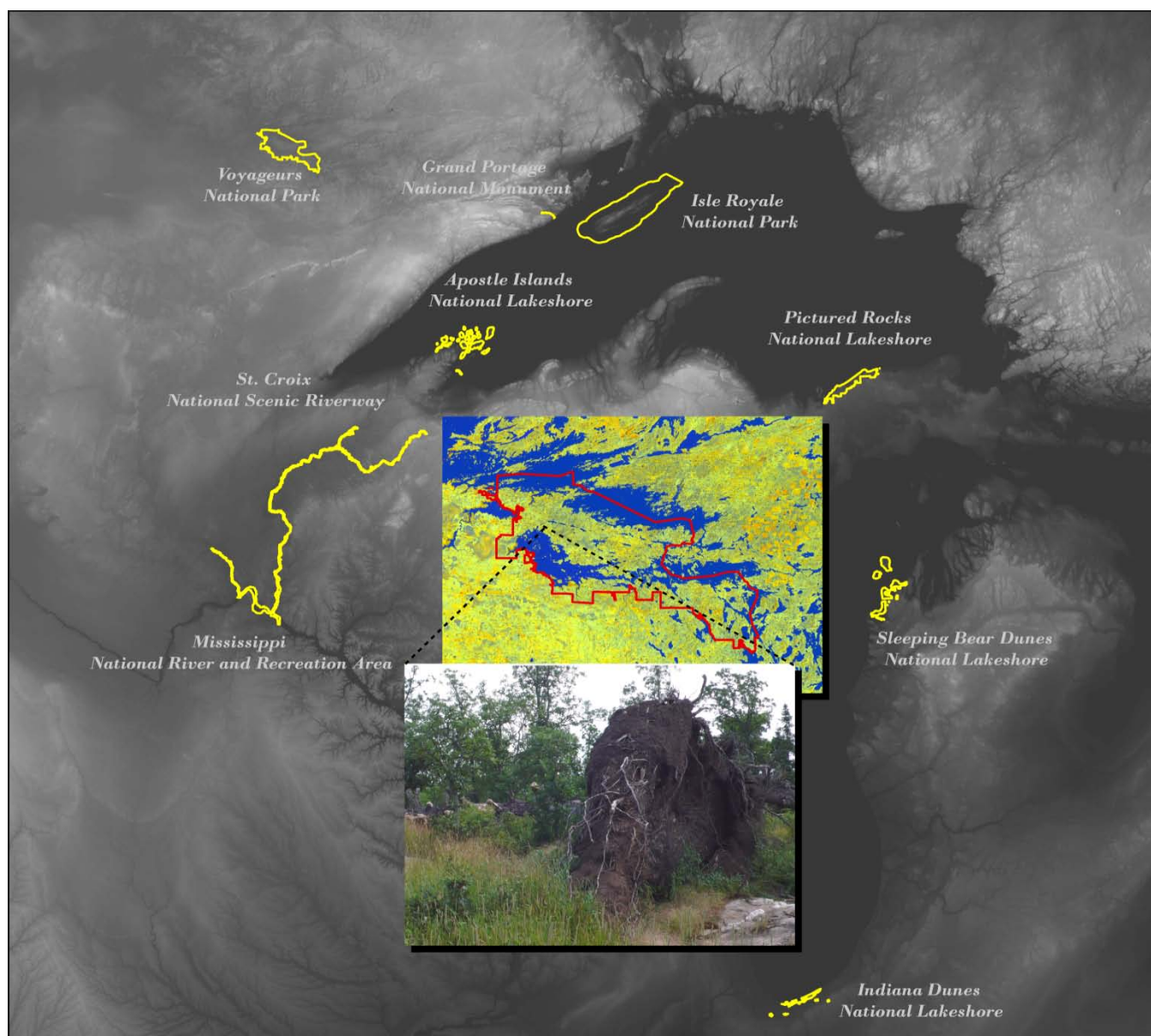




Landsat-based Monitoring of Landscape Dynamics in the National Parks of the Great Lakes Inventory and Monitoring Network (Version 1.0)

Natural Resource Report NPS/GLKN/NRR—2010/221



ON THE COVER

Locations of the nine parks of the Great Lakes Inventory and Monitoring Network (outlines in yellow) overlaid on digital elevation with insets of Voyageurs National park (top) and a picture (bottom) of a windthrown tree at LaBonty's Point inside the park.



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Natural Resource Report NPS/GLKN/NRR—2010/221

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U.S. Department of the Interior
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Natural Resource Program Center
Fort Collins, Colorado

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Executive Summary

This protocol details the objectives, methods, and data analysis for monitoring landscape changes over time using remote sensing data and technology in the western Great Lakes region of the United States. Detailed methods are in standard operating procedures (SOPs). The protocol involves compiling and processing a time series of Landsat imagery (since 1984) to automate change detection on the landscape using algorithms developed by research scientists at Oregon State University. Collectively, these algorithms comprise a trajectory-based approach known as LandTrendr (Landsat-based detection of trends in disturbance and recovery). The monitoring will take place at Apostle Islands National Lakeshore (APIS), Voyageurs National Park (VOYA), Isle Royale National Park (ISRO), Sleeping Bear Dunes National Lakeshore (SLBE), Pictured Rocks National Lakeshore (PIRO), St. Croix National Scenic Riverway (SACN), Mississippi National River and Recreation Area, and Indiana Dunes National Lakeshore (INDU). This monitoring is funded and conducted by the NPS Great Lakes Inventory and Monitoring Network (GLKN).

The primary justification for monitoring the change in landscape dynamics over time is to document the change where and when it occurs. In addition to where and when, we will also describe the agent of change (forest harvests, blowdown, fire, beaver, development, etc.) and the starting/ending vegetation class for the disturbed area. This will allow managers to better prepare for and then manage for ecosystem changes that are likely to affect processes, systems, and individual species.

This protocol will be repeated every year, with a full analysis resample time of 6 years for each park and a midterm, less intensive analysis, occurring every 3 years. Depending on feedback from park personnel, we may revisit a park every 3 years with a less intensive implementation of the protocol. If parks find the revisit unnecessary, we will pursue developing and implementing new protocols for monitoring ice/snow cover and/or phenology using remote sensing data.

Specifically, this monitoring protocol is designed to answer the following questions:

1. Where and when are disturbances (≥ 1 ha) occurring inside and outside the park?
2. What is causing these disturbances?
3. What is the mean size of disturbances?
4. Has forest harvesting occurred inside park boundaries?
5. As a result of blowdowns, beaver activity and possibly fire, where are large areas of recently downed woody debris located?

At the beginning of each year, Landsat imagery will be downloaded and processed for inclusion into LandTrendr analysis. Landsat images will be acquired which meet certain parameters for inclusion into the process. The most important parameter for inclusion is date of image acquisition. Each image chosen should have the same phenology as the remainder of images in the time series. Generally speaking, images taken in July and/or August meet the criteria, although these dates can be adjusted slightly depending on the park of interest and its specific phenology. In addition to acquisition of Landsat imagery, additional airphotos or higher resolution satellite imagery (IKONOS, Quickbird, SPOT) should be acquired when funds exist.

Additional preprocessing steps to remove clouds and radiometrically normalize the images to other images in the stack need to be taken before running the LandTrendr algorithms.

After LandTrendr has been run, laboratory validation of disturbances denoted by LandTrendr is carried out through the use of available high resolution (15-100 cm) airphotos, Landsat spectral trajectories, and Landsat tasseled-cap image chips. During laboratory validation the user determines whether or not the change is in fact real, or an artifact of phenology, misregistration, sensor drift, or atmospheric effects. In addition, other information is added to each disturbance area (polygon) during laboratory validation. This information includes disturbance agent, starting class, ending class, percent of the area affected, and confidence scores relating to the change call (true or false) the user indicated. In instances where the user is not sure whether or not the change occurred, this polygon is flagged for future field validation.

Field validation is carried out in the summer with the goal of determining whether a change occurred. The disturbed areas visited in the field are most likely subtle disturbances because they were not clearly evident in the airphotos, tasseled-cap imagery, and spectral trajectories. Information regarding the disturbance (year of disturbance, magnitude, duration, and other comments from laboratory validation) is included in the map of the disturbance which the user brings along to the field. By collecting observations within the polygon, using the laboratory validation notes and comments, and noting any evidence in the field (recently fallen trees, defoliated trees, burn scars, or windthrow) the analyst makes a final decision regarding the polygon. Upon return to the laboratory, the final decision is entered into the file geodatabase which contains all information and polygons resulting from LandTrendr, laboratory validation, and field validation.

The next step in the protocol is to export all data from the file geodatabase into a Microsoft Access database in which all quality assurance/quality control (QA/QC) queries are performed. Upon completion of the QA/QC measures, the data is ready for summarization and analysis. Various example summaries and analyses are presented in this protocol, and these examples can be modified for further, in-depth analyses. The Network will archive both the file geodatabase and Access database at multiple locations at the network office and copies will be sent to each park after the synthesis report has been completed.

Acknowledgements

This protocol was developed under the guidelines of the National Park Service, Vital Signs monitoring program, and we would like to thank Steve Fancy for his leadership and continued efforts to bring long-term monitoring into the National Park Service. The encouragement we received from network parks provided the impetus to conduct a pilot project implementing this protocol at Voyageurs National Park. Additionally, we would like to acknowledge the entire Great Lakes I&M Network staff who provided valuable input throughout the course of protocol development. Our network coordinator, Bill Route, has been extremely patient during the multiple iterations of protocol development and was extremely encouraging and supportive throughout the years. Finally, we would like to thank Ted Gostomski for the many hours of work he put into the formatting, layout, and editing of this document.

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I. Background and Objectives

The mission of the Great Lakes Network (GLKN), hereafter referred to as the Network, is to conduct long term ecological monitoring for nine parks in the Great Lakes region. These include Apostle Islands National Lakeshore (APIS), Grand Portage National Monument (GRPO), Indiana Dunes National Lakeshore (INDU), Isle Royale National Park (ISRO), Mississippi National River and Recreation Area (MISS), Pictured Rocks National Lakeshore (PIRO), Saint Croix National Scenic Riverway (SACN), Sleeping Bear Dunes National Lakeshore (SLBE), and Voyageurs National Park (VOYA) (Figure 1).

These parks span a wide range of sizes, from 287 ha at GRPO to 231,396 ha at ISRO. The parks also span a range of landscape condition, from remote, wilderness parks (ISRO, VOYA), on or near the Canadian border, to parks within urban and industrial landscapes (MISS, INDU), located within the central Midwest. Six of the parks are within the Great Lakes basin, while two parks occur in the Mississippi River basin (MISS, SACN), and one (VOYA) in the headwaters flowing north to Hudson Bay.

In addition to spanning a large range of sizes, these parks span a wide vegetation gradient from the northernmost parks of VOYA, GRPO, and ISRO being dominated by boreal forest types to the southernmost park (INDU) being dominated by sand dunes and oak savanna. The remaining parks consist of many other forest/ecological types, including pine barrens (SACN), northern hardwood forests (APIS, MISS), and beech/maple forests (PIRO, SLBE).

This regional context provides an opportunity for comparison of variability in monitoring selected indicators across these climatic and anthropogenic gradients, and monitoring potential differing climate change impacts to park condition.

Motivation

The Network was initiated in 2000, with a primary goal to conduct several biological inventories. In 2002, the Network began to develop a list of vital signs, which involved participation by park natural resource managers in selecting ecological indicators, components of the system that can be monitored to provide quantitative assessment of the status and trends of the ecological integrity within and around national parks (Route and Elias 2007).

Park staff and outside science experts helped the Network select and prioritize a suite of ecological indicators for which the Network would design monitoring protocols. As a result of this process, monitoring landscape dynamics in terms of land cover and land use (LCLU) in and around parks, was one of the vital signs selected for long term monitoring. Monitoring land cover dynamics has been identified as a high priority by virtually all of the 32 networks across the country. In partial response to this need, a National landscape dynamics program has been created (NPScape), designed to monitor changes in human population, roads, and broad land cover classification. Data from this program will compliment the data generated by this protocol by providing these broad metrics for park and adjacent landscapes, while this protocol will provide more detailed data and analysis inside and around each park.

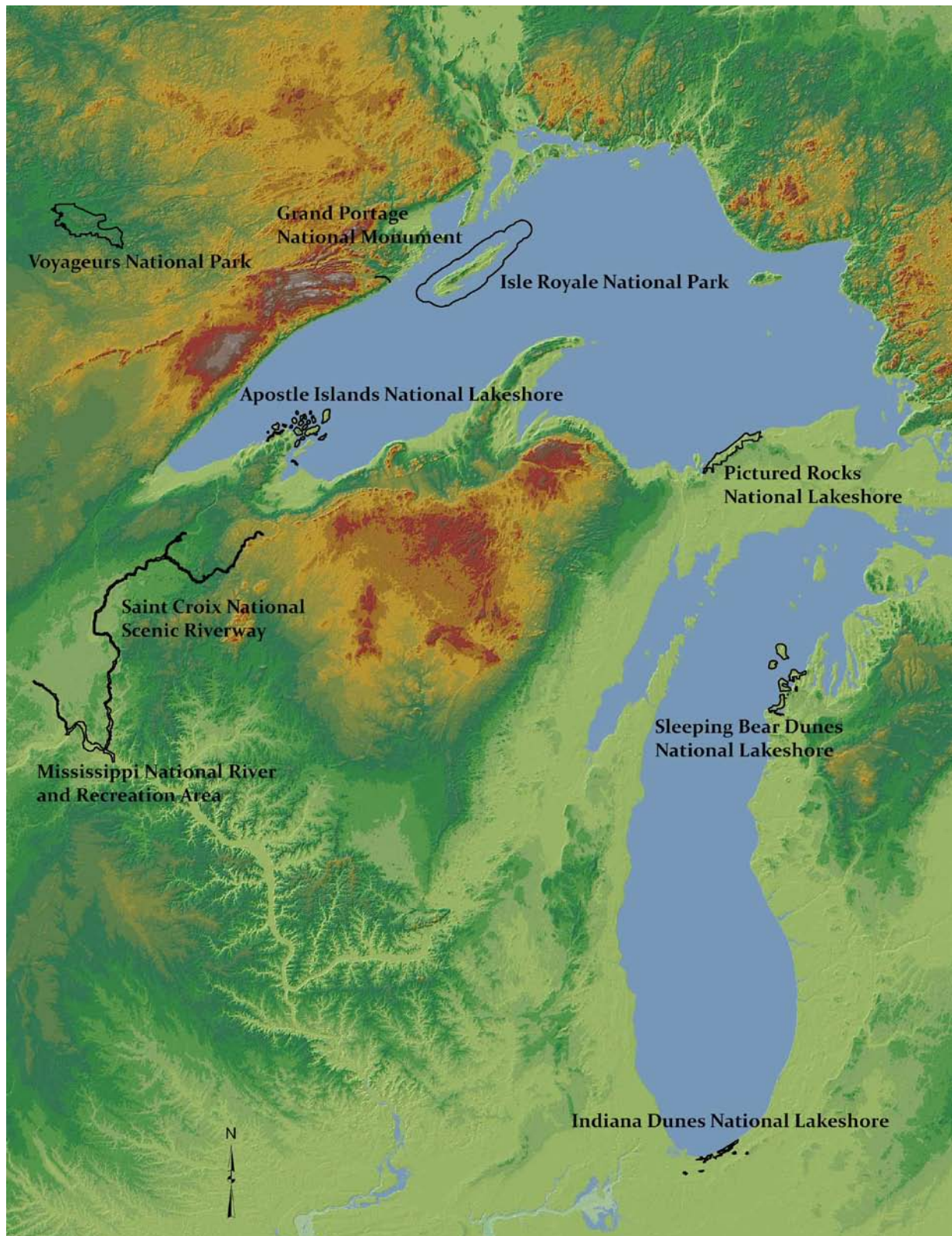


Figure 1. Locations of Great Lakes Network parks.

Several questions regarding land cover arose from the park scoping meetings. These can be summarized by the following:

- What is the magnitude and direction of change in LCLU in and adjacent to, parks over time? Spatial patterns include such measures as land cover class, corridors, fragmentation, juxtaposition, edge, and number of homes.
- What are the changes in area and shape in urban, agricultural, and other areas dominated by human land use within a defined monitoring region for each park?
- What are the changes in forest harvest amounts and patterns within and surrounding each park in specified areas?
- How has the density of human occupation, measured either by population or building density, changed in each monitoring region?

The goal of the land cover monitoring program for the nine GLKN parks is to monitor changes in LCLU over time in and around park areas, and includes quantifying disturbance events and documenting trends in human development, fragmentation, road density and land cover patch dynamics. Since the advent of NPScape, the network has focused work on filling the gap between NPScape products and the additional fine scale information the park and Network desires. As previously mentioned, NPScape provides information on a larger scale, thus missing smaller, yet still important, disturbances such as beaver dams, blowdowns, and harvests. Park and network staff recognize that changing LCLU impacts virtually all other Network vital signs; water quality, terrestrial vegetation, bioaccumulative toxins, bird communities, and air quality.

Landscape scale analysis provides a means to view the pattern, arrangement and interactions of the habitats existing in and around the parks. Examining these spatial patterns over time can reveal changes in land cover and land use that may be impacting the natural resources within parks. Forest harvesting outside park boundaries is one example of how spatial and temporal patterns of disturbances outside a park can affect ecosystem structure and function inside a park (Brunson and Reiter 1996, Singer et al. 1997, Johnson et al. 1998, Kittredge et al. 2003, Odion and Sarr 2007). Other effects can include fragmentation, degraded water quality, edge effects, spread of exotics, changes in the effective size of natural areas, flow of energy, nutrient cycling, and overall ecological functioning. Though less common generally, but perhaps more common on NPS lands, the opposite may also occur, with abandoned agriculture moving toward fallow conditions and succession into prairie or forest, and associated reduction in human population density and disturbance (Gimmi et al. 2009). Provided with this type of information, park- and network-based staff will be better prepared when park service input is needed in policy decisions. In addition to providing crucial information to natural resource management at the park level, this data also provides context and integration for other components of the Network's monitoring program.

Remote sensing has been used for over two decades to assist in answering a variety of ecological and landscape questions and issues. These include land cover classification, ecosystem function, change detection, monitoring process such as flooding and disease spread, among others (Kerr and Ostrovsky 2003, Ager and Owens 2004). Land cover and its spatial patterns are key aspects of ecological monitoring. Landscape patterns and the patchwork of vegetation communities

integrate biotic and abiotic factors in their structure and composition. Thus, remote sensing can detect changes in both the land cover type and in the variability and distribution of particular land cover types (such as vegetation). However, choosing the appropriate remote sensing technique varies greatly depending upon the reference data available and goals of the resource managers (Kennedy et al. 2009).

Past Directions

Land cover classification with remote sensing

The Network began working on the LCLU monitoring program in 2003, through several cooperative agreements with University research staff, in order to help the Network design a scientifically credible protocol. Remote sensing technologies were determined to be the primary tool for monitoring land cover changes across entire park landscapes, with early investigations involving traditional remote sensing methods of land cover classification using satellite imagery, to track and quantify changes on the landscape.

These techniques are well established in the remote sensing field, often carried out using Landsat imagery, and involve various methods of classifying the landscape into discreet, mutually exclusive classes. These methods commonly acquire imagery on a defined temporal scale, perform a classification on each image, and then compare classifications to identify differences in areal extent, location, size and arrangement of each of the mapped classes.

This method requires two stages of field work. The first round of field work is to build the classification reference dataset by establishing plots on the ground to identify the land cover, which is then linked to the spectral value(s) in the imagery. Specific spectral combinations across the bands of imagery are then attributed to specific land cover classes using one of many classification algorithms. However, building a robust classification table requires visiting several locations of each class to be mapped. The imagery is then classified, using some combination of supervised and unsupervised classification or decision trees within a software package.

The next stage of field work involves completing an accuracy assessment to quantify the accuracy of the classification procedure through ground truthing. This again involves a significant number of field visits, in order for the accuracy assessment to be statistically valid. Due to the large amount of field work, with resulting accuracies below the Network's desired level, the Network did not pursue this method. In addition, this method would not have delivered the desired products (spatially and temporally) for the Network and associated parks.

Manual delineation of change with air photos

The Network explored an alternative solution from Landsat and automated classification techniques, in acquiring high resolution aerial photography (0.2m to 0.15m) and performing manual change detection and classification. This is generally recognized as providing higher accuracies, (ca. 90%), (Rutchev and Vilchek 1999, Harvey and Hill 2001, Maheu-Giroux and de Blois 2005). The goal of this method was not to complete a 'wall-to-wall' classification at each interval, but rather to view imagery/classification at time step one in conjunction with new imagery, on a six year interval, and only map apparent changes, revising the existing vegetation mapping.

The products of this method were appealing, in that the recent National Vegetation Classification System (NVCS) mapping could be effectively updated, at least to the formation level in the classification hierarchy (Jennings et al. 2004). The formation level provides physiognomic descriptions of vegetation growth form, height, and density. This would provide natural resource managers with a useful vegetation map that reflected current conditions, as well as identify disturbances and human development occurring adjacent to park boundaries.

The Network completed a draft of the protocol and sent it out for review in February 2008. The reviews called for greater detail in specifying the objectives and methods, and required significant revisions. The Network began initial work on a pilot project to test the methods at Voyageurs National Park, and quickly recognized that this method has many drawbacks to implementation.

One of the many drawbacks included a remaining burden of field work in order to train an interpreter in recognizing the spectral and textural character of different land cover types on each set of imagery, as well as a significant commitment to accuracy assessment work in order to confirm the reliability of the mapping product. Manual interpretation, while typically attaining higher accuracy than computerized classification, involves a large degree of interpreter bias. Apparent changes may be due solely to individual mapping preferences, with no real change having actually occurred. Each new interpreter will also require extensive training in order to become proficient in conducting manual classification and change identification. In addition to the inordinate amount of field work needed, a complete census of each image set requiring the user to alternate back and forth between two years of imagery for the entire park and some pre-defined area outside the park, was deemed an unfeasible task with a high likelihood of technician burnout.

Current Direction

Hybrid approach to monitoring landscape changes

During the testing of the previous protocol, which was proving to be inadequate, the Network was in close contact with collaborators at Oregon State University and the USDA Forest Service's Pacific Northwest Research laboratory, hereafter referred to as the "Oregon group." The Oregon group had been involved with the development of remote sensing protocols at multiple I&M networks and were currently working on a new landscape dynamics protocol for the Sierra Nevada I&M network (SIEN). The protocol revolved around an innovative method which infers change from spectral trajectories across many years of imagery, rather than from differences in only two dates of imagery (Kennedy et al. 2007b). The trajectory based approach is known as LandTrendr (Landsat-based detection of trends in disturbance and recovery (Figure 2)).

The LandTrendr method infers change as deviation from long-term trends using a single spectral index. Year to year variation in spectral signal caused by ephemeral phenomena, such as vegetation phenology differences or sun angle changes caused by difference in date of image collection, become noise around longer trends (note noise in traces of grey trajectories in Figure 2a). Because of the greater signal-to-noise ratio afforded by the greater density of image signals over time, the overlap between target and non-target change is greatly reduced, allowing capture of more subtle effects and better avoidance of non-target spectral change. This provides the

opportunity to recognize slow decline or recovery of forests as well as sudden disturbance events such as fire or blowdown. Such disturbance events may be missed if imagery is acquired only every five years, for example, as vegetation will grow back within a few years, obscuring any evidence of a disturbance.

This method has an additional advantage of not being burdened by developing and testing a classification of the landscape, but rather focused directly on identifying changes on the landscape. The Network will continue to acquire high resolution imagery to verify if changes are real, and to determine the change agent, whether fire, blowdown, human development, logging, or other causes.

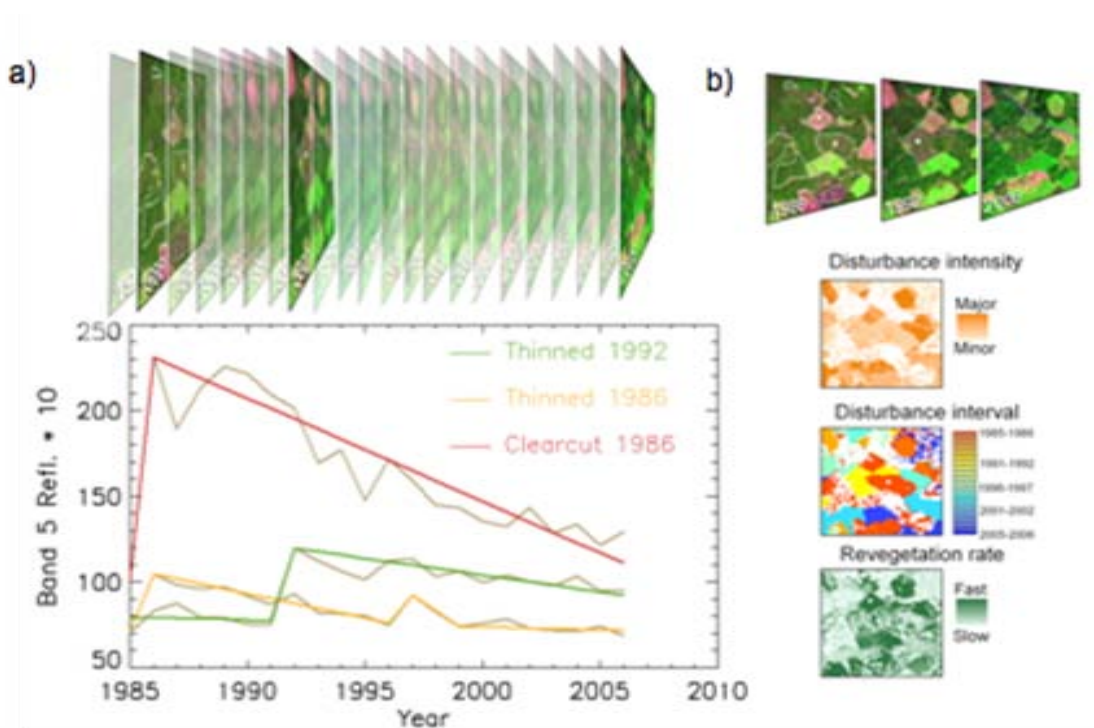


Figure 2. The core process in the LandTrendr algorithms. a) Spectral values of a single index are extracted for a pixel in a dense stack of images (grey traces). Signal extraction techniques are used to identify the years (x-axis) that form logical endpoints of segments describing consistent processes over time, and to find the vertex values (y-axis) for those years that minimize overall residual error in the fitted trends (colored traces). b) The endpoints, slope, magnitude, direction, and length of each segment can be described for each pixel in map form and used to infer the process occurring in a given time period.

Objectives

The Network has had to manage expectations of the parks, and our own expectations, regarding the products and data a landscape dynamics protocol should be able to provide. As mentioned earlier in “Past Directions” we realize there are many other techniques and analysis methods available, but choosing a scientifically robust, repeatable, and feasible methodology requires lowering overall expectations. However, we believe this protocol represents the best available option for the Network and parks. The current objectives of the protocol are:

- 1) Identify areas within the defined analysis boundary of the landscape which have experienced a minimum loss of 20% cover and are larger than 1 hectare in size since 1985.
- 2) Using high resolution imagery (aerial photography), ascribe agents of change to disturbed areas.
- 3) Using GLKN-developed crosswalk from the NVCS product for the park, ascribe starting and ending vegetation class(es) to the disturbed area.

A future objective of the protocol include implementing a probability-of-membership (POM) procedure (available through LandTrendr) to describe the dynamics of vegetation types, spatially and temporally, on the landscape.

II. Sampling Design

Because satellite images provide wall-to-wall coverage of a study area, traditional sampling concerns (site selection, sample size, etc.) are not relevant. Other sampling issues are important, however. Satellite image spatial sampling is determined by pixel size, and temporal sampling is determined by the orbit characteristics of the satellite and the field of view of the sensor. Moreover, different sensors differ in their sampling of the electromagnetic spectrum.

The sampling characteristics of Landsat Thematic Mapper (TM) make it appropriate and useful for park-wide monitoring of diverse land cover types. With a pixel-spacing of approximately 28.5 meters and an extent of 180 by 180 km, TM images capture adequate spatial detail for many landscape processes over the large areas of the GLKN parks. The spectral character of the sensor allows discrimination of vegetated from non-vegetated surfaces, hardwoods from conifers, and structurally complex canopies from smoother canopies (Cohen and Spies 1992, Cohen and Goward 2004). Landsat's temporal sampling (16 days) is adequate for capture of usable imagery at intervals appropriate for monitoring vegetation structure and composition. Relative to data from finer-grained sensors (e.g., aerial photos or high resolution satellite imagery), Landsat data offer much more cost-effective sampling of the parks, and capture more regions of the spectral domain that are critical for vegetation studies both in forested and non-forested systems (Cohen and Spies 1992, Asner and Lobell 2000, Brown et al. 2000, Trigg and Flasse 2001, Chuvieco et al. 2004, Healey et al. 2006).

Although using Landsat imagery affords the Network to monitor large areas of the landscape with little additional cost, it is still important to define discreet analysis areas which will be analyzed into the future. There are multiple alternatives in developing these boundaries, including a watershed extent, a simple distance buffer from the park boundary, or some other ecological or political boundary. The Network will work with each park before the protocol is implemented for the first time to determine a meaningful and feasible extent. At this meeting, we will guide the park through the process and by the end of the meeting, will have decided upon an analysis area to monitor into the future. Currently the Network has only worked at two parks, VOYA and ISRO, and thus has developed two of the nine analysis areas. Each of the analysis areas encompasses ca. 150,000 ha of land.

III. Methods

The core goal of this protocol is to map disturbances across parks and adjacent areas using yearly stacks of Landsat Thematic Mapper imagery. Each section of the methods flow in Figure 3 is captured in an accompanying standard operating procedure (SOP) document. Here, we describe the overall workflow and mapping steps, and provide examples of map outputs and summarizations resulting from the different methods.

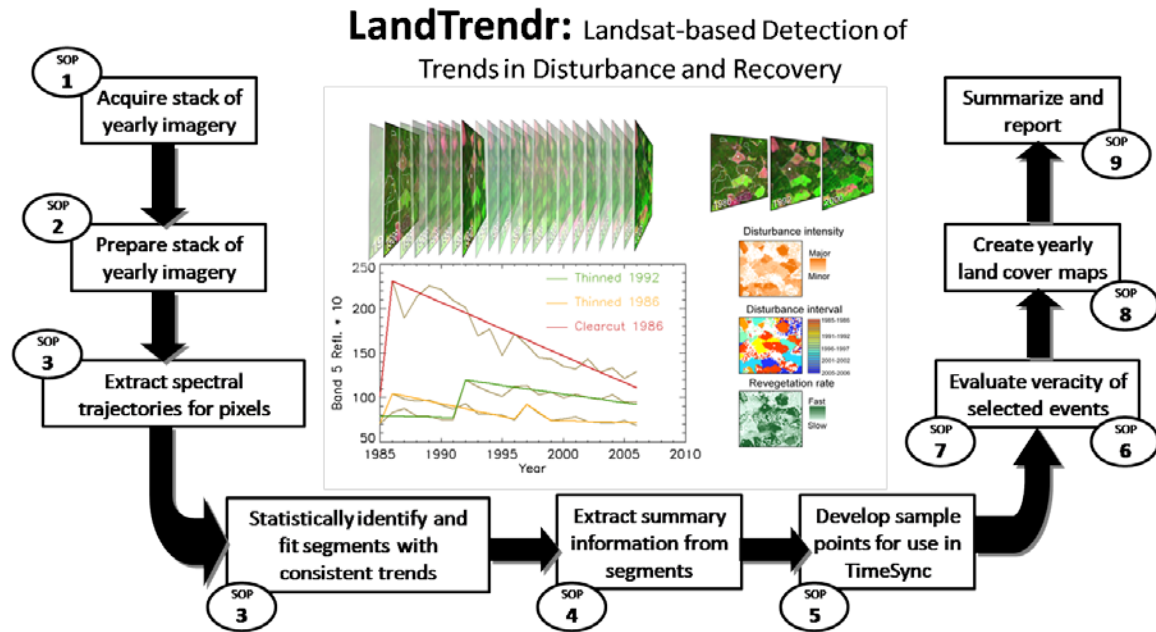


Figure 3. Diagram of the LandTrendr workflow and accompanying SOPs.

LandTrendr

The core of the LandTrendr workflow is a segmentation process that simplifies the temporal trajectories of pixels through a time stack of Landsat TM imagery (as in Figure 3 above). In the standard implementation of LandTrendr, the segments of the simplified time series are labeled as disturbance or growth based solely on a single spectral index, and then filtered to eliminate changes in estimated percent cover that are below a user-specified threshold. Percent cover estimates are derived strictly from the relationship between the single spectral index and estimates of percent vegetative cover as estimated from high resolution aerial photos. In the LandTrendr + probability of membership (POM) structure, the segmentation of the time series based on a single index is used to guide a process of temporal smoothing of other spectral indices.

The LandTrendr algorithms involve a series of preprocessing, segmentation, and mapping steps, shown in Figure 4. Each step has a series of sub-steps described in detail below.

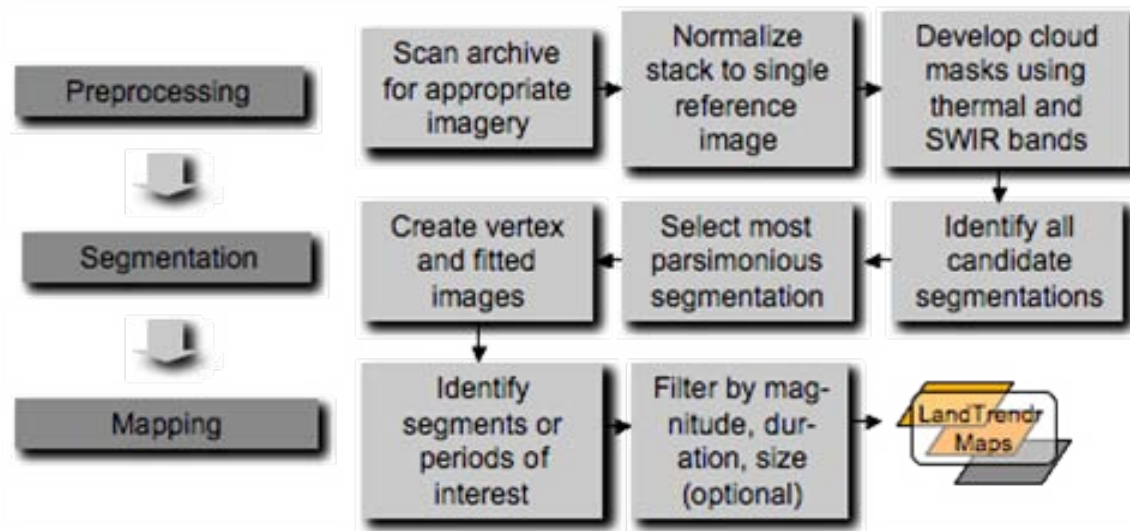


Figure 4. Showing the three main steps of the LandTrendr process with more detailed substeps.

Preprocessing

Pre-processing is a key step in any remote sensing monitoring study (Kennedy et al. 2009), that involves steps to convert essentially raw imagery into a form useful for analysis in monitoring. In the case of LandTrendr, two components of preprocessing deserve special attention. First, because comparison will be done using all images in a stack simultaneously, consistency across images is paramount. Second, because large volumes of data are used, automation in data processing is critical to making the methods feasible. These considerations come into play at all stages in preprocessing: image acquisition, radiometric normalization, and cloud-screening. The details of the methods used to conduct pre-processing are described in SOPs 1 and 2.

Acquiring images (SOP 1): With the Landsat archive now open and cost-free, there is little penalty to acquiring as many images as needed for analysis. Rather than search for cloud-free images, we instead place highest weight on images that are consistent in terms of phenology and sun angle. Reducing phenological variability in source imagery recognizes the potential confounding effect of phenology on year to year spectral signal. This is a consideration in two-date change detection, as well, but with only two dates of imagery, avoiding clouds is more important. In the case of dense temporal stacks of imagery, a masked cloud pixel in one image date is likely to be “bracketed” by non-clouded pixels in dates before and afterwards, making the penalty for clouds relatively low. Therefore, more prominence can be given to stabilizing the phenological signal, which would be much more difficult to compensate for or mask than are clouds. Appropriate images are selected and downloaded from the USGS’s GLOVIS website (Figure 5), described in SOP 1.

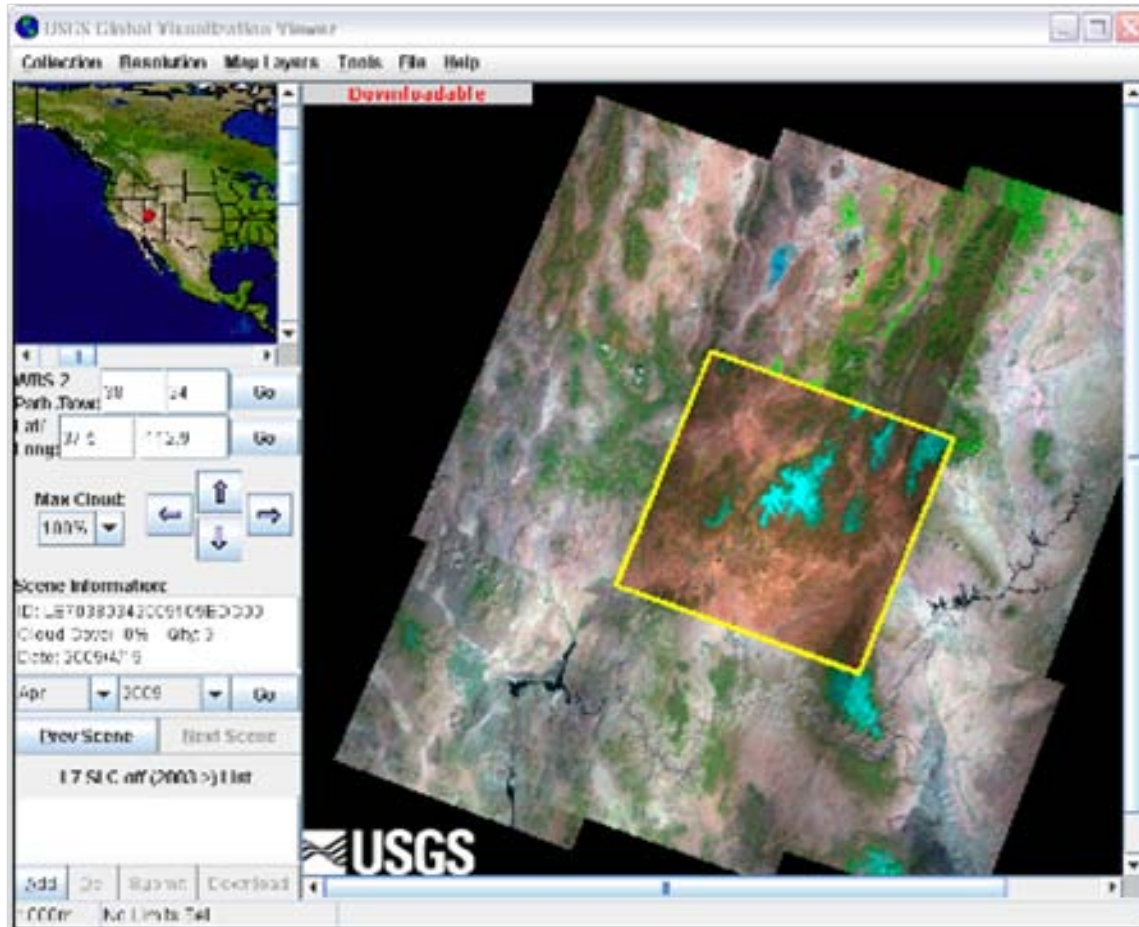


Figure 5. USGS GLOVIS interface for selecting and downloading Landsat imagery.

Atmospheric correction and normalization (SOP 2): We use the same simple atmospheric correction approach described in prior work (Kennedy et al. 2007b). For a single reference year, the COST correction is used to convert from Digital Counts to apparent surface reflectance. The COST correction includes a standard Dark Object Subtraction (DOS) correction to account for additive noise caused by aerosols, and then also includes a multiplicative correction using a first approximation of atmospheric transmission based on the cosine of the sun's zenith angle at the time of image acquisition (Chavez 1996).

The COST-corrected reference image is then used as the base for relative radiometric normalization of the remainder of the images in the stack. We use the Multiple Alteration Detection Calibration (MADCAL) automated approach for detection of stable targets, as evaluated by Schroeder et al. (2006), but applied to the special case of normalizing many images in a stack. Whereas the standard MADCAL routines derive relationships between images using a single 1000 by 1000 pixel subset, we have modified this to allow any arbitrary number of subsets. Additionally, each subset is tested for robustness for each target image/reference image pair before its no-change pixels are considered part of the larger population, thereby eliminating subsets that have clouds or other anomalies on any given target image. Therefore, a single set of

potential subsets is identified for use on all images in the stack, without the need to hand-pick clear-image subsets for each image pair. The relative normalization process can therefore proceed relatively quickly without significant human intervention.

Cloudscreening (SOP 2): It is critical to remove both clouds and cloud shadows. Our approach is to compare each target image in a stack against a single cloud-free reference image chosen by the analyst. For each target image, an automated algorithm is used to calculate two continuous-variable scores, one for clouds and one for cloud shadows (Figure 6a and 6b). These scores are derived from combinations of spectral bands and, when available, the thermal band. The analyst then manually views these cloud scores as grey-scale images, and determines an appropriate numerical threshold to separate cloud from non-cloud or cloud-shadow from non-cloud-shadow. These values are then used in an automated algorithm that develops binary masks for cloud and for cloud shadow, combines them, and then adds a buffer to allow for cloud-edge effects on neighboring pixels.

Segmentation

The core of the LandTrendr process is temporal segmentation: the identification of periods within a time-series where a consistent process is occurring, either stability, increase, or decrease in a selected spectral index (Figure 7). For example, a time-series running from 1985 to 2006 may be described as a single, stable segment with endpoints in 1985 and 2006, or by a single slowly increasing or decreasing trend with the same endpoints. Alternatively, a single abrupt disturbance in the year 1992 would result in a three-segment trajectory, with a stable initial period from 1985 to 1991, an abrupt change from 1991 to 1992, and a slow return from 1992 to 2006 (e.g. the green trace in Figure 2).

Segmentation occurs at the pixel scale as follows. For each pixel, the spectral values of a single index are extracted for each year in the stack. Although any spectral index could be used, our experience suggests that the tasseled-cap wetness index (Crist and Ciccone 1984) and the normalized burn ratio (NBR) are those most useful as all-around detectors of change. The NBR has been used in national parks as a means of observing fire severity (van Wageningen et al. 2004). Both indices include the short-wave infrared bands of Landsat, which are increasingly recognized as critical for detecting many types of change (Asner and Lobell 2000, Brown et al. 2000, Royle and Lathrop 2002, Skakun et al. 2003, Healey et al. 2006). If there are multiple images supplied for a given year in the stack, the algorithm chooses the best one based first on masking (clouded pixels are not chosen) and then date (pixels from the image closest to the median date for all images in the stack are preferred). The first algorithm examines the signal for all years that appear to represent turning points – either upward or downward – in the overall trajectory. These turning points are referred to as vertex years in the trajectory, since they describe vertices between two sequential segments. Selection of these candidate vertex years is a critical step that can be achieved with several different approaches, including evaluation of slope change with and without each vertex and deviation of the point from a longer-term straightline trend. Weight can also be given to years that precede or follow large disturbances, assuming that disturbance signals have a consistent directional character. The user specifies a series of parameters that describe the weights of these different tuning coefficients (SOP 3).

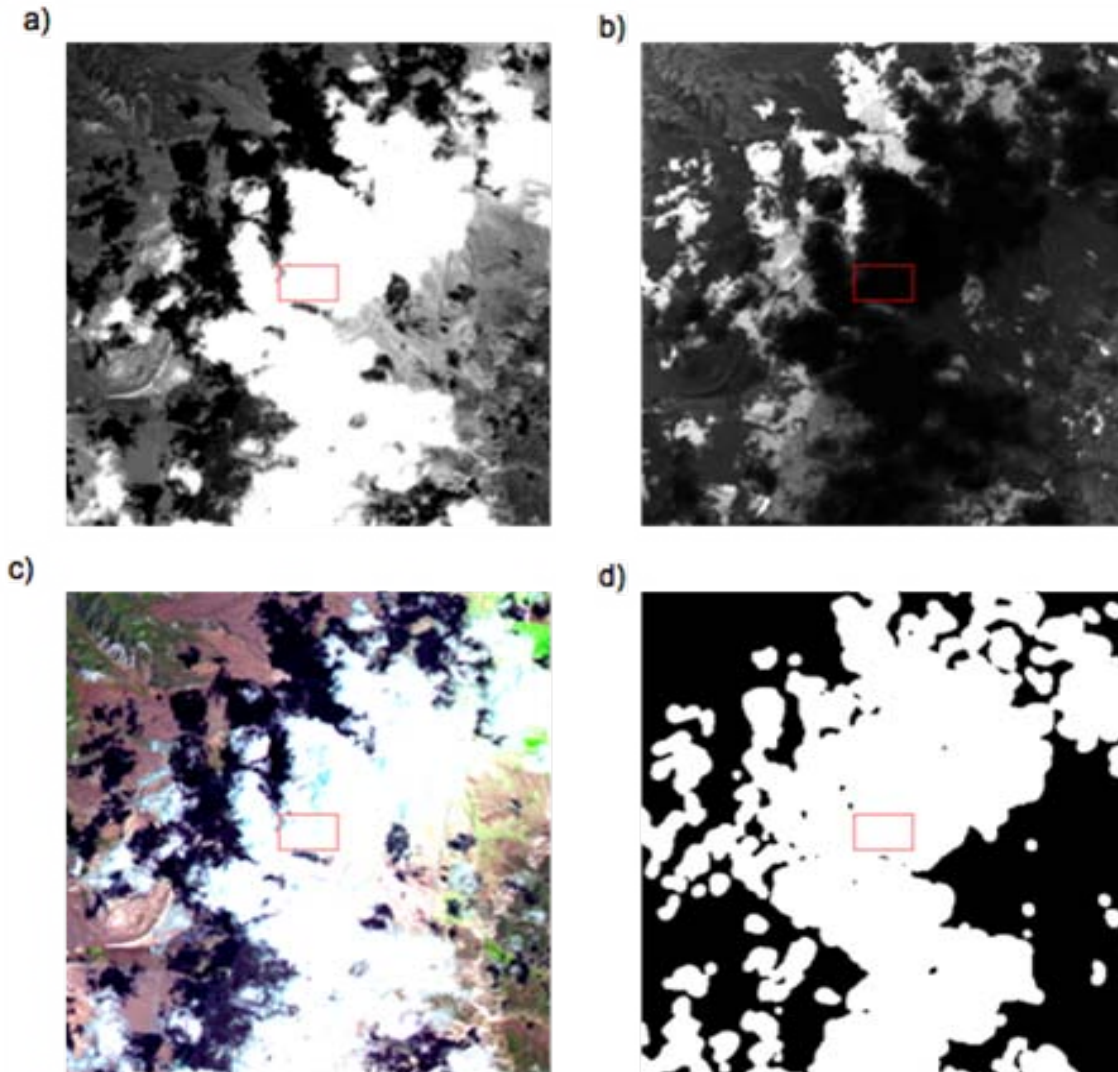


Figure 6. The cloud-masking process. For each image, a cloud score (a) and a cloud shadow score (b) image is produced. Part (c) shows the original image using a false-color 5,4,3 composite. For each image in (a) and (b), the analyst identifies a threshold below which cloud or cloud shadow is present, which is imported to a masking algorithm that combines the two into a mask (d).

Once a target number of candidate vertex years is chosen, a second set of algorithms then identifies the most parsimonious path through the vertex years (the x-axis) to describe variation in the signal (y-axis). These fitting algorithms are used again later in the LandTrendr + POM process (see next section). A third algorithm then identifies and removes the vertex whose removal caused the least penalty to overall description of variance, and then the second set of algorithms is reapplied to the smaller set of potential vertices. This vertex removal and trajectory recalculation is repeated until only one segment (with two endpoints) remains. Finally, another algorithm is used to determine which number of segments represented the best overall description of the trajectory.

The vertex years and vertex values of this “best description” of the trajectory are the foundational pieces of information for all further mapping. The vertex years and the values of the spectral index at those vertex years are written to output files for later processing. In addition to the vertices at the endpoints of segments, the fitted values at each year along the segment are also written to a “fitted value” image that has as many layers as there were years in the input image data.

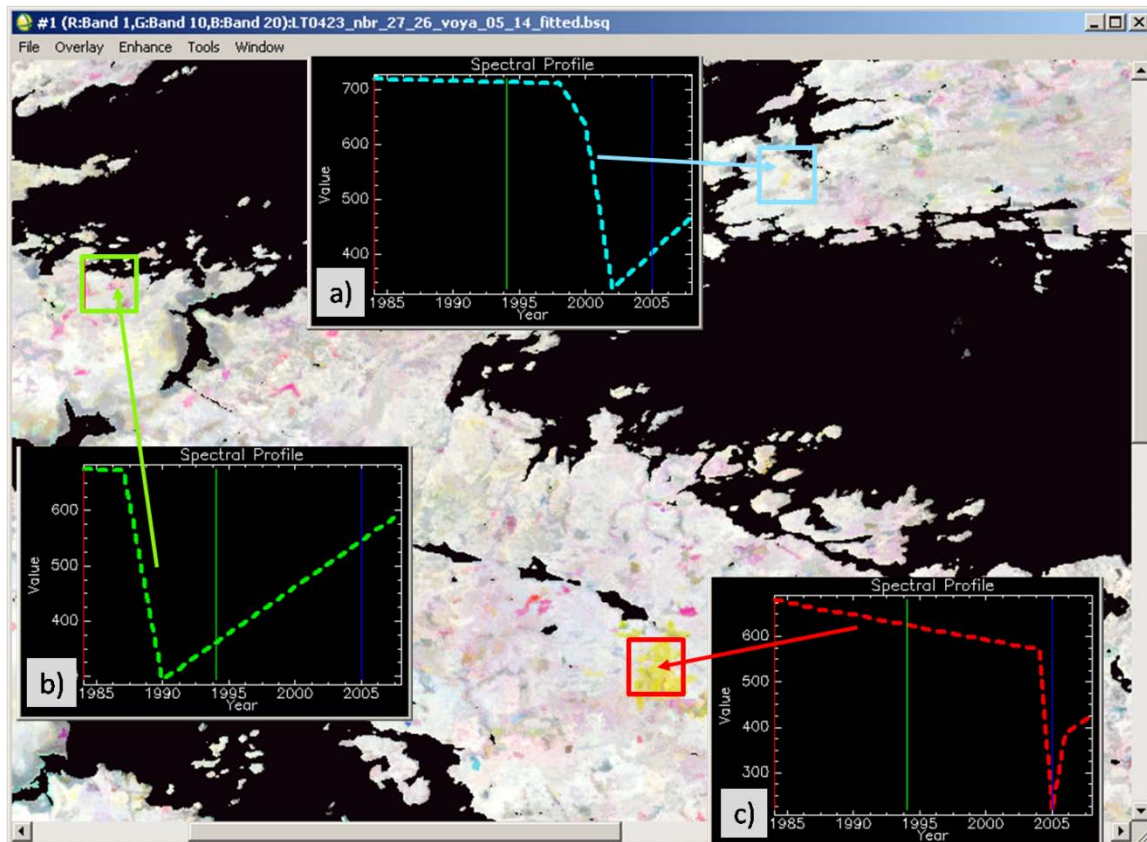


Figure 7. A false-color composite image of fitted trajectories of the normalized burn ratio (NBR) for the areas inside and outside Voyageurs NP. Shown are disturbance examples of forest harvest (a), beaver (b), and fire (c). In each inset (a,b,c) shows actual fitted trajectories of NBR (y-axis) for each disturbance example.

Change mapping

This fitted image can itself be used to display spatial patterns in the trajectories of pixels across an image and to compare visually with other datasets to understand if a particular known phenomenon is being captured by the segmentation process. However, the information is not summarized in a manner that can be interpreted quickly or quantitatively. The detail of the information exceeds the needs of most users; residual noise may also exist. Therefore, to make best use of the data, rule-based approaches must be applied to the vertex data to distill the

information into simpler forms that can be easily mapped. In essence, we seek to extract from a given trajectory its most salient or distinctive features while ignoring its uninteresting features.

There are two types of change-map that LandTrendr currently supports: segment-based and sequence-based. Each is described as a separate section below.

Segment-based mapping: The simplest means of distilling the information in the trajectories is to focus on segments in the trajectories that are associated with disturbances or recovery alone. Fires, blowdowns, harvests, insect mortality, and flooding due to beaver, are all examples of events considered as disturbances. This requires a sequence of processing steps, described in the following sections.

Segment-merging: First, each segment is identified as a disturbance or recovery segment by virtue of its direction of change in the spectral index value. The rule linking direction of change to disturbance or recovery is based on knowledge of the index involved: for both wetness and NBR, increases in the index value (toward greater positive values) are generally associated with increases in vegetative cover, and decreases in index value with decreases in vegetative cover. Therefore, if a segment moved from a lower to a higher value in either index, it was labeled recovery, and if the segment moved from higher to lower value, it was labeled disturbance. This rule, while simple and generally applicable, does not hold under certain circumstances (discussed later).

In some cases, an observed trajectory will be best described by a sequence of segments that includes two or more successive segments of the same type (either disturbance or recovery) with slightly different slopes. This is particularly common in post-disturbance recovery dynamics, where an initially steep rate of recovery of vegetative cover gradually slows as time-since-disturbance increases (Figure 8a). Some disturbance types also occur over long periods, with segments of slower and faster disturbance rate. For many applications, the component segments are not as interesting as the overall start and end of the disturbance and recovery process, and the total change from start to finish. To report those data, adjacent segments need to be coalesced.

However, we need to avoid coalescing potentially interesting and distinct processes. For example, an insect-related mortality event in forests may cause long, slow mortality with a gradually increasing disturbance signal (Figure 8b). If that is then followed by a fire with an abrupt, steep spike of disturbance, the two segments describe processes that are ecologically quite distinct and should be retained as separate pieces.

In the LandTrendr segmentation process, a simple threshold of angle-difference between segments is used to determine which adjacent segments of the same type are coalesced. Segments with similar angles in the spectral index/year space are coalesced, while those sharply different angles will be retained separately. The angle threshold for coalescence is a parameter that can be altered as desired by an analyst (SOP 4).

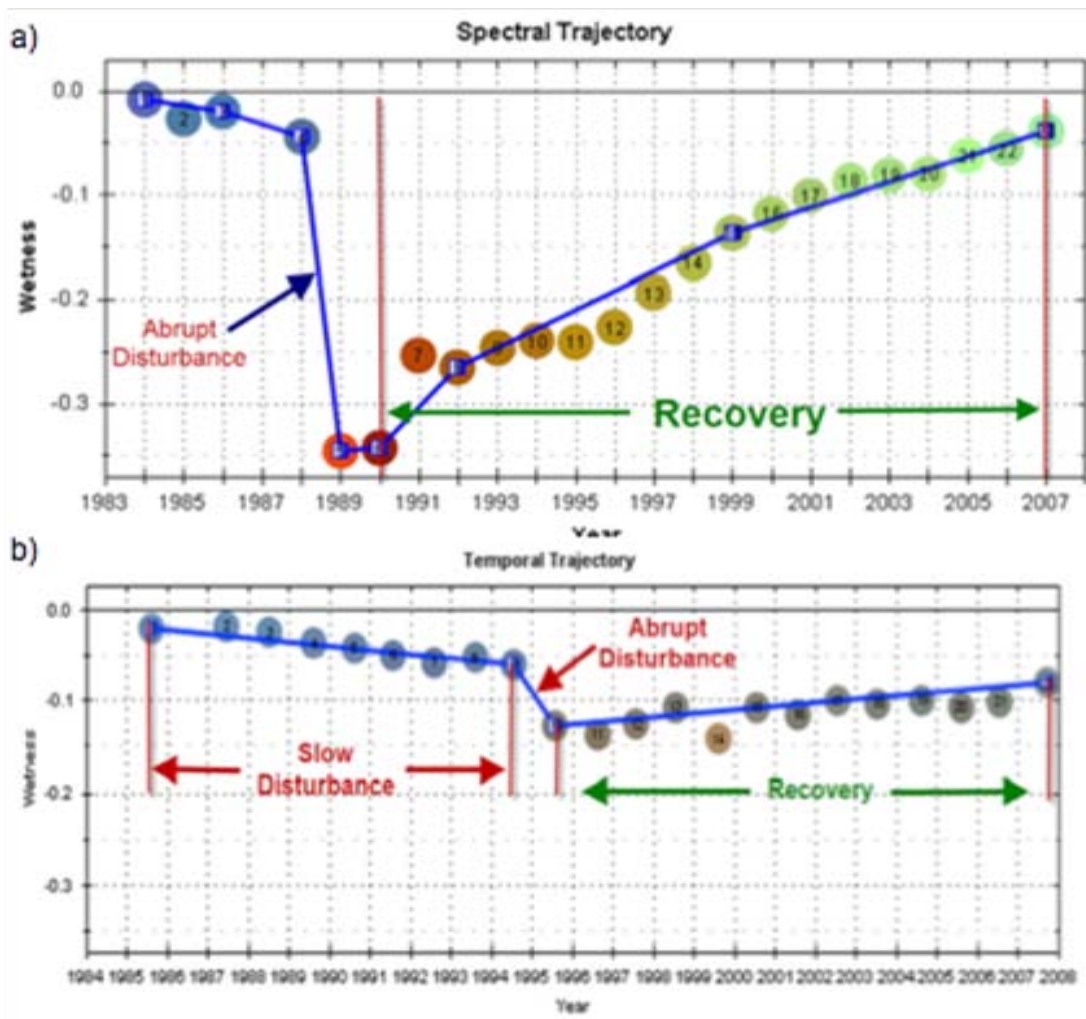


Figure 8. In many cases, the segmentation of a trajectory results in adjacent segments of the same type (disturbance or recovery) that differ only slightly in slope. a) In this example, the post-disturbance recovery period includes three straightline segments whose coalescing would simplify the information content greatly without sacrificing the key information about start, end and overall magnitude of recovery. b) Although some adjacent segments of similar type can be coalesced, others contain useful information. Here, a slow disturbance is followed by an abrupt disturbance; coalescence in this case would remove useful information about two distinct processes.

Filtering by magnitude and duration: The segmentation approach is potentially susceptible to “overfitting,” whereby an undesirable small noise event is captured as a meaningful segment. Relative to a simple two-date change detection, these “false positive” signals are greatly reduced in frequency, but they still occur. Therefore, in the LandTrendr processing flow, a thresholding process is used to remove any segment information that is indistinguishable from noise.

The threshold of change is based on percent vegetative cover. Percent vegetative cover can be estimated using statistical models linking photointerpreted percent vegetative cover with the spectral index used for LandTrendr change detection. For example, a random sample of pixels can be chosen from across a Landsat scene, and at each pixel an analyst can use airphoto

interpretation to estimate percent vegetative cover. These photointerpreted estimates of cover can then be linked to the pixel values of the NBR index, and a simple regression approach used to estimate the relationship between NBR and percent cover (described in SOP 4). Once determined, this percent cover estimate would be applied to the fitted vertex values in a trajectory segmentation, and any segments whose starting and ending vertices were closer in percent cover to each other than a given percent cover threshold would be considered “no-change.”

Once percent cover estimates are related to either the NBR or the wetness index used for segmentation, filtering is then applied differentially to disturbance and recovery processes. For segments associated with a disturbance event, the pre-disturbance cover and the relative magnitude of disturbance are considered in the filtering process. Disturbance segments that began in conditions having too little vegetation are considered noise, as are disturbance segments whose magnitude of cover change is too small. The change-magnitude criterion was adjusted relative to the duration of the disturbance process: short-duration disturbance segments are more likely to be identified by the algorithms through overfitting, and therefore require a greater magnitude of change to be considered meaningful than are segments that persist across many years of data. For segments associated with recovery events, a single magnitude of cover change is used for filtering.

At the end of this process, the remaining segments associated with each pixel’s temporal trajectory are mapped in two output image files with one layer for every year of imagery. One file corresponds to the magnitude of change beginning in the year of a given layer, and the second to the duration of that change. Because disturbance and recovery are of opposing magnitude, both disturbance and recovery events are captured in each layer.

Finally, a filtering algorithm is used to filter disturbances that are smaller than 9 pixels in size (ca. 1 ha). The result is a disturbance map that can be ingested into a standard GIS format to provide patch-level estimates of disturbance magnitude and year (Figure 9).

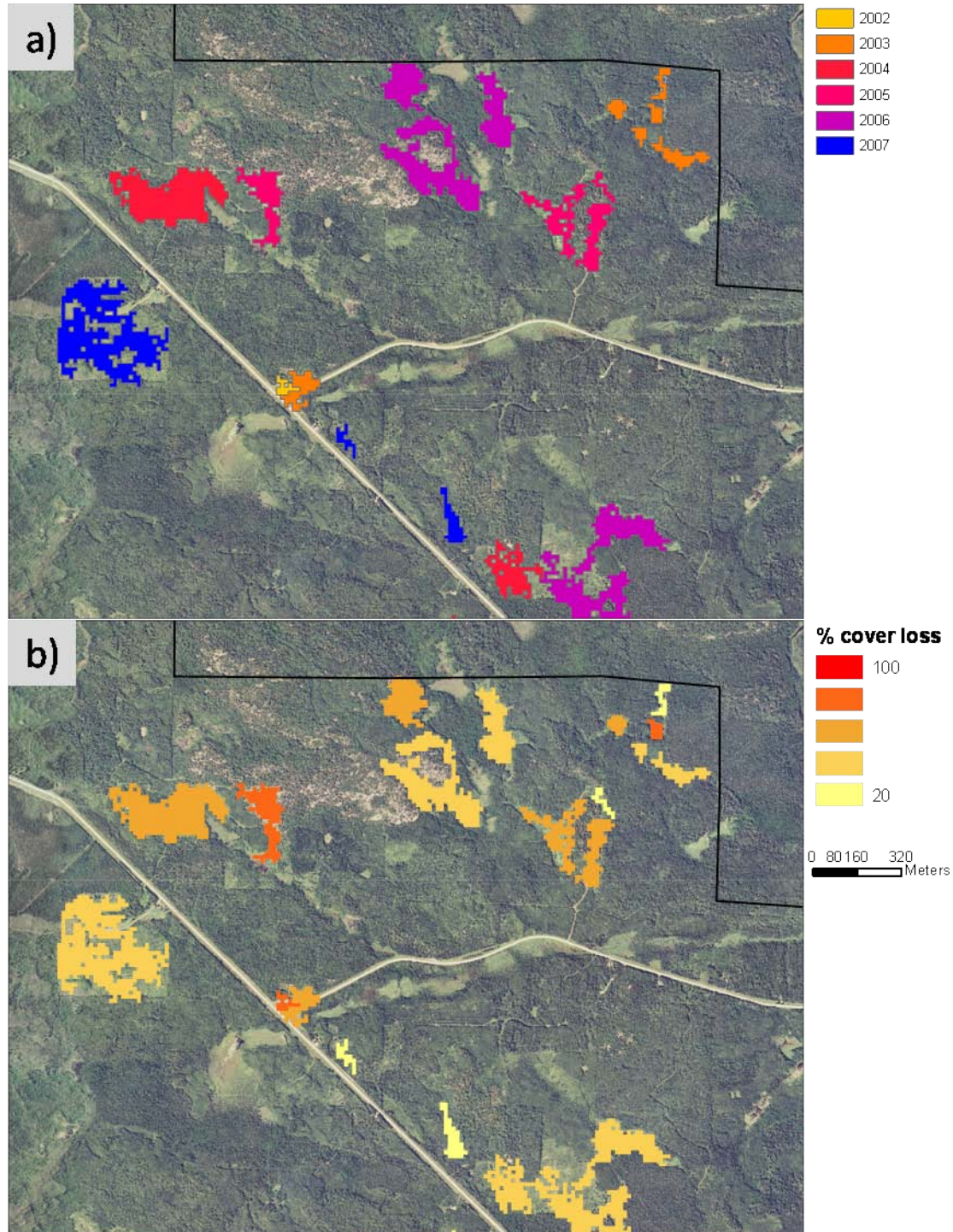


Figure 9. Disturbances outside Voyageurs NP mapped with the segment-based approach. a) Year of disturbance (colors) since 2002. b) Estimated average loss of percent vegetative cover for each area.

Sequence-based mapping: The segment-based mapping approach focuses on mapping individual events or processes, as captured by single segments in the fitted trajectory. While useful, this

approach leaves untapped a particularly useful aspect of the trajectory-based approach: the information content of sequential segments. As noted in Figure 8, disturbance events do not occur in isolation, but are followed by a post-disturbance growth or recovery process, and may be preceded by other growth or disturbance processes. The unfolding of sequential processes can sometimes provide greater insight into the underlying drivers or reasons for the change, which is ultimately of more interest to the parks than a simple map of disturbance events. For example, fire events that are followed by subsequent mortality may be quite distinct ecologically from those that show rapid regrowth of vegetation, and capturing the spatial patterns of those two types of fire effect may be more useful to the parks than simply knowing where and how severe fires were.

Therefore, LandTrendr provides “sequence-based mapping.” The user defines which sequences of fitted segment types are of particular interest, and the algorithms then analyze the fitted imagery to identify where those sequences are occurring, and labels them as such. The results are both a classified map with labels defined by the user, and maps of the magnitude, onset, and duration of the component segments in the sequence associated with each class.

Sequence-based mapping relies on the user passing information to the mapping algorithm to describe which segment types or sequences are of interest. This is achieved through a “change label syntax” coding that is passed to the mapping algorithms (detailed in SOP 4). A generic set of such change labels is provided in this protocol with the batchfiles used to create the change maps, but the GLKN parks could add any number of additional change classes as new processes or events become interesting. Generic change labels are shown in Table 1. Applied to the landscape, these rules provide maps that capture a wide range of landscape dynamics, both inside and outside the parks (Figure 10).

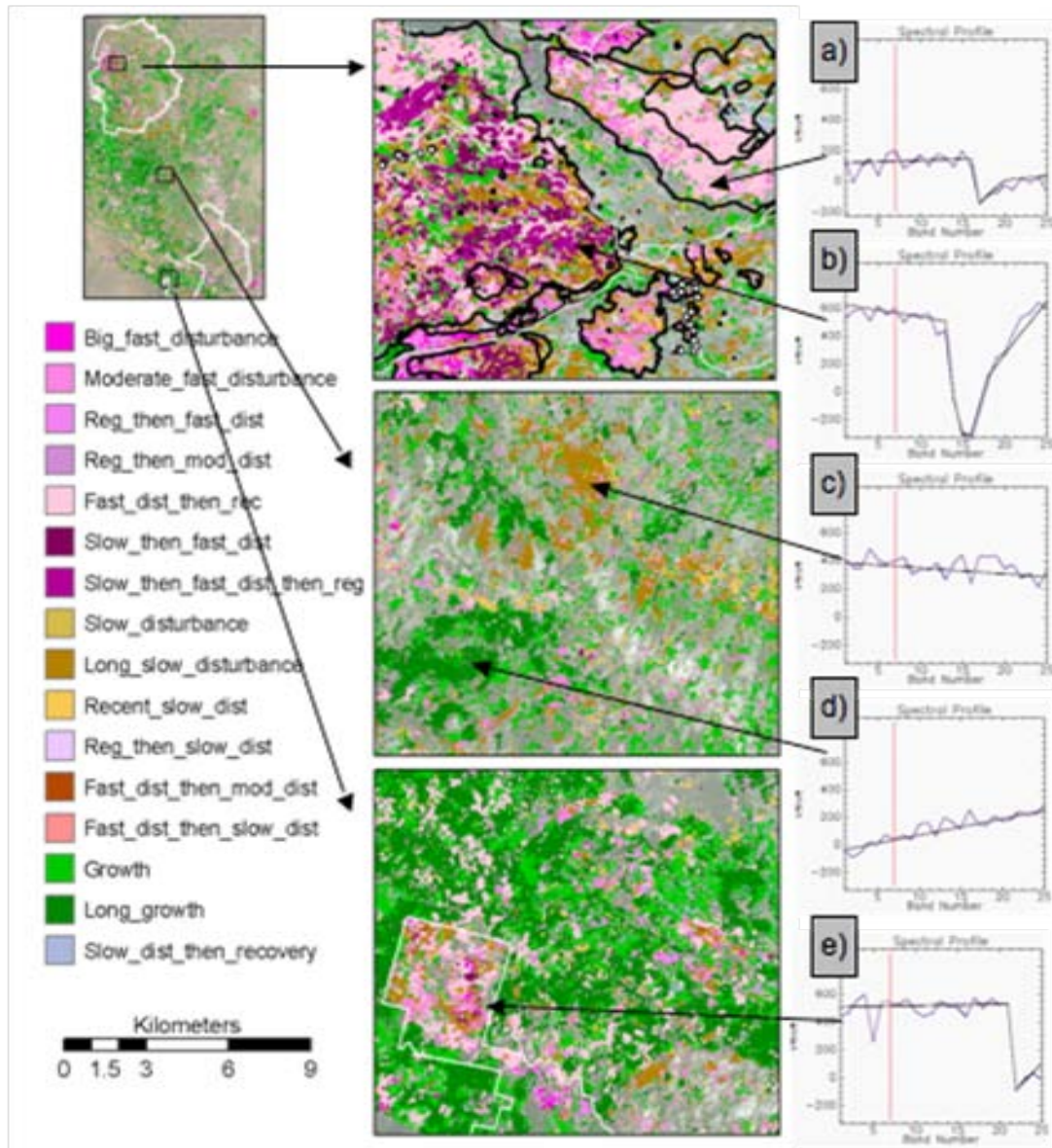


Figure 10. Segment-based mapping for the area spanning parts of both Yosemite and King's Canyon national parks. Generic change label rules are applied to fitted images to produce classified images that capture landscape dynamics. Maps capture the distinction between fire areas that burned relatively stable forest (a) from those that experienced pre-fire mortality (b), such as that likely caused by insect activity (c). The signal of growth is also captured (d), as well as the effects of relatively subtle effects of prescribed fires (e).

Table 1. Change label classes provided in the generic ruleset provided as part of this protocol.

Label	Code	Description
No change	--	Segmentation resulted in no significant deviation from mean spectral value over the period of record (1984-present)
No match	--	Initial segmentation found change, but it did not meet any of the change label criteria below
Moderate_fast_disturbance	GD0075XX0000L04	Greatest disturbance with magnitude > 75 and duration ≤ 4 yrs
Big_fast_disturbance	GD0300XX0000L03	Greatest disturbance with magnitude > 300 and duration ≤ 3 yrs
Slow_disturbance	FD0050XX0000G06	First disturbance with duration > 6 yrs and magnitude > 50
Long_slow_disturbance	FD0025XX0000G18	As prior, but with duration ≥ 18 yrs
Growth	FR0050XX0000G06	First recovery with duration > 6 yrs and magnitude > 50
Long_growth	FR0050XX0000G18	As prior, but with duration ≥ 18 yrs
Recent_slow_disturbance	FD0050GE1996G06	First disturbance beginning after 1996, with duration > 6 yrs and magnitude > 50
Rec_then_fast_dist	FR0050XX0000G06 FD0150XX0000L03	First recovery with duration > 6 yrs and magnitude > 50, followed by disturbance > 150 in magnitude and ≤ 3 yrs in duration
Rec_then_mod_dist	FR0050XX0000G06 FD0150XX0000G03	As before, but with disturbance > 100 and duration > 3 yrs
Rec_then_slow_dist	FR0050XX0000G06 FD0050XX0000G06	As before, but with disturbance > 40 and duration > 6 yrs in duration
Fast_dist_then_mod_dist	FD0150XX0000L03 FD0075XX0000G02	First disturbance > 150 in magnitude and ≤ 3 yrs in duration, followed immediately by another disturbance with duration > 2 years and magnitude > 75
Fast_dist_then_slow_dist	FD0150XX0000L03 FD0050XX0000G06	As prior, but with second disturbance of lesser magnitude and greater duration
Fast_dist_then_rec	FD0150XX0000L03 FR0050XX0000G04	As before, but with recovery instead of disturbance following an initial disturbance
Slow_then_fast_dist	FD0050XX0000G06 FD0150XX0000L03	Disturbance with duration > 6 years and magnitude > 50, followed by abrupt disturbance
Slow_then_fast_dist_then_rec	FD0050XX0000G06 FD0150XX0000L03 FR0050XX0000G04	As before, but with a recovery following the second disturbance
Slow_then_recovery	FD0050XX0000G06 FR0050XX0000G02	Disturbance with duration > 6 years, followed by recovery

LandTrendr + POM

The Great Lakes I&M network is currently waiting to implement this portion of the protocol until after all parks have had LandTrendr run on them. There are two main reasons for this approach. First, there is a large workload to establish the reference stack of Landsat imagery and

adding the probability-of-membership (POM) portion would add another workload to an already-full schedule. Second, the network staff will have more experience with LandTrendr and be prepared to add another portion of this protocol after running LandTrendr at all of the parks. However, since the network will implement this portion in the future, we have chosen to include it in this protocol and associated SOPs.

Although the LandTrendr algorithms are useful for producing labeled maps of disturbance and recovery, they only capture and label such change in one spectral dimension at a time. A single spectral index does not carry the full range of information contained in the larger spectral space, which limits the degree to which conditions and changes can be labeled. Therefore, a key component of the Oregon group's work has been to build links between LandTrendr and the POM approach which formed a major component of a previous landscape monitoring protocol for the North Coast and Cascades Network (Kennedy et al. 2007a). By combining the two approaches, the hope was that problematic phenological noise in two-date change detection could be largely removed through fitting, and then the power of landcover labeling with POM could be used to describe change.

The overall process of integration involves three broad steps (Figure 11). First, LandTrendr algorithms are used to create temporally-smoothed images that remove any non-informative year-to-year variation from the images. Then the single date of imagery closest to the park-specific land cover or vegetation map is used in the standard POM process to develop probability-of-membership lookup-tables that link the fitted spectral space to the park-specific cover map. Finally, those rules are applied to the spectral values of all fitted images to produce labeled maps based on the NPS map labels.

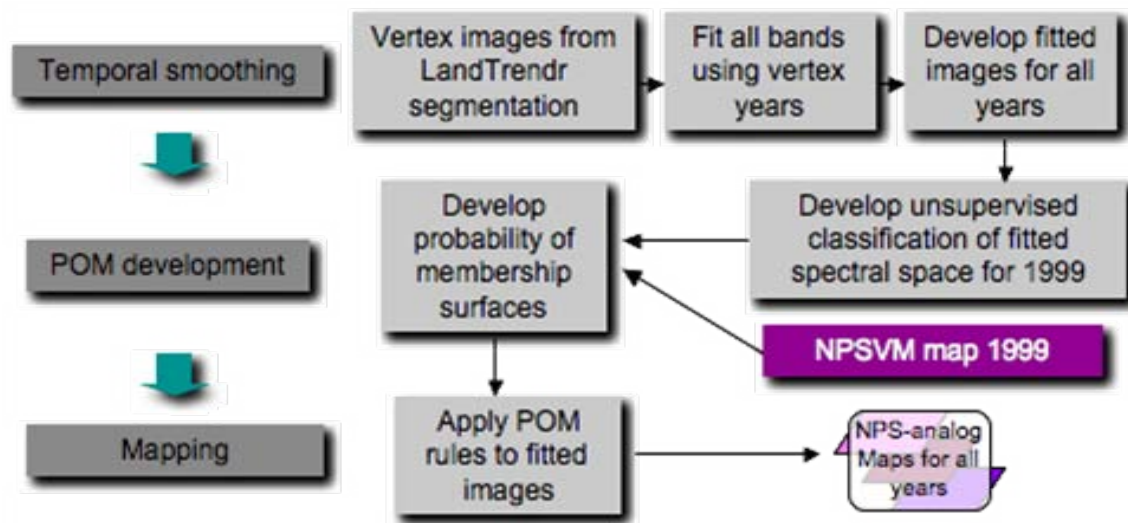


Figure 11. The overall workflow of LandTrendr + POM for a park with a 1999 landcover map from the NPS Vegetation Mapping (NPSVM) program.

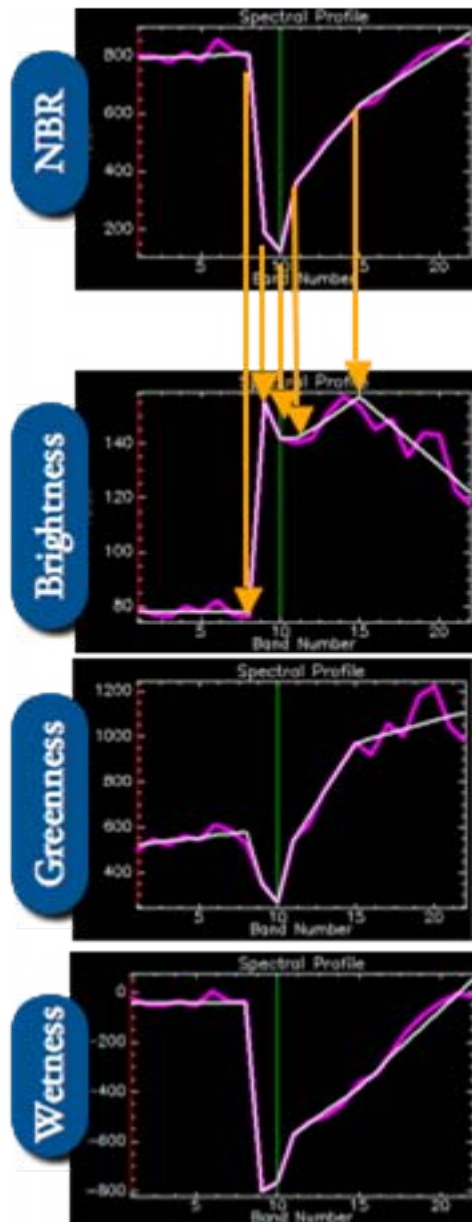


Figure 12. Once LandTrendr algorithms have been applied to a core index (here, the NBR, at top), other spectral indices (here, the tasseled-cap) can be smoothed using a constrained segmentation driven by the vertex years of the original segmentation.

Temporal smoothing

The link between LandTrendr and the POM approach is temporal smoothing of the raw spectral data. LandTrendr segmentation is applied as described in the prior section on a single spectral index or band, but rather than derive maps from the summary characteristics of the segments, we force other spectral bands to conform to the temporal segmentation of the single index (Figure 12). Vertex years from the NBR fitting are exported to the LandTrendr fitting algorithms (described in the segmentation section above) to determine the most parsimonious path through other spectral bands, given fixed vertex years. Fitted values for each year for each band are

recombined by year to create fitted “pseudo-images” that are temporally-smoothed representations of the original data.

POM development

The POM approach was designed as an attempt to merge the mapping perspectives of remote sensing scientists and ecologists. Remote sensing scientists approach mapping from the perspective of signal content within the spectral space defined by a satellite sensor, aggregating and separating land cover classes according to their distinctiveness in spectral space. Ecologists approach mapping from the perspective of ecologically-meaningful distinctions in vegetation and abiotic types, aggregating and separating land cover classes according to the functional processes or the species of interest. These two worldviews often do not produce maps with the same labels, so an approach is needed to build a map that captures the essential elements of both views.

The POM approach begins with the premise that a single-date, airphoto- and/or field-based map exists and is meaningful to park specialists. Typically, this map contains far more detail in terms of land cover class than can be captured from spectral distinctions alone. When classes are aggregated into simpler definitions, however, the satellite data could create reasonable maps.

Separately, the spectral space of the pseudoimage closest in date to the year of the NPSVM map is partitioned. A standard *k*-means non-parametric partitioning algorithm is used to create a set of image “spectral classes” that optimally divide the spectral space. The classes have no inherent meaning in terms of land cover, but capture the distinctions in spectral space on the landscape. Thus, the unsupervised classification results can be considered one optimal approach to characterizing the variability in condition on a landscape, as reflected in the spectral variability. For each unsupervised class, the Gaussian likelihood surfaces that represent the POM in each class for all parts of the spectral space are calculated (SOP 8).

Integration of the NPSVM and unsupervised classes is central to the POM approach. Each Gaussian probability surface is overlaid on a similar Gaussian probability surface for the NPSVM classes to result in an amalgam probability surface for each NPSVM class. The mathematical integration ensured that all areas of spectral space were covered, and also that all NPSVM classes had the potential to be mapped. However, this process also penalizes NPSVM classes that were spectrally ambiguous – NPSVM classes with broad distributions in spectral space dilute their probability surface over a larger area, reducing the probability of being selected as the label for any particular portion of the space. NPSVM classes that are spectrally distinct, on the other hand, are more likely to be chosen as labels for some portion of the spectral space. Thus the POM mapping process is an unbiased approach to retaining spectrally-distinct ecological classes and removing spectrally-ambiguous ecological classes. The final product of this process is a POM lookup table that links the spectral values in the pseudoimages to the probability of membership in the aggregated NPSVM landcover classes. By applying these lookup table rules to any of the yearly pseudo-images created using methods described in ‘Temporal smoothing’ section, a new landcover map can be created for the year of that pseudo-image (Figure 13).

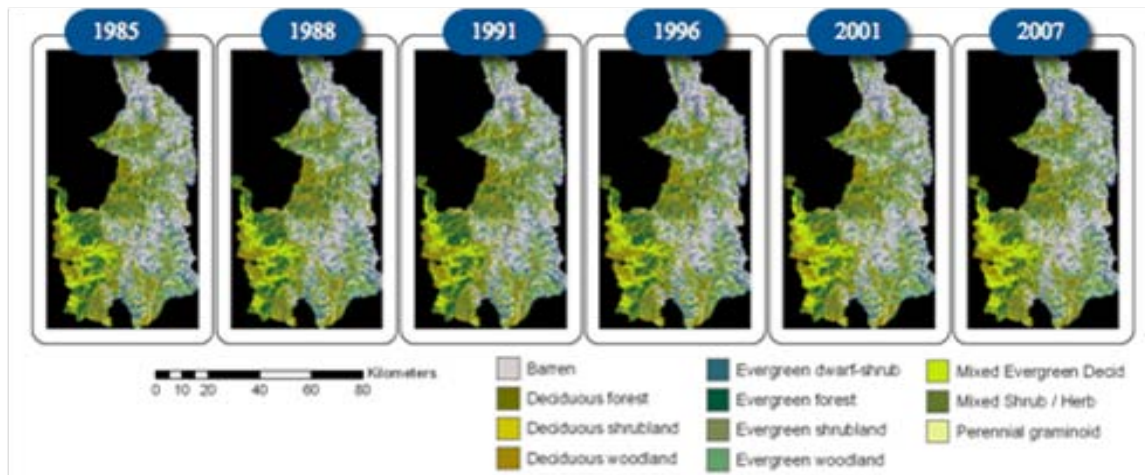


Figure 13. Landcover classes for Sequoia and Kings Canyon NP derived using the LandTrendr + POM approach for a selection of years (maps for all years from 1985 to 2008 are created).

Laboratory Validation

As was mentioned in the introduction, a main objective this network had when it started considering this protocol was to not only know where on the landscape changes were occurring, but also what was causing the changes. While the sequence-based mapping approach provides information regarding disturbances and recoveries and how these are linked together temporally, it still falls short of ascribing change agents. Being able to summarize changes in and around the park in terms of agents of change is important to the parks in the network. Laboratory validation adds significant amounts of information to an already-rich LandTrendr dataset by not only being able to ascribe change agents, but to also identify starting and ending land cover classes. Also, although a large amount of time and innovative ideas have gone into the development of LandTrendr algorithms to remove disturbances which are not of interest, also termed false positives (areas identified as change that have not actually changed on the ground), there are still a number of LandTrendr disturbances which are false. To provide more accurate estimates of disturbance characteristics and where they occur, the network has decided to manually validate each disturbance generated by LandTrendr.

To appropriately validate LandTrendr disturbances and add information such as change agent and starting/ending classes, validation data needs to be high resolution, both spatially and temporally, to provide enough detail to determine if a change has occurred and also provide information regarding the likely disturbance agent. The temporally high resolution dataset is the Landsat image stack, and the spatially high resolution dataset is high resolution (≤ 1 m) aerial photos (Figure 14). These aerial photos can come from various sources with the two most likely sources being state/federally-funded airphoto flights (National Agriculture Imagery Program) or network-funded flights which usually cover the park of interest and some small buffer (ca. <1 km) surrounding the park. The Network-funded flights will be flown during spring leaf-off conditions for three main reasons. First, these airphotos are not solely utilized by this protocol, they are also very valuable to the park and they prefer spring leaf-off imagery. By acquiring leaf-off imagery, we are able to view ground features, such as windthrown trees, on the forest floor not visible during leaf-on conditions. And lastly, peak leaf-on conditions have been historically captured by the NAIP flights and provide a valuable complement to the Network's high

resolution leaf-off imagery. By compiling all sources of airphotos for each park in the network, in conjunction with the Landsat imagery stack, we are then able to determine if a change has occurred and the likely change agent. During the laboratory validation process, detailed in SOP 6, three main pieces of information are collected: validity of disturbance event, change agents are ascribed, and starting/ending classes are denoted. The end result is a much richer dataset while at the same time eliminating false positives.

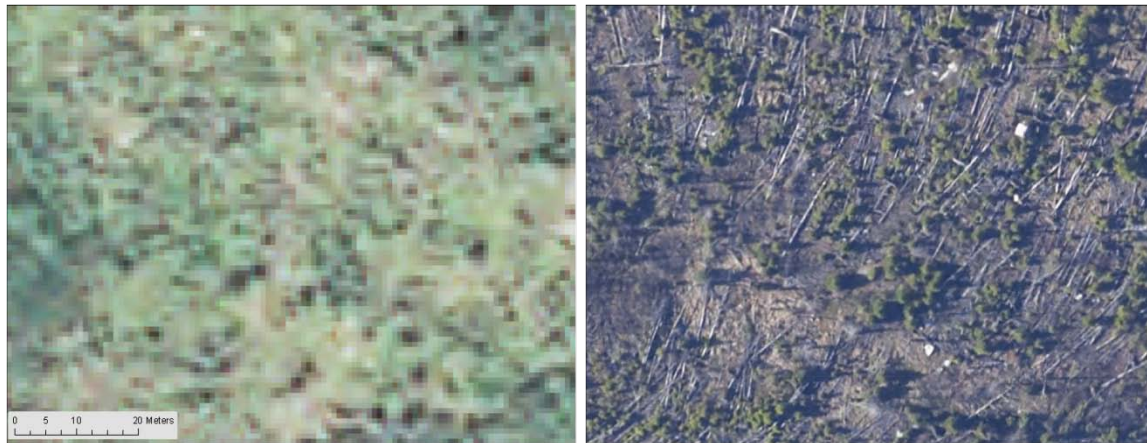


Figure 14. Comparison of two resolutions of airphotos. In the left, a 1 m resolution airphoto flown in the summer of 2008 by a federally/state-funded NAIP flight. On the right, the same area and year, with a 15 cm resolution where individual fallen trees can be distinguished.

Laboratory validation is performed using two separate programs simultaneously. First, ArcMap is used to display disturbance polygons (as detected by LandTrendr) while also providing a form the user fills out for each polygon with drop-down lists providing pre-defined options for the user (Figure 15). This program is also used to display many other sources of geospatial data which could include, but is not limited to, land cover maps, boundaries (state, federal, county, park, etc.), airphotos, digital raster graphic (DRG), digital elevation model (DEM), and a soil survey (if one exists). The second program used during laboratory validation is called TimeSync, developed by the Oregon group (Figure 16). Once a set of image stacks has been assembled for use in LandTrendr, it can also be ingested into the TimeSync program, which displays image chips from the entire stack of imagery and simultaneously displays the spectral trajectory (using any desired spectral index) of the central pixel in each image chip. By providing the interpreter with both spatial and temporal depth, detection of subtle events is vastly improved relative to single- or two-date interpretation, and ephemeral non-informative changes are easily ignored.

To reduce the amount of user bias and increase accountability, the Network has also developed user confidence scores. During laboratory validation, the user is required to quantify their decisions regarding each polygon in the form of confidence scores. Confidence scores are based on three sources of information: airphotos, spectral trajectories, and Landsat imagery. For each information source, the user indicates the confidence of their change call, ranging from 1-3, with 1 being low confidence and 3 being high confidence. For example, if the user validating a disturbance using airphotos views standing trees before the disturbance occurred (as indicated by

LandTrendr) and clearly views trees on the ground after the disturbance, the user would fill in a confidence score of 3 (high confidence) in the “airphoto confidence” field. In addition to filling out the airphoto confidence score field, the user is also required to indicate which airphotos were used to make this decision, introducing accountability and repeatability. If a disturbance is not clearly evident in the available airphotos, the user can rely on the spectral trajectories and/or Landsat image chips as displayed by the TimeSync program. These confidence scores offer a quantifiable method of validating disturbances and provide a useful and important measure of confidence through three types of data. Details and numerous examples regarding confidence scores are provided in SOP 6.

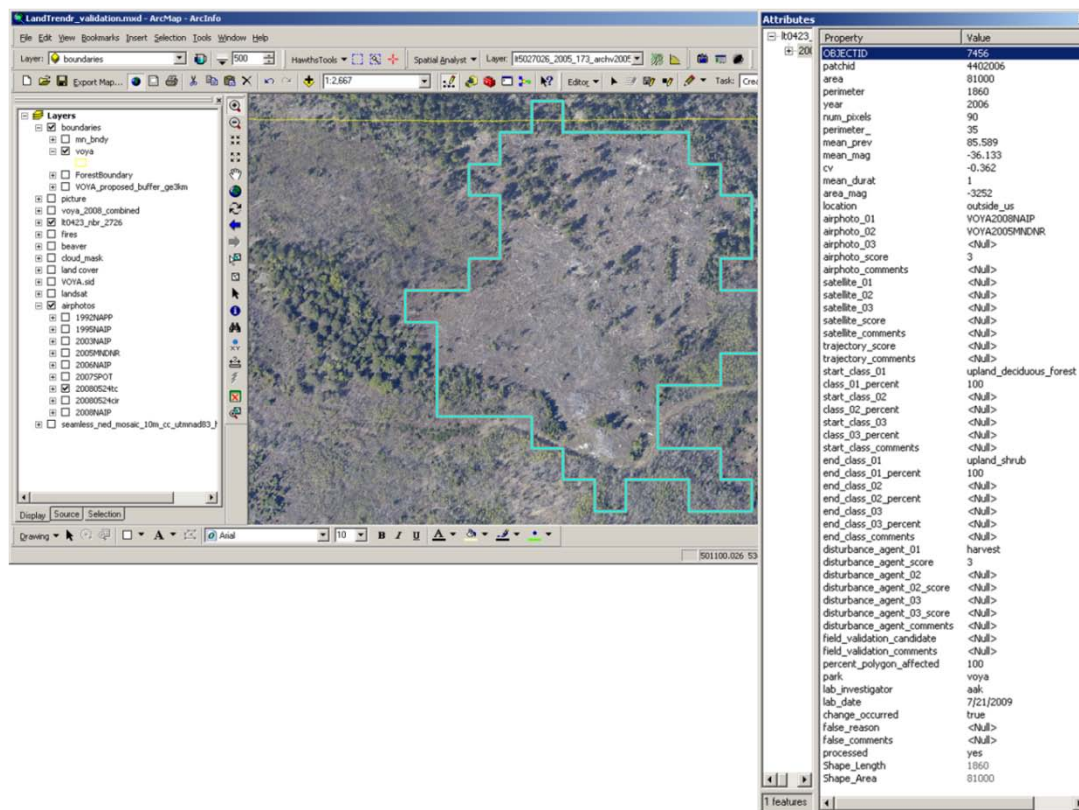


Figure 15. ArcMap project wherein the user validates each polygon using various data sources. Each polygon has a number of drop-down fields (attributes) which the user has to fill in with one of the options.

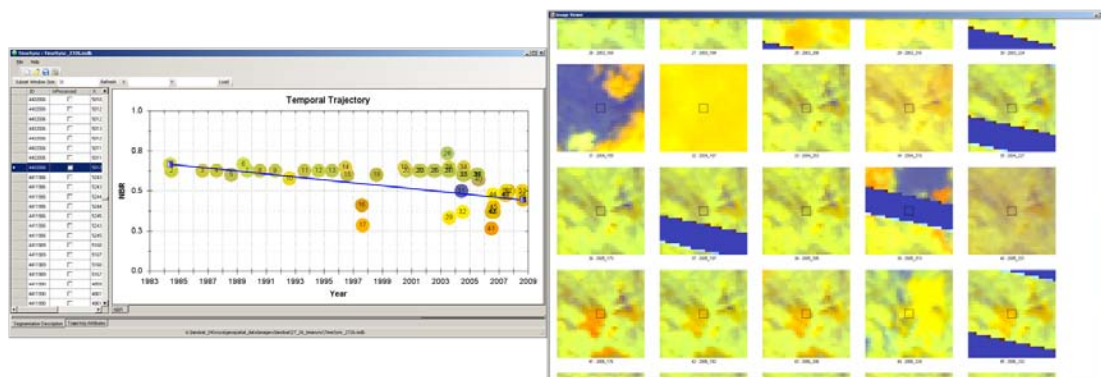


Figure 16. The TimeSync program has two windows associated with it. One window (on left) displays the average trajectory of a user-defined number of pixels (temporal trajectory). The second window (on right) displays image chips of all Landsat images in the image stack, from 1984-present.

At this time (1/1/10) the Network has contracted the Oregon group to modify version 1.0 to better suit the network's needs. The Network is not expecting to receive the final version of TimeSync 2.0 until summer of 2010. However, the Network is still able to use the current version (1.0), and will do so until the newest version is released. After the network receives the new version, the associated SOP (5) will be modified to reflect the changes in version 2.0. The network expects that the core of this SOP will remain the same, with some changes occurring in the creation of imagery lists.

Land cover classes

A major component of any vegetation monitoring protocol is land cover classification. As was stated earlier in the introduction, there are numerous ways to classify vegetation depending on the user's preference. Since GLKN's highest priority is to monitor changes and not to classify land cover (as in using stereo pairs of aerial photos), we are placing less emphasis (and time) on land classification and more emphasis on change detection over time both inside and outside the park. However, GLKN will still classify starting and ending classes, but at a less detailed level than currently available with the National Vegetation Classification System (NVCS) and no validation of cover class calls will be made in the field. We have decided to ascribe vegetation classes in more general classes than the association level of the NVCS in part because we realize the NVC map is not completely accurate. This again reflects the network's emphasis on change detection, as opposed to land cover classification. Also, these cover class calls will only be made on polygons determined to be true, or where change (as defined by LandTrendr parameters) has actually occurred. More information regarding the land cover classes used in this protocol can be found in SOP 6, Appendix 2.

Feasibility of laboratory validation

To assess if validation of each polygon was a feasible task, GLKN tested this technique at the largest park in the network, VOYA. During the pilot project, GLKN validated every polygon from 2002-2007 inside the park and the buffer area surrounding the park, which resulted in a total land area of ca. 150,000 ha. One remote-sensing specialist performed all validation in approximately 80 hours, proving that validating each polygon is a feasible task. The specialist followed SOP (6) during the validation process while providing multiple types of information for each polygon, regardless of whether it was a true or false change.

Field Validation

Field validation is the second of a two-part validation process. The authors believe field visits to a park each year are imperative in a long-term monitoring protocol. There is no substitute for being able to view the vegetation and land use practices in the park and surrounding areas from the ground or low-flying aircraft. While this is not a quantitative method, we strongly encourage the user(s) to visit the park they will be analyzing with LandTrendr, prior to actually running LandTrendr. This experience is invaluable during the winter when the user is analyzing potential disturbances and interpreting Landsat imagery. These visits will also provide the user with the opportunity to communicate with park staff (natural resource managers, amongst others) and become familiarized with the ecology of the park. In addition, Network staff are usually presented with an option to speak to the public via campground talks or learning centers in which they will be able to communicate the monitoring they are performing along with results for the current park. To ensure these opportunities are not missed, land cover and outreach programs need to be in communication throughout the year.

After validating disturbances in the laboratory using available airphotos and ancillary data sources, there will be some disturbances in which the user was unable to determine if a change occurred. These areas will be visited in the field where the final decision will be made regarding the validity of the disturbance. Details regarding measurements can be found in the next section, as well as in the field validation SOP (7).

Although field validation is an important part of any monitoring protocol, based on the pilot work performed at VOYA, there were only a total of 8 polygons in the past 6 years (2002-2007) which warranted field validation. While this was only one park, we expect the number of polygons to be field-validated every 6 years at a park to be low (<15). It should be noted that this also depends greatly upon the availability of high resolution airphotos. VOYA had numerous sets of airphotos, most notably, a 15 cm set of photos flown in the spring of 2008. Users should expect more questionable, i.e., field validation polygons, with fewer sets or lower resolution sets of airphotos. This is just one of the reasons the Network is planning to contract high resolution (≤ 25 cm) spring, leaf-off, airphoto flights for each park on a 6 year rotation.

Field sampling measurements

Once the polygons for field validation are identified, there are several important challenges associated with field sampling in support of remote sensing-based maps of landscape change. First, evidence of the change weakens with time, making it difficult to evaluate change labels that occurred in the past. Second, observation of a single condition after the change can only reliably quantify current conditions, not the contrast between the current conditions and the unknown prior conditions. Third, change labels are assigned at the grain size of a single satellite pixel, which is sometimes a larger footprint than can readily be evaluated on the ground. Despite these challenges, field validation can provide valuable insight into the processes captured (or missed) by the satellite imagery, provided these challenges are considered during the design of field sampling and during the interpretation of ground-observations.

As was mentioned earlier, depending on how long ago the disturbance occurred and how subtle it was, the user may not be able to see evidence of the change in the field. For example, if a forest tent caterpillar outbreak occurred three years ago, with a duration of two years, it could be

extremely difficult to tell whether this disturbance had occurred because the trees show no evidence of herbivory when visited in the field. The only solution for such an issue would be to detect changes the year they occur, then validate the changes the same year. We contemplated this methodology but quickly dismissed this as an option due to the infeasibility of such a rapid response system. Instead, we realize and accept this issue and have instead moved forward with a monitoring protocol which emphasizes feasibility and long-term consistent monitoring of changes on the landscape using a robust methodology.

While in the field, staff will need to navigate to the polygon of interest using a GPS in conjunction with maps developed in the laboratory (SOP 7). Once at the center of the polygon, the field crew will assess the validity of the disturbance using the validation datasheet (Figure 17) to collect needed information. For field validation, we focus on determining if a change has occurred not by quantifying percent cover or basal area, but rather by noting any evidence of visible disturbance by walking through the polygon and noting this on the datasheet, taking pictures, and recording waypoints. It is necessary to emphasize that field validation of disturbances in this protocol does not follow classic field work, but instead requires the user to view the field work as it pertains to the overall goals of the protocol. These goals are to determine where and if disturbances have occurred by using contextual information such as tree species, geographic position, surrounding vegetation types, and disturbance evidence such as fallen trees, stumps, diseased trees, or recent beaver activity.

LandTrendr Validation

We have documented steps to be taken to validate the changes LandTrendr defines, but an analysis to determine disturbances that were not identified also needs to occur. The Network has contracted with the Natural Resources Research Institute (NRRI) in Duluth, MN to provide this independent analysis of change detection. In this change detection NRRI was provided with all available airphotos and a total of 60 randomly selected 1 x 1 km boxes, with 35 and 25 located inside and outside the park, respectively. NRRI was asked to delineate any changes that LandTrendr should have detected, according the methodology we have described. For example, any disturbances less than 1 hectare in size were not delineated by NRRI because GLKN already accepts these omissions as part of the limitations of the protocol. However, any changes not attributable to phenology and year to year variations in hydrology, with areas larger than 1 ha were delineated by NRRI technicians. This project has recently been completed and at first glance, it seems that LandTrendr and the airphoto interpretation results agree. Additional analysis will be done with this data to summarize both the manual and LandTrendr results and will be included in the next version of the protocol.

Park	VOYA	PatchID	Date	Time (24hr)
Personnel		GPS unit	Camera	

GPS and pictures		
Waypoint ID	Time	# pictures @ wpt
Waypoint ID	Time	# pictures @ wpt
Waypoint ID	Time	# pictures @ wpt

Evidence of disturbance (circle)	
fresh stumps	beaver
standing dead	water fluctuation
fire scars	diseased leaves

False reason (circle)
wetland phenology
shadow
water fluctuation
misregistration

Starting/ending classes, disturbance agent	
start class 01	
start class 01 percent	
start class 02	
start class 02 percent	
start class 03	
start class 03 percent	
start class comments	
end class 01	
end class 01 percent	
end class 02	
end class 02 percent	
end class 03	
end class 03 percent	
end class comments	
disturbance agent	
disturbance agent score	
disturbance agent comments	
percent polygon affected	

Starting/ending classes
upland evergreen forest
upland deciduous forest
upland mixed forest
upland evergreen woodland
upland deciduous woodland
upland shrub
upland herbaceous
lowland evergreen forest
lowland deciduous forest
lowland mixed forest
lowland shrub
lowland herbaceous
land use building
land use agriculture
road impervious
road pervious
beaches rock
water

Comments	
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Figure 17. Datasheet used in the field to denote observations at polygon.

IV. Data Analysis and Summary

Much of the data from this protocol is most effectively displayed in summary form. While these summaries are not necessarily statistically significant, they provide insight into the current and past disturbance regimes which will help inform resource management decisions. In this section we describe and provide examples of the types of base summarizations which will be provided every 6 years for a park. The goal of these standard summaries is to provide enough information to park natural resource managers to quickly view and interpret disturbances occurring inside the analysis area as well as develop future research questions. For example, if disturbances caused by beavers inside the park have been steadily declining, this may warrant further investigation.

Data can also be summarized in the form of maps of disturbed areas. After disturbances are validated, the user is left with multiple ways to display and filter the polygons. General overviews of this information for the entire area of analysis prove to be difficult due to the large extent of the area and relatively few, and typically small, disturbances occurring in the park each year. The authors have found it more useful to look at individual areas more closely to view disturbances, which tend not to be evident at larger scales. For more details, see SOP 9: Data Analysis and Summary.

Graphs

Patch size

Patch size offers insight into the mean size of disturbances occurring in and around the park. As seen in figure 18, Canada has the largest mean patch size, a result of the large harvests occurring from 2002-2007. This parameter is important for wildlife management, due to the various needs of edge habitat, contiguous tracts of intact forest, and multi-aged forests for various animals (Stephens et al. 2004, Nielsen et al. 2008, St.-Laurent et al. 2009, Svancara et al. 2009). Depending on the wildlife of interest, the goals for patch size may vary. The authors have included a summary graph of patch size, however, this is only one way to view the data. Many other views of patch size are available if the natural resource manager would like to investigate further.

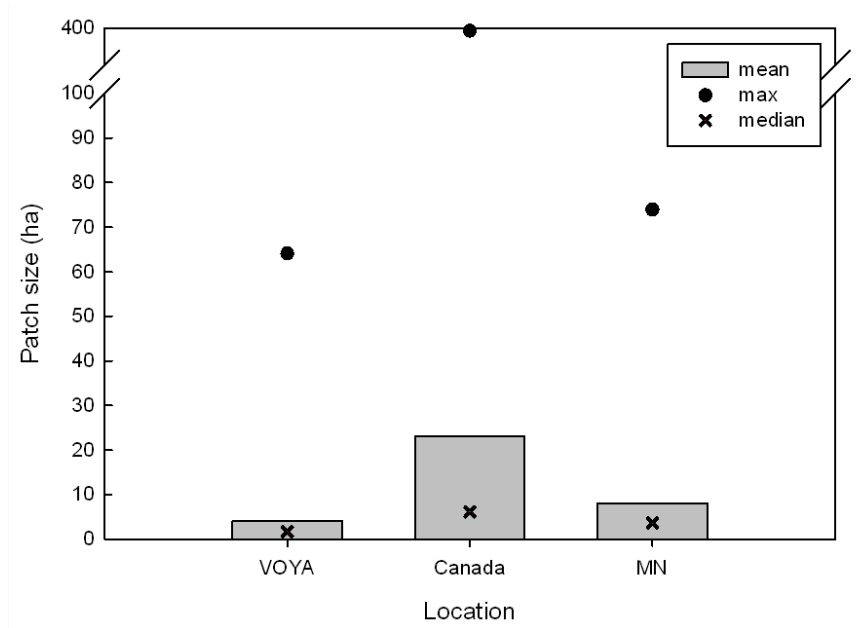


Figure 18. Patch size by location, showing the mean, maximum, and median patch size.

Percent of land affected by disturbance

Viewing disturbances as the percent of land disturbed by agent and year provides insight into how much of the land (%) is changing. For example, in figure 19 Canada has, on average, harvested ca. 2% of the land each year from 2002-2007. During the analysis period, 7.1% of the land was harvested. If this trend continues, all land area in the Canada analysis area will be harvested in ca. 84 years. Again, statistics such as this provide useful information regarding the lands bordering the park and how this may affect wildlife and water quality inside the park.

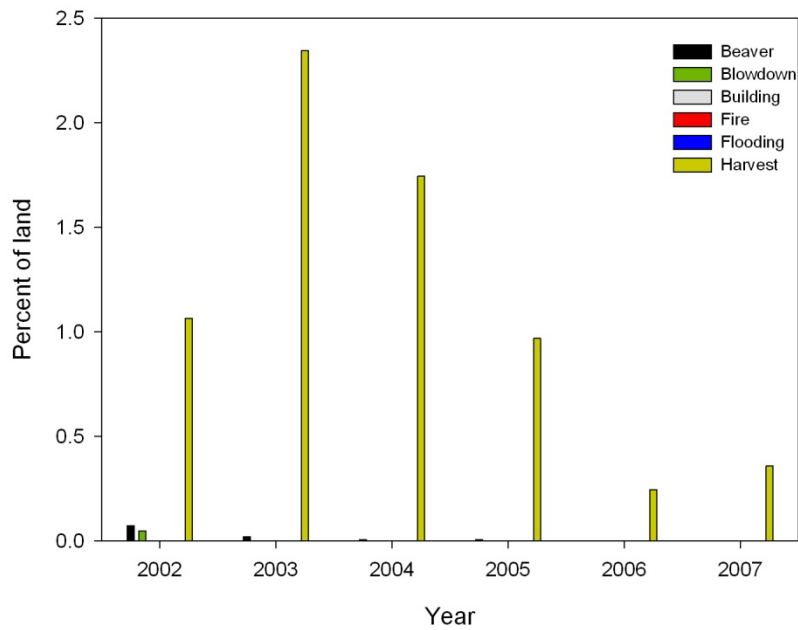


Figure 19. Percent of land affected by disturbance agent in Canada.

Area of land affected by disturbance

This summary (Figure 20) is very similar to the percent of land affected by disturbance graph, however it quantifies the area (ha) of disturbance each year.

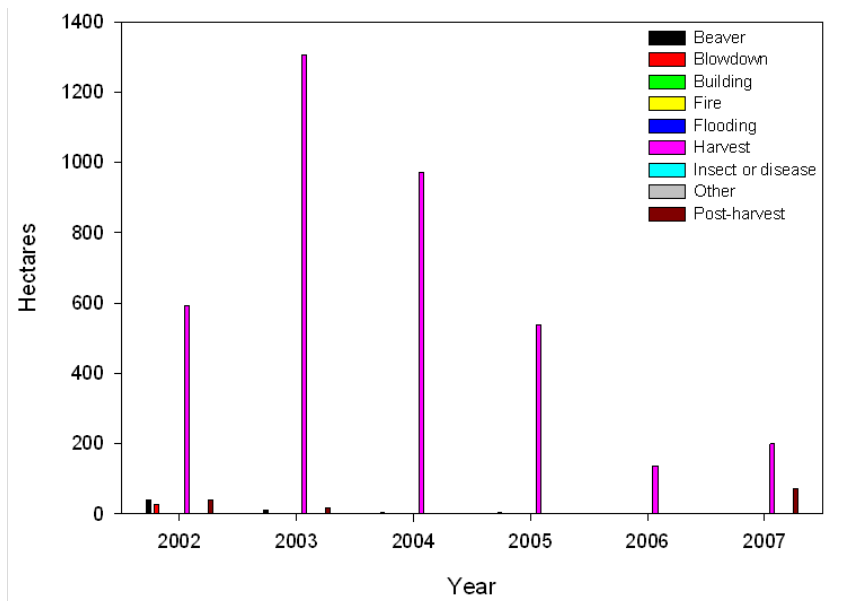


Figure 20. Area of land affected by disturbance agent in Canada.

Number of disturbances by year

A stacked bar graph is a useful way to view the number of disturbances for each location by year (Figure 21). While this does not provide information regarding the patch sizes, it provides another way to quickly view summary data for the park and surrounding areas. If climate change predictions such as an increase in extreme weather events occur, one way to view evidence of this would be to view long-term trends of the number of disturbances.

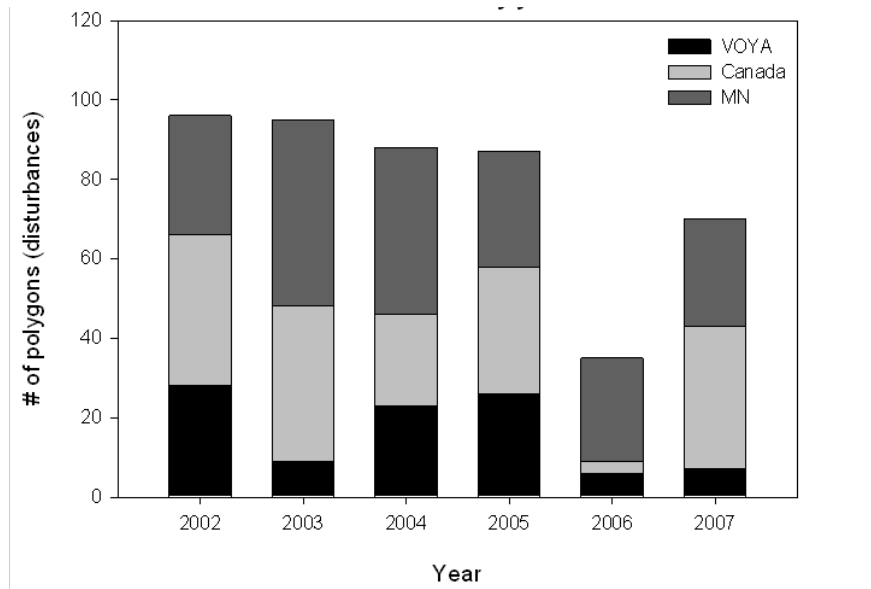


Figure 21. The number of disturbances by year and location.

Area lost by cover type

Park natural resource managers may also be interested in the cover types being disturbed, and ultimately being replaced by younger, disturbance-encouraged cover types. In figure 22 below, the natural resource manager will see that, from 2004-2006, ca. 160 ha of upland forest was loss due to disturbances inside the park. By tracking these statistics through time, natural resource managers will start to have an idea of how the disturbance regime inside the park is affecting the cover types.

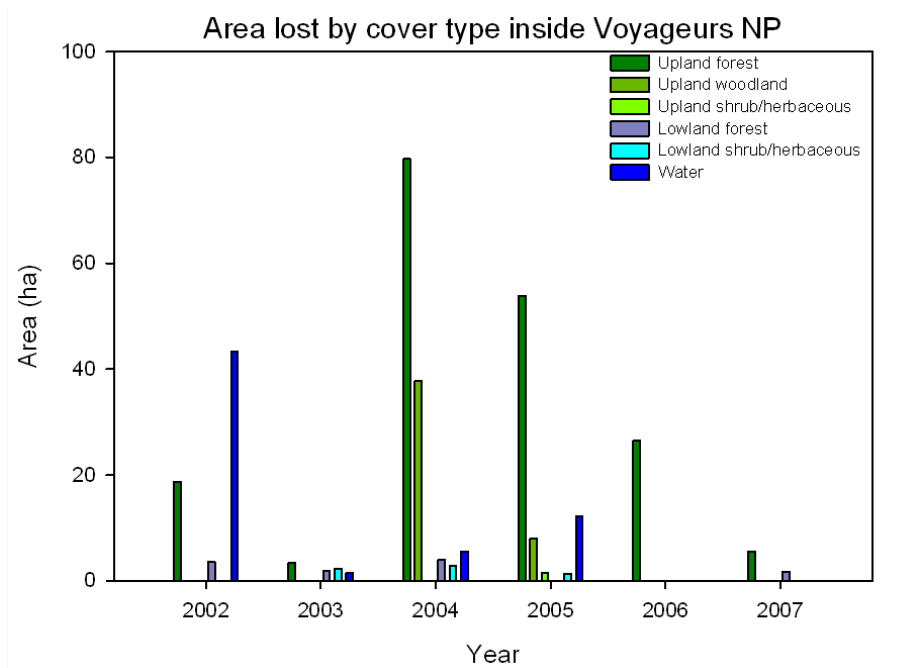


Figure 22. Area (ha) lost by cover type and year inside Voyageurs NP.

Area gained by cover type

This graph has been created to view what the disturbed areas have been converted to, in terms of cover type (Figure 23). In most cases, stand-replacing disturbances such as fire, blowdown, and forest harvest convert to upland shrub/herbaceous. The authors believe a summary graph of what the disturbances were immediately converted to is useful for resource managers. For example, if the land birds protocol showed that there was an increase in shrub-associated birds in 2005 or 2006, this may be linked to the relatively large increase in upland shrub/herbaceous cover type.

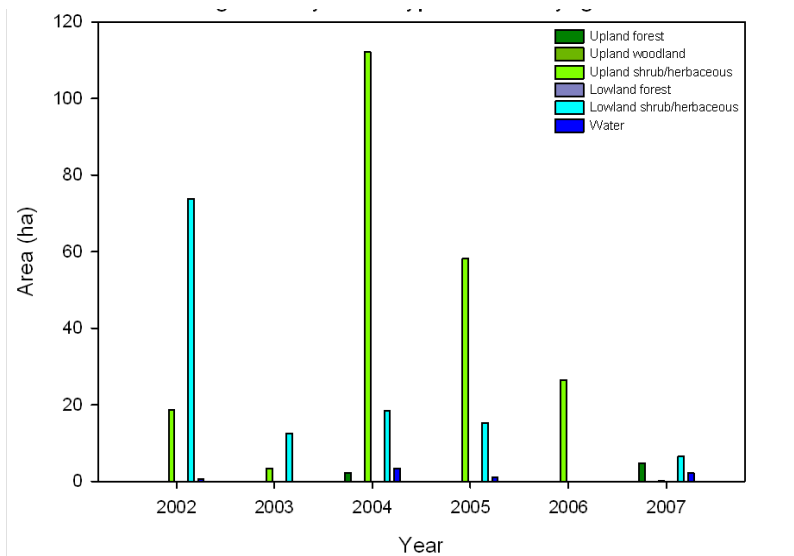


Figure 23. Area (ha) gained as a result of disturbances inside Voyageurs NP.

Landcover dynamics

When the network implements the LandTrendr+POM approach, quantitative summaries of landcover change within large disturbances may be of interest. By implementing the POM approach, the network will have the ability to track succession in landcover classes following disturbances (Figure 24). The maps and analysis in this example show an unprecedented glimpse into the actual progression of cover types that is afforded by the combination of LandTrendr fitting and POM mapping.

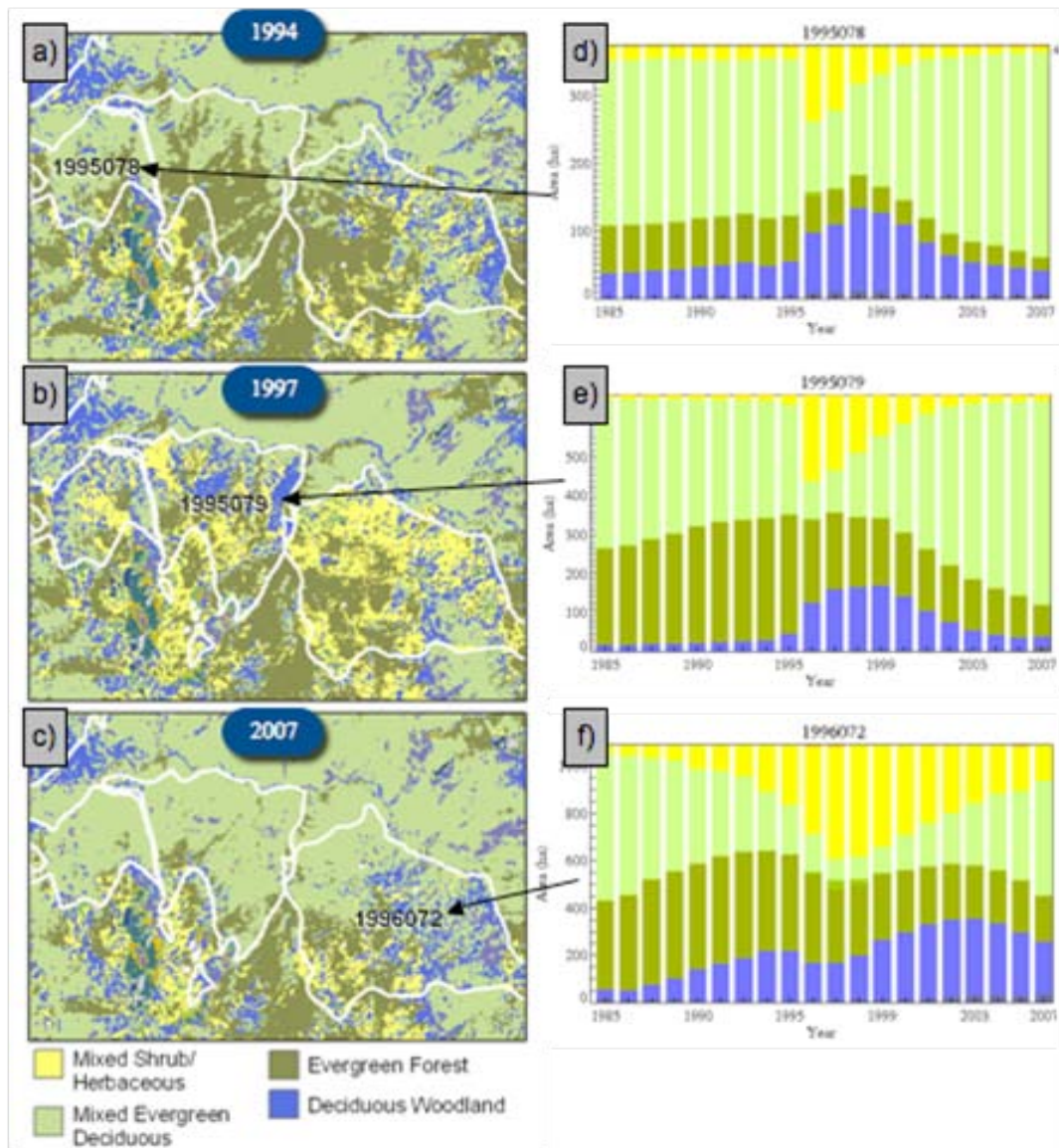


Figure 24. Pre- and post-fire landcover dynamics for three fires in SEKI a)-c) Landcover for 1994, 1997, and 2007, representing the periods before any of the fires, immediately after the fires, and 10+ years after the fire. d)-f) Proportional makeup of land within the fire perimeters for the three fires indicated by arrows. Fires occur in 1995 for d) and e, and in 1996 for f).

Maps

Disturbance polygons

Due to the geospatial nature of the data, resource managers may find it useful to view the disturbances on the landscape. There are many different ways to display this data, depending upon the question being asked. Because VOYA is large relative to the number and size of disturbances, the authors have found it useful to display the entire park and disturbances in one overall view with a DEM hillshade as background (Figure 25). This is just one example of the type of map which can be developed with this data. Ultimately the user needs to decide how they would like to display the data which should be developed based upon the question being asked or what the user would like to convey to the resource manager.

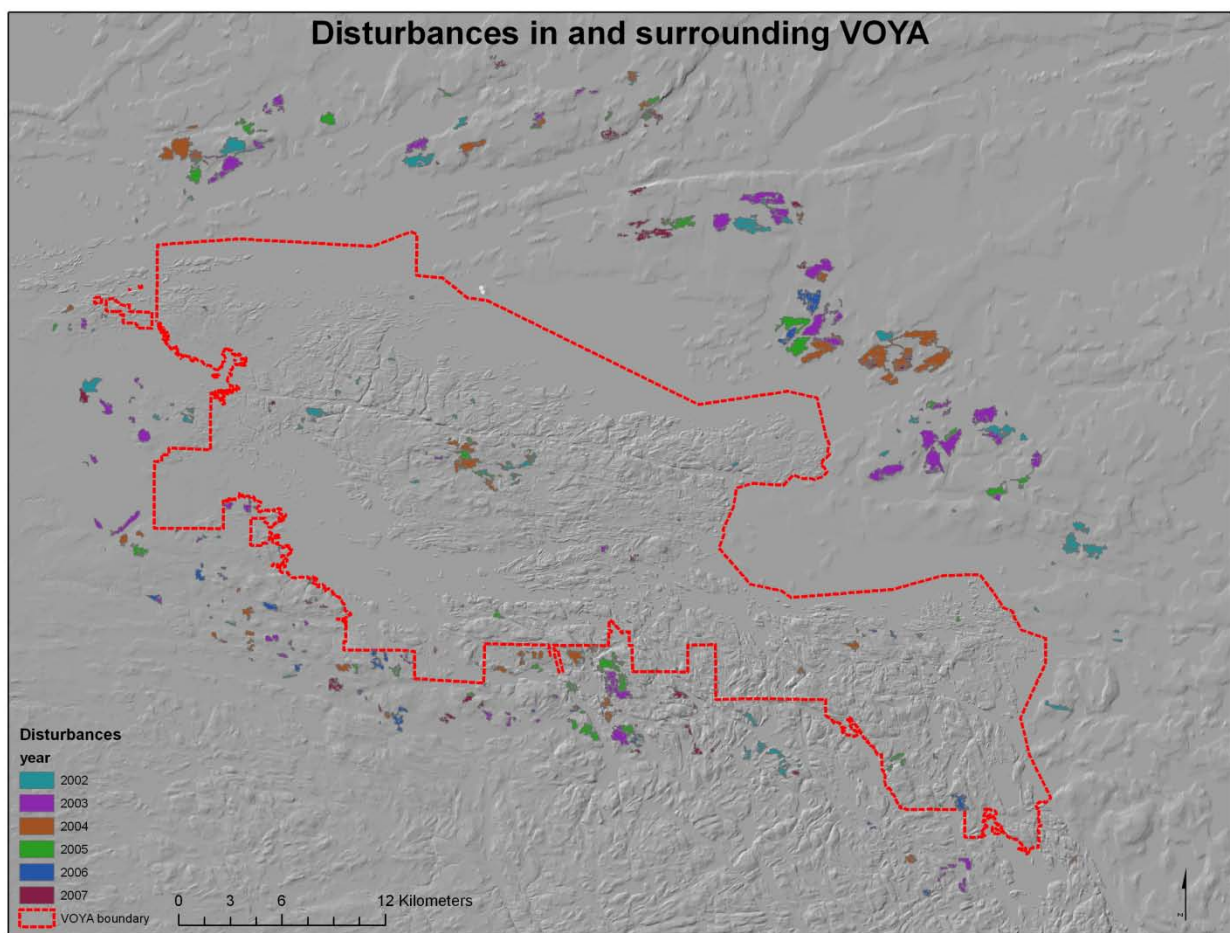


Figure 25. Overview map of disturbances in and around Voyageurs NP with a DEM hillshade as background.

Disturbance/revegetation magnitude

Due to the desire from park resource managers, a large focus of this protocol is on validating LandTrendr-produced polygons of disturbances. The authors agree this value-added procedure is

useful and necessary for the parks within the network, however LandTrendr produces additional data most appropriately viewed as maps. One such map displays the magnitude of disturbances and revegetation (Figures 26 and 27). Revegetation magnitude can provide insight into the relative speed of recovery after disturbances such as forest harvest, fire, or blowdown.

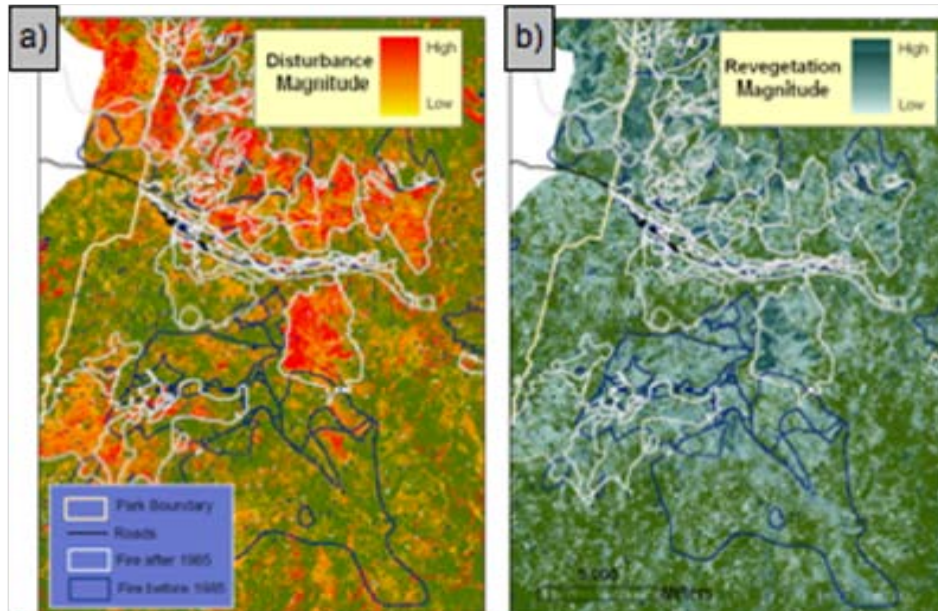


Figure 26. Disturbance and recovery dynamics of fire in Kings Canyon. a) Map of estimated disturbance magnitude, with known fire boundaries in white (during the Landsat record) and blue (preceding the Landsat record). b) Map of estimated recovery or revegetation magnitude. Note that fires preceding the Landsat record still show spectral evidence of recovering vegetation.

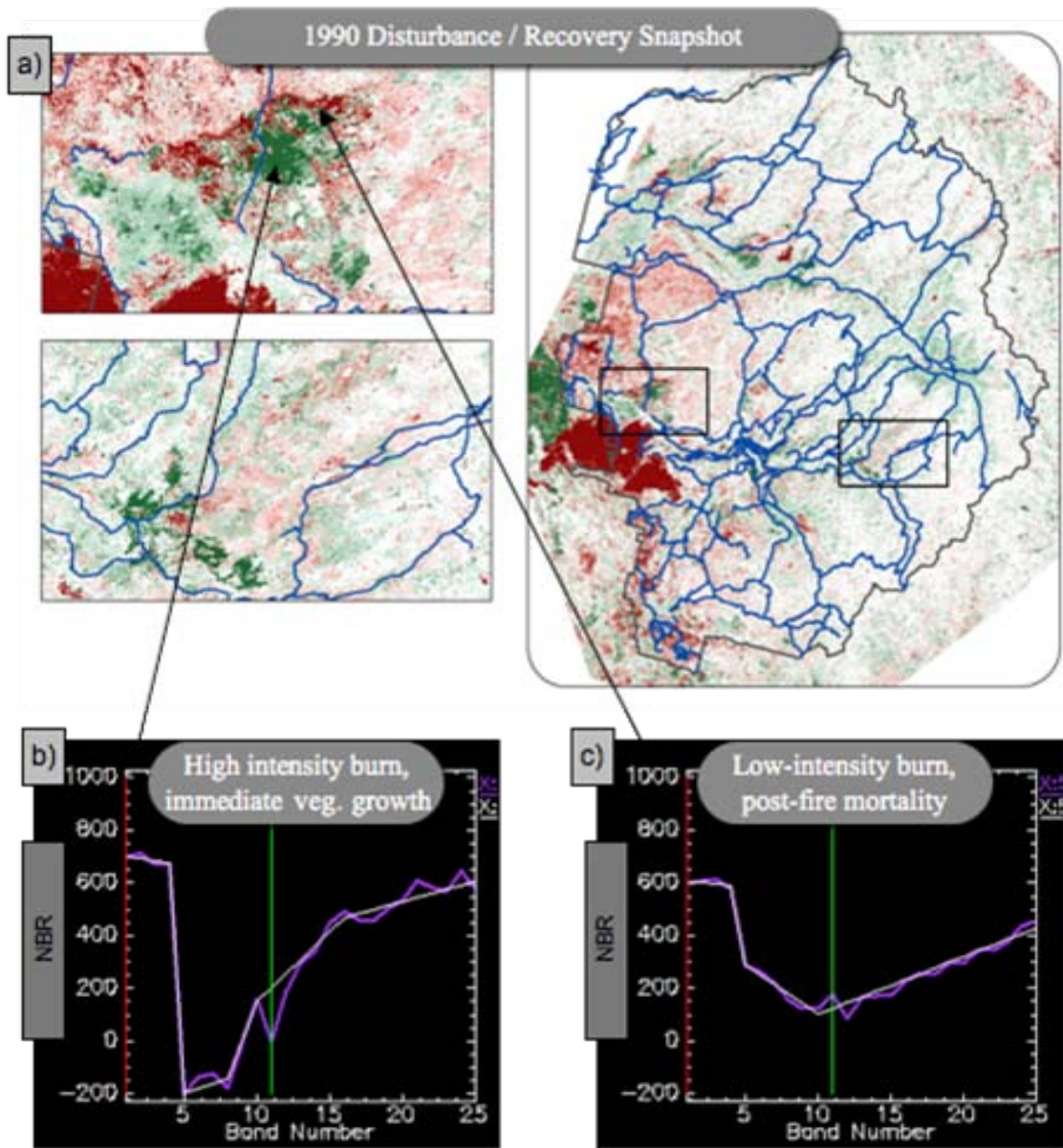


Figure 27. Post-fire dynamics captured with the slice-based approach to mapping change. a) Disturbance and recovery magnitude slices for the period 1989 to 1990 for YOSE. b) The central portion of a 1987 fire experienced substantial loss in vegetation (steep drop in NBR), but showed fairly quick regrowth by 1990. c) Marginal zones of the fire showed less intense loss during the fire, but continued to show mortality three years after the fire.

V. Data Management

Data management is critical to the success of all remote sensing projects, but particularly necessary when trajectory-based approaches are invoked, as these methods require orders of magnitude more data handling than typical remote sensing projects. For image storage and handling, consistency of file naming is central to this effort. Thus, the LandTrendr methods are all based on batchfile procedures that force compliance with file naming conventions and that produce standardized filenames for outputs, greatly reducing the possibility for ambiguity in data handling.

Management of geospatial data is an ever-changing field with GIS specialists continually trying to keep pace with new spatial database models from ESRI. The authors have tried to incorporate some of the more recent developments, especially in terms of the file geodatabase, which ESRI is heralding as the preferred method of storing spatial data. No one can possibly predict what the future may bring, especially in the ever-changing world of geospatial data. Given this fact, the authors believe the core of data management for the LandTrendr process is a stable platform to build upon. The authors employ a file geodatabase for management of initial LandTrendr outputs and use this as the data entry form. The outputs from the validation process are then stored in an Access database, with further analysis occurring in a statistical software package.

Data storage needs are large. The parks of the GLKN cover 11 Landsat scenes. Simply processing each image through SOPs 1 and 2 requires as much as 500Gb of disk storage for data stacks spanning approximately 25 years. Acquisition of supporting high resolution aerial photography for validation also entails large volumes of digital data, requiring from 500Gb to 1 terabyte or more of data storage, depending on the size of the park and pixel resolution of the imagery.

Details regarding the storage structure and documentation can be found in SOP 10: Data Management, and below in figure 28.

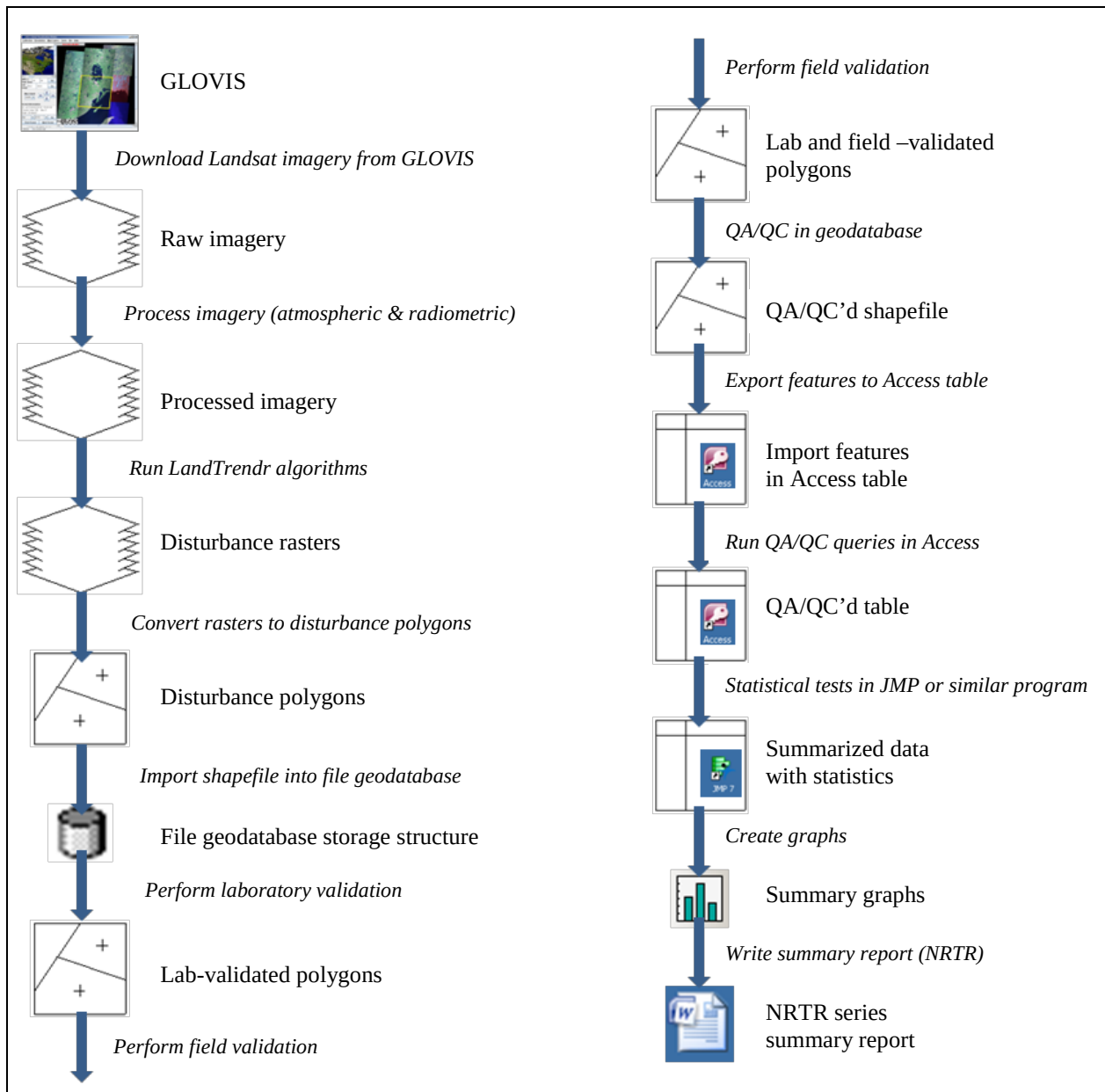


Figure 28. Data flow diagram for protocol.

VI. Staffing, Budgeting, and Scheduling

The authors' experience working with the NCCN on implementation of the original landscape dynamics protocol developed by Kennedy et al., suggests that personnel requirements for this protocol are high, and may not be readily available in all I&M networks. Carrying out pre-processing is particularly challenging for non-specialists, as it requires proficiency in the IDL coding language, ENVI, and ERDAS Imagine Image Processing software packages, as well as with geographic information system methods. Although significant efforts have been made to simplify and automate the processing through the use of batchfile analysis, ongoing LandTrendr mapping efforts on this and other projects suggests that significant expertise is still needed to diagnose and evaluate problems in processing. One of the reasons GLKN was willing to pursue and implement this protocol was due in part to the recent hire of a remote sensing specialist who had experience with this methodology and could carry out the entire protocol with minimal involvement from the Oregon group.

In addition to the requirement of a remote sensing specialist, multiple software programs are needed to implement this protocol. All of the code has to be run through IDL, an ITT program, and many of the outputs are best viewed in ERDAS Imagine. It is also suggested, although not necessary, to purchase the companion software to IDL, which is ENVI. In table 2 we list the startup and maintenance costs of these software packages, in addition to the salary and time requirements of the remote sensing specialist to implement this protocol.

A scheduling timetable in which we outline the workflow during a year and forecast this out to 2020 has been included below (Table 3). We realize the exact months each of the processes occur may change through time, however we believe that as we become more efficient with processing and the IDL code, we will be able to spend less time on some steps of the processing, freeing up additional time to implement other parts of the protocol (POM), or develop and implement new protocols such as phenology and/or ice on/off.

Table 2. GLKN's budget for implementing protocol, current as of 2010.

Software	Original cost	Recurring yearly costs (maintenance)
ERDAS Imagine	\$6,000 (v9.0)	\$770-\$1700, depending on add-ons
IDL	\$2,600 (v7.0)	\$450
ENVI	\$4,760 (v4.6)	\$840
ArcMap	NPS-wide license	NPS-wide license
Hardware	Original cost	Specifications
Workstation	\$6,000	64 bit, dual quad core 3.1 Ghz processor , 4TB hard drive, 8GB RAM
Personnel	Annual salary	Time spent on protocol and reports (%)
GIS specialist, program lead	\$92k	25
Remote sensing technician	\$65k	75
Validation data	Avg. annual cost	Specifications
Airphotos	\$70k	Minimum 0.3m resolution, spring leaf-off

Table 3. Monitoring landscape dynamics using LandTrendr timetable.

Month	Task	2010	2011	2012	2013	2014	2015	2016	2017	2018	2019	2020
January	Process imagery	ISRO	APIS	INDU	SACN/MISS	SLBE/PIRO	VOYA	ISRO/GRPO	APIS	INDU	SACN/MISS	SLBE/PIRO
March	Process imagery			VOYA	ISRO/GRPO	APIS	INDU	SACN/MISS	SLBE/PIRO	VOYA	ISRO/GRPO	APIS
April	Validate (office)	ISRO	APIS	INDU	SACN/MISS	SLBE/PIRO	VOYA	ISRO/GRPO	APIS	INDU	SACN/MISS	SLBE/PIRO
May	Airphotos	APIS	INDU/ up SACN	MISS/ low SACN	SLBE/PIRO	VOYA	ISRO/GRPO	APIS	INDU/up SACN	MISS/ low SACN	SLBE/PIRO	VOYA
June	Veg crew	ISRO	APIS	INDU	SACN/GRPO	VOYA	SLBE/PIRO	ISRO	APIS/MISS	INDU	SACN/GRPO	VOYA
July	Validate (field)	ISRO	APIS	INDU	SACN/MISS	SLBE/PIRO	VOYA	ISRO/GRPO	APIS	INDU	SACN/MISS	SLBE/PIRO
August	NAIP etc.			VOYA	ISRO/GRPO	APIS	INDU	SACN/MISS	SLBE/PIRO	VOYA	ISRO/GRPO	APIS
October	Summarize/report	ISRO	APIS	INDU	SACN/MISS	SLBE/PIRO	VOYA	ISRO/GRPO	APIS	INDU	SACN/MISS	SLBE/PIRO
November	Summarize/report			VOYA	ISRO/GRPO	APIS	INDU	SACN/MISS	SLBE/PIRO	VOYA	ISRO/GRPO	APIS
	Airphoto costs	\$50k	\$80k	\$90k	\$100k	\$80k	\$100k	\$50k	\$80k	\$90k	\$100k	\$80k

Additional notes: In June each year, the vegetation crew (another GLKN program) will start field work at a particular park.

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Appendix. Index to Standard Operating Procedures

Ten standard operating procedures (SOPs) provide thorough details for executing each step of the data acquisition, analysis, and reporting process. Because each SOP is a relatively large document and because all the SOPs are dynamic and can change more frequently than this protocol narrative, they are not included here. Readers interested in the more complex details of this Landsat-based monitoring protocol can find the SOPs on the Great Lakes Inventory and Monitoring Network website - <http://science.nature.nps.gov/im/units/GLKN/monitor/landuse/landuse.cfm>.

SOP 1. Acquiring imagery

SOP 2. Preprocessing image stacks

SOP 3. LandTrendr segmentation

SOP 4. LandTrendr mapping

SOP 5. Utilizing TimeSync for validation

SOP 6. Lab validation of LandTrendr outputs

SOP 7. Field validation of LandTrendr outputs

SOP 8. Linking LandTrendr with landcover maps

SOP 9. Data analysis and summary

SOP 10. Data management

The Department of the Interior protects and manages the nation's natural resources and cultural heritage; provides scientific and other information about those resources; and honors its special responsibilities to American Indians, Alaska Natives, and affiliated Island Communities.

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