National Park Service
U.S. Department of the Interior

Natural Resource Program Center
Fort Collins, Colorado

Vital Signs Monitoring Plan for the Southern Colorado Plateau Network

Natural Resource Report NPS/SCPN/NRR-2006/002

ON THE COVER
Pinyon-juniper woodlands, slickrock, and sandstone cliffs characterize the landscape overlooking Betatakin Canyon at Navajo National Monument.
Photo by Chris Lauver, NPS

Vital Signs Monitoring Plan for the Southern Colorado Plateau Network

Natural Resource Report NPS/SCPN/NRR-2006/002

Lisa P. Thomas, Marguerite N. Hendrie (editor),
Chris L. Lauver, Stephen A. Monroe, Nicole J. Tancreto,
Steven L. Garman[1], Mark E. Miller[2]

National Park Service, Southern Colorado Plateau Network,
Northern Arizona University, P.O. Box 5765, Flagstaff, AZ 86011

[1]National Park Service, Northern Colorado Plateau Network,
P.O. Box 848, Moab, UT 84532

[2]United States Geological Survey, Southwest Biological Science Center,
c/o Grand Staircase–Escalante National Monument
190 E. Center St., Kanab, UT 84741

October 2006

U.S. Department of Interior
National Park Service
Natural Resource Program Center
Fort Collins, Colorado

The Natural Resource Publication series addresses natural resource topics that are of interest and applicability to a broad readership in the National Park Service and to others in the management of natural resources, including the scientific community, the public, and the NPS conservation and environmental constituencies. Manuscripts are peer-reviewed to ensure that the information is scientifically credible, technically accurate, appropriately written for the intended audience, and is designed and published in a professional manner.

The Natural Resources Technical Reports series is used to disseminate the peer-reviewed results of scientific studies in the physical, biological, and social sciences for both the advancement of science and the achievement of the National Park Service's mission. The reports provide contributors with a forum for displaying comprehensive data that are often deleted from journals because of page limitations. Current examples of such reports include the results of research that addresses natural resource management issues; natural resource inventory and monitoring activities; resource assessment reports; scientific literature reviews; and peer reviewed proceedings of technical workshops, conferences, or symposia.

Printed copies of reports in these series may be produced in a limited quantity and they are only available as long as the supply lasts. This report is also available from the Southern Colorado Plateau website (http://www.nature.nps.gov/im/units/SCPN) on the internet, or by sending a request to:
Southern Colorado Plateau Network
Northern Arizona University
P.O. Box 5765
Flagstaff, AZ 86011

Please cite this publication as:
Thomas, L.P., M.N. Hendrie (editor), C.L. Lauver, S.A. Monroe, N.J. Tancreto, S.L. Garman, and M.E. Miller. 2006. Vital Signs Monitoring Plan for the Southern Colorado Plateau Network. Natural Resource Report NPS/SCPN/NRR-2006/002. National Park Service, Fort Collins, Colorado.

NPS D-46, October 2006

EXECUTIVE SUMMARY

KNOWING THE CONDITION of natural resources in national parks is fundamental to the Service's ability to manage park resources "unimpaired for the enjoyment of future generations". The National Park Service has implemented a strategy to improve its science information base so that parks with significant natural resources possess the resource information needed for effective decision-making and resource protection. Vital signs monitoring is a key element of that strategy. The approximately 270 park units with significant natural resources have been grouped into 32 monitoring networks linked by geography and natural resource characteristics. The network organization will facilitate collaboration, information sharing, and economies of scale in natural resource monitoring. Parks within each of the 32 networks collaborate with shared funding and professional staff to design and implement long-term monitoring. The Southern Colorado Plateau Network (SCPN) is composed of 19 National Park Service units located in northern Arizona, northwestern New Mexico, southwestern Colorado, and southern Utah.

Developing an ecological monitoring strategy requires a front-end investment in planning and design to ensure that monitoring will meet the most critical information needs and produce ecologically relevant and scientifically credible data that are readily accessible to managers. The SCPN monitoring program is being developed over a five-year timeframe with specific objectives and reporting requirements at each of three planning milestones. This is the final report that documents that process.

The first planning steps involved compiling and organizing relevant science information and conducting detailed park scoping to identify the most important resources and issues for each park. A second step was to collaborate with regional scientists to develop conceptual ecological models of the predominant Colorado Plateau ecosystems. The network then held a series of workshops in 2004 to identify and evaluate vital signs for long-term monitoring. During seven topical workshops park managers and scientists, collaborators from the scientific community, and SCPN staff identified and evaluated resources and potential indicators as candidates for monitoring. Following those workshops, the SCPN Technical and Science Advisory Committees met to make the final selection of network vital signs.

Over the next five years, network staff and collaborators will develop 13 monitoring protocols to address the core vital signs for the SCPN. These monitoring protocols will provide detailed study plans that explain how data are to be collected, managed, analyzed, and reported and will serve as a key component of quality assurance for vital signs monitoring.

A key partner in these planning activities is the Northern Colorado Plateau Network (NCPN), our neighboring network composed of 16 parks in Utah, Colorado, and Wyoming. NPS units across the Colorado Plateau share ecosystems and a long-history of working together on natural resource science and stewardship. The two networks have been tasked by Colorado Plateau park managers to identify common monitoring needs and work together as much as possible to design and implement ecological monitoring. The two networks collaborated on developing conceptual ecological models for Colorado Plateau ecosystems and are currently collaborating to develop monitoring protocols.

SCPN core vital signs organized within the NPS Ecological Monitoring Framework

LEVEL 1	LEVEL 2	VITAL SIGN
Air and Climate	Air Quality	Air quality
	Weather and Climate	Climate conditions and soil moisture
Geology and Soils	Soil Quality	Soil stability and upland hydrologic function
	Geomorphology	Channel morphology
Water	Hydrology	Depth to groundwater
		Stream flow
	Water Quality	Water quality of streams and springs
		Aquatic macroinvertebrates
Biological Integrity	Focal Species or Communities	Spring, seep, and tinaja ecosystems
		Vegetation composition and structure (upland & riparian)
		Habitat-based bird communities
		Ground-dwelling arthropods
	Invasive Species	Invasive non-native plants
Ecosystem Pattern and Processes	Landscape Dynamics	Land use/land cover and landscape vegetation pattern
		Vegetation condition and disturbance patterns
	Soundscape	Natural soundscape condition
	Viewscape	Night sky condition

Developing sampling designs for long-term monitoring is essential to ensure that the data collected are representative of the target populations and sufficient to draw defensible conclusions about the resources of interest. The sampling design chapter describes how sampling locations are chosen for each vital sign and how the sampling effort will be rotated through time among locations.

In order to be useful to park managers over the long term, monitoring data must be well-maintained and regularly reported. The data management chapter describes our standards and procedures to ensure the quality, security, longevity, and availability of monitoring data and associated information products. SCPN staff will use appropriate computer information technology tools and will provide high quality data stewardship at every step of the monitoring process, from protocol development and data collection through analysis, reporting, and archiving.

In the data analysis and reporting chapter, we present an overview of how data collected by the network will be analyzed and how we will effectively share the monitoring results with park managers, scientists, and the general public.

The network relies on three groups to provide program oversight and guidance. The Board of Directors, composed of five SCPN superintendents, oversees network administration and provides program guidance and advocacy. The Technical Advisory Committee, made up of park natural resource managers, advises the network regarding scientific and technical planning aspects, park-based logistic support, and resource management applications of monitoring results. The scientific panel comprises six academic scientists with regional and/or discipline expertise. They advise us on improving the scientific relevance and credibility of the program.

The network was initially funded for vital signs monitoring in FY 2002 and currently receives $1,209,000 from the NPS I&M Program on an annual basis. The NPS-Water Resources Division annually contributes an additional $124,000 for water quality monitoring.

The SCPN staff is based in Flagstaff, Arizona on the campus of Northern Arizona University. The program manager is supervised by the Colorado Plateau Cooperative Ecosystem Studies Unit (CP-CESU) Research Coordinator. In addition to the program manager, the network's permanent staff will include four scientists, a three-person data management team, and a half-time program assistant. The network will also rely on its cooperative relationship with Northern Arizona University to meet the need for seasonal monitoring crews and will use CP-CESU agreements to accomplish some monitoring projects.

ACKNOWLEDGEMENTS

MANY PEOPLE CONTRIBUTED THEIR IDEAS and hard work toward the development of the Southern Colorado Plateau Network (SCPN) and the preparation of this report.

Thanks to contributors to the Phase III Report, including Rebecca Harms and Megan Swan, NAU-SCPN Research Technicians; Anne Cully, SCPN Vegetation Ecologist; Robert Bennetts, Greater Yellowstone Network Quantitative Ecologist; and Julianne Brown and Kirby Wynn, USGS Water Resources Division. Thanks to all who contributed to preparing earlier versions of this report, especially Jodi Whittier and Julie Atkins for their work on the Phase I report. Thanks also to the park staff and many subject matter experts who participated in the 2004 workshops.

The resource managers of the Southern Colorado Plateau parks understood the importance of establishing a long-term monitoring capacity before funding or positions were in place. They contributed their time and efforts, through the SCPN Technical Advisory Committee, to laying the groundwork for the monitoring program. We thank Karen Beppler-Dorn, Cole Crocker-Bedford, Stephen Fettig, Brian Jacobs, Elaine Leslie, Mike Medrano, Steve Mitchelson, George San Miguel, Brad Shattuck, John Spence, Pat Thompson, and Paul Whitefield for their contributions.

Ron Hiebert, Colorado Plateau CESU Research Coordinator, provided early guidance and oversight for the program, building awareness and support among superintendents, establishing the Science Advisory Committee, and hiring positions. We thank him for his long-standing advocacy to improve the scientific information base of NPS and his common-sense approach to building partnerships.

We thank the SCPN Board of Directors (Scott Travis, Dennis Carruth, Larry Wiese and Palma Wilson) for their continued support, advice and advocacy. We trust that through their involvement, the program will grow to be integrated into park management and relevant to resource-related decisions. Thanks also to former board members John Lujan, Kate Cannon, and Bill Pierce.

Thanks to the SCPN Science Advisory Committee (Craig Allen, Jim Gosz, Dave Lime, Barry Noon, Jack Schmidt and Tom Sisk) for their excellent advice. Thanks also to former Science Advisory Committee member Charles Van Riper III, a long-time advocate for science in parks.

Thanks to Thom O'Dell, Angie Evenden, Steve Garman, and the staff of the Northern Colorado Plateau Network (NCPN) for 'going first'. Collaboration between the two Colorado Plateau networks will strengthen our monitoring programs and provide a broader understanding of the condition of Colorado Plateau ecosystems. Thanks also to Jayne Belnap, USGS, Southwest Biological Science Center, for including SCPN in prototype monitoring efforts.

We thank Northern Arizona University for hosting the SCPN. Thanks especially to Rod Parnell, Director, CP-CESU, and Gary Nabhan, Director, Center for Sustainable Environments, and their staffs for facilitating our interactions with the university and making us feel at home.

Thanks to Bruce Bingham, Intermountain Region I&M Coordinator, for guiding IMR networks over the last few years. You have given us sound advice, facilitated our work, sought opportunities for collaboration, and provided an encouraging voice. Thanks also to IMR staff for administrative support.

And finally, we greatly appreciate the leadership provided by Steve Fancy, NPS National Monitoring Leader; Gary Williams, NPS Inventory & Monitoring Program Manager; and Abby Miller, former Deputy Associate Director for Natural Resources Stewardship and Science. Your determination and advocacy have made this program possible.

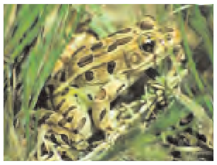


TABLE OF CONTENTS

LIST OF TABLES

LIST OF FIGURES

LIST OF APPENDICES

LIST OF SUPPORTING DOCUMENTS (CD ONLY)

LIST OF SUPPLEMENTS (CD ONLY)

CHAPTER 1

INTRODUCTION AND BACKGROUND

The Southern Colorado Plateau Network (SCPN) is one of 32 National Park Service inventory and monitoring networks developing Vital Signs Monitoring Plans to assess the condition of park ecosystems. The network approach facilitates collaboration, information sharing, and economies of scale in natural resource monitoring and will provide parks with a basic monitoring infrastructure that can be built upon in the future. This document describes the development process and implementation plan for Vital Signs Monitoring in the SCPN.

FIGURE 1-1. *Overview of Southern Colorado Plateau Network park unit locations.*

1.1 NETWORK OVERVIEW

The SCPN is composed of 19 parks located in northern Arizona, northwestern New Mexico, southwestern Colorado, and southern Utah (Figure 1-1). Most of the park units lie within the southern Colorado Plateau ecoregion, but a few are allied with the Arizona-New Mexico Mountains and Southern Rocky Mountains ecoregions. The parks range in size from 14 to more than 500,000 hectares (Table 1-1), with more than 750,000 hectares within the network designated or proposed as wilderness. While several park designations include language to protect the associated natural resources (Table 1-1), the majority of the SCPN parks were designated primarily to protect cultural resources. Three of the eighteen UNESCO World Heritage Sites in the United States are SCPN parks—Chaco Culture and Aztec Ruins as one unit, Grand Canyon, and Mesa Verde (UNESCO 2002).

Table 1-1. Establishment purpose and size of SCPN park units.

				ORIGINALLY ESTABLISHED FOR:	
PARK	ABBREVIATION	STATE	HECTARES	CULTURAL RESOURCES	NATURAL RESOURCES
Aztec Ruins National Monument	AZRU	NM	130	X	
Bandelier National Monument	BAND	NM	13,367	X	
Canyon De Chelly National Monument	CACH	AZ	37,448	X	
Chaco Culture National Historical Park	CHCU	NM	13,929	X	
El Malpais National Monument	ELMA	NM	47,352	X	X
El Morro National Monument	ELMO	NM	420	X	
Glen Canyon National Recreation Area	GLCA	AZ/UT	505,909	*	*
Grand Canyon National Park	GRCA	AZ	488,551	X	X
Hubbell Trading Post National Historic Site	HUTR	AZ	65	X	
Mesa Verde National Park	MEVE	CO	21,546	X	
Navajo National Monument	NAVA	AZ	243	X	
Petrified Forest National Park	PEFO	AZ	37,852**		X
Petroglyph National Monument	PETR	NM	2,923	X	
Rainbow Bridge National Monument	RABR	UT	66	X	X
Salinas Pueblo Missions National Monument	SAPU	NM	432	X	
Sunset Crater Volcano National Monument	SUCR	AZ	1,230		X
Walnut Canyon National Monument	WACA	AZ	1,465	X	X
Wupatki National Monument	WUPA	AZ	14,388	X	
Yucca House National Monument	YUHO	CO	13	X	

** Glen Canyon NRA was established to "…provide for public outdoor recreation use of Lake Powell…" and to "…preserve the scenic, scientific, and historic features…of the area".*

*** Recently approved boundary addition to Petrified Forest NP will bring the total area to 88,439 ha pending additional funding.*

1.2 PURPOSE OF NETWORK VITAL SIGNS MONITORING

1.2.1 *Justification and Role of Monitoring*

Knowing the condition of natural resources is fundamental to the National Park Service's ability to manage park resources. National Park managers across the country are confronted with increasingly complex and challenging issues that require broad-based understanding of the status and trends of park resources as a foundation for making decisions, working with other agencies, and communicating with the public to protect park natural systems and native species.

Monitoring data help to define the normal limits of natural variation in park resources and provide a basis for understanding observed changes and possible management connections. Understanding the dynamic nature of park ecosystems and the consequences of human activities is essential for natural resource management decision-making (Figure 1-2).

The intent of ecological monitoring is to track, through time, changes in the condition of particular resources or in the status of indicators of ecological integrity. This involves first establishing lengthy baselines in order to understand the normal limits of natural variation. Over the long term, monitoring data will describe trends in resource condition, provide a basis for judging what constitutes impairment, identify when corrective management actions may be required, and help evaluate their effectiveness. In order to achieve the

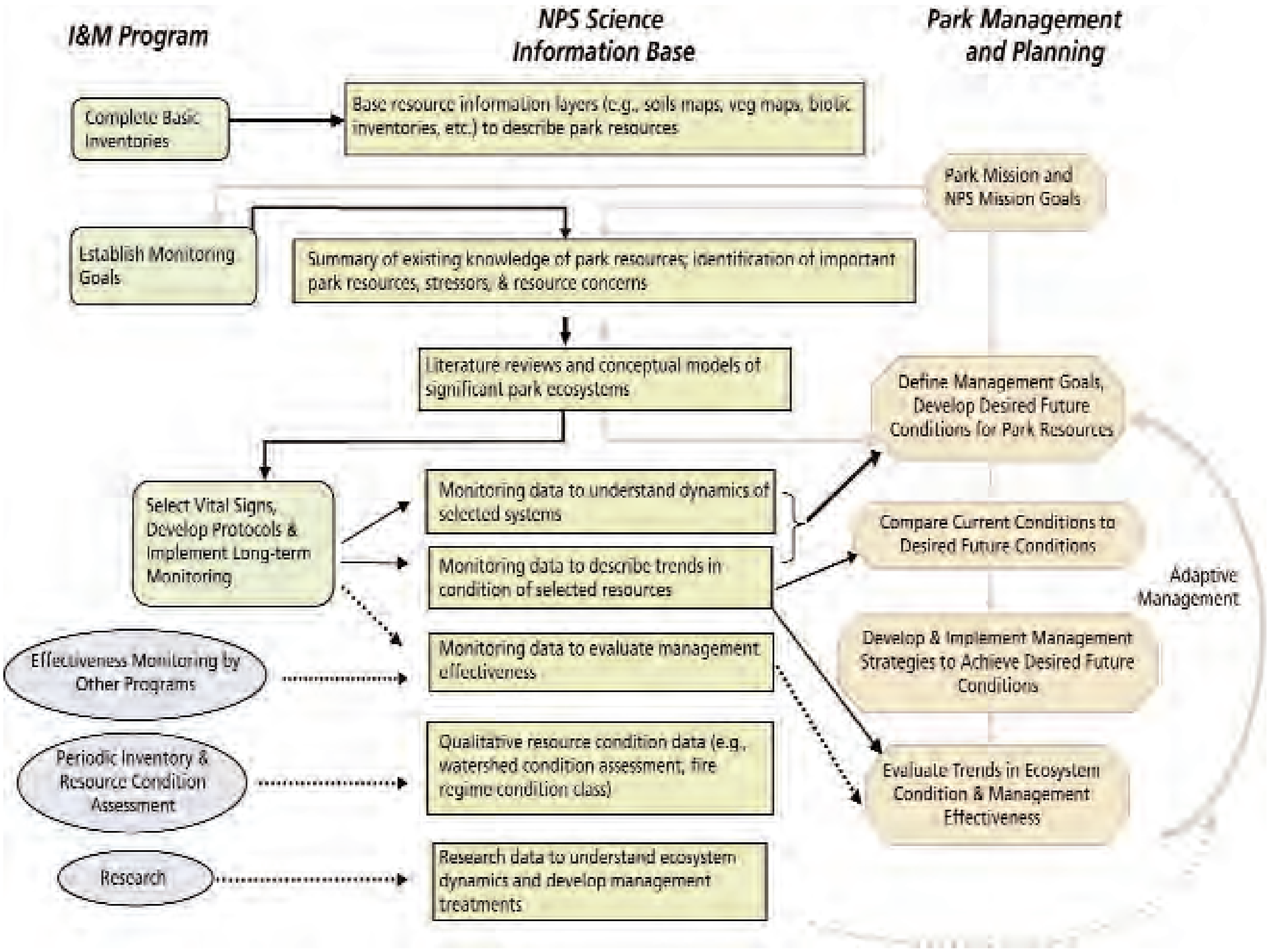


Figure 1-2. *Relationships between vital signs monitoring, the resulting science information base, and park planning/management. Several of the initial steps toward selecting vital signs, such as completing literature reviews and developing conceptual ecosystem models, are also useful for developing desired future conditions. Results from long-term monitoring will feed back into management at several stages within the planning/management process. Black boxes and arrows indicate the I&M Program; gray boxes and arrows indicate park planning/management; dotted arrows indicate information that will be supplied through multiple sources including the I&M Program.*

temporal replication necessary to measure trends through time, monitoring efforts are generally limited in scope (selected resources or indicators) and spatial extent (selected ecosystems or management areas).

"Vital signs" are selected physical, chemical, and biological elements or processes of park ecosystems that represent the overall health or condition of the park, known or hypothesized effects of stressors, or elements that have important human values. Vital signs monitoring is a key component in the Service's strategy to provide scientific data and information needed for management decision-making and education. Vital signs monitoring also contributes information needed to understand and to measure performance regarding the condition of watersheds, landscapes, and biological communities.

The Vital Signs Monitoring Program is critical to achieving Mission Goals IA and IB of the National Park Service (NPS) Strategic Plan for FY2005-FY2008:

> **Mission Goal Ia**
> Natural and cultural resources and associated values are protected, restored, and maintained in good condition and managed within their broader ecosystem and cultural context.
>
> **Mission Goal Ib**
> The National Park Service contributes to knowledge about natural and cultural resources and associated values; management decisions about resources and visitors are based on adequate scholarly and scientific information.

The monitoring program's emphasis on integration and coordination across programs and agencies, and the development of modern information systems and practices to build institutional knowledge and to make the resulting information more available and useful will have a major effect on the Service's ability to meet its mission and serve future generations. The monitoring program will also contribute to the DOI goals for management excellence by implementing practices that promote efficiency, collaboration among programs and agencies, and accountability.

1.2.2 LEGISLATION, POLICY AND GUIDANCE

National Park managers are directed by federal law and National Park Service policies and guidance to know the status and trends in the condition of natural resources under their stewardship in order to fulfill the NPS mission of leaving these resources "unimpaired for the enjoyment of future generations" (National Park Service Organic Act, 1916). Congress strengthened the National Park Service's protective function and provided language important to recent decisions about resource impairment when it amended the Organic Act in 1978 to state that "the protection, management, and administration of these areas shall be conducted in light of the high public value and integrity of the National Park System and shall not be exercised in derogation of the values and purposes for which these various areas have been established…".

More recently, the National Parks Omnibus Management Act of 1998 established the framework for fully integrating natural resource monitoring and other science activities into the management processes of the National Park System. Section 5934 of the Act requires the Secretary of the Interior to develop a program of "inventory and monitoring of National Park System resources to establish baseline information and to provide information on the long-term trends in the condition of National Park System resources". The Act charges the Secretary of the Interior to "assure the full and proper utilization of the results of scientific studies for park management decisions". A summary of federal legislation and policy related to the inventory and monitoring efforts can be found in Appendix A.

The 2001 NPS Management Policies updated previous policy and specifically directed that "natural systems in the National Park System, and the human influences upon them, will be monitored to detect change. The Service will use the results of monitoring and research to understand the detected change and to develop appropriate management actions". Along with national legislation, policy, and guidance, a park's enabling legislation provides justification and, in some cases, specific guidance for the direction and emphasis of resource management programs including inventory and monitoring (Appendix A).

The Government Performance and Results Act of 1993 (GPRA) mandates that all federal agencies use Performance Management (i.e., measurable, results-oriented, goal-driven planning and management) to accomplish their missions. To implement this management system, the Results Act requires all agencies to develop long-range Strategic Plans, Annual Performance Plans, and Annual Performance Reports. In addition to the national strategic goals, each park unit has a five-year plan that includes specific park GPRA goals (Table 1-2). Many of these park-specific goals are directly related to natural resource monitoring needs. The I&M program reports directly to two strategic planning goals (Goal 1b3A, Vital Signs Identification, and Goal 1b3B, Vital Signs Implementation), and provides

Table 1-2. GPRA goals for SCPN parks. Only natural resource-related goals are included.

GPRA GOAL	PARK-SPECIFIC ACTIVITIES	PARK UNIT(S)
Goal Ia0 Natural & Cultural resources and associated values are protected, restored and maintained in good condition and managed with their broader ecosystem	Implement and maintain corrective actions identified by environmental compliance audit	CHCU
	Paleontological localities identified	ELMA
Goal Ia0IA Restoring Formerly Developed Lands	Parklands disturbed by agriculture, erosion, disruption of natural regimes, or physical development are restored	AZRU, BAND, CHCU, ELMA, GLCA, GRCA, MEVE, RABR, SUCR, WACA, WUPA, YUHO
	Restoration of natural stream ecosystem	HUTR
Goal Ia0IB Containing Exotic Plant Species	All known exotic plants	AZRU, BAND, CACH, CHCU, ELMA, ELMO, GLCA, GRCA, HUTR, MEVE, PEFO, RABR, SAPU, SUCR, WACA, WUPA, YUHO
Goal Ia01C Land Health: Wetlands	Inventory wetland areas and identify desired conditions within park	CACH, ELMA, GLCA, GRCA, HUTR, MEVE, PEFO, WACA, WUPA, YUHO
Goal Ia01D Land Health: Riparian Areas	Inventory riparian areas and identify desired conditions within park	AZRU, BAND, CACH, CHCU, ELMA, GLCA, GRCA, HUTR, MEVE, NAVA, PEFO, RABR, WACA, WUPA
Goal Ia01E Land Health: Upland Areas	Inventory upland areas and identify desired conditions within park	ALL PARKS
Goal Ia01G Land Health: Mined Land	Lands disturbed by mineral extraction planned for mitigation	ELMA, GRCA, SAPU, WUPA
Goal Ia2 Managing T&E Species	All T&E species	AZRU, BAND, CACH, ELMA, GLCA, GRCA, MEVE, RABR, NAVA, SUCR, WACA, WUPA, YUHO
Goal Ia2B Species of Special Concern	All identified species	AZRU, CACH, CHCU, ELMA, ELMO, GLCA, GRCA, MEVE, PETR, RABR, SUCR, WACA, WUPA, YUHO
	Peregrine falcons	BAND
Goal 1a2C Invasive animal species	Reduction of feral and invasive animals and insects	CACH, GLCA, GRCA, MEVE, YUHO
Goal Ia3 Air Quality in all Measuring Parks	Stable or improved	BAND, GRCA, MEVE, PEFO
Goal Ia4 Surface Water Quality in Parks Rivers/Streams	Unimpaired in a % of park	AZRU, BAND, CACH, CHCU, ELMA, GLCA, GRCA, HUTR, MEVE, NAVA, PEFO, RABR, SAPU, SUCR, WACA, WUPA, YUHO
Goal Ia4b Surface Water Quality in Parks Dams/Reservoirs	Unimpaired in a % of park	CHCU, GLCA, GRCA
Goal Ia4c Water Quantity: Protect and Restore	Monitoring water quantity in park	CHCU, GRCA, HUTR, MEVE, SUCR, WACA, WUPA
Goal Ia9A Paleontological Localities	Maintain in good condition	GLCA, GRCA, PEFO, RABR, YUHO
Goal Ia10 Wilderness Character	Designated wilderness areas will meet wilderness character objectives	BAND, ELMA, GLCA, GRCA, MEVE, PEFO
Goal Ib1 Resource Knowledge	Completion of natural resource inventory datasets	BAND, CHCU, ELMA, ELMO, GLCA, GRCA, HUTR, MEVE, PEFO, PETR, RABR, SUCR, WACA, WUPA, YUHO
Goal Ib3 Vital Signs Identified	Vital signs identified for natural resource monitoring	ALL PARKS
Goal Ib3b Vital Signs Monitoring Implemented	Implementation of vital signs monitoring	ALL PARKS EXCEPT CACH
Goal Ib5 Wilderness Plans	Creation of approved wilderness and backcountry management plan	BAND, ELMA, GLCA, GRCA, MEVE, PEFO
Goal IIb1 Visitor Understanding and Appreciation	Visitors understand significance of park	ALL PARKS EXCEPT YUHO

data and information systems needed to report to several other Department of Interior (DOI) goals. In FY2004, land health goals relating to the condition of wetlands, riparian areas, upland areas, marine and coastal areas, and mined lands were added to the national strategic goals. Vital signs monitoring of selected resources, in combination with resource assessments based on the best available scientific information, will be used to report to these goals.

1.3 MONITORING GOALS AND VITAL SIGNS SELECTION PROCESS

1.3.1 *Introduction*

Designing a long-term ecological monitoring program to meet park needs requires consideration of diverse perspectives on the value and condition of park natural resources and on potential threats to their continued preservation. Park managers need to know the status and trends associated with key resources, understand effectiveness of management actions, and be given early warning of impending resource threats. They also realize that many resource concerns can only be addressed through cooperative action with park neighbors, local communities, and other land management agencies. Timely access to credible, relevant data is key to successfully working outside of park boundaries. Scientists may value parks for research and as relatively pristine reference sites that are useful as points of comparison to more altered sites. Finally, park visitors bring a wide range of expectations and values that challenge park managers to simultaneously meet varied recreational needs while preserving opportunities for viewing wildlife, exploring biodiversity, experiencing solitude, or journeying into wilderness. Each of these groups has a role to play in the effective stewardship of park natural resources. Consequently, their perspectives are important in defining the goals, objectives, and long-term vision for ecological monitoring.

While setting monitoring goals and objectives is dependent upon a consideration of environmental values, the process of identifying cost-efficient and reliable measures to meet stated objectives is a scientific exercise (Barber 1994, Harwell et al. 1999; Figure 1-3). In fact, inadequate grounding in ecological theory is often cited as a reason for failure of past environmental monitoring programs (Noon et al. 1999).

We anticipate that the process of developing a monitoring program will be iterative with successive rounds of setting and prioritizing objectives, defining relevant ecosystem attributes, modeling relationships between resources and stressors, and identifying appropriate measures. We are seeking assistance from the scientific community to develop a firm ecological foundation for monitoring and to identify relevant and efficient monitoring measures. A dialogue between park managers, agency scientists, and the wider scientific community is critical to the success of this endeavor. It is the role of park managers and agency scientists to create clearly stated monitoring goals and objectives that reflect both the environmental values underlying the NPS mission and our more proximate resource management concerns.

1.3.2 *Vital Signs Monitoring Program Goals*

The goals and objectives for monitoring that we define frame our expectations and drive subsequent steps in the conceptual design and protocol development process. Ultimately, monitoring data are intended to detect long-term environmental change, provide insights into the ecological consequences of change, and help decision-makers determine if observed change indicates that a correction to management practices is needed (Noon et al. 1999).

Servicewide Monitoring Goals

The Servicewide I & M Program has developed the following long-term goals to comply with legal requirements, fully implement NPS policy, and provide park managers with the data they need to understand and manage park resources:

1. Determine status and trends in selected indicators of park ecosystem conditions allowing managers to make better-informed decisions and work more effectively with other agencies and individuals for the benefit of park resources.

2. Provide early warning of abnormal conditions of selected resources to help develop effective mitigation measures and reduce costs of management.

3. Provide data that clarify the dynamic nature and condition of park ecosystems and provide reference points for comparisons with other altered environments.

4. Provide data to meet certain legal and Congressional mandates related to natural resource protection and visitor enjoyment.

5. Provide a means of measuring progress towards performance goals.

By adopting the Servicewide monitoring goals, certain aspects of the SCPN program scope and direction become apparent. The program will include retrospective or effects-oriented monitoring to detect changes in the status or condition of selected resources, predictive or stress-oriented monitoring to meet certain legal mandates (e.g., Clean Water Act), and effectiveness monitoring to measure progress toward meeting performance goals (National Research Council 1995, Noon et al. 1999). The Servicewide goals also acknowledge the importance of seeking an understanding of inherent ecosystem variability in order to interpret human-caused change and recognize the potential role of NPS ecosystems as reference sites for more impaired systems. Given the long history of human use of Colorado Plateau landscapes, the lingering effects of past land use on current resource conditions, the paucity of long-term monitoring data in SCPN parks, and the strong role of climate as a driver of ecosystem dynamics, the SCPN will emphasize goals 1 and 3 in developing Vital Signs monitoring.

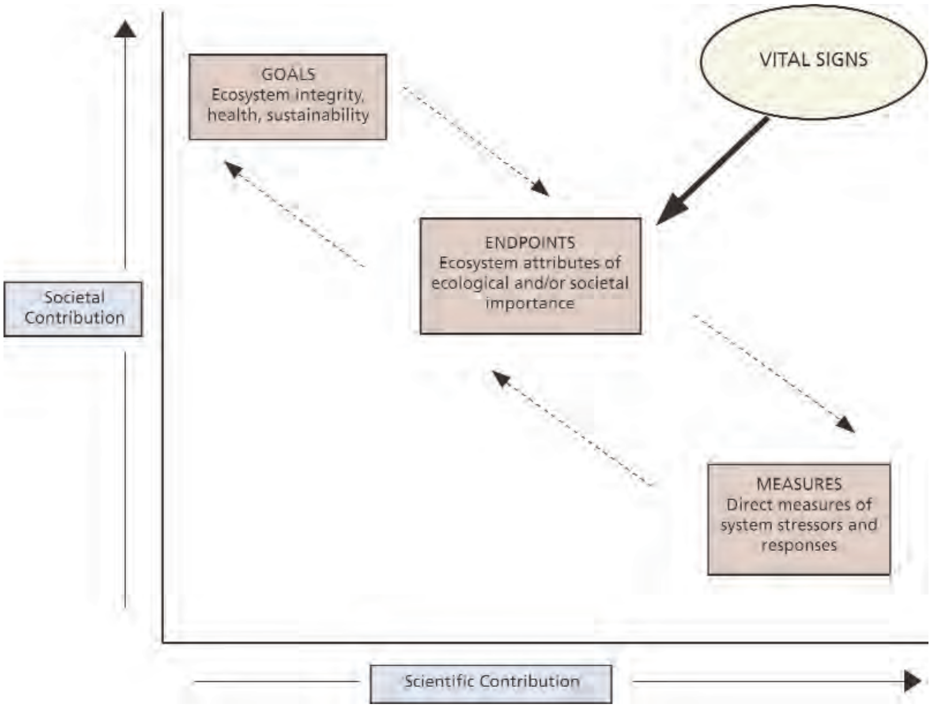


FIGURE 1-3. *Relationships among societal goals, endpoints, and scientific measures in ecological assessment and monitoring (modified from Harwell et al. 1999).*

1.3.3 *Ecological and Societal Goals for Monitoring*

The Servicewide goals described above begin to define the scope of the monitoring program and its potential role within the larger realm of natural resource management activities. Together they represent the network's program goals. A second, but perhaps equally important step is to define ecological and societal goals for monitoring (Barber 1994, Harwell et al. 1999, Gentile et al. 2001).

Assessment of Ecological Integrity

The concept of ecological integrity provides an appropriate foundation for assessing the state of ecological systems (Karr 1991, 1996, De Leo and Levin 1997, Noon 2003). A system with integrity may be defined as having the capacity to support and maintain a balanced, integrated, and adaptive community of organisms having the full range of biotic components (genes, species, assemblages) and processes (mutation, demography, biotic interactions, energetics, nutrient cycling) expected from natural ecosystems of the region (Karr and Dudley 1981, Karr 1991, 1996). An ecosystem approach requires full consideration of the geophysical template that supports the biota. Thus, abiotic components (e.g., soil resources) and processes (e.g., hydrology) of ecosystems also are encompassed within our definition of ecosystem integrity. Our use of the concept of ecological integrity as an ecological goal is also consistent with the draft DOI strategic planning goals of 'improving the health of watersheds, landscapes and marine resources' and 'sustaining biological communities' (U.S. Department of Interior 2003).

The SCPN has adopted monitoring to assess ecological integrity as the overarching theme of our long-term monitoring efforts. We have adapted a suite of ecosystem characteristics developed by Harwell and others (1999) as a means to link the ecological goal of restoring and maintaining ecosystem integrity to structural and functional ecosystem attributes. Most of these characteristics also relate directly to specific park management objectives (e.g., restoring disturbed lands, controlling invasive non-native species, maintaining sustainable populations of at-risk species; Table 1-3). By identifying ecosystem attributes during the development of goals and objectives, we explicitly acknowledge that their selection reflects both ecological importance and societal value (Figure 1-3). A synthetic consideration of these characteristics will provide an overall assessment of the condition of park resources.

Table 1-3. Management objectives relating to ecosystem integrity and associated ecosystem characteristics.

MANAGEMENT OBJECTIVE	RELATED ECOSYSTEM CHARACTERISTIC
Provide the spatial extent, mosaic landscape pattern, and connectivity required to support the natural diversity of ecosystems and species	**System Dimensions** Landscape pattern and land cover type
Protect soil resources and restore soil quality of disturbed lands	**Upland Soil, Water and Nutrient Dynamics** Upland soil stability and hydrologic function
Restore or maintain hydrologic function and protect ground and surface water quality and quantity	**Stream Hydrology and Geomorphology**
Reduce pollution in park water bodies and protect water quality of pristine waters	**Water Quality**
Provide for sustainable populations and communities of native species Restore the structure, native species composition, and natural processes of disturbed lands Reduce the spatial extent and abundance of established invasive non-native species and prevent new establishment	**Biotic Integrity** Status of predominant plant communities Status of at-risk species or communities Status of endemic species or unique Colorado Plateau communities Status of focal species or communities
Restore fire-adapted systems	**Disturbance Regimes** Fire regimes and their disruption Extreme climatic events Insect/disease outbreaks in forests and woodlands
Understand the role of extreme climatic events and climate cycles in driving ecosystem processes	**Atmospheric and Climate Conditions** Climatic conditions Air quality

Assessment of Aesthetic Qualities Relating to Wildland Values

Over 750,000 hectares within SCPN parks are designated or proposed as wilderness. Dark night skies, a hallmark of southwestern landscapes, can still be found in many SCPN units. Predominantly natural soundscapes still occur but are becoming rare. SCPN parks have identified qualities relating to human experience of wildlands as important park resources. While qualities such as natural quiet and dark night skies may also be linked to ecological integrity, they are considered here because of their societal value. Monitoring to support wildland values is the second important theme of the SCPN monitoring program.

1.3.4 *Network Monitoring in Relation to Other Efforts*

Network Approach

Spreading available funding for vital signs monitoring over all park units with significant natural resources would severely limit the ability of parks to monitor more than a few indicators. A key efficiency of the network approach is identification and monitoring of a core set of vital signs across a group of parks. In addition to increased efficiency, applying standard monitoring approaches across an ecoregion may also result in greater potential for comparison and explanatory potential in the resulting datasets. NPS adopted the strategic approach of encouraging networks and parks to seek partnerships with federal, tribal and state agencies, and adjacent landowners to leverage monitoring funding. In an optimal situation, network monitoring would form the middle tier of an integrated monitoring framework, linking national and regional monitoring programs to park-specific needs and monitoring efforts.

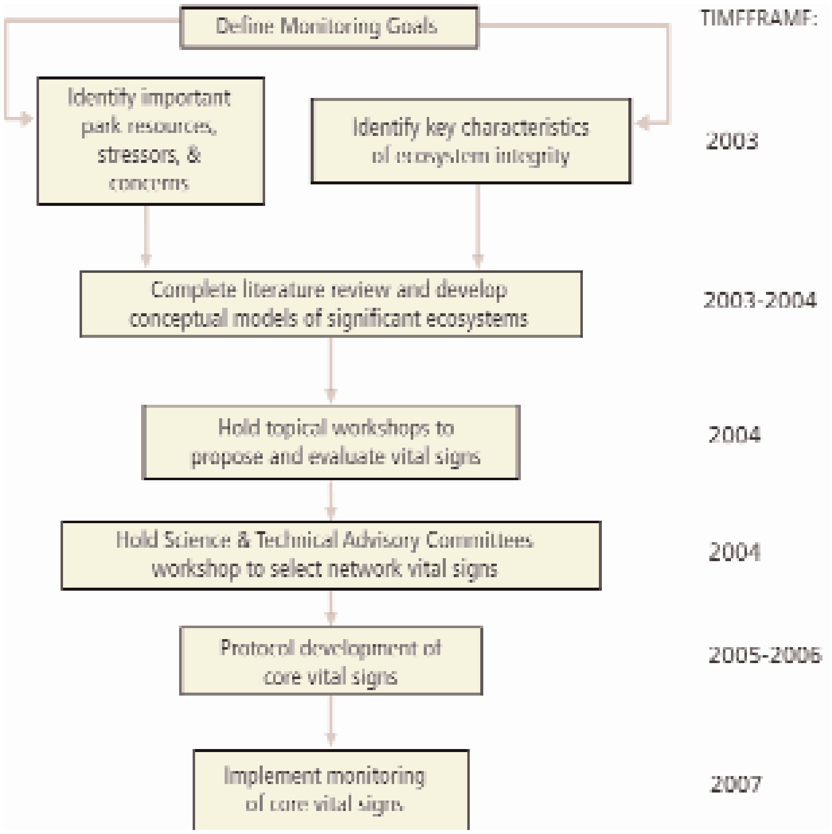


Figure 1-4. *Flow-chart of SCPN workplan to select and monitor vital signs.*

SCPN and NCPN collaboration to monitor park ecosystems across the Colorado Plateau

Parks across the Colorado Plateau have a history of working together on natural resource science and stewardship. Due to the fact that there are 35 parks on the plateau, a decision was made to divide the Colorado Plateau into two networks: the Northern Colorado Plateau Network (NCPN) and the SCPN.

Parks within the two networks share many resource concerns and issues and have established similar monitoring priorities. In FY2003, the NCPN and SCPN Technical Advisory Committees decided that the two networks would work collaboratively toward developing protocols to meet common monitoring needs. This alignment is fully supported and preferred by the Colorado Plateau Natural Resources Advisory Team, which advises managers on the Colorado Plateau on natural resources coordination, and by the Colorado Plateau-Cooperative Ecosystem Studies Unit Research Coordinator. In FY2004 the SCPN and NCPN began developing common workplans and coordinating protocol development efforts.

1.3.5 *Vital Signs Selection Process*

Identification and Selection of Network Vital Signs

The general process we used to select vital signs is summarized in Figure 1-4. In 2003, the purpose and scope of the monitoring program was defined, the existing information base was reviewed, and the most important park resources, resource concerns, and stressors were described using the resource/issues database (Support Document A). We also identified key characteristics of ecosystem integrity in a top-down approach. We first identified significant ecosystems, then reviewed the scientific literature, developed the ecological context for park resources, and evaluated the rarity and vulnerability of particular ecosystems. During 2003 and 2004, we solicited advice from the scientific community concerning key ecosystem attributes within particular systems. We also worked collaboratively with USGS and university scientists and the NCPN to develop conceptual models for four major Colorado Plateau ecosystems. These initial steps were essential in developing a preliminary list of vital signs, some of which applied broadly across ecosystems, while others applied to particular ecosystems or resource-stressor relationships.

The most difficult phase in vital signs selection involved evaluating and prioritizing among potential vital signs. During the winter and spring of 2004, we held a series of seven topical workshops to identify and evaluate candidate vital signs (Appendix G). Each workshop was undertaken with similar objectives and used consistent techniques and established evaluation criteria. The workshops were attended by more than 65 experts from NPS, cooperating agencies, private organizations, and the academic community. In May of 2004, a two-day selection workshop was held to review the topical workshop results and determine the core and secondary network vital signs. This workshop was attended by members of the SCPN Science Advisory Committee, Technical Advisory Committee, Board of Directors and SCPN staff. See Chapter 3 for more detail.

1.3.6 *Integration of Air and Water Quality Monitoring*

In addition to developing a unique set of vital signs, I&M networks are coordinating with the Air and Water Resources Divisions of the National Park Service to integrate existing and planned air and water quality monitoring with the broader vital signs monitoring program. The Air and Water Resources Divisions will provide guidance with respect to monitoring protocols in order to standardize procedures nationwide. The following sections provide a brief summary of air and water quality monitoring in SCPN park units. Detailed descriptions of these programs can be found in Appendices B and C.

Air Quality Monitoring

The primary purpose of the Clean Air Act is to provide ambient air quality standards that protect human health. Secondary standards were also set to protect the "national welfare," which is broadly defined to include parks and natural areas. Amendments to the Clean Air Act in 1977 added the "prevention of significant deterioration" (PSD) section, which charges federal land management agencies "to preserve, protect, and enhance the air quality in national parks, national wilderness areas, national monuments, national seashores, and other areas of special national or regional natural, recreational, scenic, or historic value" (42 U.S.C. Sec. 7470).

Four SCPN park units (BAND, GRCA, MEVE, and PEFO) are rated as Class I under the Clean Air Act (CAA) of 1970 as amended in 1990. Class I designations apply to national parks, national wilderness areas, and national monuments that are granted special air quality protection under section 162 (a) of the Act. Congress designated all other "clean" air regions of the country as Class II areas. The majority of air quality monitoring in the SCPN network occurs in the four Class I parks (Table 1-4). Several Class II areas have also had limited visibility and ozone monitoring in the past.

Visibility has been monitored as part of the Interagency Monitoring of Protected Visual Environments (IMPROVE) network since 1986. Every IMPROVE site deploys aerosol samplers to measure fine aerosols and particulate matter. Light extinction and light scattering are measured at select sites, and automatic camera systems are also deployed.

Other air quality parameters monitored as part of nationwide efforts include: deposition of nitrogen and sulfur compounds in rain and snow (wet deposition) as part of the National Atmospheric Deposition Program/National Trends Network (NADP/NTN), deposition of nitrogen and sulfur compounds in dryfall (dry deposition) as part of the Clean Air Status and Trends Network (CASTnet), ozone as part of the NPS Gaseous Pollutant Monitoring Network

Table 1-4. Current and past air quality monitoring in SCPN parks.

Current monitoring programs are indicated by the letter C; past monitoring programs by the letter P. Class I park names are in bold. A database of current and past air quality monitoring can be found at http://www2.nature.nps.gov/air/monitoring/MonHist/index.cfm.

SCPN PARK UNIT	IMPROVE (VISIBILITY)	OTHER VISIBILITY	WET DEPOSITION	DRY DEPOSITION	OZONE	MERCURY
BAND	C	P	C	C	P	
CHCU	P	P		P	P	
FLAG (SUCR, WACA, WUPA)		P				
GLCA		P				
GRCA	C	C	C	C	C	
MEVE	C	P	C	C	C	C
NAVA		P				
PEFO	C	P	C	C	C	

(GPMN), and mercury deposition as part of the National Atmospheric Deposition Program/Mercury Deposition Network (NADP/MDN).

Water Quality Monitoring

The NPS Natural Resource Challenge (NRC) provides funding for water quality monitoring within NPS units. The purpose is to track the attainment of the Service's long-term water quality strategic goal of significantly reducing pollution in park water bodies. Specifically, the goal was for 85% of park units to have unimpaired water quality by September 30, 2005. The NPS is also committed to preserving existing pristine water quality in parks, including waters classified as Outstanding National Resource Waters (ONRW's) or state-equivalent listed waters. As part of this initiative, the NPS Water Resources Division is providing each network with funds to conduct water resource monitoring and assist in achieving several NPS objectives:

- Protection of designated uses which involve 303(d)-listed waters, Outstanding Natural Resource Waters, or other designated waterbodies under provisions of the Clean Water Act.
- Documentation of water quality parameters that are vulnerable to alteration from various sources of contamination or land use practices.
- Establishment of water quality parameters useful for indicating ecosystem integrity of particular water resources.
- Establishment of baseline conditions.

The selection of water quality vital signs and implementation of water resource monitoring for SCPN parks is being fully integrated into the three-phase network planning process. In FY2003, SCPN water quality monitoring efforts included: partnering with USGS/WRD to synthesize electronically available water quality data for SCPN parks and completing water resource scoping and data mining in all SCPN parks to identify monitoring needs (Appendix C). In FY2004, the network continued funding of the USGS/WRD water quality data synthesis (to be completed in FY2005). NPS/WRD provided the USGS/WRD additional funding to conduct Level 1 baseline water-quality inventories of 57 key water bodies in 13 SCPN units during CY05. Preliminary analysis of data available through the water quality data synthesis and the Level 1 water quality inventory indicate that water quality conditions exceeding established USEPA and State standards exist for various constituents at many SCPN parks. These projects, in conjunction with existing information sources, are providing a sound basis for identifying and prioritizing long-term water quality monitoring needs.

Table 1-5. Impaired waters included on Section 303(d) list[1].

NAME OF WATERBODY	DESCRIPTION	STATE	PARK UNIT	EXCEEDENCES
Animas River	From Estes Arroyo to the NM-CO border	NM	AZRU	Temperature
Capulin Creek	From the mouth on the Rio Grande to the headwaters	NM	BAND	Benthic/macroinvertebrate bioassessment and sedimentation
Rito de los Frijoles	Rio Grande to headwaters	NM	BAND	DDT, Fecal coliform, temperature, and turbidity
Colorado River	Parashant Canyon to Diamond Creek	AZ	GRCA	Selenium and suspended sediments
Paria River	Utah border to Colorado River	AZ	GLCA	Suspended sediments and possibly turbidity

[1] *Sources are 2004 Integrated 305(b) Assessment and 303(d) Listing Report for Arizona and 2004-2006 State of New Mexico Integrated Clean Water Act 303(d)/305(b) Report Water Quality and Water Pollution Control in New Mexico.*

The first priorities for water quality monitoring within SCPN parks are 303(d)-listed waters (Table 1-5) and waters that are vulnerable to alteration from various sources of contamination and/or land use practices. While there are currently no designated Outstanding Natural Resource Waters within SCPN parks, monitoring to support the identification of relatively pristine waters is a secondary priority.

Ideally, the choice of vital signs for our network will reflect the unifying characteristics of network parks as well as those features and processes endemic to Southern Colorado Plateau Network park units. In the next sections, we present the regional ecological context shared by SCPN park units as well as brief descriptions of important resources and concerns identified by individual park managers. These descriptions will provide the backdrop for the presentation of SCPN vital signs.

1.4 ECOLOGICAL CONTEXT

SCPN parks encompass almost 1.2 million hectares of land area, span 374 kilometers from east to west, 218 kilometers from north to south, and cover 2.7 kilometers of vertical relief. In this section we introduce key physical and biotic qualities that characterize the Colorado Plateau

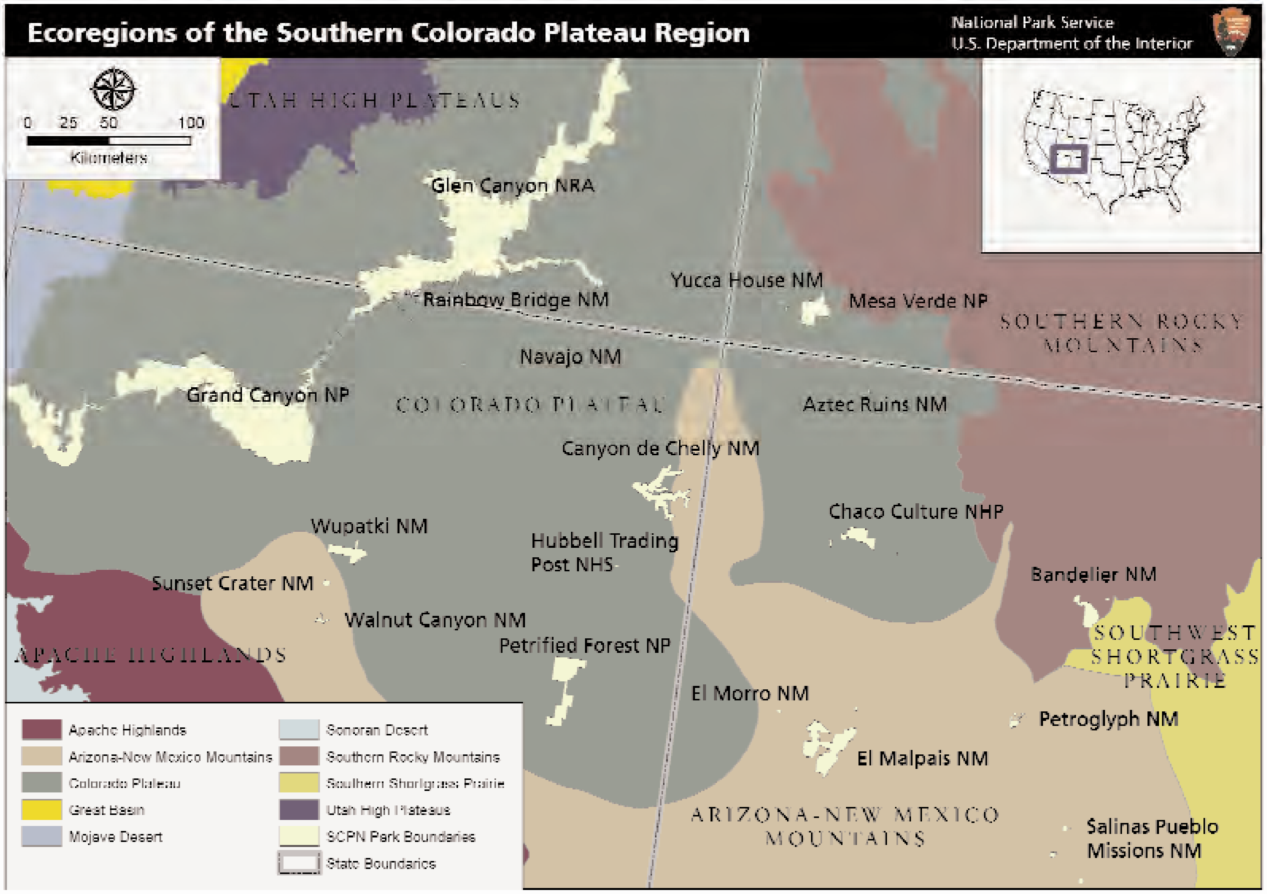


Figure 1-5. *Map of SCPN park units and corresponding ecoregion subunits.*

and may serve as drivers, state factors, and/or interactive controls of Colorado Plateau ecosystems. Describing the range of physical and biotic variation across the network sets the stage for conceptual models described in Chapter 2.

1.4.1 *Landscape Classification*

In recent years, the concept of ecoregions has emerged as the most useful land-classification system for supporting sustainable resource management practices (Bailey 1995, 1998). The Nature Conservancy (TNC) has developed a classification of ecological systems which builds on the regionalization, classification, and mapping system of the National Hierarchical Framework of Terrestrial Ecological Units (ECOMAP 1993) while making the ecoregional boundaries more closely tied to vegetation cover types defined by the U.S. National Vegetation Classification (Grossman et al. 1998), physiographic units, and ecological processes (Groves et al. 2000, Comer et al. 2003). The ecological hierarchy consists of Domains, Divisions, Provinces, and Sections (in decreasing spatial scale) described by similarities in 1) potential natural communities, 2) soils, 3) hydrological function, 4) topography and landforms, 5) lithology, 6) climate, 7) air quality, and 8) ecological processes (Cleland et al. 1997). Park units within the SCPN belong to three provinces within the Dry Domain: Colorado Plateau, Arizona-New Mexico Mountains, and the Southern Rocky Mountains (Figure 1-5).

The non-profit organization NatureServe in conjunction with state natural heritage programs has adopted the concept of ecological systems as a basis for finer scale landscape classifications. "Ecological systems represent recurring groups of biological communities that are found in similar physical environments and are influenced by similar dynamic ecological processes, such as fire or flooding," (Comer et al. 2003). The goal of defining ecological systems was to complement the National Vegetation Classification, while creating finer scale mapable units using a combination of plant communities, soils, environmental conditions, and ecological processes. A summary of potential ecological systems in the SCPN park units can be found in Table D1, Appendix D.

1.4.2 *Elevation*

Mountainous regions with wide altitudinal range and topographic complexity present a special case in landscape classification. Altitude affects climate in a manner similar to latitude and results in altitudinal zonation. SCPN park units have large topographic variability (Table D2, Appendix D). Due to the elevation gradient, vegetation communities in the SCPN range from lowland, sparsely vegetated deserts to transitional woodland mountain zones to sub-alpine vegetation (Betancourt 1990). This extreme variability is associated with discontinuous environmental gradients that present significant challenges to the design and implementation of field-based monitoring.

Summer monsoon thunderstorms provide an important source of precipitation.
PHOTO BY MARK WEISSINGER

1.4.3 *Climate*

Bailey (1995, 1998) describes climate as a prime controlling factor for ecosystem distribution. The Colorado Plateau region lies in a zone of arid-temperate climates characterized by periods of drought and irregular precipitation, relatively warm to hot growing seasons, and long winters with sustained periods of freezing temperatures (Hunt 1967). Much of the moisture from precipitation, at 10-25 cm per year in many SCPN locations (Montgomery and Harshbarger 1992), is lost through evaporation due to nearly vertical noontime solar position, clear skies, and dry, thin, high-elevation air (Durrenberger 1972).

A broad boundary that coincides with the mean northwestern extent of summer monsoonal precipitation patterns divides the Colorado Plateau into two climatic regions (Petersen 1994; Figure 1-6). Approximately two-thirds of the Plateau (including SCPN park units) lies southeast of this climatic boundary. The magnitude of the summer precipitation maximum generally weakens from southeast to northwest, and the northwestern one-third of the Plateau is dominated by winter precipitation (Figure 1-6). A shift between these two climatic regions may contribute to high inter-seasonal and inter-annual variability in precipitation in the SCPN region (Ehleringer et al. 1999). From November to March, the dominant weather patterns on the southern Plateau include precipitation from Pacific region storms. December and January tend to experience spatially-heterogeneous precipitation strongly influenced by elevation, while trends in February and March show an overall increase in precipitation on the Plateau. By May, drier conditions again prevail and last until late June when monsoonal circulation begins to gain strength (Mock 1996). Wet summer monsoons (characterized by longer periods of heavy rainfall) tend to follow dry winters and vice versa (Higgins et al. 1998).

The El Nino Southern Oscillation (ENSO) is a weak, seasonal warm, south-flowing current off the coast of Peru that occurs in a 4-7 year or multidecadal cycle and affects precipitation and climate on the southern Plateau (Wang 1995, Wang and Ropelewski 1995, Trenberth 1997, Mantua and Hare 2002). ENSO tends to bring wet winters and increased stream flow to the SCPN area through southerly displacement of storm tracks. Strong ENSO events will increase the variability of precipitation in the warm season and the frequency of precipitation in the cool-season (Trenberth 1997), and these events can greatly affect surface erosion, soil moisture, perennial stream flow, and groundwater recharge (Hereford et al. 2002). Opposite ENSO cycles are La Niña events typified by normal to relatively low warm-season precipitation and drier than normal winters (Hereford et al. 2002). At irregular intervals (about every 3 years), usually between mid-August and October, a major tropical storm moves up the Colorado River Valley from off the Baja peninsula. These events are of considerable biological significance as they can produce high levels of precipitation from September to October, corresponding to the period

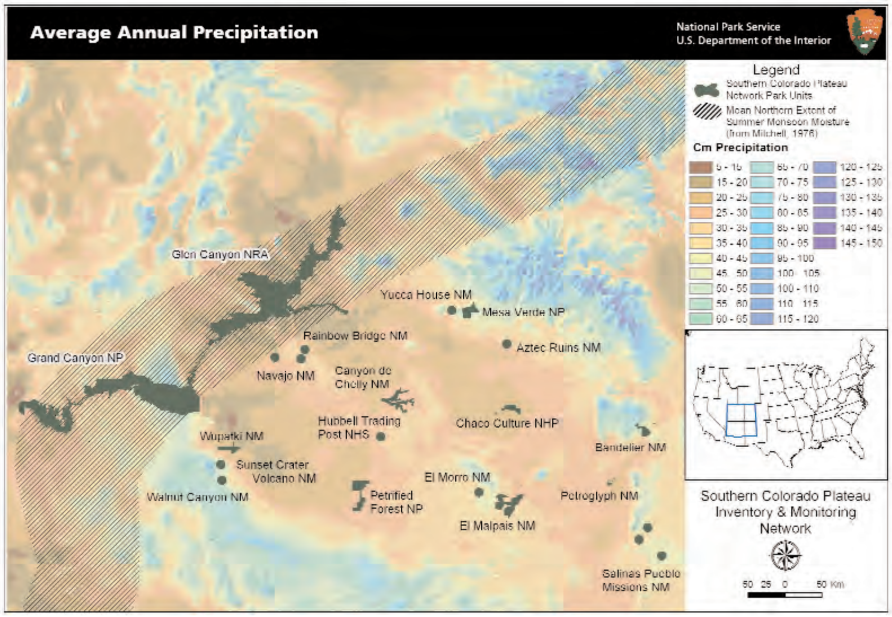


Figure 1-6. *Map of average annual precipitation for SCPN park units.*

when warm-season grasses tend to disperse seed (Spence 2001). While climate patterns on the Colorado Plateau are heterogeneous (Mock 1996), SCP weather stations reveal general patterns: 1) precipitation decreases from high elevations to low elevations, and 2) summer precipitation decreases from the southeastern portion of the Plateau to the northwest (Table D3 & Figure D1, Appendix D).

1.4.4 *Landforms and Geology*

Park units within the SCPN fall within three geologic provinces of the United States, the Colorado Plateau, Rocky Mountains, and Basin and Range (Thornbury 1965, Hunt 1967, 1974a); however, our discussion of geology focuses primarily on the most dominant province in the region, the Colorado Plateau.

The 388,000 square kilometer Plateau rises to elevations of approximately 1,525 meters near the western margins and climbs to heights in excess of 3,350 meters at the eastern boundaries (Ellwood 1996). In the west and southwest, the Plateau breaks off into escarpments that overlook the more broken and divided landscape of the Basin and Range geologic province, while its northern and eastern boundaries are bordered by the Rocky Mountains province (Durrenberger 1972). Precambrian metamorphic rocks form the geologic basement of the Plateau, and periodic flooding by Paleozoic seas deposited a sequence of sedimentary limestones, sandstones, and shales over the basement rock. Volcanic eruptions during the Mesozoic era covered parts of the Plateau with igneous material and volcanic ash. Miocene uplifting raised the region more than 2 kilometers. Geologic stresses associated with this period of uplift caused widespread faulting in the Basin and Range province but left the sedimentary formations of the Colorado Plateau relatively intact (Thornbury 1965). Sedimentary rocks forming the Plateau vary in age from the Precambrian to the Tertiary (Hunt 1974b, Ellwood 1996). Young (Tertiary) rocks are exposed in basins on the northeast side of the Plateau, whereas outcrops of older rocks are found along the southwestern rim (Durrenberger 1972).

The Plateau's episodic, slow uplifting resulted in the development of numerous structural features, such as basins, monoclines, upwarps and uplifts, fault blocks, salt structures, igneous domal uplifts, and intermediate structures (Hunt 1974a). Water-related erosion events have resulted in most of the depositional and topographical makeup of the modern Colorado Plateau (Ellwood 1996). As regional uplift occurred, streams cut through over- steepened rock strata, exposing geologic layers dating to the Pre-Cambrian Era (Crampton 1964, Hunt 1974b). Subsequent erosion and weathering of the region's resistant limestones and sandstones created scarps and steep-walled canyons. The badlands of the region, however, were created by rapid erosion of relatively soft shales (Ellwood 1996).

Soil types on the Colorado Plateau vary due to the influences of parent material, climate, biotic communities, and geomorphic processes of the region. Soil types range from badlands composed of marine shales, small areas of colluvium collected next to cliffs, sand dunes, loess-covered tablelands, and fine-textured alluvium along rivers and washes (West and Young 2000). Soils of the Plateau are predominantly alkaline, except in mountainous areas where greater precipitation rates and abundance of organic material results in acidic soils. In some places, the dominant pedogenic process is calcification, while salinization is dominant on poorly drained sites. Overall, the most commonly found soil orders in the Southern Colorado Plateau parks include Entisols, Aridisols, Mollisols, Alfisols, and Inceptisols.

1.4.5 *Hydrologic and Hydrogeologic Regimes*

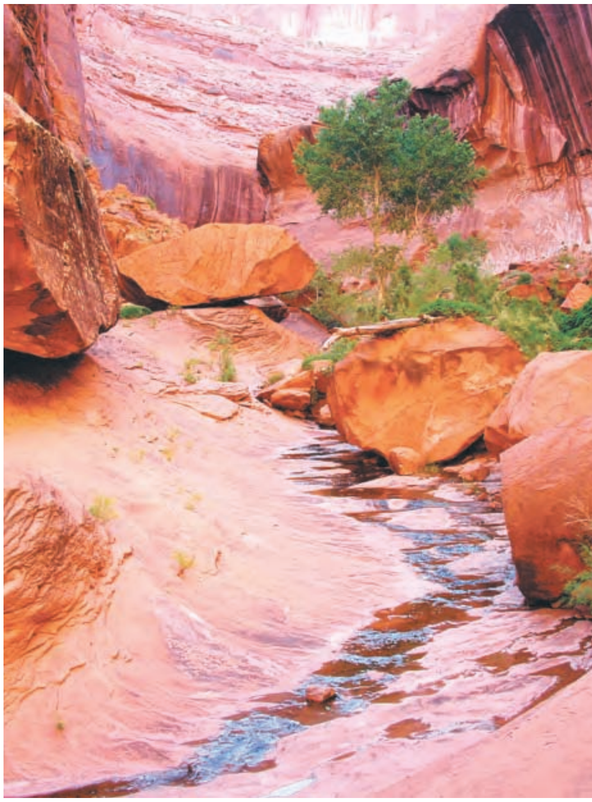
More than nine-tenths of surface water on the Plateau drains to the

Colorado River, which drops from the Rocky Mountains, dissects the Plateau, and exits at the Grand Canyon on its route to the Sea of Cortez. Major tributaries to the Colorado include the Green River (draining from the north), the San Juan River (draining from the east), and the Little Colorado River (draining from the southeast). Four SCPN parks are east of the Continental Divide, draining to the Rio Grande. Portions of the Colorado, San Juan, and Little Colorado Rivers, and the Rio Grande are located within or bordering various SCPN park units. Most of the smaller streams in SCPN parks, including those on volcanic formations, have intermittent and perennial sections, and flow rarely extends far from the foot of the mountains even when flooded. When crossing drier, lower elevations of the Plateau, perennial streams tend to lose a great deal of water to seepage through streambeds and evaporation (Hunt 1974b). Riparian areas provide important corridors for flora and fauna of the region (Benson and Darrow 1981).

Groundwater storage is limited and temporal in a variety of perched aquifers of the SCPN region, but is much greater in deep and extensive sandstone and limestone aquifer systems (Montgomery and Harshbarger 1992). Fractures and secondary openings in Paleozoic and volcanic rocks of the SCPN region, particularly faults, provide zones of large permeability allowing for lateral and vertical movement of water (Huntoon 1982, Montgomery and Harshbarger 1992, Flynn and Bills 2002). Mountain snowmelt and rainfall seeps into aquifers through sand and gravel near the edges of basins, under normally dry washes, and via sub-surface flow through fractures beneath mountains (Leake et al. 2000). Principal aquifers found in this region are the lower Tertiary Uinta-Animas, the Tertiary and upper Cretaceous Mesa Verde, the late Cretaceous to Triassic Dakota-Glen Canyon, the Permian Coconino-DeChelly, and the Mississippian and late Cambrian Redwall-Muav Limestone. Natural discharge from aquifers delivers water back to the surface via streams, springs, seeps, and other emergent wetlands (Cowardin et al. 1979) for use by the plants and animals of SCPN parks.

1.4.6 *Vegetation*

Evolution of flora and vegetation patterns in the SCPN region has been impacted by the climate change caused by the uplift of the plateau (Ruddiman and Kutzbach 1991, Adams and Comrie 1997) and by the great range of elevation (Daubenmire 1943). The extent of elevational displacement and distribution of vegetation types found in the region is due to a combination of climate, interactions between species, and parent geologic material. The Colorado Plateau region supports one of the highest levels of endemism in the U.S., with about 10% of the 3,000-3,500 plant



(top) Spring run-off flows through Chaco Wash, an intermittent stream supporting gallery cottonwood trees at Chaco Culture National Historical Park.
(above) Perennial flow supports a thin band of riparian vegetation in Stevens Canyon, Glen Canyon National Recreation Area.
PHOTOS BY STEPHEN MONROE, NPS

species estimated to be endemic (Shultz 1990). Many of these species are either federally listed or otherwise rare.

Vegetation on the Colorado Plateau consists mainly of open-woodlands of drought-adapted conifers on the high rims with extensive areas of xeric shrubs and grasses on the lower interior regions (Durrenberger 1972). At the highest elevations, significant communities of ponderosa pine, mixed conifer forests, and subalpine forests occur, especially at Grand Canyon National Park and Bandelier National Monument. Due to freezing temperatures in the winter, large succulents that characterize subtropical and warm-temperate regions are generally absent. The arid-humid boundary lies at a high elevation of 2,700 meters on the central portion of the Colorado Plateau (Spence 2001), although it is somewhat lower (ca. 2,500 meters) to the southwest on the Kaibab Plateau. Above this elevation, small areas of conifer forests and montane and subalpine meadows are found. A few small patches of alpine tundra occur on the tops of some of the higher peaks, although none occur in SCPN park units.

Portions of six floristic provinces occur in and adjacent to SCPN park units. These are the Colorado Plateau, Great Basin, southern Rocky Mountains, Sonoran, Chihuahuan, and Madrean provinces (McLaughlin 1989, McLaughlin 1992, Brown 1994). The majority of vegetation occurring in SCPN parks is characterized by Plateau assemblages. Other vegetative influences include Chihuahuan (ELMO, ELMA, and SAPU), southern Rocky Mountain (MEVE and BAND), and Madrean (WACA). Grand Canyon has a large Mojavean (or Sonoran, using McLaughlin's classification) element. Major studies discussing the flora and vegetation of this region include: Reveal (1979), Brown (1982), Axelrod and Raven (1985), McLaughlin (1986), Barbour and Billings (1988), McLaughlin (1989), Dick-Peddie and Hubbard (1977), and McLaughlin and Bowers (1999).

(top) A desert bighorn sheep (Ovis canadensis nelsoni) ewe and lamb scramble up a boulder at Grand Canyon National Park.
PHOTO BY MARK WEISSINGER

(above) The American pronghorn (Antilocapra americana) roams the grasslands of the Colorado Plateau.
NPS ARCHIVE

1.4.7 *Fauna*

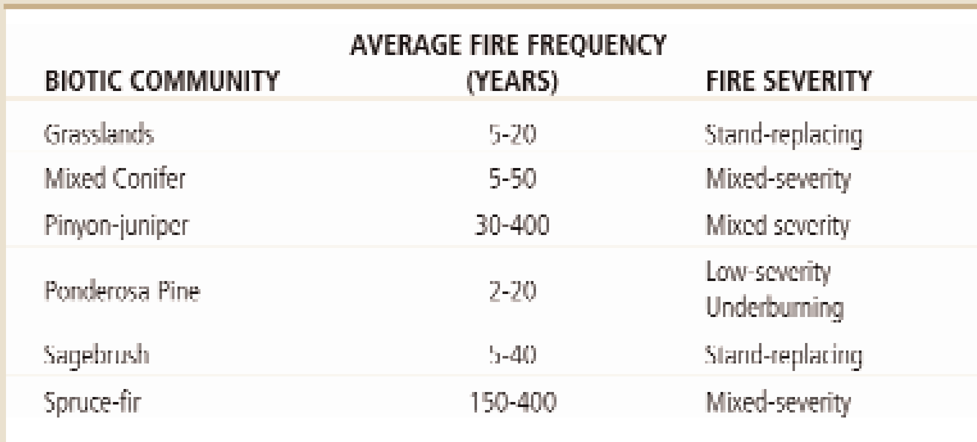
The vertebrate biota of the Colorado Plateau is in many ways impoverished compared to surrounding areas. Distribution of all vertebrate species in this arid region is limited by water availability and water-related vegetation diversity. Sixty-four percent of the Colorado River fish species are endemic (Bogan et al. 1998), and many of those are threatened or endangered. Riparian corridors are important migratory and breeding habitats for birds, many of which use this habitat exclusively (Knopf and Sampson 1994). Cooler, high elevation forests are also important refuges for several species of birds, small mammals (including the endemic Stephen's woodrat [*Neotoma stephensi relicta*]), and at least one endemic amphibian, the Jemez Mountains salamander (*Plethodon neomexicanus*). Populations of large ungulates and carnivores in mountain forests were once driven to low numbers by hunting and trapping. With the help of reintroductions, most of these species have made a comeback to the area. Grasslands and shrublands in the area are also home to a large number of reptiles (Drost and Deshler 1995), birds, and important keystone herbivores like the American pronghorn (*Antilocapra americana*) and the Gunnison's prairie dog (*Cynomys gunnisoni*).

In contrast to the vertebrate populations, invertebrates of the region have a relatively high level of endemism (Mac et al. 1998). Hydrophilic species dominate the federal T&E lists (Mac et al. 1998), and scarcity of water and sensitivity to contaminants seem to limit the distribution of crustaceans and mollusks to springs and undeveloped water systems (Arizona Game and Fish Department 2001). In addition, the southwest as a whole supports a high diversity of moths and butterflies (Powell 1995).

1.4.8 *Fire Regimes*

Except for climate, fire has probably had the largest single impact in shaping the ecology of the southern Colorado Plateau (Allen 2002, Grissino-Mayer et al. 2004). Prior to European settlement, fires would often burn for months and cover thousands of acres (Swetnam 1990, Swetnam and Baisan 1996). Ponderosa Pine forests burned every 2 to 30 years as low-intensity, area-wide fires. With greater moisture levels but heavier fuel loads, spruce-fir forests burned much less frequently but at high, stand-replacing intensity (Veblen et al. 1994, Grissino-Mayer et al. 1995). The Mesa Verde pinyon-juniper woodlands have historically experienced severe fire events that killed most aboveground vegetation, while other SCPN forests experienced frequent, low intensity, fires. Research by Weaver (1951), Cable (1975), Dieterich (1980, 1983), Grissino– Mayer et al. (1995), Moore et al. (1999), Floyd et al. (2000), Allen (2002), Allen et al. (2002), Fule et al. (1997, 2002), and Baker and Shinneman (2004) was used to establish a range of pre-settlement fire frequencies for southwestern communities (Table 1-6).

Table 1-6. Average pre-European fire frequencies in southwestern biotic communities.



BIOTIC COMMUNITY	AVERAGE FIRE FREQUENCY (YEARS)	FIRE SEVERITY
Grasslands	5-20	Stand-replacing
Mixed Conifer	5-50	Mixed-severity
Pinyon-juniper	30-400	Mixed severity
Ponderosa Pine	2-20	Low-severity Underburning
Sagebrush	5-40	Stand-replacing
Spruce-fir	150-400	Mixed-severity

Fire regimes (Table 1-6) changed dramatically with the coming of European and American settlers (Weaver 1951, Covington and Moore 1994a, Swetnam and Baisan 1996, Swetnam and Betancourt 1998, Romme et al. 2003). Livestock removed grassy fuels that carried frequent, surface fires; and roads and trails fragmented the continuity of forest fuels, contributing to further reductions in fire frequency and size (Covington and Moore 1994b). Fires that did break out were suppressed by settlers and fuels accumulated. By the early 1900s, fire exclusion began altering forest structure and fire regimes. Forests with historically frequent, low-intensity fires were those initially most affected (Arno and Ottmar 1994, Covington and Moore 1994a). Woodland, Ponderosa pine, and drier mixed conifer forests shifted from a fire regime of frequent, surface fires to stand-replacing, high-intensity fires. Fire had already been infrequent, but high-intensity in the spruce-fir forest, so suppression efforts there had minimal effect.

1.5 NATURAL RESOURCES, RESOURCE CONCERNS, AND ISSUES OF SCPN PARKS

1.5.1 *Review of Planning Documents and Management Interviews*

An essential step in the process of selecting vital signs for a network of 19 NPS units was to determine the most important priorities for monitoring at individual parks. Network staff used several sources of information to summarize the priority resources, stressors, and resource concerns for network parks: surveys of park staffs about stressors affecting park resources, review of park planning documents, and interviews of park superintendents (Support Document B). The information gathered through these sources was summarized in the park narratives (Appendix E).

The next step in the process was to consolidate and compare collected information to determine the commonalities among SCPN parks. A relational database was used to allow park resource managers to rank the importance of particular resources or issues for their parks (Support Document A). The database format allowed us to summarize significant natural resources and important resource concerns in several different ways. Most importantly, it allowed for network-wide comparison without loss of detail.

SCPN staff assigned preliminary scores based on the previously gathered information. To confirm and refine these scores, each park reviewed the scores and park-specific information in each category during an I&M Workshop held in Farmington, NM, April 1-3, 2003. The short summaries provided below capture the most important topics that emerged from the ranking process.

1.5.2 *Summary of Key Resources*

Surface Water Resources

Intermittent and ephemeral water sources include washes, runoff channels and arroyos, and other water sources such as tinajas, potholes, and water pockets (depressions in rock which collect and retain rainfall). Washes and arroyos in arid ecosystems can have relatively high sub-surface moisture levels (Ludwig and Whitford 1981) and support distinct vegetation communities from surrounding uplands (Krausman et al. 1985). These water sources are often characterized by high biological diversity and provide important pathways for species dispersal (Domingo et al. 2000).

Rain filled tinajas provide an important water source amidst the slickrock rims of Canyon de Chelly National Monument. PHOTO BY STEPHEN MONROE, NPS

Most primary water sources in SCPN parks are intermittent or ephemeral in nature (Appendix C). These sources typically flow only as a result of spring runoff or in response to rainfall events. Washes and arroyos occur in virtually all SCPN park units with varying degrees of intermittent or ephemeral flow, and some provide the only available sources of flowing water within each park. Potholes, catchments, and prehistoric impoundments are known to occur in CACH, ELMA, ELMO, GLCA, GRCA, MEVE, PEFO, SUCR, and WUPA.

Perennial streams and rivers are rare on the Colorado Plateau. Where they do occur, rivers and streams provide increased biodiversity, habitat for threatened and endangered species, and a reliable source of water. Major rivers or streams that flow through or adjacent to SCPN parks include the Colorado River (GRCA, GLCA), Animas River (AZRU), Rio Grande (BAND), Mancos River (MEVE), Little Colorado River (WUPA), and several other tributaries of the Colorado River which flow through GLCA and GRCA. Smaller perennial creeks also flow through BAND, CACH, NAVA, and RABR.

Seeps and springs support wetland and riparian habitats ranging from hanging gardens to cottonwood stands. Hanging gardens have been found to sustain many Colorado Plateau endemic plant species (Fowler et al. 1995). Wetland and riparian habitats in the southwest contribute to floral diversity and promote resident and migratory faunal diversity (Pase and Layser 1977). Springs are numerous in some SCPN park units and rare in others (Appendix C), and they provide important sources (sometimes the only perennial source) of water. Seeps are less well-known in SCPN parks, but are found in many parks, notably CHCU and WACA.

Tinajas are defined as large rock depressions associated with drainages or channels. Tinajas are differentiated from water pockets and potholes by their association with drainages, their ability to hold water year-round (except in extreme drought), and the presence of obligate phreatophytes (plants whose roots extend downward to the water table). Tinajas tend to sustain distinctive wetland communities (Spence and Henderson 1993). While no comprehensive survey of tinajas exists for the SCPN units, they are known to occur at GLCA and GRCA, and likely occur at CACH, CHCU, and NAVA.

Unique or Sensitive Habitats or Vegetation Communities

This category encompasses several habitats and vegetation types that are rare, supply high rates of biodiversity, support rare or endemic species, or are high quality examples of a regionally rare or at-risk community. Unique SCPN vegetation communities include, but are not necessarily limited to: wetland/riparian communities, high quality grasslands, cinder or lava flow communities, relict or old-growth forest communities, sagebrush shrublands, and shale, clay barren, and gypsum communities.

Dominant Vegetation Communities

This category includes those vegetation types that make up a large percentage of a park's area, thus having a major effect on wildlife species, fire regimes, soils, and ecosystem structure and function within a park. Based on preliminary data, Table D4, Appendix D estimates the percentage of park area occupied by each vegetation type. Dominant vegetation types in the SCPN region include pinyon-juniper woodlands, Ponderosa pine forests, sagebrush communities, saltbush shrublands, blackbrush shrublands, and shortgrass prairie.

Ecosystem Structure and Function

Ecosystem structure is the static aspects of an ecosystem, and ecosystem function can be thought of as the dynamic aspects of the ecosystem (Noy-Meir 1985). This category includes, but is not limited to, ecosystem characteristics such as nutrient cycling, productivity, succession, water relationships, natural disturbance, diversity of communities and habitats, and intact food chains (including top carnivores).

Specific examples of ecosystem integrity in SCPN parks include the absence of non-native amphibians, reptiles, and fishes from MEVE waterways; biological diversity that includes five of the seven life zones and three of the four deserts in North America at GRCA; and intact watershed systems at BAND.

Threatened and Endangered Species

Like all federal agencies, the National Park Service is required by the Endangered Species Act (ESA) to conserve endangered and threatened species and their critical habitats and to avoid any actions that might jeopardize their survival. The Park Service extends this responsibility to protecting federal candidate, state-listed, and state-candidate species. Based on information in the national NPS database NPSpecies and provided by park staff, 17 taxa with ESA status are considered to occur in SCPN parks (Table D5; Appendix D). There are 6 bird species, 4 fish species, 1 invertebrate species, and 6 vascular plant species.

Species and Communities of Special Interest

Faunal species and communities of special interest include species and communities that are locally rare, not federally or state listed, important contributors to ecosystems, possible indicators of ecosystem condition, and/or charismatic species. Most SCPN parks listed at least one faunal species or community of special interest (e.g., endemic small mammals, large mammals, neotropical migratory birds, amphibians, and invertebrates).

Floral species of special interest include plant species which are locally rare, endemic or of management concern, and not federally or state listed. At least one plant species of special interest occurs in 15 of the SCPN parks. Many of the floral species of concern in SCPN parks are

(top) Tuckup Canyon, Grand Canyon National Park. PHOTO BY STEPHEN MONROE, NPS
(above) Brilliant scarlet gilias bloom in a unique habitat of black volcanic cinders, Sunset Crater National Monument. PHOTO BY CHRIS LAUVER, NPS

(top) Wide unpolluted skies are a hallmark of SCPN parks, Petrified Forest National Park. PHOTO BY CHRIS LAUVER, NPS
(above) Biological soil crusts amid pinyon-juniper woodlands, El Morro National Monument. PHOTO BY CHRIS LAUVER, NPS

endemics (e.g., Sunset Crater penstemon [*Penstemon clutei*] and Cliff Palace milkvetch [*Astragalus deterio*]).

Clear Skies with Low Pollution

There are two components to air resources: clear skies allowing for good visibility (both at day and night) and low pollution. The FY2004 GPRA report for air quality (http://www2.nature.nps.gov/air/who/GPRA/GPRA2004review02042005.pdf) found that during the period 1994-2003, ozone increased significantly at GRCA and MEVE; nitrate and ammonium in precipitation increased significantly at BAND; and visibility degraded significantly on hazy days at PEFO and MEVE. In 2005, ozone concentrations exceeded EPA's air quality standard on one occasion.

Wilderness and Natural Areas

Six SCPN parks have some level of wilderness status (Table D6, Appendix D), and several more may attain status in the near future. Park Service policy is to manage recommended and potential wilderness lands as if they were designated wilderness. Wilderness-related values, such as dark night skies, natural quiet, scenic vistas, and opportunities for solitude, also exist in parks which do not have designated wilderness. In a recent paper by the National Parks and Conservation Association (1999), 82% of Intermountain Region park units consider night skies an important resource. SCPN parks with high quality night skies include BAND, CHCU, ELMO, GLCA, MEVE, NAVA, and WUPA.

The natural soundscape is a resource considered to be of value to human visitors; however, there is a growing body of evidence indicating that wildlife species are also impacted by noise intrusions into the natural soundscape (Radle 2003). SCPN parks with significant natural soundscape resources include CHCU, GLCA, GRCA, NAVA, and WUPA. Opportunities for visitors to experience solitude and scenic vistas are also important resources. As human population density increases throughout the Southwest, SCPN park units offer relief from crowding and increasing noise and light pollution for both human visitors and faunal populations.

Unfragmented Landscapes

Unfragmented landscapes refer to large tracts of land with little or no partitioning due to roads, fences, trails, or other facilities. Habitat fragmentation can lead to decreased patch size, higher edge-to-interior ratios, increased patch isolation, and variation of connectivity between patches (Saunders et al. 1991). Larger SCPN parks such as GRCA, BAND, MEVE, and ELMA preserve large elements of their broader landscapes in relatively undisturbed and unfragmented condition. These parks are refugia for rare, threatened or endangered plant and animal species, and large carnivores. Roadless areas have also been shown to be refugia for native plants, and, depending on other site conditions, deterrents to spread of non-native invasive (Gelbard and Harrison 2003). Small parks, such as WACA and YUHO, may function as important wildlife corridors for large carnivores.

Soil and Soil Quality

Soils in arid to semi-arid ecosystems, such as the Colorado Plateau, are the product of climate (strong winds and infrequent rains), parent rocks (limestones, sandstones, and metamorphic rocks), and topography (runoff and deposit patterns) (Balba 1995). According to the Soil Science Society of America, soil quality is the capacity of a soil to function (within natural or managed ecosystem boundaries) to sustain plant and animal productivity, maintain or enhance water and air quality, and support human health and habitation (Jaenicke 1998). Soil functions also include regulating water flow and storage, cycling of plant nutrients and other elements, and filtering water and air (USDA-NRCS Soil Quality Institute 2001). Of the natural agents which affect archeological resources, erosion caused by wind, water, and temperature are among the leading causes of resource loss (Nickens 1991), indicating that preserving soil quality is important to preserving cultural resources.

Closely related to soil resources are biological soil crusts composed of cyanobacteria, algae, microfungi, mosses, and lichens. They provide a crucial function in nutrient cycling, soil stability, and water infiltration and retention in arid systems (Loope and Gifford 1972, Bailey et al. 1973, Rychert and Skujine 1974, Brotherson and Rushforth 1983, Harper and Marble 1988, West and Young 2000). Biological soil crusts may form more than 70% of the living ground cover on the Colorado Plateau (Belnap 1990).

1.5.3 *Summary of Key Stressors/Resource Concerns*

The SCPN network is differentiating stressors and resource concerns by the specificity of factors impacting natural resources. Stressors are anthropogenic factors that are outside the range of disturbances naturally experienced by the ecosystem (Whitford 2002). We use the term, resource concerns, to include changes to resource condition due to unknown factors or the cumulative effects of multiple stressors on a resource. Specific descriptions of the effects of stressors on individual ecosystems will be provided in Chapter 2.

Invasive or Non-native Species

Examples of the severity of the invasive species issue include the following cases: 1) 24% of the total acreage at GLCA may be infested with invasive plant species; 2) extensive infestations of tamarisk comprise most of the vegetative cover along the Colorado River corridor and dominate much of the length of many side canyons (National Park Service 2002); and 3) cheatgrass (*Bromus tectorum*) constitutes 85% of the dominant understory at YUHO. Effects of non-native species invasions can include major changes in community composition (Bock et al. 1986), competitive displacement of native species, and alterations in ecosystem characteristics such as disturbance regimes (Hughes et al. 1991, D'Antonio and Vitousek 1992, Mack and D'Antonio 1998) and soil-resource regimes (Vitousek et al. 1987, Vitousek 1990, Evans et al. 2001).

Park staff identified numerous invasive plant species as being of particular concern because of their current rates of increase and significance (Table D7, Appendix D). Several of the most commonly cited species-of-concern impact riparian, wetland, and aquatic ecosystems that are the most resource-rich environments in the arid land SCPN parks (e.g., salt cedar [*Tamarix spp*.] and Russian olive [*Elaeagnus angustifolia*]).

Rangeland and Forestland Management on Adjacent Lands

Livestock grazing can impact species composition, function, and structure of ecosystems (Fleischner 1994). Studies have found that trampling can decrease cover of biological soil crusts (Jeffries and Klopatek 1987) and reduce or eliminate nutrient cycling (Belnap et al. 1994). The loss of nitrogen cycling can have a corresponding impact on the nitrogen content of dominant plant species (Harper and Pendleton 1993). Grazing in riparian areas can impact water quality, increase erosion and sedimentation, contribute to the establishment of invasive plants, and increase the impacts of floods by reducing vegetative cover (Windell et al. 1986).

Wildlife management is also of concern to park managers. Recent increases in populations of elk (*Cervus elaphus*) may be changing plant communities through overgrazing and browsing and could inhibit efforts toward re-establishment of native plants. Browse by elk has exceeded documented pre-European range of variation (Allen 1996). While ungulate populations are being promoted, predator control by land managers reduces a key component of a functioning ecosystem and exacerbates impacts of ungulates.

Urban/suburban/rural Development on Adjacent Lands

Major subdivisions and larger urban areas can impact natural resources in nearby parks (e.g., AZRU and PETR) through non-point source pollution such as motor and exhaust residue from streets, fertilizers and herbicides from lawns, non-native plant introductions, feral animals, altered water runoff patterns, and structures associated with development. Impacts from urban development can also be region-wide, such as the impacts to air quality at GRCA from metropolitan areas in Arizona, Nevada, and California and from development in northern Mexico.

Rural developments along park boundaries impact visitor experience, detract from the remote character of parks, and cause habitat fragmentation. Visitor experience may be impaired through the increase in noise and air pollution along with viewshed alterations. Transportation and utility corridors and range fences fragment suitable habitat thereby impairing movement of wildlife and dividing biotic communities into more vulnerable components (Sisk et al. 1997, Bright and van Riper III 2001).

Viewshed, Soundscape Intrusions

Urban developments and associated activities alter natural viewsheds of parks and contribute to haze and noise pollution at local and regional scales. In winter, high-pressure systems over the Colorado Plateau can prevent the dispersal of atmospheric pollution in river valleys and basins (Durrenberger 1972). At GRCA, over 60% of the visibility reduction has been linked to sulfates from fossil fuel combustion, smelters, and urban areas. Currently, regional haze produced from coal-fired power generating stations affects all SCPN parks.

According to a report by the National Parks Conservation Association, light pollution at national parks is a widespread problem impacting visitors' experiences (1999). Artificial light sources can impair dark skies for up to 160 kilometers (Clarke 1999). Light pollution may also alter animal behavior through disorientation leading to reduced survival. Species affected by light pollution include migrating birds (Cochran and Graber 1958, Kemper 1964, Crawford 1981), moths (Frank 1988, Blake et al. 1994), and frogs (Cornell and Hailman 1984, Buchanan 1993).

Natural soundscapes are primarily affected by vehicular traffic (i.e., private and commercial vehicles, off-road vehicles, fixed-wing aircraft, and helicopters). Soundscape impairments in SCPN parks include major roads within or near park boundaries (PEFO and ELMO), an off-road vehicle site on adjacent Forest Service property (SUCR), and aircraft noise (BAND, GRCA). Because low-elevation overflights for sightseeing and other purposes adversely impact the natural soundscape of most of GRCA, the National Parks Overflights Act of 1987 tasked the National Park Service and Federal Aviation Administration with developing a plan for tour aircraft use of Grand Canyon airspace that would limit audible aircraft noise to less than 25% of the day in 50% or more of the Park (Public Law 100-91, 18 August 1987).

Altered Vegetation Structure or Composition

This category summarizes the importance of several stressors or resource concerns collectively impacting vegetation structure or composition. Changes to vegetation structure and composition have the potential to disrupt the function of an ecosystem making it unsuitable for associated biota (MacArthur and MacArthur 1961, Rotenberry 1985, Szaro et al. 1985) and permanently shift a system away from its original state (Westoby et al. 1989, Milton et al. 1994). Examples of altered vegetation structure include the following:

- Increase in cover of pinyon-juniper forests due to site-specific mechanisms including climate change and land-use practices (Miller and Wigand 1994, Tausch 1999, West 1999).
- Changes in structure and species composition of montane coniferous systems due to fire and climate change which results in decreased biodiversity, altered spatial distribution of soil nutrients, and deteriorated tree health and consequent bark beetle infestations (Vankat and Major 1978, Waring 1983, Allen 1998, Jackson et al. 2000).
- Alteration of riparian systems due to livestock grazing (Leopold 1924, Carothers 1977, Mosconi and Hutto 1982, Szaro 1989, Chaney et al. 1990)
- Elimination of biological soil crusts by surface disturbances such as trampling and off-road vehicle use (Jeffries and Klopatek, 1987, Belnap et al. 1994)

Industrial/Extractive Uses

Mineral extraction (coal, oil, natural gas, and uranium) can impact the environment through increased sedimentation, toxic levels of chemicals such as heavy metals and hydrocarbons, and noise pollution. A byproduct of industrial and extractive uses is the increase in access roads, paved surfaces, and pipelines. These directly destroy and fragment habitat, provide a path for non-native plant invasion, lead to increased soil erosion, and increase sedimentation and runoff rates to streams. In addition, extraction of some resources (e.g., methane and uranium) requires large volumes of groundwater which can result in depletion or contamination of aquifers (Simons Li & Associates Inc 1982, Nuccio 2000, Gilbert 2002). Mineral and geothermal development can occur on State Trust lands within parks and on surrounding Trust, Federal, tribal, and private lands. Mineral resources on the Colorado Plateau include:

- Large quantities of high quality coal with low sulfur content (Durrenberger 1972, Kirschbaum 2000). Both CHCU and MEVE are situated on a large deposit of coal that extends from southern Colorado through western New Mexico (Molnia et al. 2000).
- The San Juan Basin, extending from southwest Colorado to northwest New Mexico and encompassing CHCU and MEVE, has become the second largest source of natural gas in the coterminous United States (Fassett 2000).
- Uranium mines proposed in the CHCU watershed

Other extractive uses that occur on the Colorado Plateau include mining for gravel, pumice, and landscape stones; uranium mining; logging; and geothermal development.

Water Management – Quantity

The primary concerns in this category are depletion of water resources across the region through water impoundment, diversion, and pumping from aquifers and impacts to surface and subsurface water sources. Changes in hydrology (storm water diversion, impoundments, ground water withdrawals and other practices that reduce streamflow or lower water tables) affect aquatic and terrestrial ecological resources (e.g., riparian habitats, wetlands, and stream habitats). Water is scarce on the Colorado Plateau (Durrenberger 1972), so any removal of water resources adversely impacts the biota of the area. Growing urban areas on the Colorado Plateau place increasing demands (e.g., drinking water, lawns, and irrigation) on the water resources, and the issue is compounded by the latest drought in the western United States. Groundwater withdrawals from regional aquifers in northern Arizona may impact springflow and aquatic resources at GRCA, WACA, and WUPA. Water level declines have been documented in the shallow alluvial aquifer at CHCU. Infiltration of shallow groundwater has affected cultural resources at AZRU and ELMA. Visible declines in hanging gardens and other habitats associated with surface waters have been documented at CACH and NAVA. The structure, function, and sustainability of keystone riparian and wetland ecosystems depend fundamentally on the quality and quantity of water resources.

Visitor Use

The National Park Service Organic Act of 1916 (16 U.S.C. 1 § 1) requires that parks be managed "to conserve the scenery, natural and historical objects, and wildlife therein" and concurrently provide for visitor use without impairing the

(top) An active gas well, Aztec Ruins National Monument. PHOTO BY CHRIS LAUVER, NPS
(middle) An irrigation ditch diverts water from the Animas River at Aztec Ruins National Monument. PHOTO BY STEPHEN MONROE, NPS
(above) An earthen dam impounds Tsaile Creek, creating perennial flow in the upper reaches, Canyon de Chelly National Monument. PHOTO BY STEPHEN MONROE, NPS

resources. This mandate is challenging for all parks, particularly those with high visitation numbers. Many parks of the SCPN experienced rapid growth in the number of annual recreational visits between the mid-1980s and the mid-1990s (Figure D2, Appendix D). Although visitor use of Southwest parks has decreased in the last few years, this may be a temporary trend resulting from the economy and a general reduction in tourism since 2001. Resource impacts associated with increased visitation are numerous and wide-ranging—from trampling of soils and vegetation (Liddle 1975, Weaver and Dale 1978, Whittaker 1978, Cole and Bayfield 1993), to introduction of non-native plant species (D'Antonio and Vitousek 1992), to direct interactions with and disturbances of wildlife (Brown and Stevens 1997, Miller et al. 2001), to increased levels of water and air pollutants (Carothers et al. 1976).

Aquatic resources are under heavy recreational pressure, particularly at GRCA and GLCA. Documented impacts from recreation at GRCA and GLCA include bank erosion, contamination from human waste, water pollution, trash, and trampling of plants (Carothers et al. 1976).

Erosional Loss of Soil

Erosional processes are fundamental to Colorado Plateau topography and ecosystem functioning. Water erosion redistributes soils and essential plant nutrients in pinyon-juniper systems (Wilcox et al. 1996a, Reid et al. 1999), and continued Aeolian dust deposition re-enriches the soil that otherwise would become depleted over time (Lajtha and Schlesinger 1988, Chadwick et al. 1999, Reynolds et al. 2001). However, livestock grazing, farming, logging, catastrophic fires resulting from historic fire suppression, and urban development directly and indirectly increase the rate of loss of soils and associated nutrients (Gellis 1996, West and Young 2000, Breshears and Allen 2002, Whicker et al. 2002).

Elevated rates of erosion have contributed to habitat degradation and the loss of geologic and paleo resources (Allen et al. 2002, Whicker et al. 2002). Wilcox et al. (1996b) predicted that many woodland soils at BAND would be lost within 100-200 years due to erosion levels compounded by historic grazing, fire suppression, and catastrophic fire. Erosive forces also expose paleo resources potentially degrading the value of those resources through damage and redistribution (Kidwell and Flessa 1995). Major archeological and fossil resources at PEFO are being lost to wind and water erosion.

Declining Air Quality

Pollutants from anthropogenic sources have been detected at all NPS monitoring stations (Ross 1990). Air pollution affects natural and cultural resources throughout much of the park system through impaired visibility, threats to biotic health, and degradation of historic structures and artifacts (National Park Service Air Resources Division 2002). See Appendix B for information on air quality and monitoring efforts in SCPN park units.

Fire and Fuels Management

Fire-structured habitat (e.g., pinyon-juniper woodlands and Ponderosa pine forests) composes at least one-third of the vegetation cover at six parks (BAND, ELMA, GRCA, MEVE, SAPU, WACA) in the network. The combined impact of anthropogenic practices and climatic shifts has altered wildfire characteristics in those ecosystems. Where low-intensity surface fires were commonplace, increased frequency of catastrophic fires now threaten natural and cultural resources, human communities, and ecosystem function. NPS and other federal agencies have been working to return fire to those systems and mechanically restore the structural characteristics that existed pre-European colonization.

1.6 SUMMARY OF PAST AND CURRENT MONITORING

1.6.1 *Monitoring in SCPN Parks*

A solid understanding of current and previous inventory and monitoring in and around network park units is an important foundation for development of the SCPN inventory and monitoring program. Documentation and review of existing work allows the network to identify where monitoring is adequate, where additional monitoring or protocol development is needed, which monitoring studies can be built upon and expanded, and what studies should be abandoned. Information regarding monitoring was gathered from a Servicewide inventory and monitoring database (Support Document C), and the superintendent interviews (Support Document B).

Documentation of existing inventory, monitoring, and research efforts will be an on-going SCPN data management function. With frequent turnover of park natural resource management staff, the "institutional" knowledge that is often lost when employees move to new positions will at least be partially retained in these databases. This effort should facilitate park-level natural resource program continuity. Table 1-7 is a summary of the status of resource and stressor monitoring in SCPN parks, as drawn from the various interviews and database described above.

1.6.2 *Regional or Adjacent Lands Monitoring*

By taking an ecoregional approach to vital signs monitoring, we

Table 1-7. Summary of natural resource inventory or monitoring activities in SCPN park units.

H: historical inventory or monitoring data with adequate documentation; I: short-term comprehensive inventory (1 to 2 years); M: long-term monitoring (2+ years); S: SCPN inventory

	SCPN PARKS																		
CATEGORY*	AZRU	BAND	CACH	CHCU	ELMA	ELMO	GLCA	GRCA	HUTR	MEVE	NAVA	PEFO	PETR	RABR	SAPU	SUCR	WACA	WUPA	YUHO
Air quality		M		HI			M	IM		M	H	M				H	IH	IH	
Climate	M	M	M	M	M	M	IM	M		M	M	M	M		M	M	M	M	
Earth Sciences		I	IM	IM	M	HM	I	HIM	I	IM	I	I	I		I	I	I	IM	I
Water Quality and Quantity	IS	IMS	IMS	IMS	IS	HIS	IMS	IMS	M	MS	I	IMS	MS	IMS	I	I	IM	HM	IS
Paleontological/ Paleoecological				I			IM			I		M						M	
Bird	S	IM	IS	I	IS	IS	IM	IM	IMS	M	I	HI	IS	IM	S	I		IM	MS
Fish		I	I				IM	HIM		M				IM					
Herpetofauna	S	IMS	IS	IS	IS	IS	IS	HI	SM	IM	S	I	IS		S	IS	S	IS	S
Invertebrate		M		I	I	I	I	M		III			I	I		I		I	I
Mammal	S	IM	H	I	I	IS	I	M	MS	I	S	I	IS			I	S	IS	S
Vegetation	S	IM	HIMS	I	I	IS	IM	HIM	MS	HIMS	HIS	I	IS	IM	I	I	I	I	IS
Night Sky				M															
Soundscape		I						I											
Stressor		IM		M	M		M	HM	I	M		HM	M	M		I	I	I	
Fire effects		IM			M			M		M					M	M	HM	M	

** Earth sciences: includes geology, geomorphology, soils, etc.; Stressor: includes park visitors, non-native and invasive plants and animals, herbivory and trampling by large mammals, NPS development and infrastructure, NPS management actions, adjacent land use activities, natural disturbance, etc.*

acknowledge that ecosystems are not contained within park boundaries. We envision a collaborative effort among SCPN park units and adjacent land managers in order to accurately determine the status of the nation's ecosystems both within and outside the park units. SCPN adjacent and neighboring lands are owned and/or managed by various entities, including: the Bureau of Land Management (BLM), the Bureau of Reclamation (USBR), the Forest Service (USFS), the Bureau of Indian Affairs (BIA), and states and private entities (Figure 1-7). Data collected from neighboring lands that coincides with SCPN vital signs objectives will help us to develop a broader assessment of conditions and trends.

Regional and nationwide monitoring conducted by federal agencies, academic institutions, non-profit organizations, and other conservation groups also provides valuable knowledge, skills, and resources required to provide full monitoring coverage across the Colorado Plateau. For example, the State Agricultural Experiment Station at University of Illinois coordinates the National Atmospheric Deposition Program/ National Trends Network (NADP/NTN). Initiated in 1978, NADP/NTN monitors precipitation chemistry at a nationwide network of sites. Climate data throughout the U.S. is collected by the U.S. Forest Service, Remote Automated Weather Station Network (RAWS). The 1500 stations in the RAWS network collect data on temperature, dew point, precipitation, wind speed, wind direction, relative humidity, fuel temperature, and fuel moisture. The states of Arizona, Colorado, New Mexico, Utah and the Navajo Nation all have Natural Heritage programs which collect and manage data on biological diversity within their respective areas. Specific information regarding avian diversity and trends can be found through two nationally coordinated efforts, the Breeding Bird Survey coordinated by the USGS Patuxent Wildlife Research Center and the National Audubon Society's Christmas Bird Count. Finally, several efforts to document landscape change have been initiated including the USDA Forest Service Forest Inventory and Analysis Program which includes data on federal, state, and private lands. An extensive list of long-term regional and adjacent lands monitoring and research programs was compiled by the SCPN staff (Appendix F).

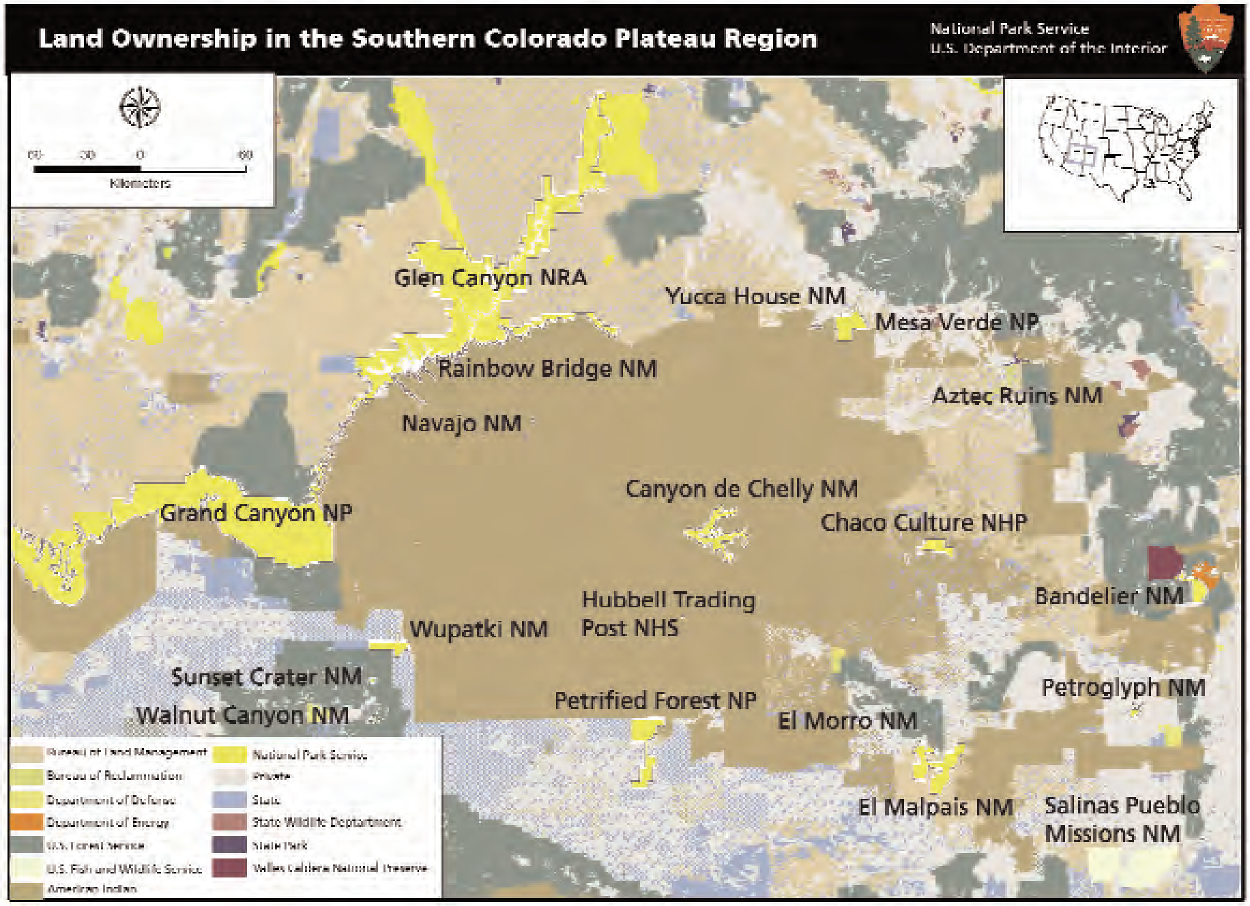


FIGURE 1-7. *Map of land ownership across the Southern Colorado Plateau.*

1.7 SCPN CORE VITAL SIGNS AND MONITORING OBJECTIVES

The ecological context of the Colorado Plateau and an assessment of important resources and management issues among network parks provide a starting point for the vital signs selection process. Chapter 2 describes our collaborative work with the Northern Colorado Plateau Network to develop conceptual models of key Colorado Plateau ecosystems. Chapter 3 summarizes our use of expert workshops to solicit and incorporate the advice of a broad array of scientists and resource professionals into our monitoring plan. The outcome of this two-year planning effort was the selection of 25 vital signs for SCPN parks. We are actively engaged in developing monitoring protocols for the highest priority, or core, SCPN vital signs (Table 1-8). We will seek to expand the monitoring program to include the remaining topics as additional resources become available or through partnership efforts. Monitoring objectives for each vital sign are included in Table 1-9.

Table 1-8. Core vital signs for monitoring in SCPN parks.

	NPS ECOLOGICAL MONITORING FRAMEWORK LEVEL 1: LEVEL 2	VITAL SIGN(S)	AZRU	BAND	CACH	CHCU	ELMA	ELMO	GLCA	GRCA	HUTR	MEVE	NAVA	PEFO	PETR	RABR	SAPU	SUCR	WACA	WUPA	YUHO
Air & Climate	Air & Climate: Air Quality	Ozone, wet & dry deposition, visibility & particulate matter	◊	•	◊	◊	◊	◊	◊	•	◊	•	◊	•	◊	◊	◊	◊	◊	◊	◊
	Air & Climate: Weather & Climate	Climate conditions & soil moisture	•	•	•	•	•	•	•	•	•	•	•	•	•	•	•	•	•	•	•
Riparian & Aquatic Ecosystems	Water: Water Quality	Aquatic macroinvertebrates	◊	+	+	-	-	-	+	+	-	+	◊	-	-	-	◊	-	-	◊	-
	Water: Water Quality	Stream water quality	+	+	+	+	-	-	+	+	+	+	◊	+	+	◊	◊	-	-	-	-
	Water: Water Quality	Spring water quality	-	+	+	+	-	+	+	+	◊	+	+	-	-	-	+	-	+	◊	+
	Biological Integrity: Focal Species or Communities	Spring, seep & tinaja ecosystems	-	+	+	+	-	+	+	+	-	+	+	+	-	-	+	-	+	+	+
	Geology & Soils: Geomorphology	Channel morphology	+	+	+	+	◊	-	+	+	+	+	+	+	+	-	+	-	+	+	-
	Water: Hydrology	Stream flow & depth to groundwater	+	•	+	+	◊	-	+	+	+	+	+	+	-	◊	+	-	+	◊	-
	Biological Integrity: Focal Species or Communities	Riparian vegetation composition & structure	◊	+	+	+	◊	-	+	+	+	+	+	+	-	-	+	-	+	◊	-
	Biological Integrity: Focal Species or Communities	Riparian bird communities	◊	+	+	◊	◊	-	+	+	◊	+	◊	◊	-	-	◊	-	◊	◊	-
Upland Ecosystems	Geology and Soils: Soil Quality	Soil stability & upland hydrologic function	+	+	+	+	+	+	+	+	◊	+	+	+	+	◊	◊	+	+	+	◊
	Biological Integrity: Focal Species or Communities	Vegetation composition & structure	+	+	+	+	+	+	+	+	◊	+	+	+	+	◊	◊	+	+	+	◊
	Biological Integrity: Focal Species or Communities	Upland bird communities	◊	+	◊	◊	◊	◊	◊	+	◊	+	◊	+	◊	◊	◊	◊	◊	+	◊
	Biological Integrity: Focal Species or Communities	Ground dwelling arthropods	◊	◊	◊	◊	◊	◊	◊	+	◊	+	◊	◊	◊	◊	◊	◊	◊	◊	◊
Landscape	Biological Integrity: Invasive Species	Invasive exotic plants (early detection)	◊	◊	+	◊	◊	+	+	+	+	+	+	◊	◊	+	+	◊	◊	◊	+
	Ecosystem Patterns & Processes: Landscape Dynamics	Land use – land cover & landscape vegetation pattern	+	+	+	+	+	+	+	+	+	+	+	+	•	+	+	+	+	+	+
	Ecosystem Patterns & Processes: Landscape Dynamics	Vegetation condition & disturbance patterns	-	+	+	+	+	+	+	+	-	+	+	+	+	-	+	+	+	+	-
Wildland Values	Ecosystem Patterns & Processes: Soundscape	Natural soundscape condition	◊	◊	+	◊	+	+	+	•	◊	◊	+	+	◊	+	◊	◊	◊	+	◊
	Ecosystem Patterns & Processes: Viewscape	Night sky condition	◊	+	◊	+	+	+	+	+	◊	+	◊	+	◊	◊	◊	◊	◊	◊	◊

+ *Vital signs that SCPN is working to develop with monitoring plans and protocols*
• *Vital signs that are monitored by a network park or another federal or state agency*
◊ *Vital signs with no known current or planned monitoring; deferred*
- *The vital sign does not apply to the park*

Table 1-9. Monitoring objectives for core SCPN vital signs.

	ECOLOGICAL MONITORING FRAMEWORK (LEVELS 1 & 2)	VITAL SIGN(S)	MONITORING OBJECTIVES
Air and Climate	Air and Climate: Air Quality	Ozone, wet & dry deposition, visibility and particulate matter	Determine status and trends in 1) ozone, 2) wet & dry deposition, and 3) visibility and particulate matter in Class I parks (BAND, GRCA, MEVE, PEFO).
	Air and Climate: Weather & Climate	Climate conditions and soil moisture	Provide monthly and annual summaries of climate data including precipitation and temperature and determine long-term trends in seasonal and annual patterns of climate parameters and soil moisture.
Riparian and Aquatic Ecosystems	Water: Water Quality	Aquatic macroinvertebrates	Determine status and trends in 1) the composition and abundance of aquatic macroinvertebrate assemblages and in 2) the distribution and condition of aquatic macroinvertebrate habitats in selected perennial streams or stream reaches.
	Water: Water Quality	Water quality of streams & springs	Determine status and trends in the water quality of selected streams and springs. Priorities for monitoring include impaired stream reaches and relatively pristine waters.
	Geology and Soils: Geomorphology	Channel morphology	Determine status and trends in physical drivers of riparian ecosystems (i.e., stream flow, depth to water in alluvial aquifers, and channel morphology) in selected streams or stream reaches.
	Water: Hydrology	Stream flow & depth to groundwater	
	Biological Integrity: Focal Species or Communities	Riparian vegetation composition & structure	Determine status and trends in composition and structure of riparian vegetation along selected streams or stream reaches.
	Biological Integrity: Focal Species or Communities	Riparian bird communities	Determine status and trends in composition and abundance of breeding bird communities associated with riparian vegetation of selected streams or stream reaches.
	Biological Integrity: Focal Species or Communities	Spring, seep & tinaja ecosystems	Determine status and trends in 1) discharge, 2) habitat area, 3) water quality, 4) vegetation composition & structure, 5) aquatic & riparian invertebrate composition & abundance, 6) *Rana pipiens* occurrence; *Hyla arenicolor* abundance.
Upland Ecosystems	Geology and Soils: Soil Quality	Soil stability & upland hydrologic function	Determine status and trends in soil stability and upland hydrologic function within selected predominant upland ecological sites.
	Biological Integrity: Focal Species or Communities	Upland vegetation composition & structure	Determine status and trends in vegetation composition, diversity, and structure of plant communities associated with selected predominant upland ecological sites.
	Biological Integrity: Focal Species or Communities	Habitat-based upland bird communities	Determine status and trends in 1) composition and abundance of breeding bird communities and in 2) reproductive success for selected breeding species in selected upland habitats. Selected habitats will be a subset of those monitored for integrated upland vital signs.
	Biological Integrity: Focal Species or Communities	Ground-dwelling arthropods	Determine status and trends in the composition and relative abundance of ground-dwelling arthropods in selected upland habitats. Selected habitats will be a subset of those monitored for integrated upland vital signs.

Table 1-9 **continued.** Monitoring objectives for core SCPN vital signs.

	ECOLOGICAL MONITORING FRAMEWORK (LEVELS 1 & 2)	VITAL SIGN(S)	MONITORING OBJECTIVES
Landscape	Biological Integrity: Invasive Species	Invasive exotic plants (early detection)	Detect incipient populations and new occurrences of selected invasive exotic plants before they become established in areas of management significance.
	Ecosystem Patterns and Processes: Landscape Dynamics	Land use - land cover & landscape vegetation pattern	Determine status and trends in 1) composition, extent, and distribution of land use/land cover and vegetation types on lands within and adjacent to SCPN parks, 2) fragmentation and connectivity of selected land cover and vegetation types within and adjacent to SCPN parks, and 3) in land cover and vegetation patterns along park boundaries.
	Ecosystem Patterns and Processes: Landscape Dynamics	Vegetation condition and disturbance patterns	Determine annual status and trends in vegetation condition (vigor and productivity) of the dominant land cover and/or vegetation types within and adjacent to SCPN parks and long-term trends in disturbance patterns (type, frequency, extent, and severity) within SCPN parks.
Wildland Values	Ecosystem Patterns and Processes: Soundscape	Natural soundscape condition	Determine status and trends in natural soundscape condition in selected parks.
	Ecosystem Patterns and Processes: Viewscape	Night sky condition	Determine status and trends in night sky condition in selected parks.

CHAPTER 2

CONCEPTUAL ECOLOGICAL MODELS

2.1 THE USE OF MODELS IN DESIGNING AN ECOLOGICAL MONITORING PROGRAM

Conceptual models of ecological systems are "caricatures of nature" (Holling et al. 2002) designed to describe and communicate ideas about how nature works. Conceptual models provide a way to organize current understanding of ecosystem structure and processes and to explore hypothesized linkages among system components. Conceptual models also improve communication among scientists from different disciplines, between scientists and managers, and between managers and the public.

Conceptual models are essential for designing credible and effective ecological monitoring programs. Ecological systems are highly integrative and complex, and their response to novel environmental or biotic conditions is often poorly understood. The intent of conceptual models for monitoring design is not to represent the full complexity of a system, but rather to use current knowledge to identify a limited set of integrative elements that provide information on multiple aspects of ecosystem condition (Noon 2003). Moreover, conceptual models motivate hypotheses regarding consequences of natural and anthropogenic processes on system structure and function. Conceptualizing the external processes that influence ecosystems (i.e., drivers), the key products of human activities or natural events that alter ecosystem integrity (i.e., stressors), and likely pathways of degradation and attendant changes in system structure and function aids in identifying key system indicators or vital signs. Concentrating monitoring efforts on these vital signs ensures the collection of information useful for understanding ecological condition and change and for informing park management.

2.1.1 *Conceptual Model Approach*

The SCPN adopted a modified version of the interactive-control model (Jenny 1941, Chapin III et al. 1996) as the overarching framework for conceptual model development (Figure 2-1). This model, also known as the Jenny-Chapin model, defines state factors and interactive controls central to the structure and function of sustainable ecosystems. Jenny (1941, 1980) proposed that soil and ecosystem processes are determined by five state factors—global climate, potential biota, relief (topography), parent material, and time since disturbance (Figure 2-1A). Chapin et al. (1996) extended this framework to define a set of four interactive controls that are regulated by the five state factors. These interactive controls—regional climate, soil resources, major functional groups of organisms, and disturbance regime—govern and respond to ecosystem attributes. (Figure 2-1B).

By substituting water quality and quantity for soil resources, the Jenny-Chapin model can be applied to aquatic as well as terrestrial ecosystems (Chapin III et al. 1996). Regional climate and disturbance regimes are external to the system and are categorized as drivers of ecosystem structure and function. Soil resources and functional groups

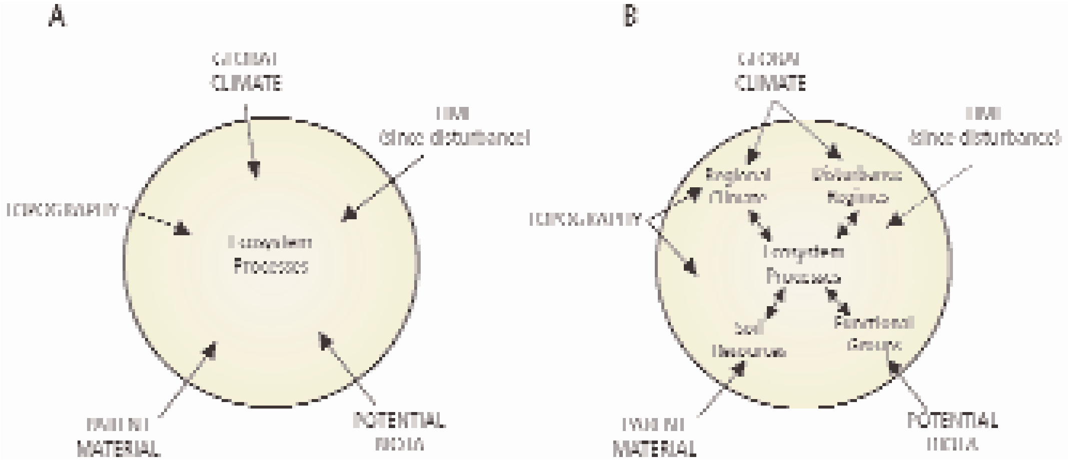


Figure 2-1. *Illustration of the Jenny-Chapin model.*

A – Jenny's (1941) five state factors. B – Relationship among state factors, interactive controls, and ecosystem processes. The circle represents the boundary of the ecosystem (from Chapin et al. 1996).

encompass system states and processes that influence overall system structure and function. Functional groups pertain to species or species assemblages likely to have profound effects on ecosystem characteristics following their introduction or loss from a system (Vitousek 1990, Chapin III et al. 1997).

A key aspect of the Jenny-Chapin model is the associated hypothesis that interactive controls must be conserved for an ecosystem to be sustained. Large changes in any of the four interactive controls are predicted to result in an ecosystem with different characteristics than the original system (Chapin III et al. 1996). For example, major changes in soil resources can greatly affect productivity, recruitment, and competitive relations of plants and result in substantive changes in the structure and function of plant communities and higher trophic levels.

Using the Jenny-Chapin model as a central theme (Figure 2-1B), a nested hierarchy of conceptual models (Figure 2-2) was developed for each of the five major ecosystems in the SCPN. Objectives and details of models varied from general representation of system structure to hypothesized responses to specific stressors. This nested hierarchy served to identify specific drivers and stressors, plausible stressor-induced degradation pathways and ecosystem responses, and measures and vital signs indicative of the domain of natural conditions and the transition to degraded conditions.

The nested hierarchy consists of three general types of conceptual model:

Ecosystem Characterization Model (Figure 2-2A) is a generalized model that includes a list of state variables and forcing functions important to the ecosystem and the focal problem. It also illustrates processes connecting components (Jorgensen 1986). The model provides a framework for organizing information from discussion and literature review around the four interactive controls.

Ecosystem Dynamics Model (Figure 2-2B) presents hypotheses concerning ecosystem dynamics, that is, how and why ecosystems change as a consequence of interacting natural and human factors. State-and-transition models are used to depict system dynamics and to pose hypotheses about ecological thresholds, transitions among states, and the effect of management activities on state transitions (Stringham et al. 2001, Jackson et al. 2002, Bestelmeyer et al. 2003). Models are developed for broad functional groupings of ecosystems with eventual development of site-specific models of selected systems.

Mechanistic Model (Figure 2-2C) provides details concerning the actual ecological processes responsible for patterns depicted in the dynamic models. These models provide insight into pathways and primary and secondary effects of particular stressors, highlight potential monitoring attributes or measures, and illustrate the linkage of these attributes in the context of the broader ecosystem. Models are developed for single or multiple combinations of stressors.

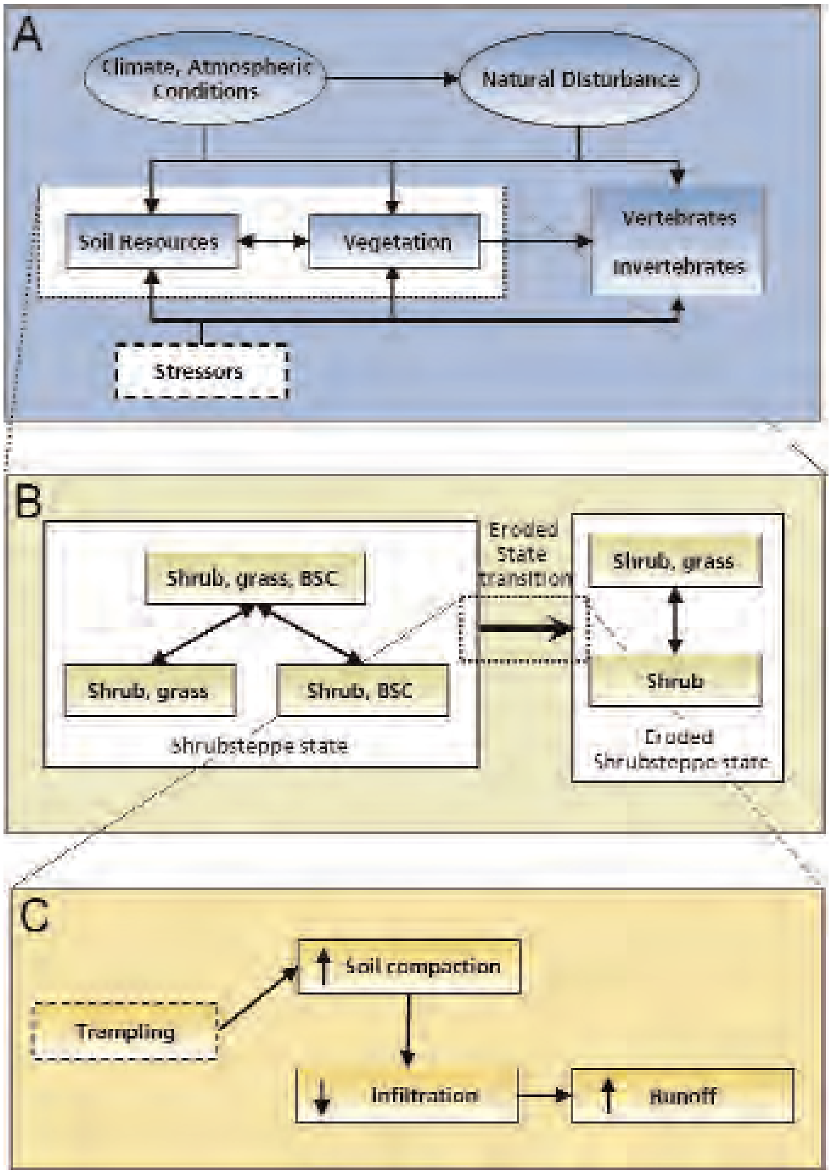


Figure 2-2. *Hierarchical conceptual model scheme used in the vital signs planning process.*

A – ecosystem characterization model showing drivers (ovals), functional components (rectangles), and stressors (dashed rectangles), B – ecosystem dynamics model using a state and transition framework, C – mechanistic model illustrating the degradation process of a stressor (trampling).

2.1.2 *Conceptual Model Development Summary*

Dr. Mark Miller, former NCPN Ecologist, developed general conceptual models for the NCPN Phase I Report (Evenden et al. 2002). The NCPN and SCPN jointly developed a conceptual model framework and workplan to guide continued model development and refinement for Colorado Plateau ecosystems. The SCPN funded the completion of dryland models and the development of montane ecosystem models. The two networks equally funded the development of conceptual models for the riparian-aquatic and spring ecosystems (Table 2-1). Conceptual models are detailed in Supplements I thru IV.

Summary conceptual models and narratives for each ecosystem are provided below to illustrate interactive controls (drivers, soil/water resources, functional groups), stressors, key degradation processes, and potential ecosystem measures for characterizing natural and degraded system conditions identified from the hierarchical scheme of models. Chapter 3 describes how conceptual models and identified ecosystem measures were used in the selection of the SCPN vital signs.

2.2 DRYLAND ECOSYSTEMS

(see Supplement I for full report)

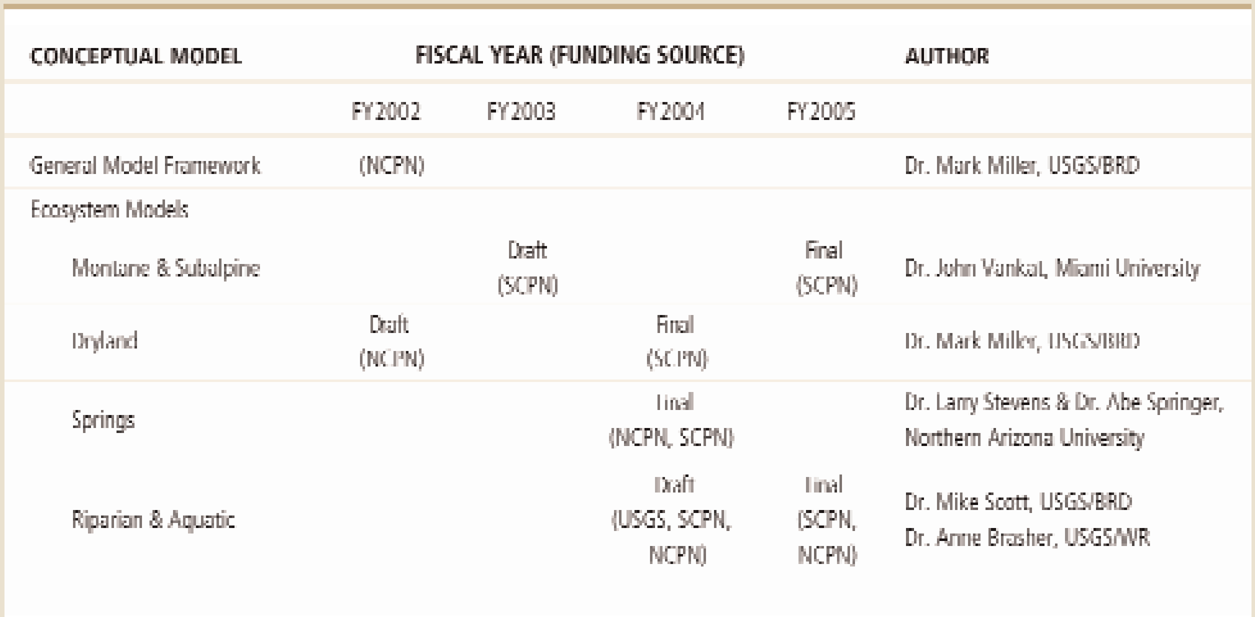
Dryland systems occur where mean annual precipitation is less than 450 mm, which includes about 85-90% of SCPN parkland area. These systems are characterized by mixtures of pygmy conifers (*Juniperus* and *Pinus* spp.), shrub and desert grasslands, and biological soil crusts. Additionally, landforms of the dryland systems include deep and sparsely vegetated canyons, lava beds, and slickrock. Limited precipitation and, in many cases, limited vegetative cover impose a high degree of vulnerability of dryland systems to changes in natural disturbance and climatic regimes and to human impacts. The summary conceptual model for dryland ecosystems is shown in Figure 2-3 and discussed below.

Drivers

Regional Climatic and Atmospheric Conditions. Precipitation regime is the most important climatic factor defining the characteristics of dryland ecosystems. Precipitation regulates key water-limited ecological processes, such as primary

Table 2-1. Timetable for completing ecosystem specific conceptual models.

Table includes conceptual model projects funded through NCPN, SCPN and the USGS/BRD Canyonlands Research Station.



CONCEPTUAL MODEL	FISCAL YEAR (FUNDING SOURCE)				AUTHOR
	FY2002	FY2003	FY2004	FY2005	
General Model Framework	(NCPN)				Dr. Mark Miller, USGS/BRD
Ecosystem Models					
Montane & Subalpine		Draft (SCPN)		Final (SCPN)	Dr. John Vankat, Miami University
Dryland	Draft (NCPN)		Final (SCPN)		Dr. Mark Miller, USGS/BRD
Springs			Final (NCPN, SCPN)		Dr. Larry Stevens & Dr. Abe Springer, Northern Arizona University
Riparian & Aquatic			Draft (USGS, SCPN, NCPN)	Final (SCPN, NCPN)	Dr. Mike Scott, USGS/BRD Dr. Anne Brasher, USGS/WR

production, nutrient cycling, and plant reproduction (Noy-Meir 1973, Comstock and Ehleringer 1992, Whitford 2002). Interactions among the seasonality, size, and duration of precipitation events determine ecosystem response to precipitation. Seasonality influences the partitioning of precipitation among evaporation, transpiration, runoff, drainage, and soil-water storage and determines vegetative dominance (Comstock and Ehleringer 1992).

Most (e.g., 70%) precipitation events are small (<5 mm) and drive soil-surface processes such as nutrient mineralization and volatilization. Larger events initiate seed germination and soil-water recharge (Ehleringer et al. 2000). Precipitation intensity, in combination with soil characteristics and soil-surface features, determine infiltration and runoff levels (Whitford 2002, Breshears et al. 2003). Orographic effects, rain shadows, and seasonal storm features determine spatial pattern of precipitation which can be highly variable during the summer.

Strong winds are common in dryland systems. Winds modify energy and water balances of plants and soils by affecting evapotranspiration rates (Larcher 1995), redistributing soil resources (Whicker et al. 2002), and interacting with topography to influence wildfire behavior.

Natural Disturbance. Extreme climatic events typify dryland ecosystems (Walker 1993, Whitford 2002) and contribute to the natural spatio-temporal variability of dryland systems. Drought, extreme precipitation events, floods, and wind storms cause widespread mortality, impairment to the establishment of long-lived plants, and massive transport and redistribution of soil resources.

The role of wildfire varies among dryland ecosystems, with greater importance in sagebrush shrublands and shrub steppe, productive semi-desert grasslands and juniper savannas (Jameson 1962, Johnsen 1962), and piñon-juniper woodlands. Low-intensity surface fires thin or eliminate fire-intolerant woody vegetation and favor the dominance of fire tolerant graminoids (Jameson 1962, Wright 1980).

Insect and disease outbreaks are linked with climatic conditions that diminish the vigor and insect resistance of host plants and affect life cycles and dispersal patterns of insect herbivores (Swetnam and Betancourt 1998, Logan et al. 2003). As with fire, insect outbreaks interact with climate to generate long-term changes in vegetation structure.

Soil Resources

The edaphic heterogeneity created by geologic and prehistoric climatic features and the tight coupling between vegetation community pattern and soil resources (Charley and West 1975, Schlesinger et al. 1990, Schlesinger et al. 1996) strongly regulates vegetative patterns across parks. Soil properties and associated biota regulate hydrologic processes and the cycling of mineral nutrients and sustain the existence and productivity of plant and animal populations. Dynamic attributes defining soil function (i.e., organic matter) vary naturally with temporally variable climatic and disturbance conditions.

Functional Groups

Biological Soil Crusts (BSC). BSC are critical components of dryland systems (Belnap and Lange 2001). BSC occur within the upper few millimeters of the soil surface (Belnap et al. 2001). BSC increase soil stability, reduce raindrop impact and erosivity, and enhance infiltration of precipitation. BSC are primary producers, and associated species of bacteria fix atmospheric nitrogen.

Vegetation. In addition to conducting photosynthesis, above-ground structures of vascular plants protect soils from erosion by raindrops, wind, and overland water flow and enhance the retention of soil resources. Plants also modify the physical environment by shading and litter deposition. Roots stabilize soils, conduct and redistribute resources, and provide organic matter to soil food webs. Vegetation is a key component for vertebrate and invertebrate habitat. Fuel loadings and fuel connectivity, the erosion potential of precipitation, and habitat connectivity for coarse-scale organisms are influenced by the spatial pattern of vegetative conditions.

Vertebrates and Invertebrates. Consumption of plant and animal material, trampling of soil and BSC by ungulates, and redistribution of energy and materials are among the key effects and functions of these species.

Stressors and Degradation Processes

Climatic Change. Increasing levels of atmospheric CO_2, increasing soil and air temperatures, and altered precipitation patterns are likely to affect physiological processes and competitive relations of vascular plants, nutrient cycles, hydrologic processes, and natural disturbance regimes. All of these can greatly alter the structure and functioning of dryland ecosystems (Alward et al. 1999, Ehleringer et al. 2000, Smith et al. 2000, Weltzin et al. 2003) and the sensitivity of these systems to other anthropogenic stressors.

Air Pollution. Nitrogen deposition has potential implications for numerous ecological patterns and processes including ecosystem susceptibility to exotic species invasions (e.g., Asner et al. 1997, Fenn et al. 2003a, Galloway et al. 2003). Although current rates of nitrogen deposition are generally low across most of the western United States, modeling indicates potential hot spots of nitrogen deposition in the vicinity of MEVE (Fenn et al. 2003b).

Fire Exclusion. Altered fire regimes attributable to past livestock grazing (fuel removal) and fire suppression efforts have caused significant changes in vegetation structure and functioning of associated ecosystem processes. Mediated by changes in vegetation structure, altered fire regimes can result in diminished hydrologic functioning (e.g., Wilcox et al. 1996b, Davenport et al. 1998, Jacobs and Gatewood 1999) and increased susceptibility to drought, other disturbances, and various stressors.

Visitors. SCPN park units experienced a rapid increase in annual visitors from mid-1980 to mid-1990 (Figure D2, Appendix D). Likely results include greater off-trail trampling of

(top) The removal of perennial grasses and shrubs allows wind-driven erosion to form coppice dunes of unstable soil.
PHOTO BY MARK MILLER, USGS

(middle) Pinyon pine and juniper on slickrock, Navajo National Monument.
PHOTO BY CHRIS LAUVER, NPS

(above) Desert shrubs and grasses, Wupatki National Monument.
PHOTO BY MEGAN SWAN, NAU

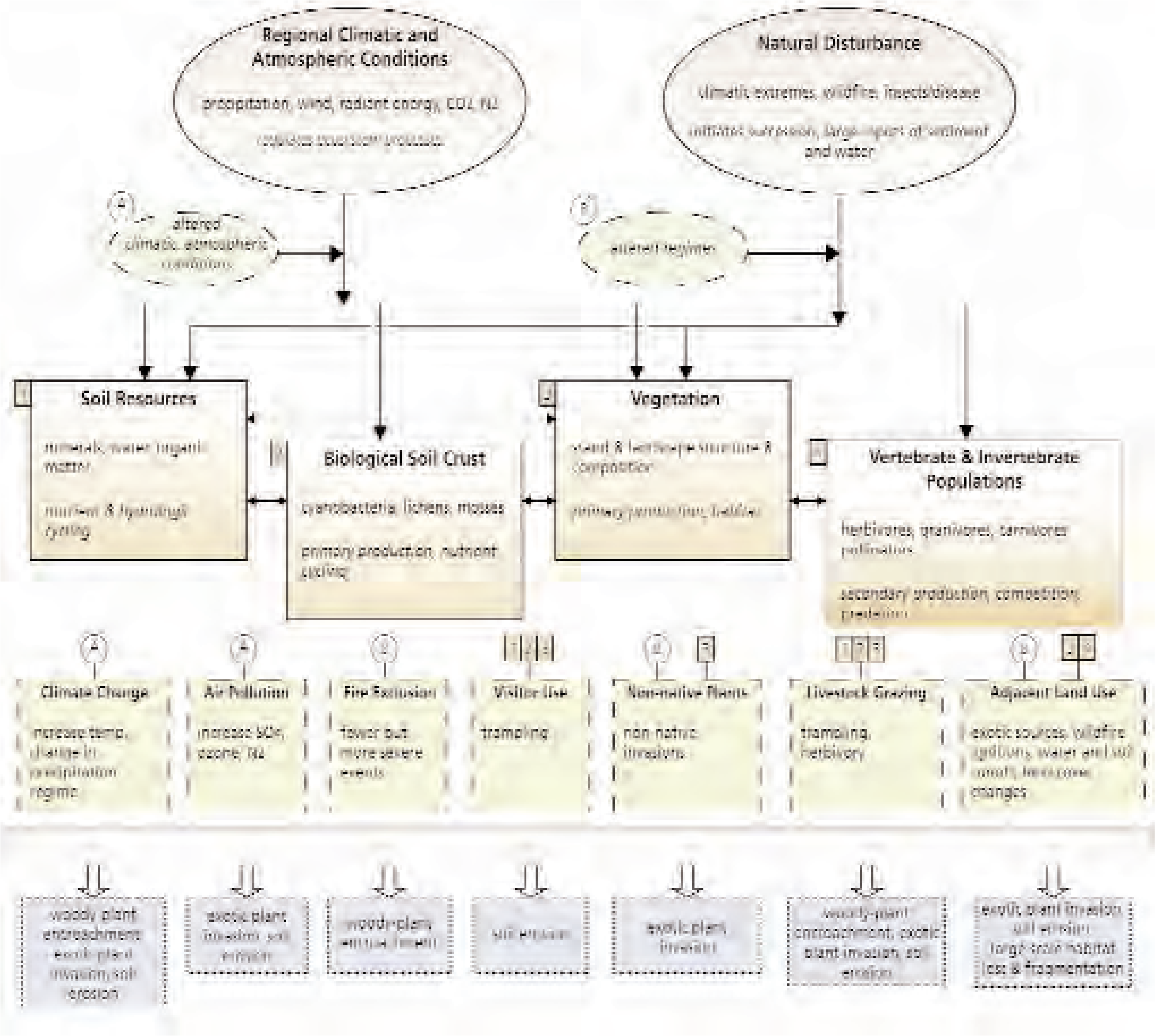


Figure 2-3. *Summary conceptual model for dryland ecosystems. Solid ovals are drivers and interactive controls, solid rectangles are system components that are interactive controls, dashed rectangles are stressors, and dotted rectangles are key degradation processes associated with each stressor (described in Table 2-2). Text for interactive controls indicates components or structure followed by function. Text for stressors shows proximate effects.*

soils and vegetation, direct interactions with and disturbances of wildlife, and increased levels of water and air pollutants. The trampling of soils is of special concern due to the wide-ranging consequences of soil compaction and the destruction of biological soil crusts (BSC). The loss of BSC decreases soil stability and increases wind and water erosion. Additionally, nitrogen fixation by BSC is critical to the productivity of dryland systems.

Invasive Non-native Plants. Non-native invasion can lead to the displacement of native species and alterations of ecosystem-level properties such as disturbance regimes (D'Antonio and Vitousek 1992, Mack and D'Antonio 1998) and soil-resource regimes (Vitousek 1990, Evans et al. 2001). Current and historic grazing on and around SCPN parks have converted significant portions of native grasslands to cheatgrass (*Bromus tectorum*) (Table D8, Appendix D).

Livestock Grazing. Livestock grazing and trailing is permitted in GLCA and trespass livestock occur in several others. Historically, most

Table 2-2. Key degradation processes and stressors, their ecosystem effects, and potential measures for dryland ecosystems.

DEGRADATION PROCESS	STRESSORS	ECOLOGICAL EFFECTS	POTENTIAL MEASURES
Woody-plant encroachment	Fire suppression and lower fire frequency due to the reduction of perennial grasses from grazing	Altered soil-hydrologic and nutrient cycling and habitat structure, loss of herb species, increased fire severity due to fine-woody branch and leaf litter, increased soil exposure and erosion with high-intensity wildfire	Vegetative composition and structure, grazing intensity, fire regime attributes
Non-native plant invasion	Livestock grazing, adjacent land use activities, climatic and atmospheric changes	Altered nutrient dynamics, soil water dynamics, major shift in functional group structure, increased fire frequency and extent due to non-native plant flammability and spatial continuity	Vegetative composition and structure, grazing intensity, adjacent land use activities, climatic-atmospheric elements
Soil erosion and redistribution	Trampling by visitors and livestock, air pollution, climatic change, adjacent land use activities	Erosion and loss of soil function due to reduction of biological soil crusts, soil compaction, soil-surface roughness, soil-aggregate stability, water infiltration, decreased N fixation, changes in vegetative composition and structure	Soil depth and structure, biological soil crust cover and distribution, vegetative composition, structure, and pattern, climatic and atmospheric elements, adjacent land use activities
Large scale habitat loss & fragmentation	Adjacent land use activities	Regional scale habitat loss, reduced connectivity of metapopulations, reduced ingress and egress potential	Land cover, land use, land condition patterns on park and adjacent lands

parks were grazed. Grazing has modified vegetative communities by removing palatable native grasses and shrubs and trampling soils and vegetation. The reduction of native plants in conjunction with soil disturbance has led to the wide-spread colonization of non-native plants on park lands.

Adjacent Land Use. Livestock grazing, forest management, urban/exurban development, and industrial and agricultural pollutants have the potential to degrade park lands. They increase the transfer of soil and water to park areas by depositing airborne and waterborne pollutants and introducing non-native biota, and they can be a source of disturbances such as wildfire. Large-scale habitat loss and reduction of landscape connectivity threaten to increase the insular nature of most SCPN parks.

Four key degradation processes are predicted in response to individual and interacting stressors (Figure 2-3, Table 2-2). These processes can lead to conditions beyond the perceived domain of naturally variable dryland systems and have important implications for ecosystem sustainability.

2.3 MONTANE AND SUBALPINE ECOSYSTEMS

(see Supplement II for full report)

Montane and subalpine ecosystems occur in 9 SCPN parks (Supplement II). Included in this suite of ecosystems are Ponderosa pine forests, mixed conifer, subalpine spruce-fir forests, montane shubland, and montane-subalpine grasslands. Conceptual models for each ecosystem are presented in Supplement II. Common interactive controls, stressors, and key degradation processes are summarized in Figure 2-4, and discussed below.

A fence demarcates the boundary between Chaco Culture National Historical Park and adjacent lands with livestock grazing. PHOTO BY STEPHEN MONROE, NPS

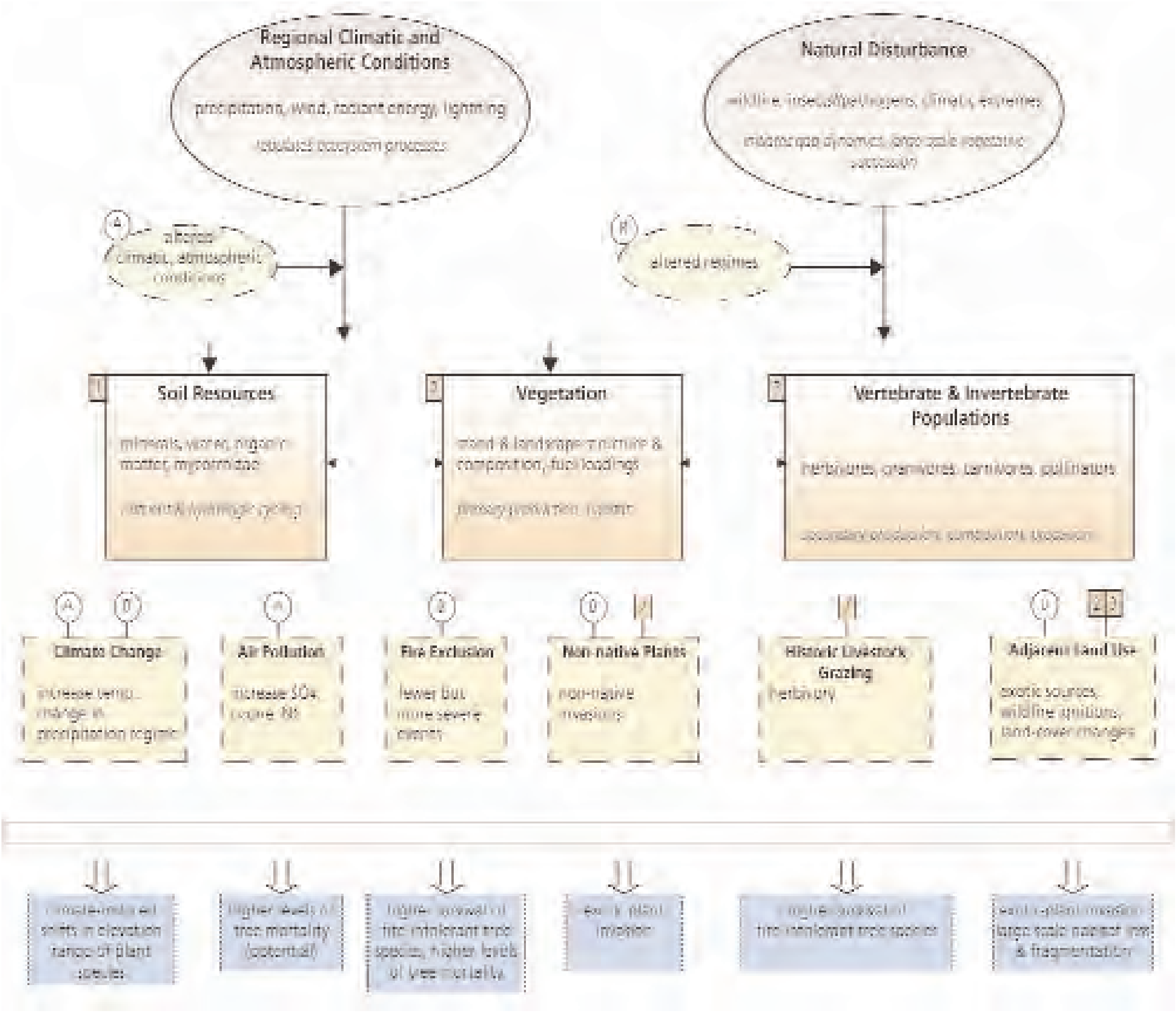


Figure 2-4. *Summary conceptual model for montane and subalpine ecosystems. Solid ovals are drivers and interactive controls, solid rectangles are system components that are interactive controls (soil resources, functional groups), dashed rectangles are stressors, and dotted rectangles are key degradation processes associated with each stressor (described in Table 2-3). Text for interactive controls indicates components or structure followed by function. Text for stressors shows proximate effects.*

Drivers

Regional Climatic and Atmospheric Conditions. The occurrence of forested systems on the Colorado Plateau is directly related to mountainous terrain and elevation-mediated precipitation gradients. A winter snowpack is common in mixed conifer and subalpine systems and contributes to summer water for plants. A critical weather component in these systems is the high frequency of lightning which provides an abundant source of forest fire ignitions.

Natural Disturbance. Fire is a major disturbance with regimes and effects varying with elevation. High frequency, low intensity surface fires at lower elevations consume surface fuels and small stems and rarely result in overstory mortality. Park-like, old-growth Ponderosa forests are maintained by frequent surface fires. Low frequency, high intensity, stand-replacing fires occur at higher elevations, creating a patch mosaic of post-fire successional forests. In montane meadows, the natural fire regime inhibits the establishment of trees.

Wind events at scales from microbursts to large storms occasionally result in gap formation. Large windthrow patches notably occur in subalpine forests. Winter winds in combination with ice and snow result in the breakage of branches and large windthrow patches. Downed coarse woody debris resulting from windthrow provides important habitat for ground-dwelling animals and saprophytic species and is important to nutrient cycling.

The major pests and pathogens impacting montane and subalpine systems are native species. Bark beetles—usually present in low numbers and persisting in less productive living trees and in fresh windthrows—occasionally kill trees. Large-scale tree mortality occurs when climate- and pathogen-induced stress weakens tree defenses against beetles.

Soil Resources

Soils range from shallow to deep, but are generally permeable and capable of storing snowmelt. This provides available water for all or most of the growing season. Mycorrhizae are essential components in forested systems, facilitating tree-root uptake of critical nutrients.

Functional Groups

Vegetation. Forests are a significant source of primary production and a unique habitat for numerous plants and animals. At the landscape scale, the spatio-temporal variability of natural disturbances and successional development creates a mosaic of stand conditions and ages, promoting broad-scale diversity of flora and fauna.

Vertebrates and Invertebrates. The roles of these species are similar to that in dryland systems.

Stressors and Degradation Processes

Climatic Change. Predicted increases in temperature can increase physiological stress in trees, leading to greater susceptibility to infestation by insects and pathogens. Increased temperatures can also alter the elevation domain of species, leading to the migration of forest communities farther upslope.

Air Pollution. The air pollutants of greatest concern are ozone, sulfate, and nitrogen-based compounds such as nitrate and ammonium/ammonia. Ozone injures foliage, reduces growth, and may combine with other air pollutants to cause even more damage. Nitrogen may enhance vegetative growth in nitrogen-limited systems, but it can offset that growth with an increased flux of nitrogenous trace gases from soil, decreased diversity of mycorrhizae and lichens, altered carbon cycling and fuel accumulation in forests, and physiological perturbation of overstory trees. Air pollutants potentially can affect patterns of tree mortality and regeneration and thereby affect species composition and vegetation dynamics.

Fire Exclusion. Fewer fires can lead to dramatic changes in forest structure and composition and fuel structure. In general, fire exclusion increases tree densities and decreases herb and shrub cover. It also leads to increased buildup of fuels, providing conditions for high-intensity fires in systems naturally maintained by low-intensity surface fires.

Invasive Non-native Plants. Non-native plants compete with and displace native species, resulting in lower biodiversity and altering soil-nutrient cycling. Non-native invasion is most important in Ponderosa pine forests, where non-native plants can comprise 21% of the plant ground cover.

Historic Livestock Grazing. Grazing in high-elevation forests and meadows has greatly reduced the amount of herbaceous cover. This has reduced the amount of fine fuels that once carried surface fires and

(top) Mixed conifer forest fringes a montane meadow, Grand Canyon National Park. NPS ARCHIVE
(above) Ground fire burns through Ponderosa pine forest in Grand Canyon National Park.
NPS ARCHIVES

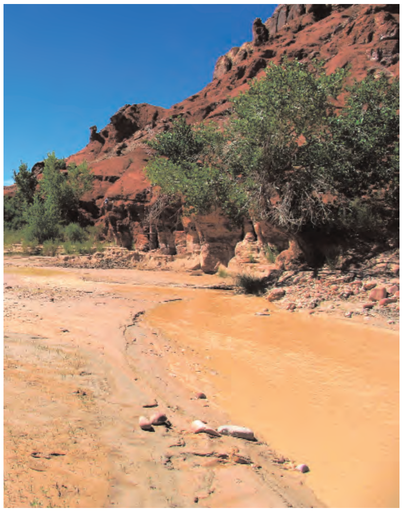
Table 2-3. Key degradation processes and stressors, their ecosystem effects, and potential measures for montane and subalpine ecosystems.

DEGRADATION PROCESS	STRESSORS	ECOLOGICAL EFFECTS	POTENTIAL MEASURES
Higher survival of fire-intolerant tree species (leading to denser stands with large proportion of fire-intolerant species	Fire exclusion, historical livestock grazing (reduction of fine fuels resulting in lower fire frequencies	Changes in stand structure and composition result in substantive change in functional groups, with implications to nutrient cycling and other soil-vegetation processes Ponderosa pine forests: denser tree understory (pine and white fir), reduction of herbaceous cover, stand-replacing crown fires instead of surface fires, post fire successional stands (gambel oak and quaking aspen), denser old-growth stands of Ponderosa pine with a large component of fire-intolerant white-fir Mixed conifer, subalpine spruce forests: higher stand density, more evenly distributed age classes at landscape level, higher severity fires leading to altered successional stages containing higher hardwood component, old-growth stands denser with a large component of fire-intolerant true-fir species Montane-subalpine grasslands: woody shrub and tree encroachment, eventual displacement of herbaceous species	Fire regime attributes, historical and current livestock grazing intensity, vegetative composition and structure, land cover and land condition patterns
Tree mortality (higher rates in mid, late seral stages due to higher stocking densities)	Insect and disease outbreaks (due to dense stands and homogenous vegetation pattern reinforced by fire exclusion), air pollutants (potentially)	Higher insect/disease mortality due to density induced physiological stress, higher spatio-temporal frequency of snags and downed, coarse-woody debris; larger contiguous fire patterns due to high fuel loads and fuel connectivity, decreased landscape-scale diversity of forest types (successional stages)	same as above plus insect/disease mortality, atmospheric conditions
Non-native plant invasion	Non-native invasion, adjacent land use	Altered nutrient dynamics, soil-water dynamics, shift in functional group structure, increased fire frequency and extent due to non-native plant flammability, and spatial continuity	Vegetative composition and structure, adjacent land use
Climate-induced shifts in elevation range of species, leading to changes in elevation range of communities	Climate change	Displacement of species and communities higher along elevation moisture gradient, altered landscape structure and attendant processes	Land cover, land condition, climatic elements
Large-scale habitat loss & fragmentation	Adjacent land use activities	Regional-scale habitat loss, reduced connectivity of metapopulations, reduced ingress and egress potential	Land cover, land use, land condition patterns on park and adjacent lands

has led to increased woody-plant encroachment in meadows and higher understory stem densities in forests.

Adjacent Land Use. Adjacent lands can serve as sources of disturbance, notably fire. Forest harvest and other land use practices can lead to large-scale habitat loss, decrease regional habitat connectivity, and overall, increase insularization of park lands.

Five key degradation processes are predicted for montane and subalpine systems (Figure 2-4, Table 2-3).



The Paria River in Glen Canyon National Recreation Area transports sediment downstream to the Colorado River in Grand Canyon National Park. NPS ARCHIVE

Mancos River, Mesa Verde National Park. PHOTO BY CHRIS LAUVER, NPS

Flattened vegetation is an indicator of recent flooding, Hubbell Trading Post National Historic Site. PHOTO BY CHRIS LAUVER, NPS

2.4 RIPARIAN AND AQUATIC ECOSYSTEMS

(see Supplement III for full report)

Riparian and aquatic ecosystems provide water and unique habitat for numerous plant and animal species in the predominantly dry landscape of the SCPN. Aquatic systems include surface water and channel characteristics of streams. Riparian zones occupy landscape positions transitional between upland and aquatic systems and are physically dynamic and more biologically diverse than surrounding uplands. Conceptual models of aquatic and riparian systems encompass perennial, ephemeral, and intermittent streams (Supplement III). A summary conceptual model was developed for the two systems combined given their high degree of overlap (Figure 2-5) and is discussed below.

Drivers

Regional Climatic and Atmospheric Conditions. Precipitation drives fluvial geomorphic processes and water-limited ecological processes and, thus, is a key factor shaping aquatic and riparian ecosystems. The general importance of precipitation seasonality, size, and duration are discussed under the dryland conceptual model (2.2). Precipitation intensity is especially relevant in terms of runoff and the potential for debris flows and flash floods. Additionally, decadal-scale variations in precipitation patterns are especially important in shaping riparian areas (Hereford et al. 2002, Mantua and Hare 2002). During wet cycles, increased water flow results in erosion of the riparian zone. In subsequent dry periods, channel narrowing, flood plain aggradation, and riparian vegetation establishment on the former channel occurs. The marked shift from wet conditions in 1999 continues to the present and suggests a continued transition to a dry phase for the next two to three decades (Hereford et al. 2002).

Natural Disturbance. Heavy flooding results in widespread geomorphic change and plant mortality as well as the establishment of relatively long-lived riparian species (Schumm and Lichty 1963). For instance, seeds of *Populus* spp. and *Salix* spp. germinate and grow on moist, freshly deposited alluvial sediments following floods (Auble and Scott 1998, Cooper et al. 2003). Large magnitude floods redistribute sediment in channels and the floodplain and create topographic diversity through large-scale erosion and deposition of sediments. More frequent, low-magnitude floods create hydrologic gradients that control patterns of vegetation establishment and successional processes (Brinson et al. 1981).

Regional drought reduces surface flows and depletes alluvial groundwater aquifers. Mild water stress reduces plant productivity. Under more severe conditions, trees die from water stress or insects, pathogens, and diseases.

Upland Watershed Characteristics. The form of channels, floodplains, and many attributes of riparian ecosystems are determined by the flux of water and sediment from upland watersheds. Soils, vegetative pattern and composition, initial relief, geology, watershed age, and climate ultimately determine water and sediment inputs to rivers.

Stream Flow Regime. The stream flow regime determines the mechanical forces that erode, transport, and deposit sediment which influences channel dimensions of aquatic systems. Stream flow variation influences the occurrence of suitable habitat patches and species abundance (Bain et al. 1988, Johnson 1992, Poff and Allen 1995, Auble and Scott 1998). Riparian ecosystems are structured by geomorphic processes and hydrologic conditions found in channels and on associated flood plains. Reductions in the riparian zone area result from diminished flow variability. Shallow alluvial groundwater is an important feature of riparian flood plain soils and is tightly linked to surface water dynamics.

Flood Plain Soil Resources, Fluvial Geomorphic Processes, Water Quality

Flood Plain Soil Resources. Soil biota contribute to the structure and functioning of riparian ecosystems by mediating nutrient cycling, water infiltration and storage, soil aggregate stability, and water and nutrient uptake by plants (Skujins 1984, Whitford 1996, Lavelle 1997, Wardle 2002, Whitford 2002). Functioning of these below-ground processes depends on the amounts and types of organic-matter inputs from vegetation and on soil conditions such as moisture availability, soil structure, soil aeration, and soil temperature (Mitsch and Gosselink 1993, Whitford 1996, Whitford 2002). The periodic wetting and drying of riparian soils is critical to the release of nutrients from leaf litter in riparian environments (Mitsch and Gosselink 1993). Soil-water holding characteristics in addition to amount of alluvial groundwater influence occurrence and survival of riparian plants.

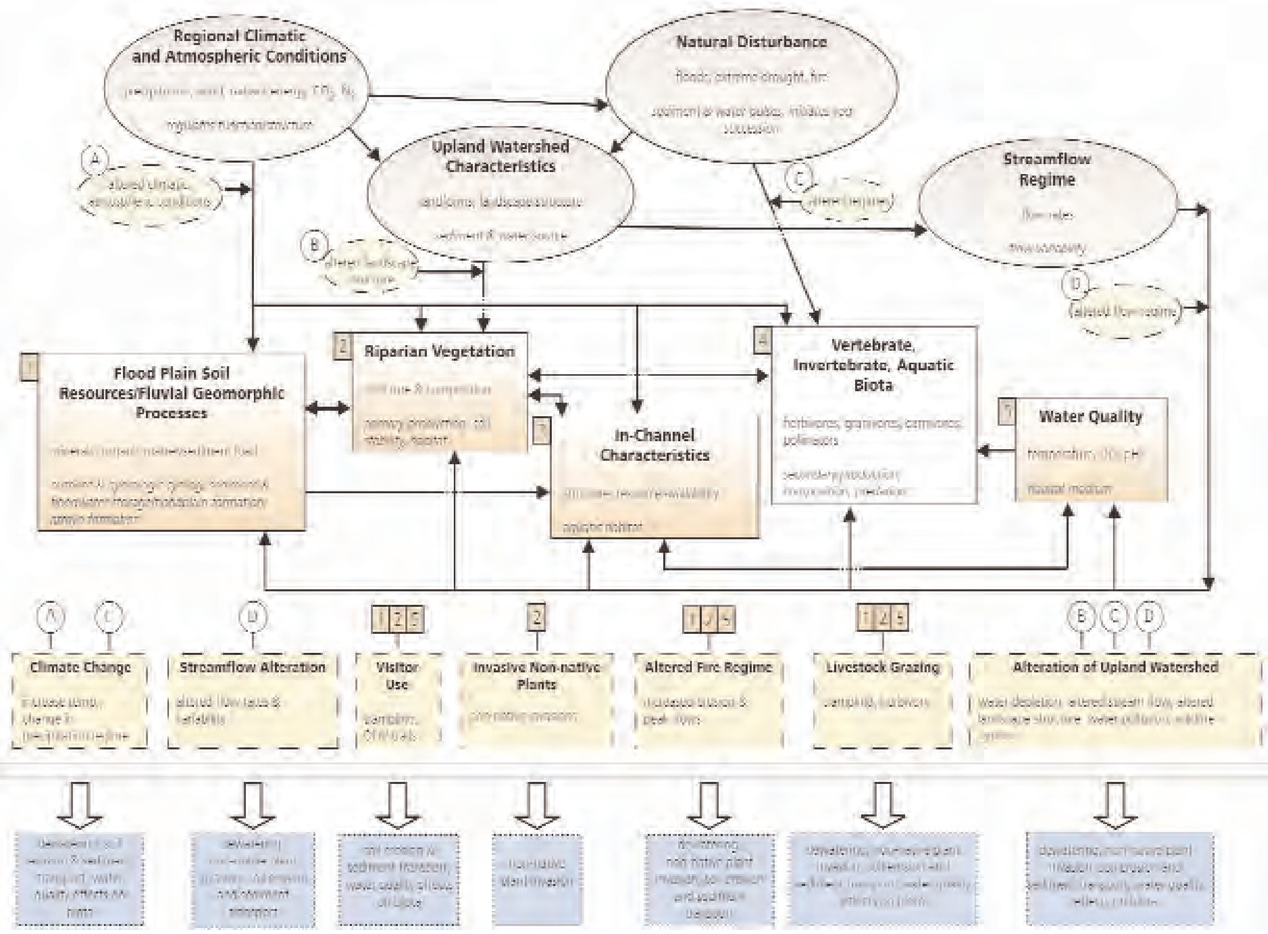


FIGURE 2-5. *Summary conceptual model for riparian and aquatic ecosystems. Solid ovals are drivers and interactive controls, solid blue rectangles are system components that are interactive controls, clear rectangles are other biotic components, dashed rectangles are stressors, and dotted rectangles are key degradation processes associated with each stressor (described in Table 2-4). Text for interactive controls indicates components or structure followed by function. Text for stressors shows proximate effects.*

Fluvial Geomorphic Processes. Stream channels adjust to variations in the amount and size of the sediments supplied by the watershed. Suspended sediment and bed load influence channel form. Channel patterns and forms are a function of changes in stream power, channel gradient, and sediment loads, and occur naturally in response to floods and droughts and changes in the upland watershed. The vertical accretion of sediments forms flood plains which are critical substrate for riparian vegetation.

Water Quality. Dissolved oxygen, pH, and temperature are critical factors regulating aquatic biota. Aquatic biota are adapted to temporal variations in these factors but are susceptible to extremes. Conditions outside the normal range of variation can result in the loss of the most sensitive species, substantive shifts in species composition, or at the extreme, the loss of all biota and associated functions. Changes in flow regime, human activities, nutrient loading by livestock, and other stressors can drastically alter water quality.

In-channel Characteristics

Variations in channel form and substrate creates a range of geomorphic features such as pools, riffles, meanders, and sand bars. These features provide a variety of microhabitats for aquatic biota. Flow velocity and refuge availability determine the distribution and suitability of microhabitats for benthic macroinvertebrates.

Functional Groups

Vegetation. Vegetation is the dominant functional type in riparian ecosystems with woody trees and shrubs as the defining elements. In addition to conducting photosynthesis, the above-ground structure of vascular plants protects floodplain soils from erosion and enhances the deposition and retention of nutrient-rich sediments during floods. Litter from plants reduces the erosive impacts of rainfall and adds organic matter for nutrient cycling. Shading and litter deposition by riparian plants affect spatial and temporal patterns of soil-resource availability to other organisms. Roots stabilize soils and stream banks serve as conduits for resource acquisition and redistribution and provide organic-matter inputs to soil food webs. Providing habitat for a diverse array of secondary consumer and decomposer communities is an important function of riparian vegetation.

Aquatic Biota. Benthic macroinvertebrates are a vital link in aquatic and riparian systems. They consume algae and provide food for aquatic and terrestrial vertebrates. Macroinvertebrates respond to physical parameters such as temperature, substrate, and current velocity. They are also influenced by their chemical environment, including pH, oxygen availability, and contaminants. Diversity and abundance of aquatic macroinvertebrates generally increases with substrate stability and the presence of organic detritus (Allan 1995).

Stressors and Degradation Processes

Climatic Change. Increasing levels of atmospheric CO_2, rising soil and air temperatures, and altered precipitation patterns, including a potential increase in the frequency of extreme events, are likely to affect competitive relations of vascular plants, nutrient cycles, hydrologic and geomorphic processes, and disturbance regimes. Effects on water availability and flow variability have the potential to greatly alter the structure and functioning of riparian ecosystems (e.g., Alward et al. 1999, Ehleringer et al. 2000, Smith et al. 2000, Weltzin et al. 2003) and the sensitivity of these systems to other anthropogenic stressors.

Streamflow Alteration. Surface and groundwater extractions on lands upstream from some park units contribute to streamflow depletion and reduced streamflow variability. Water extractions can lead to dewatering of the channel and floodplain, resulting in the mortality of riparian vegetation and encroachment of upland vegetation. Decreased bank stability associated with the loss of riparian vegetation increases channel erosion, resulting in the loss of floodplain soil resources and degradation of site conditions. Reduced stream transport leads to channel narrowing, affecting in-stream habitat of aquatic species.

Visitor use can trample vegetation and muddy the water in narrow riparian areas, Glen Canyon National Recreation Area. PHOTO BY STEPHEN MONROE, NPS

Dams have significantly altered the Rio Grande and the Colorado River in the SCPN by disrupting the natural hydrologic regime and fragmenting riparian corridors. This disruption has altered habitats and competitive interactions, degrading biotic integrity. Impoundments created by dams modify water temperatures and interrupt sediment transport, negatively affecting all aquatic biota. In general, flow regulation and depletion leads to widespread loss or ecological simplification of riparian ecosystems (Friedman et al. in press).

Table 2-4. Key degradation processes and stressors, their ecosystem effects and potential measures for riparian and aquatic ecosystems.

DEGRADATION PROCESS	STRESSORS	ECOLOGICAL EFFECTS	POTENTIAL MEASURES
Dewatering	Damming and diversion of stream flow, heavy grazing, visitor use (trampling, road and trail development in riparian areas), global climatic change	Conversion of riparian and wetland vegetation to stream side vegetation dominated by upland or xeroriparian species, such as net leaf hackberry (*Celtis reticulata*), single-leaf ash (*Fraxinus anomola*) and Utah serviceberry (*Amelanchier utahensis*) reduced productivity and diversity of riparian vegetation; simplification of aquatic communities	Surface flow, ground water dynamics, channel form, adjacent land use and visitor activities, land cover and land use patterns of the greater park ecosystem, riparian vegetative structure and composition, macroinvertebrate community structure
Non-native plant invasion	Reduced stream flow variability, livestock grazing and trampling, adjacent land use (alteration of upland watershed)	Altered biotic structure, composition, and functioning; altered ecosystem processes; displacement of native riparian and wetland species; channel narrowing and simplification	Same as above
Water quality	Adjacent land use (alteration of upland watershed)	Altered biotic structure, composition, and functioning	Land use patterns, water quality
Altered erosional and depositional processes	Climatic change, upland fire, streamflow alteration, visitor use and grazing (trampling)	Channel narrowing, enhanced flood plan formation, channel widening, bank erosion, channel incision, reduced productivity and mortality of riparian and wetland vegetation, simplification of macroinvertebrate communities	Channel form; ground water dynamics; composition and structure of macroinvertebrate communities; riparian vegetation structure and composition

Stream channel alterations intended to improve drainage or flood-carrying capacity occur upstream from some SCPN parks. Channel alterations frequently result in downstream decreases in flow variability, increases in turbidity and sedimentation, and elevated water temperatures. Increases in sedimentation result in a decrease of primary productivity. Increased temperatures compromise habitat conditions for species adapted to colder waters.

Visitor Use. Trails in and adjacent to riparian zones and hiking in slot canyons can lead to increased erosion and stream channel instability, dispersal of invasive non-native species, increased levels of water and air pollutants, and changes in water quality. Recreational Jeep trails often traverse streams. Driving through streams and riparian areas breaches stream banks and levees, increases hydraulic roughness, removes vegetation, and degrades water quality. Also, rutted Jeep trails can alter stream flow paths.

Invasive Non-native Plants. Riparian corridors are prone to invasion by non-native plant species (Malanson 1993) and typically host relatively high percentages (25-30%) of non-native species. Tamarisk (*Tamarix ramosissima*) and Russian-olive (*Elaeagnus angustifolia*) are invading riparian areas along most of the perennial waterways in SCPN, including the Escalante, Little Colorado, Rio Grande, Animas, Chaco, and Colorado Rivers. Tamarisk may promote fire disturbance by producing large numbers of dead stems.

Altered Fire Regime. An increase in catastrophic fire has resulted in removal or reduction of the forest canopy and surface vegetation contributing to accelerated erosion, increases in suspended and bed-load sediment, and increased peak flows following floods. Ash can increase levels of nutrients, ions, pH, and turbidity and decrease levels of oxygen in aquatic systems.

Livestock Grazing. Long-term grazing by livestock removes plant biomass, alters plant population age structures, and simplifies plant composition and structure (Schultz and Leininger

1990). These changes reduce abundance and diversity of riparian-dependent species including birds (Dobkin et al. 1998, Scott et al. 2003). Also, trailing, trampling, and widespread reductions in vegetation cover by cattle can increase upland runoff, reduce channel stability, and initiate arroyo cutting (Cooke and Reeves 1976, Brinson et al. 1981).

Alteration of Upland Watersheds. Activities of concern include livestock grazing, forest management, urban/exurban development, emissions of industrial and agricultural pollutants, and stream flow diversion or regulation. Associated resource issues include increased transfer of soil and water resources, deposition of airborne and waterborne pollutants, introduction of non-native plant and animal species, reduced groundwater recharge, lowered groundwater levels, and reduced stream flows. Organic pollutants, such as livestock excretion and pesticide use in urban and agricultural areas, can kill in-stream biota and affect potability. Metal contaminants from upstream mines have similar impacts.

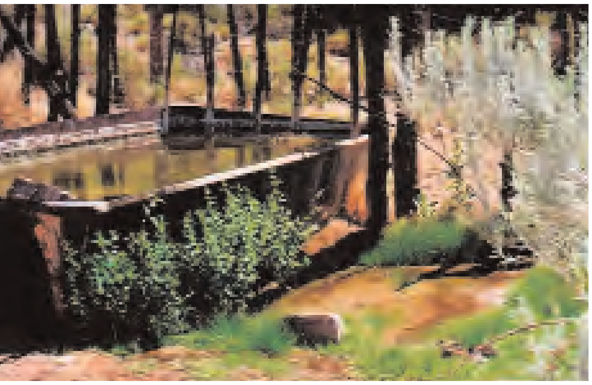
Five key degradation processes are predicted for aquatic and riparian systems (Figure 2-5, Table 2-4).

2.5 SPRINGS

(see Supplement IV for full report)

Springs are important point sources of biodiversity and productivity in otherwise low productivity desert landscapes (Stevens and Nabhan 2002a, b). Aridland springs often function as keystone ecosystems, providing the only available water and habitat in the landscape for many plant and animal species. Also, endemism is common due to adaptation to harsh conditions or the highly dissolved mineral content of some spring water. Springs occur in 14 of the 19 SCPN parks and are viewed as

Vasey's Paradise, Grand Canyon National Park.
PHOTO BY REBECCA HARMS, NAU



(top) Bubbling Spring, Canyon de Chelly National Monument.
PHOTO BY STEPHEN MONROE, NPS

(middle and above) Modifications for livestock use are a common feature at many Colorado Plateau springs.
NPS ARCHIVE PHOTOS

a significant resource by park managers. A spring ecosystem includes the aquifer providing groundwater, the spring orifice and associated biota, and the biota supported by the post-orifice surface flow. These features were integrated into the summary conceptual model (Figure 2-6) and are reviewed collectively below.

Drivers

Regional Climatic and Atmospheric Conditions. Precipitation is critical to the existence of springs. Constrained by geology and geomorphic processes, precipitation sources infiltrate variably permeable or fractured rock strata and follow groundwater flow paths to surface openings. Size, frequency, and duration of precipitation events are key factors influencing spring water availability.

Natural Disturbance. Flooding, sheetwash, rockfall, seismic disturbance, and other erosional factors influence aquifer dynamics, lead to changes in groundwater flow rates, and influence the position, shape, and size of spring orifices. Flooding and rockfall may kill existing plants and rearrange microsite topography, providing colonization opportunities. Heavy precipitation may lead to habitat patches for colonization by long-lived plant species. Subsurface flow paths may become blocked or new paths generated by seismic activities. Drought results in seasonal or erratic desiccation of spring ecosystems and reduces aquatic and wetland biotic diversity. Fire in surrounding areas can modify water flow rates and sediment load, resulting in the removal of above-ground vegetative growth, altered soil structure and nutrient spiraling, and altered population dynamics.

Hydrologic Regime, Geology and Geomorphology, and Water Quality

Hydrologic Regime. Water flow rates influence the ability of a spring system to maintain biotic components and the proper functioning of nutrient and hydrologic cycles. Variable flow rates maintain diverse microhabitat conditions critical to spring biota.

Geology and Geomorphology. Geologic structure and composition of an aquifer (degree of fracture and faulting and rock type) influence aquifer recharge rates and groundwater quality. Geomorphic characteristics determine the microclimate of a spring such as the angle and aspect of the spring orifice which, in turn, affect ambient temperature and rates of groundwater emergence. Rockfall and erosion can potentially alter the geomorphology of a spring and subsequently microhabitat and microclimatic conditions.

Water Quality. Temperature, geochemistry, and bacteria content all contribute to the composition of species assemblages present at springs. Biodiversity may be reduced at mineralized springs with total dissolved solids (TDS) concentrations of >1000 mg/L.; in general, fresh, geothermal waters >30°C have reduced biodiversity. However, harsh environments created by unusual water quality conditions can lead to adaptational endemism of spring-associated species. Water quality is affected by flow rates, geology, pollutants, and grazing by ungulates.

Functional Groups

Riparian, Wetland, and, Aquatic Habitats. Spring supported habitats and vegetation provide critical animal habitat, improve water quality, promote nutrient cycling, and contribute to the net primary production of aridland systems. The microhabitat structure of spring ecosystems determines invertebrate species assemblages. Flow alteration and terrestrial and aquatic disturbances eliminate or create new microhabitat

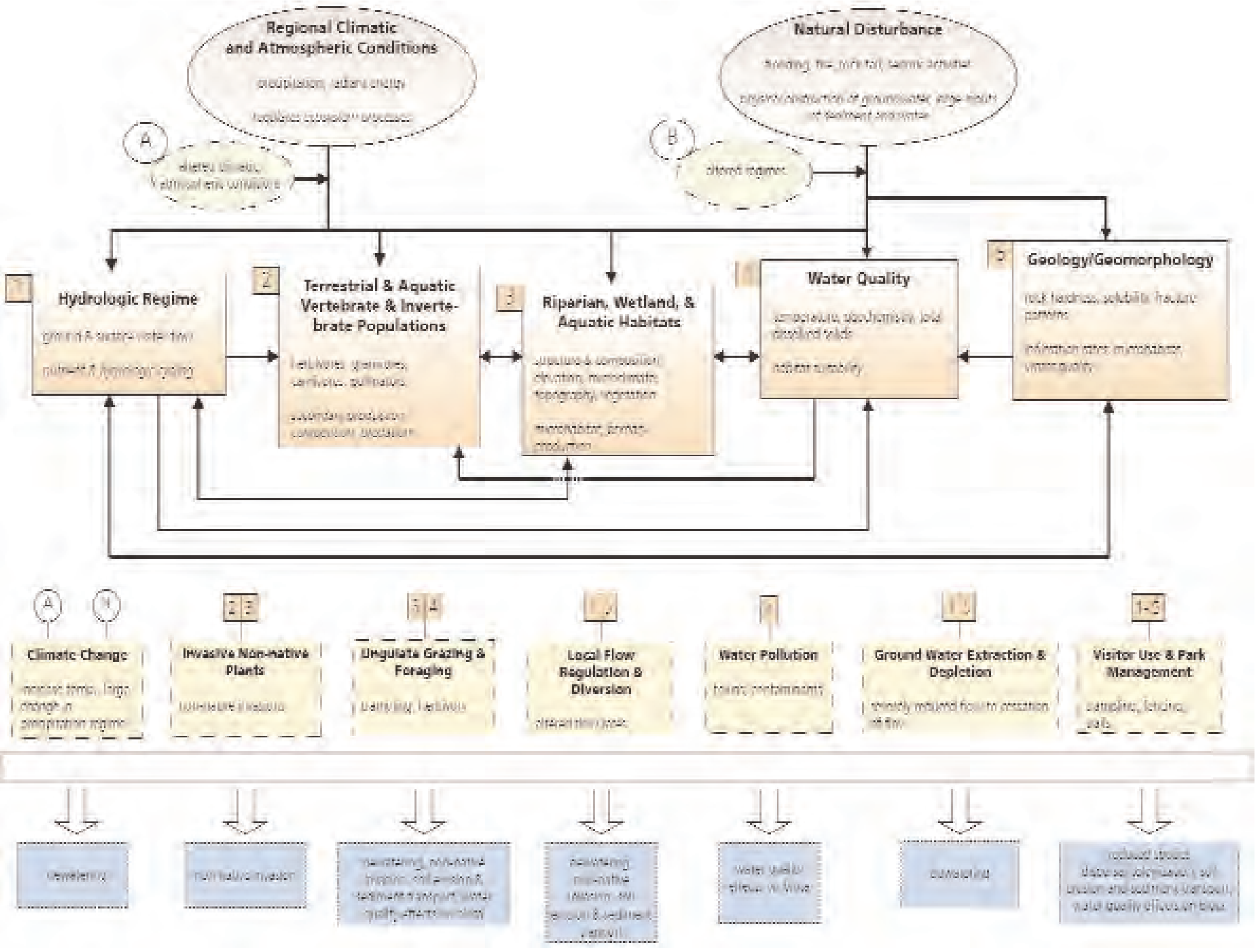


FIGURE 2-6. *Summary conceptual model for spring ecosystems. Solid ovals are drivers and interactive controls. Solid rectangles are system components that are interactive controls. Dashed rectangles are stressors, and dotted rectangles are key degradation processes associated with each stressor (described in Table 2-5). Text for interactive controls indicates components or structure followed by function. Text for stressors shows proximate effects.*

and, in turn, influence the dynamics of spring biota.

Terrestrial and Aquatic Vertebrates and Invertebrates. Vertebrates and invertebrates occupy various niches in the aquatic and water-mediated terrestrial component of spring systems. Species are key components of trophic structures, consuming plant and animal material and providing food for higher-trophic organisms.

Stressors and Degradation Processes

Climatic Change. Changes in precipitation regime can dramatically alter spring systems. Increased flooding or drought can alter aquifers and thus flow levels, variability, and microhabitat structures, leading to substantive changes in biota.

Non-native Invasion. Invasion by non-native species can greatly compromise ecological functioning at springs. Non-natives may displace native species, leading to changes in plant and animal composition, and altering nutrient cycling and trophic dynamics.

Ungulate Grazing and Foraging. Ungulates can alter spring ecosystems by removing vegetation cover, altering plant and invertebrate assemblages, increasing erosion, and contaminating surface water (Grand Canyon Wildlands Council 2002).

Groundwater Depletion. Changing spring flows may arise from several anthropogenic impacts on aquifers. Groundwater extraction may partially or wholly empty individual springs or entire complexes of springs resulting in habitat fragmentation, increased isolation of spring ecosystems, and interrupted biologic processes at micro-site-regional spatial scales. Urbanization leads to an increase in impervious surface area over an aquifer, decreasing the potential for recharge. Changes in land use and livestock grazing intensity can change the role of plant-water use in a watershed and cause a subsequent reduction of recharge rates.

Local Flow Regulation and Diversion. Local diversion by facilities constructed over the point of emergence (spring boxes, spring houses, etc.) alters the natural flow regime of many springs. The construction of cattle tanks on upstream sources can affect flow variability at some springs. Flow diversion or regulation interrupts natural disturbance events such as flooding and alters structural, functional, and trophic attributes of springs.

Pollution. Groundwater and surface water pollution strongly affect springs ecosystems. Upstream agricultural groundwater pollution may shift ecosystem nutrient dynamics to entirely novel trajectories, creating conditions to which few native species may be able to adapt.

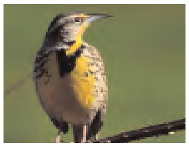
Visitor Use and Park Management. Recreational use at springs leads to trampling around the outflow, degrading native plant communities and potentially introducing invasive non-native plants. Managers often try to protect springs by prohibiting visitors or creating discrete trails to the springs. Such actions may actually damage spring ecosystems. Fencing out livestock may allow excess vegetation to develop, eliminating surface water and threatening aquatic species persistence (Grand Canyon Wildlands Council 2002). Surfaced trails may eliminate leaf litter and prohibit movement of spring-associated land snails and other invertebrate species.

Four key degradation processes are predicted in response to individual and interacting stressors (Figure 2-6, Table 2-5).

Table 2-5. Key degradation processes and stressors, their ecosystem effects and potential measures for springs ecosystems.

DEGRADATION PROCESS	STRESSORS	ECOLOGICAL EFFECTS	POTENTIAL MEASURES
Severe dewatering (loss of most or all habitat medium) or severe reduction in water quality	Persistent climatic change (decrease in precipitation), groundwater depletion, extraction and diversion from the orifice, water pollution	Decreased or total loss of biotic diversity (extinction of endemic species), decreased or loss of nutrient cycling, primary production, and system functions	Water flow, upstream land use, biotic structure and composition
Non-native invasion	Non-native invasion (due to natural dispersal, visitor use of springs)	Altered habitat structure, population dynamics, species diversity, trophic structure, and nutrient cycling	Biotic structure and composition (native vs. non-native)
Reduced species dispersal/colonization	Park management actions (fencing and road construction blocking immigration from external sources)	Reduced biotic structure and composition	Biotic composition and structure, occurrence of physical structures near, around springs
Soil erosion and sediment transport	Trampling by humans, trampling and grazing by livestock, flow regulation	Altered soil-hydrologic function (slower turnover, cessation of cycling pathways) due to soil compaction, altered run-off paths, altered biotic composition	Human and livestock trail development near springs, biotic structure and composition

CHAPTER 3



VITAL SIGNS

In this chapter, we present the decision-making process used by SCPN to identify, prioritize, and select the network vital signs and the outcome of those efforts. Included in this process were seven topical workshops conducted in 2004 to identify and evaluate potential vital signs as well as a final workshop held with the SCPN Science and Technical Advisory Committees to select the network vital signs. The conclusion of this process was the selection of 22 vital signs for the SCPN. Of these, 17 were identified as the network's core vital signs—those for which we will develop monitoring protocols and implementation plans over the next five years.

This chapter also describes how we used conceptual models developed for major Colorado Plateau ecosystems in the vital signs selection process. We discuss how key ecosystem characteristics influenced both the selection and proposed integration of biotic and physical vital signs.

3.1 IDENTIFICATION AND SELECTION OF VITAL SIGNS

3.1.1 *Workshops*

The SCPN held a series of workshops during the winter and spring of 2004 to identify and evaluate candidate vital signs (Table 3-1). The workshops were attended by 76 experts from NPS, cooperating agencies, private organizations, and the academic community. The workshop objectives were to produce 1) a prioritized list of vital signs to monitor relating to the workshop topic, and 2) group recommendations regarding desired scales, approaches, data sources, and/or monitoring questions to be addressed in applying some of the recommended vital signs. Participants nominated potential vital signs using a standardized form (example in Appendix G), and then a lengthy discussion of this initial list of proposed vital signs followed. This discussion led to a significant number of modifications to the initial vital signs list and provided each participant with a good understanding of each vital sign that remained for consideration.

To prioritize the final list of proposed vital signs, participants evaluated each vital sign by completing a standardized form (Appendix G) containing a set of criteria statements in four areas (ecological significance, management significance, feasibility and cost of implementation, and data utility and application; Table 3-2). Participants responded to the statements, which were scored, normalized, summarized using the vital signs database (Support Document A), and then presented for further evaluation and discussion.

Selection Criteria

We used a three-step process to conduct evaluations of candidate vital signs (Tables 3-2 and 3-3).

Canyon de Chelly National Monument. PHOTO BY CHRIS LAUVER, NPS

Table 3-1. SCPN topical workshops held in 2004 to identify and evaluate candidate vital signs.

SCPN WORKSHOP	FOCUS
Terrestrial Montane and Subalpine Ecosystems	Processes influencing and components of the biotic integrity of ponderosa pine, mixed conifer, and spruce-fir forests, montane shrubland, and montane-subalpine grasslands.
Terrestrial Dryland Ecosystems	Processes influencing and components of the biotic integrity of pinyon-juniper woodlands, shrublands and grasslands with and without significant natural fires, and sparsely vegetated communities in canyons, tablelands, badlands, dunes, volcanic rock, and cinder lands.
Riparian and Aquatic Ecosystems	Stream flow, hydrologic function, groundwater, water quality, and biotic components of perennial, intermittent, and ephemeral rivers and streams.
Landscape Patterns and Land Use Change	Use of remotely sensed data to monitor spatial and temporal aspects of landscape patterns (e.g., vegetation condition, habitat fragmentation) and land use change, including the agents that cause change (natural disturbances, development, visitor use, and other human related stressors).
Fauna Populations & Communities	At-risk faunal species or communities, endemic species or unique Colorado Plateau communities, and keystone fauna species.
Flora Populations & Communities	At risk flora species or communities, endemic species or unique Colorado Plateau communities, and keystone species of flora.
Wildland Values	Qualities relating to human experience of wildlands, including wilderness, natural soundscapes (natural quiet), and dark night skies.

Table 3-2. Criteria used to evaluate candidate SCPN vital signs.

TYPE	CATEGORY (WEIGHT)	CRITERIA
Ecosystem Components, Processes or Stressors	**Ecological significance** (Step one 50%) (Step two 35%)	• Reflects or influences an important ecosystem or key characteristic of ecosystem integrity. • Demonstrated link between the vital sign and the ecological function or critical resource it is intended to represent or affect. • Integrates ecosystem stresses over space and time, or is an overall indicator of ecosystem condition.
	Management significance (Step one 50%) (Step two 35%)	• High management importance relative to other resources and/or resource concerns or issues. • The vital sign and its information have great potential to support management decisions and/or influence outside decisions. • Anticipatory of changes in resource or ecosystem condition or integrity.
Physical Drivers	**Significance** (Step one NA) (Step two 70%)	• A central driver of ecosystem dynamics. • Will support monitoring and interpretation of results related to other ecosystem components and/or processes. • Will contribute to larger, collaborative efforts to understand ecosystem dynamics and/or trends in resource condition.
Information Return	**Feasibility and Cost of Implementation** (Step one NA) (Step two 15%)	• Monitoring methods are well-documented or are feasible to develop. • Vital sign is relatively cost-effective to monitor (consider sampling complexity, frequency, and extent). • Logistical requirements of monitoring are feasible.
	Data Utility and Application (Step one NA) (Step two 15%)	• Displays a high signal to noise ratio. It is likely to detect ecologically significant changes within a reasonable timeframe. • Responsive to stressors and/or sensitive to change in the condition of related resources. • Produces results that are interpretable and easily communicated and understood by scientists, policy makers, managers, and the public. • Linked to multiple monitoring questions or ecosystem structure/function components.

Table 3-3. Criteria considered by workshop participants during selection of vital sign sets.

STEP III: BALANCE AND RELEVANCE TO MONITORING GOALS
• The set of monitoring vital signs are complementary in their information content.
• The vital signs span a range of spatial scales, temporal scales (e.g., slow, moderate and fast response times) and ecological levels.
• The set of vital signs includes effects oriented monitoring of key resources and ecosystems, stressor oriented monitoring to address high priority threats, and effectiveness monitoring to measure progress toward meeting performance goals.

Candidate vital signs were divided into two categories: 1) ecosystem components and processes or stressors and 2) physical drivers. In the first step, we used ecological and management significance of ecosystem components processes or stressors to distinguish higher ranking signs from those of less importance. This step did not apply to the physical driver category as the criteria were not separated into ecological and management significance. The second step involved using differential weightings to maintain the emphasis on ecological and management significance but also include feasibility, cost, and data utility and application for a more complete assessment of implementing monitoring of the evaluated vital sign. In Step 3, participants were asked to consider the criteria shown in Table 3-3 while formulating 3 sets of vitals signs: the single, most important sign, the best set of 3, and the best set of 5 vital signs. This exercise fulfilled several objectives: 1) it produced a quick expert opinion of the most important vital signs, 2) it provided an unconstrained comparison or check of the other two evaluation steps, and 3) it highlighted sets that were generally complementary and spanned a range of scales and ecological levels.

A complete summary of each topical workshop, including discussion summaries and scores can be found in Appendix G. An overall summary of vital sign scores can be found in Support Document A.

3.1.2 *Selecting Network Vital Signs*

A final workshop was held in May of 2004 to select core and secondary vital signs. In attendance were members of the SCPN Science Advisory Committee, Technical Advisory Committee, and Board of Directors, a USGS scientist representing the Northern Colorado Plateau Network, and SCPN staff.

Park resource managers and SCPN staff selected monitoring vital signs through a series of workshops. NPS ARCHIVE

A major objective was to review and consider the results of previous workshops (Table 3-1). In reviewing the workshop results, participants were asked to consider the following questions:

- Are the resulting prioritized vital signs consistent with park priorities regarding the most important resource concerns and issues?
- Are the resulting prioritized vital signs consistent with important ecosystem elements identified through literature review and conceptual model development?

Participants used and discussed the workshop results as a basis for developing a final list of core and secondary vital signs for long-term monitoring within the SCPN.

3.2 SOUTHERN COLORADO PLATEAU NETWORK VITAL SIGNS

The outcome of the selection workshop described above and the resulting list of core and secondary network vital signs are shown in Table 3-4. The core vital signs reflect the highest priorities for network monitoring. The SCPN plans to develop monitoring protocols to address the core vital signs over the next five years. Secondary vital signs include important monitoring needs that only apply to a few parks or network-monitoring needs that ranked in the second tier of priorities. The network has no immediate plans to develop protocols or implement monitoring for these vital signs but will reconsider once the core vital signs are implemented and as partnership opportunities arise.

Once the vital signs selection process was completed, network staff visited each of the nineteen parks in the network. Park staff and resource managers from SCPN park units were asked to evaluate the network vital signs list in terms of individual park priorities (Appendix H). During this evaluation period, network staff worked with park resource managers to develop a list of park-specific vital signs not addressed by the network list (Appendix H). Although these specific monitoring needs will not be addressed directly by the network, SCPN staff will assist with protocols, sampling design, or other aspects of monitoring plan development when needed.

Table 3-4. SCPN vital signs organized within the NPS Ecological Monitoring Framework. Core vital signs are indicated in bold text.

LEVEL 1	LEVEL 2	VITAL SIGN
Air and Climate	Air Quality	**Air quality**
	Weather and Climate	**Climate conditions and soil moisture**
Geology and Soils	Soil Quality	**Soil stability and upland hydrologic function**
	Geomorphology	**Channel morphology**
Water	Hydrology	**Depth to groundwater**
		Stream flow
	Water Quality	**Water quality of streams and springs**
		Aquatic macroinvertebrates
Biological Integrity	Focal Species or Communities	**Spring, seep, and tinaja ecosystems**
		Vegetation composition and structure (upland & riparian)
		Habitat-based bird communities
		Ground-dwelling arthropods
		Fish communities
	At-risk Biota	Special status plant and animal species or communities
		Federally listed species
	Invasive Species	**Invasive exotic plants (early detection)**
Ecosystem Pattern and Processes	Landscape Dynamics	**Land use/land cover and landscape vegetation pattern**
		Vegetation condition and disturbance patterns
	Soundscape	**Natural soundscape condition**
	Viewscape	**Night sky condition**
Human Use	Visitor and Recreation Use	Impacts of visitor use
	Point-Source Human Effects	Agents of anthropogenic change and other disturbances

3.3 RATIONALE FOR SELECTION OF VITAL SIGNS AND LINKAGE TO CONCEPTUAL MODELS

The bond between the integrity of the environment and human welfare provides the ultimate rationale for monitoring (Noon et al. 1999). Monitoring the state or condition of ecosystems (i.e., ecosystem structure and function) is of primary importance because the current system state influences resistance and resilience to disturbances and stressors and determines natural diversity and associated processes. SCPN has adopted monitoring ecological integrity as the overarching theme of our long-term monitoring efforts. The concept of ecological integrity provides an appropriate foundation for assessing the state of ecological systems (Karr 1991, 1996, De Leo and Levin 1997, Noon 2003).

Use of Conceptual Models to Inform the SCPN Vital Sign Selection Process

Because monitoring all of the processes and biotic components that contribute to ecological integrity is impractical, we used expert opinion and conceptual models of key Colorado Plateau ecosystems to guide the selection of a more limited suite of vital signs. The intent of conceptual models for monitoring design is not to represent the full complexity of a system, but rather to use current knowledge to identify a limited set of integrative elements that provide information on multiple aspects of ecosystem condition (Noon 2003).

During our topical workshops on dryland and montane systems, Mark Miller and John Vankat, respectively, set the stage for identifying candidate vital signs by presenting their conceptual models for these systems. During the nomination phase of the workshop, posters of these models were available to inform the nomination process. Other, less formalized conceptual models were presented at 3 other topical workshops, including a presentation by Mike Scott of a draft version of the riparian/aquatic model.

Key Ecosystem Characteristics and Implications for Monitoring

Several key ecosystem characteristics can be discerned from the dryland, montane, and riparian/aquatic conceptual models that were developed.

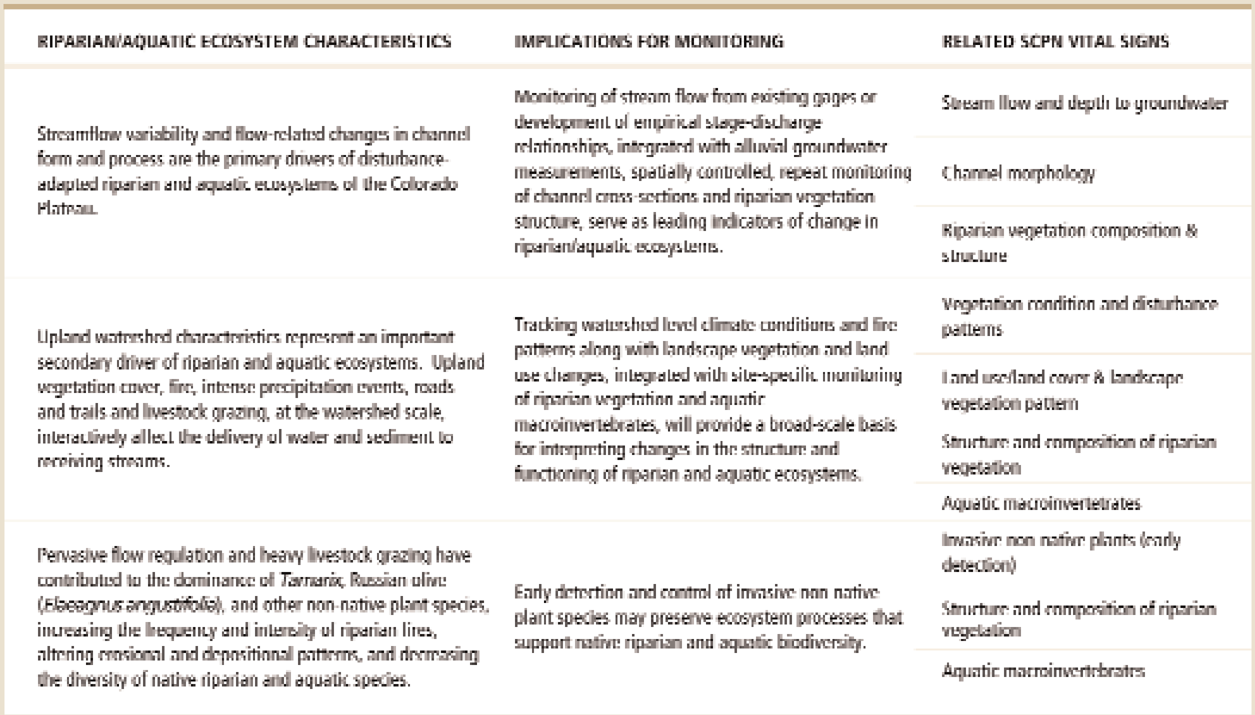
A partial listing of these characteristics, their implications for monitoring, and the related vital signs are shown in Table 3-5. Spring ecosystems were selected as a core vital sign because of their high conservation value and their status as focal ecosystems in arid landscapes. For this reason, we are taking a fairly comprehensive approach to monitoring springs by including most of the important ecosystem components as indicated in the springs conceptual models (Supplement IV).

One of the features highlighted in the dryland models was the overriding influence of precipitation and extreme climatic events in driving ecosystem dynamics and thus the significance of monitoring climate. According to the models, fire plays a secondary role as a driver of dryland systems, and only at the upper end of the moisture/fuel gradient. For these communities (e.g., pinyon-juniper woodlands), ecosystem dynamics are a function of the interaction of fire, climate, and insect outbreaks. Thus, monitoring vegetation condition (e.g., decreases in tree productivity) and related disturbance patterns may provide early warning of ecosystem change. The models also emphasize the role of degradational processes in influencing dryland system dynamics. From the dryland topical workshop, three factors that affect ecosystem susceptibility to degradation were identified based on the dryland models: 1) inherent ecosystem characteristics that determine ecosystem resistance and resilience to natural

Table 3-5. Key ecosystem characteristics, implications for monitoring, and related vital signs.
For dryland, montane, and riparian ecosystems.

DRYLAND ECOSYSTEM CHARACTERISTICS	IMPLICATIONS FOR MONITORING	RELATED SCPN VITAL SIGNS
Precipitation regime is a major driver of water limited dryland ecosystems. Extreme climatic events (e.g., droughts, floods, wind storms) act as key disturbances.	Climate monitoring is required to understand ecosystem dynamics.	Climate conditions and soil moisture
	Tracking spatial and temporal patterns associated with fire, extreme climatic events, and insect outbreaks are necessary to understand ecosystem dynamics.	Vegetation condition and disturbance patterns Climate conditions
Fire is a secondary driver at upper end of moisture / fuel gradient (e.g., semidesert grasslands, big sagebrush shrubsteppe, piñon-juniper woodlands). Fire, climate, and insect outbreaks interact to control ecosystem dynamics.	Monitoring vegetation condition at the landscape scale may provide early warning of ecosystem change.	Vegetation condition and disturbance patterns
Soils play a key role in mediating bioavailability of water and mineral nutrients in dryland ecosystems.	Vegetation monitoring should be integrated with monitoring of soil stability and upland hydrologic function to better understand ecosystem interactions.	Soil stability and upland hydrologic function
Tight linkages between soil resources and vegetation are central to ecosystem dynamics.		
Fire suppression and past overgrazing have resulted in reduced perennial grass cover in degraded sites.	Early detection and control of invasive non-native plant populations may prevent transitions to degraded states.	Invasive non-native plants
Increased rates of soil erosion and redistribution are evident in degraded sites.		Soil stability
MONTANE ECOSYSTEM CHARACTERISTICS	**IMPLICATIONS FOR MONITORING**	**RELATED SCPN VITAL SIGNS**
Fire is a primary driver of montane ecosystems of the Colorado Plateau.	Tracking spatial and temporal patterns associated with fire, extreme climatic events and insect outbreaks are necessary to understand ecosystem dynamics.	Vegetation condition and disturbance patterns
Extreme drought events, especially in Ponderosa pine forest, interact with fire and insect outbreaks to control system dynamics.	Climate monitoring is required to understand ecosystem dynamics.	Climate conditions
	Monitoring vegetation condition at landscape scales may provide early warning of ecosystem change.	Vegetation condition and disturbance patterns
Altered fire regimes (from frequent, low intensity surface fires or mixed-severity fires to infrequent, high intensity crown fires) have changed forest structure, fuel loads and landscape-scale vegetation patterns.	Using remotely sensed data to monitor landscape vegetation patterns will complement plot-based vegetation composition/structure monitoring and promote understanding of relationships between forest structure and disturbance.	Landscape vegetation patterns

Table 3-5 **continued.** Key ecosystem characteristics, implications for monitoring, and related vital signs.



RIPARIAN/AQUATIC ECOSYSTEM CHARACTERISTICS	IMPLICATIONS FOR MONITORING	RELATED SCPN VITAL SIGNS
Streamflow variability and flow-related changes in channel form and process are the primary drivers of disturbance-adapted riparian and aquatic ecosystems of the Colorado Plateau.	Monitoring of stream flow from existing gages or development of empirical stage-discharge relationships, integrated with alluvial groundwater measurements, spatially controlled, repeat monitoring of channel cross-sections and riparian vegetation structure, serve as leading indicators of change in riparian/aquatic ecosystems.	Stream flow and depth to groundwater Channel morphology Riparian vegetation composition & structure
Upland watershed characteristics represent an important secondary driver of riparian and aquatic ecosystems. Upland vegetation cover, fire, intense precipitation events, roads and trails and livestock grazing, at the watershed scale, interactively affect the delivery of water and sediment to receiving streams.	Tracking watershed level climate conditions and fire patterns along with landscape vegetation and land use changes, integrated with site-specific monitoring of riparian vegetation and aquatic macroinvertebrates, will provide a broad-scale basis for interpreting changes in the structure and functioning of riparian and aquatic ecosystems.	Vegetation condition and disturbance patterns Land use/land cover & landscape vegetation pattern Structure and composition of riparian vegetation Aquatic macroinvertetrates
Pervasive flow regulation and heavy livestock grazing have contributed to the dominance of *Tamarix*, Russian olive (*Elaeagnus angustifolia*), and other non-native plant species, increasing the frequency and intensity of riparian fires, altering erosional and depositional patterns, and decreasing the diversity of native riparian and aquatic species.	Early detection and control of invasive non native plant species may preserve ecosystem processes that support native riparian and aquatic biodiversity.	Invasive non native plants (early detection) Structure and composition of riparian vegetation Aquatic macroinvertebrates

disturbances and stressors, 2) ecosystem exposure to anthropogenic stressors that drive degradational processes, and 3) ecosystem condition—the functional status of ecological processes required to sustain the ecosystem. The models show tight linkages between soil resources and vegetation, emphasizing the importance of integrating vegetation condition monitoring with monitoring of soil stability and upland hydrologic function.

In contrast to the dryland models, fire was featured in the montane models as the primary driver of montane ecosystems. The montane models depict various historical and current fire regimes for the major montane ecosystems, but across all systems there is a clear need to monitor fire, climate, and vegetation in order to ascertain ecosystem dynamics. As with dryland systems, climate is a major driver of montane systems and must be monitored because of the potential interactions with fire and insect outbreaks to cause changes in vegetation condition.

Models of riparian and aquatic ecosystems emphasize that these systems are primarily driven by streamflow variability and geomorphic processes associated with channel change (Table 3-5). The models also indicate a tight linkage between flood plain soil resources and moisture availability for riparian vegetation. These processes and interactions provide the dynamic physical template upon which riparian and aquatic biotic communities are organized. Therefore, direct monitoring of stream discharge, cross-sectional channel geometry, related shallow alluvial groundwater dynamics, and riparian vegetation structural complexity represent important leading indicators of change in riparian and aquatic ecosystems. The models further illustrate that because of strong longitudinal and lateral connectivity to upland ecosystems, monitoring of riparian vegetation condition (e.g., increases in non-native plant populations) and stream macroinvertebrates (e.g., changes in functional feeding groups) provide important insights into degradational changes in water quantity and quality. These changes are the result of climatic factors as well as broad-scale, anthropogenic changes in water- and land-use such as groundwater extraction and livestock grazing. Thus, monitoring climate and land-cover patterns at a watershed scale is important for interpreting change in riparian and aquatic ecosystems as well, since these factors influence the delivery of water and sediment from the uplands to receiving streams.

CHAPTER 4

SAMPLING DESIGN

4.1 INTRODUCTION

This chapter presents the sampling design for the network's core vital signs. The design describes the process for selecting sampling locations and the allocation of sampling effort through time among locations. A primary goal of the design is to provide unbiased and defensible inferences from sample observations to the intended target populations. A brief overview of sampling definitions and concepts is presented below followed by a description of the statistical sampling designs the SCPN employs for vital signs monitoring.

4.2 SAMPLING CONCEPTS AND DEFINITIONS

Survey sampling is the foundation for the SCPN monitoring plan. Defining the finite (target) population and using probability sampling are two critical aspects of survey sampling (Cochran 1977). A given area for which inferences are desired (e.g., a forest or stream within a park) can be partitioned into a finite collection of non-overlapping sample units. In general, sample units are predefined entities in which measurements are taken. The total collection of sample units is the (target) population. This set of units, also known as the sampling frame, is the pool from which samples are selected in order to make inferences to the rest of the unsampled population. Sample units can be represented as points (e.g., springs), linear features (e.g., stream segments), or areas (e.g., mapped soil types, or pixels from remotely sensed images). Responses are the measurements taken on the sample units. The collection of responses from the chosen sample units is called the sample. Probability sampling is where each sampling unit in the finite population has a known probability (a selection probability) of being included in a sample. Each unit can have the same selection probability (equal probability sampling) or the probabilities may vary among groups of units (unequal probability sampling). Where possible, we have chosen a probability sampling approach to monitor vital signs of the SCPN.

Two common methods for selecting samples are simple random sampling and stratified random sampling. For a simple random sample, a random process is used to select the desired number of sampling units from a known population. In this scheme, each member of the population has an equal chance of being included in the sample. In stratified random sampling, the sampling frame is divided into sub-populations by using mutually exclusive strata. The desired number of samples is then randomly selected from each sub-population. Strata are artificial constructs defined prior to sample selection that should never change, regardless of conditions on the ground (Geissler and McDonald 2003). Strata are typically defined such that variation within a stratum is less than among strata. Reasons for using this technique include increased precision, increased efficiency, and greater information about sub-populations (Cochran 1977, Lohr 1999). Vegetation types have often been used as strata, but, because vegetation may change in a particular area over time, this approach leads to problems with data analysis and future sample selection decisions. Domains are sub-populations (e.g., vegetation types)

Table 4-1. Tabular and notational representation of three example revisit designs. "X" in a cell denotes that all members of the panel are sampled during that occasion.

	SAMPLE OCCASION							
PANEL	1	2	3	4	5	6	7	8
	Always Revisit Design [1-0]							
1	X	X	X	X	X	X	X	X
	Never Revisit Design [1-n]							
1	X							
2		X						
3			X					
4				X				
5					X			
6						X		
7							X	
8								X
	Split-Panel Design [1-0, 1-4]							
1	X	X	X	X	X	X	X	X
1	X					X		
2		X					X	
3			X					X
4				X				
5					X			

defined after sampling occurs, can be changed, and are used during data analysis to derive estimates of the sub-populations of interest.

Most sample designs of the SCPN rotate field sampling efforts through various sets of sample units over time. A group of sample units that are always sampled together during a sampling occasion is called a panel. Sample effort can be rotated among panels through time, which effectively rotates field effort among sample units and therefore space. The way in which units in the population become members of a panel is called the membership design (McDonald 2003). The pattern of visits through time to all panels is the revisit design, which specifies the temporal sampling schedule. The notation commonly used for revisit designs is a pair of digits. The first digit is the number of consecutive occasions that a panel is sampled, the second is the number of consecutive occasions that a panel is not sampled (McDonald 2003). For example, if a single panel is visited every sampling occasion, its revisit design can be expressed as [1-0] (Table 4-1). If a panel is to be sampled once, then never revisited, the notation is [1-n]. The notation [1-0, 1-4] signifies that units in panel one are visited every occasion and units in the second set of panels are visited once every 5 years (Table 4-1).

4.3 SAMPLE SELECTION

SCPN monitoring efforts are using five fundamentally different schemes for collecting measurements on vital signs. (1) Grid-based sampling uses a grid of points to represent units of a target population and draws a probability sample. (2) Linear-based sampling delineates sampling units along linear segments and draws a probability sample. (3) List-based sampling constructs a list of sample units and either draws a probability sample or attempts to census all units. (4) Index sites are used to collect information on areas or points that were hand-picked to yield adequate data on a particular vital sign. These samples are usually picked as "representative" sites, and statistical inference to a larger area is not possible because a probability sample was not employed. (5) For certain vital signs, sampling is not required because they can be monitored at the full spatial extent of a park.

Table 4-2. Summary of sampling design, spatial allocation of samples, and revisit plan for monitoring of SCPN vital signs.

SAMPLING DESIGN	SCPN VITAL SIGN	SPATIAL ALLOCATION	REVISIT PLAN
Grid-Based	Upland vegetation composition and structure [1]	GRTS	[2-3, 1-4] *
	Upland hydrologic function [1]	GRTS	[2-3, 1-4] *
	Upland soil / site stability [1]	GRTS	[2-3, 1-4] *
	Upland bird communities	GRTS	TBD
	Invasive non-native plants	GRTS	[1-4]
Linear-Based	Riparian vegetation composition and structure [2]	GRTS	[1-4]
	Stream flow and depth to groundwater [2]	GRTS	Continuous to monthly
	Channel morphology [2]	GRTS	[1-4]
	Water quality of streams	GRTS	Quarterly
	Aquatic macroinvertebrates of streams	GRTS	[1-0]
	Riparian bird communities	GRTS	TBD
List-Based	Ground-dwelling arthropods	GRTS	TBD
	Spring, seep, and tinaja ecosystems	GRTS	TBD
Index Sites	Ozone, wet & dry deposition, visibility and particulate matter	NA	Continuous
	Climate conditions and soil moisture	NA	Continuous
	Night sky condition	Judgment	TBD
	Natural soundscape condition	Judgment	TBD
	Riparian vegetation composition and structure [2]	GRTS	[1-4]
	Stream flow and depth to groundwater [2]	GRTS	Continuous to monthly
	Channel morphology [2]	GRTS	[1-4]
	Water quality of streams	Judgment	Quarterly
	Aquatic macroinvertebrates of streams	Judgment	[1-0]
	Spring, seep, and tinaja ecosystems	Judgment	TBD
Census	Land use/land cover and landscape vegetation patterns	NA	[1-4]
	Vegetation condition	NA	Seasonal to annual
	Vegetation disturbance patterns	NA	[1-4]

1 Co-located, co-visited as part of the Integrated Upland Protocol
2 Co-located, co-visited as part of the Integrated Riparian Protocol
** Potential revisit plan for medium-size parks (revisit plan varies by park size).*

For these vital signs, a census is employed to observe status and trends. This chapter contains a section for each of the five sampling schemes with further details presented by vital sign. A summary of sampling designs, spatial allocation of samples, and revisit plans for vital signs monitoring is presented in Table 4-2.

4.4 SPATIAL ALLOCATION AND FACTORS INFLUENCING SAMPLE SELECTION

Traditionally, methods used to determine sampling units in a population generally have employed a form of random sampling along with an attempt to distribute the units such that good interspersion is achieved throughout the population. The SCPN uses two methods to spatially allocate sample units. The majority of vital sign sampling units are chosen with the relatively new Generalized Random-Tessellation Stratified (GRTS) design (Stevens and Olsen 2004). The purpose of the GRTS design is to produce a spatially balanced random sample, and it can be applied to populations consisting of points, linear features, or areas. In general, GRTS disperses sample units evenly over the extent of the sampling frame and is more efficient than simple random sampling (Stevens and Olsen 2004). The method uses a function that maps two-dimensional space (area) into one-dimensional space (linear) and employs a restricted randomization algorithm to produce randomly ordered linear results that are spatially well-balanced (Stevens and Olsen 2004). The flexibility of the GRTS design allows for maintaining a spatially balanced random sample in each of the following cases: selecting any number of sample points from the resulting output, replacing samples that are lost because in the field they are discovered to be part of the nontarget population or are inaccessible, and adding new samples to monitor a particular vital sign when funding levels or other resources are increased. SCPN is also using judgment samples for spatial allocation in a limited number of situations. This method is used to monitor water quality at sites that have a long history of data collection, to monitor night sky and natural soundscape condition, and to monitor springs in parks that contain relatively few occurrences of these ecosystems.

The SCPN monitoring program will consider several factors when selecting sampling sites including accessibility, travel costs, and efficiency. Given the often steep, rugged, and remote terrain that exists within many SCPN parks, access to many potential sampling sites is either prohibitively expensive, presents safety issues, and/or is practically impossible for human ground or water-based surveys. Two parks in particular (GLCA and GRCA) have vast amounts of backcountry with limited access and present significant sampling challenges. To address these issues and to modify the sampling frame accordingly, geospatial data sets of accessibility and travel costs will be created for each park unit using the Landscape Access Model (developed by S. Garman, NCPN). In this model, steep slopes (e.g., > 50%) within a park are delineated, classified as inaccessible, and excluded from the sampling frame. Travel costs (i.e., slope-corrected hiking distances) are also created using road and trail layers and DEMs (digital elevation models). Selection probabilities are then assigned to discrete travel cost classes (e.g., < 2 km, 2 to 4 km, and > 4 km).

Another method of sampling sites efficiently is to co-locate and co-visit multiple vital signs. Co-location is monitoring multiple vital signs at the same physical location, and co-visitation is taking measurements on multiple vital signs during a sampling occasion. Monitoring multiple vital signs at the same place and time increases operational efficiency because costs associated with travel, plot set-up, and sampling are much less than those associated with individual and separate monitoring efforts. The SCPN will employ the efficiencies of co-location and co-visitation in two integrative efforts: monitoring three vital signs associated with upland soils and vegetation and monitoring the aquatic resource vital signs including water quality, aquatic macroinvertebrates, and the integrated riparian protocol. A mixed approach will be used to select aquatic rescource monitoring sites: a linear-based design, use of judgement to identify suitable index sites, or a combination of the two.

4.5 GRID-BASED SAMPLING

Grid-based sampling is the primary spatial sampling method for vital signs associated with upland soils, upland vegetation, and bird monitoring. The sampling frame is constructed as a randomly oriented grid of equidistant points. The points represent the center of a sampling unit or plot. Some points may then be eliminated because of accessibility problems and/or prohibitive costs associated with access. Unique and non-overlapping sampling units thus represent the accessible target population of a vital sign. Specific details of grid-based sampling are described below for each vital sign.

4.5.1 *Upland Vital Signs*

SCPN staff will concurrently monitor vegetation composition and structure, upland hydrologic function, and upland soil/site stability at co-located ground-based sampling plots. The initial sampling frame is a randomly-oriented systematic grid of evenly-spaced (100m) points (e.g., Figure 4-1A). Inaccessible

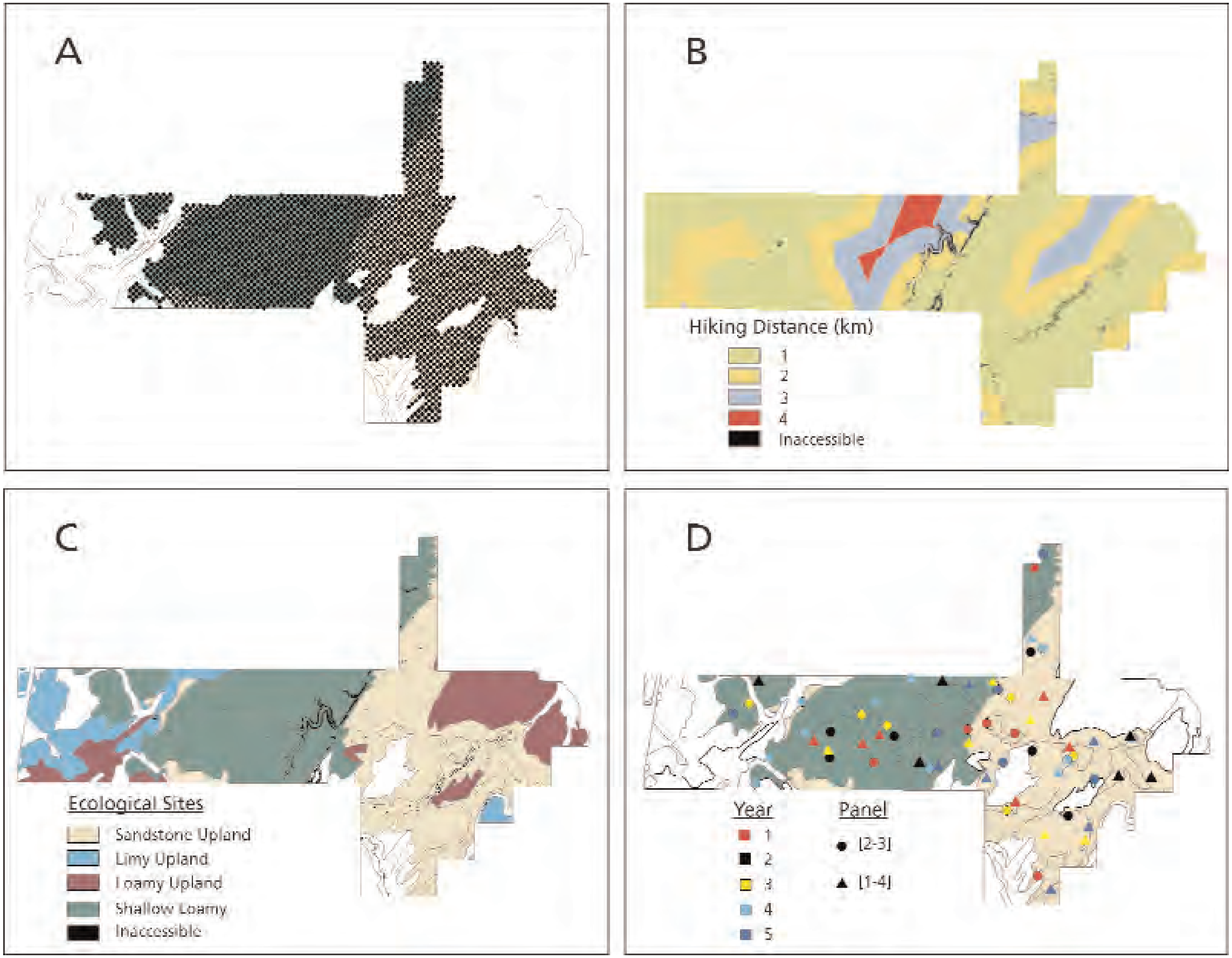


FIGURE 4-1. *Spatial data layers used to create an accessible and spatially balanced random sample (GRTS) for monitoring upland vital signs in Wupatki National Monument. (A) Sampling frame with 100m spacing for two target ecological sites (Frame program, S. Garman, NCPN). (B) Accessibility and travel cost layer showing hiking distances (LAM, S. Garman, NCPN). (C) Ecological sites (NRCS). (D) GRTS sample with 30 sampling locations for each of the two target ecological sites (Sandstone Upland and Shallow Loamy) with the split-panel revisit design shown in Table 4-3a.*

points will be eliminated from the initial frame (e.g., Figure 4-1B). We will also eliminate points that occur in riparian areas (using a geospatial data set of riparian corridors created for each park using 10m digital elevation models). Upland vital signs are measured on 3 evenly-spaced, parallel transects within a 1 ha plot centered on the grid point. The 100m grid spacing ensures unique, non-overlapping sampling plots.

SCPN has adopted the characterization of landscapes into ecological sites as the basis for sampling site selection for monitoring upland vital signs. An ecological site is a landscape division with specific physical characteristics that differs from other landscape divisions in its ability to produce distinctive types and amounts of vegetation and in its response to management (Society for Range Management Task Group on Unity in Concepts and Terminology 1995). Ecological sites have characteristic soils, hydrology, plant communities, and disturbance regimes and responses (Natural Resources Conservation Services 2003). A map of four ecological sites (derived from NRCS soil map units and associated data) within Wupatki National Monument is shown in Figure 4-1C as an example. The following criteria (from http://esis.sc.egov.usda.gov/ESIS/About.aspx, accessed during May 2006) are used to differentiate one ecological site from another:

- Significant differences in the species or species groups that are in the characteristic plant community.
- Significant differences in the relative proportion of species or species groups in the characteristic plant community.
- Soil factors that determine plant production and composition, the hydrology of the site, and the functioning of the ecological processes of the water cycle, mineral cycles, and energy flow.
- Differences in the kind, proportion, and production of the overstory and understory plants due to differences in soil, topography, climate, and environment factors, or the response of vegetation to management.

There are several advantages to using ecological sites to determine target areas for sampling. Ecological sites are defined by a US federal agency (NRCS), and because SCPN parks span four US states, it's important to use an upland classification system that is at least regional in scope. Individual ecological sites are expected to occur in distinct areas on the landscape. This will be useful in stratifying natural variation in areas (parks) with similar climates. Because ecological sites contain characteristic soils that have developed over time, they can often be distinguished from each other on the basis of other soil development factors, including parent material and landscape position (Bestelmeyer et al. 2004). As defined, ecological sites are not expected to change, and SCPN is using them as strata to define upland target populations. Additionally, ecological sites are characterized by state and transition models that describe vegetation dynamics and management interactions with each site. These models are useful for determining which ecological sites are more resistant and resilient to disturbances (Bestelmeyer et al. 2004). Monitoring ecological sites will also help to ensure that status and trend observations will be interpretable within and among the interrelated upland vital signs. Many of our monitoring questions pertain to changes that occur within the predominant vegetation types (e.g., what are the trends in bare soil and canopy cover within pinyon-juniper woodlands?). These and other related questions are evaluated through the use of domains (e.g., vegetation types) during data analysis.

The process for selecting ecological sites to monitor is as follows. First, ecological sites that represent the target ecological systems are selected. The potential area (or sampling frame) is evaluated in terms of its size and accessibility. If the potential sampling frame poses significant limitations for monitoring because of these issues (e.g., the extensive desert grasslands and shrublands below the rim at Grand Canyon NP), the frame is refined to include ecological sites that are reasonably accessible and are of high management concern to park resource managers.

For ecological sites without significant accessibility problems, the sampling frame is adjusted by masking out inaccessible sites (using the Landscape Access Model) and a geospatial data set of travel cost is created. Sampling sites are then allocated using a GRTS sample (e.g., Figure 4-1D) with unequal probabilities. Selection probabilities are based on travel costs and the spatial extent of the targeted ecological sites.

In designing a network-wide sampling approach for these vital signs, we recognized that there are vast differences in SCPN park sizes and decided that one size does not fit all. Six of the target parks are less than 3,000 ha in size, and nine of the remaining target parks range from 13,254 to 505,868 ha. The revisit design will vary by park size (e.g., small, medium, and large). For the six small parks (AZRU, ELMO, NAVA, PETR, SUCR, WACA), one objective is to employ an operationally efficient design by sampling parks that are geographically close to one another. For the nine larger parks, two potential revisit designs are shown in Table 4-3. A number of

Table 4-3. Two potential revisit designs for monitoring upland vital signs.

	YEAR							
PANEL	1	2	3	4	5	6	7	8
1	X	X				X	X	
2		X	X				X	X
3			X	X				X
4				X	X			
5	X				X	X		
1	X					X		
2		X					X	
3			X					X
4				X				
5					X			

(a) Split-panel design [2-3, 1-4] (each X represents a minimum of 3 plots).

	YEAR									
PANEL	1	2	3	4	5	6	7	8	9	10
1	X	X		X			X			X
2		X	X		X			X		
3			X	X		X			X	
4	X			X	X		X			X
5		X			X	X		X		
6			X			X	X		X	
7	X			X			X	X		X
8		X			X			X	X	
9			X			X			X	X

(b) Panel design adapted from a partially augmented serially alternating design (Urquhart and Kincaid 1999). Each X represents a minimum of 3 plots.

factors may influence the selection of a final revisit design, including analysis of spatial and temporal variation from sampled plots after the first several years of monitoring, simulation studies, analysis of other existing data where available, and consultation with local experts.

Panel membership is accomplished by assigning sequential sets of sampling points from the GRTS output to individual panels. As an example, using the panel design shown in Table 4-3a, the first 3 points of the GRTS output could be assigned to panel 1 of the [2-3] revisit design, points 4 to 6 to panel 1 of the [1-4] design, points 7 to 9 to panel 2 of the [2-3] design, points 10 to 12 to panel 2 of the [1-4] design, and so on until all panels are filled. Both of the designs in Table 4-3 balance the need to revisit sampling sites in consecutive years to collect trend data and account for annual variations with the need to spread samples out to capture spatial variation within targeted ecological sites.

4.5.2 *Upland Bird Communities*

Upland bird communities will be monitored in 5 SCPN parks (BAND, GRCA, MEVE, PEFO, and WUPA). The goal is to provide status and trends of bird communities in several upland habitats (e.g., pinyon-juniper woodland) that commonly occur across these parks. The initial target populations for bird monitoring are a subset of the target ecological sites designated for upland vital signs monitoring. For each of the target ecological sites, the sampling frame is a randomly-oriented systematic grid of points that are evenly spaced 250m apart. Depending on topography and the spatial extent of the target populations, monitoring is conducted on either 2 linear transects consisting of 15 points each (spaced 250m apart) or on 3 linear transects of 10 points each (spaced 250m apart), for a total of 30 sites per target population. Using GIS, each point in the sampling frame is evaluated for its use as a starting point in locating either a 10-point or 15-point linear transect within the target ecological site(s). Thus, the sampling frame is modified to include only those points capable of including the desired transect length (2.25 km or 3.5 km). The sampling frame is further adjusted by masking out inaccessible sites (using the Landscape Access Model). In addition, a geospatial data set of travel costs is created. Sampling sites (and corresponding transects) are then allocated by generating a GRTS sample with unequal probabilities. Selection probabilities are based on travel costs. Each sampling point along a transect is sampled 3 times per year (during the breeding season), and the revisit design is yet to be determined.

At each of the transect points, a 10-minute survey is performed. Observations of birds by sight or call are recorded along with the distance from point center to the first detection of an individual. We will use the histogram of detection distances to estimate a function that accounts for decreased probability of detection at large distances. The software program Distance (Laake et al. 2004) performs estimation of the detection function and the density for each species (Buckland et al. 2004). Observations of target species are also recorded while walking between point locations along the transect. Target species are those that are uncommon or of special concern and that typically are under-represented on point-count surveys. Detection distances are recorded for target species. However, given the tendency for a limited number of observations of these species, transect observations generally provide status rather than trend information.

For monitoring nesting success of selected bird species, SCPN employs a dual frame approach to sampling. Within the target ecological sites, a second list-based sampling frame is composed of known locations of nesting sites derived from previous and current sampling. Sampling sites are selected from the list-based sampling frame for each target ecological site by using an unequal probability GRTS sample. Selection probabilities are based on accessibility (travel costs), and inferences are made within target populations from sampled to unsampled nests. The revisit design is to be determined.

4.5.3 *Invasive Exotic Plants*

Detection of new populations of invasive exotic species prior to establishment in areas of management significance is the focus of this vital sign. The initial sampling frame is a randomly oriented systematic grid of points with a large spacing (> 500m) within each park, which is then adjusted by masking out inaccessible areas. Predictive models of exotic plant invasion and dispersal will be used to create geospatial zones of invasibility for each park. These zones differ in their degree of vulnerability to invasion based on several factors including (1) propagule pressure and invasion pathways, (2) resource availability, (3) physical site attributes, and (4) vegetation cover. Sampling sites are allocated by generating a GRTS sample with unequal selection probabilities due to invasibility. Sampling sites are members of a single panel monitored once every five years ([1-4]). We will rotate monitoring effort among the SCPN park units (e.g., four parks monitored per year).

Given the vast areas of management significance in the SCPN, detecting new occurrences of exotic species is likely to be a rare event. Thus, we are employing adaptive sampling for this vital sign. Using decision rules that vary by species and by the spatial extent of new populations, sampling intensities can increase around the newly detected populations. Although this method is cost-efficient, it will introduce bias for which we will account using estimators developed for adaptive designs (Thompson 2002).

4.6 LINEAR-BASED SAMPLING

Linear-based sampling is the primary spatial sampling method for vital signs associated with riparian and aquatic habitats. These vital signs will be monitored within linear corridors associated with flowing water. River and stream populations are resources that occur only on a linear-based network within a bounded area (Stevens and Olsen 2004). To sample linear resources, the finite populations are often divided into discrete and arbitrary fixed-length intervals (Stevens and Olsen 2004). SCPN has adopted this approach. The location and extent of SCPN target populations are connected, non-overlapping segments of streams and rivers. Specific details of linear-based sampling are described below for each vital sign.

4.6.1 *Integrated Riparian*

The integrated riparian vital signs including riparian vegetation composition and structure and channel morphology will be monitored concurrently at co-located sampling locations at twenty sites selected using a linear-based sampling design. Additionally, streamflow will be monitored at nineteen of these sites, and depth to alluvial groundwater will be monitored at eight of the sites. The monitoring focus is on intermittent and perennial streams. At four parks (BAND, GLCA, GRCA, and PEFO), water quality, aquatic macroinvertebrate, and integrated riparian vital signs are co-located at sites selected using linear-based sampling. A list of streams selected for integrated riparian monitoring is presented in Table 4-4.

Table 4-4. Preliminary list of perennial (P) and intermittent (I) rivers and streams selected for monitoring riparian and aquatic vital signs. "L" designates vital signs monitored using linear-based sampling, and "In" denotes those signs monitored using index sites.

PARK	RIVERS & STREAMS	STREAM TYPE	INTEGRATED RIPARIAN				AQUATIC MACRO-INVERTEBRATES	WATER QUALITY
			Riparian Vegetation Composition & Structure	Channel Morphology	Stream Flow	Depth to Groundwater		
AZRU	Animas River	P	-	L	-	In	-	In
BAND	Capulin Creek	P	L	L	L	-	L	L
	Rito de los Frijoles	P	-	-	-	-	In	In
CACH	Upper Tsaile Creek	P	L	L	L	-	In	In
	Lower Tsaile Creek - above Junction	I	L	L	L	L	-	-
	Lower Chinle Wash - above Junction	I	L	L	L	L	-	-
	Chinle Wash - below Junction	I	L	L	L	L	-	In
CHCU	Charo Wash	I	In	In	In	In		In
GLCA	Paria River	P	-	-	-	-	-	In
	Wahweap Creek	P	L	L			L	L
	Escalante River	P	L	L	L	-	In	In
	Coyote Gulch	P	L	L	L	-	In	In
	Lake Canyon	P	I	I	I		I	I
	Wilson's Creek	P	L	L	L	-	L	L
GRCA	Cottonwood Creek	I	L	L	L	-	In	In
	Hermit Creek	P	I	I	I		In	In
	Bright Angel Creek	P	L	L	L	-	L	L
	Kanab Creek	P	I	I	I		I	I
	Robbers Roost Creek	P	L	L	L	-	L	L
HUTR	Pueblo Colorado Wash	I	In	In	In	In		In
MEVE	Mancos River	P	L	L	L	L	In	In
NAVA	Keet Seel Canyon	P	L	L	L	-	-	-
PEFO	Puerco River	I	L	L	L	L		L
PETR	North Boca Negra Arroyo	I	-	In	-	-	-	In
SAPU	Abó Arroyo	I	L	L	L	-	-	-
WACA	Walnut Creek	I	L	L	L	L	-	-
WUPA	Little Colorado River	I		I				

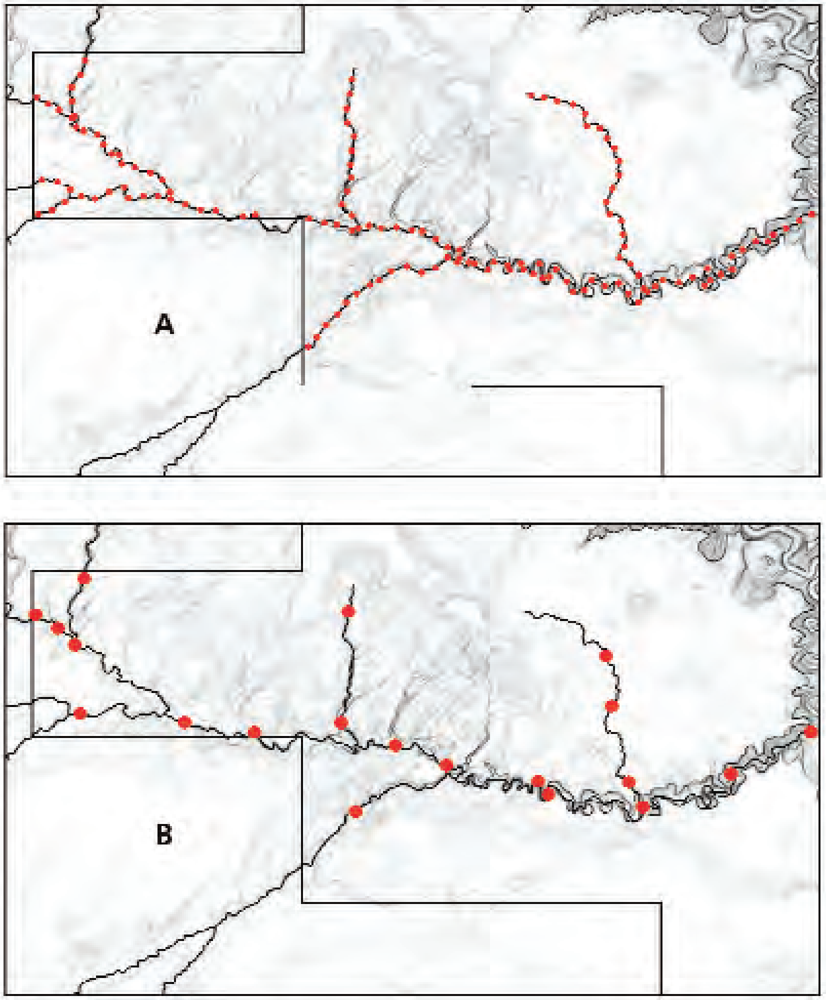


Figure 4-2. *Example of the sampling design for monitoring riparian and aquatic vital signs.*

(A) Sampling frame composed of points spaced 300m apart in Coyote Gulch and associated tributaries in Glen Canyon NRA. (B) A GRTS sample of 20 sampling locations.

A hierarchical, process-based stream classification guides the sampling design. The classification system is based on three fundamental physical conditions: 1) the availability of water, 2) the spatial and temporal patterning of sediment storage, and 3) the balance between stream power and resistance of riparian vegetation. Classification is accomplished using topographic maps, remotely sensed data, and field verification. The objective of the classification is to group functionally similar physical environments and channel types and to classify stream channels by their potential response to disturbances. Selected watersheds of individual stream systems represent the bounds of the targeted populations.

There are multiple sampling frames corresponding to individual stream systems (e.g., the Escalante River in GLCA), and frames are stratified by stream order (i.e., main stem or tributary). Thus, inferences are made from sampled to unsampled stream units within similarly classified (valley segment, channel reach, and geomorphic setting) stream segments of the main stem or tributaries. For each stream system, the sampling frame is composed of sampling units that are equal distance apart. The frame is subdivided into stream segments for the main stem and segments for tributaries. The linear length of sampling units within the main stem is 500m and 300m for units within tributaries. The allocation of samples is determined from an unequal probability GRTS sample. Selection probabilities are based on geomorphic settings with certain settings (e.g., alluvial) having higher probabilities. Figure 4-2 shows an example of this design.

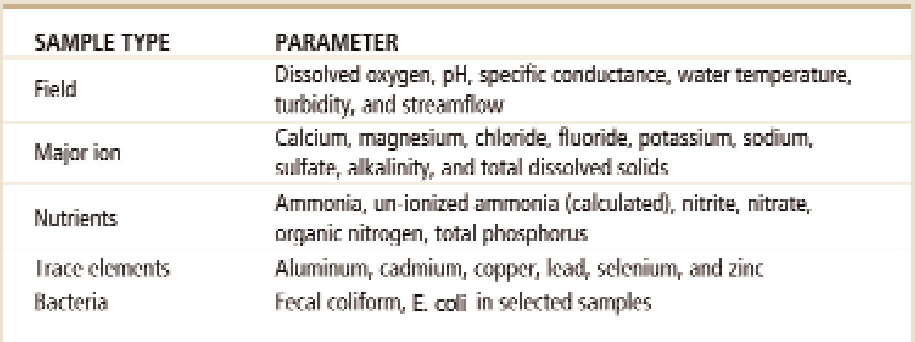
The revisit design varies by vital sign. Accessibility is a common issue for monitoring all of the vital signs in Table 4-4, and thus selection probabilities are based on travel costs. A rotating panel design similar to that used for monitoring upland vegetation will be used for sampling riparian vegetation and channel morphology, with a revisit plan of once every five years [1-4]. These vital signs can be affected by random disturbance events such as high-magnitude flooding. If extreme flooding occurs in a stream with an integrated riparian monitoring site, the site will be sampled as soon after the event as possible. Frequent site visits are required to adequately characterize stream flow and depth to groundwater, and the revisit plan is quarterly. Water level sensors and dataloggers used to monitor these vital signs will collect and store data at continuous to monthly intervals. Aquatic macroinvertebrate vital signs co-located with integrated riparian monitoring sites will be revisited once a year [1-0].

4.6.2 *Riparian Bird Communities*

Riparian bird communities will be monitored in five SCPN parks (BAND, CACH, GLCA, GRCA, and MEVE).

The target populations are the riparian corridors along the streams and rivers in these parks that are the focus of riparian and aquatic vital sign monitoring (Table 4-4). The bird sampling frame corresponds to individual stream systems. As with the monitoring of upland bird communities, points are sampled along linear transects and spaced 250m apart. The number of sampling points required for monitoring riparian bird communities within a stream ecosystem is to be determined. The sampling points selected for riparian and aquatic vital sign monitoring (using a GRTS sample with unequal probabilities) represent the starting locations for the riparian bird transects. If the initial starting point is insufficient to fully include the minimum transect length within the target riparian corridor, additional points are selected from the GRTS sample (while maintaining the spatially balanced order). Each sampling point along a transect is sampled 3 times per year (during the breeding season), and the revisit design is to be determined.

Table 4-5. Water quality sample types and parameters.



SAMPLE TYPE	PARAMETER
Field	Dissolved oxygen, pH, specific conductance, water temperature, turbidity, and streamflow
Major ion	Calcium, magnesium, chloride, fluoride, potassium, sodium, sulfate, alkalinity, and total dissolved solids
Nutrients	Ammonia, un-ionized ammonia (calculated), nitrite, nitrate, organic nitrogen, total phosphorus
Trace elements	Aluminum, cadmium, copper, lead, selenium, and zinc
Bacteria	Fecal coliform, *E. coli* in selected samples

4.6.3 *Water Quality of Streams*

The SCPN water quality monitoring effort is designed to collect and interpret water quality data to support NPS and network water quality objectives including determination of status and trends in the water quality of selected streams. Priorities for monitoring include impaired stream reaches and relatively pristine waters. The stream water-quality and integrated riparian vital signs will be co-located at seven streams in SCPN parks. The aquatic macroinvertebrate vital sign will also be co-located at most of these sites. Sample design is described in Section 4.6.1. Streams were chosen because one or more of the following conditions were met:

- presence of documented water quality impairments
- existence of potential threats to water quality
- presence of pristine conditions
- availability of a significant amount of historic water quality data, and/or
- water quality data is needed to meet the resource management needs at selected parks.

A list including eight streams selected for stream water-quality monitoring using a GRTS sample with unequal probabilities is presented in Table 4-4 and on Figure 4-3.

The revisit design for monitoring stream water quality is monthly to quarterly and will be determined on a site-specific basis. Monitoring these sites will provide representative data at site and network levels because most of the significant surface-water sources identified in the scoping phase of vital sign selection are included in this sample, and the revisit plans will be designed to obtain water quality data representing a wide range of hydrologic conditions (Appendix I). The final panel design for monitored streams will be largely contingent on schedules and budgets of other monitoring efforts and partnerships that can be developed. Monitoring of the aquatic resource vital signs, including water quality, will be directly managed and funded by the SCPN.

Water quality field parameters measured at each selected stream site include dissolved oxygen, pH, specific conductance, water temperature, turbidity, and streamflow. Water samples collected at each index site will be analyzed for a suite of parameters including major ions, nutrients, selected trace elements, and in some cases bacteria (Table 4-5). Additional parameters will be selected at certain sites based on known or suspected water-quality issues. Parameter selection was restricted to parameters most likely to produce a data set useful for assessment of status and trends in park water-quality conditions and early warning of threats to water quality.

4.7 LIST-BASED SAMPLING

List-based sampling is the spatial sampling method for monitoring terrestrial arthropods and is one of the spatial sampling methods for vital signs associated with spring ecosystems and aquatic habitats (water quality and macroinvertebrates). The location and extent of target populations for arthropods will be developed from grids (modified to include only highly accessible sites), while target populations for springs are from inventories. Both are organized into lists to derive sampling locations. Further details of list-based sampling are described below.

4.7.1 *Ground-Dwelling Arthropods*

The monitoring of ground-dwelling arthropods will be limited to a few sites within pinyon-juniper woodland habitat in two SCPN parks (GRCA and MEVE). The sampling frame (one for each park) consists of a list of accessible upland sites (derived from the upland vital signs grid-based sampling frame) of the target habitat. Sampling sites are allocated by generating a GRTS sample with equal probabilities. Arthropod sampling will occur three times during the growing season, and the revisit design is to be determined.

4.7.2 *Spring Ecosystems*

Due to the large number of springs and relatively few spring types at GLCA, this is the only park where we will use a list-based sampling scheme. The sampling frame is a list of known spring locations derived from previous and current inventories. Sampling sites are selected by using an unequal probability GRTS sample. Selection probabilities are based on accessibility (travel costs), groundwater flow systems, and spring type. Inferences are made within the park from sampled to unsampled springs that are part of the same groundwater flow system and spring type. The revisit design is to be determined.

4.8 INDEX SITES

Twelve vital signs are monitored using index sites. These include vital signs associated with air quality, weather and climate, wildland values, and water quality of streams. Vital signs associated with springs, seeps, and tinajas (i.e., water quality, vegetation composition and structure, spring flow, and macroinvertebrates) are also monitored using index sites in all parks except Glen Canyon. Index sites are specific points or locations that are hand-picked by lead investigators and monitored to yield adequate data on a particular vital sign. The use of index sites is justified because of the high costs of the surveys or equipment involved in the measurements. In some cases (e.g., water quality sites), an index approach was selected to maintain continuity with existing data sets. Statistical inference to a larger area (such as a park or portion of a park) is not possible because the index sites were not chosen with a probability sample. However, monitoring these vital signs at specific sites is appropriate because they contain the vast majority of the population of monitored subjects or the spatial fluctuation in measures across a larger area is inconsequential for long-term monitoring purposes.

4.8.1 *Air Quality*

At present, air quality monitoring is occurring at Bandelier NM, Grand Canyon NP, Mesa Verde NP, and Petrified Forest NP. Three vital signs (ozone, wet and dry deposition, and visibility and particulate matter) will continue to be monitored at existing stations within these parks by programs external to the SCPN I&M effort.

4.8.2 *Weather and Climate*

Climate conditions are monitored at existing climate and precipitation monitoring stations. An inventory of climate stations across all NPS I&M networks is currently being conducted by the Western Region Climate Center (administered by NOAA, National Oceanic & Atmospheric Administration). When completed for SCPN, the inventory results will be used to evaluate the existing protocols, metadata, and spatial coverage of climate data across the network.

To support interpretation of trend data from the upland monitoring plots, additional micro-climate stations may be located near these plots. These temperature and rain gauges will have a recording frequency ranging from 15 minutes to 1 hour.

4.8.3 *Wildland Values*

The status and trends of two vital signs, night sky condition and natural soundscape condition, are monitored at index sites that were independently selected. Sampling sites are located within parks that contain substantial wilderness or backcountry areas. The revisit design is to be determined.

4.8.4 *Water Quality of Streams*

The focus of the SCPN water quality monitoring effort is to collect and interpret water quality data to support NPS and network water quality objectives. Emphasis is on perennial and intermittent streams in the SCPN parks. Thirteen streams in SCPN parks function as index sites for water quality monitoring (Table 4-4 and Figure 4-3). Streams were chosen because one or more of the following conditions were met:

- presence of documented water quality impairments
- existence of potential threats to water quality
- water quality data is needed to meet the resource management needs

In addition, specific index water-quality monitoring sites at each stream were selected where:

- a significant amount of historic water quality data are available
- an active stream flow gage exists, or
- known water quality threats exist

Water quality parameters, stream flow and, in some cases, aquatic macroinvertebrates are monitored at selected sites (Table 4-4). Stream flow gages are associated with eight of the selected water quality monitoring sites (Appendix I).

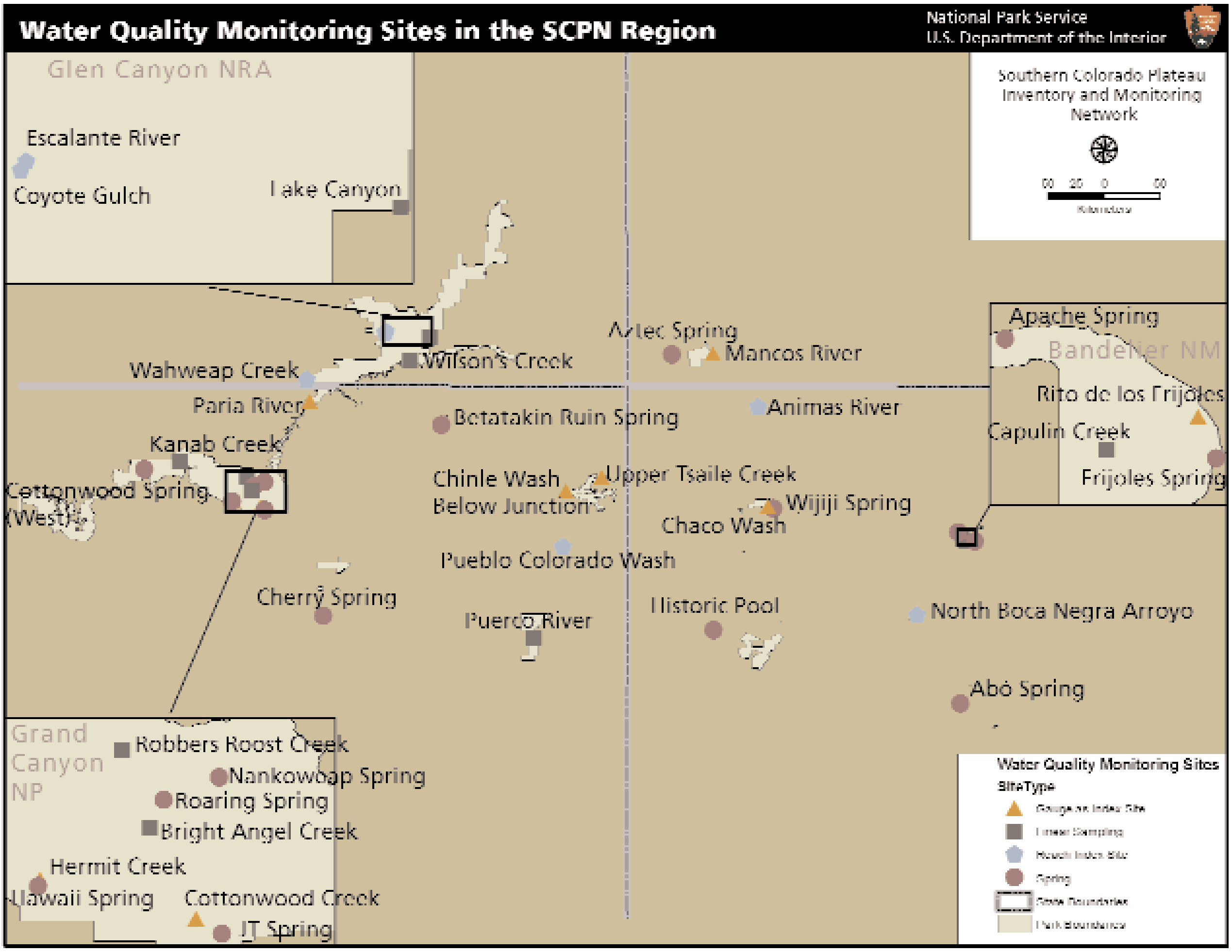


FIGURE 4-3. *Map of proposed water quality monitoring sites at index springs, streams, and rivers.*

Currently water quality monitoring programs exist in only two SCPN parks. Water quality monitoring that partially addresses critical data needs is ongoing in GLCA and GRCA. Details regarding the scope and utility of these monitoring efforts are presented in Appendix C.

The revisit designs for monitoring stream water quality field parameters that will be measured at each selected stream site are described in Section 4.6.3.

4.8.5 *Aquatic Macroinvertebrates of Streams*

The aquatic macroinvertebrate vital sign is monitored in conjunction with water quality at index sites within streams at BAND, CACH, GLCA, GRCA, and MEVE (Table 4-4). The revisit design for aquatic macroinvertebrates is annual [1-0]. Sampling should be conducted during base-flow conditions, and timing of sampling will be determined on a site-specific basis. Appropriate index periods established by State or Federal agencies will be used.

4.8.6 *Spring, Seep, and Tinaja Ecosystems*

Four vital signs are monitored at springs, seeps, and tinajas using index sites. The vital signs are vegetation composition and structure, flow, aquatic macroinvertebrates, and water quality. The spring index sites are distributed in parks that contain few occurrences of these ecosystems and in GRCA, a park that has significant numbers of springs and tinajas (Table 4-6 and Figure 4-3). Proposed index sites at GRCA were selected to represent springs discharging from principal aquifers of the north and south rims, to include a variety of spring types, and to include pristine and developed sites. Both CACH and MEVE have numerous seeps and springs. Information describing these resources is limited and monitoring sites at these parks will be selected following further inventory and reconnaissance.

4.9 CENSUS

Satellite imagery is used to monitor three vital signs associated with ecosystem patterns and processes. These vital signs are: land use/land cover and landscape vegetation patterns, vegetation condition, and vegetation disturbance patterns. Monitoring is a census approach (rather than sampling) because imagery is acquired for the full spatial extent of the park or for the full extent of the greater park ecosystem. The greater ecosystem includes the area of the park and the lands surrounding it that potentially influence the park area. Criteria used to define the greater ecosystem include gravitational flows (erosion potential), animal habitat corridors for dispersal or migration, and potential corridors for exotic plant invasion. Monitoring the greater park ecosystem occurs for the land use/land cover and vegetation condition vital signs.

4.9.1 *Land Use/Land Cover and Landscape Vegetation Patterns*

This vital sign monitors the status and trends in the composition, extent, and distribution of land use/land cover and vegetation types on lands within and adjacent to SCPN parks. The data source for monitoring is satellite imagery with medium spatial and spectral resolution (e.g., digital Landsat data). Satellite scenes will be classified to create geospatial layers of the initial conditions (i.e., baseline maps) of land cover and vegetation indicators. With subsequent monitoring and additional imagery, change detection methods will be employed at the pixel level to assess direction and magnitude of spectral change. Pixels with spectral changes of sufficient magnitude are assigned to new land cover or vegetation types. The costs associated with acquiring and classifying digital images require a minimum revisit design of [1-4], or once every five years. Given the census approach, there is no membership design. Monitoring will be rotated among the SCPN park units with approximately four parks monitored every year.

4.9.2 *Vegetation Condition*

This vital sign monitors vegetation greenness and productivity on park lands and the surrounding landscape. Digital data from the MODIS instrument aboard the Terra satellite

Table 4-6. A preliminary list of springs (S) and tinajas (T) selected for monitoring four vital signs.

PARK	SITE NAME	SITE TYPE	VEGETATION COMPOSITION & STRUCTURE	SPRING FLOW	MACRO-INVERTEBRATES	WATER QUALITY
BAND	Frijoles Spring	S	X	X	X	X
	Apache Spring	S	X	X	X	X
CACH	TBD	-	-	-	-	-
	TBD	-	-	-	-	-
	TBD	-	-	-	-	-
CHCU	Wijiji Spring	S	X	X	X	X
ELMO	Historic Pool	T	X	X	X	X
GLCA	TBD	-	-	-	-	-
	TBD	-	-	-	-	-
	TBD	-	-	-	-	-
	TBD					
GRCA	JT Spring	S	X	X	X	X
	Hawaii Spring	S	X	X	X	X
	Nankoweap Spring	S	X	X	X	X
	Roaring Springs	S	X	X	X	X
	Cottonwood Spring (west)	S	X	X	X	X
MEVE	TBD	-	-	-	-	-
	TBD					
	TBD	-	-	-	-	-
	TBD	-	-	-	-	-
NAVA	Betatakin Ruin Spring	S	X	X	X	X
PEFO	Kokopelli Spring	T	-	X	-	-
SAPU	Abó Spring	S	X	X	X	X
WACA	Cherry Spring	S	X	X	-	X
YUHO	Aztec Spring	S	X	-	-	X

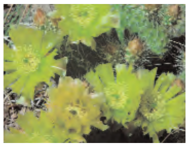
PHOTO BY LISA THOMAS, NPS

(with a spatial resolution of 250 m) will be used as surrogates to monitor vegetation greenness, annual productivity, length of season, and date and level of maximum production. Methods using MODIS Normalized Difference Vegetation Index (NDVI) data (available every 16 days) are employed to derive vegetation phenological metrics. Seasonal and annual NDVI curves are used to track vegetation green-up times, production levels, and senescence periods. Costs associated with acquiring and processing MODIS data are relatively low. These data are analyzed year-round for each greater park ecosystem. Vegetation condition is monitored seasonally and annually, and there is no membership design. Changes in vegetation condition are identified with year-to-year comparisons of NDVI curves. Monitoring data of associated vital signs (climate, vegetation disturbance patterns, and vegetation structure and composition) are used to understand changes to vegetation condition.

4.9.3 *Vegetation Disturbance Patterns*

This vital sign includes fire, insect, and disease disturbance and is monitored using satellite imagery with medium spatial and spectral resolution (e.g., digital Landsat data). Satellite scenes will be classified to create baseline maps that delineate the type, extent, and severity of disturbance. Existing maps will be used (when available) in cases involving large and recent disturbances. With subsequent monitoring and additional imagery, change detection methods will be employed at the pixel level to assess direction and magnitude of spectral change. Pixels are assigned to new disturbance classes if spectral changes of sufficient magnitude are detected. Monitoring data of associated vital signs (vegetation condition, climate, and vegetation structure and composition) will be used to understand large-scale changes to vegetation disturbance patterns. The costs associated with acquiring and classifying digital images require a minimum revisit design of [1-4], or once every five years. Given the census approach, there is no membership design. Monitoring will be rotated among the SCPN park units (e.g., four parks monitored every year) with a flexible schedule that is capable of responding to large-scale disturbances at a given park.

CHAPTER 5



MONITORING PROTOCOLS

Monitoring protocols are detailed study plans that explain how data are to be collected, managed, analyzed, and reported and are key components of quality assurance for natural resource monitoring programs (Oakley et al. 2003). In order to collect high-quality and consistent data over a period of decades, monitoring protocols include detailed standard operating procedures for all aspects of the project (Beard et al. 1999). As procedures are refined or modified through time, those changes are documented within the protocol.

While one may think of monitoring protocols as dealing primarily with sampling methods, effective protocols are more comprehensive. Monitoring projects that incorporate an initial investment in carefully defining objectives, identifying target populations, developing appropriate sampling designs, and determining how monitoring results will be analyzed and reported are more likely to succeed over the long term (Oakley et al. 2003). Consequently, these elements are essential to the monitoring protocols that will be developed through this program.

5.1 PROTOCOL DEVELOPMENT

Over the next five years (FY2006 – FY2010) the SCPN plans to develop 13 monitoring protocols that will cover 17 vital signs (Table 5-1). Most of these protocols will be developed in collaboration with the Northern Colorado Plateau Network. A wide range of academic and USGS scientists are involved in protocol development. Draft protocols will undergo peer review by 3 subject area experts, including a statistician. Table 5-2 summarizes the rationale and objectives for vital signs included in these 13 monitoring protocols. Detailed protocol development summaries are included in Appendix J.

5.2 STEPS TOWARD AN INTEGRATED MONITORING PROGRAM

Throughout the scoping and vital signs selection process, there was explicit recognition that SCPN parks required a balanced monitoring program incorporating vital signs to represent multiple spatial scales and ecological levels, as well as monitoring of key components, processes, and stressors. This need was reflected in the ecosystem characteristics that relate to ecological integrity (see Table 1-3) and in the use of the Jenny-Chapin model as the foundation for developing conceptual models (Chapter 2). The end result is a set of vital signs that will be complementary in their information content and provide an overall assessment of the condition of park ecosystems. By designing an integrated monitoring program that takes advantage of these complementary aspects, the resulting monitoring data will provide a "weight of evidence" approach in detecting changes in overall ecosystem integrity. In some cases, an integrated monitoring approach may also provide insight into the underlying causes of ecosystem change.

We can optimize the utility of the monitoring program by early consideration of important relationships between vital signs and an evaluation of which monitoring objectives require integrated data collection and/or interpretation. This is particularly important because financial resources and logistic constraints preclude our ability to measure everything everywhere.

Table 5-1. Vital signs, protocols and current cooperators for the SCPN. NCPN and SCPN are collaborating in protocols indicated in bold.

VITAL SIGN	PROTOCOL	COOPERATOR(S)
Climate conditions and soil moisture	Climate conditions and soil moisture	
Aquatic macroinvertebrates	**Aquatic macroinvertebrates**	USGS WRD (Anne Brasher)
Water quality of streams & springs	Water quality of streams & springs	SCPN In House
Channel morphology	**Integrated riparian**	USGS BRD (Mike Scott)
Stream flow & depth to groundwater		
Riparian vegetation composition & structure		
Spring, seep & tinaja ecosystems	**Spring, seep & tinaja ecosystems**	NAU (Abe Springer, Larry Stevens)
Soil stability & upland hydrologic function	**Integrated upland**	USGS-BRD (Mark Miller)
Upland vegetation composition & structure		
Upland bird communities	Habitat-based bird communities	NAU (Jennifer Holmes, Matt Johnson)
Riparian bird communities		
Ground dwelling arthropods	Ground dwelling arthropods	NAU (Neil Cobb)
Invasive exotic plants (early detection)	**Invasive exotic plants (early detection)**	USGS BRD (Matt Brooks, Kathyrn McEachern, Noel Pavlovic);UC-Davis (Robert Klinger)
Land use - land cover & landscape vegetation pattern	**Land use - land cover & landscape vegetation pattern**	USDA-Forest Service (Warren Cohen, Robert Kennedy); OSU (Zhiqiang Yang)
Vegetation condition and disturbance patterns	**Vegetation condition and disturbance patterns**	USGS EROS Data Center (Brad Reed); USU (Michael White)
Natural soundscape condition	Natural soundscape condition	
Night sky condition	Night sky condition	

Table 5-2. SCPN core vital signs, monitoring location, justification and objectives.

ECOLOGICAL MONITORING FRAMEWORK (LEVELS 1 & 2)	VITAL SIGN(S)	PARKS	JUSTIFICATION	MONITORING OBJECTIVES
Air and Climate: Air Quality	Ozone, wet and dry deposition, visibility and particulate matter	BAND, GRCA, MEVE, PEFO (thru existing programs)	Programs that monitor ecosystem health need to consider the composition of the atmosphere and its interactions with the biological and physical components of the ecosystems under investigation (Nash et al. 1995). These vital signs are being monitored in the four Class I parks within SCPN to ensure that Clean Air Act standards are being met.	Determine status and trends in 1) ozone, 2) wet and dry deposition, and 3) visibility and particulate matter in Class I parks.
Air and Climate: Weather & Climate	Climate conditions and soil moisture	All 19 Parks	Climate is a key driver of Colorado Plateau ecosystems. Because observed ecosystem trends may be in response to a variety of factors including short-term climate fluctuation, climate monitoring is crucial to interpreting trends in ecosystem condition. Winter precipitation is particularly important with respect to soil moisture conditions and vegetation establishment, survival, and vulnerability to fire. In semiarid landscapes, the composition and structure of plant communities depends largely on the amount and spatial distribution of soil moisture (Breshears and Barnes 1999). Measuring soil moisture in association with integrated upland monitoring sites will provide a critical link between broader climate monitoring and local vegetation patterns.	Provide monthly and annual summaries of climate data, including precipitation and temperature, and determine long-term trends in seasonal and annual patterns of climate parameters. Determine long-term trends in soil moisture.
Water: Water Quality	Aquatic macroinvertebrates	BAND, CACH, GLCA, GRCA, MEVE	Macroinvertebrates serve as bio-indicators of overall aquatic integrity. Because it focuses on living organisms, biological monitoring can detect chemical, physical, and biological impacts, as well as their cumulative effects (Karr and Chu 1999). Arizona and New Mexico are developing regulatory criteria relating to macroinvertebrates.	Determine status and trends in 1) the composition and abundance of aquatic macroinvertebrate assemblages and in 2) the distribution and condition of aquatic macroinvertebrate habitats, in selected perennial streams or stream reaches.
Water: Water Quality	Water quality of streams & springs	AZRU, BAND, CACH, CHCU, ELMO, GLCA, GRCA, HUTR, MEVE, NAVA, PEFO, PETR, SAPU, YUHO	This vital sign integrates the influences of climate, hydrologic function, geomorphology, and impacts resulting from flow diversion, effluent discharge, recreational use, grazing, resource extraction, exotic species, fire, and flood.	Determine status and trends in the water quality of selected streams and springs. Priorities for monitoring include stream reaches that are impaired and relatively pristine waters.

Table 5-2 continued. SCPN core vital signs, monitoring location, justification and objectives.

ECOLOGICAL MONITORING FRAMEWORK (LEVELS 1 & 2)	VITAL SIGN(S)	PARKS	JUSTIFICATION	MONITORING OBJECTIVES
Biological Integrity: Focal Species or Communities	Spring, seep & tinaja ecosystems	BAND, CACH, CHCU, ELMO, GLCA, GRCA, MEVE, NAVA, PEFO, SAPU, WACA, WUPA, YUHO	Springs, seeps, and tinajas provide important sources of water in dry landscapes, support unique plant associations (e.g., hanging gardens), and sustain high levels of biotic diversity including rare and endemic species.	Determine status and trends in 1) discharge, 2) habitat area, 3) water quality, 4) vegetation composition & structure, 5) aquatic & riparian invertebrate composition & abundance, 6) *Rana pipiens* occurrence; *Hyla arenicolor* abundance.
Geology and Soils: Geomorphology	Channel morphology (integrated riparian)	AZRU, BAND, CACH, CHCU, GLCA, GRCA, HUTR, MEVE, NAVA, PEFO, PETR, SAPU, WACA, WUPA	This and the following two vital signs are interactive controls of riparian ecosystems; they will be monitored together. The vital sign includes channel cross section, bed material, planform, and slope. A number of parks are interested in channel dynamics and channel morphology and have concerns regarding human caused alterations to channel dynamics. There is a need for improved understanding of differences between the ranges of natural variability of cut and fill cycles and human caused geomorphic change, particularly in relation to ecosystem function and to the preservation of archeological sites in floodplains.	Determine status and trends in physical drivers of riparian ecosystems (i.e., stream flow, depth to water in alluvial aquifers, and channel morphology) in selected streams or stream reaches.
Water: Hydrology	Stream flow & depth to groundwater (integrated riparian)	AZRU, BAND, CACH, CHCU, GLCA, GRCA, HUTR, MEVE, PEFO, SAPU, WACA	Stream flow is a measure of surface water flowing in a river or stream channel. Measures of groundwater include depth to water in existing wells, depth to groundwater in alluvial aquifers, and spring flow. The maintenance of natural flow regimes is widely recognized as essential for sustaining the structure and functioning of riparian and aquatic ecosystems (Baron et al. 2002, Bunn and Arthington 2002, Naiman et al. 2002). In many SCPN parks, shallow subsurface water in intermittent drainages is critical to maintaining riparian habitats.	
Biological Integrity: Focal Species or Communities	Riparian vegetation composition & structure (integrated riparian)	BAND, CACH, CHCU, GLCA, GRCA, HUTR, MEVE, NAVA, PEFO, SAPU, WACA	Riparian vegetation serves a dominant functional role in controlling fluvial geomorphic processes and contributes species and habitats to the biotic diversity of riparian ecosystems. In many SCPN parks, native riparian vegetation is threatened by altered hydrology, grazing impacts, and invasion by non-native species.	Determine status and trends in composition and structure of riparian vegetation along selected streams or stream reaches.
Biological Integrity: Focal Species or Communities	Riparian bird communities	BAND, CACH, GLCA, GRCA, MEVE,	Bird communities will serve as another indicator of overall ecosystem condition in riparian habitats where integrated riparian monitoring is in place. Their high body temperature, rapid metabolism, and high ecological position in most food webs make them a good indicator of the effects of local and regional changes in ecosystems. Riparian habitats and some obligate riparian species are considered to be of conservation concern due to changes in habitat condition. In some cases, relatively undisturbed NPS sites serve as a reference for comparison with more degraded riparian conditions on adjacent lands.	Determine status and trends in composition and abundance of breeding bird communities associated with riparian vegetation of selected streams or stream reaches.

Table 5-2 **continued.** SCPN core vital signs, monitoring location, justification and objectives.

ECOLOGICAL MONITORING FRAMEWORK (LEVELS 1 & 2)	VITAL SIGN(S)	PARKS	JUSTIFICATION	MONITORING OBJECTIVES
Geology and Soils: Soil Quality	Soil stability & upland hydrologic function (integrated upland)	AZRU, BAND, CACH, CHCU, ELMA, ELMO, GLCA, GRCA, MEVE, NAVA, PEFO, PETR, SUCR, WACA, WUPA	This and the following vital sign are interactive controls of sustainability in arid upland ecosystems; they will be monitored together. Soil stability is the capacity of a site to limit redistribution and loss of soil resources by wind and water (Pellant et al. 2000). Hydrologic function is defined as the capacity of a site to capture, store, and safely release water from rainfall, run on, and snowmelt, to resist a reduction in this capacity, and to recover this capacity following degradation (Pellant et al. 2000).	Determine status and trends in soil stability and upland hydrologic function within selected predominant upland ecological sites.
Biological Integrity: Focal Species or Communities	Upland vegetation composition & structure (integrated upland)	AZRU, BAND, CACH, CHCU, ELMA, ELMO, GLCA, GRCA, MEVE, NAVA, PEFO, PETR, SUCR, WACA, WUPA	This vital sign focuses on monitoring vegetation composition and structure in predominant plant communities because of their central role in primary production, nutrient and hydrologic cycles, earth-atmosphere interactions, disturbance regimes, and in the provision of resources and habitat structure for wildlife at multiple scales. Relevant issues include the legacy of past livestock grazing, altered fire regimes and the effects of adjacent land use.	Determine status and trends in vegetation composition, diversity, and structure of plant communities associated with selected predominant upland ecological sites.
Biological Integrity: Focal Species or Communities	Habitat-based upland bird communities	BAND, GRCA, MEVE, PEFO, WUPA	Bird communities will serve as another indicator of ecosystem condition in a selected subset of upland habitats where integrated upland monitoring is in place. High body temperature, rapid metabolism, and high ecological position in most food webs make birds a good indicator of the effects of local and regional changes in ecosystems. Many bird species are obligates in habitats that are widely distributed across the network. Some species are considered to be of conservation concern due to changes in habitat condition. Relatively undisturbed NPS sites may serve as a reference for comparison with more degraded conditions on adjacent lands.	Determine status and trends in 1) composition and abundance of breeding bird communities, and in 2) reproductive success for selected breeding species, in selected upland habitats. Selected habitats will be a subset of those monitored for integrated upland vital signs.
Biological Integrity: Focal Species or Communities	Ground-dwelling arthropods	GRCA, MEVE	Monitoring ground dwelling arthropods provides important data on the connection between primary producers and consumers. Because invertebrates are low in the food chain, changes in their populations may reflect changes in the health of terrestrial ecosystems much faster than monitoring other higher level groups of plants or animals.	Determine status and trends in the composition and abundance of ground-dwelling arthropods within selected upland habitats. Selected habitats will be a subset of those monitored for integrated upland vital signs.
Biological Integrity: Invasive Species	Invasive exotic plants (early detection)	CACH, ELMO, GLCA, GRCA, HUTR, MEVE, NAVA, RABR, SAPU, YUHO	The time lag between the initial establishment of an invasive exotic species and its expansion toward community dominance provides a window for successful and cost effective control (Hobbs and Humphries 1995). Monitoring this vital sign will involve developing and testing spatial models of landscape invasibility as an aid in targeting monitoring efforts toward those park areas that are most likely to experience new invasions.	Detect incipient populations and new occurrences of selected invasive exotic plants before they become established in areas of management significance.

Table 5-2 continued. SCPN core vital signs, monitoring location, justification and objectives.

ECOLOGICAL MONITORING FRAMEWORK (LEVELS 1 & 2)	VITAL SIGN(S)	PARKS	JUSTIFICATION	MONITORING OBJECTIVES
Ecosystem Patterns and Processes: Landscape Dynamics	Land use/land cover and landscape vegetation pattern	AZRU, BAND, CACH, CHCU, ELMA, ELMO, GLCA, GRCA, HUTR, MEVE, NAVA, PEFO, RABR, SAPU, SUCR, WACA, WUPA, YUHO	Monitoring land use/land cover and landscape vegetation patterns is critical to understanding present and future ecosystem states and dynamics, biodiversity patterns, available habitats, movements of organisms, and flows of energy and materials. Land management and development on adjacent lands are among the most significant issues common to all SCPN parks. Increased development and intensification of land use practices on lands bordering parks have several ecological consequences. Combining these exterior issues of adjacent land use with past legacies of livestock grazing and altered fire regimes within SCPN parks further creates this demand to monitor these patterns.	Determine status and trends in the composition, extent, and distribution of land use/land cover and vegetation types on lands within and adjacent to SCPN parks. Determine status and trends in fragmentation and connectivity of selected land cover and vegetation types within and adjacent to SCPN parks. Determine status and trends in land cover and vegetation patterns along park boundaries.
Ecosystem Patterns and Processes: Landscape Dynamics	Vegetation condition and disturbance patterns	BAND, CACH, CHCU, ELMA, ELMO, GLCA, GRCA, MEVE, NAVA, PEFO, PETR, SAPU, SUCR, WACA, WUPA	Monitoring vegetation condition focuses on using satellite data to track broad-scale patterns in vegetation phenology and season-long greenness (or production). The combined effect of recent drought, altered fire regimes, and an associated rise in insect outbreaks (both in extent and severity) has increased the need to monitor disturbance patterns across SCPN ecosystems. Both vital signs will contribute to understanding ecosystem condition at landscape scales.	Determine annual status and trends in vegetation condition (vigor and productivity) of the dominant land cover and/or vegetation types within and adjacent to SCPN parks. Determine long-term trends in disturbance patterns (type, frequency, extent, and severity) within SCPN parks.
Ecosystem Patterns and Processes: Soundscape	Natural soundscape condition	CACH, ELMA, ELMO, GLCA, NAVA, PEFO, RABR, WUPA	Natural soundscapes are a resource considered to be of value both to NPS and to human visitors of NPS units. In a 1995 report to Congress, the National Park Service stated that "Preserving natural quiet is an integral part of the mission of the NPS. This is confirmed in law, policy, and the beliefs of NPS managers" (Report to Congress, p.76). Monitoring will describe the condition of the natural soundscape of wildlands and adjacent areas, including anthropogenic sound and its effect on the natural soundscape.	Determine status and trends in natural soundscape condition in selected parks.
Ecosystem Patterns and Processes: Viewscape	Night sky condition	BAND, CHCU, ELMA, ELMO, GLCA, GRCA, MEVE, PEFO,	Dark night skies are an important resource for many NPS units in the Intermountain Region (National Parks and Conservation Association 1999). High quality night skies are typically associated with wilderness areas in western US parks. SCPN has extensive wildlands: over 750,000 ha within network parks are designated or proposed as wilderness. Over the last 40 years, night sky condition has degraded in many areas by the widespread growth of light pollution (Duriscoe and Moore 2001), both within and external to NPS parks.	Determine status and trends in night sky condition in selected parks.

PHOTO BY MARK WEISSINGER

As we develop sampling designs and monitoring protocols, we must consider trade-offs concerning the scale, scope, and statistical power of our sampling efforts (Hall 2000). The need for integration will be one element of those discussions.

A preliminary task toward developing a framework for integrated monitoring is to define the spatial scales and replication and measurement efforts associated with particular vital signs. This framework will assist us with consideration of the best means for integrating monitoring data collected across disparate spatial and temporal scales. It will also be useful in assessing the relative cost and effort associated with particular vital signs. We have modified a framework developed by Jenkins and colleagues (2002) to help with this task. Spatial scale consists of two parts: extent, or the total area over which observations are made, and grain, the smallest interval of space measured (O'Neill and King 1998). Replication includes a spatial component (the number of independent sample plots dispersed through space) and a temporal component (the sampling frequency or number of samples through time). Measurement effort refers to the amount of information that is gathered at each sampling site and may also include processing time (e.g., for remotely sensed data).

Table 5-3 provides a preliminary assessment of these attributes for SCPN core vital signs. Landscape-level vital signs may generally be considered as extensive monitoring components (i.e., extensive coverage, low to moderate measurement effort with coarse-grained data). Many plot-based efforts are intermediate in terms of spatial scale, measurement effort, and replication. Those vital signs that require expensive instrumentation or high measurement efforts are typically poorly replicated, even if the intended spatial scale to which they apply is large (e.g., climate stations).

As we drafted protocol development summaries, we identified a number of park monitoring questions that depend on data from two or more linked vital signs. It was also apparent that a number of 'big picture' monitoring questions could only be addressed through more complex combinations of monitoring results. As we continue developing the monitoring program, we will begin to describe the data integration needs for the main SCPN monitoring themes. This will include consideration of park monitoring needs within the context of specific ecosystem models. Figure 5-1 provides an example of combining results from multiple vital signs to answer 'big picture' monitoring questions.

Table 5-3. Spatial scale, replication effort, and measurement effort for the SCPN core vital signs.

Color coding indicates a general scale from low to high (blue, green, yellow, orange, pink) for each attribute.

VITAL SIGN	SPATIAL SCALE		REPLICATION EFFORT		MEASUREMENT EFFORT (INCLUDES PROCESSING EFFORT)
	Extent	Grain	Spatial Replication	Monitoring Frequency	
Atmospheric and Climate Conditions					
Air quality	park/adj lands	very fine (point)	very low	continuous	automated
Climate conditions and soil moisture	park/adj lands	very fine (point)	very low	continuous	automated
Riparian & Aquatic Ecosystems					
Aquatic macroinvertebrates	focused	fine (reach)	low	high (1 yr)	very high
Water quality of streams & springs	focused	fine (reach)	low	very high (monthly to quarterly)	very high
Integrated Riparian					
Channel morphology	focused	fine (reach)	mod	low (5 yr)	med
Stream flow and depth to groundwater	focused	very fine (point)	mod	continuous	automated
Vegetation composition & structure	focused	fine (reach)	mod	low (5 yr)	med
Riparian bird communities	focused	fine (reach)	mod	mod (2-5 yr)	med
Seep, spring and tinaja ecosystems	focused	fine (site)	mod	low (5 yr)	very high
Upland Ecosystems					
Vegetation composition & structure	intermed	fine (plot)	low	mod (2-5 yr)	med
Soil stability and upland hydrologic function	intermed	fine (plot)	low	mod (2-5 yr)	med
Habitat-based bird communities	intermed	fine (plot)	low	mod (2-5 yr)	med
Ground-dwelling arthropods	intermed	fine (plot)	very low	low (5 yr)	very high
Landscape					
Invasive exotic plants (early detection)	park/adj lands	med (large plot)	mod	low (5 yr)	low
Land use/land cover & landscape vegetation pattern	region	coarse to very coarse	complete	low (5 yr)	low
Vegetation condition & disturbance patterns	region	very coarse	complete	high (1 yr)	low
Wildland Values					
Night sky condition	park/adj lands	very fine (point)	very low	very low (5-7 yr)	high
Natural soundscape condition	park/adj lands	very fine (point)	very low	very low (5-7 yr)	high

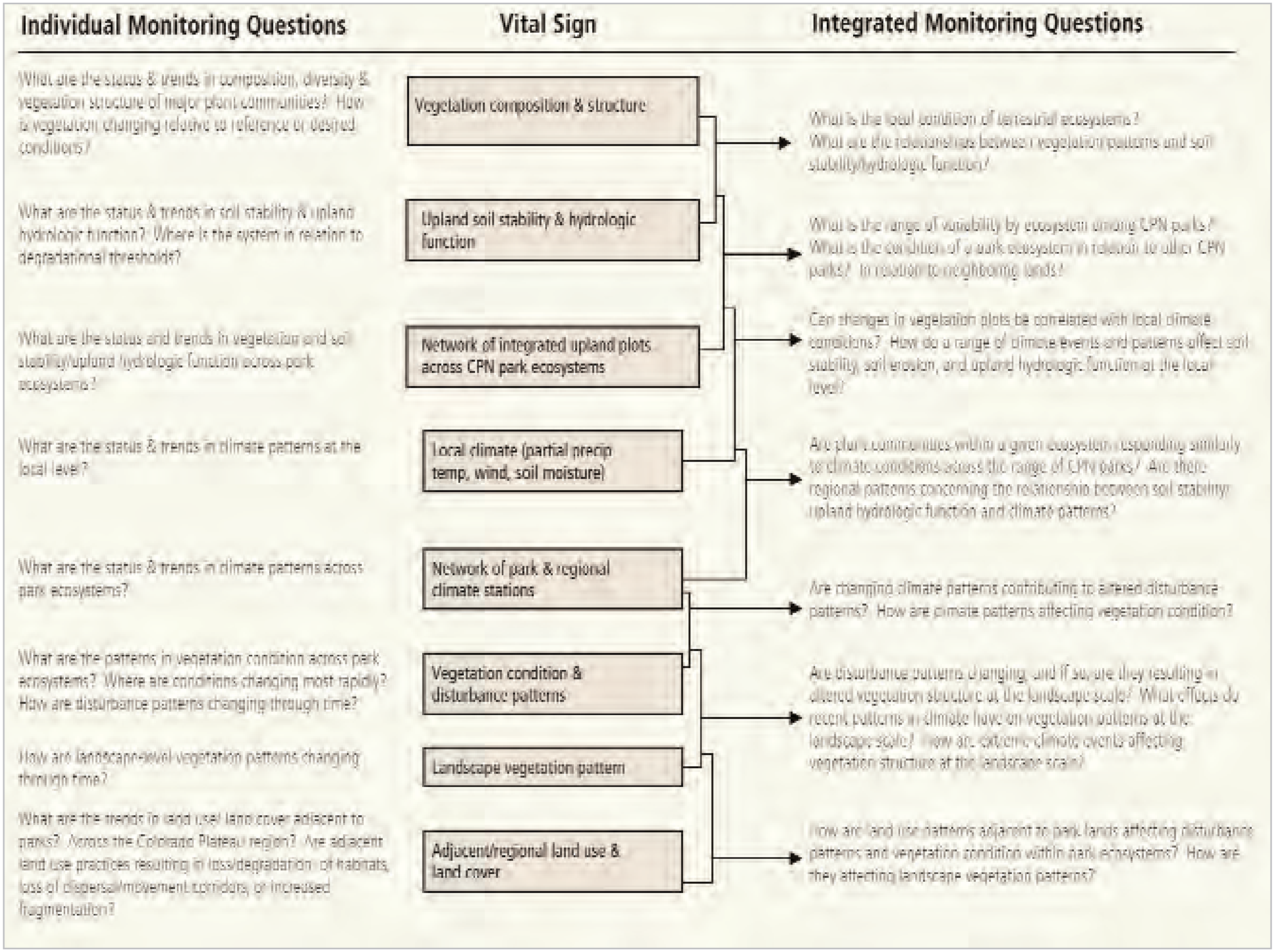


Figure 5-1. *Example of integrated monitoring questions relating to SCPN upland ecosystems.*

CHAPTER 6

DATA MANAGEMENT

Data become information through the process of analysis, synthesis, modeling, or other types of interpretation. Data management provides a means for organizing, documenting, and archiving data so that the original information potential is maintained through time. This is particularly important for long-term programs where the lifespan of a data set will likely be longer than the careers of those who developed it. A data management system that can effectively produce, maintain, and distribute monitoring results is central to the success of the I&M Program.

This chapter summarizes the general data management standards; expected roles and responsibilities; and data processing, storage, and distribution guidelines for the SCPN. A more detailed description can be found in the SCPN Data Management Plan (Supplement V), which will be revised periodically. Detailed data management procedures for monitoring projects will be based on these guidelines.

6.1 GOALS AND OBJECTIVES

The SCPN approach to data management is user oriented, the user ranging from SCPN staff to cooperating scientists and park managers. The primary goal of the SCPN data management program is to ensure the quality, clarity, security, longevity, and availability of SCPN I&M data.

Quality – SCPN I&M data will be used by park staff to inform management decisions regarding park natural resources; it is essential that these data be accurate and complete. Appropriate quality assurance measures will be employed throughout the process of collecting, processing, and maintaining data. Good data stewardship habits and attitudes will be encouraged.

Clarity – Confusing and cryptic data sets are of little use and can be easily misinterpreted. All data and information products will be accompanied by complete documentation so that users will be aware of the applicability and limitations of the data.

Security – All information products will be maintained so that appropriate levels of access are provided to SCPN and park staff. Existing technologies will be utilized to protect I&M data from corruption or loss, ensuring the long-term security and integrity of the data.

Longevity – Many factors combine to increase the longevity of a data set: proper documentation, organization, and standardization to modern technologies. SCPN will ensure that all data sets are completely documented. Data sets will be organized in a logical and consistent manner so that nothing is lost over time. As software and hardware technologies change, data sets will be updated so that they remain readable and accessible.

Availability – I&M data can only be useful to park managers if it is easily available in a timely manner and in a useful form. Information products will be distributed to park management on a regular schedule and, when appropriate, will be made available to a broader audience.

Table 6-1. Roles of SCPN network staff and cooperators working on monitoring projects.

ROLE	DATA STEWARDSHIP RESPONSIBILITIES
Network Program Manager	Coordinate and oversee all network activities
Network Data Manager	Develop and support network data management system Ensure project data are organized, compliant, and safe Provide for dissemination of project data to end users
Project Manager	Supervise and train project crew in proper data collection techniques Validate data Provide dataset documentation and metadata Perform statistical analysis and interpret results
Network GIS Specialist	Process, manage, validate and document spatial data Provide spatial data to support monitoring projects Conduct spatial analyses Work with Data Manager to integrate spatial and tabular data
Project Crew Leader	Lead field crew in data collection Organize and verify data
Network Quantitative Ecologist (or consulting statistician)	Collaborate with Project Managers to analyze project data
Project Crew Member	Collect, record, enter and verify data
Information Technology Specialist	Provide IT support for hardware, software, networking

Table 6.2. SCPN infrastructure service or support providers.

SERVICE OR SUPPORT PROVIDED	NAU	CPRS	NPS	SCPN
Telecommunications Hardware and Service	X			
Networking Hardware	X			
Networking Services	X	X		
Networking Security		X		X
Computer Hardware Support and Maintenance		X		X
Computer Software Installation and Support				X
Email Administration and Support			X	
Web Services			X	
Clearinghouse Repositories			X	
Data Backup			X	X

6.2 SOURCES OF NATURAL RESOURCE DATA

The existence of numerous potential sources of ecological data about park natural resources requires SCPN to prioritize data management. Some sources of natural resource data include:

- Inventories
- Monitoring
- Special focus studies completed by parks
- External research projects
- Studies by other land management agencies on adjacent lands
- Resource impact evaluations related to park planning and compliance regulations
- Resource management and restoration work

SCPN will be able to maintain the highest level of control on data collected through the network monitoring program, and thus our data management efforts will focus on these data. However, the goal is to apply the same standards, procedures, and attitudes about data management to other sources of natural resource data over the long-term and to work toward raising the level of data management for projects originating outside the I&M program. Our data management staff may also serve as consultants for new park monitoring projects, contributing good data management practices to those efforts.

6.3 ROLES AND RESPONSIBILITIES

Data management and stewardship is the responsibility of all participants in SCPN network I&M activities; it requires true collaboration among many people with a broad range of tasks and responsibilities. Good habits and attitudes are as important as standards and procedures. Although primary responsibility resides with the data manager, project managers, and GIS specialist who make up the core data management team, all SCPN staff and cooperators are responsible for ensuring data stewardship is practiced throughout the life of a monitoring project. Table 6.1 summarizes the roles and responsibilities of SCPN staff and cooperators with respect to data stewardship.

6.4 INFRASTRUCTURE AND SYSTEM ARCHITECTURE

Management and dissemination of monitoring data is made possible by information technology infrastructure and system architecture. Infrastructure refers to the network of computers and servers that information systems are built upon. System architecture refers to the application, database system, repositories, and software tools that make up the framework of the SCPN's data management enterprise.

SCPN relies on cooperative agreements with Northern Arizona University (NAU) and the USGS Colorado Plateau Research Station (CPRS) as well as NPS regional and national information technology personnel and resources for maintenance and support of computer and networking infrastructure (Table 6-2).

6.4.1 *SCPN System Architecture*

Working files, master libraries, and digital archives will be stored on SCPN file and data servers. A template project directory for databases, files, and project documentation will be used for each monitoring project. This directory will contain working files for which all project team members will have read/write access. Master libraries are repositories for final information products and certified databases. Master libraries will be organized according to type – databases will be stored together, documents will be stored together, etc. – and only certain SCPN personnel will have full access. Digital archives will be repositories for packages of data and information that can easily be redistributed and will have extremely limited write access.

Rather than developing a single integrated database system, SCPN will develop stand-alone project databases that share design standards and centralized lookup tables for data shared across projects. These modular databases allow for greater flexibility to accommodate each project's needs, and sufficient standardization can ensure the ability to aggregate and summarize data across multiple projects. SCPN currently uses Microsoft Access for all project databases and is investigating the need to move to a client-server relational database management system such as Microsoft SQL Server.

6.4.2 *National System Architecture*

The national I&M program provides several repositories for hosting SCPN information products and applications for summarizing park data at a national level. The applications are available online and allow users to access basic natural resource information for SCPN parks:

- NatureBib – master database for natural resource bibliographic references
- NPSpecies – master database for species occurrence records and evidence (voucher specimens, references, observations or data sets) at each park
- NR-GIS Metadata and Data Store – master database of metadata for GIS and natural resource data sets and a repository for that data

6.5 DATA MANAGEMENT PROCESS AND WORKFLOW

Within the context of a monitoring project SCPN data management tasks can be divided into several types of activities. These activities (Figure 6-1) provide the backbone for planning and executing data management procedures for each monitoring project. Specific procedures and guidelines for each of these activities are explained in the data management plan. Data design refers to the design and development of project data sheets, the database, and database applications. During data acquisition, data are collected in the field or acquired from other sources, entered into the project database, and verified. Data will then be validated to ensure they are within normal ranges, summarized, and exported for analysis. Documentation will be completed, data and information products will be distributed, and both digital and analog products will be archived.

Data and documentation take different forms and are maintained in different places throughout the phases of a project. These phases can be modeled as a sequence of events and tasks which involve interaction with the following items:

- Raw data – Analog data recorded by hand on field data sheets and digital files from handheld computers, GPS receivers, telemetry data loggers, etc.
- Working database – A project-specific database for entering and processing data for the current season (or other logical time period). This may be the only database for short-term projects with no need to distinguish current season data from the full set of validated data.
- Certified data and metadata – Completed data and documentation for short-term projects, or one season of completed data for long-term monitoring projects. Certification is a confirmation by the project manager that the data have passed all quality assurance requirements and are complete

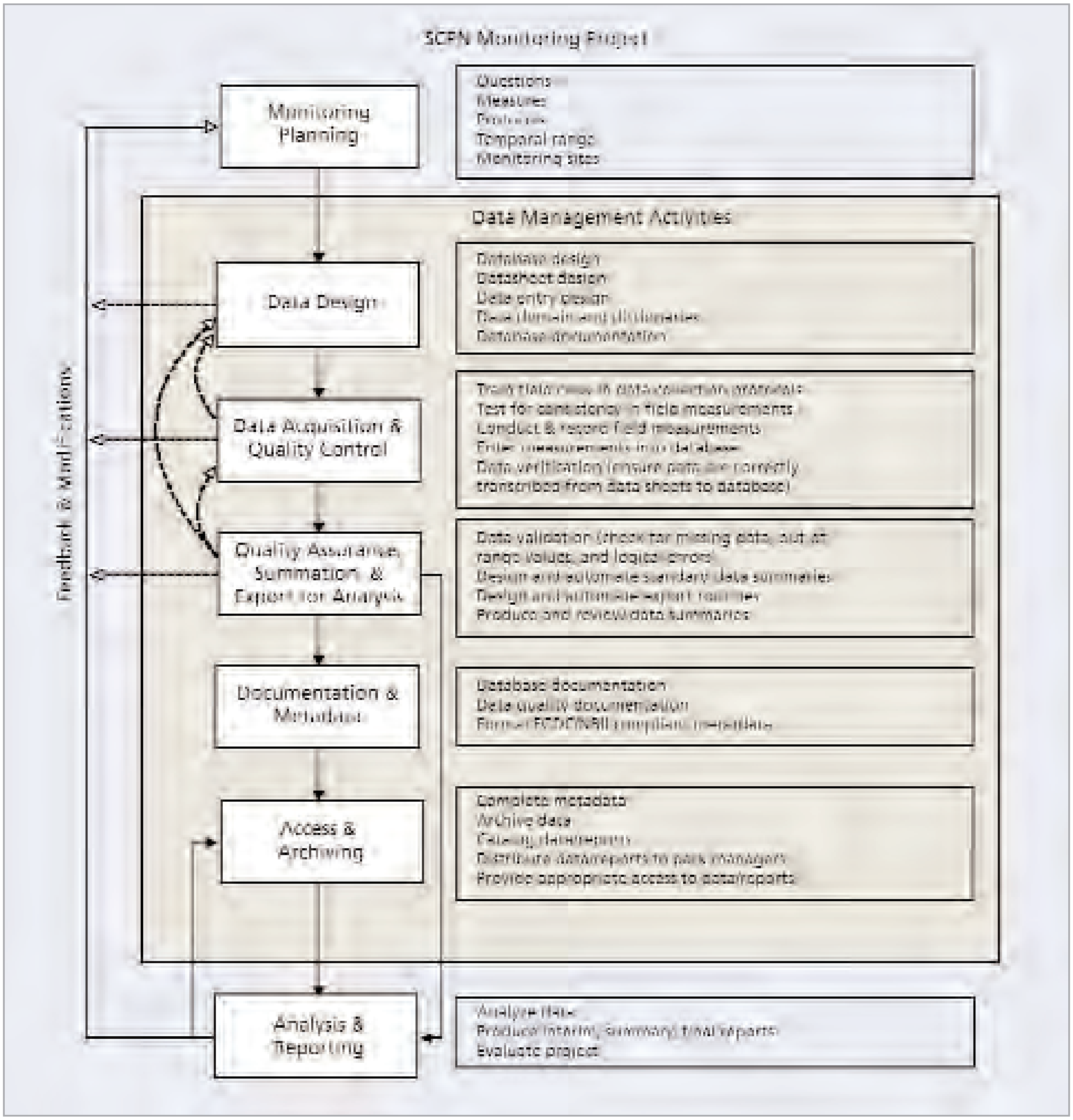


Figure 6-1. *Data management activities within the context of a monitoring project.*

and ready for distribution. Metadata records include detailed information about project data needed for proper use and interpretation.

- Master database – Project-specific database for storing the full set of validated project data used for viewing, summarizing, and analysis. Current season data from the working database must pass all quality assurance steps prior to upload into this master project database.
- Reports and data products – Information that is derived from certified project data.
- Edit log – A means of tracking changes to certified data.
- National databases and repositories – Applications and repositories maintained at the national level, primarily for the purpose of integration among NPS units and for sharing information with cooperators and the public.

- Archived data – Digital and hard-copy data stored and maintained for the long-term.

6.6 WATER QUALITY DATA

Water quality data collected as part of the network's monitoring program have distinct data management requirements. Data must be managed according to guidelines from the NPS Water Resources Division (WRD; http://www.nature.nps.gov/water/infoanddata/index.cfm). NPS WRD has selected the Environmental Protection Agency's national STOrage and RETrieval water quality database (STORET) as the standard for archiving NPS water quality data. WRD maintains a copy of STORET and requires that all I&M chemical, physical, and biological water quality data be archived in this copy. SCPN will use the Microsoft Access database application (called NPSTORET) developed by WRD to fulfill this requirement.

The USGS/WRD-Colorado developed a water quality database that enables assessment of the temporal and spatial distribution characteristics of water quality data available for the 19 SCPN park units. For the purpose of developing the Water Quality Vital Signs Monitoring Plan, this database provides a useful tool for evaluation of historical water quality of the waters in and surrounding SCPN park units and determination of historical and current water quality conditions in and near these parks. SCPN plans to maintain and regularly update the water quality database through data retrievals from NPSTORET or STORET, enabling it to serve as a dynamic tool for the network's long-term water quality monitoring and analysis needs.

6.7 DATA DESIGN

The data manager and project manager will collaborate on design of field data sheets, database structure, and database application for each monitoring project. Databases will be standardized where possible following the I&M recommended guidelines for database structure and naming conventions developed in the Natural Resource Database Template (NRDT) and the Recommended Naming Standards. SCPN will also develop standardized lookup tables for data elements shared across many monitoring projects. Database design will also be guided by a data modeling process involving the creation of three types of data models: conceptual, logical, and physical.

6.8 DATA ACQUISITION AND QUALITY CONTROL

Data managed and utilized by the network will originate from three types of sources: within the network, other NPS data collection efforts, and outside the NPS altogether.

- Network Data – any data produced from projects that are initiated (funded) by the SCPN I&M Program or projects that in some way involve the I&M Program.
- NPS Data – any data produced by the NPS that did not involve the inventory and monitoring program.
- External Data – any data produced by agencies or institutions other than the National Park Service.

SCPN staff are responsible for the acquisition and quality control of network data. Project crew leaders and members are primarily responsible for data collection, data entry, and verification of data acquired from field data collection. Each monitoring project protocol will detail procedures for these data acquisition steps based on guidelines outlined in this plan. As data are collected and entered into a database, quality control procedures will be used to increase accuracy and limit transcription mistakes. A verification procedure will be used to check for and correct any transcription mistakes.

NPS and external data will be acquired only with complete documentation and metadata. These data will undergo limited processing and quality control by SCPN staff to ensure compatibility with SCPN project databases, if necessary. Legacy data from parks will be evaluated and prioritized for digitizing or converting to modern database formats. Some external ancillary data, such as climate data, will be acquired when needed in subsets rather than stored by SCPN in its entirety.

6.9 QUALITY ASSURANCE, DATA SUMMARIZATION, AND EXPORT FOR ANALYSIS

Quality assurance, data summary, and data analysis are the responsibility of the project managers; however, the data manager will provide tools to project managers to facilitate these three activities. Data validation (ensuring measures are within normal ranges and logical) procedures will be detailed in each monitoring protocol and will generally include outlier detection and other exploratory analyses.

Routine data summaries will be produced after data have been verified on a schedule specific to each project. Summaries will generally be automated within the database application, but park-specific data reports can be produced for management needs. Automated exports will also be included in each database application to enable project managers to export subsets of data in a format ready for import into specific statistics or other analytic software programs.

6.10 DOCUMENTATION

Dataset documentation is the responsibility of the project manager and data manager. All datasets will be documented with formal metadata, using Federal Geographic Data Committee and USGS National Biological Information Infrastructure standards.

Table 6-3. Repositories for SCPN information products.

REPOSITORY	INFORMATION PRODUCTS
SCPN Project Directories	Working database, metadata, protocols, SOPs, reports, administrative records, digital photos
SCPN Project Databases	Certified data sets, comprehensive data for multi-year products
Park Collections and /or National Archives	Administrative records, voucher specimens, raw data forms, hard copy reports
Specialized Museum Facilities (e.g., Museum of Southwestern Biology, NAU Deaver Herbarium)	Voucher specimens
NPSpecies	Compiled information about species occurrences, abundance, residency, and nativity
NatureBib	Natural resource documents, I&M reports
NPSTORET	Water quality data
NR GIS Metadata and Data Store	Metadata and non sensitive digital data sets

Documentation accompanying database applications will include a manual with instructions for using the application, an entity relationship diagram, a data dictionary, and programming code documentation.

6.11 ACCESS AND ARCHIVING

6.11.1 *Data Ownership and Sensitivity*

SCPN data products are owned by the National Park Service provided under OMB Circular A-110, Section 36. The Freedom of Information Act (FOIA) establishes that the federal government, the NPS included, must provide access to non-protected data and information of interest to the public through reading rooms or the Internet.

The NPS is directed to protect information about the nature and location of sensitive park resources under one Executive Order and four resource confidentiality laws:

- Executive Order No. 13007: Indian Sacred Sites
- National Parks Omnibus Management Act (NPOMA; 16 U.S.C. 5937)
- National Historic Preservation Act (16 U.S.C. 470w-3)
- Federal Cave Resources Protection Act (16 U.S.C. 4304)
- Archaeological Resources Protection Act (16 U.S.C. 470hh)

All monitoring information products will be vetted for sensitive data prior to making them available to the general public. Classification of sensitive I&M data will be a shared responsibility that includes network staff, park resource management staff, park superintendents, and investigators working on individual projects. Park management has ultimate responsibility for deciding which information is sensitive and should not be released to the public. The network has ultimate responsibility for ensuring that sensitive data are not released to the public.

6.11.2 *Dissemination and Access*

Dissemination of monitoring and information products from SCPN will follow these guidelines:

- data will be easily located and acquired
- only data subjected to full quality control and quality assurance measures will be released
- data will be accompanied by complete metadata
- sensitive data will be identified and protected from unauthorized access

Information products will be made available primarily through websites and clearinghouses which will allow users to search for and download reports, summarized data, maps and metadata, and other associated information. Distribution means will include (but may not be limited to):

- SCPN public website
- NR-GIS Metadata and Data Store
- Service-wide databases, such as NPSTORET, NPSpecies, and NatureBib
- Regional, Network, or Park data servers protected with read-only access
- FTP sites, CDs, DVDs, or hard drives, as appropriate

6.11.3 *Archiving and Storage*

Digital and analog information products will be stored, archived, and maintained in a variety of repositories (Table 6-3). Digital products resulting from monitoring projects will be archived on SCPN file servers and national file and data servers and protected from catastrophic loss by regular, automated backups to external media. Analog products will be archived to NPS standards by individual park facilities or approved non-NPS institutions. At the termination of a project or at regular milestones, an archival package will be prepared and delivered to the desired location.

7 CHAPTER

DATA ANALYSIS AND REPORTING

The information obtained through the SCPN monitoring program has a wealth of applications including management decision-making, research, education, and promotion of public understanding of SCPN park resources. Park managers are the primary audience for the results of vital signs monitoring. Our goal is to provide superintendents and resource managers with the data they need to make and defend management decisions and to work with others for the benefit of park resources. Other key audiences for monitoring results include park planners, interpreters, researchers and other scientific collaborators, and the general public. To be effective, monitoring data must be analyzed, interpreted, and provided at regular intervals to each of these audiences in a format they can use. With these varied constituencies, it is important to analyze SCPN monitoring data at several different scales, and the same information needs to be distributed in different formats to resonate with different audiences.

This chapter presents an overview of how the SCPN proposes to analyze, synthesize, and disseminate monitoring results to a wide variety of audiences in a timely manner.

7.1 DATA ANALYSIS

To conduct an appropriate analysis of monitoring data, one must consider the monitoring objectives, the spatial and temporal aspects of the sampling design used, the intended audiences, and management uses of these data. Selection of specific analytical methods should occur following determination of monitoring objectives and sampling design and before sampling. Each monitoring protocol will contain detailed information on analytical tools and approaches for data analysis and interpretation including rationale for a particular approach, advantages and limitations of each procedure, and standard operating procedures (SOPs) for each prescribed analysis. General categories of analysis for SCPN vital signs are presented in Table 7-1.

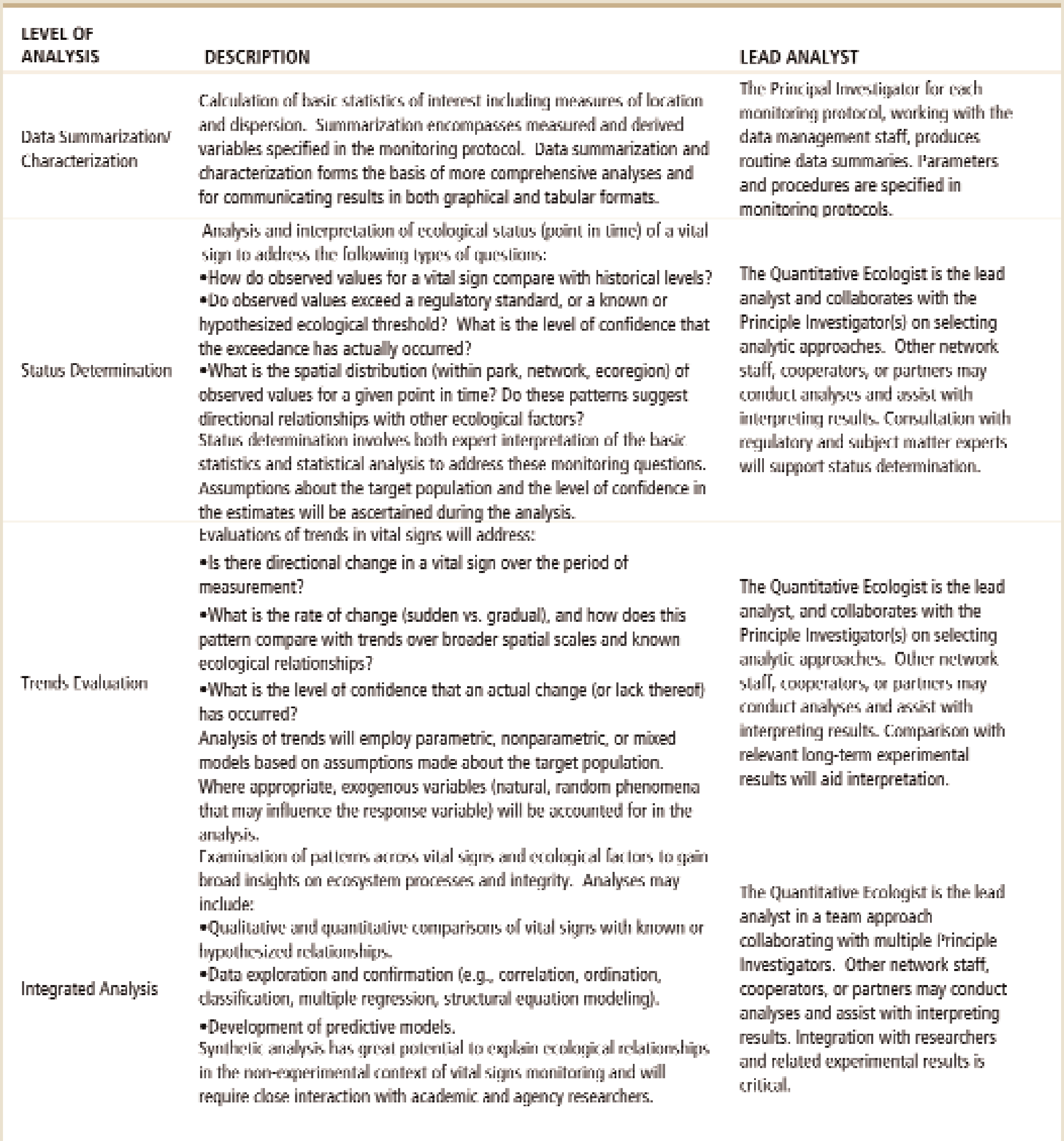
In general, the quantitative ecologist and principal investigator for a particular project will collaborate on selection of analytic approaches for status and trends analyses. They will also share responsibilities for conducting and reporting the analyses. Integrated analyses that examine patterns across vital signs will require a team approach where multiple principal investigators will collaborate with the quantitative ecologist. An exception to these analytical activities is with the air quality vital signs; analyses and reports of air quality are produced by NPS-ARD and other agencies (EPA-CASTNET and IMPROVE).

To provide a context for data analysis, a brief conceptual overview of five types of analyses is presented below. More specific details of the proposed analyses for the SCPN vital signs are presented in Table 7-2.

7.1.1 *Parameter Estimation*

The most common type of analysis for SCPN vital signs will be parameter estimation.

Table 7-1. Categories of analysis for SCPN vital signs.



LEVEL OF ANALYSIS	DESCRIPTION	LEAD ANALYST
Data Summarization/ Characterization	Calculation of basic statistics of interest including measures of location and dispersion. Summarization encompasses measured and derived variables specified in the monitoring protocol. Data summarization and characterization forms the basis of more comprehensive analyses and for communicating results in both graphical and tabular formats.	The Principal Investigator for each monitoring protocol, working with the data management staff, produces routine data summaries. Parameters and procedures are specified in monitoring protocols.
Status Determination	Analysis and interpretation of ecological status (point in time) of a vital sign to address the following types of questions: •How do observed values for a vital sign compare with historical levels? •Do observed values exceed a regulatory standard, or a known or hypothesized ecological threshold? What is the level of confidence that the exceedance has actually occurred? •What is the spatial distribution (within park, network, ecoregion) of observed values for a given point in time? Do these patterns suggest directional relationships with other ecological factors? Status determination involves both expert interpretation of the basic statistics and statistical analysis to address these monitoring questions. Assumptions about the target population and the level of confidence in the estimates will be ascertained during the analysis.	The Quantitative Ecologist is the lead analyst and collaborates with the Principle Investigator(s) on selecting analytic approaches. Other network staff, cooperators, or partners may conduct analyses and assist with interpreting results. Consultation with regulatory and subject matter experts will support status determination.
Trends Evaluation	Evaluations of trends in vital signs will address: •Is there directional change in a vital sign over the period of measurement? •What is the rate of change (sudden vs. gradual), and how does this pattern compare with trends over broader spatial scales and known ecological relationships? •What is the level of confidence that an actual change (or lack thereof) has occurred? Analysis of trends will employ parametric, nonparametric, or mixed models based on assumptions made about the target population. Where appropriate, exogenous variables (natural, random phenomena that may influence the response variable) will be accounted for in the analysis.	The Quantitative Ecologist is the lead analyst, and collaborates with the Principle Investigator(s) on selecting analytic approaches. Other network staff, cooperators, or partners may conduct analyses and assist with interpreting results. Comparison with relevant long-term experimental results will aid interpretation.
Integrated Analysis	Examination of patterns across vital signs and ecological factors to gain broad insights on ecosystem processes and integrity. Analyses may include: •Qualitative and quantitative comparisons of vital signs with known or hypothesized relationships. •Data exploration and confirmation (e.g., correlation, ordination, classification, multiple regression, structural equation modeling). •Development of predictive models. Synthetic analysis has great potential to explain ecological relationships in the non-experimental context of vital signs monitoring and will require close interaction with academic and agency researchers.	The Quantitative Ecologist is the lead analyst in a team approach collaborating with multiple Principle Investigators. Other network staff, cooperators, or partners may conduct analyses and assist with interpreting results. Integration with researchers and related experimental results is critical.

Table 7-2. Summary of proposed analyses for SCPN vital signs.

VITAL SIGNS	PROPOSED ANALYSIS
Air Quality Vital Signs (ozone, wet and dry deposition, visibility and particulate matter)	Status: Monthly and annual means of air quality parameters for each station in four Class 1 parks (BAND, GRCA, MEVE, and PEFO). Trend: Analyses of major ions, particulates, and number of days with exceedances for ozone; qualitative comparisons of regional trends.
Climate Conditions and Soil Moisture	Status: Monthly and annual means of climate measures for each climate station in a park; number of days above 95th percentile and below 5th percentile for both air temperature and precipitation; monthly means of soil moisture. Trend: Descriptive comparisons of current year climate measures to historical trends on a yearly and monthly basis; qualitative and quantitative comparisons of annual climate conditions and trends, and climatic extremes among SCPN park units and with regional trends; comparisons of monthly and annual soil moisture trends; correlative analyses of trend slopes between climate conditions and soil moisture.
Aquatic Macroinvertebrates	Status: Mean and variance of measured attributes; stream-level inference of monitored attributes. Trend: Regression-based analyses; correlative analyses of trend slopes with other riparian vital signs (e.g., vegetation composition and structure, water quality, stream flow) and with broader-scale measures such as climate; analyses of change in community attributes using indices (diversity, similarity, dissimilarity) and ordination (nonmetric multidimensional scaling) techniques; qualitative and quantitative comparisons of status and trends of measured attributes among streams and/or among SCPN park units and among other networks (e.g., NCPN).
Water Quality	Quarterly data review: Quality assurance and control; identify anomalous values indicating need for re-analyzing samples; flag values exceeding state standards and report to parks. Status (annual summary): Summarize site data by season and tabulate values exceeding and approaching exceedance of standards (20% or less below the applicable standard); summary tables, histograms, and box and whisker plots to show frequency distribution, median and interquartile ranges (for non-normally distributed data), mean and standard deviation (for normally distributed data), and 95% confidence intervals for means and medians of parameters at each site. Trend: Site level trend analysis adjusted for season and flow for individual constituents. Statistical tests include Seasonal Kendall tests for monotonic trends and Seasonal Rank Sum tests for step trends.
Riparian Vital Signs (vegetation composition and structure, stream flow, depth to groundwater, and channel morphology)	Status: Mean and variance of measured attributes; stream-level inferences of monitored attributes. Trend: Regression-based analyses; correlative analyses of trend slopes among riparian vital sign measures, climate, and related vital signs (aquatic macroinvertebrates and water quality); analyses of change in vegetation community attributes using indices (diversity, similarity, dissimilarity) and ordination (nonmetric multidimensional scaling) techniques; qualitative and quantitative comparisons of status and trends of measured attributes among SCPN park units, and among other networks (e.g., NCPN).
Riparian and Upland Bird Communities	Status: Number of observations, density, and nesting success by species, by ecological site (for upland birds), and by stream (for riparian birds). Trend: Regression based analyses of breeding bird density and comparison of trends among ecological sites/streams and SCPN park units; analyses of change in community attributes using indices (diversity, similarity, dissimilarity) and ordination (nonmetric multidimensional scaling) techniques; correlative analyses of trend slopes among measured attributes and climate and related upland or riparian vital signs.

Table 7-2 **continued.** Summary of proposed analyses for SCPN vital signs.

VITAL SIGNS	PROPOSED ANALYSIS
Spring, Seep, and Tinaja Ecosystems	Annual water quality data review: Quality assurance and control; identify anomalous values indicating need for re-analyzing samples; flag values exceeding state standards and report to parks. Status: Mean and variance of measured attributes; inferences of monitored attributes by ecosystem, groundwater flow system, and/or spring type. Summarize (annually) water quality data and tabulate values exceeding and approaching exceedance of standards (20% or less below the applicable standard); summary tables, histograms, and box and whisker plots to show frequency distribution, median and interquartile ranges (for non-normally distributed data), mean and standard deviation (for normally distributed data), and 95% confidence intervals for means and medians of parameters at each site. Trend: Regression-based analyses; correlative analyses of trend slopes among climate and related vital signs (spring flow, macroinvertebrates, vegetation composition and structure, and water quality); analyses of change in community attributes using indices (diversity, similarity, dissimilarity) and ordination (nonmetric multidimensional scaling) techniques; qualitative and quantitative comparisons of status and trends of measured attributes among SCPN park units and among other networks.
Upland Vital Signs (vegetation composition and structure, hydrologic function, soil/site stability)	Status: Mean and variance of measured attributes; inferences of monitored attributes by targeted ecological sites. Trend: Regression-based analyses; correlative analyses of trend slopes among upland vital sign measures (including climate at localized and generalized scales); correlative analyses of trend slopes with landscape-level land cover and vegetation type attributes; analyses of change in vegetation community attributes using indices (diversity, similarity, dissimilarity) and ordination (nonmetric multidimensional scaling) techniques; qualitative and quantitative comparisons of status and trends of measured attributes among ecological sites and predominant vegetation types and among other networks (e.g., NCPN).
Ground-Dwelling Arthropods	Status: Mean and variance of measured attributes. Trend: Regression-based analyses; correlative analyses of trend slopes among measured attributes, climate, and related upland vital sign measures; analyses of change in community attributes using indices (diversity, similarity, dissimilarity) and ordination (nonmetric multidimensional scaling) techniques; qualitative and quantitative comparisons of status and trends of measured attributes among SCPN park units.
Invasive Exotic Plants (early detection)	Status: Mean and variance of measured attributes; park-level inferences of monitored attributes. Trend: Regression based analyses of new occurrences of selected exotic species; qualitative and quantitative comparisons of status and trends of measured attributes within and among zones of invasability and within and among SCPN park units.
Land Use/Land Cover and Landscape Vegetation Pattern	Status: Description and measures (including abundance, spatial distribution, and connectivity) of land use/land cover and vegetation types within and adjacent to SCPN parks from classified remotely sensed imagery and from use of landscape metrics software programs. Trend: Change detection of land cover and vegetation types and patterns using spectral comparison methods; regression based analyses of changes in land cover and vegetation patterns within and adjacent to park units; correlative analyses of changes outside park units to changes along and within park boundaries; correlative analyses of broad-scale climate changes with changes in landscape vegetation pattern; qualitative and quantitative comparisons of status and trends of land cover and vegetation patterns among SCPN park units and among other networks (e.g., NCPN).
Vegetation Condition and Vegetation Disturbance Patterns	Status: Seasonal and annual trends in vegetation greenness and phenology using a surrogate from remotely sensed imagery (MODIS-NDVI); description and measures (including extent and spatial distribution) of the type, extent, and severity of disturbances to vegetation detected from remotely sensed imagery; measures of continuous total vegetation cover (%) and/or bare ground cover. Trend: Analyses (regression-based, ANOVA) of measures of vegetation phenology and vegetation disturbance measures by land cover type; regression-based analyses of total vegetation and/or bare ground cover; correlative analyses of broad-scale climate changes with changes in measured (interrelated) attributes; quantitative comparisons of changes in the interrelated attributes among SCPN park units and among other networks (e.g., NCPN).
Wildland Values Vital Signs (natural soundscape condition and night sky condition)	Status: Mean and variance of measured attributes. Trend: Regression-based analyses; correlative analyses of trend slopes among measured attributes and landscape land use/land cover attributes; qualitative and quantitative comparisons of status and trends of measured attributes among SCPN park units.

This can involve either the estimation of the state or condition of a given resource (status) or the change in that resource state over time (trend). This analysis focuses on measuring and describing the attributes of a population in terms of its distribution and structural features. Using this method requires an understanding of the distribution from which the samples are drawn such as the bias in the estimate of central tendency and the precision or variability in the data. If the expected value of the estimate (e.g., the mean from repeated samples) is equal to the true value of the parameter, then the estimator is considered unbiased. If the parameter estimate differs systematically from the true value (e.g., repeated samples are always greater than the true value), then the estimator is biased. Precision reflects variation in the data; the greater the precision (or tendency of the samples to be close to the true value), the less variation in the data.

Evaluation of trend estimates (and determining if change has occurred over time) is a primary focus of our long-term monitoring program. SCPN will employ several common statistical and graphical techniques to evaluate trends. One easily interpreted method of representing trends of the estimated parameters is to use graphs. This simple technique plots values of the parameter through time, and can easily show if the parameter is increasing, decreasing, fluctuating, or not changing significantly. A common statistical tool for evaluating the relationship of one or more independent variables to a single, continuous dependent variable is regression analysis. We will use regression analysis to calculate the trend slope of parameter estimates over time. In this case, determining if change has occurred is a form of hypothesis testing where the null hypothesis is that the slope is 0. Analysis of variance-based (ANOVA) trend analysis will be employed when populations are categorized into domains of interest (e.g., vegetation types).

7.1.2 *Hypothesis Testing*

Related to detecting change in parameter estimates over time, we will also use hypothesis testing for other selected purposes. In scientific settings, hypothesis testing is a keystone approach in experimental research to determine effects of treatments. For our purposes, this method will be used when the status of a given resource is tested against reference values, such as legal thresholds (e.g., water quality exceedance standards) or desired conditions. We will use this method to test whether or not conclusions can be drawn about the relationship between the parameter estimate and the reference to which it is being compared.

7.1.3 *Model Selection*

A third analytical approach we will use is model selection to help better understand the dynamic relationships among park resources, ecosystem drivers, and stressors. One goal in developing models is to provide early warning of abnormal conditions and impairment of park resources and to inform park management decision-making. This approach considers multiple lines of evidence within the monitoring data to support development of a suite of models that represent multiple hypotheses concerning the desired relationships. The model selection approach will be used in developing the SCPN integrated analysis reports (see 7.2.3).

Model selection will be based on the principle of parsimony, where the appropriate model should contain only enough (significant) parameters to account for the variation in the data. One objective is to compare models with varying numbers of parameters and then select an "optimal" model that is neither too simple nor too complex and is biologically meaningful. A companion objective is to use information-theoretic approaches (Burnham and Anderson 2002) to compare the relative strength of competing models. Models can be evaluated and ranked using criteria such as how well data fit the model and presence of excessive parameters.

7.1.4 *Bayesian Approaches*

We will consider use of a fourth analytical approach, Bayesian statistical methods, as an alternative to traditional, frequentist statistics. In general, Bayesian approaches allow for the incorporation of previous evidence (data) along with new information to estimate the probability of a particular outcome. This technique may be useful during model selection. These statistical methods are based on Bayes's theorem (Bayes 1763). More specifically, Bayesian methods use the observed data to calculate the probability of the value of a parameter. With additional data, Bayesian techniques draw on this prior (a priori) distribution to derive a new (posterior) distribution that incorporates the likelihood of the data given the prior distribution. This approach is appealing because it takes into account all of the information accumulated and enables an assessment about the probability of a given hypothesis being true, rather than rejection or acceptance based on a specified threshold (i.e., the α-level or p-value of traditional statistics). A Bayesian approach may be well suited in selecting models to relate the dynamic nature of park resources over the long-term because of its ability to continually incorporate updates to parameter estimates as data accumulate.

7.1.5 *Spatial Pattern Analysis*

We will use a fifth analytical approach, spatial pattern analysis, to investigate landscape land cover and vegetation patterns and patterns pertaining to early detection of invasive exotic plants. Issues of concern include patch dynamics of land cover and vegetation types of interest and habitat fragmentation. An abundance of landscape metrics (e.g., patch shape, mean patch size, average perimeter-area ratio) can be employed to evaluate spatial patterns, but many indices have been shown to be correlated (Ritters et al. 1995). One approach to this problem is to define independent components of spatial pattern and then develop a suite of metrics that measure the components (Li and Reynolds 1994, Ritters et al. 1995). For example, spatial heterogeneity can be divided into number and proportion of land cover types, patch shape, spatial arrangement of the patches, and contrast between neighboring patches (Li and Reynolds 1995). We will use a similar approach and select a small set of metrics that individually describe independent pattern components but collectively cover the complexity of spatial patterns.

7.2 DATA REPORTING

We will use a variety of approaches to disseminate the results of the SCPN monitoring program to park managers, scientists, and the general public. The network will regularly prepare two types of data reports for each monitoring project: annual data summary reports and long-term (3 to10 year) trend reports. These reports will form the basis for a variety of secondary information products. On a longer time interval, synthetic reports that integrate trend data from linked monitoring projects will be prepared to describe the overall condition or integrity of a park resource or ecosystem. In addition to these regular reporting formats, network staff will work individually with SCPN parks to meet special park data requests. Parks engaged in the preparation of planning documents (e.g., General Management Plans, Resource Stewardship Plans, Fire Management Plans) or management assessments may require specific data summaries to meet a particular need. Three types of reports are described below, as well as our other approaches to data dissemination.

7.2.1 *Annual Reports for Specific Monitoring Projects*

The primary purposes of annual reports for specific monitoring projects are to:

- Summarize annual data and document monitoring activities for the year
- Describe current conditions of the resources sampled, and
- Provide data back to park managers in a timely way to increase data utility and improve communication within and among SCPN parks.

Several of our monitoring projects involve data collection each year (e.g., climate, water quality) and the protocols for these vital signs include producing annual reports. For monitoring projects involving less frequent data collection (e.g., bird communities, riparian vegetation composition and structure), summary reports will be prepared in those years when sampling occurs. Where possible, annual reports will be based on automated data summarization routines built into the database for each protocol. The automation of data summaries and annual reports will facilitate the network's ability to manage multiple projects and to produce reports with consistent content from year to year at timely intervals. For more complex analyses, data will be analyzed using statistical software packages. Reporting for some vital signs (e.g., water quality) will include an evaluation of current status against historical levels, reference conditions, or regulatory standards. Annual reports will be reviewed at the network level.

7.2.2 *Trend Reports for Specific Monitoring Projects*

The primary purpose of trend reports is to report on the following:

- Patterns and trends in condition of resources being monitored
- New characteristics of resources and correlations among related vital signs
- Degree of change that can be detected by the current level of sampling, and
- Interpretation of monitoring data in a park, multi-park, and regional context.

Examples of trend reports for SCPN include:

- Water quality trends at Bandelier NM.
- Changes in riparian geomorphology and riparian vegetation on the Escalante River.
- Trends in mixed-conifer breeding bird communities across three SCPN parks.

Trend reports will be prepared every 3 to 5 years for vital signs that are sampled annually and at a 10-year interval for vital signs that are monitored less frequently. Trend reports will be peer-reviewed by an external 3-member panel.

7.2.3 *Integrated Analysis Reports*

The primary purpose of integrated analysis reports is to examine patterns across vital signs and ecological factors to gain broad insights into ecosystem processes and trends in ecosystem integrity.

This may be accomplished through:

- Qualitative comparisons of monitoring trends with known or hypothesized relationships
- Data exploration and confirmation of hypothesized relationships (e.g.,

ordination, classification, multiple regression, structural equation modeling), and
- Development of predictive models.

Examples of integrated analysis reports for SCPN include:

- Trends in water quality and macroinvertebrate communities on Capulin Creek.
- Trends in terrestrial arthropod assemblages, breeding bird communities, and vegetation dynamics in the pinyon-juniper woodlands of Mesa Verde NP.
- Trends in landscape vegetation pattern, vegetation condition, and mixed-conifer stand structure across two SCPN parks.

These analyses will contribute to our understanding of ecological relationships and provide a weight-of-evidence approach to describing changes in ecosystem condition. Integrated analysis reports will be prepared at 10-year (or longer) intervals and will be peer reviewed by an external 3-member panel.

7.2.4 *Data Dissemination*

The SCPN will provide monitoring data through a variety of means including workshops, presentations, publications, newsletters, and websites.

Network Workshops. Network staff, park scientists, and collaborators involved in monitoring SCPN vital signs will routinely meet with park managers to provide a briefing on the condition of park natural resources and discuss possible implications for management. These workshops may be organized by ecosystems or by broad monitoring topics. The workshops will serve to increase the availability and utility of monitoring results for park managers and promote communication among the contributing scientists and park managers.

Scientific Publications, Presentations, and Outreach. Publishing scientific journal articles and book chapters is a key method for communicating advances in knowledge and improving the scientific rigor of the monitoring program. Network staff, park scientists, and collaborators will also periodically present their findings at professional symposia, conferences, and workshops to communicate the latest findings and identify emerging issues relevant to natural resource monitoring and management. Along with providing scientific reports, each scientist involved with network monitoring will be asked to contribute materials (e.g., story ideas, photographs) for use in newsletters, interpretive talks and exhibits, and other media in order to inform and entertain the general public.

Internet and Intranet Websites. Internet and NPS intranet websites are contemporary tools useful for promoting communication, coordination, and collaboration among the many people, programs, and agencies involved in the SCPN monitoring program. All written products of the monitoring effort, unless they contain sensitive or commercially valuable information that needs to be restricted, will be posted to the SCPN internet website: http://www1.nature.nps.gov/im/units/scpn/index.htm.

Documents available on this network website will include this monitoring plan; all protocols; annual, trend, and integrated analysis reports; and other materials of interest to NPS staff and our collaborators. Additionally, to promote communication and coordination within the network, we will maintain a password-protected intranet website where draft products, works in progress, and other materials that require restricted access can be shared within the program.

CHAPTER 8

PROGRAM ADMINISTRATION

This chapter provides information on the administrative organization of the Southern Colorado Plateau Network, including staffing, operations and partnerships.

8.1 NETWORK ORGANIZATION

A multi-level organizational structure has been identified to ensure that an effective I&M Program is created and implemented for the SCPN (Appendix K: SCPN Charter). This organizational structure comprises a Board of Directors, Technical Advisory Committee, Scientific Panel, and SCPN Staff.

8.1.1 *Board of Directors*

The Board of Directors (BOD) provides guidance, oversight, and advocacy in the development and implementation of the I&M Program for the 19 NPS units within the SCPN.

8.1.2 *Technical Advisory Committee*

The Technical Advisory Committee (TAC) is responsible for the scientific and technical planning aspects, park-based logistic support, and resource management applications of the I&M Program for the 19 NPS units within the network.

8.1.3 *Scientific Panel*

The primary purpose of the scientific panel is to provide scientific guidance to the SCPN in the design and implementation of the monitoring program. Current panel members are:

- Dr. Craig Allen, USGS/Jemez Mountains Field Station
- Dr. Jim Gosz, Sevilleta LTER Program
- Dr. Dave Lime, University of Minnesota
- Dr. Barry Noon, Colorado State University
- Dr. Jack Schmidt, Utah State University
- Dr. Tom Sisk, Northern Arizona University

8.2 STAFFING

In November 2005, the SCPN Technical Advisory Committee and Board of Directors approved an operational staffing plan for the SCPN (Appendix L). The plan reflects the shared belief that the network requires a core staff of highly qualified NPS scientists to implement this important, long-term program (Figure 8-1). At the same time the BOD recommended a conservative strategy toward allocating funds toward permanent personnel and other fixed costs. The current plan maintains these costs at below 65% of the program's operational base. The staffing plan also maintains a commitment to continuing partnerships with USGS and our CESU partners. Approximately one third of the program's budget will be directed toward accomplishing monitoring objectives through cooperative relationships. In addition, we will reserve 5% of the operational program budget for continued research, development, and analysis. Table 8-3 describes SCPN positions and their responsibilities.

8.3 OPERATIONS

8.3.1 *Facilities*

The SCPN is currently housed with the Colorado Plateau Cooperative Ecosystem Studies Unit (CP-CESU) on the campus of Northern Arizona University. To date, the university has provided office space as in-kind support to the program. The SCPN and

Table 8-1. Board of Directors membership and responsibilities.

MEMBERSHIP:	CURRENT VOTING BOARD MEMBERS:
The BOD has five voting members comprising superintendents or assistant superintendents from five of the 19 NPS units within the SCPN. The Technical Advisory Committee Chair, the SCPN Program Manager, the Intermountain Region I&M Coordinator and the CP CESU Research Coordinator serve as non-voting members. The BOD chair is elected by the voting BOD members and serves a two-year term.	- Dennis Carruth, Superintendent AZRU - Scott Travis, Chair, Superintendent CACH - Larry Wiese, Superintendent MEVE and YUHO - Palma Wilson, Superintendent SUCR, WACA, and WUPA - 5th Board Position Vacant

RESPONSIBILITIES:

- Provide general guidance and input on strategies for network inventory and monitoring.
- Promote accountability for the I&M Program by reviewing progress and providing quality control for the network.
- Review and approve reports, annual workplans and budgets, and staffing plan proposals recommended by the TAC.
- Review, approve, and distribute annual accomplishment reports to the Intermountain Regional Office (IMR) and WASO.
- Advocate an active and effective biological inventory and natural resource monitoring program for the network.
- Decide on strategies and procedures for leveraging network funds and personnel to best accomplish the natural resource inventory and monitoring and other needs of the network parks.
- Ensure that the network inventory and monitoring work is fully integrated with park resource management programs and other NPS natural resource funding initiatives.
- Facilitate communication and coordination about network inventory and monitoring activities with natural resource managers in the network and region.
- Serve as liaison to Cluster Leadership Council(s) and the IMR Regional Stewardship Advisory Team.
- Identify and help develop internal and external partnerships to meet the goals of the Natural Resource Challenge and NPS I&M Program.

Table 8-2. Technical Advisory Committee membership and responsibilities.

MEMBERSHIP:

The TAC comprises NPS natural resource representatives from the 19 SCPN NPS units, plus the CP-CESU Research Coordinator and the SCPN Program Manager. Other SCPN staff members may participate in TAC meetings at the discretion of the Program Manager. The superintendent or chief of resources management for each SCPN NPS unit may designate one representative to the TAC. The representative should be a park-based natural resource specialist, technical specialist, scientist, or hold a position with natural resource project management as a collateral duty. The TAC chair is elected by the TAC members and serves a two-year term.

Current TAC Chair: Elaine Leslie, Deputy Superintendent CACH

RESPONSIBILITIES:

- Review and recommend annual workplans, budgets, and staffing plan proposals for approval by the BOD.
- Review and recommend annual accomplishment reports for approval by the BOD.
- Assist the SCPN Program Manager and staff with developing and implementing the SCPN Vital Signs Monitoring Plan.
- Compile and summarize existing information about park resources.
- Host meetings, workshops and other activities needed to develop and implement the SCPN I&M Program.
- Solicit professional guidance, as needed, from scientific panel members and other individuals and organizations.
- Ensure that SCPN inventory and monitoring activities are integrated into the planning and compliance process within network parks in accordance with regulations and NPS policy.
- Organize and facilitate periodic program reviews.
- Work with individual park staff (particularly in other resource areas) to build support for a fully integrated inventory and monitoring program.
- Ensure that the network inventory and monitoring work is fully integrated with park resource management programs and other NPS natural resource funding initiatives.
- Develop and foster partnerships with other agencies and organizations which support overall I&M objectives.

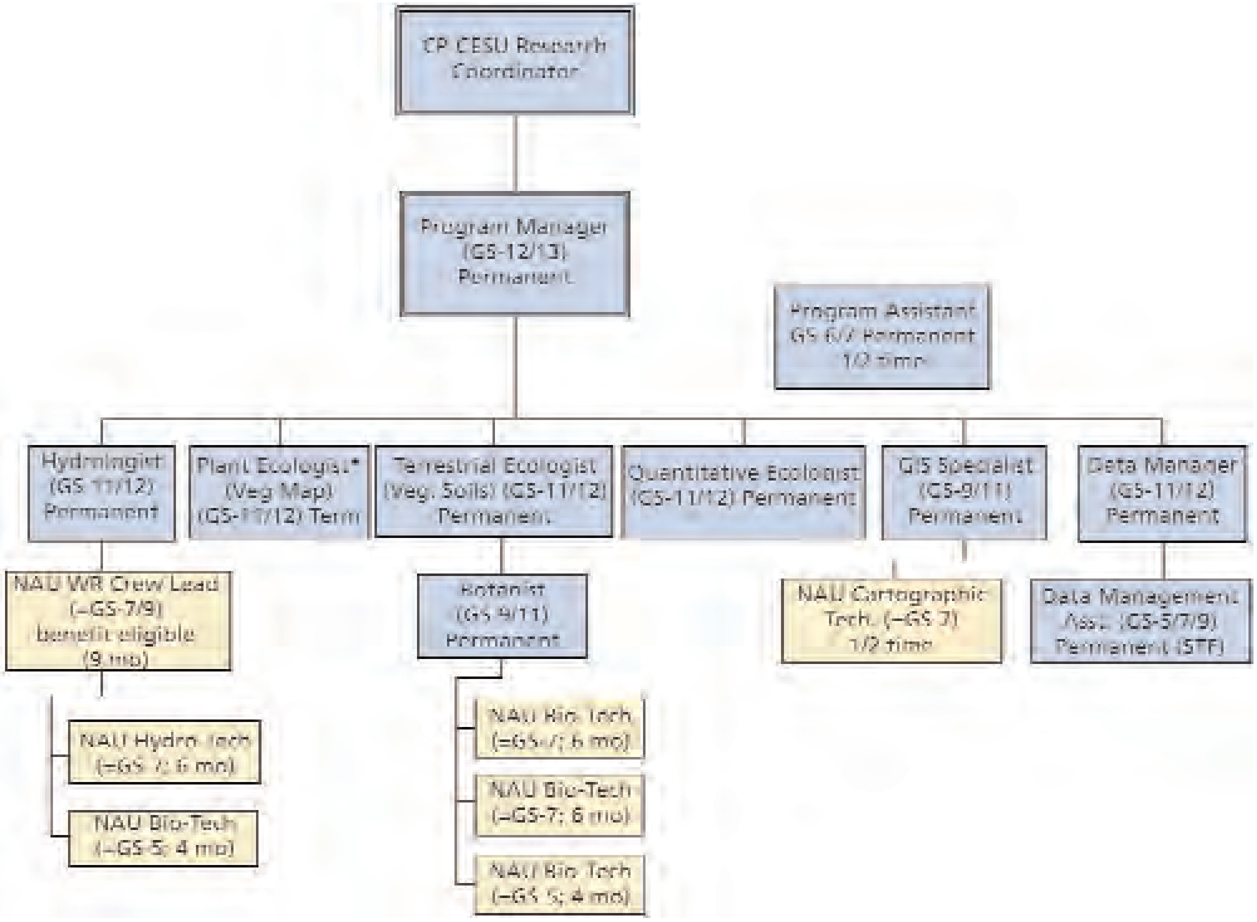


Figure 8-1. *SCPN organization chart.*

** Propose ending position as vegetation mapping projects are completed (FY2007).*

CP-CESU are anticipated to be tenants in the NAU Applied Research and Development Building, scheduled for completion in 2007. The new building will include office space and dry lab facilities for the program. Negotiations with the university regarding lease rates will occur in 2006.

8.3.2 *In-house Monitoring Crews*

We plan to use our cooperative relationship with Northern Arizona University to staff two field crews. A water resources field crew will monitor water quality, aquatic macroinvertebrates, and integrated riparian vital signs under the direction of the SCPN Hydrologist. An uplands field crew will monitor vegetation and soil stability vital signs under the direction of the SCPN Terrestrial Ecologist. See Appendix L for details.

Training. The quality of data resulting from long-term monitoring is only as good as the field crews who collect the data. Routine training prior to the field season is essential to ensure that high-quality and consistent data are collected over the years. During the training period, the project manager will provide crew members with review and/or training for all standard operating procedures included in the monitoring protocols. This period will also allow the project manager to evaluate the skills and experience-level of new crew members.

Safety. Field work can involve exposure to harsh conditions, hazardous plants and animals, and extreme weather conditions. Worker safety is of paramount concern in conducting a field-based monitoring program. The SCPN monitoring program will be operated in accordance with safety laws, regulations and policies, and appropriate training will be provided.

Equipment. The network will supply the equipment and supplies necessary to conduct in-house monitoring projects. Property and equipment will

Table 8-3. Roles and responsibilities of network staff positions.

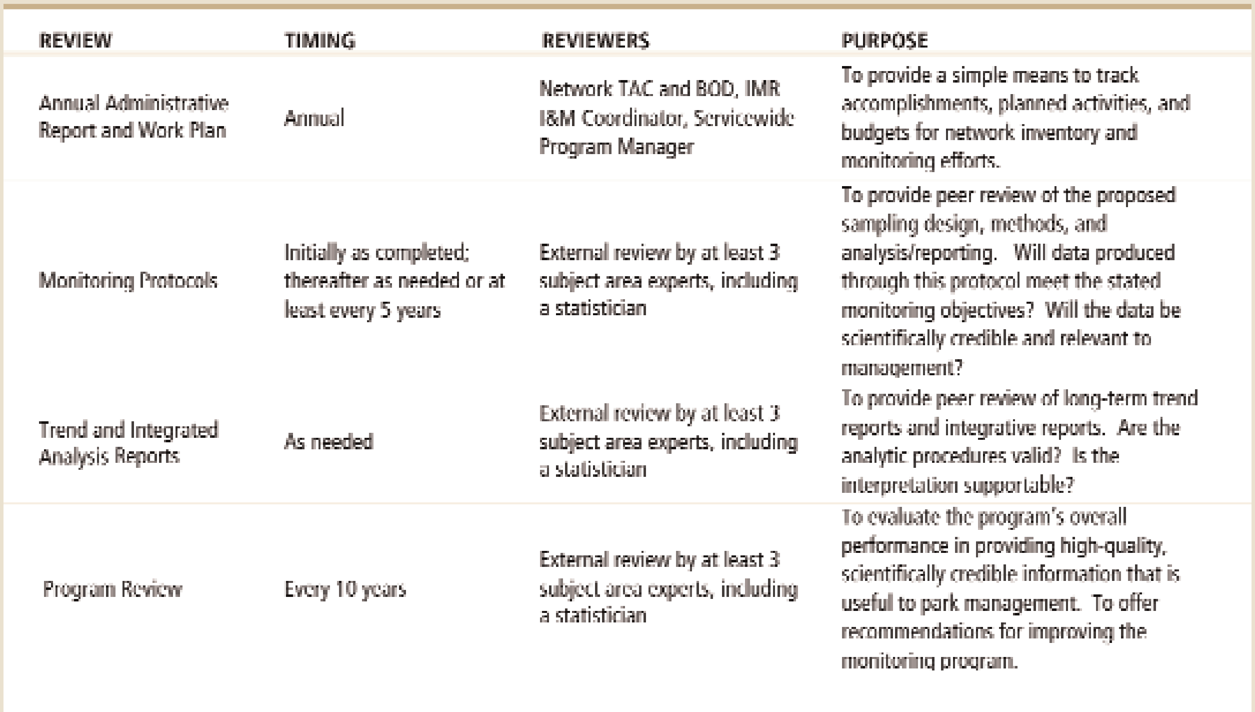
POSITION	ROLES AND RESPONSIBILITIES
Program Manager	The Program Manager is responsible for the overall management and supervision of the program. Duties include developing the process for selecting indicators, overseeing the development and testing of monitoring protocols, hiring and supervising network staff, managing the implementation of monitoring projects, and ensuring that resulting data are appropriately analyzed and reported.
Program Assistant	The 1/2 time Program Assistant serves as office manager for the program. Duties include timekeeping, travel management, procurement, property inventory and budget tracking.
Data Manager	The Data Manager is responsible for the information and data stewardship of the program. The Data Manager designs databases for monitoring projects, writes data management plans and protocols, and works with network and park staff, cooperating scientists, and others to ensure that datasets are fully documented and validated.
GIS Specialist	The GIS Specialist is responsible for managing the network's spatial data and providing GIS support to monitoring projects. Duties include managing, documenting, and distributing spatial data resulting from monitoring projects, maintaining a library of relevant park spatial data, and serving as a co-investigator on landscape monitoring projects.
Data Management Assistant	The Data Management Assistant works with the data manager and GIS Specialist to build and maintain project databases and GIS files, populate NPS Servicewide databases, maintain digital document libraries, and maintain the SCPN website.
Quantitative Ecologist	The Quantitative Ecologist is responsible for developing the overall sampling design, inference strategy, and analytic components of the program. Duties include providing statistical and analytic support to monitoring projects, serving as a subject matter expert in a particular science discipline, and collaborating with staff and cooperators to complete analyses and write trend analyses and integrative reports.
Hydrologist	The Hydrologist is responsible for developing and implementing monitoring projects relating to water resources (water quality, aquatic macroinvertebrates, springs ecosystems, and integrated riparian vital signs). Duties include overall integration, analysis, and reporting of monitoring results.
Terrestrial Ecologist	The Terrestrial Ecologist is responsible for developing and implementing monitoring projects relating to upland vegetation composition and structure, soil stability, and upland hydrologic function. The Terrestrial Ecologist also contributes to monitoring projects relating to riparian vegetation, habitat-based bird communities, arthropod communities, and early detection of invasive exotic plants. Duties include overall integration, analysis, and reporting of monitoring results.
Botanist	The Botanist serves as the plant taxonomy expert for the program and works with the Vegetation Ecologist to implement monitoring program components relating to upland vegetation, riparian vegetation, and vegetation associated with spring ecosystems. The Botanist is responsible for accurate identification of plant species from across the program's ecological range and for establishing and maintaining a herbarium reference collection.
Vegetation Ecologist	The Vegetation Ecologist is responsible for developing and implementing the network vegetation mapping and classification project. Duties include development and oversight of vegetation mapping cooperative agreements and contracts. The Vegetation Ecologist also coordinates the completion of vertebrate and vascular plant inventories for SCPN parks.

be managed according to Directors Order #44: Property Management. Sensitive property (cameras, computers, etc.) and property sensitive to theft, loss or damage (GPS units, radios, and binoculars) will be managed as accountable property. Purchasing of equipment likely to depreciate will be scheduled over time to reduce the impact of replacing substantial amounts of equipment in any given year. Calibration of equipment will follow manufacturer directions and will be included in an appendix to the monitoring protocol. Vehicles will normally be leased through General Services Administration (GSA).

8.4 PARTNERSHIPS

We have initiated a number of cooperative and interagency agreements to develop monitoring protocols and complete projects in support of the

Table 8-4. **Monitoring program review.**



REVIEW	TIMING	REVIEWERS	PURPOSE
Annual Administrative Report and Work Plan	Annual	Network TAC and BOD, IMR I&M Coordinator, Servicewide Program Manager	To provide a simple means to track accomplishments, planned activities, and budgets for network inventory and monitoring efforts.
Monitoring Protocols	Initially as completed; thereafter as needed or at least every 5 years	External review by at least 3 subject area experts, including a statistician	To provide peer review of the proposed sampling design, methods, and analysis/reporting. Will data produced through this protocol meet the stated monitoring objectives? Will the data be scientifically credible and relevant to management?
Trend and Integrated Analysis Reports	As needed	External review by at least 3 subject area experts, including a statistician	To provide peer review of long-term trend reports and integrative reports. Are the analytic procedures valid? Is the interpretation supportable?
Program Review	Every 10 years	External review by at least 3 subject area experts, including a statistician	To evaluate the program's overall performance in providing high-quality, scientifically credible information that is useful to park management. To offer recommendations for improving the monitoring program.

monitoring program (see Table 5-1). We anticipate forming additional partnerships as we move into implementation of the monitoring program. A few key relationships are described below.

8.4.1 *Integration with the Northern Colorado Plateau Network*

The SCPN staff is working in close collaboration with the Northern Colorado Plateau Network to develop a series of protocols for shared monitoring needs. The two networks began coordinating their planning efforts in order to meet the goal of developing a common set of conceptual models for Colorado Plateau ecosystems (see Chapter 2). More recently, the two networks have established several cooperative and interagency agreements to develop monitoring protocols for aquatic macroinvertebrates, riparian, upland and springs ecosystems, and for landscape vital signs. The main benefits from this partnership are cost-efficiency for protocol development, monitoring consistency across a larger geographic area, and the resulting opportunity to evaluate trends more broadly across NPS units of the Colorado Plateau.

8.4.2 *Colorado Plateau Cooperative Ecosystems Studies Unit*

Organizationally, the SCPN is part of the Colorado Plateau Cooperative Ecosystem Studies Unit (CP-CESU) with close ties to the CP-CESU and its host university, Northern Arizona University. The CESU mission is to improve access to scientific research and technical assistance within the federal land management agencies and to create effective partnerships among federal agencies and universities. The CP-CESU provides the network with ready access to university and nonprofit members for technical assistance needed to develop and implement the monitoring program.

8.4.3 *National Park Service*

Air Resources Division (ARD). The ARD coordinates air quality monitoring (ozone, wet and dry deposition, particulates, visibility) for the NPS. The SCPN will rely on ARD data collection and reporting to summarize these data for Class I parks.

Fire Effects Monitoring Program. The fire effects monitoring program documents basic information for wildland fires and monitors prescribed fire effects on vegetation. There is the potential for a partnership between the SCPN and Fire Effects Monitoring Program to achieve common monitoring objectives.

Water Resources Division (WRD). The WRD provides technical support for hydrologic monitoring (water quantity and quality) in SCPN parks. The water quality component of the Natural Resource Challenge (NRC) requires that Vital Signs Networks archive all physical, chemical, and biological water quality data collected with NRC water quality funds in the National Park Service's STORET database maintained by WRD.

8.4.4 *U.S. Geological Survey Scientists*

The network is currently working with USGS scientists from the Colorado Plateau and Canyonlands Field Stations of the Southwest Science Center, the Fort Collins Science Center, and the Water Resources Discipline of USGS to develop monitoring protocols. The Earth Resources Observations Systems (EROS) Data Center is providing MODIS NDVI data for monitoring vegetation condition.

8.4.5 *Other Federal, State or Tribal Monitoring Programs*

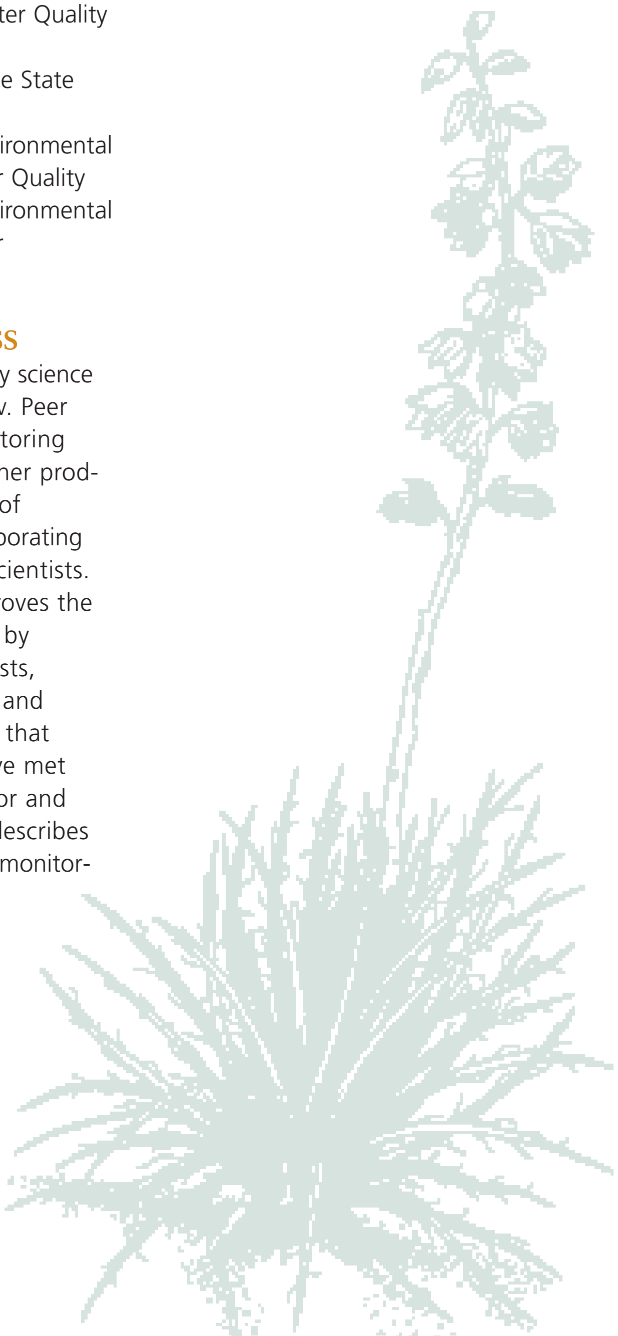
The network relies on multiple agencies for data from their weather station networks. These networks include the NOAA National Weather Service Cooperative Observing Program and Climate Research Network (CRN) and the Remote Automated Weather Stations (RAWS) network supported by the Interagency Fire Center. We will also work with the Western Region Climate Center of NOAA.

The SCPN will work with a number of state and tribal agencies on monitoring related to water quality and water quantity:

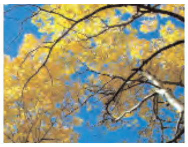
- Arizona Department of Environmental Quality Water Quality Division
- Arizona Department of Water Resources
- Colorado Department of Public Health and Environment Water Quality Control Division
- Colorado Division of Water Resources
- Navajo Nation Department of Water Resources
- Navajo Nation Environmental Protection Agency
- New Mexico Environment Department Surface Water Quality Bureau
- New Mexico Environment Department Ground Water Quality Bureau
- New Mexico Office of the State Engineer
- Utah Department of Environmental Quality Division of Water Quality
- Utah Department of Environmental Quality Division of Water Resources

8.5 REVIEW PROCESS

An essential element of any science program is periodic review. Peer review of proposals, monitoring protocols, reports, and other products improves the quality of scientific research by incorporating the knowledge of other scientists. Effective peer review improves the credibility of the program by conveying to other scientists, policy-makers, managers, and the public the knowledge that the resulting products have met accepted standards of rigor and accountability. Table 8-4 describes the review process for the monitoring program.



CHAPTER 9



SCHEDULE

This chapter describes the SCPN timeline to develop monitoring protocols for core vital signs and to implement those protocols across network parks. It also summarizes the frequency and timing of monitoring for each core vital sign.

9.1 PROTOCOL DEVELOPMENT

In Table 9-1 we describe the expected timeline to complete protocol development and implement 13 monitoring protocols covering 18 core vital signs. We initiated six protocol development projects in FY2005 (five in collaboration with the Northern Colorado Plateau Network) and plan to initiate six additional projects in FY2006. See Appendix J for detailed descriptions of particular protocol development projects.

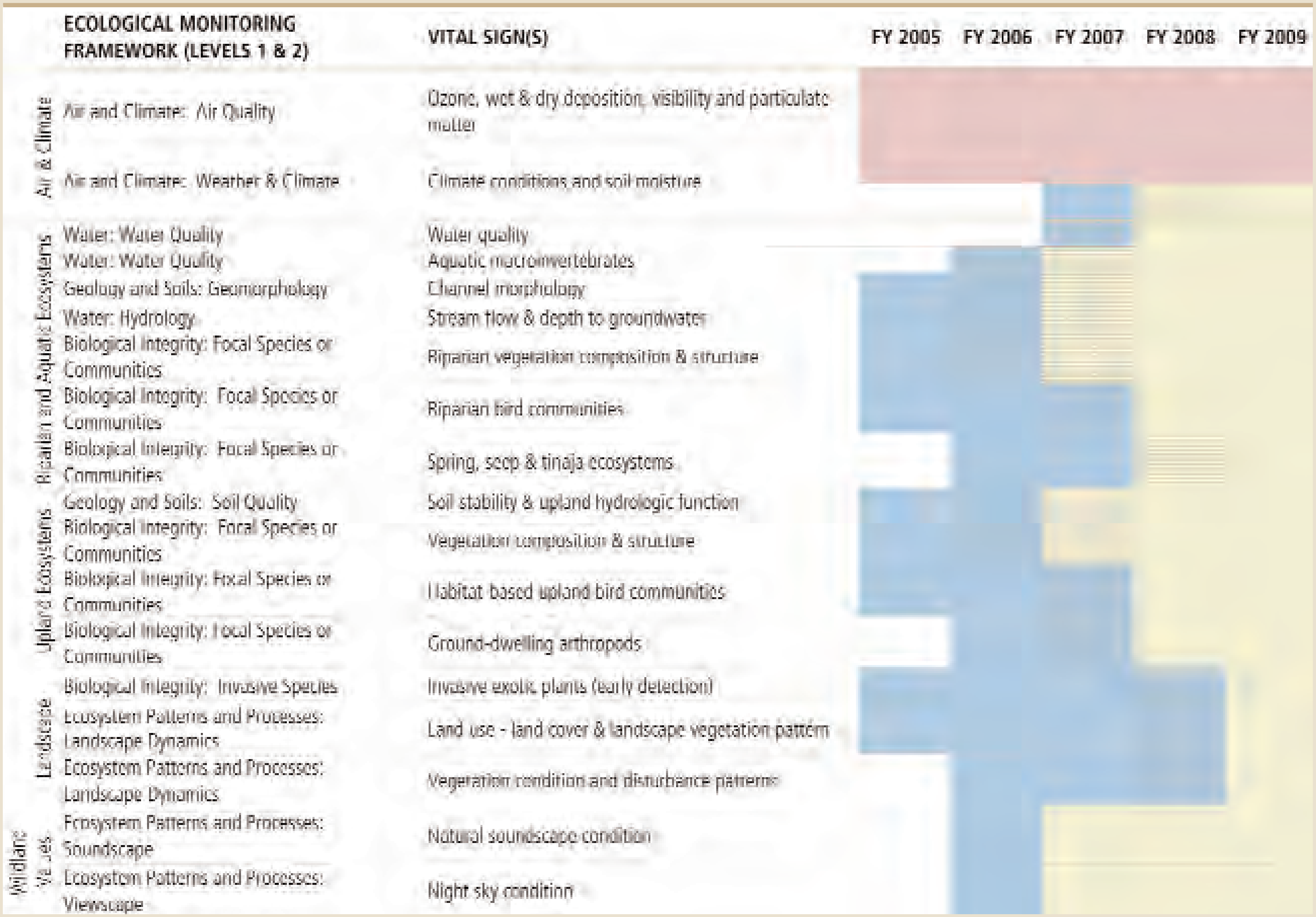
For several of our most broadly applied monitoring topics (i.e., upland, riparian), we have identified a two-year window for site selection and establishment in order to address problems or uncertainties that could arise as we attempt to apply our stratification and inference-based site selection approaches to park-specific situations. Some of these uncertainties are the result of the scale and accuracy of available map layers. For instance, we are exploring the use of ecological sites as the basis for upland stratification. In our initial trials, we have discovered that multiple ecological sites are often mapped as a single map unit complex. In this type of situation, it is likely that an initial GIS stratification will need to be combined with field-based decision rules in order to select sites within the target population. Another problem is insufficient base spatial data. In spite of recent network and Servicewide I&M Program efforts, many SCPN parks still lack basic inventory layers such as recent soils maps or accurate maps of perennial stream reaches. Notwithstanding these potential obstacles, we are committed to working with SCPN park resource managers to identify long-term target populations and maintain appropriate inference strategies.

9.2 SAMPLING SEASON AND MONITORING FREQUENCY

Table 9-2 summarizes the frequency and timing of monitoring for each core vital sign. The frequency of sampling (or revisit design) ranges from continuous data collection (e.g., automated weather stations) to remotely-sensed data that may be acquired every five years. See Chapter 4 for more detailed description of our proposed revisit designs.

An index period refers to a time frame for sampling that optimizes the cost-efficiency or information content of the data. For biotic populations or communities, the index period may correspond to life cycle or phenologic stages. For water quality, index periods correspond to phases of the hydrologic cycle, including snow-melt, baseflow, and runoff generated by summer thunderstorms. Sampling during an index period can minimize between-year variability due to natural events and optimize the accessibility of the target community or attribute. Table 9-2 currently contains rough estimates of the index period associated with a particular vital sign. As protocol development continues, index periods will be refined to meet site and protocol-specific requirements.

Table 9-1. Timeframe for implementing the SCPN monitoring program.



	ECOLOGICAL MONITORING FRAMEWORK (LEVELS 1 & 2)	VITAL SIGN(S)	FY 2005	FY 2006	FY 2007	FY 2008	FY 2009
Air & Climate	Air and Climate: Air Quality	Ozone, wet & dry deposition, visibility and particulate matter	🟥	🟥	🟥	🟥	🟥
	Air and Climate: Weather & Climate	Climate conditions and soil moisture	🟥	🟥	🟥	🟥	🟥
Riparian and Aquatic Ecosystems	Water: Water Quality	Water quality			🟦	🟨	🟨
	Water: Water Quality	Aquatic macroinvertebrates		🟦	▨	🟨	🟨
	Geology and Soils: Geomorphology	Channel morphology	🟦	🟦	▨	🟨	🟨
	Water: Hydrology	Stream flow & depth to groundwater	🟦	🟦	▨	🟨	🟨
	Biological Integrity: Focal Species or Communities	Riparian vegetation composition & structure	🟦	🟦	▨	🟨	🟨
	Biological Integrity: Focal Species or Communities	Riparian bird communities	🟦	🟦	🟦	🟨	🟨
	Biological Integrity: Focal Species or Communities	Spring, seep & tinaja ecosystems		🟦	🟦	▨	🟨
Upland Ecosystems	Geology and Soils: Soil Quality	Soil stability & upland hydrologic function	🟦	🟦	🟨	🟨	🟨
	Biological Integrity: Focal Species or Communities	Vegetation composition & structure	🟦	🟦	🟨	🟨	🟨
	Biological Integrity: Focal Species or Communities	Habitat based upland bird communities	🟦	🟦	🟦	🟨	🟨
	Biological Integrity: Focal Species or Communities	Ground-dwelling arthropods		🟦	🟦	🟨	🟨
Landscape	Biological Integrity: Invasive Species	Invasive exotic plants (early detection)	🟦	🟦	🟦	🟦	🟨
	Ecosystem Patterns and Processes: Landscape Dynamics	Land use - land cover & landscape vegetation pattern	🟦	🟦	🟦	🟦	🟨
	Ecosystem Patterns and Processes: Landscape Dynamics	Vegetation condition and disturbance patterns		🟦	🟦	🟦	🟨
Wildland Values	Ecosystem Patterns and Processes: Soundscape	Natural soundscape condition		🟦	🟨	🟨	🟨
	Ecosystem Patterns and Processes: Viewscape	Night sky condition		🟦	🟨	🟨	🟨

🟦 Protocol development, field trials, needs assessment
▨ Site selection & establishment
🟨 Full implementation
🟥 Partially or fully implemented through other sources

Table 9-2. Index period and general revisit plan for vital signs monitoring.

	ECOLOGICAL MONITORING FRAMEWORK (LEVELS 1 & 2)	VITAL SIGN(S)	INDEX PERIOD	REVISIT DESIGN*
Air and Climate	Air and Climate: Air Quality	Ozone, wet & dry deposition, visibility and particulate matter	Continuous	Continuous
	Air and Climate: Weather & Climate	Climate conditions and soil moisture	Continuous	Continuous
Riparian and Aquatic Ecosystems	Water: Water Quality	Aquatic macroinvertebrates	Early Fall	[1-0]
	Water: Water Quality	Water quality of streams & springs	Year Around	Quarterly
	Geology and Soils: Geomorphology	Channel morphology	Spring through Fall	[1-4]
	Water: Hydrology	Stream flow & depth to groundwater	Continuous	Continuous to monthly
	Biological Integrity: Focal Species or Communities	Riparian vegetation composition & structure	Spring through Fall	[1-4]
	Biological Integrity: Focal Species or Communities	Riparian bird communities	Early Summer	TBD
	Biological Integrity: Focal Species or Communities	Spring, seep & tinaja ecosystems	Spring through Fall	TBD
Upland Ecosystems	Geology and Soils: Soil Quality	Soil stability & upland hydrologic function	Spring through Fall	[2-3, 1-4] **
	Biological Integrity: Focal Species or Communities	Upland vegetation composition & structure	Spring through Fall	[2-3, 1-4] **
	Biological Integrity: Focal Species or Communities	Habitat based upland bird communities	Early Summer	TBD
	Biological Integrity: Focal Species or Communities	Ground-dwelling arthropods	Summer	TBD
Landscape	Biological Integrity: Invasive Species	Invasive exotic plants (early detection)	Spring through Fall	[1-4]
	Ecosystem Patterns and Processes: Landscape Dynamics	Land use - land cover & landscape vegetation pattern	Multi-seasonal (spring, summer, fall)	[1-4]
	Ecosystem Patterns and Processes: Landscape Dynamics	Vegetation condition and disturbance patterns	Condition: continuous Disturbance: multi-seasonal	Condition: annual Disturbance: [1-4]
Wilderness Values	Ecosystem Patterns and Processes: Soundscape	Natural soundscape condition	Summer	TBD
	Ecosystem Patterns and Processes: Viewscape	Night sky condition	TBD	TBD

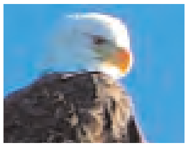
** Notation follows McDonald (2003). See Chapter 4 for explanation.*

*** Revisit plan for medium-size parks (revisit plan varies by park size).*

PAGE INTENTIONALLY LEFT BLANK

PAGE INTENTIONALLY LEFT BLANK

CHAPTER 11



LITERATURE CITED

Adams, D. K., and A. C. Comrie. 1997. The North American monsoon. Bulletin of the American Meteorological Society 78:2197-2214.

Allan, J. D. 1995. Stream ecology: structure and function of running waters. Chapman & Hall, London.

Allen, C. D. 1996. Elk response to the La Mesa Fire and current status in the Jemez Mountains. Pages 179-195 in C. D. Allen, editor. Fire effects in southwestern forests: Proceedings of the second La Mesa Fire Symposium. USDA Forest Service, Rocky Mountain Forest and Range Experiment Station, Los Alamos, NM.

Allen, C. D. 1998. A ponderosa pine natural area reveals its secrets. Pages 551-552 in M. J. Mac, P. A. Opler, C. E. Puckett Haecker, and P. D. Doran, editors. Status and trends of the nation's biological resources. U.S. Department of Interior, U.S. Geological Survey, Reston, Virginia.

Allen, C. D. 2002. Lots of lightning and plenty of people: An ecological history of fire in the upland Southwest. Pages 143-193 in T. Vale, editor. Fire, Native Peoples, and the Natural Landscape. Island Press, Washington, D.C.

Allen, C. D., M. Savage, D. A. Falk, K. F. Suckling, T. W. Swetnam, T. Schulke, P. B. Stacey, P. Morgan, M. Hoffman, and J. T. Klingel. 2002. Ecological restoration of southwestern ponderosa pine ecosystems: A broad perspective. Ecological Applications 12:1418-1433.

Alward, R. D., J. K. Detling, and D. G. Milchunas. 1999. Grassland vegetation changes and nocturnal global warming. Science 283:229-231.

Arizona Game and Fish Department. 2001. Wildlife 2006. Arizona Game and Fish Department, Phoenix, Arizona.

Arno, S. F., and R. D. Ottmar. 1994. Reducing hazard for catastrophic fire. Department of Agriculture, Forest Service, Pacific Northwest Research Station, Portland, Oregon.

Asner, G. P., T. R. Seastedt, and A. R. Townsend. 1997. The decoupling of terrestrial carbon and nitrogen cycles. Bioscience 47:226-234.

Auble, G. T., and M. L. Scott. 1998. Fluvial disturbance patches and cottonwood recruitment along the upper Missouri River, Montana. Wetlands 18:546-556.

Axelrod, D. I., and P. H. Raven. 1985. Origins of the cordilleran flora. Journal of Biogeography 12:21-47.

Bailey, D. A., P. Mazurak, and J. R. Rosowski. 1973. Aggregation of soil particles by algae. Journal of Phycology 9:99-101.

Bailey, R. G. 1995. Description of the ecoregions of the United States, 2nd edition revised and expanded. U.S. Department of Agriculture Forest Service, Washington, D.C.

Bailey, R. G. 1998. Ecoregions: the ecosystem geography of the oceans and continents. Springer, New York, New York.

Bain, M. B., J. T. Finn, and H. E. Booke. 1988. Streamflow regulation and fish community structure. Ecology 69:382-392.

Baker, W. L., and D. J. Shinneman. 2004. Fire and restoration of piñon-juniper woodlands in the western United States: a review. Forest Ecology and Management 189:1-21.

Balba, A. M. 1995. Management of problem soils in arid ecosystems. CRC Press Inc., Boca Raton, Florida.

Barber, M. C. 1994. Environmental monitoring and assessment program indicator development strategy. in. Environmental Protection Agency, Office of Research and Development, Environmental Research Laboratory, Athens, GA.

Barbour, M. G., and W. D. Billings, editors. 1988. North American terrestrial vegetation, Second edition. Cambridge University Press, Cambridge, UK.

Bayes, T. 1763. An essay towards solving a problem in the doctrine of chances. Philosophical Transactions of the Royal Society of London 53:370-418.

Beard, G. R., W. A. Scott, and J. K. Anderson. 1999. The value of consistent methodology in long-term environmental monitoring. Environmental Monitoring and Assessment 54:239-258.

Belnap, J. 1990. Microbiotic crusts: their role in past and present ecosystems. Park Science 10:3-4.

Belnap, J., B. Büdel, and O. L. Lange. 2001. Biological soil crusts: characteristics and distribution. in J. Belnap and O. L. Lange, editors. Biological soil crusts: structure, function, and management. Springer-Verlag, Berlin.

Belnap, J., T. Harper, and S. D. Warren. 1994. Surface disturbance of cryptobiotic soil crusts; nitrogenase activity, chlorophyll contenct and chlorophyll degradation. Arid Soil Research and Rehabilitation 8:1-8.

Benson, L. D., and R. A. Darrow. 1981. Trees and shrubs of the Southwestern deserts, 3rd edition. University of Arizona Press, Tucson, Arizona.

Bestelmeyer, B. T., J. R. Brown, K. M. Havstad, R. Alexander, G. Chavez, and J. E. Herrick. 2003. Development and use of state-and-transition models for rangelands. Journal of Range Management 56:114-126.

Bestelmeyer, B.T., J.E. Herrick, J.R. Brown, D.A. Trujillo, and K.M. Havstad. 2004. Land management in the American Southwest: a state-and-transition approach to ecosystem complexity. Environmental Management 34: 38-51.

Betancourt, J. L. 1990. Late quarternary biogeography of the Colorado Plateau. Pages 259-292 in J. L. Betancourt, T. R. Van Devender, and P. S. Martin, editors. Packrat Middens: The last 40,000 years of biotic change. University of Arizona Press, Tucson, Arizona.

Blake, D., A. M. Hutson, P. A. Racey, J. Rydell, and J. R. Speakman. 1994. Use of lamplit roads by foraging bats in southern England. Journal of Zoology 234:453-462.

Bock, C. E., J. H. Bock, K. L. Jepson, and J. C. Ortega. 1986. Ecological effects of planting African lovegrasses in Arizona. National Geographic Research 2:456-463.

Bogan, M. A., C. D. Allen, E. H. Muldavin, S. P. Platania, J. N. Stuart, G. H. Farley, P. Melhop, and J. Belnap. 1998. Southwest. in M. J. Mac, P. A. Opler, C. E. Puckett Haecker, and P. D. Doran, editors. Status and trends of the nation's biological resources. United States Geological Survey, Biological Resources Division, Reston, Virginia.

Breshears, D. D., and C. D. Allen. 2002. The importance of rapid, disturbance-induced losses in carbon management and sequestration. Global Ecology and Biogeography 11:1-5.

Breshears, D. D., J. J. Whicker, M. P. Johansen, and J. E. Pinder III. 2003. Wind and water erosion and transport in semi-arid shrubland, grassland and forest ecosystems: Quantifying dominance of horizontal wind-driven transport. Earth Surface Processes and Landforms 28:1189-1209.

Bright, J. L., and C. van Riper III. 2001. The influence of habitat types, water sources, and movement barriers on pronghorn antelope home ranges in northern Arizona. Pages Pages 33-71 in C. van Riper III, K. A. Thomas, and M. A. Stuart, editors. Proceedings of the Fifth Biennial Conference of Research on the Colorado Plateau. USGS, Flagstaff, AZ.

Brinson, M. M., B. L. Swift, R. C. Plantico, and J. S. Barclay. 1981. Riparian ecosystems: their ecology and status. U.S. Fish and Wildlife Service.

Brotherson, J. D., and S. R. Rushforth. 1983. Influence of cryptogamic crusts on moisture relationships of soils in Navajo National Monument. Great Basin Naturalist 43:73-78.

Brown, B. T., and L. E. Stevens. 1997. Winter bald eagle distribution is inversely correlated with human activity along the Colorado River, Arizona. Journal of Raptor Research 31:7-10.

Brown, D. E. 1982. Biotic communities of the American southwest United States and Mexico. Desert Plants 4:1-342.

Brown, D. E. 1994. Biotic communities: southwestern United States and northwestern Mexico. University of Utah Press, Salt Lake City, Utah.

Buchanan, B. W. 1993. Effects of enhanced lighting of the behaviour of nocturnal frogs. Animal Behaviour 45:893-899.

Buckland, S. T., D. R. Anderson, K. P. Burnham, J. L. Laake, D. L. Borchers, and L. Thomas. 2004. Advanced distance sampling. Oxford University Press, Oxford.

Burnham, K.P. and D.R. Anderson. 2002. Model selection and multimodel inference: a practical information-theoretic approach. Springer. New York, New York.

Cable, D. R. 1975. Range management in the chaparral type and its ecological basis: the status of our knowledge. U.S. Department of Agriculture, Forest Service, Rocky Mountain Forest and Range Experiment Station, Fort Collins, CO.

Carothers, S. W. 1977. Importance, preservation, and management of riparian habitats: an overview. Pages 2-4 in R. R. Johnson and D. A. Jones, editors. Importance, preservation, and management of riparian habitat: a symposium. U.S. Forest Service, Rocky Mountain Forest and Range Experiment Station, Tucson, AZ.

Carothers, S. W., S. W. Aitchison, M. M. Karpiscak, G. A. Ruffner, and N. J. Sharber. 1976. An ecological survey of the riparian zone of the Colorado River between Lees Ferry and the Grand Wash Cliffs, Arizona. National Park Service.

Chadwick, O. A., L. A. Derry, P. M. Vitousek, B. J. Huebert, and L. O. Hedin. 1999. Changing sources of nutrients during four million years of ecosystem development. Nature 397:491-497.

Chaney, E., W. Elmore, and W. S. Platts. 1990. Livestock grazing on western riparian areas. U.S. Environmental Protection Agency, Region 8, Denver, Colorado.

Chapin III, F. S., M. S. Torn, and M. Tateno. 1996. Principles of ecosystem sustainability. The American Naturalist 148:1016-1037.

Chapin III, F. S., B. H. Walker, R. J. Hobbs, D. U. Hooper, J. H. Lawton, O. E. Sala, and D. Tilman. 1997. Biotic control over the functioning of ecosystems. Science 277:500-504.

Charley, J. L., and N. E. West. 1975. Plant-induced soil chemical patterns in some shrub-dominated semi-desert ecosystems of Utah. Journal of Ecology 63:945-963.

Clarke, W. M. 1999. Vanishing night skies. National Parks July/August:22-25.

Cleland, D. T., P. E. Avers, W. H. McNab, M. E. Jensen, R. G. Bailey, T. King, and W. E. Russell. 1997. National hierarchical framework of ecological units. Pages 181-200 in M. S. Boyce and A. Haney, editors. Ecosystem management: applications for sustainable forest and wildlife resources. Yale University Press, New Haven, Connecticut.

Cochran, W. G. 1977. Sampling techniques. John Wiley & Sons, New York, NY.

Cochran, W. W., and R. R. Graber. 1958. Attraction of nocturnal migrants by lights on a television tower. Wilson Bulletin 70:378-380.

Cole, D. N., and N. G. Bayfield. 1993. Recreational trampling of vegetation: standard experimental procedures. Biological Conservation 63:209-215.

Comer, P., D. Faber-Langendoen, S. Gawler, C. Jossee, G. Kittel, S. Menard, M. Pyne, M. Reid, K. Schultz, K. Snow, and J. Teague. 2003. Ecological systems of the United States: A working classification of U.S. Terrestrial Systems. NatureServe, Arlington, Virginia.

Comstock, J. P., and J. R. Ehleringer. 1992. Plant adaptation in the Great Basin and Colorado Plateau. Great Basin Naturalist 52:195-215.

Cooke, R. U., and R. W. Reeves. 1976. Arroyos and environmental change in the American southwest. Clarendon Press, Oxford, England.

Cooper, D. J., D. R. D'Amico, and M. L. Scott. 2003. Physiological and morphological response patterns of Populus deltoides to alluvial groundwater declines. Environmental Management 31:215-226.

Cornell, E. A., and J. P. Hailman. 1984. Pupillary responses of two Rana pipiens-complex anuran species. Herpetologica 40:356-366.

Covington, W. W., and M. M. Moore. 1994a. Postsettlement changes in natural fire regimes and forest structure: Ecological restoration of old-growth ponderosa pine forests. Pages 153-181 in R. N. Sampson and D. L. Adams, editors. Assessing Forest Ecosystem Health in the Inland West. Haworth Press, New York, New York.

Covington, W. W., and M. M. Moore. 1994b. Southwestern ponderosa forest structure: changes since Euro-American settlement. Journal of Forestry 92:39-47.

Cowardin, L. M., V. Carter, F. C. Golet, and E. T. LaRoe. 1979. Classification of wetlands and deepwater habitats of the United States. U.S. Department of the Interior, U.S. Fish and Wildlife Service, Washington, DC.

Crampton, C. G. 1964. Standing up country: the Canyonlands of Utah and Arizona. Alfred Knopf and University of Utah Press, in association with Amon Carter Museum of Western Art, New York, New York.

Crawford, R. L. 1981. Weather, migration and autumn bird kills at a north Florida TV tower. Wilson Bulletin 93.

D'Antonio, C. M., and P. M. Vitousek. 1992. Biological invasions by exotic grasses, the grass/fire cycle, and global change. Annual Review of Ecology and Systematics 23:63-87.

Daubenmire, R. F. 1943. Vegetational zonation in the Rocky Mountains. Botanical Review 9:325-393.

Davenport, D. W., D. D. Breshears, B. P. Wilcox, and C. D. Allen. 1998. Viewpoint: Sustainability of pinyon-juniper ecosystems— a unifying perspective on soils erosion thresholds. Journal of Range Management 51:231-240.

De Leo, G. A., and S. Levin. 1997. The multifaceted aspects of ecosystem integrity. Conservation Ecology [online] 1:3.

Dick-Peddie, W. A., and J. P. Hubbard. 1977. Classification of riparian vegetation. Pages 85-90 in R. R. Johnson and D. A. Jones, editors. Importance, Preservation and Management of Riparian Habitat: A symposium. USDA Forest Service, Rocky Mountain Forest and Range Experiment Station, Tucson, AZ.

Dieterich, J. H. 1980. Chimney Spring forest fire history. U.S. Department of Agriculture, Forest Service, Rocky Mountains Forest and Range Experiment Station, Fort Collins, Colorado.

Dieterich, J. H. 1983. Fire history of southwestern mixed conifer: a case study. Forest Ecology and Management 6:13-31.

Dobkin, D. S., A. C. Rich, and W. H. Pyle. 1998. Habitat and avifaunal recovery from livestock grazing in a riparian meadow system of the northwestern Great Basin. Conservation Biology 12:209-221.

Domingo, F., L. Villagarcia, M. M. Boer, L. Alados-Arboledas, and J. Puigdefabregas. 2000. Evaluating the long-term water balance of arid zone stream bed vegetation using evapotranspiration modelling and hillslope runoff measurements. Journal of Hydrology 243:17-30.

Drost, C. A., and E. Deshler. 1995. Amphibian and reptile diversity on the Colorado Plateau. Pages 326-328 in E. T. LaRoe, G. S. Farris, C. E. Puckett, P. D. Doran, and M. J. Mac, editors. Our living resources: a report to the nation on the distribution, abundance, and health of U.S. plants, animals, and ecosystems. U.S. Department of the Interior, National Biological Service, Washington, D.C.

Duriscoe, D., and C. A. Moore. 2001. Preserving endangered night skies. National Park Service.

Durrenberger, R. 1972. The Colorado Plateau. Annals of the Association of American Geographers 62:211-236.

ECOMAP. 1993. National hierarchical framework for ecological units. USDA Forest Service, Washington, D.C.

Ehleringer, J. R., S. Schwinning, and R. Gebauer. 1999. Water use in arid land ecosystems. Pages 347-365 in M. C. Press, J. D. Scholes, and M. G. Barker, editors. Physiological Plant Ecology. Blackwell Science, Oxford, UK.

Ehleringer, J. R., S. Schwinning, and R. Gebauer. 2000. Water use in arid land ecosystems. Pages 347-365 in M. C. Press, J. D. Scholes, and M. G. Barker, editors. Physiological Plant Ecology. Proceedings of the 39th Symposium of the British Ecological Society. Blackwell Science, University of York.

Ellwood, B. B. 1996. Geology and America's national park areas. Prentice Hall, Upper Saddle River, NJ.

Evans, R. D., R. Rimer, L. Sperry, and J. Belnap. 2001. Exotic plant invasion alters nitrogen dynamics in an arid grassland. Ecological Applications 11:1301-1310.

Evenden, A., M. Miller, M. Beer, E. Nance, S. Daw, A. Wight, M. Estenson, and L. Cudlip. 2002. Northern Colorado Plateau vital signs network and prototype cluster, plan for natural resources monitoring: Phase I report, October 1, 2002. [Two volumes]. National Park Service, Northern Colorado Plateau Network, Moab, UT.

Fassett, J. E. 2000. Geology and coal resources of the Upper Cretaceous Fruitland Formation, San Juan Basin, New Mexico and Colorado. Pages 1-8 in M. A. Kirschbaum, L. N. R. Roberts, and L. R. H. Biewick, editors. Geologic assessment of coal in the Colorado Plateau: Arizona, Colorado, New Mexico, and Utah. U.S. Geological Survey, Denver, CO.

Fenn, M. E., J. S. Baron, E. B. Allen, H. M. Rueth, K. R. Nydick, L. Geiser, W. D. Bowman, J. O. Sickman, T. Meixner, D. W. Johnson, and P. Neitlich. 2003a. Ecological effects of nitrogen deposition in the western United States. Bioscience 53:404-420.

Fenn, M. E., R. A. Haeuber, G. S. Tonnesen, J. S. Baron, S. Grossman-Clark, D. Hope, D. A. Jaffe, S. Copeland, L. Geiser, H. M. Rueth, and J. O. Sickman. 2003b. Nitrogen emissions, deposition, and monitoring in the western United States. Bioscience 53:391-403.

Fleischner, T. L. 1994. Ecological costs of livestock grazing in western North America. Conservation Biology 8:629-644.

Floyd, M. L., W. H. Romme, and D. D. Hanna. 2000. Fire history and vegetation pattern in Mesa Verde National Park, Colorado, USA. Ecological Applications 10:1666-1680.

Flynn, M. E., and D. J. Bills. 2002. Investigation of the geology and hydrology of the Coconino Plateau of Northern Arizona: A project of the Arizona rural watershed initiative. U.S. Government Printing Office, Flagstaff, AZ.

Fowler, J. F., N. L. Stanton, R. L. Hartman, and C. L. Hartman. 1995. Level of endemism in hanging gardens of the Colorado Plateau. Pages 215-223 in C. van Riper III, editor. Proceedings of the second biennial conference on research in Colorado Plateau National Parks. National Park Service, Flagstaff, AZ.

Frank, K. D. 1988. Impact of outdoor lighting on moths: an assessment. Journal of the Lepidopterists' Society 42:63-93.

Friedman, J. M., G. T. Auble, P. B. Shafroth, M. L. Scott, M. F. Merligiano, M. D. Freehling, and E. R. Griffin. 2005. Dominance of non-native riparian trees in western USA. Biological Invasions 7:747-751.

Fule, P. Z., W. W. Covington, and M. M. Moore. 1997. Determining reference conditions for ecosystem management of southwestern ponderosa pine forests. Ecological Applications 7:895-908.

Fule, P. Z., W. W. Covington, M. M. Moore, T. A. Heinlein, and A. E. M. Waltz. 2002. Natural variability in forests of the Grand Canyon, USA. Journal of Biogeography 29:31-47.

Galloway, J. N., J. D. Abner, J. W. Erisman, S. P. Sietzinger, R. W. Howarth, E. B. Cowling, and B. J. Cosby. 2003. The nitrogen cascade. Bioscience 53:341-356.

Geissler, P. H., and T. L. McDonald. 2003. Sampling designs for National Park monitoring. in, Paper presented to the George Wright Society, April 17, 2003.

Gelbard, J. L., and S. Harrison. 2003. Roadless habitats as refuges for native grasslands: interactions with soil, aspect, and grazing. Ecological Applications 13:404-415.

Gentile, J. H., M. A. Harwell, J. Cropper, W. , C. C. Harwell, D. DeAngelis, S. Davis, J. C. Ogden, and D. Lirman. 2001. Ecological conceptual models: a framework and case study on ecosystem mgmt for South Florida sustainability. The Science of the Total Environment 274:231-253.

Gilbert, S. 2002. Coal bed methane: boon for industry, bane for wildlife. Intermountain Journal of Sciences 8:252.

Grand Canyon Wildlands Council. 2002. Inventory of 100 Arizona Strip springs, seeps, and natural ponds: final project report. Arizona Water Protection Fund, Phoenix, AZ.

Grissino-Mayer, H. D., C. H. Baisan, and T. W. Swetnam. 1995. Fire history in the Pinaleno Mountains of southeastern Arizona: effects of human-related disturbances. Pages 399-407 in L. F. DeBano, P. F. Ffolliott, A. Ortega-Rubio, G. J. Gottfried, R. H. Hamre, and C. B. Edminster, editors. Biodiversity and management of the Madrean Archipelago: the Sky Islands of southwestern United States and northwestern Mexico. Department of Agriculture, Forest Service, Rocky Mountain Forest and Range Experiment Station, Tucson, Arizona.

Grissino-Mayer, H. D., W. H. Romme, M. L. Floyd, and D. D. Hanna. 2004. Climatic and human influences on fire regimes of the southern San Juan Mountains, Colorado, USA. Ecology 84:1708-1724.

Grossman, D. H., D. Faber-Langendoen, A. W. Weakley, M. Anderson, P. S. Bourgeron, K. Crawford, S. Goodin, K. Landaal, K. Metzler, M. Patterson, P. M., M. Reid, and L. Sneddon. 1998. International classification of ecological communities: Terrestrial vegetation of the United States. Volume I: The national vegetation classification standard. The Nature Conservancy, Arlington, VA.

Groves, C. R., L. L. Valutis, D. Vosick, B. Neely, K. Wheaton, J. Toval, and B. Runnels. 2000. Designing a geography of hope: A practitioners handbook to ecological conservation planning Vol II. The Nature Conservancy.

Hall, S. L. 2000. Land management strategies and marbled murrelet occurrence on the Olympic Peninsula, WA. M.S. Thesis. University of Washington, Seattle, WA.

Harper, K. T., and J. R. Marble. 1988. A role for nonvascular plants in management of arid and semiarid rangelands. Pages 135-169 in T. Tueller, editor. Application of plant science to rangeland management and inventory. Kluwer Academic, Amsterdam, Netherlands.

Harper, K. T., and R. L. Pendleton. 1993. Cyanobacteria and cyanolichens: can they enhance availability of essential mineral for higher plant? Great Basin Naturalist 53:59-72.

Harwell, M. A., V. Myers, T. Young, A. Bartuska, N. Gassman, J. H. Gentile, C. C. Harwell, S. Appelbaum, J. Barko, B. Causey, C. Johnson, A. McLean, R. Smola, P. Templet, and S. Tosini. 1999. A framework for an ecosystem integrity report card. Bioscience 49:543-556.

Hereford, R., R. H. Webb, and S. Graham. 2002. Precipitation history of the Colorado Plateau Region, 1900-2000. USGS.

Higgins, R. W., Y. Yao, and X. L. Wang. 1998. Influence of North American monsoon system on the United States summer precipitation regime. Journal of Climate 10:2600-2622.

Hobbs, R. J. and s. E. Humphries. 1995. An integrated approach to the ecology and management of plant invasion. Conservation Biology 9:761-770.

Holling, C. S., L. H. Gunderson, and D. Ludwig. 2002. In quest of a theory of adaptive change. Pages 3-22 in L. H. Gunderson and C. S. Holling, editors. Panarchy: Understanding transformations in human and natural systems. Island Press, Washington, D.C.

Hughes, F., P. M. Vitousek, and T. Tunison. 1991. Alien grass invasion and fire in the seasonal submontane zone of Hawai'i. Ecology 72:743-747.

Hunt, C. B. 1967. Chapter 14: Colorado Plateau. Pages 277-307 in C. B. Hunt, editor. Physiography of the United States. W. H. Freeman and Company, San Francisco, California.

Hunt, C. B. 1974a. Chapter 15: Colorado Plateau - Land of colors and canyons. Pages 424-479 in C. B. Hunt, editor. Natural Regions of the United States and Canada. W.H. Freeman & Co., San Francisco, CA.

Hunt, C. B. 1974b. Natural Regions of the United States and Canada. W.H. Freeman & Co., San Francisco, CA.

Huntoon, P. W. 1982. The ground water systems that drain to the Grand Canyon of Arizona. University of Wyoming, Laramie, Wyoming.

Jackson, L. E., J. C. Kurtz, and W. S. Fisher. 2002. Evaluation guidelines for ecological indicators. U.S. Environmental Protection Agency, Office of Research and Development, Research Triangle Park, NC.

Jackson, R. B., H. J. Schenk, E. G. Jobbagy, J. Canadell, G. D. Colello, R. E. Dickinson, C. B. Field, P. Friedlingstein, M. Heimann, K. Hibbard, D. W. Kicklighter, A. Kleidon, R. P. Neilson, W. J. Parton, O. E. Sala, and M. T. Sykes. 2000. Below ground consequences of vegetation change and their treatment in models. Ecological Applications 10:470-483.

Jacobs, B. F., and R. G. Gatewood. 1999. Restoration studies in degraded pinyon-juniper woodlands of north-central New Mexico. in Proceedings: Ecology and management of pinyon-juniper communities within the Interior West. U.S. Department of Agriculture, Forest Service, Rocky Mountain Research Station, Provo, UT.

Jaenicke, E. C. 1998. From the ground up: Exploring soil quality's contribution to environmental health. Henry A. Wallace Institute for Alternative Agriculture.

Jameson, D. A. 1962. Effects of burning on a galleta-black grama range invaded by juniper. Ecology 43:760-763.

Jeffries, D. L., and J. M. Klopatek. 1987. Effects of grazing on the vegetation of the blackbrush association. Journal of Range Management 40:390-392.

Jenkins, K., A. Woodward, and E. Schreiner. 2002. A framework for long-term ecological monitoring in Olympic National Park: prototype for the coniferous forest biome. USGS Forest and Rangeland Ecosystem Science Center, Olympic Field Station, Port Angeles, WA.

Jenny, H. 1941. Factors of soil formation: a system of quantitative pedology. McGraw-Hill, NewYork.

Jenny, H. 1980. The soil resource: origin and behavior. Springer-Verlag, New York.

Johnsen, T. N. J. 1962. One-seed juniper invasion of northern Arizona grasslands. Ecological Monographs 32:187-207.

Johnson, W. C. 1992. Dams and riparian forests: case study from the upper Missouri River. Rivers 3:229-242.

Jorgensen, S. E. 1986. Fundamentals of ecological modelling. Elsevier, Amsterdam, The Netherlands.

Karr, J. R. 1991. Biological integrity: a long neglected aspect of water resources management. Ecological Applications 1:66-84.

Karr, J. R. 1996. Ecological integrity and ecological health are not the same. Pages 97-109 in P. C. Schultz, editor. Engineering within ecological constraints. National Academy Press, Washington, D.C.

Karr, J. R., and D. R. Dudley. 1981. Ecological perspective on water quality goals. Environmental Management 5:55-68.

Kemper, C. A. 1964. A tower for TV, 30,000 dead birds. Audubon Magazine 66:89-90.

Kidwell, S. M., and K. W. Flessa. 1995. The quality of the fossil record: populations, species, and communities. Annual Review of Ecology and Systematics 26:269-299.

Kirschbaum, M. A. 2000. Geologic assessment of coal in the Colorado Plateau: Arizona, Colorado, New Mexico, and Utah. U.S. Geological Survey, Denver, Colorado.

Knopf, F. L. and F. B. Samson. 1994. Scale perspectives on avian diversity in western riparian ecosystems. Conservation Biology 8:669-676.

Krausman, P. R., K. R. Rautenstrauch, and B. D. Leopold. 1985. Xerioriparian systems used by desert mule deer in Texas and Arizona. Pages 144-149 in R. R. Johnson, C. D. Ziebell, D. R. Patton, P. F. Ffolliott, and R. H. Hamre, editors. Riparian ecosystems and their management: Reconciling conflicting uses. USDA Forest Service, Tucson, AZ.

Laake, T. L., S. Strindberg, F. F. C. Marques, S. T. Buckland, D. L. Borchers, D. R. Anderson, K. P. Burnham, S. L. Hedley, J. H. Pollard, and J. R. B. Bishop. 2004. Distance 4.1. Release 2. in Research Unit for Wildlife Population Assessment University of St. Andrews, editor., St. Andrews, Scotland.

Lajtha, K., and W. H. Schlesinger. 1988. The biogeochemistry of phosphorus cycling and phosphorus availability along a desert soil chronosequence. Ecology 69:24-39.

Larcher, W. 1995. Physiological plant ecology, 3rd edition. Springer-Verlag, Berlin.

Lavelle, P. 1997. Faunal activities and soil processes: adaptive strategies that determine ecosystem function. Advances in Ecological Research 27:93-132.

Leake, S. A., A. D. Koniecski, and J. A. H. Rees. 2000. Desert basins of the Southwest. U.S. Geological Survey.

Leopold, A. 1924. Grass, brush, timber, and fire in southern Arizona. Journal of Forestry 6:1-10.

Li, H., and J. F. Reynolds. 1994. A simulation experiment to quantify spatial heterogeneity in categorical maps. Ecology 75:2446-2455.

Li, H., and J. F. Reynolds. 1995. On definition and quantification of heterogeneity. Oikos 73:280-284.

Liddle, M. J. 1975. A selective review of the ecological effects of human trampling on natural ecosystems. Biological Conservation 7:17-36.

Logan, J. A., J. Régnière, and J. A. Powell. 2003. Assessing the impacts of global warming on forest pest dynamics. Frontiers in Ecology and Environment 1:130-137.

Lohr, S. L. 1999. Sampling: design and analysis. Duxbury Press, New York, NY.

Loope, W. L., and G. F. Gifford. 1972. Influence of a soil microfloral crust on select properties of soils under pinyon-juniper in southeastern Utah. Journal of Soil Water Conservation 27:164-167.

Ludwig, J. A., and W. G. Whitford. 1981. Short-term water and energy flow in arid ecosystems. Pages 85-91 in D. W. Goodall and R. A. Perry, editors. Arid-land ecosystems: structure, functioning and management, Vol. 2. Cambridge University Press, Cambridge, Massachusetts.

Mac, M. J., P. A. Opler, C. E. Puckett Haecker, and P. D. Doran. 1998. Status and trends of the nation's biological resources - southwest. United States Geological Survey, Biological Resources Division, Reston, Virginia.

MacArthur, R. H., and J. W. MacArthur. 1961. On bird species diversity. Ecology 42:594-598.

Mack, M. N., and C. M. D'Antonio. 1998. Impacts of biological invasions on disturbance regimes. Trends in Ecology and Evolution 13:195-198.

Malanson, G. P. 1993. Riparian Landscapes. Cambridge University Press, Cambridge, England.

Mantua, N. J., and S. R. Hare. 2002. The Pacific decadal oscillation. Journal of Oceanography 58:35-44.

McDonald, T. L. 2003. Environmental trend detection: a review. Environmental Monitoring and Assessment 85:277-292.

McLaughlin, S. P. 1986. Floristic analysis of the southwestern United States. Great Basin Naturalist 46:46-65.

McLaughlin, S. P. 1989. Natural floristic areas of the western United States. Journal of Biogeography 16:239-248.

McLaughlin, S. P. 1992. Are floristic areas hierarchically arranged? Journal of Biogeography 19:21-32.

McLaughlin, S. P., and J. E. Bowers. 1999. Diversity and affinities of the flora of the Sonoran floristic province. Pages 12-35 in R. H. Robichaux, editor. Ecology of Sonoran desert plants and plant communities. University of Arizona Press, Tucson, Arizona.

Miller, R. F., and P. E. Wigand. 1994. Holocene changes in semiarid pinyon-juniper woodlands. Bioscience 44:465-474.

Miller, S. G., R. L. Knight, and C. K. Miller. 2001. Wildlife responses to pedestrians and dogs. Wildlife Society Bulletin 29:124-132.

Milton, S. J., W. R. J. Dean, M. A. du Plessis, and W. R. Siegfried. 1994. A conceptual model of arid rangeland degradation. Bioscience 44:70-76.

Mitsch, W. J., and J. G. Gosselink. 1993. Wetlands 2nd Edition. Van Nostrand Reinhold Co. Inc., New York, NY.

Mock, C. J. 1996. Climatic controls and spatial variations of precipitation in the western United States. Journal of Climate 9:1111-1125.

Molnia, C. L., L. N. R. Roberts, L. R. H. Biewick, and L. M. Osmonson. 2000. Federally owned coal and federal lands in the Colorado Plateau Region. U.S. Geological Survey, Denver, Colorado.

Montgomery, E. L., and J. W. Harshbarger. 1992. Arizona hydrogeology and water supply. Applied Hydrogeology 1:25-40.

Moore, M. M., W. Covington, and P. Z. Fule. 1999. Reference conditions and ecological restoration: A southwestern Ponderosa Pine Perspective. Ecological Applications 9:1266-1277.

Mosconi, S. L., and R. L. Hutto. 1982. The effect of grazing on the land birds of a western Montana riparian habitat. Pages 221-233 in L. Nelson, J. M. Peek, and P. D. Dalke, editors. Proceedings of the wildlife-livestock relationships symposium. Forest, Wildlife, and Range Experiment Station, Moscow, ID.

National Park Service. 2002. Grand Canyon National Park: Tamarisk management and tributary restoration, environmental assessment / assessment of effect.

National Park Service Air Resources Division. 2002. Air quality in the National Parks, second edition. National Park Service Air Resources Division, Lakewood, Colorado.

National Parks and Conservation Association. 1999. Vanishing night skies. NPCA Policy Papers.

National Research Council. 1995. Review of EPA's environmental monitoring and assessment program: overall evaluation. in. National Academy Press, Washington, D.C.

Natural Resources Conservation Services. 2003. National range and pasture handbook. USDA, NRCS, Grazing Lands Technology Institute.

Nickens, P. R. 1991. The destruction of archeological sites and data. in G. S. Smith and J. E. Ehrenhard, editors. Protecting the past. CRC Press Inc.

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

Noon, B. R., T. A. Spies, and M. G. Raphael. 1999. Conceptual basis for designing an effectiveness monitoring program. USDA Forest Service.

Noy-Meir, I. 1973. Desert ecosystems: Environment and producers. Annual Review of Ecology and Systematics 4:25-51.

Noy-Meir, I. 1985. Chapter four: Desert ecosystem structure and function. Pages 93-103 in M. Evenari, I. Noy-Meir, and D. W. Goodall, editors. Hot Deserts and Arid Shrublands. Elsevier, Amsterdam, Netherlands.

Nuccio, V. 2000. Coal-bed methane: potential and concerns. U.S. Geological Survey.

Oakley, K. L., L. P. Thomas, and S. G. Fancy. 2003. Guidelines for long-term monitoring protocols. Wildlife Society Bulletin 31:1000-1003.

O'Neill, R. V., and A. W. King. 1998. Homage to St. Michael; or, why are there so many books on scale? Pages 3-15 in D. L. Peterson and V. T. Parker, editors. Ecological Scale: Theory and Applications. Princeton University Press, Princeton, NJ.

Pase, C. P., and E. F. Layser. 1977. Classification of riparian habitat in the southwest. Pages 5-9 in R. R. Johnson and D. A. Jones, editors. Importance, preservation, and management of riparian habitats: a symposium. USDA Forest Service, Rocky Mountain Forest and Range Experiment Station, Tucson, AZ.

Petersen, K. L. 1994. Modern and Pleistocene climatic patterns in the West. Pages 27-54 in K. T. Harper, L. L. St.Clair, K. H. Thorne, and W. M. Hess, editors. Natural History of the Colorado Plateau and Great Basin. University of Colorado Press, Niwot, Colorado.

Poff, N. L., and J. D. Allen. 1995. Functional organization of stream fish assemblages in relation to hydrological variability. Ecology 76:602-627.

Powell, J. A. 1995. Lepidoptera inventories in the continental United States. Pages 168-170 in E. T. LaRoe, G. S. Farris, C. E. Puckett, P. D. Doran, and M. J. Mac, editors. Our living resources: a report to the nation on the distribution, abundance, and health of U.S. plants, animals, and ecosystems. U.S. Department of Interior, National Biological Service, Washington, D.C.

Radle, A. L. 2003. The effect of noise on wildlife: A literature review. in.

Reid, K. D., B. P. Wilcox, D. D. Breshears, and L. MacDonald. 1999. Runoff and erosion in a pinyon-juniper woodland: Influence of vegetation patches. Soil Science Society of America Journal 63:1869-1879.

Reveal, J. L. 1979. Biogeography of the Intermountain region. Mentzelia 4:1-92.

Reynolds, R., J. Belnap, M. Reheis, P. Lamothe, and F. Luiszer. 2001. Aeolian dust in Colorado Plateau soils: nutrient inputs and recent change in source. Proceedings of the National Academy of Science 98:7123-7127.

Ritters, K. H., R. V. O'Neill, C. T. Hunsaker, J. D. Wickham, D. H. Yankee, S. P. Timmins, K. B. Jones, and B. L. Jackson. 1995. A factor analysis of landscape pattern and structure metrics. Landscape Ecology 10:23-39.

Romme, W. H., M. L. Floyd-Hanna, and D. D. Hanna. 2003. Ancient piñon-juniper forests of Mesa Verde and the West: A cautionary note for forest restoration programs. in Proceedings of the Conference on Fire, Fuel Treatments, and Ecological Restoration: Proper Place, Appropriate Time. U.S. Forest Service, Fort Collins, CO.

Ross, M. N. 1990. The clean air act. Pages 51-65 in M. A. Mantell, editor. Managing National Park System Resources: A Handbook on Legal Duties, Opportunities, and Tools. The Conservation Foundation, Washington, D.C.

Rotenberry, J. T. 1985. The role of habitat in avian community composition: physiognomy or floristics? Oecologia 67:213-217.

Ruddiman, W. F., and J. E. Kutzbach. 1991. Plateau uplift and climatic change. Scientific American 264:66-75.

Rychert, R. C., and J. Skujine. 1974. Nitrogen fixation by blue-green algae-lichen crusts in the Great Basin Desert. Soil Science Society of America 38:768-771.

Saunders, D. A., R. J. Hobbs, and C. R. Margules. 1991. Biological consequences of ecosystem fragmentation: a review. Conservation Biology 5:18-32.

Schlesinger, W. H., J. F. Reynolds, G. L. Cunningham, L. F. Huenneke, W. M. Jarrell, R. A. Virginia, and W. G. Whitford. 1990. Biological feedbacks in global desertification. Science 247:1043-1048.

Schultz, T. T., and W. C. Leininger. 1990. Differences in riparian vegetation structure between grazed areas and exclosures. Journal of Range Management 43:295-299.

Schumm, S. A., and R. W. Lichty. 1963. Channel widening and floodplain construction along Cimarron River in southwestern Kansas.

Scott, M. L., S. K. Skagen, and M. F. Merligiano. 2003. Relating breeding bird diversity to geomorphic change and grazing in riparian forests. Conservation Biology 17:284-296.

Simons Li & Associates Inc. 1982. Erosion study at Chaco Culture National Historical Park, New Mexico: final report to the National Park Service. Southwest Region NPS Office, Santa Fe, NM.

Sisk, T. D., N. M. Haddad, and P. R. Ehrlich. 1997. Bird assemblages in patchy woodlands: modeling the effects of edge and matrix habitats. Ecological Applications 7:1170-1180.

Skujins, J. 1984. Microbial ecology of desert soils. Advances in Microbial Ecology 7:49-91.

Smith, S. D., T. E. Huxman, S. F. Zitzer, T. N. Charlet, D. C. Housman, J. S. Coleman, L. K. Fenstermaker, J. R. Seemann, and R. S. Nowak. 2000. Elevated CO2 increases productivity and invasive species success in an arid ecosystem. Nature 408:79-82.

Society for Range Management Task Group on Unity in Concepts and Terminology. 1995. New concepts for assessment of rangeland condition. Journal of Range Management 48:271-282.

Spence, J. R. 2001. Climate of the central Colorado Plateau, Utah and Arizona: Characterization and recent trends. Pages 187-203 in K. Thomas and C. Van Riper III, editors. Proceedings of the Fifth Biennial Conference on Research on the Colorado Plateau. U.S. Geological Survey Report Series USGSFRESC/COPL/2001/24.

Spence, J. R., and N. R. Henderson. 1993. Tinajas and hanging garden vegetation of Capital Reef National Park, Southern Utah, USA. Journal of Arid Environments 24:21-36.

Stevens, D. L., and A. R. Olsen. 2004. Spatially balanced sampling of natural resources. Journal of the American Statistical Association 99:262-278.

Stevens, L. E., and G. P. Nabhan. 2002a. Biodiversity: plant and animal endemism, biotic associations, and unique habitat mosaics in living landscapes. Pages 41-48 in Center for Sustainable Environments, Terralingua, and Grand Canyon Wildlands Council, editors. Safeguarding the uniqueness of the Colorado Plateau: an ecoregional assessment of biocultural diversity. Center for Sustainable Environments, Northern Arizona University, Flagstaff.

Stevens, L. E., and G. P. Nabhan. 2002b. Hydrological diversity: water's role in shaping natural and cultural diversity on the Colorado Plateau. in Center for Sustainable Environments, Terralingua, and G. C. W. Council, editors. Safeguarding the uniqueness of the Colorado Plateau: an ecoregional assessment of biocultural diversity. Center for Sustainable Environments, Northern Arizona University, Flagstaff, Arizona.

Stringham, T. K., W. C. Krueger, and D. R. Thomas. 2001. Application of non-equilibrium ecology to rangeland riparian zones. Journal of Range Management 54:210-217.

Swetnam, T. W. 1990. Fire history and climate in the Southwestern United States. in J. S. Krammes, editor. Effects of Fire Management of Southwestern Natural Resources. U.S. Dept. of Agriculture, Forest Service, Rocky Mountain Forest and Range Experiment Station, Tucson, AZ.

Swetnam, T. W., and C. H. Baisan. 1996. Historical fire regime patterns in the Southwestern United States since AD 1700. Pages 11-32 in C. D. Allen, editor. Fire Effects in Southwestern Forests: Proceedings of the Second La Mesa Fire Symposium. USDA Forest Service, Los Alamos, New Mexico.

Swetnam, T. W., and J. L. Betancourt. 1998. Mesoscale distrubance and ecological response to decadal climatic variability in the American Southwest. Journal of Climate 11:3128-3147.

Szaro, R. C. 1989. Riparian forest and scrubland community types of Arizona and New Mexico. Desert Plants 9:69-138.

Szaro, R. C., S. C. Belfit, J. K. Aitkin, and J. N. Rinne. 1985. Impact of grazing on a riparian garter snake. Pages 359-363 in R. R. Johnson, C. D. Ziebell, D. R. Patton, P. F. Ffolliott, and F. H. Hamre, editors. Riparian ecosystems and their management: reconciling conflicting uses. U.S. Forest Service, Rocky Mountain Forest and Range Experiment Station, Tucson, Arizona.

Tausch, R. J. 1999. Historic pinyon and juniper woodland development. Pages 12-19 in S. B. Monsen and R. Stevens, editors. Proceedings: ecology and management of pinyon-juniper communities within the Interior West. U.S. Department of Agriculture, Forest Service, Rocky Mountain Research Station, Provo, Utah.

Thompson, S. K. 2002. Sampling, 2nd edition. John Wiley & Sons, New York, NY.

Thornbury, W. D. 1965. Regional geomorphology of the United States. John Wiley, New York.

Trenberth, K. E. 1997. The definition of El Nino. Bulletin of the American Meteorological Society 78:2771-2777.

U.S. Department of Interior. 2003. Revised strategic plan for FY 2003-2008 U.S. Department of the Interior, National Park Service. 2002. Tamarisk Management and Tributary Restoration, Environmental Assessment, Grand Canyon National Park. Grand Canyon, AZ.

UNESCO. 2002. Properties inscribed on the world heritage list. World Heritage Centre, Paris, France.

USDA-NRCS Soil Quality Institute. 2001. Soil quality - introduction. in USDA-NRCS Soil Quality Institute, editor. Soil Quality Information Sheets. USDA-NRCS Soil Quality Institute, Washington, D.C.

Vankat, J. L., and J. Major. 1978. Vegetation changes in Sequoia National Park, California. Journal of Biogeography 5:377-402.

Veblen, T. T., K. S. Hadley, E. M. Nel, T. Kitzberger, M. Reid, and R. Villalba. 1994. Disturbance regime and disturbance interaction in a Rocky Mountain subalpine forest. Journal of Ecology 82:125-135.

Vitousek, P. M. 1990. Biological invasions and ecosystem processes: towards an integration of population biology and ecosystem studies. Oikos 57:7-13.

Vitousek, P. M., L. R. Walker, L. D. Whiteaker, D. Mueller-Dombois, and P. A. Matson. 1987. Biological invasion by Myrica faya alters ecosystem development in Hawaii. Science 238:802-804.

Walker, B. H. 1993. Rangeland ecology: understanding and managing change. Ambio 22:80-87.

Wang, B. 1995. Interdecadel changes in El Nino onset in the last four decades. Journal of Climate 8:267-285.

Wang, X. L., and C. F. Ropelewski. 1995. An assessment of ENSO-scale secular variability. Journal of Climate 8:1584-1599.

Wardle, D. A. 2002. Communities and Ecosystems: Linking the aboveground and belowground components. Princeton University Press, Princeton, NJ.

Waring, R. H. 1983. Estimating forest growth efficiency in relation to canopy leaf area. Advances in Ecological Research 13:327-354.

Weaver, H. 1951. Fire as an ecological factor in the southwestern ponderosa pine forests. Journal of Forestry 49:93-98.

Weaver, T., and D. Dale. 1978. Trampling effects of hikers, motorcycles and horses in meadows and forests. Journal of Applied Ecology 15:451-457.

Weltzin, J. F., M. E. Loik, S. Schwinning, D. G. Williams, P. A. Fay, B. M. Haddad, J. Harte, T. E. Huxman, A. K. Knapp, G. Lin, W. T. Pockman, M. R. Shaw, E. E. Small, M. D. Smith, S. D. Smith, D. T. Tissue, and J. C. Zak. 2003. Assessing the response of terrestrial ecosystems to potential changes in precipitation. Bioscience 53:941-952.

West, N. E. 1999. Distribution, composition, and classification of current juniper-pinyon woodlands and savannas across western North America. Pages 20-23 in S. B. Monsen and R. Stevens, editors. Proceedings: ecology and management of pinyon-juniper communities within the Interior West. U.S. Department of Agriculture, Forest Service, Rocky Mountain Research Station, Provo, Utah.

West, N. E., and J. A. Young. 2000. Intermountain valleys and lower mountain slopes. Pages 256-284 in M. G. Barbour and W. D. Billings, editors. North American Vegetation. Cambridge Univercity Press, Cambridge, UK.

Westoby, M., B. Walker, and I. Noy-Meir. 1989. Opportunistic management for rangelands not at equilibrium. Journal of Range Management 42:266-274.

Whicker, J. J., D. D. Breshears, P. T. Wasiolek, T. B. Kirchner, R. A. Tavani, D. A. Schoep, and J. C. Rodgers. 2002. Temporal and spatial variation of episodic wind erosion in unburned and burned semiarid shrubland. Journal of Environmental Quality 31:599-612.

Whitford, W. 2002. Ecology of desert systems. Academic Press, Elsevier Science Ltd., San Diego, California.

Whitford, W. G. 1996. The importance of the biodiversity of soil biota in arid ecosystems. Biodiversity and Conservation 5:185-195.

Whittaker, P. L. 1978. A comparison of surface damage by hiking and horseback riding in Great Smoky Mountains National Park. U.S. Department of Interior, National Park Service, Great Smoky National Park, TN.

Wilcox, B. P., B. D. Newman, C. D. Allen, K. D. Reid, D. Brandes, J. Pitlick, and D. W. Davenport. 1996a. Runoff and erosion on the Pajarito Plateau: observations from the field. Pages 433-439 in New Mexico Geological Society Guidebook, 47th Field Conference, Jemez Mountains Region.

Wilcox, B. P., J. Pitlick, C. D. Allen, and D. W. Davenport. 1996b. Runoff and erosion from a rapidly eroding pinyon-juniper hillslope. Pages 61-77 in M. G. Anderson and S. M. Brooks, editors. Advances in Hillslope Processes, Volume 1. John Wiley & Sons Ltd, New York, New York.

Windell, J. T., B. E. Willard, D. J. Cooper, S. Q. Foster, C. Knud-Hansen, L. P. Rink, and G. N. Kiladis. 1986. An ecological characterization of Rocky Mountain montane and subalpine wetlands. U. S. Department of the Interior, Fish and Wildlife Service, U. S. Department of the Interior, Washington, D. C.

Wright, H. A. 1980. The role and use of fire in the semi-desert grass-shrub type. U.S. Department of Agriculture, Forest Service, Intermountain Forest and Range Experiment Station, Ogden, UT

The U.S. Department of the Interior (DOI) is the nation's principal conservation agency, charged with the mission *"to protect and provide access to our Nation's natural and cultural heritage and honor our trust responsibilities to Indian tribes and our committements to island communities."* More specifically, Interior protects America's treasures for future generations, provides access to our nation's natural and cultural heritage, offers recreation opportunities, honors its trust responsibilities to American Indians and Alaska Natives and its responsibilities to island communities, conducts scientific research, provides wise stewardship of energy and mineral resources, fosters sound use of land and water resources, and conserves and protects fish and wildlife. The work that we do affects the lives of millions of people; from the family taking a vacation in one of our national parks to the children studying in one of our Indian schools.

NPS D-46, October 2006

National Park Service
U.S. Department of the Interior

Natural Resource Program Center
1201 Oak Ridge Drive, Suite 150
Fort Collins, CO 80525

www.nature.nps.gov

EXPERIENCE YOUR AMERICA^T