Remote Sensing of Environment 113 (2009) 1346–1356

Contents lists available at ScienceDirect

Remote Sensing of Environment

journal homepage: www.elsevier.com/locate/rse

Monitoring land use and cover around parks: A conceptual approach

Danielle A. Jones [a,*], Andrew J. Hansen [a], Kristy Bly [b], Kevin Doherty [c], Jake P. Verschuyl [a], Justin I. Paugh [a], Robin Carle [a], Scott J. Story [a]

[a] Department of Ecology, Montana State University, Bozeman, MT 59717, USA
[b] Department of Land Resources and Environmental Sciences, Montana State University, Bozeman, MT 59717, USA
[c] College of Forestry and Conservation, University of Montana, Missoula, MT 59812, USA

ARTICLE INFO

Article history:
Received 30 November 2007
Received in revised form 4 August 2008
Accepted 9 August 2008

Keywords:
Land use
Land cover
Indicator
Inventory and monitoring program
National parks
Conceptual models

ABSTRACT

Many of the habitats and resources which influence ecological functioning within National Parks, and protected areas in general, are located outside of their borders in unprotected areas. Hence, land use and land cover changes in surrounding areas may substantially influence the natural resources within parks. The US National Park Service has recognized these threats and incorporated land use and land cover monitoring into its Inventory and Monitoring Program. The purpose of this paper is to provide a framework based on a conceptual approach for planning and implementing monitoring within this Program. We present a conceptual model, based on ecological theory, which illustrates how land use and land cover change impact park resources, and helps to identify monitoring indicators that will measure relevant attributes of land use and land cover change. We also discuss potential sources of data for quantifying indicators of land use and land cover change over time, including remote sensing data and ancillary spatial datasets. Finally, we describe steps for analyzing monitoring data so that the intensity and direction of changes in land use and land cover over time are quantified, as well as trends in the status of important park resources impacted by these changes. Integration of land use and land cover monitoring data and park resource data will allow for analysis of change from past to present, and can be used to project trends into the future to provide knowledge about potential land use and land cover change scenarios and ecological impacts. We illustrate our monitoring approach with an example from the Inventory and Monitoring Program's Greater Yellowstone Network.

1. Introduction

A primary goal of the US National Park Service (NPS) is to maintain native species and ecological processes (Sellars, 1997). However, boundaries of parks, monuments, preserves, and other protected areas administered by the NPS (all hereafter referred to as "parks") were largely drawn to protect places of scenic beauty, geologic uniqueness, and historical significance rather than to maintain ecological condition (Schullery, 1997). Consequently, many of the habitats and resources which influence ecological functioning within parks are located in unprotected natural areas outside of park borders (Newmark, 1985; Salwasser et al., 1987; Schonewald-Cox & Bayless, 1986). Hence, land use and land cover (referred to here as "LULC") changes in surrounding areas may substantially influence park natural resources (Hansen & DeFries, 2007; Pringle, 2000; US General Accounting Office, 1994).

Park managers nationwide have identified threats originating outside of park borders among their top management concerns (US General Accounting Office, 1994). Monitoring LULC change around parks would provide information to mitigate or minimize negative impacts of these external threats to park resources. The NPS Natural Resource Inventory and Monitoring (I&M) Program (Fancy et al., 2009) provides the infrastructure for monitoring LULC change. Goals of the I&M Program include quantifying the status and trends in park natural resources and providing early warning of potential threats so that managers have the scientific information needed to make better-informed decisions. Within the I&M Program, the NPS parks are grouped into 32 networks based on geographic and ecological similarities. Parks within each network collaborate to develop long-term monitoring programs. Many of these networks are now developing protocols for monitoring LULC change.

The purpose of this paper is to provide steps for the planning and implementation of monitoring LULC change in and around parks (Fig. 1). First, we demonstrate the use of conceptual models for identifying specific aspects of LULC to monitor. Models will help to identify the impacts that human activities outside of the parks may have on the ecological condition within the park; it is necessary to understand these potential impacts in order to select appropriate monitoring variables. Additionally, models can help one to understand what region surrounding the park may be influenced by LULC change, and define

---

[*] Corresponding author. Tel.: +1 406 994 2670; fax: +1 406 994 3190.
E-mail address: danielle.jones@montana.edu (D.A. Jones).

0034-4257/$ – see front matter © 2009 Elsevier Inc. All rights reserved.
doi:10.1016/j.rse.2008.08.018

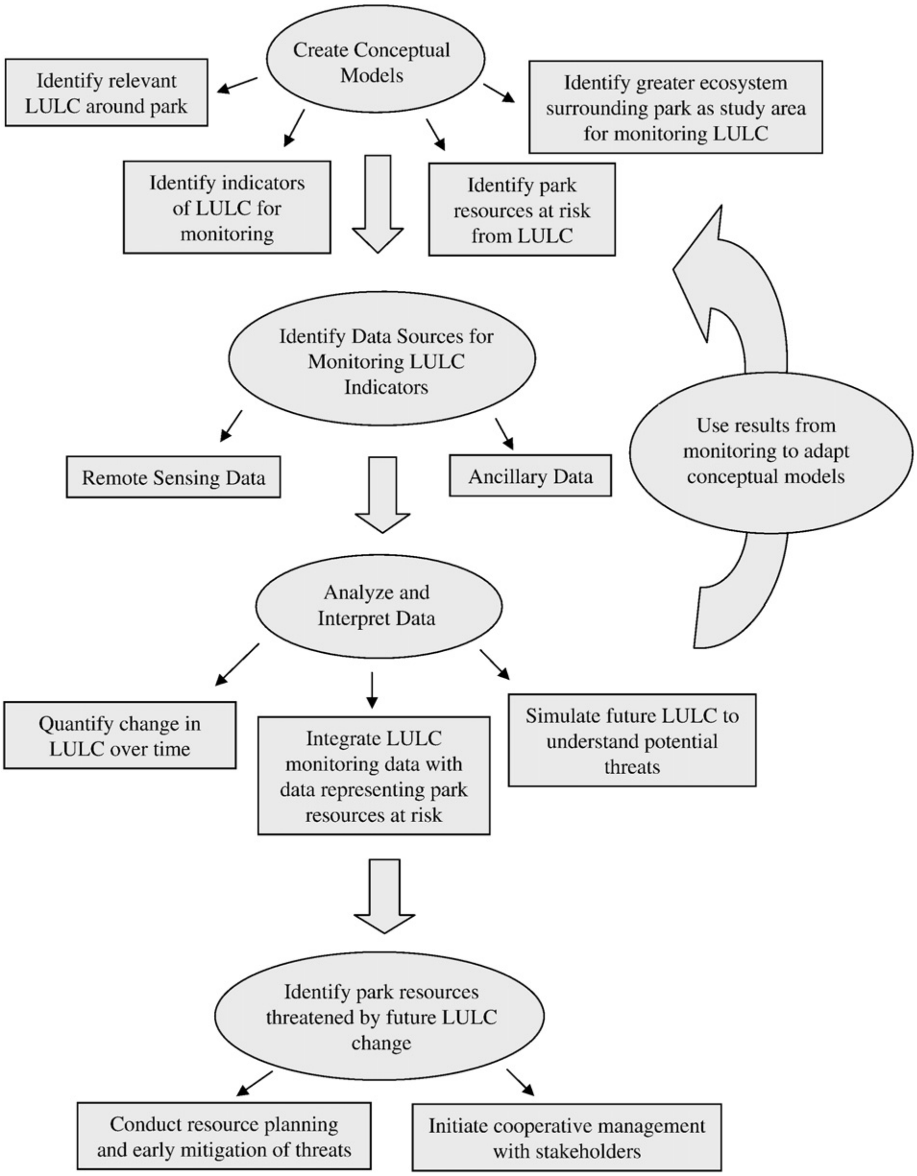

Fig. 1. General steps outlining an approach for monitoring land use and cover (LULC) change around parks and other protected areas.

the boundaries over which monitoring will be done. Second, we discuss existing data sources and methods available for quantifying LULC variables, including measures of the human activity that take place on the land (i.e. use) and measures of the physical characteristics of the surface of the land (i.e. cover; Turner et al., 2001). Last, because a common shortcoming of monitoring is a failure to collect and present data in a way that is useful to managers (Failing & Gregory, 2003), we present an approach for data analysis that adds value to monitoring data to enable management decisions. Monitoring data can be integrated with other ecological data to quantify specific ecological impacts of LULC change to park resources over time. We illustrate these steps using a case study from the Greater Yellowstone Network (GRYN), where monitoring protocols were recently developed.

While we discuss these steps in the context of parks administered by the NPS, issues related to LULC change are relevant to protected areas in general. Change in LULC surrounding protected areas, and the resulting threats to resources within the borders of these areas, is a global phenomenon (Wittemyer et al., 2008). The development of conceptual models to identify human impacts, consideration of data sources available for quantifying LULC change, and review of potential analyses for monitoring data can be generally applied to long-term monitoring programs within all protected areas.

2. Identifying monitoring indicators

Monitoring should measure aspects of LULC change that will quantify impacts to park resources and provide information about ecological condition. Therefore, it is necessary to understand the relationships between LULC change and park ecosystem components and processes when choosing variables for a monitoring program. Here we present a conceptual model, based on ecological theory, which illustrates relationships between LULC change and park resources.

The I&M Program has formalized terminology to guide development of conceptual models (NPS, 2006), and we use these terms in our models. *Drivers* are major forces, such as natural disturbance, climate, or land use that exert large scale influences on natural systems. *Ecological mechanisms* are the means by which a driver causes change in an ecological response variable. *Ecological response variables* are park resources impacted by a driver. Finally, *indicators* are a subset of monitoring attributes that are particularly important because they are indicative of the quality, health, or integrity of the larger ecological system to which they belong. In this paper, indicators represent attributes of the driver, LULC change. However, many of the land cover indicators can also represent ecological response variables, such as the extent of the distribution of a plant species or community (e.g., riparian woodland).

A protected area such as a national park exists within a coupled human–natural system (Michener et al., 2001; Liu et al., 2007a,b), characterized by strong interactions between ecological and human components, including land use. These interactions are especially relevant to park management because parks provide natural amenities attractive to humans that may spur the intensification of land use in surrounding unprotected areas (Rasker & Hansen, 2000). Parks may be connected to the larger, unprotected ecosystem through flows of energy, materials, and organisms (Grumbine, 1994; Hansen & DeFries, 2007; Theberge, 1989; Fig. 2a); LULC change may disrupt these flows and alter ecological processes within the park.

Four ecological mechanisms through which LULC change may impact resources within protected areas have previously been described by Hansen and DeFries (2007; Table 1). First, LULC change may destroy natural habitats and reduce the effective size of the larger natural ecosystem surrounding the protected area (Fig. 2b). Second, LULC change may alter characteristics of flows of air, water, and natural disturbance moving through the larger ecosystem and the protected area (Fig. 2c). Third, LULC change may eliminate or isolate crucial habitats outside protected area borders (Fig. 2d). Fourth, LULC change may cause increased exposure to human activity within protected areas, resulting in higher incidences of disturbance and changes in community structure (Fig. 2e).

Determining relevant LULC change indicators based on conceptual foundations is only the first step (Kurtz et al., 2001). These conceptual models can be further evaluated and revised to emphasize management priorities and important ecosystem components and processes when identifying final monitoring variables (Lookingbill et al., 2007). Attributes of LULC that would serve as useful monitoring indicators can be identified by evaluating ecological mechanisms that represent impacts to park resources, and then choosing indicators that will quantify those impacts. For example, fragmentation of natural land cover may decrease the effective ecosystem size for a species of park management concern. The spatial configuration and area of natural cover types can be monitored to quantify that impact.

Conceptual models also provide information for delineating the boundary of the larger ecosystem that encompasses the park, which is the area where interactions between LULC and ecological processes will be most relevant to park ecosystems. The boundary of the larger ecosystem will define the region for monitoring LULC change, and can be delineated based on the distribution of multiple ecosystem attributes, such as watersheds representing hydrologic flows, movement corridors for migratory organisms, and wildfire initiation and run-out zones (Hansen & DeFries, 2007; Table 1). Criteria that can be used to define greater ecosystems around protected areas are currently being developed (DeFries et al., in press).

2.1. Example: identifying monitoring indicators for the GRYN

The GRYN includes Yellowstone and Grand Teton National Parks and Bighorn Canyon National Recreation Area. These parks are encompassed within the Greater Yellowstone Ecosystem (GYE), which is centered on the Yellowstone Plateau and was originally delineated as the range of the Yellowstone grizzly bear (*Ursus horribilis*; Craighead, 1991; Fig. 3). The boundary was subsequently expanded by Rasker (1991) to include the twenty counties included within the GYE because many socioeconomic data sets are compiled at the county level. The GRYN used this latter boundary of the GYE to delineate the study area for monitoring LULC change, with further expansion to include the counties surrounding Bighorn Canyon National Recreation Area (Fig. 3).

The network developed a conceptual model to identify the important ecological mechanisms linking LULC change to resources and processes within parks. The final model reflected the ecological

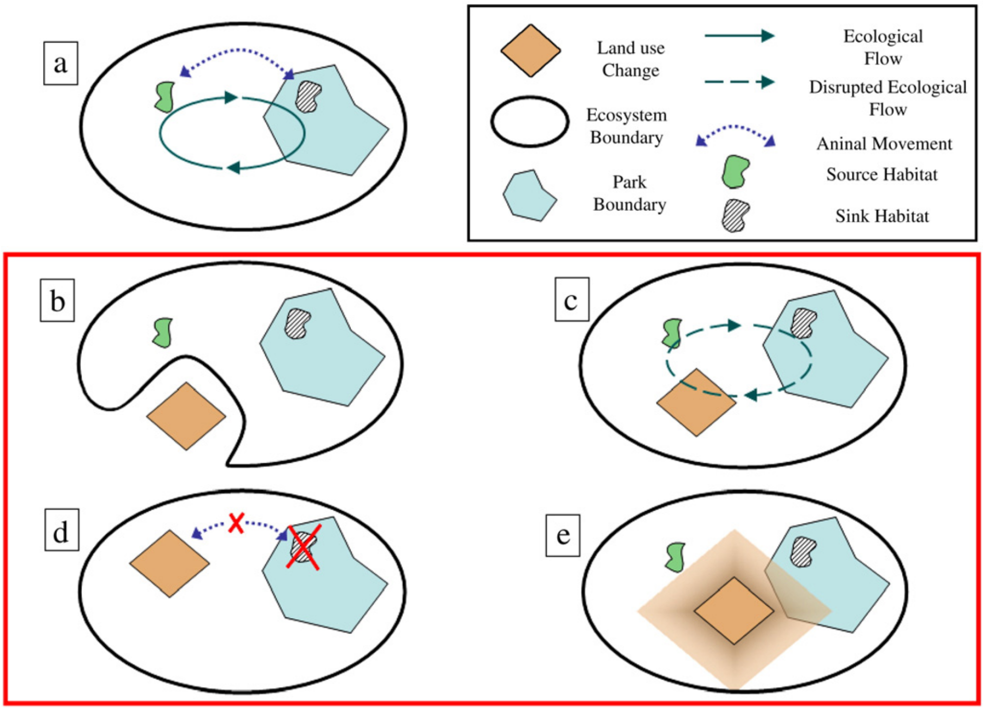

Fig. 2. Conceptual model illustrating the effects of land use change on ecosystem function. (a) Ecosystem unaffected by land use change, (b) land use change reduces effective size of ecosystem, (c) land use change alters ecological flows, (d) land use change eliminates unique habitats and disrupts source-sink dynamics, and (e) edge effects from land use negatively influence park. From Hansen and DeFries (2007).

Table 1
General mechanisms by which land use surrounding protected areas may alter ecological processes within reserves.

General mechanism	Ecological property undergoing change	Description
Decrease effective size of larger ecosystem	Minimum dynamic area	As the area of the larger ecosystem falls below what is needed to maintain the temporal stability of seral stages relative to the size of natural disturbance, the diversity of seral stages may be lost within the protected area
	Species area relationships	Risk of species extinction increases inside the protected area as the area of the larger ecosystem becomes smaller
	Trophic structure	Organisms at higher trophic levels generally require larger home ranges; these species may be at higher risk of extinction within the protected area as the larger ecosystem gets smaller
Change in ecological flows across the larger ecosystem	Initiation and runout zones	Conditions within certain areas may be more favorable for the initiation or spread of natural disturbance. If these "initiation" and "runout" zones are eliminated by land use, the incidence of disturbance within the ecosystem (and protected area) may be reduced
	Flows of air or water	Land use in upper watersheds or airsheds may alter characteristics of flows of air or water into a protected area that is down wind or stream
Loss of crucial habitat within larger ecosystem	Ephemeral habitats	Elimination due to land use of unique habitats that are required on a seasonal basis by protected area organisms may result in population declines
	Dispersal/ migration habitats	Loss of corridors required for dispersal among protected areas or for migration to ephemeral habitats may isolate protected area populations
	Core areas	As habitat is fragmented and core area declines, edge effects are introduced that may change community structure and biotic interactions within a protected area
	Population source–sink habitats	Loss of habitats outside of protected areas that are population "source" areas may result in the extinction of natural "sink" populations in the protected area
Increased human population and exposure to human impacts	Direct disturbance to plants and animals	Incidence of displacement and direct mortality for protected area populations increases due to increased encounters with humans and pets
	Proliferation of human-adapted species	Exotic and native human-adapted species may change community structure and biotic interactions within the protected area, especially at protected area edges

Modified from Hansen and DeFries (2007).

relationships that were considered most important for understanding potential impacts to biodiversity and ecosystem processes of highest priority to NPS scientists (Fig. 4). Within the GRYN, three land use drivers were identified as having high potential to influence park resources: residential development, resource extraction activities (e.g. logging), and agriculture. These land uses drive ecosystem changes by altering natural disturbance regimes, converting surrounding natural land cover, and causing increased exposure to human impacts in and around parks. These drivers may influence ecosystem functioning within the parks through mechanisms that change the characteristics of ecological flows through the park, decrease the effective ecosystem size, eliminate crucial habitats, cause direct disturbance to plants and wildlife, and result in the proliferation of human-adapted species. General ecological responses to these impacts stem from changes in population demography and community structure, which may result in population declines for some park species.

Monitoring indicators representing relevant attributes of LULC were identified to measure aspects of residential development, roads, natural and non-natural land cover, agriculture, and natural disturbance. The network drew upon previous GYE LULC mapping efforts (Parmenter et al., 2003; Powell et al., in press) to aid in identification of land cover types relevant to the GRYN landscape. Land cover indicators included dominant land cover types (cover types covering a substantial portion of the ecosystem) in the area, such as Douglas-fir (*Pseudotsuga menziesii*), as well as less common communities of special monitoring concern to the network, such as aspen (*Populus tremuloides*; Table 2). Indicator classes representing various levels of home densities and roads were included to measure the intensity of these land uses, which may influence the magnitude of the ecological impact (Hansen et al., 2005). Burned areas were included to quantify the occurrence of natural disturbance. Finally, classes measuring agriculture were included to represent this widespread regional land use type (Table 2).

Indicators were organized in hierarchical levels so that data could be summarized at appropriate scales for evaluating ecological impacts of LULC change (Table 2). For example, change in the effective size of the larger ecosystem could be measured by the Level I natural vegetation indicator class. The distribution of Level IV mature whitebark pine (*Pinus albicaulis*) could be used to quantify the availability of an important grizzly bear food source, and may serve as an indicator of habitat suitability. Finally, Level III classes representing the distribution of rural homes and urban areas may allow managers to quantify increased exposure to human impacts through the expansion of residential development in areas surrounding parks.

3. Quantifying monitoring indicators

Data for quantifying indicators of LULC change are derived from two main sources. Remote sensing images provide information about characteristics of the landscape, and ancillary demographic and infrastructure data provide information about how the land is populated and used. These types of data are generally compiled by third-parties through other existing programs and then acquired for monitoring. To be appropriate for use in monitoring, these data must be obtained consistently over time and updated regularly on a long-term basis. Consequently, feasibility of monitoring will depend on the availability of existing data sources, and the costs and logistical constraints associated with acquiring and manipulating those data.

3.1. Remote sensing data sources

From either satellite or aircraft platforms, remote sensors capture images of the landscape that provide information about properties of land cover and some land uses. Sensors differ in the spatial, spectral, and temporal resolution of data collected. Spatial resolution is a measure of the smallest surface unit that can be resolved by a sensor, spectral resolution refers to the number and type of spectral bands that are detected, and temporal resolution measures how often a sensor collects data from a certain area. Issues concerning resolution are central to evaluating which sensors are appropriate for quantifying specific monitoring indicators. Spatial extent of data, as well as cost of acquisition and manipulation, is also an important consideration.

Rogan and Chen (2004) provided a comprehensive review of the remote sensing technology available for monitoring LULC change. They discussed the attributes of sensors with various spatial, spectral, and temporal resolutions. Coarse and medium spatial resolution sensors

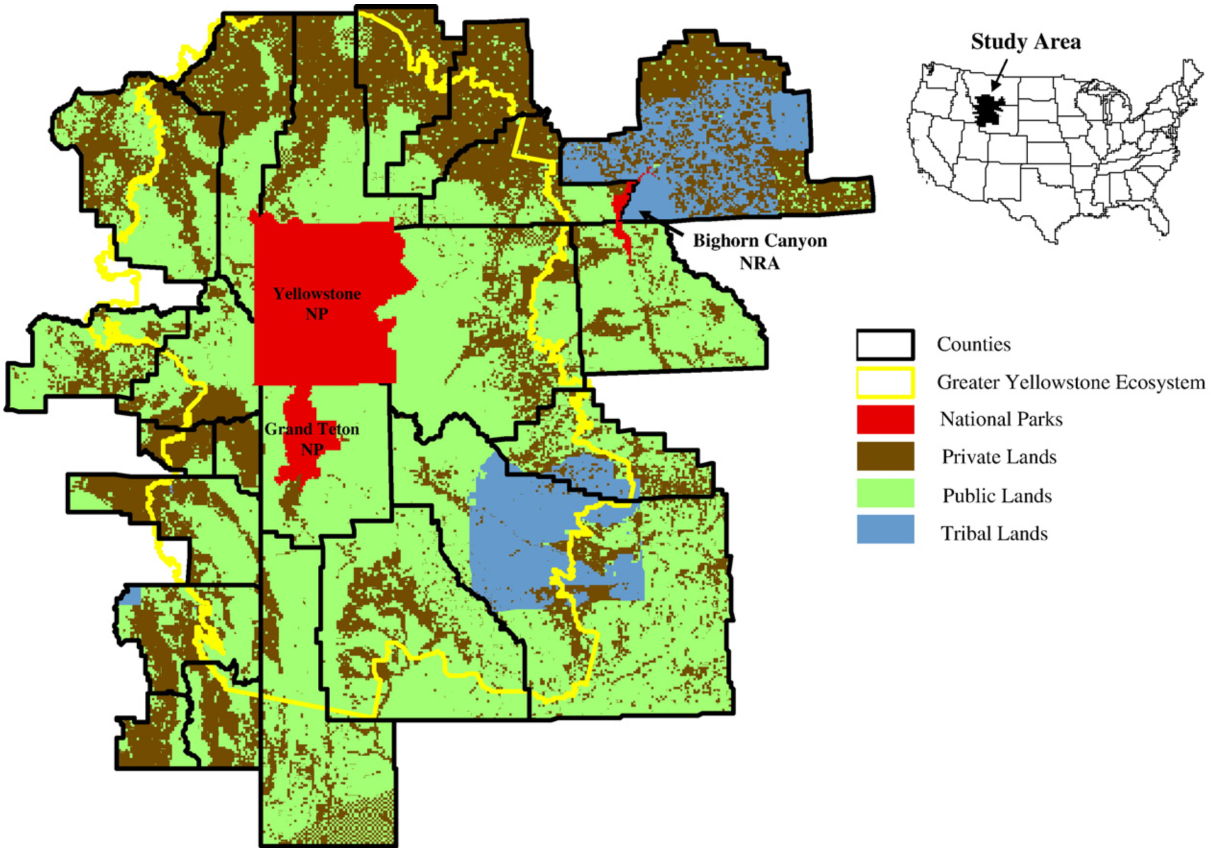

Fig. 3. Study area for monitoring land use and land cover change in the Greater Yellowstone Network. The area was delineated based on the boundary of the Greater Yellowstone Ecosystem, which surrounds Yellowstone and Grand Teton National Parks, with expansion to include Bighorn Canyon National Recreation Area and county boundaries.

generally provide low-cost data that can be acquired over large geographic extents, and methods for data processing and manipulation are well-established. However, the spatial resolution of the data can be a limiting factor for quantifying cover types distributed in small patches. Sensors with high spatial and spectral resolution can distinguish between indicator classes at a finer scale and are able to capture patchy

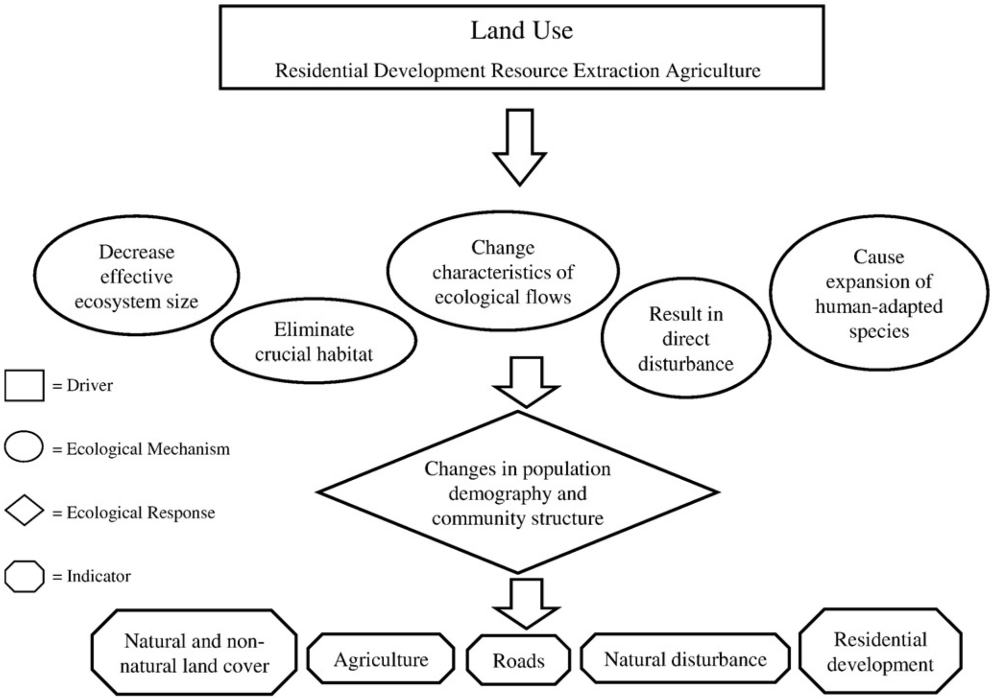

Fig. 4. A generalized conceptual model diagram illustrating important land use drivers, ecological mechanisms, ecological responses, and potential indicators for monitoring land use and land cover change around parks of the Greater Yellowstone Network.

Table 2
Hierarchical classification of indicators for the Greater Yellowstone Network and potential data sources.

Level I	Level II	Level III	Level IV	Data source	Spatial scale	Citation for methods
Natural vegetated				US Geological Survey (USGS) Landsat imagery	30 m	Parmenter et al. (2003); Powell et al. (in press)
	Herbaceous/shrubland					
	Deciduous forest					
			Cottonwood			
			Willow			
			Aspen			
	Conifer forest					
		Seedling/sapling				
		Pole-aged				
		Mature				
			Whitebark pine			
			Douglas-fir			
			Rocky Mountain juniper			
			Mixed conifer			
		Mixed seral				
Natural non-vegetated						
	Water					
	Burned			GEOMAC wildland fire support	Fire bounds	http://geomac.usgs. gov
Agriculture				Census of Agriculture	County	Nat'l Statistics Service *www.nass.usda.gov*
	Irrigated agriculture			USGS Landsat imagery	30 m	Parmenter et al. (2003); Powell et al.,(in press)
		Cropland		Census of Agriculture	County	National Statistics Service www.nass.usda.gov
		Pasture				
	Non-irrigated agriculture					
		Cropland				
		Pasture				
Non-natural non-vegetated				USGS Landsat imagery	30 m	Parmenter et al. (2003); Powell et al. (in press)
	Urban/Built-up					
		Rural homes		County tax assessors	Public lands section (1mi^2)	Gude et al. (2006)
			Agricultural density*			
			Exurban density**			
		Incorporated cities		TIGER/ Line files	.005 decimal degrees	US Census Bureau Decennial Census *www.census.gov*
		Roads				
			Interstate			
			US highway			
			State/county highway			
			Local road			
			Four-wheel drive road			

*Agricultural density: 1–15 homes/miles^2/2.59 km^2; ** Exurban density: ≥16 homes/miles^2/2.59 km^2 (Hansen et al., 2005).

LULC types, but applicability may be limited by high costs and large data volumes, smaller extent of coverage, low signal-to-noise ratios which compromise classification and change detection accuracy, and complex data processing techniques (Aspinall, 2002; Gianinetto & Lechi, 2004; Thenkabail et al., 2004). High spatial and spectral resolution data may be most appropriate for monitoring very specific resources within smaller geographic areas.

LULC maps derived from remote sensing data are available for the US from two sources. The National Land Cover (NLC) Dataset was created by the US Geological Survey using data collected in 1992 from the multispectral, medium resolution TM sensor onboard Landsat satellites (Vogelmann et al., 2001). This map provides national coverage at 30-meter resolution, and includes modified Anderson Level II land cover classes (Anderson et al., 1976). The NLC Dataset is scheduled to be revised every ten years (US Geological Survey, 2005); NLC Database 2001, the newest generation of the NLC products, has recently been released (Homer et al., 2004, 2007). However, it is important to note that there were differences in the classification methods used to create the NLC products in 1992 and 2001, and any direct comparison of these two products to quantify change would be subject to error (Homer et al., 2007). This highlights the importance of scrutinizing the methodologies used to create data layers that will be compared over time, to ensure that any changes in LULC are representative of true change rather than differences in the methods used to create the datasets. The NLCD team is creating a new map product to aid in change analysis between the two time periods (Homer et al., 2007).

Additionally, the National Aeronautics and Space Administration (2005) produces LULC maps using the coarse resolution, multispectral MODIS sensor. These maps identify 17 classes of natural and non-natural cover types at 1-km resolution and are currently updated on an annual basis. Suitability of these maps can be determined by evaluating if the temporal, spatial, and spectral resolutions are appropriate for quantifying monitoring indicators. There are other datasets that would be useful for monitoring LULC, such as the LANDFIRE Existing Vegetation Cover data layer (LANDFIRE, 2007), if they were going to be updated in the future. However, until it is clear that a particular data set is likely to be updated on a regular basis, it is unsuitable for inclusion in a long-term monitoring program.

If suitable maps do not already exist, they can be created for monitoring using unclassified remote sensing data. Rogan and Chen (2004) review steps for processing and converting remote sensing data to LULC maps. Image processing can be complicated and expensive because methods require the use of sophisticated statistical techniques and advanced computer software programs. However, creating maps from unclassified imagery is often the only way to accurately quantify high-priority indicators. Additionally, integrating digital change detection into image processing is easier and can be done with fewer errors versus applying change detection methods to existing LULC maps. Lu et al. (2004) and Rogan and Chen (2004) provide comprehensive reviews of methods for performing digital change detection.

Accuracy assessment of data processing, classification, and change detection is essential to understanding the value and limitations of final maps. Many techniques exist for conducting accuracy assesments of remotely sensed data (Congalton, 1991; Congalton & Green, 1999; Liu et al., 2007a,b; Stehman & Czaplewski, 1998). When using existing LULC maps created by other organizations, it is important to review accuracy assessments to fully understand the potential limitations of the data for quantifying indicators.

3.2. Ancillary data sources

There are many land use activities that cannot be accurately quantified through remote sensing. For example, residential development is often too dispersed and roads too narrow to be detected by many sensors. Consequently, it is necessary to use ancillary data to monitor these aspects of land use change.

Ancillary data are derived from on-the-ground surveys of land use activities. Many local and national programs have been established which collect and update data consistently over time that can contribute to land use monitoring (Table 3). Data are often widely distributed at no- or low-cost, and data processing requirements are generally minimal. However, the use of ancillary data may be limited because many types of data are collected only at coarse spatial resolutions (e.g. the regional or state level), and are not appropriate for monitoring local land use activities. Consequently, availability and spatial resolution of data are important considerations when evaluating the feasibility of using ancillary data sources for quantifying certain monitoring indicators. Additionally, it is important to ensure that data collection methods are consistent over time, so that spurious changes in LULC are not recorded as an artifact of changes in methodology.

Table 3
Potential ancillary data sources for monitoring certain attributes of land use.

Dataset	Source	Measure	Spatial scale
Human population	US Census Bureau Decennial Census	Number of people; updated every 10 years	Census block
Home densities within cities	US Census Bureau Decennial Census; TIGER/Line files	Boundaries of incorporated areas (i.e. cities) and associated home densities; updated every 10 years	Census block
Home densities within rural areas	County Tax Assessors or State Departments' of Revenue	Number of rural (i.e. unincorporated) homes within a given section of land; updated annually	Section (1mile^2)
Roads	US Census Bureau TIGER/Line Files	Locations of roads, from gravel roads to interstates; updated every 10 years	Individual road
Water quality	US Environmental Protection Agency WATERS (database housing local, regional, and national data sets)	Various measures of water quality and documentation of point and non-point sources of pollution; data sets updated at various time intervals	Watershed
Stream condition	US Environmental Protection Agency and State water quality agencies, Wadeable Streams Assessment	Status report and ecological assessment of stream condition based on standardized surveys; data sets updated at various time intervals	Watershed
Distribution of fires	GEOMAC Wildland Fire Support (USGS)	Boundaries of fire perimeters and area of fires for each year; updated annually	Individual fire perimeter
Status and trends in forest resources	US Department of Agriculture Forest Inventory and Analysis Program	Characteristics of forests on all forest land in the US, e.g. forest area, size and health of trees, or rates of mortality and harvest; surveyed annually	Forest plot
Agricultural statistics	US Department of Agriculture National Agricultural Statistics Service Census of Agriculture	Area and percent of land in certain types of agriculture; updated every 5 years	County
Mining claims on federal lands	Bureau of Land Management State offices or US Department of Agriculture Forest Service Regional Offices	Mineral records and locations of mining claims within each state; data sets updated at various time intervals	Mining claim

Sources range from local (i.e. county) to national-level datasets.

3.3. Example: quantifying monitoring indicators for the GRYN

The GRYN created a hierarchical classification system of LULC indicators (Table 2) and decided to quantify indicators to the finest levels in the hierarchy. The network reviewed existing LULC mapping efforts that included the entire study area, including MODIS and the National Land Cover Dataset. Although these maps may be adequate for quantifying indicators at Levels I or II, they were not sufficient for quantifying the Level III and IV land cover indicators identified for monitoring. The network instead chose to employ previously established methods to create their own maps using unclassified remote sensing data. Methodology using images acquired by sensors onboard Landsat, outlined by Parmenter et al. (2003) and Powell et al. (in press), was incorporated into monitoring protocols. These methods use a combination of aerial photo interpretation, satellite imagery classification, and change detection techniques to compare characteristics of LULC over time. The multispectral, medium-resolution data acquired by Landsat were appropriate for quantifying most of the potential indicators, while financial and logistical issues related to data acquisition, processing, and storage were also acceptable. Hyperspectral and high-resolution data were not considered because of the substantial financial costs of image acquisition, complex methodologies for data processing, and data volume issues related to the large extent of the study area.

Satellite sensors could not adequately measure many of the indicators specific to land use, so ancillary data sources were considered for those classes. Existing methods and data sources were evaluated for quantifying urban, rural residential, and agricultural land use classes, as well as classes of roads (Table 2). The GRYN incorporated methods established by Gude et al. (2006) which outlined the use of county tax assessor data for quantifying home densities in rural areas. Additionally, data collected by the US Census Bureau national decennial census provides information on the location of urban areas and roads. Finally, data provided by the US Department of Agriculture Census of Agriculture were included to quantify agricultural classes at the county level.

4. Analyzing and interpreting monitoring data

A key challenge in any monitoring program is to produce results that are useful to decision-makers (Kurtz et al., 2001). Analysis of monitoring data should quantify trends over time in the status of park resources impacted by LULC change, and provide information for evaluating the success of past management (Bricker & Ruggiero, 1998). Calculating metrics such as the extent and spatial configuration of LULC can quantify the intensity and direction of change over time. Additionally, LULC data can be combined with spatially-referenced data measuring ecological response variables that represent important park resources to investigate spatial patterns. Ecological response data not collected during LULC monitoring, such as animal home range or habitat suitability maps, may be acquired through collaboration with other researchers within or outside of the I&M. Integrated maps of monitoring and response data created over time will allow for analyses of LULC change from past to present, and can be used to project trends into the future to provide knowledge about potential LULC scenarios and ecological impacts.

4.1. Calculating landscape metrics

Both the composition and spatial pattern of LULC across a landscape can influence ecological processes. Turner et al. (2001) provide a review of methods for quantifying and analyzing landscape pattern. Metrics describing landscape composition include the area and relative abundance of each class, and the number and diversity of classes present. Metrics describing spatial pattern include size and shape, amount of edge, adjacency, and contagion of patches. Specific management questions should dictate which landscape metrics are included in analyses, as each metric will provide different information about LULC change. Li and Wu (2004) discuss how to avoid potential misapplication of landscape metrics. Existing software packages, such as r.le (Baker & Cai, 1992), RULE (Gardner, 1999), FRAGSTATS (McGarigal et al., 2002), and Patch Analyst (Rempel, 2008) facilitate the calculation of these metrics. For some portions of the US, LULC metrics have already been calculated using data from the National Land Cover Dataset, and can be acquired for use in monitoring (Riitters et al., 2000).

4.2. Adding value to monitoring data

Ecological relationships depicted in conceptual models can identify response variables of high park priority that are most threatened by LULC change. Analyses of monitoring data can provide information to help parks manage these response variables. Integration of LULC monitoring data with data representing response variables may measure the threats associated with LULC change, and quantify how these threats may be changing over time. Data representing response variables that are not collected during LULC monitoring may be acquired directly from other research or monitoring projects. The structure of the I&M Program, with simultaneous monitoring projects ongoing for various park resources, offers tremendous opportunity for collaboration and data-sharing within the program. When data on a specific response variable do not exist, a surrogate response, such as habitat suitability, may sometimes be derived from LULC data using knowledge about the particular ecological attributes of that variable. These data may include the distribution of preferred cover types (e.g. plant species or successional stage), abundance of certain food resources, density of human population, or occurrence of natural disturbance (Verner et al., 1986; see Mladenoff et al. (1995) for an example using wolves). Validation of integrated products is essential for identifying their strengths and limitations for management.

4.3. Assessing trends and predicting change

Analyzing LULC monitoring data, and response variable data when available, from past to present can track change over time in the status and condition of park resources. Rates of change derived from past and current trends can be used to estimate parameters for computer simulation models that forecast future conditions. Variation in these parameter estimates can be used to generate several alternative plausible LULC scenarios that will illustrate the possible intensity and direction of LULC change. Shenk and Franklin (2001), Starfield and Bleloch (1991), and Stephenne and Lambin (2001) review the types of simulation models used for landscape analysis, and discuss applications and data needs. It is essential that model validation and estimates of uncertainty accompany any simulation efforts.

Integration of data depicting response variables with data on possible future LULC scenarios can identify areas or resources that are threatened by predicted future LULC change, and allow for early mitigation, resource planning, or cooperative management with other stakeholders. Additionally, simulation models can be used to evaluate the potential effectiveness of alternative management plans, and validate (and revise, when needed) conceptual models describing important relationships between land use and park resources.

4.4. Example: analyzing and interpreting data for the GRYN

The GRYN has not yet initiated LULC monitoring, so here we draw upon previous research conducted in the GYE to illustrate methods for analyzing GRYN monitoring data collected in the future. Over the past few decades the area in urban land uses has increased almost 350% while other cover types, such as agriculture, declined in area (Parmenter et al., 2003). Therefore, we focus on residential development for this discussion of methods for analyzing LULC data. The following examples are centered on the use of ancillary monitoring data because residential development is best quantified with these types of data. However, monitoring data derived from remotely sensed sources can also be used in analysis and interpretation when the LULC changes of interest are best represented with these types of data (e.g. forest fragmentation or forest expansion).

Data representing attributes of LULC can be integrated with ecological response data to quantify past and current trends. Using ancillary data acquired from county tax assessor offices, Gude et al. (2006) created historical maps of rural residential development in the GYE from 1980 to 2000. They used these maps to investigate the potential impacts of development on important ecological response variables over time (Gude et al., 2007). Maps of rural homes were overlaid with maps depicting twelve ecological response variables, including the current ranges of four wildlife species of concern, the distribution of four land cover types, and the occurrence of four different indices of biodiversity (Table 4). They reported that the percent area of currently occupied habitat (representing the geographical distribution of response variables) that is impacted by homes has at least doubled for most variables since 1980 (Table 4).

We conducted further analysis using the rural homes data collected by Gude et al. (2006) to illustrate the assessment of trends in landscape metrics over a longer time period. Maps of rural home density within the GYE were integrated with maps of bird hotspots, identified as areas of highest bird abundance and diversity. Maps of rural homes were created for each decade from 1950 to 2000, with each public land survey section (i.e. 1 mile^2; 2.59 km^2) coded as having at least one home or having zero homes. Sections with 16 or more homes (the lower limit of the widely used definition of exurban (Hansen et al., 2005)) were buffered by an additional section on all sides to represent the extended ecological impacts of higher densities

Table 4
The percent of area impacted by exurban development for each of twelve ecological response variables.

			Growth scenario			Growth management type	
			Status quo	Low	Boom	Moderate	Aggressive
Response	1980	1999	2020*	2020	2020	2020	2020
Pronghorn (*Antilocapra americana*) range	2.00%	3.35%	5.83%	5.05%	7.58%	6.06%	4.73%
Moose (*Alces alces*) range	2.73%	5.49%	7.96%	6.83%	11.11%	7.24%	6.26%
Grasslands	2.99%	5.57%	8.36%	7.02%	11.97%	8.01%	6.87%
Grizzly bear range	3.13%	5.98%	8.52%	7.68%	10.70%	7.74%	6.88%
Douglas-fir	2.91%	6.01%	8.85%	7.07%	13.31%	7.82%	7.09%
Elk (*Cervus elaphus*) winter range	2.36%	6.26%	9.98%	8.61%	13.47%	9.00%	7.23%
Aspen	5.55%	13.92%	19.53%	15.58%	28.39%	18.74%	17.60%
Bird Hotspots	8.42%	16.91%	23.20%	19.23%	34.36%	21.04%	20.23%
Riparian Habitat	10.22%	17.30%	23.64%	19.43%	31.27%	22.45%	18.77%
Potential corridors	8.89%	18.79%	24.43%	20.83%	35.38%	22.96%	21.80%
Irreplaceable areas[1]	11.41%	23.15%	29.61%	25.69%	40.08%	30.88%	26.92%
Integrated index[2]	11.80%	23.24%	29.93%	25.84%	40.66%	29.28%	26.43%

The impacts of exurban development were assumed to extend into one neighboring section (1.61 km). Table adapted from Gude et al. (2007).
*Responses are ranked by the proportion impacted in the Status Quo 2020 scenario; [1] Multicriteria assessment based on habitat and population data for GYE species (Noss et al., 2002); [2] Top 25% of lands important to the four responses most impacted by development under the Status Quo 2020 scenario, including bird hotspots, riparian habitat, potential corridors, and irreplaceable areas.

of rural homes. Existing bird hotspot maps were acquired for the analysis. Hansen et al. (2004) had previously developed models describing relationships between bird richness and abundance (as calculated from US Geological Survey Breeding Bird Survey data) and topography, climate, and vegetation composition and productivity to predict bird hotspots across the GYE. We quantified, using landscape metrics, how land use had changed the extent and distribution of hotspot habitat over time.

The total area of hotspot habitat that is not impacted by homes declined by 22% over the 50 year time period. Mean patch area of unimpacted hotspots declined by 24%, while mean core area of patches declined 26%. Finally, the distance to the nearest unimpacted hotspot neighbor patch increased 3.5%. Based on these landscape metrics, it seems rural home development has substantially changed the extent and configuration of unimpacted bird hotspots in the GYE. Hotspots have become more fragmented, with smaller patch sizes and less core habitat area. Analyses that measure how land use activities change the extent and spatial configuration of habitat can help to identify the ecological mechanisms through which land use may be impacting park resources, such as bird species, and provide information for mitigating those negative impacts.

Gude et al. (2007) used past and current trends of rural home development to simulate potential scenarios in the GYE twenty years into the future. They then quantified the possible impacts of future land use change on ecological response variables. Rates of home development and management policies were manipulated to simulate five plausible scenarios of rural home development for the year 2020, ranging from low growth, to status quo (current rates of growth continue), to booming growth, and included two scenarios depicting development under growth management (Table 4). The five resulting maps depicted potential future land use scenarios, and were integrated with each of the twelve maps delineating the current distribution of ecological response variables previously used for historical analyses (Table 4). Percent area of currently occupied habitat impacted by rural homes varied, with five of the responses, including bird hotspots (Fig. 5), riparian habitat, potential corridors,

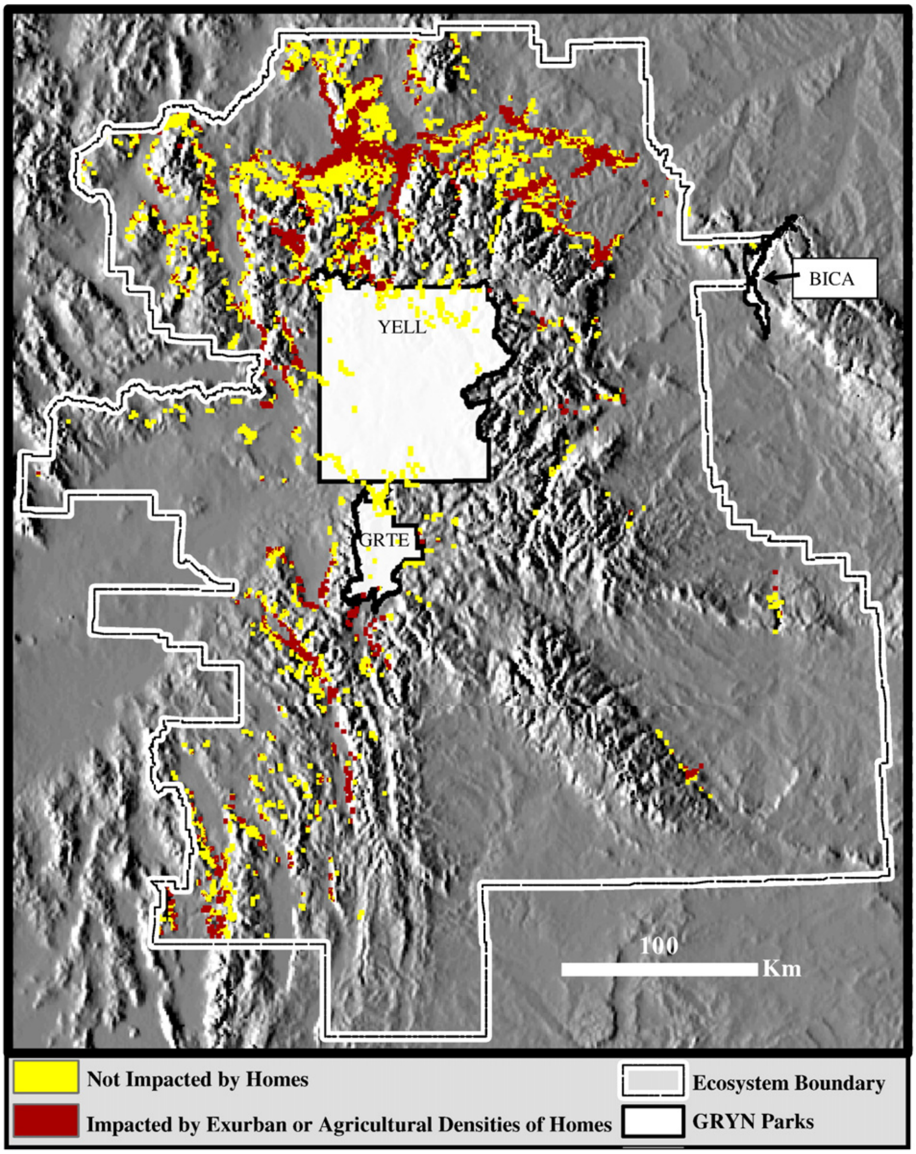

Fig. 5. Simulated impacts of rural home development on bird hotspots around parks of the Greater Yellowstone Network (GRYN) in 2020 based on the Status Quo scenario of growth. The boundary of the Greater Yellowstone Ecosystem, which encompasses only Yellowstone (YELL) and Grand Teton (GRTE) National Parks, was used for this simulation. For future monitoring in the GRYN, the ecosystem boundary will be expanded to also encompass Bighorn Canyon National Recreation Area (BICA). Red depicts bird hotspots which are impacted by exurban (>15 homes/miles^2) and agricultural (1–15 homes/miles^2) densities of rural homes. Yellow depicts hotspots that are not impacted by rural homes. Areas that are not red or yellow are not bird hotspots.

irreplaceable areas, and integrated biodiversity index, forecasted to experience degradation in at least 20% of their area under the status quo, and 30 to 40% under the boom scenario (Table 4). Early warning of the vulnerability of these ecological response variables to land use changes may help managers to develop strategies for mitigating future effects.

Hansen and Rotella (2002) demonstrated how rural residential development may impact a particular ecological response variable in the GYE, the Yellow Warbler (*Dendroica petechia*). They reported that low elevation habitats on private lands provide a longer breeding season and more nesting opportunities for warblers compared with higher elevation protected areas, where harsher abiotic conditions may limit bird productivity. Consequently, private lands likely have historically served as source areas (birth rates exceed mortality rates) for nearby natural sink populations (mortality exceeds birth) within park borders. However, they found that reproductive rates in low elevation lands were below the threshold needed to maintain populations due to higher rates of nest predation and parasitism, so that these historically productive lands are population sinks instead of sources. This may result in an increased risk of extinction for sink populations at higher elevations within park borders. Analyses which evaluate the status of populations in the context of surrounding land use can provide an understanding of the impacts that LULC change outside of parks can have on park populations. Consequently, managers can look for opportunities to protect source areas threatened by LULC change and mitigate effects for park species.

5. Conclusion

LULC change in regions surrounding parks may substantially influence park natural resources. Parks are often parts of larger ecosystems, and in many cases land use is rapidly intensifying in the unprotected portions of these ecosystems. Monitoring LULC across these larger ecosystems provides a basis for quantifying and anticipating changes that may have undesirable impacts on natural resources within parks. Fortunately, new technologies and data sets are available which allow for increasingly advanced, yet cost effective, monitoring of LULC change. Analyses which integrate LULC maps with maps depicting important park resources can be especially useful for identifying resources threatened by changes in land use. The I&M Program offers a unique opportunity for collaboration among monitoring studies within and across networks to facilitate this integration. For example, data collected for monitoring amphibian populations or water quality may be integrated with LULC monitoring data to understand current and potential future management concerns for these resources.

The examples from the GRYN illustrate the overall approach for monitoring LULC. We reviewed how the GRYN used conceptual models to identify monitoring indicators of LULC and determined appropriate data sources and methods for quantifying those indicators. Additionally, we provided examples of how monitoring data collected by the GRYN in the future can be analyzed. Results from these types of analyses can directly contribute to management of resources within parks, as well as the conservation of vulnerable resources within the larger ecosystem outside of park boundaries. For example, results from the biodiversity analyses conducted by Gude et al. (2007) were distributed to county planners and land trust organizations within the GYE to guide land use planning and identify for conservation the private lands that are most important to retaining biodiversity within Yellowstone and Grand Teton National Parks. As monitoring progresses within the network, this framework can be used in an adaptive context to increase the effectiveness of current and future management decisions.

Many networks within the I&M Program are now, or will be in the near future, developing protocols for monitoring LULC change. We hope this paper provides guidance for these protocols and enhances consistency in monitoring efforts across networks of parks. Additionally, the framework we have outlined can be applied to monitoring in protected areas in general, not only national parks. When data and methods are standardized across parks and other protected areas, monitoring can help to identify broad scale trends in LULC change, and can contribute to the mitigation of negative ecological impacts.

Acknowledgements

We thank those within the Greater Yellowstone Network and Heartlands Network Inventory and Monitoring Programs for funding and helpful suggestions, especially Robert Bennetts, Cathie Jean, and Brent Frakes. We thank John Gross, Robert Bennetts, Cathie Jean, and three anonymous reviewers for insightful manuscript comments. We also thank the editors of this special issue of Remote Sensing of the Environment.

References

Anderson, J. R., Hardy, E. E., Roach, J. T., & Witmer, R. E. (1976). A land use and land cover classification system for use with remote sensor data. Geological Survey Professional Paper 964, US Department of Interior, Geological Survey. Washington, DC.

Aspinall, R. (2002). Use of logistic regression for validation of maps of the spatial distribution of vegetation species derived from high spatial resolution hyperspectral remotely sensed data. *Ecological Modelling*, *157*, 301−312.

Baker, W. L., & Cai, Y. (1992). The r.le programs for multiscale analysis of landscape structure using the GRASS Geographic Information System. *Landscape Ecology*, *7*, 291−302.

Bricker, O. P., & Ruggiero, M. A. (1998). Toward a national program for monitoring environmental resources. *Ecological Applications*, *8*, 326−329.

Congalton, R. G. (1991). A review of assessing the accuracy of classifications of remotely sensed data. *Remote Sensing of Environment*, *37*, 35−46.

Congalton, R. G., & Green, K. (1999). *Assessing the Accuracy of Remotely Sensed Data: Principles and Practices.* Boca Raton: Lewis Publishers.

Craighead, J. J. (1991). Yellowstone in transition. In R. B. Kieter & M. S. Boyce (Eds.), *The Greater Yellowstone Ecosystem: Redefining America's Wilderness Heritage* (pp. 27−40). New Haven: Yale University Press.

DeFries, R., Rovero, F., Wright, P., Ahumada, J., Andelman, S., Brandon, K., Dempewolf, J., Hansen, A., Hewson, J., & Liu, J. (in press). Linking plot-level bodiversity measurements with human influences over multiple spatial scales in the tropics: a conceptual framework. *Frontiers in Ecology and the Environment.*

Failing, L., & Gregory, R. (2003). Ten common mistakes in designing biodiversity indicators for forest policy. *Journal of Environmental Management*, *68*, 121−132.

Fancy, S. G., Gross, J. E., & Carter, S. L. (2009). Monitoring the condition of natural resources in US National Parks. *Environmental Monitoring and Assessment*, *151*, 161−174.

Gardner, R. H. (1999). RULE: a Program for the generation of random maps and the analysis of spatial patterns. In J. M. Klopatek & R. H. Gardner (Eds.), *Landscape Ecological Analysis: Issues and Applications* (pp. 280−303). New York: Springer-Verlag.

Gianinetto, M., & Lechi, G. (2004). The development of superspectral approaches for the improvement of land cover classification. *IEEE Transactions on Geoscience and Remote Sensing*, *42*, 2670−2679.

Grumbine, R. E. (1994). What is ecosystem management? *Conservation Biology*, *8*, 27−38.

Gude, P. H., Hansen, A. J., & Jones, D. A. (2007). Biodiversity consequences of alternative future land use scenarios in the Greater Yellowstone. *Ecological Applications*, *17*, 1004−1018.

Gude, P. H., Hansen, A. J., Rasker, R., & Maxwell, B. (2006). Rates and drivers of rural residential development in the Greater Yellowstone. *Landscape and Urban Planning*, *77*, 131−151.

Hansen, A. J., & DeFries, R. (2007). Ecological mechanisms linking nature reserves to surrounding lands: a conceptual framework for assessing implications of land use change. *Ecological Applications*, *17*, 974−988.

Hansen, A. J., DeFries, R., & Turner, W. (2004). Land use change and biodiversity: a synthesis of rates and consequences during the period of satellite imagery. In G. Gutman & C. Justice (Eds.), *Land Change Science: Observing, Monitoring, and Understanding Trajectories of Change on the Earth's Surface* (pp. 277−299). New York: Springer-Verlag.

Hansen, A. J., Knight, R., Marzluff, J., Powell, S., Brown, K., Hernandez, P., et al. (2005). Effects of exurban development on biodiversity: patterns, mechanisms, research needs. *Ecological Applications*, *15*, 1893−1905.

Hansen, A. J., & Rotella, J. J. (2002). Biophysical factors, land use, and species viability in and around nature reserves. *Conservation Biology*, *16*, 1112−1122.

Homer, C., Dewitz, J., Fry, J., Coan, M., Hossain, N., Larson, C., et al. (2007). Completion of the 2001 National Land Cover Database for the conterminous United States. *Photogrammetric Engineering and Remote Sensing*, *73*, 337−341.

Homer, C., Huang, C., Yang, L., Wylie, B., & Coan, M. (2004). Development of a 2001 National Land-Cover Database for the United States. *Photogrammetric Engineering and Remote Sensing*, *70*, 829−840.

Kurtz, J. C., Jackson, L. E., & Fisher, W. S. (2001). Strategies for evaluating indicators based on guidelines from the Environmental Protection Agency's Office of Research and Development. *Ecological Indicators*, *1*, 49−60.

LANDFIRE (2007). Homepage of the LANDFIRE Project, US Department of Agriculture, Forest Service and US Department of Interior. http://www.landfire.gov

Li, H., & Wu, J. (2004). Use and misuse of landscape indices. *Landscape Ecology*, *19*, 389−399.

Liu, J., Dietz, T., & Carpenter, S. (2007). Complexity of coupled human and natural systems. *Science*, *317*, 1513−1516.

Liu, C. R., Frazier, P., & Kumar, L. (2007). Comparative assessment of the measures of thematic classification accuracy. *Remote Sensing of Environment*, *107*, 606−616.

Lookingbill, T. R., Gardner, R. H., Townsend, P. A., & Carter, S. L. (2007). Conceptual models as hypotheses in monitoring urban landscapes. *Environmental Management*, *40*, 171−182.

Lu, D., Mausel, P., Brondizio, E., & Moran, E. (2004). Change detection techniques. *International Journal of Remote Sensing*, *25*, 2365−2407.

McGarigal, K., Cushman, S. A., Neel, M. C., & Ene, E. (2002). FRAGSTATS: Spatial Analysis Program for Categorical Maps. University of Massachusets, Amherst. http://www.umass.edu/landeco/research/fragstats/fragstats.html

Michener, W. K., Baerwald, T. J., Firth, P., Palmer, M. A., Rosenberger, J. L., Sandlin, E. A., et al. (2001). Defining and unraveling biocomplexity. *BioScience*, *51*, 1018−1023.

Mladenoff, D. J., Sickley, T. A., Haight, R. G., & Wydeven, A. P. (1995). A regional landscape analysis and prediction of favorable gray wolf habitat in the northern Great Lakes region. *Conservation Biology*, *9*, 279−294.

National Aeronautics and Space Administration (2005). *MODIS Web: Data Products.* http://modis.gsfc.nasa.gov/data/

National Park Service (NPS) (2006). *Glossary of Terms Used by the NPS Inventory and Monitoring Program.* http://science.nature.nps.gov/im/monitor/glossary.cfm

Newmark, W. D. (1985). Legal and biotic boundaries of western North America national parks: a problem of congruence. *Biological Conservation*, *33*, 197−208.

Noss, R. F., Carroll, C., Vance-Borland, K., & Wuerthner, G. (2002). A multicriteria assessment of the irreplaceability and vulnerability of sites in the Greater Yellowstone Ecosystem. *Conservation Biology*, *16*, 895−908.

Parmenter, A., Hansen, A., Kennedy, R., Cohen, W., Langner, U., Lawrence, R., et al. (2003). Land use and land cover change in the Greater Yellowstone Ecosystem: 1975–1995. *Ecological Applications*, *13*, 687−703.

Powell, S. L., Hansen, A. J., & Cohen, W. B. (in press). Mapping the extent and distribution of conifer cover increase in the Greater Yellowstone Ecosystem. In A. Dupont & H. Jacobs (Eds.), *Landscape Ecology Research Trends. Hauppauge*, New York: Nova Science Publishers, Inc.

Pringle, C. M. (2000). Threats to US public lands from cumulative hydrologic alterations outside of their boundaries. *Ecological Applications*, *10*, 871−989.

Rasker, R. (1991). Dynamic economy versus static policy in the Greater Yellowstone Ecosystem. *Proceedings to the Conference on the Economic Value of Wilderness, Jackson, Wyoming.*

Rasker, R., & Hansen, A. J. (2000). Natural amenities and population growth in the Greater Yellowstone region. *Human Ecology Review*, *7*, 406−433.

Rempel, R. (2008, January 17). *Patch Analyst 4. Centre for Northern Forest Ecosystem Research (Ontario Ministry of Natural Resources).*Thunder Bay, Ontario: Lakehead University Campus http://flash.lakeheadu.ca/~rrempel/patch/index.html

Riitters, K. H., Wickham, J. D., Vogelmann, J. E., & Jones, K. B. (2000). National land-cover pattern data. *Ecology*, *81*, 604.

Rogan, J., & Chen, D. M. (2004). Remote sensing technology for mapping and monitoring land-cover and land-use change. *Progress in Planning*, *61*, 301−325.

Salwasser, H., Schonewald-Cox, C., & Baker, R. (1987). The role of interagency cooperation in managing for viable populations. In M. E. Soule (Ed.), *Viable Populations* (pp. 147−173). New York: Cambridge University Press.

Schonewald-Cox, C. M., & Bayless, J. W. (1986). The boundary model: a geographical analysis of design and conservation of nature reserves. *Biological Conservation*, *38*, 305−322.

Schullery, P. (1997). *Searching for Yellowstone: Ecology and Wonder in the Last Wilderness.* Boston: Houghton Mifflin Company.

Sellars, R. W. (1997). *Preserving Nature in the National Parks: A History.* Ann Arbor: Edwards Brothers, Inc.

Shenk, T. M., & Franklin, A. B. (2001). *Modeling in Natural Resource Management.* Washington, DC: Island Press.

Starfield, A. M., & Bleloch, A. L. (1991). *Building Models for Conservation and Wildlife Management.* Edina: Burgess International Group.

Stehman, S. V., & Czaplewski, R. L. (1998). Design and analysis for thematic map accuracy assessment: fundamental principles. *Remote Sensing of Environment*, *64*, 331−344.

Stephenne, N., & Lambin, E. F. (2001). A dynamic simulation model of land-use changes in the African Sahel (SALU). *Agriculture Ecosystems and Environment*, *85*, 145−162.

Theberge, J. B. (1989). Guidelines to drawing ecologically sound boundaries for national parks and nature reserves. *Environmental Management*, *13*, 695−702.

Thenkabail, P. S., Enclona, E. A., Ashton, M. S., & Van Der Meer, B. (2004). Accuracy assessments of hyperspectral waveband performance for vegetation analysis applications. *Remote Sensing and Environment*, *91*, 354−376.

Turner, M. G., Gardner, R. H., & O'Neill, R. V. (2001). *Landscape Ecology in Theory and Practice: Pattern and Process.* New York: Springer-Verlag.

US General Accounting Office (1994). National Park Service: activities outside park borders have caused damage to resources and will likely cause more. *GAO/RCED-94-59* Washington, DC: US General Accounting Office.

US Geological Survey (2005). *MRLC Consortium.* http://www.mrlc.gov/

Verner, J., Morrison, M. L., & Ralph, C. J. (1986). *Wildlife 2000: Modeling Habitat Relationships of Terrestrial Vertebrates.* Madison: The University of Wisconsin Press.

Vogelmann, J. E., Howard, S. M., Larson, C. R., Wylie, B. K., & Van Driel, N. (2001). Completion of the 1990s National Land Cover Data Set for the conterminous United States from Landsat Thematic Mapper data and ancillary data sources. *Photogrammetric Engineering and Remote Sensing*, *67*, 650−662.

Wittemyer, G., Elsen, P., Bean, W. T., Coleman, A., Burton, O., & Brashares, J. S. (2008). Accelerated human population growth at protected area edges. *Science*, *321*, 123−126.