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Review

Remote sensing change detection for ecological monitoring in United States protected areas

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ABSTRACT

Remote sensing allows for cost- and time-efficient monitoring of landscapes vital to the conservation of natural resources, ecosystems, and biodiversity. This review synthesizes and recommends best practice change detection methods for land management groups to monitor chief ecological change indicators currently monitored in United States protected areas. The indicators frequently monitored via change detection and reviewed here include: land use/land cover, disturbance, and phenology. Landsat data products are recommended for monitoring land use/land cover and disturbance, due to their continuous data accessibility free of cost since 1972. Data from the Moderate Resolution Imaging Spectrometer (MODIS) are recommended for monitoring changes in phenology due to its 1–2 day return interval at any given location. Best-practice remote sensing methods are stressed, such as careful validation of results, either by combination of remotely sensed datasets with high resolution imagery or *in situ* data, in order to increase accuracy and to better align the remotely sensed data to the scale of the on-the-ground processes. Reported results should always be presented with utmost clarity in a manner that is both applicable to managers and understood by the general public. Increased collaborations between ecologists, land managers, conservation groups, and scientists are compulsory for successful integration of remote sensing-based monitoring, which is vital for effective conservation in protected areas. Remote sensing change detection quantifies the effects of humans on a landscape scale without creating further disturbances to ecologically sensitive areas; the results of which can be used for efficient conservation management into the future.

Contents

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1. Introduction

Monitoring ecological processes is essential to understanding and protecting the natural environs and to preserving biodiversity. Remote sensing change detection methods improve conservation abilities by monitoring changes in ecological status, and can assess the effectiveness of management without further disturbing the landscape (Cook and Hockings, 2011; Franklin et al., 2002; Lindenmayer and Likens, 2010; Miller and Rogan, 2007; Pettorelli et al., 2014; Rogan et al., 2002; Sergeant et al., 2012). However, there is often a gap between remote sensing science and the real world needs of conservation resource managers in decreed protected areas (Wiens, 2002). Managers and ground monitoring personnel do not always have remote sensing training or access to the imagery and analytic software necessary to develop and maintain a landscape monitoring database (Laurance et al., 2012). The following sections provide a best-practice model summary of current change detection methods effective for land managers who wish to incorporate remote sensing into a landscape monitoring plan.

Monitoring at a landscape scale gives a broad perspective on the pattern of changes occurring throughout the entire conservation area and allows for a future downscaled focus to cause (Kennedy et al., 2009). The drivers of change are often identified by choosing an ecosystem indicator, or an ecological mechanism that represents and quantifies the impacts on natural resources (Crabtree et al., 2009; Kurtz et al., 2001). Ecosystem indicators are "a subset of monitoring attributes that are important because they are indicative of quality, health, or integrity of the larger ecological system to which they belong," (Jones et al., 2009) and are often standardized (e.g. the National Land Cover Dataset, digital elevation models, digital maps, soil maps, climate data sets; Crabtree et al., 2009). An example is the use of "vital sign" measures, which are used by the National Park Service and include indicators such as fire occurrence and intensity, land use pattern change, habitat type conversion, or detection of non-native invasive species (Cameron et al., 2006).

Remote sensing is applicable to ecological indicators since it can be applied at a variety of spatial and temporal scales, and is an efficient, unbiased, non-invasive, quantitative method useful for ecological monitoring (Cook and Hockings, 2011; Crabtree et al., 2009; Franklin et al., 2000; Kennedy et al., 2009; Miller and Rogan, 2007; Nemani et al., 2009; Rogan et al., 2002; Townsend et al., 2009; Wiens et al., 2009). There are tradeoffs between using the highest spatial resolution possible in order to correctly inventory ecological indicators while balancing an appropriate continuous temporal resolution and minimizing cost (Nemani et al., 2009). Common issues specific to remotely sensing methodologies are associated with: data availability and cost (Wang et al., 2009; Wiens et al., 2009), atmospheric contamination from sources such as haze, clouds, and shadows (Kerr and Ostrovsky, 2003; Nagendra et al., 2013), errors in the sensor (Wang et al., 2012), and differences in temporal/spatial scale in need of monitoring versus the scale of sensor data available (Spanhove et al., 2012).

The need for accurate monitoring is a pressing matter, given the current debate on "new conservation," changing conceptions of wilderness, and the ideas of sustainability alongside increasing human influence in the biosphere (Nash, 2014; Soulé, 2013). The viewpoints surrounding protected areas have been in constant flux since Muir and Pinchot first debated the ideas of "conservation" versus "preservation" of natural lands (MacDonald, 2014; Philippon, 2005). Nevertheless, conservation of natural landscapes is vital to preserving biodiversity regardless of the ideology driving ecological management (i.e. according to managerial, ecological, or heroic values; Kerasote, 2001; Soulé, 2013). The focus of debates such as "parks vs. people" and "new conservation" on social justice and ecological sustainability highlights the degree to which humans are intertwined with the natural environment. These new understandings surrounding societal involvement with conservation demonstrate the need for remote ecological monitoring, especially with increasing human pressure on natural landscapes. We need to monitor protected lands in order to understand the varying types of interactions and the scales at which they occur. In turn, effective monitoring policies may even aid in melding together these various ideologies surrounding protected areas for ultimately more effective conservation results (Miller et al., 2011).

This methodological review has three primary objectives: To provide an account of (1) remote sensing ecological monitoring change detection methods used by land management groups, (2) applications of change detection to conservation in the United States using recent case studies, and (3) recommendations for the most effective use of these current methodologies. First, common change detection methods encountered in the field of remote sensing are reviewed. Then recent advances in United States conservation-based land management groups are addressed relating specifically to changes in land use and land cover, ecological disturbance, and phenology. Finally, suggestions are provided regarding improved correspondence between research organizations and the benefits of standardized methods for conservation programs.

2. Terminology

Landscape dynamics monitoring is often identified as a priority by conservation managers. Thus, change detection techniques are the focus of this paper. However, remote sensing is currently used in many monitoring applications other than change-based methods, such as fragmentation and connectivity of habitat (Gottschalk et al., 2005), landscape permeability (Theobald et al., 2011, 2012), and studies focusing on individual species (Gottschalk et al., 2005; Kerr and Ostrovsky, 2003; Ohse et al., 2009). Change detection is the procedure used to identify differences in the state of an object or phenomenon by observing it at different times (Singh, 1989). In monitoring protected areas, this method is often used to monitor "landscape dynamics," or changes in area and distribution of ecological systems (Wang and Zhou, 2008). Change detection methods identify variations from the normal spectra of pixels from remotely sensed data to detect areas undergoing rapid changes such as from land use and land cover (Coppin et al., 2004; Defries et al., 2000; Friedl et al., 2002; Kennedy et al., 2009; Lu et al., 2004; Rogan et al., 2002; Singh, 1989) or disturbance (Cohen et al., 2010; Huang et al., 2009; Kennedy et al., 2009; Nagendra et al., 2013; Nemani et al., 2008).

3. Methods

The majority of literature reviewed included both peer-reviewed journal articles and ecological reports produced by conservation and land management groups in the United States which utilize remote sensing-based change detection for ecological monitoring. Searches for these studies and reports were conducted through online databases using search terms such as: "remote sensing; conservation; management; protected areas; ecological monitoring; change detection; phenology; land use; land cover; ecological disturbance." Studies were reviewed referring to analysis of digital imagery collected from space borne sensors (i.e. not including flyovers, photography, or *in situ* cameras), and focused on change detection methods, thus does not include ecological monitoring studies regarding habitat connectivity and fragmentation. Habitat studies and the field of landscape ecology are also essential to conservation of protected areas, yet utilize methodologies of fragmentation metrics or proxies, rather than change detection (Goetz et al., 2009, 2011; McGarigal et al., 2002; Theobald, 2010; Turner, 1989; Wiens et al., 2009).

Protected areas in the US represent more than 27% of the land area as well as 10% of global protected landscapes (Chape, 2003; Gergely and McKerrow, 2013). Change detection studies focused in the United States are reviewed here due to the increase in focus of US land management groups on the implementation of change detection monitoring programs, and the relatively wide availability of remotely sensed and GIS data (Antonova et al., 2010; Gergely and McKerrow, 2013; Goetz et al., 2011; Goetz and Fiske, 2009; Huettmann, 2005; Kennedy et al., 2007, 2010a; Kirschbaum and Gafbert, 2010; Reed et al., 2006; Theobald, 2009; Thomas et al., 2011; Townsend et al., 2006). The land management stakeholders of focus in this paper exclude those in the private sector, since results are often difficult to access, may be unpublished, or are applied to regions outside of the US. Some of these groups, such as the Nature Conservancy (TNC), also base their management efforts on data collected from species inventories rather than remote sensing methods to determine threats such as development and disturbance (Wiens et al., 2009).

4. Satellite imagery review

Landsat products, including the Thematic Mapper (TM), Enhanced Thematic Mapper Plus (ETM+), and Operational Land Imager (OLI), have ideal sampling characteristics for monitoring diverse land cover types at a regional and historic level (Cohen and Goward, 2004; Kennedy et al., 2010b; Miller and Rogan, 2007; Rogan and Chen, 2004). The 30 m spatial resolution of Landsat sensors allows for spatial detail to be captured at a scale appropriate for monitoring vegetation structure and composition. General changes in land cover classes are also detectable through Landsat, such as conversion between agricultural land and water resources (i.e. in Nevada/Utah; USGS, 2012). The Landsat Data Continuity Mission (LDCM), with OLI sensor may be used for current monitoring purposes since its launch in early 2013. Either automated or binary change detection using Landsat imagery is common for monitoring ecosystems. Associated methods are rapidly evolving due to free access to data, increased automated algorithms, and detailed information becoming available over large geographical swaths (Cohen et al., 2010).

Managers of some protected areas find high spatial resolution data optimal, such as the use of QuickBird in the US Fish and Wildlife Service Desert National Wildlife Refuge (USGS, 2012). Other space borne sensors used for land use/land cover change by protected areas in the US include IKONOS/Geoeye, Advanced Land Observing Satellite (ALOS), Earth Observing Mission 1 (EO-1), Advanced Land Imager (ALI), and Advanced Spaceborne Thermal Emission and Reflection Radiometer (ASTER) (Wiens et al., 2009). Landsat is highlighted in this review since many other sensors do not offer freely available data, and a cost-benefit analysis must often be run before considering the utilization of these generally higher resolution satellites (i.e. Table 1). Different satellites ensure that varying scales of vegetation can be studied; Landsat is useful for vegetation communities, whereas SPOT or QuickBird may be used for species- or genera-specific vegetation change monitoring. For example, the Bureau of Land Management uses high-resolution aerial imagery along with QuickBird to monitor changes in sensitive ecosystems such as upland, riparian, and aquatic habitat in Oregon and Wyoming (USGS, 2012).

5. Change detection methods and requirements

Prior to change detection, delineation of study area and the choice of appropriate spatial and temporal resolution provide the basis for a sound change detection study (Kennedy et al., 2009; Townsend et al., 2009). Delineation of study area should consider the inclusion of buffer zones either adjacent to or within the borders of protected boundaries to account for outside ecological influences (Gross et al., 2009; Hansen and DeFries, 2007; Jones et al., 2009; Svancara et al., 2009). The Protected Area Centered Ecosystems (PACE) framework follows this model and is considered best practice for determining study area (Hansen and Davis, 2011).

Spatial and temporal scale must match up with the phenomenon studied to ensure that changes in the remotely sensed data are representing the correct ecological process (Table 1) (Jensen, 2007; Nagendra et al., 2013; Rogan and Chen, 2004; Sergeant et al., 2012; Wiens et al., 2009). In remote sensing, spatial scale is often referred to as either coarse, medium, or fine resolution, referring to approximately 250–500 m, 30 m, and <1 m pixel size respectively. Pixel sizes for monitoring purposes usually range from ~0.5 m to 500 m. For example, a medium resolution (30 m pixel) sensor such as Landsat may be used to monitor vegetation community-type changes, yet is not appropriate to monitor species-type change. The next factor of scale which should be considered is temporal resolution; how long should the process be measured for and how often? Effective change detection should be carried out over a time period of at least 10 years (Huang et al., 2009). The temporal sampling interval will depend on the ecological application and system being monitored, but typically ranges from 1 to 16 days.

Change detection commences with image classification analysis, or the process of associating observed or vector-based land cover classes with remote sensing spectral data. When choosing datasets it is necessary to account for future data continuity and systematic improvements in remote sensing technology (Gross et al., 2009). Many standard vector-based datasets are based on a large spatial scale, and can be scaled to a finer resolution by integrating satellite-based data with high resolution satellite, aerial-based, or *in situ* data (Kerr and Ostrovsky, 2003; Nagendra et al., 2013). The chosen classification system should be applicable to a variety of land cover types to allow for comparison of land cover data, satellite data, and output change results between protected areas.

Change detection has historically been used to look at changes in land use/land cover and disturbance using binary comparisons contrasting conditions during two discrete time periods (Cohen et al., 2002; Collins and Woodcock, 1996; Coppin et al., 2004; Franklin et al., 2002; Goetz et al., 2011; Healey et al., 2005; Lu et al., 2004; Nelson, 1983; Reed et al., 2006; Townsend et al., 2006; Wiens et al., 2009), and have been reviewed in the past (Healey et al., 2005; Rogan et al., 2002; Woodcock and Ozdogan, 2004). Techniques are increasingly using automated approaches to detect multi-temporal changes over a large stack of imagery representing a number of discrete time periods (Antonova et al., 2010; García-Haro et al., 2001; Goetz et al., 2011; Goodwin et al., 2008;

Table 1
Example of a [2014] cost-benefit analysis for choosing appropriate satellite imagery.

Satellite	Background information	Spatial resolution	Nominal revisit time	2014 Base cost for archived images (per km^2)	2014 Base cost for custom images (per km^2)	Spectral resolution	Applications
MODIS	NASA product on Terra and Aqua satellite, launched 1999	250 m (bands 1–2), 500 m (bands 3–7), 1000 m (bands 8–36)	1–2 days	Free	n/a	36 Bands available at different resolutions	Phenology
Landsat TM/ETM+/OLI	NASA product since 1972	30 m	16 days	Free	n/a	7 Bands on Landsat 5, 8 bands on Landsat 7	Land use/land cover change
IKONOS	First high resolution color imaging satellite since 1999, owned by DigitalGlobe	0.80 m pan[a], 2.4 m multi[b]	3–5 days	\$10 (minimum order 25 km^2)	\$20 (minimum order 100 km^2)	Pan[a], multi[b] (4-band), natural color (3-band), color IR[c] (4-band) pan-sharpened, or pan[a] + multi[b]	Data validation
GeoEye-1	Highest resolution commercial color imagery satellite since 2008, owned by DigitalGlobe	0.46 m pan[a], 1.84 m multi[b]	<3 days	\$13–29 (minimum order 272 km^2)	\$22–38 (minimum order 100 km^2)	Pan[a] or multi[b] (4-or 8-band)	Data validation
Quickbird	Owned by DigitalGlobe, launched 2001	0.61 m pan[a], 2.4 m multi[b]	1–3.5 days	\$13–29 (minimum order 272 km^2)	\$22–38 (minimum order 100 km^2)	Pan[a] or multi[b] (4-or 8-band)	Data validation
SPOT 1-7	Launched in 1986, owned by Spot Image, France	2014: 1.5 m pan[a], 6 m multi[b]; 2002–2014: 2.5–5 m pan[a], 10 m multi[b] 1986–2002: 10 m pan[a], 20 m multi[b]	1–3 days	\$32 (minimum order 60 km^2)	\$24–72 (minimum order \$3600)	Pan[a] or multi[b] (4-band)	Data validation
ASTER	NASA product on Terra satellite, launched 1999	15 m visible near IR[c], 30 m shortwave IR[c], 90 m thermal IR[c]	16 days	\$1.50/imagery\$0.75/ DEM[d]	n/a	15 bands	Supplementary data source, DEM[d]

[a] Pan – panchromatic includes one greyscale band of combined red, green, and blue of visible electromagnetic spectrum.
[b] Multi – multispectral covers multiple bands along the electromagnetic spectrum.
[c] IR – Infrared.
[d] DEM – Digital Elevation Model.

Hansen and Davis, 2011; Healey et al., 2006; Hostert et al., 2003; Huang et al., 2010; Kennedy et al., 2007; National Park Service, 2014; Nemani et al., 2008; Viedma et al., 1997; Vogelmann et al., 2009).

Automated algorithms such as the Landsat-based Detection of Trends in Disturbance and Recovery (LandTrendr) and Vegetation Change Tracker (VCT) have expedited the process for change detection by comparing deviations in multiple images and dates (Huang et al., 2009, 2010; Kennedy et al., 2010b). Both programs can either track slow processes over time or abrupt events (Kennedy et al., 2010b), and can also detect errors or background noise inherent in data, which are predicted to increase with climate change (Hicke et al., 2006; Logan et al., 2003).

In order for any method of change detection to be effective, the appropriate pre- and post-processing calibration and validation are needed, and must also improve to keep up with the refinement in temporal scale created by automated algorithms (Rogan and Chen, 2004). Cohen et al. (2010) have begun to address this by creating an automated validation tool, TimeSync, which also can be used to output spectral changes with their biological applications.

The error inherent in the ability of remote sensing to describe on the ground processes is a trade off with its ability to assess an entire landscape. Accuracy is maximized by identifying error sources with multiple analysis runs, and then applying appropriate changes to the algorithm. Sources of error are identified via ground-based field validation and/or visual interpretation of high resolution images (Congalton, 1991; Huang et al., 2009; Stehman and Czaplewski, 1998).

Once classes are randomly tested, an accuracy assessment may be run, which validates a classification by comparing its output to input ground-truth data in a confusion matrix format. The overall accuracy is expressed as a percentage value, and for land management purposes is typically deemed acceptable if above 85% (Fitzpatrick-Lins, 1980). The percentage accuracy and numerical pixel value are reported for each land use class along with the number of misclassified pixels.

6. Change detection applications to conservation

Change detection is used as an overarching method to analyze (1) uniform conversions between land use and land cover classes; (2) irregular variations such as disturbance; and (3) continuous fluctuations such as seasonal plant cycling. Each application is first defined here, followed by a discussion of methods, and finally techniques to standardize these methodologies are suggested.

6.1. Uniform change detection: land use and land cover change

Land use and land cover change (LULCC) is a primary cause of significant recent alterations to the biosphere, and increased climate change is expected to amplify its effects in the future (Cohen et al., 2010; Lambin et al., 2001; Parmesan and Yohe, 2003). LULCC has increased globally, especially in areas surrounding protected lands (Hansen et al., 2004), which is likely to progressively impact landscapes within protected zones.

Land cover describes features covering the land such as natural vegetation, crops, buildings, and water. Land use is defined as human uses of the land such as for open space, agriculture, and residential areas. LULCC monitoring often aims to identify which areas of land are changing, the extent of change, and which class it is changing to/from (Wang et al., 2009). This information is fundamentally important to planners, researchers, and other groups interested in managing protected areas. Remote sensing is specifically vital to monitoring LULCC in many protected areas where direct access is not often available to easily monitor from the ground and identify where changes are occurring (Wiens et al., 2009).

Human-induced land cover change can occur in the forms of agricultural land-clearance, suburban sprawl, and timber harvests and influences processes, organisms, and natural resources within and surrounding protected areas (Hansen and Rotella, 2002; Lambin et al., 2001; Sala et al., 2000; Soulé, 1991; Wang et al., 2009; Wessels et al., 2012). This introduces higher levels of human disturbance, causing changes in air, water, and natural disturbance, generates natural habitat loss and fragmentation, and ultimately severely threatens biodiversity (Grumbine, 1994; Hansen and DeFries, 2007; Jones et al., 2009; Theberge, 1989).

6.1.1. LULCC monitoring methods

Well-designed management plans minimize negative impacts from LULCC on protected areas by maximizing connectivity and size of protected zones, minimizing fragmentation, targeting migration zones, and keeping a close eye on human impacts especially around edges of protected zones (Hansen and DeFries, 2007). For example, the Land Cover Trends Project of the USGS was created to map large-scale changes in major land cover types using Landsat imagery from 1973 to 2000 (Loveland et al., 2002). Projects such as these can help create an inventory of where and how land cover classes are changing over the landscape. These inventories may then be utilized to change environmental policy and to focus management needs.

LULCC techniques are applicable to a variety of ecosystem types. Several current examples of these applications include monitoring changes between grasslands and mixed grass/sagebrush in rangelands (Huang et al., 2010); evaluating sensitive areas in the Florida Everglades for land use change and biogeochemistry based on vegetative health and condition (Hogan et al., 2012; Jones et al., 2011); and mapping vegetation across National Parks and the Midwest USFWS lands (UMESC, 2014).

LULCC is quantified using both binary and automated change detection methodologies. A supervised-type classification is the most intuitive method for land cover classification, which uses baseline data often collected in the field or from an existing land cover dataset to assign classes to certain pixels (Rogan and Chen, 2004). The spectral information within those pixels is then used to apply the assigned landscape classes to the remainder of an image, thereby creating a baseline land cover image. The accuracy of this image can then be tested for errors. Validation points for land use classes can be chosen based on a randomized draw, such as the Geometric Stratified-Random Sampling Technique (Wiens et al., 2009).

6.1.2. LULCC standardizing techniques

National standardized vector datasets have been developed for country-wide comparison of land cover, many of which were created with remotely sensed data, such as the National Land Cover Dataset by the US Geological Survey (USGS) based on Landsat data (Homer et al., 2004). The USGS GAP Analysis Program is another example of a vector dataset, was created from Landsat imagery in 2001, and is deemed 85% accurate by field validation. GAP data are commonly used in LULCC studies or for habitat mapping (Davis et al., 1995; Lowry et al., 2005). The USGS is also working with the USFWS to standardize vegetation classification maps across several states, including Texas, Oklahoma, Louisiana, Mississippi, and Alabama (USGS, 2012). The National Vegetation Classification System is a program specifically developed by conservation organizations and used for wildlife habitat monitoring (Kerr and Ostrovsky, 2003). Site-specific land cover datasets such as that used by the Southern California Association of Governments (SCAG) in some cases may be more accurate, but often do not contain standardized vegetation and land use types for multiple locations (SCAG, 2014).

6.2. Irregular change detection: disturbance

Ecological disturbance to a protected area is defined as "a cause; a physical force, agent, or process, either abiotic or biotic, causing a perturbation (which includes stress) in an ecological component or system; relative to a specified reference state and system; defined by specific characteristics" (Rykiel, 1985). Disturbance types monitored in US protected areas occur across a variety of scales and rates of change, and include fire, invasive plant and animal species, disease, grazing, flooding, and deforestation (Dennison et al., 2009; Jones et al., 2013; USGS, 2012; Wiens et al., 2009). Satellite-based remote sensing is essential to the study of disturbed areas, since remote studies do not increase the amount of disturbance on the ground especially in sensitive ecological zones or areas cut off to public access (Dennison et al., 2009; Epting et al., 2005; Ohse et al., 2009; Wiens et al., 2009).

6.2.1. Disturbance monitoring methods

Disturbances are classified based on differences in the behavior of the spectral changes. For example, disturbance by insect infestation is evident in remotely sensed data by looking at slow deterioration or spectral changes that occur over a longer period of time (Kennedy et al., 2012). In contrast, fire is a large scale, sporadic occurrence, which in turn limits *in situ* access due to the danger it introduces to humans (Kennedy et al., 2012). Remote sensing is used to monitor fire potential, severity, frequency, post-fire scarring, and recovery by looking at multiple years of spectral data in a series (Jones et al., 2013; Wiens et al., 2009). Results can be used to capture the location of the fire event, as well as the full multi-annual effects of fire on the vegetation. Fire is monitored across a variety of ecosystem types, such as the Florida Everglades, Alaskan boreal forest, and grasslands in Buenos Aires National Wildlife Refuge in Arizona (Epting et al., 2005; Jones et al., 2009; USGS, 2012; Wiens et al., 2009).

The effects of disaster events such as flooding, tornadoes, earthquakes, and tsunamis are tracked at a consistent time interval in a particular region after the event. Immediately after Hurricane Katrina, the USGS used remote sensing for post-disaster relief monitoring in Louisiana and Mississippi (USGS, 2012). Multiple occurrence disaster and natural disturbance events can also be monitored to determine potentially affected adjacent zones, such as the identification of floodplain locations based on flood regimes in the Connecticut River Watershed (Wiens et al., 2009). Studies in high security zones require remotely sensed monitoring due to lack of land access such as in the Eglin Air Force Base of the Florida Everglades (Wiens et al., 2009). An area may also be sensitive to ground-based monitoring due to possible impacts on water quality, riparian habitats, and endangered species presence (Dennison et al., 2009). For example, remote sensing is used in the Colorado River Plateau to maximize bioremediation by monitoring biocontrol of invasive tamarisk species using salt cedar leaf beetles (Dennison et al., 2009; Dudley et al., 2001).

6.2.2. Disturbance standardizing techniques

Automated change detection programs are recommended for monitoring disturbance since continuous temporal measurements help identify disturbance type and severity. Disturbance type and severity are classified according to the amount of time it takes for pixels to change and the manner in which they change, so it is difficult to offer a blanket approach of methods for all disturbance types. For example, fire occurrence and insect infestation are reflected differently in pixel changes, and thus may require use of different input data. MODIS data are recommended for disturbances occurring over larger (50–100 m^2) swaths of land such as fire, whereas ASTER is useful in spectrally complex cases such as insect infestation due to its high spatial resolution (15–90 m^2) at multiple bands (Dennison et al., 2009). Landsat products (30 m^2) may also be useful for specific events, such as to determine fire extent (Jones et al., 2013).

Management efforts in sensitive areas such as the Eglin Air Force Base are exemplary for their collaborative efforts between conservation groups and stakeholders, in this case including: The Nature Conservancy, Eglin Air Force Base, USFWS, Florida Natural Areas Inventory, and the Joseph W. Jones Ecological Research Center (Wiens et al., 2009). The USGS has also led collaborative efforts to create fire-based national data products for fire potential, presence, and burn severity, including the Fire Potential Index (FPI), Landscape Fire and Resource Management Planning Tools (LANDFIRE), and Monitoring Trends in Burn Severity (MTBS) (USGS, 2012). These data are used by the USGS/USFS Burn Area Emergency Response (BAER) Teams to protect property, natural resources, human lives, and land cover recovery (USGS, 2012). For example, wildfires from 1972 to 2010 were mapped and evaluated in the Mojave Bioregion in order to gain knowledge on fire dynamics, local effects, and to identify useful management strategies to implement in future practices (USGS, 2012).

6.3. Continuous change detection: phenology

Climate change has a significant effect on natural landscapes, and can affect ecosystem dynamics even on relatively a short timescale (Nemani et al., 2009). As climate change continues, it may eventually decrease biodiversity within protected areas regardless of direct human influence. One of the known effects of climate change is reflected in changes to the local phenology of plants (Parmesan and Yohe, 2003). Phenology is the variation in seasonal patterns of natural phenomena on land surfaces, and can be detected via remote sensing by changes in spectral index values (Pettorelli et al., 2005; Reed et al., 1994; Zhang et al., 2004). Plant phenology is often used as a proxy for climate change since it is a direct measure of the effects of climate change on plant vitality (Morisette et al., 2008; Nagendra et al., 2013; Schwartz, 2003). Changes in seasonal timing such as the start and end of season, duration of growing season, and maximum productivity can in turn have an impact on a large number of species that are dependent on natural cycles of vegetation.

6.3.1. Phenology monitoring methods

Changes in plant phenology are often measured through the use of the Normalized Difference Vegetation Index (NDVI) (Goetz et al., 2011; Goetz and Fiske, 2009; Justice et al., 1985; Melton et al., 2010; Nemani et al., 2008; Pettorelli et al., 2005; Piekielek et al., 2010; Zhang et al., 2003). NDVI is a useful indicator of photosynthetic capacity, measured as a band combination ratio from one of a number of satellites including NOAA AVHRR, MODIS, or Landsat, and is given by:

$$\mathrm{NDVI} = (\rho\mathrm{NIR} - \rho\mathrm{RED})/(\rho\mathrm{NIR} + \rho\mathrm{RED}),$$

where ρNIR is reflectance in the near infrared band and ρRED is reflectance in the red band (Dennison et al., 2005; Huete et al., 2002; Reed et al., 1994; Tucker, 1979; Zhang et al., 2003). Seasonality metrics may also be calculated from other spectral indices, such as the Enhanced Vegetation Index (EVI). EVI is used to calculate seasonality metrics in areas where NDVI is not a valuable indicator of the change in seasons due to greenness saturation in areas of high biomass (Chéret and Denux, 2011).

The annual cycles of vegetation phenology that can be inferred by remote sensing are usually characterized by four key transition dates: (1) greenup, the date of onset of photosynthetic activity; (2) maturity, the date at which plant green leaf area is maximum; (3) senescence, the date at which photosynthetic activity and green leaf area begin to rapidly decrease; and (4) dormancy, the date at which physiological activity becomes near zero (Zhang et al., 2004). Analysis of the temporal variations in NDVI from MODIS datasets has become the most commonly used technique to measure these four transitions in phenological changes, and is used across the country in Shenandoah, Delaware, Rocky Mountains, Yellowstone, Yosemite, Santa Monica Mountains, Channel Islands, and Alaska National Parks (USGS, 2012). A decline in NDVI could be attributed to a number of climatic and environmental factors, including drought, temperature, precipitation, fire, insects, diseases, nutrient limitations (Goetz et al., 2005).

Changes in phenology are part of a complex system, and can be influenced by outside forces other than long-term climate change, such as precipitation or fire. These must be accounted for in monitoring methodologies, such as masking out fire areas to eliminate burn zone anomalies in NDVI values. Other anomalies in phenology indices may be explained by climate records such as soil moisture levels or precipitation events, which affect the short-term uptake of water by plants and may ultimately alter plant greenness (Bertrand et al., 2011; Zhang et al., 2013). These short-term influences may be eliminated by de-trending time series data, or they may be incorporated into the phenology cycles, depending on the monitoring intentions (Chéret and Denux, 2011).

6.3.2. Phenology standardizing techniques

Detecting changes in phenology requires the use of remotely sensed datasets with high temporal resolution. MODIS-derived indices are recommended for monitoring phenology in vegetation due to the variety of phenology-related data products (i.e. NDVI, EVI, Leaf Area Index (LAI), Albedo) and their high temporal resolution (8- and 16-day). MODIS has also recently created a data product (MCD12Q2) which produces direct estimates of phenological timing (MODIS subsetted land products, 2014).

A combination of satellite and ground-based data along with climate records or model simulations can be used to provide information about ecosystem phenology indicators (Nemani et al., 2003; Schwartz, 2003). Many climate modeling and forecasting systems are not utilized by managers of protected areas due to lack of training or experience with modeling (Nemani et al., 2009). The automated program Terrestrial Observation and Prediction System (TOPS) is designed to facilitate in this process and to integrate remotely sensed, ground, and climate data along with climate models in order to predict ecological conditions such as phenology for protected areas (Ichii et al., 2008; Nemani et al., 2003, 2008: 200; White and Nemani, 2004).

Remote sensing-based phenological studies are most robust when performed in combination with *in situ* studies. The USGS is at the forefront of collaborative studies in phenology and in combining these datasets. One example is their extrapolation of ground-based data obtained by the US Phenology Network across the nation (USGS, 2012). The USGS is also in the process of developing a Land Surface Phenology Viewer using MODIS data in conjunction with the NPS and NASA (USGS, 2012). These initiatives often utilize citizen science by compiling data such as geo-located, time-stamped images of plants collected from smart phones from the general public to increase sample size and accuracy (Brigham et al., 2009; Graham et al., 2011).

7. Links between science and management

It is rare that scientists have extensive knowledge in ecology, management, and remote sensing, making collaboration between scientists and conservation groups crucial (Wiens et al., 2009). Effective remotely sensed monitoring programs contain elements of information, policy, and participation in order to improve communication between managers and scientists (Skidmore et al., 1998). Collaborations such as with the USGS in phenology and between groups at Eglin Air Force Base managing disturbance are exemplary of effective remote sensing management studies.

Many land management organizations integrate GIS programs to their conservation efforts, yet do not have access to remote sensing software (Woodcock et al., 1983). The fields of remote sensing and GIS are similar in scope and in scale, which makes communication between remote sensing scientists and land managers relatively simple. Improved interdisciplinary learning between ecologists, land management groups, and remote sensing experts will continue to be essential to future effective monitoring of protected areas (Nagendra et al., 2013). Comprehensive written reviews may also aid in this communication; a review of remote sensing technologies available for land management application purposes was written over 30 years ago (Woodcock et al., 1983), but many reviews since with similar themes have not been written with conservation-based land managers as the primary audience (Gross et al., 2009; Pettorelli et al., 2014; Remote sensing of protected lands, 2012; Vacik et al., 2014).

Several working groups have formed in recent years in order to better communicate and combine efforts in remote sensing for conservation purposes. The USGS Land Remote Sensing Program contributes significantly to the remote sensing community by producing both data and research. The USGS chairs the Department of the Interior Remote Sensing Working Group (DOIRSWG), which maintains a website with all current research project overviews (USGS, 2012). The DOIRSWG encompasses research from the following groups: Bureau of Indian Affairs (BIA), Bureau of Land Management (BLM), Bureau of Reclamation (BOR), Bureau of Ocean Management, Regulation, and Enforcement, National Park Service (NPS), Office of Surface Mining (OSM), US Fish and Wildlife Service (USFWS), and the US Geological Survey (USGS). This group produced a Land Imaging Report in 2012, and will likely continue to produce future reports. The North American Network for Remote Sensing Park Ecological Condition (NARSEC) is another working group, organized in 2005 by the National Park Service (Remote sensing of protected lands, 2012). However, a workshop in 2007 was the last reported NARSEC event. Collaborative working groups such as these are vital to the continuation and evolution of remote sensing standardization across protected areas in the United States.

However, communication of methodological choices alone is not enough to ensure effective conservation management. Increased data accessibility is another essential element to effective remotely sensed monitoring. Open access type models are a progressive step toward sustainable management methods (Ohse et al., 2009). Once the appropriate methodological protocol is fully established, the implementation plan must clearly translate the scientific results to policy standards. In other words, how will the resulting data be used so they are relevant to policy and accessible to the general public? These questions will guide reports to address management needs as well as the debates at large surrounding conservation and sustainability.

8. Conclusions

This review has provided a comprehensive assessment of remote sensing change detection methods currently employed for monitoring and management of protected lands in the United States. At present the United States contains a high concentration of successful conservation programs utilizing effective change detection methods for monitoring, with additional programs being developed. Change detection methods are useful for monitoring uniform, irregular, and continuous ecological dynamics for on-the-ground applications such as LULCC, disturbance, and phenology.

Forming collaborations within and between working groups with improved communication between research scientists, field ecologists, and land management groups, as well as elucidating current methods and highlighting operative applications of remote sensing in land management are vital steps toward improving conservation in protected areas. We need land management groups to utilize remote sensing monitoring in order to improve management and conservation. By creating remote sensing monitoring programs, we can inventory the current status of ecological systems in order to quantify the changes occurring over landscapes. This allows for a better understanding of the current biological status and justifies the need for conservation programs overall. Once we have an inventory of ecological status we can see where further management is needed in order to protect biodiversity. Remote sensing change detection is a means to address this management need in a non-invasive manner over entire landscapes, so as to effectively monitor large areas without creating further disturbance. This is especially important in today's changing world given the increased pressures from humans via land use conversion, natural and anthropogenic disturbance, and climate change.

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Appendix A. Supplementary material

Supplementary data associated with this article can be found, in the online version, at http://dx.doi.org/10.1016/j.biocon.2014.12.006.

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