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Remote Sensing for Inventory and Monitoring of U.S. National Parks

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CONTENTS

2.1	Introduction.....	30
2.2	PALMS: Park AnaLysis and Monitoring Support	33
2.3	PALMS Ecological Indicators	34
2.3.1	Protected-Area-Centered Ecosystems.....	35
2.3.2	Stream Biota.....	38
2.3.3	Connectivity	40
2.3.4	Land Surface Phenology	42
2.3.5	Primary Production.....	43
2.4	Effectively Delivering Results to the NPS.....	45
2.4.1	Documentation of Indicators and Methods	46
2.4.2	Websites.....	47
2.4.3	Dynamic Web Interfaces and Data Services	47
2.4.4	Project Completion Calls	48
2.5	Lessons Learned and Recommendations.....	48
2.5.1	Allocate Sufficient Time to Develop a Genuine Science–Management Partnership.....	49
2.5.2	Communicate Results in a Management-Relevant Context	49
2.5.3	Conform or Embellish Existing Frameworks and Processes	49
2.5.4	Plan for Persistence and Change	50
2.5.5	Build on Existing, Widely Used Data Analysis Tools and Software Frameworks, Even If They Seem Inefficient.....	50
2.5.6	Practice Rigorous Scope Control to Maximize the Chance of Success	50
2.6	Summary.....	50
	Acknowledgments	51
	References.....	52

2.1 Introduction

U.S. National Park Service (NPS) units ("parks") are important components in a system of reserves that protect biodiversity and other natural and cultural resources. To meet the NPS mission to manage resources so that they are left "... unimpaired for the enjoyment of future generations" (16 USC 1) it is essential to know what resources occur in parks and to monitor the status and trends in the condition of key resource indicators. The NPS Inventory and Monitoring (I&M) Program (see Table 2.1 for a list of acronyms) was designed to provide the infrastructure and staff to identify critical environmental indicators ("vital signs") and to implement long-term monitoring of natural resources in more than 270 parks that contain significant natural resources (Fancy et al. 2009). These parks are organized into 32 ecoregional networks (Figure 2.1). Each of the 32 I&M networks consists of core professional staff (program manager, data manager, ecologists, field technicians, etc.), and each I&M network supports monitoring in parks within the network.

The overall purpose of I&M is to provide sound scientific information that enhances management of natural resources. To do so, I&M collects, organizes, and makes available natural resource data and contributes to the

TABLE 2.1

Acronyms Used in This Chapter

Acronym	Meaning
AOA	Area of analysis
DEWA	Delaware Water Gap Recreation Area
GIS	Geographical Information System
GPP	Gross primary productivity
I&M	Inventory and Monitoring Program
LAI	Leaf area index
MODIS	Moderate Resolution Imaging Spectroradiometer
N	Naturalness
NARSEC	North American Network for Remote Sensing Park Ecological Condition
NASA	U.S. National Aeronautics and Space Administration
NDVI	Normalized difference vegetation index
nEPT	Number of <i>Ephemeroptera</i> , <i>Plecoptera</i> , and <i>Tricoptera</i> species
NPP	Net primary productivity
NPS	National Park Service
PACE	Protected-area-centered ecosystem
PALMS	Park AnaLysis and Monitoring Support
SOP	Standard operating procedure
TOPS	Terrestrial Observation and Prediction System
UPDE	Upper Delaware Scenic and Recreational River



FIGURE 2.1

Map of the U.S. National Park Service ecoregional inventory and monitoring (I&M) networks for the continental United States (Alaska and Pacific Islands not shown). Each network consists of staff and infrastructure to support long-term ecosystem monitoring for natural resource parks within the network. Focal parks (names in boxes) are served by the Sierra Nevada, Greater Yellowstone, Rocky Mountain, and Eastern Rivers and Mountains Networks.

service's knowledge by adding value to data through analysis, synthesis, and modeling. I&M initiated 12 basic natural resource inventories to collect the information needed as a foundation for monitoring and to determine the current status of park resources (Table 2.2). Most inventories are now complete, except for the more expensive and time-consuming vegetation and geological resource inventories.

The NPS I&M instituted systems-based "vital signs" monitoring to provide sound scientific information on trends in the condition of park natural resources. "Vital signs" are a subset of physical, chemical, and biological elements and processes of park ecosystems that are selected to represent the overall health or condition of park resources, known or hypothesized effects of stressors, or elements that have important human values (Fancy et al. 2009). I&M networks worked extensively with park personnel and other experts to identify the highest-priority vital signs—a lengthy process that involved more than 1000 people. Landscape dynamics, along with climate and invasive species, was ranked as one of the highest priorities for long-term monitoring across all the 32 I&M networks. Despite the high ratings,

TABLE 2.2

Baseline Inventories Undertaken by the National Park Service Inventory and Monitoring Program for Parks with Significant Natural Resources, and the Percent Completed by July 2011

Inventory	Percent Completed
Geologic resources inventory	32 ^a
Vegetation inventory	38 ^b
Soil resources inventory	77
Baseline water quality data	100
Base cartography data	100
Species lists	99
Air quality data	100
Air quality-related values	100
Climate inventory	100
Natural resource bibliography	100
Species occurrence and distribution	100
Water body location	100

^a A total of 184 parks (68% of total) have completed digital maps; 88 (32% of total) of these have a final comprehensive report.

^b An additional 154 parks (57% of total) have vegetation inventories in progress.

few I&M networks have successfully developed landscape monitoring protocols and implemented landscape monitoring.

The slow development of landscape-scale monitoring reflects the complex decisions needed to identify a small set of indicators that are reasonably comprehensive, informative, relevant, and affordable. To facilitate progress in developing operational landscape monitoring, NPS, Parks Canada Agency, U.S. National Aeronautics and Space Administration (NASA), and other agencies cosponsored workshops to share experiences and knowledge (NARSEC 2005, 2007; Gross et al. 2009). A clear need identified at these workshops was for organized teams of experts to focus on developing general methods, at relevant scales, which could be widely applied to distribute and share the costs of development. It is simply too difficult and expensive for individual parks or I&M networks, on their own, to undertake development of a full suite of landscape dynamics monitoring protocols. To address needs for broad-scale data on landscape attributes across the entire system of parks, the I&M Program Office developed the NPScope project. NPScope provides landscape-level data, methods, tools, and evaluations for a limited set of attributes derived from data on land cover, population and housing, roads, and land ownership (NPScope 2010). Data and results from NPScope are provided for all the more-than-270 I&M park units. A central goal of NPScope was to reduce per-park cost by identifying and documenting a small set of highly relevant landscape-scale measurements that could be derived from national-scale data, and then centralizing data acquisition, processing, analysis, and reporting. NPScope is founded on the principle of economy of scale, and the

huge variations in park geographical location, ecological context, and size make it impossible for NPScope to address many questions that require park-specific data or other local data. Although the needs for landscape-scale monitoring in and around Canadian parks differ somewhat from those in the United States, Parks Canada Agency found they were in a similar position. In response to these needs, Parks Canada Agency and the Canadian Space Agency cofunded multiyear studies to develop and enhance operational use of remotely sensed data for park monitoring.

Although NPScope and other national programs will meet many NPS needs for broad-scale, relatively coarse resolution indicators, there remained a need for complementary monitoring protocols that operate at finer resolutions, that can address park-specific contexts, but that are still broadly relevant and easily adopted by and incorporated into the NPS I&M. The goal of this chapter is to describe a project that focused on addressing this need and to facilitate further progress in using remotely sensed data to support the management of protected areas. We describe a multiyear project that worked with geographically dispersed parks from a variety of settings. This chapter is effectively a case study, illustrating approaches and results that will help implement routine use of remotely sensed data for monitoring in and around parks. We describe the rationale, design, and products of a project to enhance use of NASA data and technology by the NPS I&M. While we focused on the needs of the NPS I&M, the issues, approaches, and results are broadly applicable to monitoring many types of protected areas. Interested readers can refer to other sources for detailed reviews of the NPS I&M Program (Fancy et al. 2009; <http://science.nature.nps.gov/im/index.cfm>), conceptual frameworks that support landscape-scale monitoring (Hansen and DeFries 2007; Jones et al. 2009), and technical considerations that must be addressed when designing remote-sensing-based monitoring indicators (Phinn et al. 2003; Kennedy et al. 2009; papers in Gross et al. 2009).

2.2 PALMS: Park AnaLysis and Monitoring Support

The overall goal of the PALMS (Park AnaLysis and Monitoring Support) project was to enhance the quality of natural resource management in parks by better integrating the routine acquisition and analysis of NASA Earth System Science products and other data sources into the NPS I&M. NASA supported the project via a program that specifically targets applied science (versus basic research). Each participating I&M network and the national I&M office supported the project by allocating time of personnel with expertise that would contribute to the project. This included time of Geographic Information System (GIS)/data specialists and ecologists with local knowledge of focal parks. I&M networks also served as liaisons with the (much larger) park staff, thereby ensuring participation of decision-makers and

others when appropriate. We felt the explicit contribution of NPS resources to the project was important to encourage shared ownership of results and to share risks that might result from inadequate engagement.

Specific objectives of the PALMS project were to

1. (a) Identify NASA and other products useful as indicators for NPS I&M monitoring, and (b) delineate the boundaries of the surrounding protected-area-centered ecosystems (PACE) appropriate for monitoring.
2. Add value to these datasets for understanding change through analysis and forecasting.
3. Deliver these products and a means to integrate them into the NPS I&M decision support framework.

The project focused on four sets of national parks to develop and demonstrate the approach (Figure 2.1): Sequoia-Kings Canyon and Yosemite National Parks (Sierra Nevada I&M Network), Yellowstone and Grand Teton National Parks (Greater Yellowstone I&M Network), Rocky Mountain National Park (Rocky Mountain I&M Network), and a combination of Delaware Water Gap National Recreation Area (DEWA) and Upper Delaware Scenic and Recreational River (UPDE) (Eastern Rivers and Mountains I&M Network). Selection of focal parks was based almost entirely on the familiarity of the principal investigators with these parks, and access to data and resources that supported the goals of the project. Other parks and networks were keen to participate in this project, but we lacked the capacity to expand the study and include additional parks. An expanded, follow-on project is pending.

The PALMS project was designed from the outset to be highly collaborative. All the investigators were experienced, had worked with the NPS, and had some idea of the type and extent of communication that would be required. The explicit contribution of staff time from each participating I&M network clearly promoted this approach. Nonetheless, a surprisingly substantial and sustained effort by all project staff was required to keep park and network collaborators informed and engaged throughout the project. Park personnel, especially those in supervisory positions, tend to have many fixed-time commitments that made scheduling complicated. When working with parks, the time required to schedule meetings or provide products and obtain reviews can be considerable.

2.3 PALMS Ecological Indicators

Every monitoring project must balance the desire to deliver the most comprehensive, useful, and interesting information with constraints imposed by

technical feasibility, cost, staff expertise, and available resources (Phinn et al. 2003; Jones et al. 2009; Kennedy et al. 2009). All NPS I&M networks undertook a multiyear effort to identify high-priority vital signs before we initiated this project, and "landscape dynamics" was consistently ranked among the highest of all monitoring needs. Beyond identifying the need for landscape-scale monitoring, few networks had identified any specific variables for monitoring. Furthermore, networks clearly understood the importance of landscape changes outside park boundaries (GAO 1994; Parks and Harcourt 2002; Hansen and DeFries 2007), but all networks were struggling to define the boundaries of scientifically credible and defensible areas for monitoring landscape-scale changes outside park boundaries.

Our first step was to identify candidate indicators for further development by consulting I&M network monitoring plans and related documents—that is, glean what we could from existing information (Jean et al. 2005; Britten et al. 2007; Marshall and Piekielek 2007; Mutch et al. 2008). I&M monitoring plans described park resources and threats to resources, existing and planned monitoring, and related information that could help identify suitable indicators. We held a series of meetings with park and network staff to discuss and refine definitions of indicators, and we also relied on our collective experiences and expertise. The process of identifying and refining indicators was iterative, and the final resolution of some indicators took more than two years of discussion and development. All forms of inputs proved to be valuable contributions to the final selection and development of the indicators.

The complete set of PALMS indicators and their geospatial attributes is summarized in Table 2.3. The suite of PALMS indicators includes measurements of weather and climate, stream health (water), land cover and land use, disturbances, primary production, and monitoring area. In the following sections, we briefly summarize features of exemplar indicators that are novel to this project or that are otherwise of particular interest. More complete descriptions of methodology and results are available in the following descriptions of PALMS products and other publications (Goetz and Fiske 2008; Jantz and Goetz 2008; Goetz et al. 2009; Nemani et al. 2009; Theobald et al. 2009; Bierwagen et al. 2010; Jantz et al. 2010; Theobald 2010; Hansen et al. 2011).

2.3.1 Protected-Area-Centered Ecosystems

Identifying a suitable area of analysis (AOA) is challenging because the extent of the most appropriate AOA varies with the specific issue, process, or species that is of most interest. Ideally, a long-term monitoring program would simply define an AOA that encompassed the broadest-scale issue anticipated. This is an impractical solution for most parks because the cost of imagery acquisition, processing, and analysis is directly related to the size of the AOA. There is thus a strong incentive to constrain many analyses to the smallest area necessary. Following Hansen and DeFries (2007), we developed

TABLE 2.3

Indicators Selected for Development by the Park Analysis and Monitoring Support Project and Some of Their Attributes

Level	Category	Indicator	Extent	Resolution
Air and climate	Weather and climate	Phenology (normalized difference vegetation analysis—NDVI; annual anomaly)	CONUS	1 km (all); 8 and 16 days
		Climate gridded daily (1980–2010)	DEWA, ROMO, YELL, YOSE	1 km
		Climate scenarios (monthly)	YOSE, DEWA, GYE, CONUS	12 km
Water	Stream health	Bioitic index of biological integrity; sensitive taxa	DEWA	1:24 K; 1:100 K
Landscape dynamics	Land cover	Ecosystem-type composition; summary by spatial scale	DEWA, ROMO, YELL, YOSE	30 m
		Bird hotspots and key habitat types	GYE	1 km
		Impervious cover change	DEWA	30 m
		Housing density class (1940–2100, decadal)	CONUS	100 m
		Landscape connectivity of forests	Eastern United States	270 m
	Extreme disturbance events	Pattern of natural landscapes	CONUS	270 m
		Past to future modeling	DEWA	30 m
		Fire effects via changes in phenology and related measures	DEWA, ROMO, YELL, YOSE	1 km; monthly anomalies/annual summaries
	Primary production	Gross and net primary productivity (via simulation model results)	DEWA, ROMO, YELL, YOSE	1 km daily and/or monthly summaries; annual trends
	Monitoring area	Greater park ecosystem boundaries	DEWA, ROMO, YELL, YOSE	30 m
	Land use	Land use	CONUS	90 m

CONUS, Continental United States (lower 48 states); DEWA, Delaware Water Gap National Recreation Area (including Upper Delaware Scenic and Recreational River); GYE, Greater Yellowstone Ecosystem; ROMO, Rocky Mountain National Park; YELL, Yellowstone National Park; YOSE, Yosemite National Park.

a framework for delineating the ecosystem surrounding a protected area that is likely to strongly influence ecological function and biodiversity within the protected area. Termed “protected area centered ecosystems” (PACEs; Hansen et al., 2011), this area becomes the logical place to focus on monitoring, research, and collaborative management to maintain protected area function

and condition. The PACE framework is founded on five ecological mechanisms (processes) by which human activities impact on ecosystem functioning (Table 2.4). The PACE served two very important purposes. First, it defined a spatial context for conducting analyses and reporting results. Second, it is, by itself, an indicator of landscape condition, because the shape, composition, and extent of the PACE respond to and reflect human impacts in the area around a park.

To illustrate the approach in a variety of geographic and land-use settings, we defined PACEs for the NPS units included in the PALMS project and in two additional regions (the Pacific Northwest and the Appalachian Highlands). The resulting PACEs were on average 6.7 times larger than the

TABLE 2.4

Mechanism, Rationale, and Criteria Used to Define the Protected-Area-Centered Ecosystem (PACE)

Mechanism ^a	Rationale	PACE Criterion
Change in effective size of reserve	Fewer species are supported in small areas; species can be lost as habitats are isolated.	Specific habitat areas in the PACE are proportional to those in the park, up to the area specified by the species–area relationship.
Changes in ecological flows into and out of reserve	Water, sediments, nutrients, hydrological patterns may be altered by upstream land uses.	Watershed boundaries around park; or subbasins or subwatersheds that intersect park boundaries.
	Atmospheric transport of dust and pollutants affect parks; upwind land use can affect local climates.	Airsheds based on sources of pollutants or climate.
	Disturbances that originate outside parks can move into parks; conditions in initiation and run-on zones affect likelihood of disturbance and provide key habitats.	Perimeter around park based on historic disturbance rates, size, and shape.
Loss of crucial habitats	Includes seasonal habitats or ranges, movement paths, source populations, and parts of large home ranges that are outside of parks and that may be altered or destroyed.	Key habitats for migration, seasonal use, or otherwise crucial for park organisms (requires local knowledge).
Edge effect due to human activity	Human activities in areas adjacent to parks can directly or indirectly disturb or kill wildlife. Examples include hunting, poaching, pets (dogs, cats), introduction of exotic species, effects of noise and light, etc.	Create 25 km buffer around park and select human-dominated areas; create 5 km buffer around crucial habitat polygons.

Source: Adapted from Hansen, A. J., and R. DeFries. *Ecological Applications*, 17:974–988, 2007; Hansen, A. J. et al., *BioScience*, submitted.

^a Mechanisms describe the ways in which human activities around parks may impact on ecosystem processes and biodiversity.

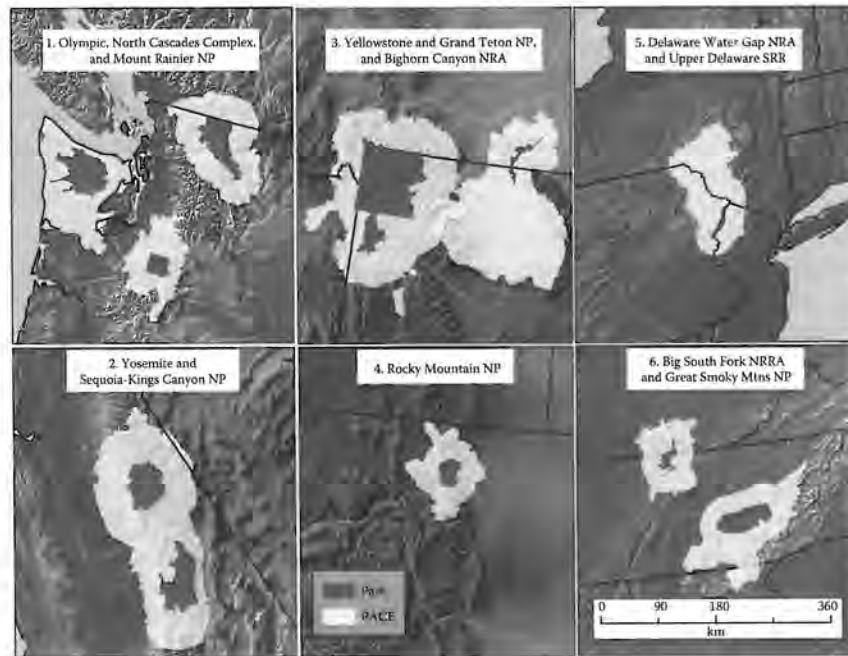


FIGURE 2.2
(See color insert.) Maps of protected-area-centered ecosystems (PACs) delineated in this study for 13 U.S. National Park Service units. PACs were defined by the criteria in Table 2.4.

park for those in upper watersheds and 44.6 times larger for those in mid-watersheds (Figure 2.2). PACs in the eastern US were dominated by private lands with high rates of land development, suggesting that they offer the greatest challenge for management. Our NPS collaborators generally embraced this approach for delineating the area to be monitored around national parks and suggested that the approach helps facilitate research and conservation across the parks and important surrounding lands.

2.3.2 Stream Biota

Stream macroinvertebrate diversity is a commonly used indicator of aquatic health, reflecting overall ecological integrity within a watershed (Van Sickle et al. 2006). Urbanization and associated impervious surface cover have adverse effects on aquatic systems, including greater variability in stream flow (flashiness), lower base flows, and increased bank and stream bed erosion (Schueler et al. 2009). These effects can be mitigated by near-stream vegetation buffers and other actions that reduce the force of overland flows, absorb excess nutrients, maintain stream bank integrity, and provide shade that reduces warming of stream water (Snyder et al. 2003; Goetz 2006). We mapped and modeled these processes in watersheds that encompass the

UPDE and the DEWA. Of primary interest to the Eastern Rivers and Mountains Network, and more generally to the NPS I&M effort, is information on stream biota and how these are likely to be impacted on by expanding urbanization, including low-density residential development. We addressed this need by adapting statistical models of the relationship of stream health indicators developed in data-rich watersheds of the mid-Atlantic region (Goetz and Fiske 2008). These models were based on relating *in situ* observations from the Maryland Biological Stream Survey (Roth et al. 2004; Kazyak et al. 2005) to land-cover variables, translated into relatively simple procedures that can be conducted in a GIS environment (Goetz and Fiske 2010). The procedures allow prediction of the richness and abundance of stream macroinvertebrates as well as integrated indices of stream biological integrity. As the models use land-cover metrics to predict the variation of stream biotic metrics, they can be used across small watersheds as indicators of stream impairment and thus to focus on monitoring, restoration, and protection management objectives. An example prediction of the diversity of *Ephemeroptera*, *Plecoptera*, and *Trichoptera* species (nEPT; genera are mayfly, stone fly, and caddis fly, respectively), which are known to be sensitive to stream pollution and sedimentation, is shown in Figure 2.3.

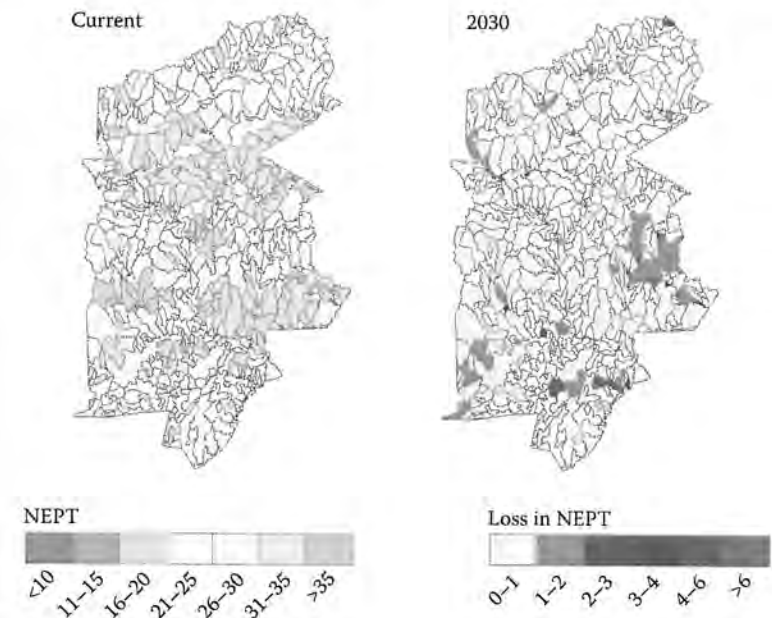


FIGURE 2.3
Maps of the Upper Delaware river basin showing the predicted number of sensitive stream taxa (abundance of EPT species; see text) for the present (left) and as predicted to change by 2030 using future land cover based on simulations of continued urbanization trends for watersheds (right).

Future predictions of urbanization under different land management scenarios, where they exist, can also be used to assess the potential impact of impervious cover in new residential and commercial developments on stream biota. As part of PALMS, we developed such predictions (Jantz et al. 2010) and used them to predict the status of future stream biotic condition, as expressed by the nEPT (Figure 2.3). The results clearly show the potential for reducing the impacts of impervious areas through mitigation measures such as maintaining riparian buffers and overall natural vegetation cover within a watershed.

Watershed biotic diversity maps of this sort, based on land-cover variables, provide a baseline against which *in situ* stream measurements can be compared and assessed as NPS monitoring programs develop. Moreover, the predictions are useful to I&M and park staff as they evaluate the sampling design for long-term monitoring of stream health and assess the risk of future residential and commercial development on aquatic biota.

2.3.3 Connectivity

Habitat fragmentation poses one of the foremost threats to biodiversity in parks and other protected areas in the United States (Hilty et al. 2006). Fragmentation is generally caused by loss of habitat, and results in the isolation of parks. Isolated parks are unable to support levels of biodiversity that existed prior to landscape changes (Newmark 1986; Parks and Harcourt 2002), and the ability of animals to move between large tracts of natural habitat is necessary to sustain the full range of biota and ecological processes in parks.

Connectivity of landscapes for the conterminous United States was estimated using a GIS-based least-cost-distance method that provides two novel aspects. First, this approach does not require patches to be first identified, as do patch-matrix approaches. Rather, the method considers the landscape as a gradient (Kupfer et al. 2006; McGarigal et al. 2009), which better reflects the gradual transitions that commonly occur between many land-cover types. Second, the method provides a quantitative estimate of the importance of each linkage or movement pathway. The application of these quantitative estimates can assist selection and prioritization of local and on-the-ground efforts.

Two products were generated from our approach. First, four cost-distance maps, each reflecting the weighted distance from the left, right, top, and bottom of the map extent, are averaged together to compute an overall landscape connectivity surface, similar to traditional least-cost "corridor" maps generated from the average value from two cost-distance maps (Beier et al. 2006; Theobald 2006). These maps are useful to understand general patterns of natural landscapes, where additional information about the landscape configuration is added. Permeability to movement was estimated by the "naturalness," N , which ranged from 1.0 (natural) to 0.0 (intensely

human-modified) at 270 m resolution as a function of land-cover types, housing density, presence of roads, and effects of highway traffic (Theobald 2010). Resistance values (or cost weights) were calculated as $1/N$. Second, pathways that flow across the surface maps are found, similar to the flow of water across the terrain forming dendritic networks (Figure 2.4). Rather than forming a hydrologic network, a network of potential movement pathways is formed. The flow accumulation is weighted by N at each pixel, so that movement pathways incorporate both the pattern of movement as well as the importance of that movement. This flow-accumulated value is a computationally efficient approximation of the "betweenness" centrality measure (Borgatti 2005).

Identification of corridors by this approach has proved useful to parks. A key attribute of the method is the clarity of the result. "Dendritic" corridors identified by the method were easily interpreted, and they were very intuitive to park staff and partners. The approach permits calculations over very large grids ($>10^8$ cells); hence, we were able to provide results that identified important corridors at local to continental scales. These results are valuable

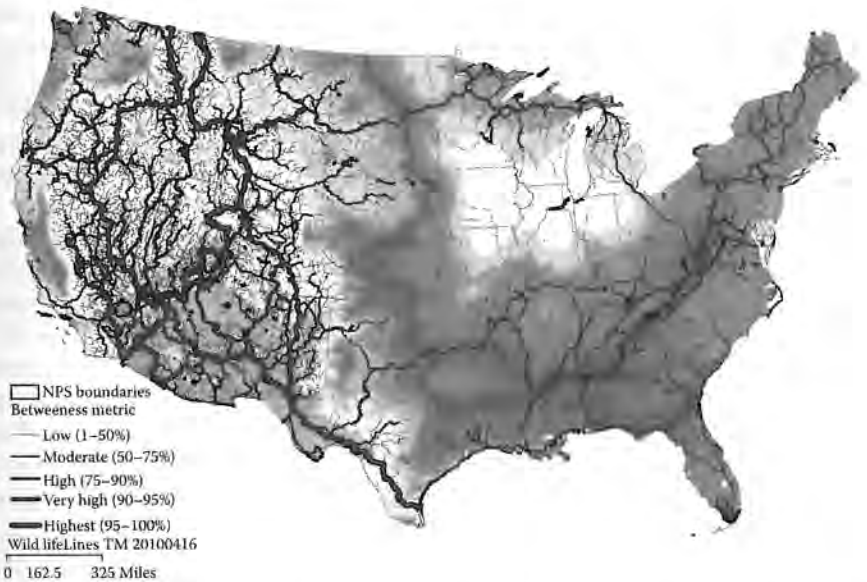


FIGURE 2.4
(See color insert.) Map showing connectivity of natural landscapes in the United States. The thickness of red lines indicates magnitude of cumulative movement, assuming that animals avoid human-modified areas. The surface underneath the pathways depicts the averaged cost-distance surfaces, or the overall landscape connectivity surface. Colors range from green through yellow and purple to white, where green is greatest connectivity (lowest travel cost) and white indicated lowest connectivity (highest travel cost). National Park Service units are outlined in black.

to parks because they clearly communicated the important role of parks as links in pathways that provide for very broad-scale movements (Figure 2.4). Results for DEWA, in particular, aligned very well with landscape-scale connectivity assessments (Goetz et al. 2009) and ongoing local conservation efforts. Local-scale analyses had identified high-priority areas for conservation at a fine scale, but they had not identified or realized how these local corridors would likely contribute to regional-scale conservation.

2.3.4 Land Surface Phenology

Variability and trends in the timing of seasonal biological events (phenology) are thought to be responsive indicators of global change (Schwartz 2003; Morisette et al. 2009). The onset and length of the growing season through their impact on primary production or simply plant growth are excellent indicators of ecosystem function with broad consequences for biodiversity. For example, spatial and temporal patterns of grassland and shrubland productivity in and near Yellowstone National Park are of particular interest due to their importance to migratory elk and bison (NRC 2002; White et al. 2010). These seasonally migratory ungulates have historically crossed public-private land boundaries in search of high-quality forage and to avoid deep snow during winter months, sometimes creating conflicts between landowners and wildlife managers. Working with the PALMS team, Yellowstone National Park staff identified forage phenology as a high-priority indicator, with a desire to better understand how land use and climate patterns influence forage availability and thus the spatial distribution of ungulates.

PALMS developed multiple phenology indicators based on NASA Moderate Resolution Imaging Spectroradiometer (MODIS) 250 m normalized difference vegetation index (NDVI) data products (Justice et al. 1998; Huete et al. 1999; Huete et al. 2002). For a pilot study centered on the Yellowstone Northern Range, we created annual NDVI curves and calculated phenology metrics based on properties of those curves for each eight-day interval for 2003–2009. These phenology metrics included measures of date of spring green-up, length of the growing season, and peak annual NDVI (White et al. 2009; deBeurs and Henebry 2010). Collectively, these metrics describe annual characteristics of grassland growth across space and interannual patterns of growth through time. We separated habitats that provide ample grassland cover for ungulate foraging and incorporated these into an annual, three-dimensional animation of greenness to help park staff visualize patterns of forage productivity at the landscape scale in and adjacent to their park. Further investigation of the spatial and temporal dimensions of grassland productivity demonstrates the degree to which productivity is influenced by climate and land use. With interacting effects, land use and climate change have the potential to significantly alter spatial and temporal patterns of grassland productivity in the Greater Yellowstone

ecosystem in ways which will increase the likelihood of future conflicts between private landowners and wildlife managers. One intended use of phenology measurements is to use phenology as a leading indicator of animal movements, thereby enabling Yellowstone National Park managers to anticipate animal space use and plan strategies to mitigate conflicts with private landowners in areas surrounding the park.

2.3.5 Primary Production

Gross primary production (GPP) is the rate at which plants and other producers in an ecosystem capture and store energy as biomass via photosynthesis. Some fraction of this energy is used to maintain existing tissues or is lost through plant respiration, and net primary production (NPP) is the remaining amount that is “fixed” or stored by an ecosystem. As indicators of ecosystem productivity, GPP and NPP provide an integrative measure of ecosystem condition that incorporates seasonal climatic influences and satellite measures of vegetation condition, as well as information on topography, soils, and water availability.

To characterize ecosystem productivity for each of the partner I&M networks, we followed the general approach used by the MODIS MOD17A2 algorithms (Running et al. 2000) and applied a simplified version of the BIOME-BioGeochemical Cycles (BGC) ecosystem model (Thornton et al. 2002; Thornton et al. 2005) within the Terrestrial Observation and Prediction System (TOPS) (Nemani et al. 2009). TOPS is a modeling and climate and satellite data assimilation framework maintained by NASA Ames for use in ecological forecasting and ecosystem modeling research and applications. Relative to standard MODIS productivity products, TOPS uses gridded climate data at a much finer spatial resolution (1 km) to account for the steep heterogeneous terrain in many of our partner I&M networks and parks. TOPS uses satellite-derived estimates of leaf area to estimate various water (evaporation, transpiration, stream flows, and soil water), carbon (net photosynthesis, plant growth), and nutrient (uptake and mineralization) flux processes on a daily time step. BIOME-BGC requires as inputs spatially continuous data layers to describe the land cover, soil texture and depth, daily meteorology, and elevation across the land surface. To evaluate spatial and temporal patterns in GPP, daily maps were produced for the PACE surrounding each of the focal parks for the period from 2001 to 2010. Feedback from collaborators indicated that daily and monthly GPP maps were useful, but difficult to translate into summary products. We thus compiled the GPP data into seasonal and annual summaries of cumulative GPP (Figure 2.5) by park, PACE, and major ecosystem type, and evaluated the data to characterize baseline conditions for future monitoring and identify any emerging trends over the past decade. A standard operating procedure (SOP) was prepared for the productivity products (Melton et al. 2010), and the summary products were distributed via a dynamic web interface (Figure 2.6).

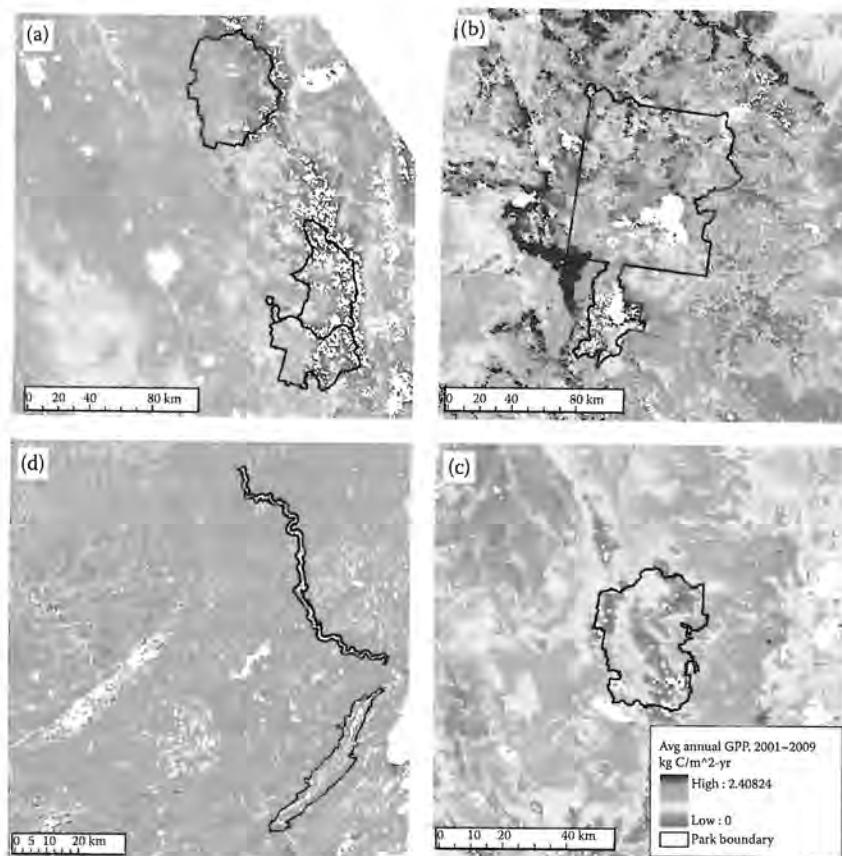


FIGURE 2.5

Daily estimated gross primary production (GPP) was summarized to convey spatial and temporal patterns in productivity in the parks and surrounding ecosystems. Maps of average annual total GPP for 2001–2009 are shown for these National Park Service units: (a) Yosemite/Sequoia-Kings Canyon, (b) Yellowstone/Grand Teton, (c) Rocky Mountain, (d) Delaware Water Gap/Upper Delaware.

Patterns in GPP varied by park, region, and ecosystem type. For example, in the Sierra Nevada parks, the indicator captured the significant interannual variability in productivity driven by year-to-year variations in the timing of snow accumulation and melt. In contrast, parks in the Eastern Rivers and Mountains I&M network showed sustained declines in GPP over the past decade, which may be due in part to increasing tree mortality resulting from infestations of the hemlock wooly adelgid (*Adelges tsugae*) throughout the region. While a 10-year data record is too short to identify long-term trends, the indicator was shown to capture the impact of climate variation and disturbance events on ecosystem condition.

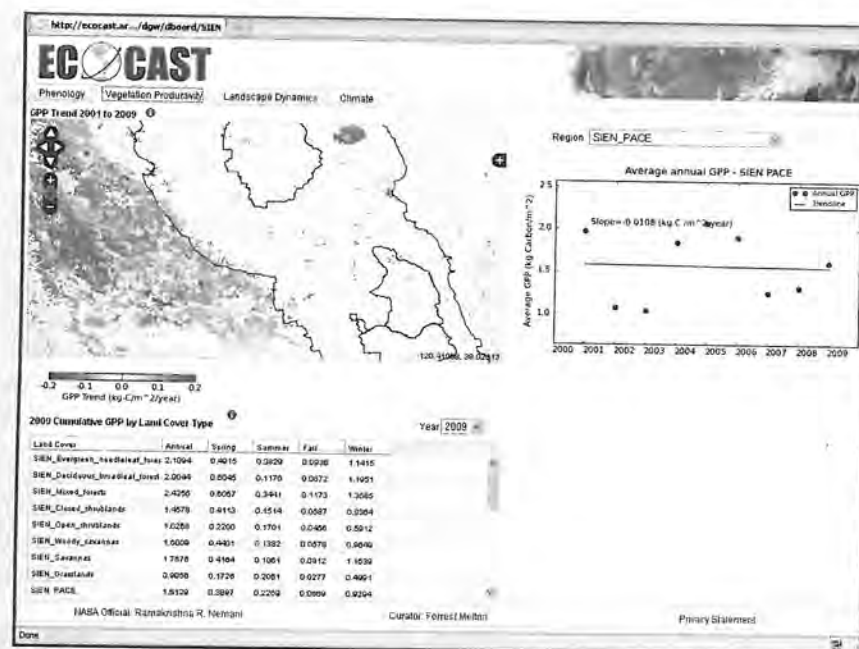


FIGURE 2.6

The Ecocast dashboard was used to display summaries of results for indicators directly estimated from remotely sensed data (e.g., phenology, snow cover), and results from simulations that estimated many other ecosystem variables (e.g., gross primary production—GPP—illustrated here; see text for explanation). The Ecocast summaries included maps showing regions with emerging trends or anomalies, and graphs and charts summarizing patterns by park or protected-area-centered ecosystem (PACE), time period, and/or ecosystem type.

2.4 Effectively Delivering Results to the NPS

There was an unusually high rate of turnover in cooperating NPS staff during our project, which led us to reconsider our plans for transferring PALMS products and knowledge to NPS. We had planned to place a high priority on training individual staff who would serve as NPS experts on PALMS products and methods. This strategy involved considerable investment in individuals, and that investment would be lost if they left their NPS positions. We consulted NPS collaborators and concluded that the most effective means for transferring project results included NPS-hosted websites, a set of site-specific project completion calls, park-specific reports, datasets, detailed methods (SOPs, see below), and peer-reviewed publications. This variety of products clearly reflected the general desires articulated by park managers in an earlier survey (Hubbard 2006). The suite of products and close-out activities we employed are, in our experience, rather unusual, and we believe

this can serve as a good model for many projects that seek transfer of knowledge and technologies to specific partner programs or agencies. The following sections describe our strategy in more detail.

2.4.1 Documentation of Indicators and Methods

Our project partners felt that one- to two-page "resource briefs" on individual indicators would effectively communicate results to decision-makers and serve as quick introductions to the indicators for ecologists and other resource professionals. Each brief included a short description of the indicator issue, why it was useful, and a very short (one to two paragraphs) summary of results. Results were always illustrated with one or more maps, tables, and/or graphs. For each park, the briefs were combined into a single package (document) that included an abstract, table of contents, one-page overview of the project, and a table (similar to Table 2.3) with information on all the indicators for that park. The set of briefs did not include details on methods, and they included only the highlights of results. Recipients found the set of briefs to be much more accessible than a technical report or peer-reviewed publication.

A fundamental goal for PALMS was to develop indicators and methods that would be adopted by the NPS I&M. A major impediment to adopting an indicator or new method is the cost of development of an approved protocol. All NPS I&M networks are required to develop a detailed peer-reviewed protocol that meets published guidelines for each indicator they monitor (Oakley et al. 2003; Fancy et al. 2009). These guidelines were established to ensure that I&M procedures are completely documented and remain consistent through time and across changes in personnel. The work required to write a complete protocol is usually well beyond the scope of an externally funded research or development project, but projects may be able to draft parts of protocols and greatly reduce the time and cost required to complete a protocol.

Protocols compliant with NPS I&M standards consist of a narrative describing the goals and overall approach of the protocol, and a set of SOPs that describe, in detail, the specific procedures for a discrete task or operation. The PALMS team focused on writing SOPs for the core procedures for calculating each project indicator. These SOPs are highly detailed documents that permit I&M staff to repeat analyses or conduct the same analysis on new datasets. SOPs contain more details than the methods section in a typical peer-reviewed paper. For protocols that rely on GIS software and remotely sensed data, SOPs are usually illustrated with screen shots of key steps and, when appropriate, include step-by-step instructions for computer procedures.

To facilitate replication of GIS-based PALMS analyses, we developed ArcGIS (ESRI 2009) tools with Arc ModelBuilder. These tools automated complex or repetitive tasks, and served to reduce the level of software-specific expertise needed to reproduce our results or to repeat analyses with other datasets for different locations or time frames.

2.4.2 Websites

The range of products from PALMS is probably typical of a large, complex, multiagency monitoring development project. The large number of products, diverse array of product formats, extended period for delivery, and large volumes of data motivated the use of a tiered website to communicate and deliver products to project and park participants. We developed a public website on an NPS server for posting SOPs, reports, links to related sites, and links to data or information for acquiring large datasets. Because NPS was the target "client," the use of an NPS server (rather than one hosted elsewhere) helped ensure delivery of all relevant products and methods to NPS and it increased the likelihood that products would be properly cataloged, archived, and remain accessible to NPS staff in the long term. These websites will be removed as the required quality checks are completed and the products are fully integrated into and retrievable from the NPS information system.

Sustained interactions with park-based personnel required the addition of site-specific web pages that supported the completion calls (see Section 2.4.4) and facilitated review and discussion of products as they were being developed.

2.4.3 Dynamic Web Interfaces and Data Services

Satellite data analysis and ecosystem modeling are specialized fields, and park managers may be unfamiliar with satellite-derived indices and model parameters (e.g., NDVI, leaf area index, GPP, NPP), presenting a barrier to their adoption and use in park monitoring. To address this challenge, we developed a dynamic web interface based on the TOPS Ecocast framework (Figure 2.6) to present visual examples to NPS collaborators and to demonstrate how indicators derived from satellites and ecosystem models could be applied to characterize spatial and temporal patterns in park ecosystem conditions. This interface utilized open-source tools and software libraries to provide an interface that was driven by an OPeNDAP data server (Open-source Project for a Network Data Access Protocol; <http://www.opendap.org/>) and included dynamic web maps to characterize spatial patterns, and graphs and charts to summarize temporal patterns in the satellite- and model-derived indicators. This interface was effective in providing concrete examples of the use of the satellite and model data to dynamically summarize park ecosystem conditions.

To be sustainable as long-term I&M indicators, the source data used to calculate indicators must be readily accessible via data services and tools that are compatible with NPS information systems. Source data are needed to allow I&M networks to update indicators, and to develop customized analyses and summaries that can address park-specific issues. The PALMS project used ArcGIS (ESRI 2009) compatible geodatabases to store and distribute data for many of the PALMS indicators. We also tested the use of open-source software for data distribution, including an OPeNDAP server, which was

used to distribute satellite and ecosystem model results from TOPS (<http://ecocast.arc.nasa.gov/opendap>). OPeNDAP is optimized to distribute large archives of raster data, such as those provided by TOPS, and it provides functionality for both temporal and spatial subsetting of geospatial data archives. ArcGIS tools are widely used within the NPS and this approach had the advantage of providing data in a form that can be directly imported into I&M geodatabases and incorporated into NPS projects. The NPS is currently enhancing the I&M data system with tools that automate data retrieval via web services, data transformation and analysis, and visualization of results. Data services used by the PALMS project are fully compliant with and support this growing I&M data infrastructure.

2.4.4 Project Completion Calls

Several factors posed significant challenges to using traditional project meetings for presenting our results. The integrated nature of the project meant that all investigators contributed important results for all parks, but project and park personnel were located at more than a dozen sites across the United States. The number and complexity of project indicators (Table 2.3) ensured that any presentation of all site-specific results would be an overwhelming volume of information. Furthermore, we were convinced that deep local knowledge was required to fully interpret our results and ensure that they addressed issues that were relevant and important to managers. Full interpretation required a series of conversations.

To meet these challenges, we scheduled a series of project "completion calls" lasting about 2 h. Each site participated in at least three webinars, and we scheduled additional webinars on specific results, methods, or topics as required. Call participants included project staff, principal NPS collaborators from each park, and interested management staff. These calls seemed to be effective by delivering results in measured "doses" and facilitating discussions of the results and outcomes. They also permitted time for park staff to review and discuss results between calls, and for additional interaction that might be needed to clarify, refine, or revise our work. We conducted a total of 14 such sessions over the final year of the project.

2.5 Lessons Learned and Recommendations

Many remote-sensing-based monitoring projects, especially those that involve many sites and collaborators, will likely face challenges similar to those we experienced. Some of these are common to most large problems, whereas others are more specific to working with complex technologies and management agencies such as the NPS. Here, we summarize a few important lessons, emphasizing things that worked well for us.

2.5.1 Allocate Sufficient Time to Develop a Genuine Science-Management Partnership

To effect a genuine collaboration between scientists, resource specialists, and managers takes more time, potentially *much* more time, to design, develop, implement, conduct, communicate, report, and deliver products than is typical for research projects. Remote-sensing projects tend to involve complex technology, sophisticated methods, and sometimes obscure measurements. "Black box" calculations that managers do not understand are unlikely to sway opinion or usefully contribute to important decisions unless they are skillfully explained by scientists. Time is required to develop a common language and explain how results were obtained and what they mean.

The transition of methods and results from research to operations requires a long-term commitment from all parties. Efforts to apply research data products for operational decision support often discover that more research is needed. Methods that apply at one site may not work well elsewhere, or it may be necessary to develop additional ecological or physical relationships to convert results of spectral analysis into units that are meaningful to managers. There is rarely a finite hand-off or delivery of research results accompanied by a seamless integration into a management decision support framework. In most cases, only through the long-term development of scientific understanding and collaboration with managers will decision-making be positively influenced by research results.

2.5.2 Communicate Results in a Management-Relevant Context

Uptake of results occurs most readily when they are available to the right people, at the right time, and in the right format. In parks, budget exercises, annual work plan, and field activities are typically conducted at the same time each year. Monitoring data need to be available when results can feed into decisions. Results should be expressed using formats and language familiar to managers and connections should be made between results and attributes that affect decisions. For example, it may be possible to correlate soil moisture and plant stress (as estimated from a simulation model driven by MODIS products) into a coarse measure of fire risk. Patterns of soil moisture may be of little interest to managers, but fire risk is almost always of great interest. Critical evaluation by end users will likely be required to ensure that the data products for decision support are available at the appropriate spatial and temporal scales.

2.5.3 Conform or Embellish Existing Frameworks and Processes

For PALMS, this included using the existing I&M network and program structure as a primary means to communicate across parks and project staff. We built on existing guidelines and formats for publications, method documents,

and fact sheets, and we linked our efforts to specific personnel and positions within I&M. NPS collaborators were familiar with these products, and we minimized the costs associated with designing these products. We largely followed existing practices and produced reports and results for specific audiences.

2.5.4 Plan for Persistence and Change

NPS I&M is charged with conducting long-term monitoring. Protocols or products that do not persist through time will not meet program goals. The PALMS team's strategy to produce versioned SOPs was very well aligned with I&M protocol development needs. Production of detailed methods ensures persistence of standard methodology, and versioning provides a clear means to update individual procedures or an entire protocol with changes in technology or understanding.

2.5.5 Build on Existing, Widely Used Data Analysis Tools and Software Frameworks, Even If They Seem Inefficient

The use of existing tools and frameworks permits rapid development and reduces development costs. It increases client "buy-in" because the efficacy of application components is known, and it ensures usability. If possible, personnel should be exchanged to gain cross-enterprise experience in the tools and day-to-day processes used for data management and decision-making. NPS and the NASA-Ames groups employed software development teams with complementary skills; each group was familiar with the technologies, programming languages, and infrastructure that they could support after the initial development project ended. Communication between the groups was important to identify technologies that would most likely be adopted.

2.5.6 Practice Rigorous Scope Control to Maximize the Chance of Success

Operational use of remotely sensed data and technology requires robust, repeatable, credible, and defensible methods. Through discussion with collaborators, we continually refined the scope of work and avoided "mission creep" by focusing on specific functions, variables, and reporting products.

2.6 Summary

The PALMS framework, approach, and methods were developed specifically to meet the needs of NPS I&M, but the resources and impacts the indicators

address are common to protected areas worldwide. Very few North American parks—and probably no NPS units—are sufficiently remote and large enough to sustain the biodiversity once native to the park, or to be unaffected by activities outside park boundaries (GAO 1994; Carroll et al. 2004). Human development is increasing more rapidly near the boundaries of protected areas than elsewhere in the United States (Radeloff et al. 2010) and other continents (Wittemyer et al. 2008). Furthermore, climate changes are projected to result in huge shifts in ranges of species and habitats (Iverson et al. 2008; Belant et al. 2010; Cole 2010; Gonzalez et al. 2010). These threats emphasize the need for integrated assessments of the condition of landscapes around protected areas at a range of spatial scales.

PALMS is unusual among monitoring projects for the breadth of attributes addressed by the suite of indicators, and the use of various models to assimilate data. The suite of indicators developed by PALMS can provide a rich picture of landscape context and the condition of attributes that conserve or threaten biodiversity in and around parks. Other reviews have illustrated the value of remotely sensed data to monitor traits not addressed by PALMS, but also important to supporting biodiversity (Turner et al. 2003; Bergen et al. 2009) and the broader goals of protected area monitoring (Kerr and Ostrovsky 2003; Gross et al. 2006; Gross et al. 2009; this volume). The potential to increase the use of remote sensing for operational monitoring is great, especially when the value of remotely sensed data is enhanced through multifactor analyses and modeling.

Here, we illustrated just a few of the indicators developed by PALMS, and we focused on the approaches that worked for us. I&M networks have worked with partners to explore a variety of useful methods for monitoring landscapes that are well suited to specific situations. These include multi-scale monitoring of land-cover change (Wang et al. 2009), graph-based analyses of connectivity (Goetz et al. 2009; Townsend et al. 2009), phenology and snow cover (Reed et al. 2009), and forest monitoring (Kennedy et al. 2011, this volume).

Remotely sensed data will become increasingly important to NPS I&M as technologies improve, costs decline, and analyses become more integrative and sophisticated. As the chapters in this book attest, there are many new and exciting applications of remotely sensed data that will contribute to better informing management of protected areas.

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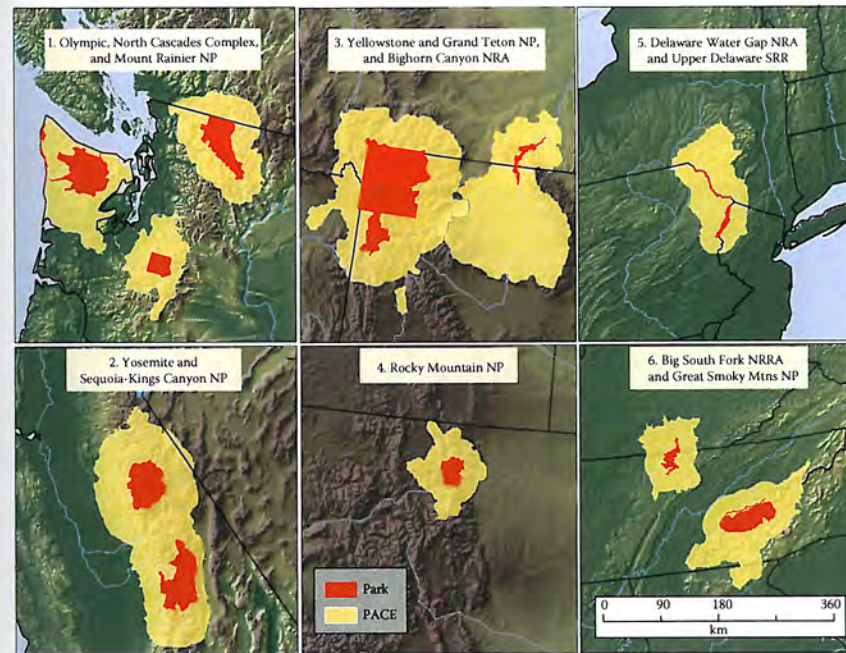


FIGURE 2.2

Maps of protected-area-centered ecosystems (PACES) delineated in this study for 13 U.S. National Park Service units. PACES were defined by the criteria in Table 2.4.

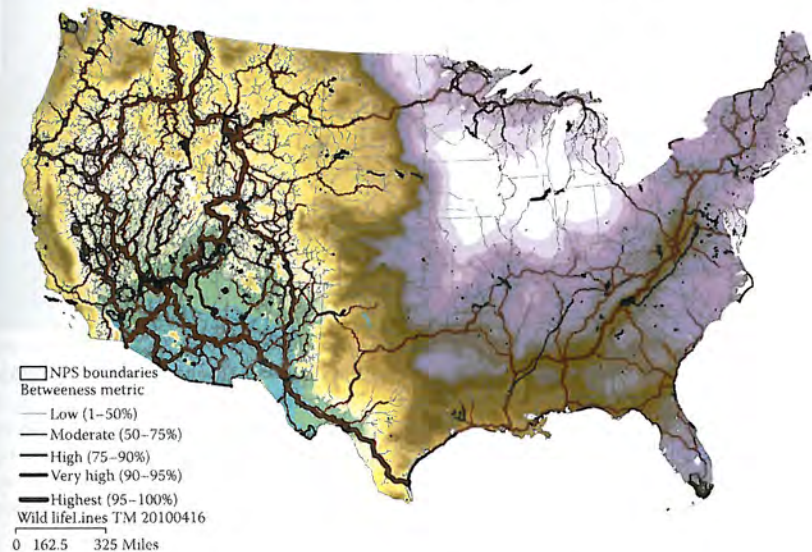


FIGURE 2.4

Map showing connectivity of natural landscapes in the United States. The thickness of red lines indicates magnitude of cumulative movement, assuming that animals avoid human-modified areas. The surface underneath the pathways depicts the averaged cost-distance surfaces, or the overall landscape connectivity surface. Colors range from green through yellow and purple to white, where green is greatest connectivity (lowest travel cost) and white indicated lowest connectivity (highest travel cost). National Park Service units are outlined in black.