where a panel is a collection of sample units that are sampled during the same time interval, typically within a season. A complete revisit design involves surveying all sites in a panel each year and a split-panel design involves surveying some panels each year and other panels with a longer between-sample interval, such as every five years. In general, designs that involve multiple panels have advantages over complete revisit designs because they have greater spatial coverage and provide estimates with higher precision. Careful temporal design can remedy problems associated with an initially poor spatial sampling design (Urquhart and Kincaid 1999). Primary disadvantages are that split- or rotating-panel designs are more complex to implement and analyze.

10.1.3 Power Analysis

We will use the vegetation data collected in spring 2010 as the basis for a set of power analyses designed to determine the number of plots necessary to detect trends in vegetation attributes. Statistical power analyses are best used in the planning stage of a monitoring program to estimate number of samples needed to achieve a high probability of detecting a biologically meaningful change in population or community parameter (Peterman 1990, Steidl et al. 1997). Power analysis allows for us to integrate components important to the design of monitoring programs: sample size, α (the probability of incorrectly concluding that a trend has occurred when one has not [Type I error rate]), β (probability of failing to detect a trend when one has occurred [Type II error rate]) and effect size, which is the magnitude of the trend of interest (e.g., a 10% change in density of woody vegetation over ten years). The ability to accurately detect effect size is dependent on whether a change has occurred and the amount of natural variability and precision of estimates: the lower the precision of an estimate, the more difficult it is to determine a trend (Gerrodette 1987).

10.2 Expert Review

The process that we have outlined in this report represents a new approach for planning long-term ecological monitoring programs. As such, it will be important for this report to be reviewed by regional and national experts in ecology and ecological monitoring. This review will take place over the coming months. Reviews by local experts and by staff of the Arizona Game and Fish Department, will be incorporated into the final monitoring report, to be completed by July 2010. Reviews by national experts will take place after the submittal of the final report.

11 Glossary

Attribute: The general feature of a target that could be measured for monitoring. For example, if the target of interest is a single population of a rare vertebrate, relevant attributes might include abundance, presence, survival, or reproductive success of that species.

Candidate Species: The species list from which *Target Species* were chosen. There are 231 Candidate Species.

Components (design): The four main categories that were used in our design process: species, environmental features, threats, and processes.

Covered Species: The list of species that Pima County is proposing for coverage under the forthcoming Section 10 permit and which were not included in the list of *Target Species*.

Desert upland: The Sonoran Desert upland typifies the Sonoran Desert and comprises the majority of the monitoring plan area. Dominant plants include a variety of short trees and shrubs, succulents, and many cacti, including large columnar saguaros (*Carnegiea gigantea*). Annual plants are common, particularly following sufficient winter rainfall.

Design: The targets, attributes, and parameters to measure to achieve the objectives of the monitoring program, plus the timing and location of where those measurements will be made.

Direct Effect: the initial effect that a threat has on a target. In the case of wildland fire, primary effects might include vegetation burned, mortality of animals as a result of the fire, and air pollution. Compare with Secondary Effects.

Environmental Features: Biotic and abiotic characteristics of the environmental that are important to one or more Target Species and Covered Species. The relative importance of environmental features were noted for each species.

Habitat: A species-specific term referring to the area with a combination of biotic and abiotic features that provides individuals of a species all or some of the resources they need to survive and reproduce (Morrison et al. 1998).

Mesoriparian: Plant community category includes mesoriparian and hydroriparian areas, which are characterized by shallow ground water and in some situations by persistence of surface water (hydoriparian), which provides conditions for dense stands of deciduous trees such as Fremont cottonwood (*Populus fremontii*), Arizona sycamore (*Platanus wrightii*), and velvet ash (*Fraxinus velutina*). In some of these areas, invasive woody species such as tamarisk (*Tamarix* spp.) and Russian olive (*Elaeagnus angustifolius*) may be present.

Open Water/Marsh: Include lakes, ponds, and marshes and their associated perimeter vegetation. Species found in these areas include those that use the open water (like fishes), those that are attracted by the presence of water, but use only the communities around it (e.g., song sparrows and red-winged blackbirds), and those that use both the open water and surrounding habitats (such as waterfowl).

Parameter: The value of an attribute measured across an entire target population. For example, if the target population of interest is red squirrels on Mt. Graham, and the attribute of interest in abundance, then the value of the parameter is the true number of red squirrels on Mt. Graham. Although values of parameters are what we want know, we usually estimate them using data from samples. Within the context of monitoring, parameter is often used to represent an attribute of the environment that can be measured or estimated to provides insight into the system of interest (Busch and Trexler 2003).

Processes (ecological and biological): the metabolic functions of ecosystems: energy flow; elemental cycling; production, consumption and decomposition of organic matter; and other biological processes (Young and Sanzone 2002). Processes are central to the maintenance of ecosystem structure and function, and as such are key features for managers to preserve (Manley et. al. 2000).

Priority Vulnerable Species: Species used in Pima County's Sonoran Desert Conservation Plan and Multiple-species Conservation Plan planning processes.

Protocol: The detailed methodology for measuring a parameter, including what to measure, how to measure it, and where and when to perform those measurement. For example,

Sampling Design. The method of selecting where and how often to sample is referred to as; these choices ultimately determine the power and precision, spatial and temporal inference, and overall cost of a monitoring program.

Secondary Effect: Consequences of primary effects, usually separated by time. Examples of secondary effects for wildland fire are soil erosion, siltation, and reduced water quality that result from removal of vegetative cover.

Semi-desert Grassland: occur at higher elevations than desert uplands and include valley bottoms, alluvial flats, swales, bajadas, mesas, plains, and the flanks of the "Sky Island" mountain ranges. These grasslands were once dominated by stands of native perennial bunchgrasses and had low shrub density, but now typically include native shrubs, which have invaded these areas.

Target: The natural resource, ecological process, or anthropogenic threat that are the focus of the monitoring program and therefore the focus of design-related decisions. Common targets should be identified explicitly in the goals or objectives of the monitoring program, and might include a single population of a rare vertebrate, distribution of that vertebrate across a geographic region, composition of a plant or animal community, rate of invasion by a nonnative species, or frequency of fire in a grassland ecosystem. Synonymous with **conservation target**.

Target Species: The subset of vertebrate species (N = 122) in the Planning Area for which we gathered background information and indentified *Environmental Features*. The species included 109 species chosen at random from the list of candidate species and 13 species of interest to Pima County (Priority Vulnerable Species; PVS).

Target Species (Candidate): Species (N = 228) that were considered for inclusion in the list of Target Species.

Threat: Any activity with the potential to degrade or destroy ecosystem structure or impair ecosystem function originating from an anthropogenic source. Many threats result from past human actions, but which no longer require such actions for the threat to be significant, such as the introduction (accidental or otherwise) of non-native species.

Xeroriparian: Vegetation community found primarily along ephemeral washes and are characterized by dense stands of velvet mesquite (*Prosopis velutina*) and netleaf hackberry (*Celtis reticulata*). In mesquite forests (bosques), however, connection to groundwater resources is common.

12 Acknowledgements

We are grateful to the many biologists and ecologists who generously shared their time and expertise to support this effort. We thank to Courtney Conway, Dominic LaRoche, Chris Kirkpatrick, Don Swann, Eric Wallace, and Erin Zylstra for helping us to identify environmental features most important to vertebrates and Aaron Flesch, Julia Fonseca, Andy Hubbard, Bill Mannan, Barry Noon, Cecil Schwalbe, Bill Shaw, Don Swann, and Dale Turner for design strategies and background information on species. Ginny Fitzpatrick and Megan Bell served up data for inclusion into the environmental features and species matrix and conducted background research for this effort. This project was funded by a Section 6 planning grant from the U.S. Fish and Wildlife Service. The grant was administered by the Arizona Game and Fish Department and we thank Dennis Abbate, Kathy Crawford, Mike Ingraldi, and Locana de Souza for their administrative and technical contributions throughout the process. Technical and administrative support was also provided by Scott Richardson and Sherry Barrett at the Tucson office of the U.S. Fish and Wildlife Service. Additional thanks to Cecily Westphal and Laura Kateri Opalka of the School of Natural Resources and the Environment at the University of Arizona for administrative assistance. This report was funded by a Section 6 planning grant from the U.S. Fish and Wildlife Service.

13 Literature Cited

Andrewartha, H. G., and L. C. Birch. 1984. The ecological web. The University of Chicago Press, Chicago, IL.

Atkinson, A. J., P. C. Trenham, R. N. Fisher, S. A. Hathaway, B. S. Johnson, S. G. Torres, and Y. C. Moore. 2004. Designing monitoring programs in an adaptive management context for regional multiple species conservation plans. USGS Geological Survey Technical Report. USGS Western Ecological Research Center, Sacramento, CA.

Barrows, C. W., M. B. Swartz, W. L. Hodges, M. F. Allen, J. T. Rotenberry, B. L. Li, T. A. Scott, and X. W. Chen. 2005. A framework for monitoring multiple-species conservation plans. Journal of Wildlife Management 69:1333-1345.

Breckenridge, R. P., W. G. Kepner, and D. A. Mouat. 1995. A process for selecting indicators for monitoring conditions of rangeland health. Environmental Monitoring and Assessment 36:45-60.

Carignan, V., and M. A. Villard. 2002. Selecting indicator species to monitor ecological integrity: A review. Environmental Monitoring and Assessment 78:45-61.

Cauglan, L., and K. L. Oakley. 2001. Cost considerations for long-term ecological monitoring. Ecological Indicators 1:123-134.

Christensen, N. L., A. M. Bartuska, J. H. Brown, S. Carpenter, C. D' Antonio, R. Francis, J. F. Franklin, J. A. Macmahon, R. F. Noss, D. J. Parsons, C. H. Peterson, M. G. Turner, and R. G. Woodmansee. 1996. The report of the Ecological Society of America Committee on the scientific basis for ecosystem management. Ecological Applications 6:665-691.

Clark, J. A., and E. Harvey. 2002. Assessing multi-species recovery plans under the Endangered Species Act. Ecological Applications 12:655-662.

Corman, T. E., and C. Wise-Gervais. 2005. Arizona breeding bird atlas. University of New Mexico Press, Albuquerque, NM.

Cowling, R. M., and R. L. Pressey. 2001. Rapid plant diversification: Planning for an evolutionary future. Proceedings of the National Academy of Sciences of the United States of America 98:5452-5457.

Cushman, S. A., K. S. McKelvey, C. H. Flather, and K. McGarigal. 2008. Do forest community types provide a sufficient basis to evaluate biological diversity? Frontiers in Ecology and the Environment 6:13-17.

Dale, V. H., and S. C. Beyeler. 2001. Challenges in the development and use of ecological indicators. Ecological Indicators 1:3-10.

Degenhardt, W. G., C. W. Painter, and A. H. Price. 1996. Amphibians and reptiles of New Mexico. University of New Mexico Press, Albuquerque, NM.

Elzinga, C. L., D. W. Salzar, J. W. Willoughby, and J. P. Gibbs. 2001. Monitoring plant and animal populations. Blackwell Publishing, Malden, MA.

Field, S. A., P. J. O'Connor, A. J. Tyre, and H. P. Possingham. 2007. Making monitoring meaningful. Austral Ecology 32:485-491.

Fleishman, E., and R. Mac Nally. 2003. Distinguishing between signal and noise in faunal responses to environmental change. Global Ecology and Biogeography 12:395-402.

Fleishman, E., J. R. Thomson, R. M. Nally, D. D. Murphy, and J. P. Fay. 2005. Using indicator species to predict species richness of multiple taxonomic groups. Conservation Biology 19:1125-1137.

Fonseca, J., J. Regan, and C. P. Jones, M. 2009. Changes in Pima County, Arizona land cover, 1992-2001. Report to the Pima County Board of Supervisors, Tucson, AZ.

Fonseca, J., D. Scalero, W. Shaw, R. J. Steidl, N. Kline, S. Ruther, G. Nabhan, M. Falk, S. Prchal, D. Duncan, and C. Schwalbe. 1999. Determining vulnerable species within Pima County, Arizona. A draft discussion paper for the Sonoran Desert Conservation Plan. Report to the Pima County Board of Supervisors, Tucson, AZ.

Gerrodette, T. 1987. A power analysis for detecting trends. Ecology 68:1364-1372.

Gibbs, J. P., S. Droege, and P. Eagle. 1998. Monitoring populations of plants and animals. Bioscience 48:935-940.

Hall, L. S., P. R. Krausman, and M. L. Morrison. 1997. The habitat concept and a plea for standard terminology. Wildlife Society Bulletin 25:173-182.

Harding, E. K., E. E. Crone, B. D. Elderd, J. M. Hoekstra, A. J. Mckerrow, J. D. Perrine, J. Regetz, L. J. Rissler, A. G. Stanley, and E. L. Walters. 2001. The scientific foundations of Habitat Conservation Plans: A quantitative assessment. Conservation Biology 15:488-500.

Hilty, J., and A. Merenlender. 2000. Faunal indicator taxa selection for monitoring ecosystem health. Biological Conservation 92:185-197.

Hoekstra, J. M., J. A. Clark, W. F. Fagan, and P. D. Boersma. 2002. A comprehensive review of Endangered Species Act recovery plans. Ecological Applications 12:630-640.

Hoffmeister, D. F. 1986. Mammals of Arizona. University of Arizona Press: Arizona Game and Fish Department, Tucson, AZ.

Holthausen, R., R. L. Czaplewski, D. DeLorenzo, G. Hayward, W. B. Kessler, P. Manley, K. S. McKelvey, D. S. Powell, L. F. Ruggiero, M. K. Schwartz, B. V. Horne, and C. D. Vojta. 2005. Strategies for monitoring terrestrial animals and habitats. pp General Technical Report RMRS-GTR-161. USDA Forest Service, Rocky Mountain Research Station, Fort Collins, CO.

Hyman, J. B., and S. G. Leibowitz. 2001. JSEM: A framework for identifying and evaluating indicators. Environmental Monitoring and Assessment 66:207-232.

Jackson, L. E., J. C. Kurtz, and W. S. Fisher. 2000. Evaluation guidelines for ecological indicators. Evironmental Protection Agency Report EPA/620/R-99/005. U.S. Environmental Protection Agency, Office of Research and Development, Research Triangle Park, NC.

Kareiva, P., S. Andelman, D. Doak, B. Elderd, M. Groom, J. Hoekstra, L. Hood, F. James, J. Lamoreux, G. LeBuhn, C. McCulloch, J. Regetz, L. Savage, M. Ruckelshaus, D. Skelly, H. Wilbur, K. Zamudio, and NCEAS HCP working group. 1999. Using science in habitat conservation plans. National Center for Ecological Analysis and Synthesis and the American Institute of Biological Sciences, Santa Barbara, CA, Washington, DC.

Kelly, J. R., and M. A. Harwell. 1990. Indicators of ecosystem recovery. Environmental Management 14:527-545.

Kincaid, T. M., D. P. Larsen, and N. S. Urquhart. 2004. The structure of variation and its influence on the estimation of status: Indicators of condition of lakes in the northeast, U.S.A. Environmental Monitoring and Assessment 98:1-21.

Klein, C., K. Wilson, M. Watts, J. Stein, S. Berry, J. Carwardine, M. S. Smith, B. Mackey, and H. Possingham. 2009. Incorporating ecological and evolutionary processes into continental-scale conservation planning. Ecological Applications 19:206-217.

Krebs, C. J. 1999. Ecological methodology, 2nd ed. Addison-Welsey Educational Publishers, Menlo Park, CA.

Landres, P. B., J. Verner, and J. W. Thomas. 1988. Ecological uses of vertebrate indicator species: A critique. Conservation Biology 2:316-328.

Larsen, D. P., P. R. Kaufmann, T. M. Kincaid, and N. S. Urquhart. 2004. Detecting persistent change in the habitat of salmon-bearing streams in the Pacific Northwest. Canadian Journal of Fish and Aquatic Sciences 61:283-291.

Legg, C. J., and L. Nagy. 2006. Why most conservation monitoring is, but need not be, a waste of time. Journal of Environmental Management 78:194-199.

Lindenmayer, D., R. J. Hobbs, R. Montague-Drake, J. Alexandra, A. Bennett, M. Burgman, P. Cale, A. Calhoun, V. Cramer, P. Cullen, D. Driscoll, L. Fahrig, J. Fischer, J. Franklin, Y. Haila, M. Hunter, P. Gibbons, S. Lake, G. Luck, C. MacGregor, S. McIntyre, R. M. Nally, A. Manning, J. Miller, H. Mooney, R. Noss, H. Possingham, D. Saunders, F. Schmiegelow, M. Scott, D. Simberloff, T. Sisk, G. Tabor, B. Walker, J. Wiens, J. Woinarski, and E. Zavaleta. 2008. A checklist for ecological management of landscapes for conservation. Ecology Letters 11:78-91.

Lindenmayer, D. B., A. D. Manning, P. L. Smith, H. P. Possingham, J. Fischer, I. Oliver, and M. A. Mccarthy. 2002. The focal-species approach and landscape restoration: A critique. Conservation Biology 16:338-345.

Low, G. 2003. Landscape-scale conservation: A practitioner's guide. The Nature Conservancy.

Lusk, J. J., S. G. Smith, S. D. Fuhlendorg, and F. S. Guthery. 2006. Factors influencing northern bobwhite nest-site selection and fate. Journal of Wildlife Management 70:564-571.

Lyons, J. E., M. C. Runge, H. P. Laskowski, and W. L. Kendall. 2008. Monitoring in the context of structured decision-making and adaptive management. Journal of Wildlife Management 72:1683-1692.

Manley, P. N., B. V. Horne, J. K. Roth, W. J. Zielinski, M. M. McKenzie, T. J. Weller, F. W. Weckerly, and C. Vojta. 2005. Multiple species inventory and monitoring technical guide. pp, United States Department of Agriculture.

Manley, P. N., W. J. Zielinski, C. M. Stuart, J. J. Keane, A. J. Lind, C. Brown, B. L. Plymale, and C. O. Napper. 2000. Monitoring ecosystems in the Sierra Nevada: The conceptual model foundation. Environmental Monitoring and Assessment 64:139-152.

Marcot, B. G., R. S. Holthausen, M. G. Raphael, M. M. Rowland, and M. J. Wisdom. 2001. Using Bayesian belief networks to evaluate fish and wildlife population viability under land management alternatives from an environmental impact statement. Forest Ecology and Management 153:29-42.

Minckley, W. L. 1973. Fishes of Arizona. Arizona Game and Fish Department, Phoenix, AZ.

Morrison, M. L., and B. G. Marcot. 1995. An evaluation of resource inventory and monitoring program used in national forest planning. environmental Management19 1.

Murtaugh, P. A., and P. S. Pooler. 2006. Evaluating ecological indicators: Lakes in the northeastern United States. Environmental Monitoring and Assessment 119:83-96.

National Research Council. 2000. Ecological indicators for the nation. National Academy Press, Washington, DC.

Nichols, J. D., and B. K. Williams. 2006. Monitoring for conservation. Trends in Ecology & Evolution 21:668-673.

Niemeijer, D., and R. de Groot. 2006. Framing environmental indicators: Moving from causal chains to causal networks. Environment, Development and Sustainability.

Niemeijer, D., and R. S. de Groot. 2008. A conceptual framework for selecting environmental indicator sets. Ecological Indicators 8:14-25.

Noon, B. R. 2003. Conceptual issues in monitoring ecological resources. Pages 27-71. *In* D. E. Busch and J. C. Trexler, editors. Monitoring ecosystems: Interdisciplinary approaches for evaluating ecoregional initiatives. Island Press, Washington, DC.

Noon, B. R., and K. S. McKelvey. 2006. The process of indicator selection. Pages 944-951. *In* C. Aguirre-Bravo, P. J. Pellicane, D. P. Burns, and S. Draggan, editors. Monitoring science and technology symposium: Unifying knowledge for sustainability in the western hemisphere. Proceedings RMRS-P-42CD. USDA Forest Service, Rocky Mountain Research Station, Fort Collins, CO.

Noon, B. R., T. A. Spies, and M. G. Raphael. 1999. Conceptual basis for designing an effectiveness monitoring program. Pages 21-48. *In* B. Mulder, B. R. Noon, T. A. Spies, M. G. Raphael, C. J. Palmer, A. R. Olsen, G. H. Reeves, and H. H. Welsh, editors. The strategy and design of the effectiveness monitoring program for the Northwest Forest Plan. General Technical Report PNW-437. USDA Forest Service, Pacific Northwest Research Station, Portland, OR.

North-South Environmental Inc. 2000. A comparison between the EMAN core monitoring variables and monitoring activities at EMAN sites. Campbellville, Ontario.

Noss, R. F. 1990. Indicators for monitoring biodiversity: A hierarchical approach. Conservation Biology 4:355-364.

Odum, E. P. 1985. Trends expected in stressed ecosystems. Bioscience 35:419-422.

Palmer, C. J., and B. S. Mulder. 1999. Components of the effectiveness monitoring program. Pages 69-97. *In* B. S. Mulder, B. R. Noon, T. A. Spies, M. G. Raphael, C. J. Palmer, A. R. Olsen, G. H. Reeves, and H. H. Welsh Jr., editors. The strategy and design of the effectiveness monitoring program for the Northwest Forest plan. General Technical Report PNW-437. USDA Forest Service, Pacific Northwest Research Station, Portland, OR.

Parker, K. C., A. J. Parker, and T. R. Vale. 2001. Vertebrate feeding guilds in California's Sierra Nevada: Relations to environmental condition and change in spatial scale. Annals of the Association of American Geographers 91:245-262.

Parr, T. W., M. Ferretti, I. C. Simpson, M. Forsius, and E. Kovacs-Lang. 2002. Towards a long-term integrated monitoring programme in Europe: Network design in theory and practice. Environmental Monitoring and Assessment 78:253-290.

Parrish, J. D., D. P. Braun, and R. S. Unnasch. 2003. Are we conserving what we say we are? Measuring ecological integrity within protected areas. Bioscience 53:851-860.

Pearman, P. B., M. R. Pemskar, E. H. Schools, and H. D. Enander. 2006. Identifying potential indicators of conservation value using natural heritage occurrence data. Ecological Applications 16:186-201.

Peterman, R. M. 1990. The importance of reporting statistical power: The forest decline and acidic deposition example. Ecology 71:2024-2027.

Pima County. 2000. Draft preliminary Sonoran Desert Conservation Plan. Report to the Pima County Board of Supervisors for the Sonoran Desert Conservation Plan. Tucson, AZ.

Pima County. 2001. Priority Vulnerable Species: Analysis and review of species proposed for coverage by the Multiple-species Conservation Plan. Draft report to the Pima County Board of Supervisors for the Sonoran Desert Conservation Plan. Tucson, AZ.

Pima County. 2009. Pima County Multiple Species Conservation Plan. Report to the Pima County Board of Supervisors for the Sonoran Desert Conservation Plan, Tucson, AZ.

Possingham, H., I. Ball, and S. Andelman. 2000. Mathmatical methods for identifying representative reserve networks. Pages 291-305. *In* S. Ferson and M. Burgman, editors. Quantitative methods for conservation biology. Springer-Verlag, NY.

Powell, B. F., W. L. Halvorson, and C. A. Schmidt. 2006. Vascular plant and vertebrate inventory of Saguaro National Park, Rincon Mountain District. Open-File Report 2006-1075. U.S. Geological Survey, Southwest Biological Science Center, Sonoran Desert Research Station, University of Arizona, Tucson, AZ.

Pressey, R. L., R. M. Cowling, and M. Rouget. 2003. Formulating conservation targets for biodiversity pattern and process in the Cape Floristic Region, South Africa. Biological Conservation 112:99-127.

Purvis, A., J. L. Gittleman, G. Cowlishaw, and G. M. Mace. 2000. Predicting extinction risk in declining species. Proceedings of the Royal Society B-Biological Sciences 267:1947-1952.

Rahn, M. E., H. Doremus, and J. Diffendorfer. 2006. Species coverage in multispecies habitat conservation plans: Where's the science? Bioscience 56:613-619.

Ramsey, D., and C. Veltman. 2005. Predicting the effects of perturbations on ecological communities: What can qualitative models offer? Journal of Animal Ecology 74:905-916.

Raphael, M. G., M. J. Wisdom, M. M. Rowland, R. S. Holthausen, B. C. Wales, B. G. Marcot, and T. D. Rich. 2001. Status and trends of habitats of terrestrial vertebrates in relation to land management in the interior Columbia river basin. Forest Ecology and Management 153:63-88.

RECON Environmental Inc. 2000. Priority vulnerable species: Habitat data analysis. Report to the Pima County Board of Supervisors for the Sonoran Desert Conservation Plan, Tucson, AZ.

Reeves, G. H., D. B. Hohler, D. P. Larsen, D. E. Busch, K. Kratz, K. Reynolds, K. F. Stein, T. Atzet, P. Hays, and M. Tehan. 2004. Effectiveness monitoring for the aquatic and riparian component of the Northwest Forest Plan: Conceptual framework and options. General Technical Report PNW-GTR-557. USDA Forest Service, Pacific Northwest Research Station, Portland, OR.

Reynolds, K. 1999a. EMDS users guide (version 2.0): Knowledge-based decision support for ecological assessment. General Technical Report PNW-GTR-470. USDA Forest Service, Pacific Northwest Research Station, Portland, OR.

Reynolds, K. 1999b. NetWeaver for EMDS user guide (version 1.1): A knowledge base development system. General Technical Report PNW-GTR-471. USDA Forest Service, Pacific Northwest Research Station, Portland, OR.

Reynolds, K. 2004. Decision support for evaluating the U.S. national criteria and indicators for forest ecosystem sustainability. Pages 729-735. *In* C. Aguirre-Bravo, P. J. Pellicane, D. P. Burns, and S. Draggan, editors. Monitoring science and technology symposium: Unifying knowledge for sustainability in the Western hemisphere. Proceedings RMRS-P-42CD. USDA Forest Service, Rocky Mountain Research Station, Fort Collins, CO.

Reynolds, K. M., K. N. Johnson, and S. N. Gordon. 2003. The science/policy interface in logic-based evaluation of forest ecosystem sustainability. Forest Policy and Economics 5:433-446.

Riley, S. P. D., J. P. Pollinger, R. M. Sauvajot, E. C. York, C. Bromley, T. K. Fuller, and R. K. Wayne. 2006. A Southern California freeway is a physical and social barrier to gene flow in carnivores. Molecular Ecology 15:1733-1741.

Roman, C. T., and N. E. Barrett. 1999. Conceptual framework for the development of long-term monitoring protocols at Cape Cod National Seashore. USGS Patuxent Wildlife Research Center, Narragansett, RI.

Rosen, P. C. 2003. Biological survey of Ironwood Forest National Monument. Unpublished report to the Bureau of Land Management, Tucson, AZ.

Rouget, M., R. M. Cowling, R. L. Pressey, and D. M. Richardson. 2003. Identifying spatial components of ecological and evolutionary processes for regional conservation planning in the Cape Floristic Region, South Africa. Diversity and Distributions 9:191-210.

Salafsky, N., and R. Margoluis. 1999. Threat reduction assessment: a practical and cost-effective approach to evaluating conservation and development projects. Conservation Biology 13:830-841.

Salafsky, N., D. Salzer, A. J. Stattersfield, C. Hilton-Taylor, R. Neugarten, S. H. M. Butchart, B. Collen, N. Cox, L. L. Master, S. O'Conner, and D. Wilkie. 2008. A standard lexicon for biodiversity conservation: Unified classifications of threats and actions. Conservation Biology 22:897-911.

Schmoldt, D. L., and D. L. Peterson. 1997. Using the AHP in a workshop setting to elicit and prioritize fire research needs. Pages 151-162. Annual convention and exposition technical papers. Resource Technology Institute, Seattle, WA.

Schmoldt, D. L., and D. L. Peterson. 2000. Analytical group decision making in natural resources: Methodology and application. Forest Science 46:62-75.

Schmoldt, D. L., D. L. Peterson, and D. G. Silsbee. 1994. Developing inventory and monitoring programs based on multiple objectives. Environmental Management 18:707-727.

Sibley, D. 2000. The Sibley guide to birds. 1st ed edition. Alfred A. Knopf Incorporated, New York, NY.

Smith, C. S., A. L. Howes, B. Price, and C. A. McAlpine. 2007. Using a Bayesian belief network to predict suitable habitat of an endangered mammal - The Julia Creek dunnart (*Sminthopsis douglasi*). Biological Conservation 139:333-347.

Steidl, R. J., J. P. Hayes, and E. Schauber. 1997. Statistical power analysis in wildlife research. Journal of Wildlife Management 61:270-279.

Steidl, R. J., W. W. Shaw, and P. Fromer. 2009. A science-based approach to regional conservation planning. Pages 217-234. *In* A. X. Esperanza and G. McPherson, editors. A planner's guide to natural resouce conservation: The scienc of land development beyond the metropolitan fringe. Springer-Verlag, New York.

Steidl, R. J., and L. Thomas. 2001. Power analyis and experimental design. *In* S. M. Scheiner and J. Gurevitch, editors. Design and analysis of ecological experiments. Oxford University Press, Oxford, NY.

Stige, L. C., K.-S. Chan, Z. Zhang, D. Frank, and N. C. Stenseth. 2007. Thousand-year-long Chinese time series reveals climatic forcing of decadal locust dynamics. Proceedings of the National Academy of Sciences 104:16188-16193.

Tegler, B. 1999. Selecting core variables for tracking ecosystem change at EMAN sites. Geomatics International Inc., Guelph, ON.

Tegler, B., M. Sharp, and M. A. Johnson. 2001. Ecological Monitoring and Assessment Network's proposed core monitoring variables: An early warning of environmental change. Environmental Monitoring and Assessment 67:29-56.

The Nature Conservancy. 2007. Conservation action planning handbook: Developing strategies, taking action and measuring success at any scale. The Nature Conservancy, Arlington, VA.

Theobald, D. M. 2003. Targeting conservation action through assessment of protection and exurban threats. Conservation Biology 17:1624-1637.

Theobald, D. M., and W. H. Romme. 2007. Expansion of the US wildland-urban interface. Landscape and Urban Planning 83:340-354.

Thompson, I. D. 2006. Monitoring of biodiversity indicators in boreal forests: A need for improved focus. Environmental Monitoring and Assessment 121:263-273.

Thompson, S. K. 2002. Sampling. Second edition. John Wiley and Sons, New York, NY.

Thompson, W. L., G. C. White, and C. Gowan. 1998. Monitoring vertebrate populations. Academic Press, San Diego, CA.

Trombulak, S. C., and C. A. Frissell. 2000. Review of ecological effects of roads on terrestrial and aquatic communities. Conservation Biology 14:18-30.

U.S. Fish and Wildlife Service. 1996. Habitat conservation planning and Incidental Take Permit processing handbook. Washington, D.C.

U.S. Fish and Wildlife Service. 2000. Final addendum to the Handbook for Habitat Conservation Planning and Incidental Take Permit. Washington, DC.

Urquhart, N. S., S. G. Paulsen, and D. P. Larsen. 1998. Monitoring for policy-relevant regional trends over time. Ecological Applications 8:246-257.

Walters, C. J. 1986. Adaptive management of renewable resources. Macmillan Press, New York, NY.

Wiens, J. A. 1985. Habitat selection in variable environments: Shrub-steppe birds. Pages 191-226. *In* M. L. Cody, editor. Habitat selection in birds. Academic Press, Orlando, FL.

Wiens, J. A. 1989. Spatial scaling in ecology. Functional Ecology 3:385-397.

Wiens, J. A., G. D. Hayward, R. S. Holthausen, and M. J. Wisdom. 2008. Using surrogate species and groups for conservation planning and management. Bioscience 58:241(212).

Wilhere, G. F. 2002. Adaptive management in habitat conservation plans. Conservation Biology 16:20-29.

Wilson, K., R. L. Pressey, A. Newton, M. Burgman, H. Possingham, and C. Weston. 2005. Measuring and incorporating vulnerability into conservation planning. Environmental Management 35:527-543.

Yoccoz, N. G., J. D. Nichols, and T. Boulinier. 2001. Monitoring of biological diversity in space and time. Trends in Ecology & Evolution 16:446-453.

Young, T. F., and S. Sanzone. 2002. A framework for assessing and reporting on ecological condition: An SAB report. USEPA Science Advisory Board Report no. EPA-SAB-EPEC-02-009. Science Advisory Board, Washington, DC.

Appendix A: Review of Conceptual Models for Choosing Parameters

We explored existing conceptual models to determine to help develop the strategy described in this report (Table A.1).

Table A.1. Characteristics, strengths, and weaknesses of conceptual modeling methods for choosing parameters for monitoring.

Group	Method	Description	How is it developed?	Strengths	Weaknesses	Citation(s)
Qual-itative	Analytical Hierarchy Process (AHP)	Decision-making framework that uses a hierarchical structure to describe a problem and paired comparisons to rank alternatives	Groups-decision process based on expert opinion, usually in workshop setting	Fast, with strategies to reduce effects of individuals who dominate discussion	Opinion-based, biased by experiences of participants	(Schmoldt and Peterson 1997, Schmoldt and Peterson 2000)
	Design matrices	Simple conceptual constructs usually used to establish relationships among agents of change and ecosystem responses	Often developed with expert opinion and expressed in 2-diminsional tables	Opportunity to link threats with all possible parameters. Can be expanded to include scores of the relative strengths of interactions	Can be used to extend AHP. Difficult to extract information for choosing parameters	(Roman and Barrett 1999, North-South Environmental Inc. 2000, Tegler et al. 2001)
	Evaluate parameters using selection criteria	Useful for choosing indicators based on explicit statements of what is important to program	Experts choose among dozens of criteria. Evaluations made using continuous or binary (yes/no) responses	Being explicit about criteria is important for any process	Does not produce a list of the most appropriate/promising parameters. Subjective approach that can be seriously biased	(Kelly and Harwell 1990, Breckenridge et. al. 1995, Jackson et. al. 2000, Holthausen et. al. 2005)
	Box and arrow diagrams	Visual, conceptual models that depict the structural and functional properties of ecological processes to link ecological components	Diagrams begin as simple box and arrows and parameter experts refine. Strengths of interactions can be represented	Can be explicit about connections among threats, habitat, species, etc. Excellent for conveying results to the public about other decision processes	Models can be extremely complex; lines and arrows may not be sufficient to convey all information. Difficult to compare among models at different scales	(Breckenridge et al. 1995, Manley et al. 2000)
	Casual chain frameworks	Extension of box and arrow diagrams into three causal chain frameworks	Expert opinion	Parameters chosen from a threats-perspective. Can help understand cause and effect from threats. Better than box and arrows for focusing on	See box and arrow diagrams	(Parr et. al. 2002, Niemeijer and de Groot 2006, Noon and

Group	Method	Description	How is it developed?	Strengths	Weaknesses	Citation(s)
				threats. A similar approach developed by (Noon and McKelvey 2006)		McKelvey 2006, Niemeijer and de Groot 2008)
	Envirograms	Hypothesizes ecological linkages among factors affecting abundance of a species Creates a dichotomy between factors that drive or limit population growth	Expand level of detail from box and arrow diagrams. Identify factors that directly affect an organism's abundance and resources	Separates proximate and ultimate drivers of population change	Can be complex and requires a detailed understanding of species' biology. Linkages between species occurrence and abundance with environmental parameters is scale dependent	(Andrewartha and Birch 1984, Barrows et al. 2005)
Quant-itative	Retrospective Selection	Measure a host of parameters across a gradient of impacts and determine which has most explanatory power. Subset that exhibit the most impact is desirable for monitoring	Compares data collected for many parameters to determine the one (or group) that responses most to environmental change	Allows for quantitative assessment of the importance of a parameter	Can be very costly	(Urquhart et al. 1998, Kincaid et. al. 2004, Larsen et. al. 2004, Fleishman et. al. 2005, Murtaugh and Pooler 2006)
	Spatially explicit conceptual models	Generate hypotheses about environmental correlates that describe distribution of species. Most models include a GIS-layer with coordinates for locations of each target species	Aggregate existing data from and correlating their presence with dominate vegetation type.	Good broad-scale planning tool to identify areas of potential species co-occurrence	Correlations may not be linked mechanistically to the specific resources that influence the distribution of the species. Resolution of map dictates the scale of analysis	(Noon et al. 1999, Barrows et al. 2005)
	Predictive models	Reflect biological mechanisms needed to explicitly incorporate demographic processes affected by habitat change at the individual, local population, and metapopulation	Identify habitat components that affect demographics and monitor only those components	Explicit links from the species to environmental components	Very expensive and development is a long-term endeavor	(Noon et al. 1999)

Group	Method	Description	How is it developed?	Strengths	Weaknesses	Citation(s)
		scales				
	Loop Analysis	Links species and environmental features via symbols that represent interactions	Positive and negative effects identified. Feedback loops analyzed at different levels to determine whether stability criteria are met	Can indicate stability of a given system	Works well if the focus in on single species or a small group of species; broader links is not possible.	(Ramsey and Veltman 2005)
	Bayesian Belief Networks	Variables represented as a network of nodes that are linked by probabilities. Ways to organize thinking, formalize evaluation criteria, identify gaps in information	Comprised of a set of variables and a set of connections among variables that has a set of possible mutually exclusive states with an associated probability	Incorporates expert opinion and empirical data, and makes connections explicit. Can determine which inputs most affect responses. Can revise models with new information	Can be confusing and model output may conflict with expert opinion. Confidence in output is limited by the confidence have in the probabilities. Unable to link multiple models together, so this approach not appropriate for choosing among parameters	(Marcot et. al. 2001, Smith et. al. 2007)
	Structural equation modeling (SEM)	Combination of path analysis, conceptual modeling, and regression. Uses linear models to establish relationships	Uses same two-step process as JSEM (below), but the focus is on developing regression parameters that describe interrelationships among variables in a conceptual model	Based on data, not expert opinion	Need data on all variables in the model.	(Hyman and Leibowitz 2001)
	Judgment-based SEM (JSEM)	A quantitative framework to structure and evaluate information about relationships between and among parameters. This is a modified SEM to incorporate expert opinion	Two stage process: Build a conceptual model relating variables with linkages and analyze the linkages to evaluate adequacy of indicators based on expert opinion in the absence of quantified	Uses judgment-based and data-based information. Attempts to reduce overlap in information explained by multiple variables. Models can be updated	Assumes all relationships can be expressed with linear models and are directional. No feedback loops allowed. Evaluation of the adequacy of indicators is within a given model, and not comparable among models. Unable to link multiple models, so not appropriate for choosing among parameters.	(Hyman and Leibowitz 2001)

Group	Method	Description	How is it developed?	Strengths	Weaknesses	Citation(s)
			information			
	Fuzzy logic	Develop models of systems where relations among variables are not defined precisely	Represents problems as logical arguments that can be supported by data. Expresses a system as a series of entities and relationships among entities	Graphical information is easily conveyed. Conclusions are explicit and re-traceable. Can adjust weights to alter contribution of evidence. Can identify thresholds. Evaluates effect of missing information. Software (NetWeaver) developed for this application.	Adjusting weights is not recommended. Unclear how much data is needed. Complex models—with many systems and species—may be hard to construct	(Reynolds 1999a, b, Reynolds et. al. 2003, Reeves et. al. 2004, Reynolds 2004)
	Artificial neural networks (ANN)	A mathematical or computational model based on neural networks. Adaptive system that changes its structure based information that flows through the network during learning phase		Finds the form of the response in the data. Does not require a priori knowledge of the nature of the relationships between predictors and responses. Models can "learn" as data become available	May be negatively influenced by sparse data. Data requirements intensive	(Lusk et. al. 2006)

Appendix B. Additional information on the Selection of Species to Include in the Conceptual Model

This appendix provides additional information on how we selected species for this planning effort.

Sorting Anomalous Groups

As noted in **Section 3.1.1**, we assigned all species identified as occurring in the monitoring plan area into groups based on all combinations of subcategories identified for four sorting criteria: taxonomy, vegetation-community association, trophic level, and size class. Then we chose one species at random from each of these combinations to include in a set of target species, which was a foundational component of our conceptual model. Before selecting species, however, we checked all groups created by our sorting process for any anomalies in species numbers or shared life history characteristics and sorted anomalous groups further by adding appropriate attributes.

We found only two anomalous groups: the subcategory combination of mammals, Sonoran Desert upland, herbivore, and size class 1 and the combination of mammals, semi-desert grassland, herbivore, and size class 1. Both of these combinations contained a large number of rodents which we saw could be further divided according to whether they prefer high or sparse ground cover in their habitats. Therefore, we divided each combination accordingly and included the new groupings in our selection process.

Specifically, we further divided the Sonoran Desert upland-herbivore group into one group requiring high ground cover: Botta's pocket gopher, desert woodrat, white-throated woodrat, and Arizona cotton rat; and another group requiring sparse ground cover: Arizona pocket mouse, rock pocket mouse, desert pocket mouse, Bailey's pocket mouse, and Merriam's kangaroo rat. Likewise, we further divided the grassland herbivore group into a high-cover group: Botta's pocket gopher, yellow-nosed cotton rat, and white-throated woodrat; and a sparse-cover group: Bailey's pocket mouse, Merriam's kangaroo rat, banner-tailed kangaroo rat, and fulvous harvet mouse. Although Botta's pocket gopher is mainly fossorial, it was included in both of the high-cover groups because, in a sense, its burrows are a form of high cover and the gopher digs burrows where it has an adequate supply of tuberous roots and plant material for food.

Body-size Groupings

We sorted each of the 231 species that we identified as occurring in the monitoring plan area into its appropriate body size class as one step in the process of grouping the species in preparation for selecting a subset of them as a foundational component of our conceptual model for the PCEMP. Average mass or length was used for body size uniformly within a taxon, depending on which data were available. Specifically, we used mass measurements for birds and mammals and length measurements for the herpetofauna and fish. Measurement data were gathered from standard field guides (Minckley 1973, Hoffmeister 1986, Degenhardt et. al. 1996, Sibley 2000), and we determined the following size categories for each taxonomic group.

<u>Birds</u>: Because mass was fairly continuous among the 113 species, we used the "near-quartile" sorting as follows:

Size class 1 = 2.9-14 g (20 species)
Size class 2 = 14.5-40 g (33 species)

Size class 3 = 44-130 g (30 species)
Size class 4 = 147.5-5,800 g (30 species, only two of which are very large)

Mammals: We sorted the 45 species into 3 size classes based on large breaks in the continuum of their masses:
Size class 1 = 4-209 g (22 species)
Size class 2 = 550-4950 g (12 species)
Size class 3 = 8500-152,000 g (12 species)

Amphibians: Because there were only 10 species and their lengths did not differ greatly, we grouped all 10 into one size class.

Turtles: Because there were only three species and their lengths did not differ too greatly, we grouped all three into one size class.

Lizards: Because all species had lengths of 13 cm or less except for two species which were substantially larger, we divided species into two size groups with size class 2 containing only the two larger species:
Size class 1: ≤ 13 cm (23 species)
Size class 2: > 13 cm (2 species)

Snakes: Because length was fairly continuous for the 32 species, we divided them into three size classes of nearly equal numbers:
Size class 1 ≤ 48 cm (11 species)
Size class 2: 48.01– 88 cm (10 species)
Size class 3: > 88 cm (11 species)

Attributes Considered but Rejected from Future Consideration

We considered a host of other species attributes for the planning process, but we chose not to include these attributes because of the following reasons:

Functional guilds. Used to represent a diverse array of species groupings (e.g., management indicator, area-limited umbrella, dispersal-limited, keystone, process-limited, and dispersal-limited), many of which are not well defined, so creating a consistent and defensible classification is challenging (Carignan and Villard 2002). Some of these features are captured by other characteristics that we selected; for example, dispersal-limited and area-limited species reflects space use, which is captured by body size.

Degree of rarity/endangerment. There is no consensus on whether protecting rare species consistently benefit other species or whether rare species can provide unique information (Pearman et. al. 2006). Further, in addition to (or in lieu of) classifying the degree of rarity of species, it is necessary to assess whether species inhabits a rare or declining environment (Thompson 2006). Consequently, we found it important to distinguish natural rarity (a species near the edge of its range or that requires a large area) from rarity caused by anthropogenic factors such as habitat loss, hunting, or toxins. Once we made this distinction, we found that natural rarity overlapped largely with habitat specificity, which is related to vegetation-community association, and geographic extent, which is related to body size. We concluded that anthropogenic rarity was related to threats, which we considered separately.

Habitat specificity. There is no consensus on whether specialists or generalists are preferred for monitoring or planning purposes (Hilty and Merenlender 2000), and some species are not easily classified as specialists or generalists. Specialists may be more sensitive to environmental change (Landres et al. 1988, Carignan and Villard 2002), but some likely respond to only very specific environmental changes; generalists may not respond to environmental changes at rates that are detectable within time periods relevant to the monitoring program. The combination of the four characteristics that we used help ensure that we include both specialists and generalists in our list of target species.

Spatial scale/home-range size. Unknown for many species and captured largely by body size.

Distributional pattern. Whether species are distributed evenly, patchily, or otherwise across the landscape relates somewhat to habitat specificity, spatial scale/home-range size, and rarity, which we rejected but are represented somewhat by the four characteristics we used.

Reproductive strategy/survival/turnover. Can vary appreciably over time and in response to short-term changes to the landscape, therefore these less useful as long-term indicators of change (Landres et al. 1988). This category is also captured in part by body size.

Sensitivity to threats. Others have chosen species to monitor based on those most likely to be affected by anthropogenic threats (e.g., Raphael et. al. 2001, Lindenmayer et. al. 2002). We rejected this approach because of the wide breadth of potential threats in the large geographic areas covered by regional monitoring plans and because species-specific responses to threats in not available for a great many combinations of species and threats.

Table B.1. As a foundation of our conceptual model for the PCEMP, we selected a set of species that represents a wide range of ecosystem components in the plan area. To do so, we first identified 228 vertebrate species in the plan area which meet the following criteria: are native to Pima County, occur primarily below the oak woodland vegetation community, and breed in the County (Section 3.1.1). We then categorized each of these species by four attributes (shown in table below and discussed in Section 3.1.2.1): taxonomy, body size (1 = smallest; 4 = largest), trophic level (O = omnivore; C = carnivore; H = herbivore), and primary vegetation-community association. Next, we sorted all species into groups representing all combinations of subcategories for the four attributes (Section 3.2.2). Finally, we randomly selected one species from each group and added it to a subset of species which served as the foundational component of our conceptual model. This subset consisted of 109 species (underlined in table below): 8 amphibians, 3 turtles, 10 lizards, 13 snakes, 45 birds, and 30 mammals.

							Vegetation-community Association				
Taxon	Order	Family	Scientific name	Common name	Body size	Trophic level	Mesic riparian	Xeric riparian	Grass-land	Desert upland	Open water
Amphibians	ANURA	BUFONIDAE	*Bufo alvarius*	Sonoran desert toad	1	C	X	X	X	X	X
			Bufo cognatus	Great Plains toad	1	C	X	X	X	X	X
			Bufo punctatus	Red-spotted toad	1	C	X	X	X	X	
			Bufo retiformis	Sonoran green toad	1	C		X	X	X	
		HYLIDAE	*Hyla arenicolor*	Canyon treefrog	1	O	X	X	X	X	
		MICROHYLIDAE	*Gastrophryne olivacea*	Great Plains narrow-mouthed toad	1	C	X		X		X
		PELOBATIDAE	*Scaphiopus couchii*	Couch's spadefoot	1	C		X	X	X	
			Spea multiplicata	Mexican spadefoot	1	C	X	X	X	X	
		RANIDAE	*Rana chiricahuensis*	Chiricahua leopard frog	1	O	X		X	X	X
			Rana yavapaiensis	Lowland leopard frog	1	O	X		X	X	
Reptiles:											
Turtles	TESTUDINES	EMYDIDAE	*Terrapene ornata*	Desert box turtle	1	O			X		
		KINOSTERNIDAE	*Kinosternon sonoriense*	Sonoran mud turtle	1	O	X				X
		TESTUDINIDAE	*Gopherus agassizii*	Desert tortoise	1	H		X		X	
Lizards	SQUAMATA	ANGUIDAE	*Elgaria kingii*	Madrean alligator lizard	1	C	X		X		
		CROTAPHYTIDAE	*Crotaphytus collaris*	Eastern collared lizard	1	O		X	X	X	
			Crotaphytus nebrius	Sonoran collared lizard	1	O		X		X	
			Gambelia wislizenii	Long-nosed leopard lizard	1	C				X	
		GEKKONIDAE	*Coleonyx variegatus*	Western banded gecko	1	C				X	
		HELODERMATIDAE	*Heloderma suspectum*	Gila monster	2	C	X	X	X	X	
		IGUANIDAE	*Dipsosaurus dorsalis*	Desert iguana	1	O		X		X	
			Sauromalus ater	Chuckwalla	2	H				X	
		PHRYNOSOMATIDAE	*Callisaurus draconoides*	Zebra-tailed lizard	1	O		X		X	
			Cophosaurus texanus	Greater earless lizard	1	C		X	X	X	
			Holbrookia maculata	Common lesser earless lizard	1	C		X	X		
			Phrynosoma hernandesi	Greater short-horned lizard	1	C			X		
			Phrynosoma platyrhinos	Desert horned lizard	1	C		X		X	
			Phrynosoma solare	Regal horned lizard	1	C				X	
			Sceloporus clarkii	Clark's spiny lizard	1	O	X	X	X	X	

							Vegetation-community Association				
Taxon	Order	Family	Scientific name	Common name	Body size	Trophic level	Mesic riparian	Xeric riparian	Grass-land	Desert upland	Open water
			Sceloporus magister	Desert spiny lizard	1	O		X		X	
			Sceloporus undulatus	Eastern fence lizard	1	C	X		X		
			Urosaurus ornatus	Ornate tree lizard	1	C	X	X	X	X	
			Uta stansburiana	Side-blotched lizard	1	C			X	X	
		SCINCIDAE	*Eumeces obsoletus*	Great Plains skink	1	C	X	X	X		
		TEIIDAE	*Aspidoscelis burti stictogrammus*	Giant spotted whiptail	1	C	X	X			
			Aspidoscelis burti xanathanotus	Red-backed whiptail lizard	1	C		X		X	
			Aspidoscelis tigris	Western whiptail lizard	1	C	X	X	X	X	
			Cnemidophorus flagellicaudus	Gila spotted whiptail	1	C	X		X		
			Cnemidophorus sonorae	Sonoran spotted whiptail	1	C	X	X	X		
Snakes	SQUAMATA	BOIDAE	*Lichanura trivirgata gracia*	Desert rosy boa	2	C				X	
		COLUBRIDAE	*Arizona elegans*	Glossy snake	3	C		X	X	X	
			Chilomeniscus cinctus	Banded sand snake	1	C		X		X	
			Chionactis occipitalis	Western shovel-nosed snake	1	C		X		X	
			Chionactis palarostris	Sonoran shovel-nosed snake	1	C		X		X	
			Diadophis punctatus	Ringneck snake	2	C	X		X		
			Hypsiglena torquata	Night snake	1	C			X	X	
			Lampropeltis getula	Common kingsnake	3	C	X	X	X	X	
			Masticophis bilineatus	Sonoran whipsnake	3	C	X	X	X	X	
			Masticophis flagellum	Coachwhip	3	C		X	X	X	
			Phyllorhynchus browni	Saddled leafnose snake	1	C				X	
			Phyllorhynchus decurtatus	Spotted leafnose snake	1	C				X	
			Pituophis catenifer	Gopher snake	3	C		X	X	X	
			Rhinocheilus lecontei	Long-nosed snake	3	C		X	X	X	
			Salvadora grahamiae	Eastern patch-nosed snake	2	C			X		
			Salvadora hexalepis	Western patch-nosed snake	2	C			X		
			Senticolis triaspis	Green rat snake	3	C	X		X		
			Sonora semiannulata	Ground snake	1	C			X	X	
			Tantilla hobartsmithi	Smith's black-headed snake	1	C	X		X	X	
			Thamnophis cyrtopsis	Black-necked garter snake	2	C	X				X
			Thamnophis eques megalops	Mexican garter snake	2	C	X				X
			Thamnophis marcianus	Checkered garter snake	2	C	X	X	X		X
			Trimorphodon biscutatus	Lyre snake	2	C			X	X	
		ELAPIDAE	*Micruroides euryxanthus*	Sonoran coralsnake	1	C		X	X	X	
		LEPTOTYPHLOPIDAE	*Leptotyphlops humilis*	Western threadsnake	1	C	X	X		X	
		VIPERIDAE	*Crotalus atrox*	Western diamondback rattlesnake	3	C	X	X	X	X	
			Crotalus cerastes	Sidewinder	2	C				X	
			Crotalus mitchellii	Speckled rattlesnake	3	C				X	
			Crotalus molossus	Black-tailed rattlesnake	3	C	X	X	X	X	
			Crotalus scutulatus	Mojave rattlesnake	3	C		X	X	X	
			Crotalus tigris	Tiger rattlesnake	2	C			X	X	
Birds	ANSERIFORMES	ANATIDAE	*Anas cyanoptera*	Cinnamon teal	4	O					X

Taxon	Order	Family	Scientific name	Common name	Body size	Trophic level	Vegetation-community Association: Mesic riparian	Xeric riparian	Grass-land	Desert upland	Open water
			Anas platyrhynchos	Mallard	4	O					X
			Dendrocygna autumnalis	Black-bellied whistling-duck	4	H	X				X
	APODIFORMES	TROCHILIDAE	*Archilochus alexandri*	Black-chinned hummingbird	1	O	X	X			
			Calypte anna	Anna's hummingbird	1	O	X			X	
			Calypte costae	Costa's hummingbird	1	O		X		X	
			Cynanthus latirostris	Broad-billed hummingbird	1	O	X	X			
	CAPRIMULGIFORMES	CAPRIMULGIDAE	*Caprimulgus ridgwayi*	Buff-collared nightjar	3	C		X			
			Chordeiles acutipennis	Lesser nighthawk	3	C	X	X	X	X	
			Chordeiles minor	Common nighthawk	3	C			X		
			Phalaenoptilus nuttallii	Common poorwill	3	C			X	X	
	CHARADRIIFORMES	CHARADRIIDAE	*Charadrius vociferus*	Killdeer	3	C	X				X
		RECURVIROSTRIDAE	*Himantopus mexicanus*	Black-necked stilt	4	C					X
			Recurvirostra americana	American avocet	4	O					X
	CICONIIFORMES	ARDEIDAE	*Ardea herodias*	Great blue heron	4	C					X
			Ixobrychus exilis	Least bittern	3	C					X
			Nycticorax nycticorax	Black-crowned night-heron	4	C	X				X
	COLUMBIFORMES	COLUMBIDAE	*Columbina inca*	Inca dove	3	H	X	X			
			Columbina passerina	Common ground-dove	2	H	X	X			
			Zenaida asiatica	White-winged dove	4	H	X	X	X	X	
			Zenaida macroura	Mourning dove	3	H	X	X	X	X	
	CORACIIFORMES	CERYLIDAE	*Chloroceryle americana*	Green kingfisher	2	C					X
	CUCULIFORMES	CUCULIDAE	*Coccyzus americanus*	Western yellow-billed cuckoo	3	C	X	X			
			Geococcyx californianus	Greater roadrunner	4	C	X	X	X	X	
	FALCONIFORMES	ACCIPITRIDAE	*Accipiter cooperii*	Cooper's hawk	4	C	X	X			
			Asturina nitida	Gray hawk	4	C	X	X			
			Buteo albonotatus	Zone-tailed hawk	4	C	X	X			
			Buteo jamaicensis	Red-tailed hawk	4	C	X	X	X	X	
			Buteo swainsoni	Swainson's hawk	4	C	X	X	X		
			Buteogallus anthracinus	Common black-hawk	4	C	X				
			Elanus leucurus	White-tailed kite	4	C		X	X		
			Parabuteo unicinctus	Harris's hawk	4	C		X	X	X	
		FALCONIDAE	*Falco sparverius*	American kestrel	3	C	X	X	X	X	
	GALLIFORMES	ODONTOPHORIDAE	*Callipepla gambelii*	Gambel's quail	4	H	X	X	X	X	
			Callipepla squamata	Scaled quail	4	O			X		
			Colinus virginianus ridgwayi	Masked bobwhite quail	4	O			X		
			Cyrtonyx montezumae	Montezuma quail	4	O			X		
	GRUIFORMES	RALLIDAE	*Fulica americana*	American coot	4	O					X
			Gallinula chloropus	Common moorhen	4	O					X
			Porzana carolina	Sora rail	3	O					X
			Rallus limicola	Virginia rail	3	C					X
	PASSERIFORMES	ALAUDIDAE	*Eremophila alpestris*	Horned lark	2	O			X		
		CARDINALIDAE	*Cardinalis cardinalis*	Northern cardinal	3	O	X	X	X	X	
			Cardinalis sinuatus	Pyrrhuloxia	2	O		X	X	X	

Taxon	Order	Family	Scientific name	Common name	Body size	Trophic level	Vegetation-community Association: Mesic riparian	Xeric riparian	Grass-land	Desert upland	Open water
			Guiraca caerulea	Blue grosbeak	2	O	X	X	X		
			Passerina cyanea	Indigo bunting	2	O	X				X
			Passerina versicolor	Varied bunting	1	O		X			
		CORVIDAE	*Corvus corax*	Common raven	4	O	X		X	X	
			Corvus cryptoleucus	Chihuahuan raven	4	O		X	X		
		EMBERIZIDAE	*Aimophila botterii*	Botteri's sparrow	2	O			X		
			Aimophila carpalis	Rufous-winged sparrow	2	O		X	X	X	
			Aimophila cassinii	Cassin's sparrow	2	O			X		
			Aimophila ruficeps	Rufous-crowned sparrow	2	O			X		
			Ammodramus savannarum	Grasshopper sparrow	2	O			X		
			Amphispiza bilineata	Black-throated sparrow	1	O		X		X	
			Chondestes grammacus	Lark sparrow	2	O			X		
			Melospiza melodia	Song sparrow	2	O	X				X
			Pipilo aberti	Abert's towhee	3	O	X	X			
	PASSERIFORMES		*Pipilo fuscus*	Canyon towhee	3	O	X	X	X	X	
		FRINGILLIDAE	*Carduelis psaltria*	Lesser goldfinch	1	H	X	X			X
			Carpodacus mexicanus	House finch	2	H	X	X	X	X	
		HIRUNDINIDAE	*Progne subis*	Purple martin	3	C				X	
			Stelgidopteryx serripennis	Northern rough-winged swallow	2	C	X	X			X
		ICTERIDAE	*Agelaius phoeniceus*	Red-winged blackbird	3	O					X
			Icterus bullockii	Bullock's oriole	2	O	X	X	X		
			Icterus cucullatus	Hooded oriole	2	O	X	X			
			Icterus parisorum	Scott's oriole	2	O		X	X	X	
			Sturnella magna	Eastern meadowlark	3	O			X		
		LANIIDAE	*Lanius ludovicianus*	Loggerhead shrike	3	C			X	X	
		MIMIDAE	*Mimus polyglottos*	Northern mockingbird	3	O		X	X	X	
			Toxostoma bendirei	Bendire's thrasher	3	O			X	X	
			Toxostoma crissale	Crissal thrasher	3	O	X	X			
			Toxostoma curvirostre	Curve-billed thrasher	3	O		X	X	X	
		PARIDAE	*Baeolophus wollweberi*	Bridled titmouse	1	C	X				
			Dendroica petechia	Yellow warbler	1	C	X				
			Geothlypis trichas	Common yellowthroat	1	C	X				X
			Icteria virens	Yellow-breasted chat	2	O	X	X			
			Vermivora luciae	Lucy's warbler	1	C	X	X			
		PTILOGONATIDAE	*Phainopepla nitens*	Phainopepla	2	O	X	X	X	X	
		REMIZIDAE	*Auriparus flaviceps*	Verdin	1	O		X	X	X	
		SYLVIIDAE	*Polioptila melanura*	Black-tailed gnatcatcher	1	C				X	
			Polioptila nigriceps	Black-capped gnatcatcher	1	C		X			
		THRAUPIDAE	*Piranga rubra*	Summer tanager	2	O	X	X			
		TITYRIDAE	*Pachyramphus aglaiae*	Rose-throated becard	2	O	X				
		TROGLODYTIDAE	*Campylorhynchus brunneicapillus*	Cactus wren	2	O		X	X	X	
			Catherpes mexicanus	Canyon wren	1	C				X	
			Salpinctes obsoletus	Rock wren	2	C			X	X	

Taxon	Order	Family	Scientific name	Common name	Body size	Trophic level	Vegetation-community Association: Mesic riparian	Xeric riparian	Grass-land	Desert upland	Open water
			Thryomanes bewickii	Bewick's wren	1	C	X	X			
		TYRANNIDAE	*Camptostoma imberbe*	Northern beardless-tyrannulet	1	C	X	X			
			Contopus sordidulus	Western wood-pewee	1	C	X				
			Empidonax traillii extimus	Southwestern willow flycatcher	1	O	X				
			Myiarchus cinerascens	Ash-throated flycatcher	2	O	X	X	X	X	
			Myiarchus tuberculifer	Dusky-capped flycatcher	2	O	X				
			Myiarchus tyrannulus	Brown-crested flycatcher	3	O	X	X		X	
			Pyrocephalus rubinus	Vermillion flycatcher	2	C	X	X			
			Sayornis nigricans	Black phoebe	2	C	X	X			X
			Sayornis saya	Say's phoebe	2	C			X	X	
			Tyrannus crassirostris	Thick-billed kingbird	3	C	X				
			Tyrannus melancholicus	Tropical kingbird	2	O	X				
			Tyrannus verticalis	Western kingbird	2	O	X	X	X	X	
			Tyrannus vociferans	Cassin's kingbird	3	O	X		X		
		VIREONIDAE	*Vireo bellii*	Bell's vireo	1	C		X			
	PICIFORMES	PICIDAE	*Colaptes auratus*	Northern flicker	3	O	X				
			Colaptes chrysoides	Gilded flicker	3	O		X		X	
			Melanerpes uropygialis	Gila woodpecker	3	O	X	X	X	X	
			Picoides scalaris	Ladder-backed woodpecker	2	O	X	X	X	X	
	PODICIPEDIFORMES	PODICIPEDIDAE	*Podilymbus podiceps*	Pied-billed grebe	4	C					X
	STRIGIFORMES	STRIGIDAE	*Athene cunicularia*	Burrowing owl	4	C			X		
			Bubo virginianus	Great-horned owl	4	C	X	X	X	X	
			Glaucidium brasilianum cactorum	Cactus ferruginous pygmy-owl	3	C		X	X	X	
			Micrathene whitneyi	Elf owl	2	C			X	X	
			Otus kennicottii	Western screech-owl	4	C	X	X	X	X	
		TYTONIDAE	*Tyto alba*	Barn owl	4	C	X	X	X	X	
Mammals	ARTIODACTYLA	ANTILOCAPRIDAE	*Antilocapra americana*	Pronghorn	3	H			X		
		BOVIDAE	*Ovis canadensis*	Desert bighorn	3	H				X	
		CERVIDAE	*Odocoileus hemionus*	Mule deer	3	H			X	X	
			Odocoileus virginianus	Whitetail deer	3	H				X	
		TAYASSUIDAE	*Pecari tajacu*	Collared peccary	3	H				X	
	CARNIVORA	CANIDAE	*Canis latrans*	Coyote	3	C			X	X	
			Urocyon cinereoargenteus	Gray fox	2	O				X	
			Vulpes macrotis	Kit fox	2	C			X	X	
		FELIDAE	*Lynx rufus*	Bobcat	3	C				X	
			Puma concolor	Mountain lion	3	C		X		X	
		MEPHITIDAE	*Conepatus mesoleucus*	White-backed hog-nosed skunk	2	O	X	X		X	
			Mephitis macroura	Hooded skunk	2	O	X	X	X		
			Mephitis mephitis	Striped skunk	2	O	X	X	X	X	
			Spilogale gracilis	Western spotted skunk	2	O	X	X		X	
		MUSTELIDAE	*Taxidea taxus*	Badger	3	C			X	X	
		PROCYONIDAE	*Bassariscus astutus*	Ringtail cat	2	O				X	
			Nasua narica	Coati	3	O	X	X			

Taxon	Order	Family	Scientific name	Common name	Body size	Trophic level	Vegetation-community Association Mesic riparian	Xeric riparian	Grass-land	Desert upland	Open water
			Procyon lotor	Raccoon	3	O	X				X
		URSIDAE	*Ursus americanus*	Black bear	3	O	X		X		
	CHIROPTERA	PHYLLOSTOMIDAE	*Leptonycteris curasoae*	Lesser long-nosed bat	1	H			X	X	
			Macrotus californicus	California leaf-nosed bat	1	O				X	
	DIDELPHIMORPHIA	DIDELPHIDAE	*Didelphis virginiana*	Virginia opossum	2	O	X	X			X
	INSECTIVORA	SORICIDAE	*Notiosorex crawfordi*	Desert shrew	1	C	X	X	X	X	X
			Lepus alleni	Antelope jackrabbit	2	H			X	X	
			Lepus californicus	Black-tailed jackrabbit	2	H			X	X	
			Sylvilagus audubonii	Desert cottontail	2	H			X	X	
	RODENTIA	ERETHIZODONTIDAE	*Erethizon dorsatum*	North American porcupine	3	H	X	X			
		GEOMYIDAE	*Thomomys bottae*	Botta's pocket gopher	1	H			X	X	
		HETEROMYIDAE	*Chaetodipus baileyi*	Bailey's pocket mouse	1	H			X	X	
			Chaetodipus intermedius	Rock pocket mouse	1	H				X	
			Chaetodipus penicillatus	Desert pocket mouse	1	H				X	
			Dipodomys merriami	Merriam's kangaroo rat	1	H			X	X	
			Dipodomys spectabilis	Banner-tailed kangaroo rat	1	H			X		
			Perognathus amplus	Arizona pocket mouse	1	H				X	
		MURIDAE	*Neotoma albigula*	White-throated woodrat	1	H	X	X	X	X	X
			Neotoma lepida auripila	Desert woodrat	1	H				X	
			Onychomys torridus	Southern grasshopper mouse	1	C			X	X	
			Peromyscus eremicus	Cactus mouse	1	O			X	X	
			Peromyscus maniculatus	Deer mouse	1	O	X	X	X		
			Peromyscus merriami	Merriam's mouse	1	O		X			
			Reithrodontomys fulvescens	Fulvous harvest mouse	1	H			X		
			Reithrodontomys megalotis	Western harvest mouse	1	O			X		
			Sigmodon arizonae	Arizona cotton rat	1	H	X	X		X	X
			Sigmodon ochrognathus	Yellow-nosed cotton rat	1	H			X		
		SCIURIDAE	*Ammospermophilus harrisii*	Harris' antelope ground squirrel	1	O				X	
			Spermophilus tereticaudus	Round-tailed ground squirrel	1	O				X	
			Spermophilus variegatus	Rock squirrel	2	O	X	X	X	X	X

Appendix C: Protocol for Gathering Information on Environmental Features

To gather information on environmental features relevant to each species, we completed comprehensive and methodical literature searches by querying major scientific databases. We followed a search protocol to ensure that we searched the same set of sources most likely to provide environmental feature information for all species or for closely-related species. We documented these searches in a search history table for each species and stored source citations in EndNote databases. After sources were gathered for a species, we reviewed them and selected those most relevant to our information goals. Then we reviewed the selected literature for information on environmental features, which we recorded in the species-environmental features matrix (**Section 3.2**).

Search Procedures

Major Sources Searched. The major online databases we searched were ISI Web of Knowledge (most often Web of Science), the University of Arizona library and journal databases, and Google Scholar. We often searched additional sites and sources that were specific to each taxon, such as *Birds of North America Online* for birds and the book *Mammals of Arizona* for mammals (**Table C.1**).

Search History Table. We created a search-history table (e.g., **Table C.1**) for each species that we named using the format "Search History_Species common name." Each table has four sections: "source" name; "website address" when applicable; "citation" for the source in an abbreviated format described below; and a "notes" section. Source name identifies the database, book, or website searched and does not indicate the author of the material. Website address is that of the homepage for each electronic site. The citation for each source is abbreviated using the format of "Author(s)_Year_Journal abbreviation" for journal articles, and other frequently used sources were cited according to the recommendations of the sources. The notes section includes page numbers within sources when applicable, indicates whether a report was found for the species in a source, indicates whether a source was searched, and briefly annotates the subject of each journal article.

Source Name Abbreviations. We abbreviated source names by using a set of arbitrary rules and maintained a reference list of abbreviations. We abbreviated titles using first initials of the main words of the titles (e.g., Journal of Wildlife Management = JWM). If an abbreviation already existed on the list, the first two letters of the first word in the journal were used, followed by the initials of the remaining words (e.g., Environmental Management = EnM). If a journal title was only one word, the first four letters of the title were used (e.g., Herpetologica = Herp). If none of these rules worked or a duplicate abbreviation resulted for some reason, we used personal judgment to create a logical abbreviation.

Table C.1. Example of a search-history table used to document literature searches completed for each species used in the conceptual modeling work for the PCEMP. This example is for the Arizona cotton rat.

Source	Website Address	Citations	Notes
Mammals of Arizona	Book	Hoffmeister 1986	Pages: 391 - 394
USFWS	www.fws.gov	USFWS_Year_Final Recovery Plan	No report found
SW ReGAP	http://fws-nmcfwru.nmsu.edu/swregap/habitatreview/	USGS.2005	Report found
Pima County PVS Report		RECON 2002	No report found
AZGFD	http://www.azgfd.gov/	For HDMS animal abstract: AGFD_2004_HDMS	Report found
BISON	http://www.bison-m.org/	BISON-M Last Updated Date	two reports found for subspecies *arizonae* and *cienegae*
Beier Linkages Reports	http://www.corridordesign.org/arizona/	(1) Beier_etal_2006_AML:IPLD (2) Beier_etal_2006_AML:SRTLD (3) Beier_etal_2006_AML:RSRWLD	(1) No report found (2) No report found (3) No report found
Web of Science	http://apps.isiknowledge.com (Web of Science tab)	(1) Andersen_Nelson_1999_RRRM	(1) use of riparian habitat
UA databases	http://www.library.arizona.edu/		Searched – redundant
Google Scholar			Searched – redundant or not app to EF

Electronic Files

<u>All Sources Found.</u> We saved literature for a species in a folder named with the common name of the species. We named articles, reports, and accounts added to a species folder with the same format used in the "citations" section of the search history table (i.e., Author(s)_Year_Journal abbreviation). We named species accounts from frequently used sources with the format "Source citation_Species common name" (e.g., SWReGAP_Bobcat). Adding the species common name to these citations was necessary to avoid confusion if the files of these accounts for individual species are moved from the species folder. We documented hardcopy sources in the electronic species folders with a Word document named in the same citation format as for species accounts described above (e.g., Hoffmeister 1986_Antelope jackrabbit). The Word document contains the common name of the species, the abbreviated citation for the source, and the page numbers used from the source. Similarly, we created Word documents for large electronic sources from which only a portion of information was used. These documents follow the same citation format as described above and also contain a copy of the section of information used from the source.

<u>Sources Used for Environmental Feature (EF) Matrix.</u> We created a separate electronic folder called "Sources Used for EF Matrix" for each species and copied into it citations of literature sources we

ultimately selected and used to collect information for the species-environmental features matrix. These folders were titled as follows: "Species common name_EF Matrix Sources."

EndNote Databases. We stored all citations from literature searches in EndNote databases. Specifically, all citations of all sources found for all species were stored in a database titled "All Citations EF Matrix Species Searches." Citations for sources actually used to gather EF data were stored in a database titled "EF Matrix Citations Used." We also created separate EndNote databases for each species and titled them with the common names of the species. For the priority vulnerable species added to the matrix for other analyses (Section 3.1.2.3), the same types of EndNote databases were created as for the EF Matrix species: one for citations of all sources found for all species, titled "Other PVS All Citations"; one for citations of sources actually used for species-EF matrix data, titled "Other PVS Used Citations"; and one for each species, titled by species common name. We tagged file names of sources in a species folder with "_EN" after we entered citations for the sources into the EndNote databases. However, we added frequently used sources from which information for many species was gathered (e.g., (RECON Environmental Inc. 2000) to the EndNote databases only once and not for every species. Therefore, we did not tag these source citations with "_EN" in each of the species folders.

Species Completion Log. In a "Species Completion Log," we recorded completion dates and initials of the name(s) of executors of the three main steps for gathering data for the species-environmental features matrix: searching for literature, selecting sources from all the literature found in searches to review for environmental features data, and actually gathering data for the matrix from the selected sources. The log is stored with the other electronic folders for species-environmental features matrix.

Storage of Electronic Files. All electronic files will be archived by Pima County.

Reviewing the Literature

For each species, we reviewed sources identified in literature searches then selected and printed copies of those that provided ecological and natural-history information for the species. We then reviewed these documents in detail and marked the sections that described environmental features used by the species.

Before we decided to use the procedure described above, we electronically copied and pasted relevant information on environmental features from PDF documents into a Word document for each species to create a rough species account with which to enter data into the EF Matrix. We completed these accounts for five species, and these documents are included in the electronic and hardcopy files of sources used for the species- environmental features matrix. In addition, before we decided to print hardcopies of all sources to be reviewed for a species, we read and took notes from some PDFs and hardcopy sources for many species. These hand-written notes are included in the hard-copy files for those species.

We found that printing and marking hardcopies of sources selected for each species and then using the hardcopies to enter data into the species- environmental features matrix was the easiest and most accurate method for this process. Although PDFs could have been marked on the computer, the hardcopies were much easier to refer back to when checking data and comparing information among sources.

However, with Adobe Acrobat, PDFs could be marked on the computer and then printed, giving both an electronic and hard copy of the information collected for a species. Similarly, hardcopy sources (such as sections of books) could be scanned into the computer and then marked and printed for use. This method, though probably more time consuming, is an option for future work of this type if electronic files are required or desired at this detailed level of work.

Appendix D. Additional Information on Environmental Features

We edited and reorganized the original EF-species matrix for prioritization analyses. First, in the reorganization of the environmental features for surface water, we set aside the two original super-categories of presence of perennial and intermittent surface water and more finely organized the types of water sources listed for each according to the description of reorganization given above. Then, we "unrolled" the two original super-categories of presence of perennial and intermittent surface water according to the following rules: (1) If only one or both of these super-categories and none of their subcategories had been marked for a species in the original matrix, then all representative environmental features of water types in the final organization of environmental features for prioritization were ranked at the same rank as the original super-category; and (2) If all ranks of representative EFs of water types in the final organization of environmental features for prioritization were lower than that of the rank of the original super-category for a species, then the ranks of all representative environmental features in the final organization of environmental features for prioritization were raised to the rank of the original super-category (this occurred in the perennial water category for three species: common ground dove, lesser goldfinch, and striped skunk).

We excluded a host of environmental features that are too slow to change during the course of the proposed monitoring program (**Table D.1**). This information will be collected on the first visit to long-term monitoring sites, but will not be collected thereafter. A host of other environmental features were excluded from this analysis because 1) The feature was relevant to <5% of target species; 2) the likelihood of detecting a change in the feature was low; 3) the feature was related to anthropogenic factors (except for surface water) (**Table D.2**).

Table D.1. Physical environmental features excluded from the environmental features x species matrix because they were too slow to change. Many of these features will be noted prior to the beginning of monitoring or on the first visit to long-term monitoring site.

1st order Category	2nd Order Category	Example(s)
Topography	Elevation	≤1000m, 1001-1500m
	Landform	Ridges, valleys
	Orientation	North, southwest
	Terrain	Rocks, limestone outcrops, lava
Subterranean	Natural shelters	Caves, rock shelters
Soils	Types	Gravel, sand, sandy loam
	Depth	Shallow (<1 m), Moderately deep (1-3 m)
Stream channels	Morphology	Sandy banks
	Channel material	Bedrock, cobble, silt

Table D.2. List of environmental features that were evaluated for all species but were excluded because: 1) The feature was relevant to <5% of target species; 2) the likelihood of detecting a change in the feature was low; 3) the feature was related to anthropogenic factors (except for surface water).

Group	1st Order	2nd Order	Environmental feature	Reasons excluded
Physical	Soils	Condition	Disturbed	1
			Moisture level (Low, High)	2
	Subterranean	Anthropogenic shelters	Mines, culverts	3
			Agricultural ditchbanks, storm/sewer drains, water diversion tunnels	1, 3
	Surface water	Quality	Within bounds of normal variation	1
		Intermittent	Raindrops and dewdrops on vegetation; falling rain; fog	1, 2
		Other	Depth of water body/area: shallow, deep	2
Biological	Terrestrial vegetation	Composition	Fungi, lichens, moss	1
			Agricultural species, other human planted species	3
	Aquatic vegetation	Composition	Detritus	1
	Animal-made features	Structures	Tent caterpillar webs	1, 2
			Bird and squirrel nests, insect cocoons, spider silk, eggs sacks	1, 2
		Habitat alterations	Vole runways (in grass habitats)	1, 2
		Waste	Livestock dung	1,2
Anthropogenic	Development-related features	Structures	Buildings and other structures: carports, lean-to's, powerlines, billboards, fences, pole	3
			Lights (street lamps, other bright lights)	1, 3
		Waste	Garbage sites; trash/litter on ground; debris piles, abandoned structure and equipment	3
		Structures for wildlife	Nest boxes; other artificial nest sites	3
			Bird feeders	1, 3
		Landscape alterations	Roads and trails, road cuts/embankments, road and railroad underpasses, rail lines, gravel pits, quarries	1, 3
			Roadside and agricultural ditches	3

Appendix E. Additional information on threats

Table E.1. List of threats in Pima County that we evaluated for inclusion into the design matrix.

Threat	Description
Aggregate or fill removal	Extraction of sand, gravel, and fill, primarily from river courses. Mostly confined to river bottom, but old meanders can be mined for gravel, so upland components (e.g., vegetation) are affected.
Agriculture	Monocultures. Can have hedgerows, but highly regulated systems with few or no native plants, lots of invasive plants, standing water, etc. All activities related to the clearing land, and the existence of crops. Does not include application of pesticides, GMOs, etc.
Air-born pollutants	From fires, smog and ozone from vehicles, atmospheric deposition of sulfur, mercury, and especially sulphur dioxide from copper smelters, which result in toxic levels of cadmium in water, etc.
Aquatic invertebrates	Crayfish
Aquatic vertebrates	Bullfrogs, non-native fish
Bank stabilization	Activities related to construction, maintenance, and operations.
Below-ground lines	Major gas, water, and power service lines and right of ways. Activities related to construction, maintenance, and ongoing operations
Cattle grazing	Feral and managed, especially at excessive stocking rates.
Cave closures (filling)	Elimination of resource.
Domestic cats and dogs	Household and feral; actions of pets in natural areas.
Electrical Lines, Phone Lines, sewer lines: above-ground lines	Evaluated as minor service lines, not a major power lines that have a greater footprint. Impacts related to areas of disturbance where posts or power lines are located. Service roads not maintained. Activities related to construction, maintenance, and operations.
Hunting, trapping, collecting	Recreational hunting, predator control, collection of plants and animals.
Impoundments for wildlife or cattle	Includes the impoundment, the pond created, and associated features such as water. Activities related to construction, maintenance, and operations.
Invasive grasses	Buffelgrass, fountaingrass, Lehmann's lovegrass.
Invasive trees	Tamarisk *spp*.
Motorized off-road vehicle use	Off-road vehicle use, military operations (ground), pursuit of illegal immigrants and drug smugglers by law enforcement. Use from OHVs, cars and trucks, etc.
Native birds	Brown-headed and bronzed cowbirds
Nitrogen deposition	Excess amounts.
Noise from planes, cars, etc.	Military and civilian flight paths, training, dynamite.
Non-motorized activities: off trail	Hiking, rock climbing, mountain biking, horseback riding, picnicking, camping, research, illegal human and drug trafficking.
Non-motorized activities: on trail	Hiking, rock climbing, mountain biking, horseback riding, picnicking, camping.
Open-pit mines and quarries	Mines for extraction of minerals and rock. All activities related to clearing the land, and building and maintaining structures, operating equipment, and disposal of waste.
Pumping aquifers	
Pumping shallow groundwater	Threshold for threat: pumping to the point that it affects hydrologic function such as availability of surface water, plants (including annuals and perennial plants).

Threat	Description
Recharge in infiltration ponds	Ponds that provide for storage and infiltration of water from the Central Arizona Project, which can destroy vegetation during construction and operations. Evaluated as a net positive on processes such as recharge.
Roads: Gravel	Activities related to construction and maintenance as well as continued vehicle use.
Roads: Major Highways and bridges	Interstate, federal, and state highways. All structures are above-grade. Activities related to the construction and maintenance as well as continued vehicle use.
Roads: Secondary Highways, Paved Streets, railroad tracks and infrastructure	Paved city and county roads. Many structures are above-grade. Activities related to construction and maintenance as well as continued vehicle use.
Rural	Ranches and ranchettes in a rural setting, typically with dirt roads, usually >40 acres per house. Does not include land-use activities such as grazing, but includes all activities related to the clearing land, and building and maintaining structures.
Sewage waste	*E. coli*, nitrogen, and phosphorus, and pharmaceuticals released from municipal waste facilities, untreated sewage spills from septic tanks and feedlots. Usually impacts riparian areas.
Terrestrial invertebrate	Africanized bees
Tourist sites, recreational areas, abandoned farmland	Urban parks, golf courses, campgrounds, orchards. Few or no human dwellings. Vegetation, but not necessarily native and often modified. All activities related to the clearing land, and building and maintaining structures.
Toxic chemicals: Non-point source	Chemicals from farms, homes, illegal dumping, household fertilizer and herbicide runoff, oil and sediment from roads.
Toxic chemicals: Point source	Chemicals from factories, leakages from fuel tanks, mine tailings, municipal waste facilities.
Urban Core	High-density housing, commercial development, rail yards, shopping centers, landfills, airports, wastewater treatment facilities, solar farms, some military bases. Areas with little or no native vegetation, soil coverage, or naturally functioning hydrologic systems. Includes all activities related to the clearing land, and building and maintaining structures.
Urban Fringe	Medium-density housing in planned and unplanned subdivisions, and some military bases, typically with 1 residence on 3-4 acres. Natural vegetation, soils, and some moderate impairment of functioning hydrological features. Includes all activities related to the clearing land, and building and maintaining structures.
Vandalism and littering	Campfires outside of designated sites, vandalism, trash, including dumping by illegal immigrants. Spillover from municipal waste facilities, litter from cars, illegal dumping, trash flows in rivers.
Water diversions	Canals for agriculture, municipal use. Activities related to the construction, maintenance, and operations. Direct effects include disturbance but also removal of water from primary source, manipulating river/wash channels.
Water pollution	Suspended sediment above acceptable levels.
Wildlife diseases	Chytridiomycosis, Trichomoniasis, West Nile virus

Characteristic of threats that were considered for evaluation, but not chosen:

- **Spatial Extent**. Spatial extent of threats for eastern Pima County would be ideal, but was not possible given the lack of spatial information for most threats. Also, no other component of the design framework incorporated a spatial component.

- **Primary and Secondary Effects**. We classified an effect as *primary* when it was the initial effect of a threat has on an environmental feature. For example, land clearing associated with residential development has a primary effect of removal of vegetation, but this primary effect can lead to *secondary effects*, such as siltation of rivers and the rate of discharge to streams. Despite this potential for a series of related effects, we focused on primary effects of each threat on environmental features.

- **Climate and Weather**. We did not consider threats due to climate change and weather events, such as drought, because these are large-scale processes that likely will affect the entire planning area and offer little opportunity for local-scale management to ameliorate their effects. Despite not including these in our assessment, effects of these and other process will be captured as part of the monitoring program by measuring precipitation and natural processes.

- **Positive Influence of Threats**. Some threats can affect environmental features or other conservation targets in a positive. For example, moderate density housing developments away from riparian areas can increase cover of overstory vegetation that can improve habitat quality for some species, even if the plant species planted are nonnative. Despite the potential for occasional positive effects, we evaluated threats only based on their adverse effects. Similarly, when evaluating effects of threats on water-related environmental features, we did not evaluate the effects of threats on human-made features such as stock tanks because this would have required balancing the adverse effects of each threat on natural features with the positive effects on human-made water features.