Landsat-based monitoring of landscape dynamics in the national parks of the Sierra Nevada Inventory & Monitoring Network (SIEN)

Narrative

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Attachments: Standard Operating Procedures 1-8

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1. Backgound and Objectives

1.1 Introduction

Ecological monitoring is a key element of park stewardship. Effective monitoring allows managers to identify and track the status and trend in the condition of key park resources, evaluate the efficacy of resource management activities, improve understanding of natural variation in ecological patterns and processes, and provide an early warning of potential threats to ecological integrity and sustainability.

To achieve greater efficiency in the design and implementation of inventory and monitoring work, and to foster the exchange of ideas and information among parks in a similar ecoregional context, the National Park Service (NPS) has grouped parks and monuments into monitoring networks. The NPS Sierra Nevada Network (SIEN) includes Devils Postpile National Monument (DEPO), Sequoia and Kings Canyon National Parks (SEKI), and Yosemite National Park (YOSE) (Figure 1).

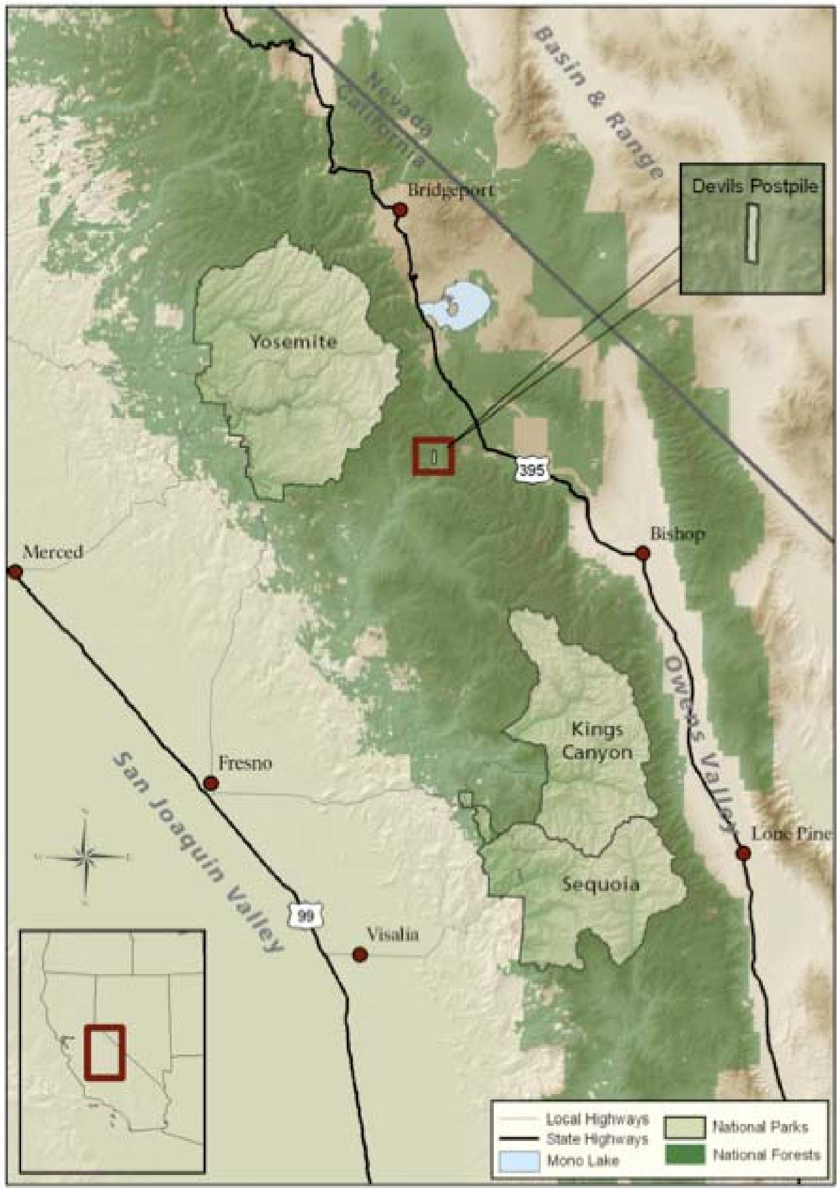

Figure 1. Sierra Nevada region showing Sierra Nevada Network parks and other federal lands.

1.2 Vital signs

Through its **vital signs monitoring program**, the NPS has begun numerous initiatives across the country aimed at tracking key physical, chemical, and biological elements and processes in park ecosystems (Fancy et al. 2008). This narrative and associated Standard Operating Procedures (SOPs) describe a protocol to use satellite remote sensing to monitor vital signs related to landscape dynamics and fire regimes in the parks of the SIEN. The protocol was developed through collaboration of SIEN staff with researchers at Oregon State University and the USDA Forest Service's Pacific Northwest Research Lab (the "Oregon group").

Table 1. Vital signs that were selected for protocol development by the Sierra Nevada Network, organized into categories as defined by the NPS Inventory and Monitoring Program. **Bolded** vital signs are those that can be addressed by monitoring using remote-sensing methods. See Mutch et al. (2008) for a complete list of high-priority vital signs and a description of the selection process.

Level 1	Level 2	Vital Sign
Air and Climate	Weather and Climate	Weather and Climate
		Snowpack
Water	Hydrology	Surface water dynamics Wetland water dynamics
	Water quality	Water chemistry
Biological Integrity	Invasive species	Non-native invasive plants
	Focal species or communities	Wetland plant communities
		Macroinvertebrates (wetlands) Amphibians Birds Forest population dynamics
Landscapes (Ecosystem pattern and process)	Fire and fuel dynamics	**Fire regimes**
	Landscape dynamics	**Landscape mosaics**

In addition to those listed in Table 1, a vital sign that was ranked as a high priority by SIEN parks is already being monitored by the NPS Fire Effects Monitoring Program (USDI National Park Service 2003) – *fire effects on plant communities*. Thus it was not originally targeted for protocol development by the network. However, the remote-sensing methods discussed in this protocol provide complementary approaches to the plot-based fire effects monitoring conducted by the NPS staff in SIEN parks, and we include fire effects on plant communities in our objectives.

Another high-priority vital sign that was not originally targeted for protocol development due to limited resources is *phenological events* (such as flowering and leaf-out of plants). *Phenological events* and *snowpack* monitoring development are being pursued through other multi-network efforts with other funding, and snowpack is also being addressed through SIEN's weather and climate monitoring protocol. These vital signs cannot be addressed with the remote-sensing methods described in this protocol, thus will be discussed only in the context of the meetings and scoping done to determine the scope and focus of this protocol.

1.3 Importance, drivers, and stressors

The Sierra Nevada parks encompass large areas of federally protected lands (approximately 658,000 hectares), and are bounded primarily by US Forest Service lands, also mostly designated as Wilderness. Together they help to protect one of the nation's and the world's most biotically unique and diverse regions. Consistently, the California Floristic Province (of which the Sierra Nevada is a part) is identified as a global biodiversity hotspot (Meyers et al. 2000; Whittaker 2005) where large concentrations of endemic species are threatened by loss of, or degradation of habitat. In accordance with this level of global biodiversity, resource managers of the Sierra Nevada Network parks must use any and all methods available to document and assess impacts to these lands they manage. Understanding landscape dynamics is the critical foundation on which much of the management of these systems must rest.

There are three primary justifications for wanting to monitor landscape dynamics, including fire, over time. One is to document when and where individual change events and processes occur on the landscape. This provides managers a means of preparing scientifically informed responses to environmental change. Second, by evaluating longer-term and park-wide patterns in these changes, managers and monitoring scientists can begin determining trends in key indicators of landscape condition, and further inform management responses to change. Finally, these status and trend data can be used to build models of potential future landscape mosaic patterns. This will allow managers to better prepare for and then manage for ecosystem changes that are likely to affect processes, systems, and individual species. Understanding landscape dynamics requires a basic understanding of the drivers and functions of those landscapes.

1.3.1. Landscape drivers, system components and functions

Climate and atmosphere, geology and topography, and various processes of change are core drivers that influence the Sierra Nevada landscape, and interact with each other to influence patterns of vegetation, animal distributions, water dynamics, and soil characteristics. The landscape model (Figure 2) highlights core drivers, system components and functions, and stressors that interact to influence landscape dynamics and patterns. (See glossary for definitions).

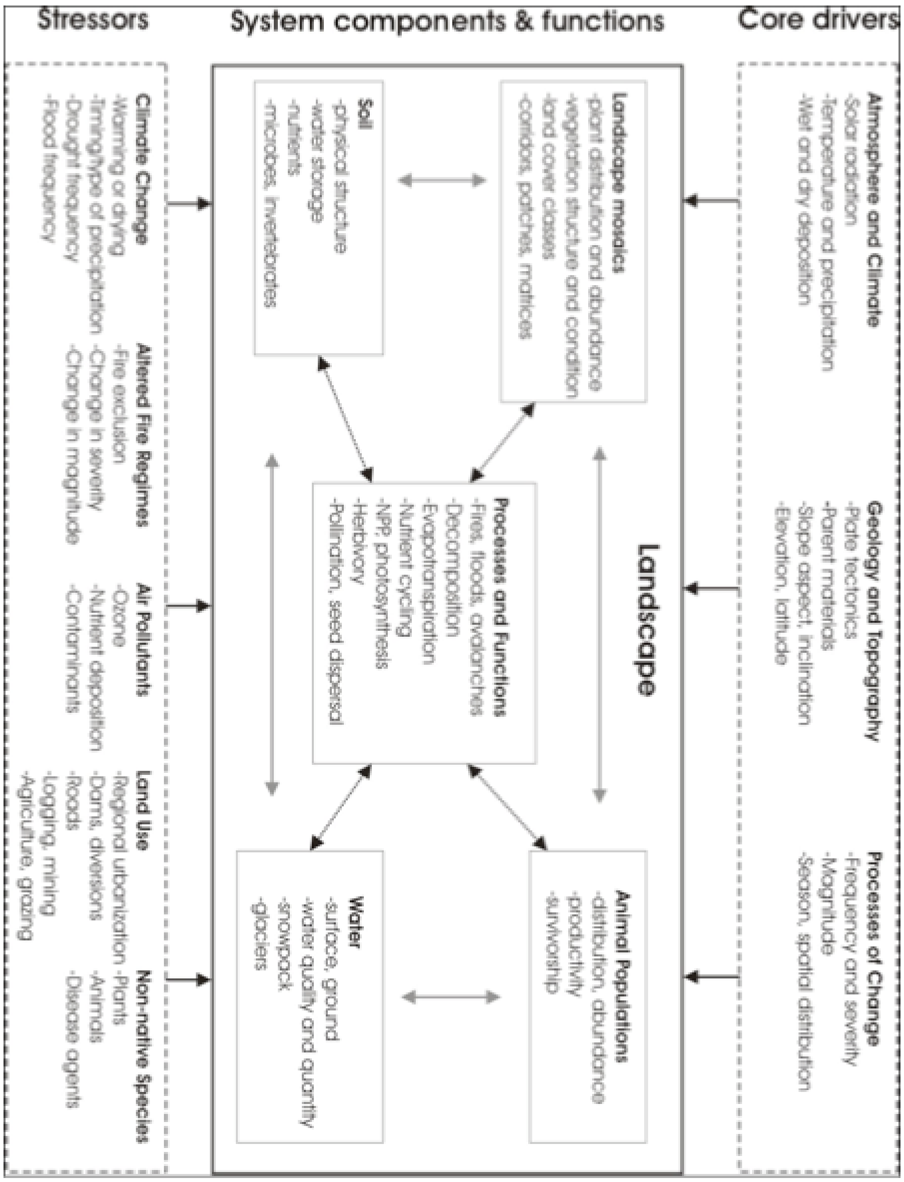

Figure 2. Sierra Nevada landscape dynamics model (adapted from Mutch et al. 2008).

Climate

Climatic forces are a major driver of Sierra Nevada ecosystems. Strong climatic gradients occur with changing elevation from west to east. Low to mid-elevations have a Mediterranean climate, characterized by hot, dry summers and cool, wet winters. Higher elevations are dominated by a micro-thermal (or Boreal) climate. As a result, a steep temperature gradient parallels the elevation gradient as one climbs from the hot lowlands to the alpine crest (Stephenson 1988). The west slope of the Sierra receives between 50 and 200 cm of rainfall each year, depending on elevation. Above 2,100 m on the western slope, about 50% of precipitation falls as snow (Stephenson 1988), creating a significant snowpack in the montane and subalpine elevations. East of the crest, the mountains create a rain shadow with significantly less moisture falling throughout the season. Long-term changes in past climate regimes have resulted in shifts in fire regimes and vegetation distribution.

Geology & Topography

The Sierra Nevada range has been formed and shaped by a variety of geologic events:

- Uplift and tilting to the west from a magma intrusion approximately 215–70 million years ago, giving the range its asymmetric geometry (gentle west slope, steep east escarpment)
- Erosion and incision from streams, resulting in deep canyons
- Volcanic activity at approximately 100 thousand years ago on the eastern flank of the Sierra Nevada that sent a lava flow into a valley, now designated Devils Postpile National Monument, which cooled uniformly, contracted, and fractured into hexagonal columns for which the monument is named
- Several glacial periods in the Sierra Nevada, beginning at approximately 1 million years ago and continuing until approximately 10 thousand years ago, which scoured and eroded the landscape and resulted in landforms that include U-shaped canyons, jagged peaks, rounded domes, waterfalls, moraines, and lakes & ponds

Many of these processes continue to gradually change the terrain of the Sierra Nevada today.

Massive granite outcrops dominate the range. The granite formed deep within the Earth when molten rock solidified, and later was exposed following erosion of overlying rocks. Layered metamorphic rocks in the western foothills and along the eastern margin near the Sierra crest are remnants of ancient sedimentary and volcanic rocks. Most of these rocks were long ago eroded away to expose the granitic core of the range, and only small isolated remnants remain.

Topography of the Sierra Nevada interacts with climate to strongly influence the distribution of plants and animals. Temperature, precipitation, and moisture available to plants vary with changes in elevation, latitude, and slope inclination. The length and elevation range of the Sierra Nevada, combined with its topographic diversity result in large gradients in temperature and precipitation and high diversity of plants and animals.

Water & Soil

Additional landscape components or elements that we emphasize in our model include water, soil, landscape mosaics, and animal populations. These components interact directly through exchange of materials or provision of habitat as represented by the solid grey arrows linking landscape element boxes. Much of the interaction and exchange among landscape elements occurs via processes and functions shown in the middle box of the model. For example, key processes such as decomposition, fire, and herbivory result in exchanges of nutrients from one “box” to another. As a result of fire, organic matter tied up in fuel and vegetation can be deposited as nutrients in soil.

Water in a landscape context is characterized by drainage networks across an elevation gradient. Drainage networks provide surface pathways for water flow across the landscape, and the distribution of species is strongly influenced by the spatial and temporal patterns of water availability. Water quantity in the Sierra Nevada and the region at large is strongly influenced by the winter snowpack, which serves as a reservoir that gradually releases water through snowmelt and runoff. Atmospheric deposition, surface runoff, sedimentation, and processes such as fire, erosion, and flooding all influence water quality.

Soil provides physical structure and habitat for plants as well as other organisms (microbes, fungi, invertebrates, vertebrates). Soil is the medium through which nutrients and water are made available to most plants, and provides varying levels of water storage capacity. Soil formation depends upon parent materials, slope, exposure, hydrology, organic matter content, and surface vegetation, among other factors. The soils of the large parks are primarily granitic in origin. Depths vary from several feet in limited low elevation areas on the western slope, to a very thin or nonexistent soil mantle at higher elevations which resulted from glacial scouring in the alpine and subalpine areas. Soil depth is an important factor in determining water availability to plants, and thus plays a role in the distribution of vegetation. Devils Postpile National Monument is predominantly covered with pumice, indicating post-glacial volcanic activity in the Mono Lake - Mono Basin area. This pumice plays an important role in the area's phytogeography and vegetation development. On slopes underlain by basalt and andesite, where the water table is low and percolation is high, a sparse conifer forest normally exists. These dry, unstable soils result in slow recovery of vegetation after human disturbance and more prolonged re-vegetation periods in areas that have burned.

Animals

The distribution and abundance of animal populations are tied closely to the pattern of landscape mosaics and the varieties of wildlife habitat that they provide. The mobility of many animal populations makes them sensitive to changes that occur in landscapes both within and outside of park boundaries. Animals can form links among different landscape mosaics (lakes, wetlands, forests) by spending parts of their life cycles in different environments, or by moving among various environments for foraging and hunting. Animal productivity and survivorship are sensitive to weather patterns, fire regimes, and other factors that influence habitat availability and quality. Animals affect vegetation dynamics through herbivory, pollination, and seed dispersal. They influence nutrient cycling in both aquatic and terrestrial systems. Animals contribute substantially to the biodiversity of the Sierra Nevada landscape, and they are major components of complex food webs.

Fire

Fire is a process that helps link terrestrial, atmospheric, and aquatic systems through its role in moving nutrients across these systems. Fire regimes–in combination with climate and topography–shape vegetation structure and pattern on the landscape, affect water quality and quantity, and indirectly affect wildlife habitat.

Fire has played a pivotal role in shaping ecosystems and landscapes in the Sierra Nevada for many millennia (Anderson and Smith 1997; Davis and Moratto 1988; Smith and Anderson 1992; SNEP 1996). It affects numerous aspects of ecosystem dynamics such as soil and nutrient cycling, decomposition, succession, vegetation structure and composition, biodiversity, insect outbreaks, and hydrology (Kilgore 1973; SNEP 1996). Frequent surface fires in many vegetation types minimized fuel accumulation while their variable nature helped create diverse landscapes and forest conditions (SNEP 1996; Stephenson et al. 1991). Historically, fire frequency, size, intensity, and severity varied spatially and temporally across the landscape depending on number of ignitions, climate, elevation, topography, vegetation, fuels, and edaphic conditions (Skinner and Chang 1996).

Prior to Euramerican settlement, fires were common, often burning for months and covering large areas. Extensive research in mixed-conifer forests has shown that low intensity surface fires were common and tended to keep the forests open (Biswell 1961; Hartesveldt and Harvey 1967; Harvey et al. 1980; Kilgore 1971, 1972; Weaver 1967, 1974).

Many species and most plant communities show clear evidence of adaptation to recurring fire, indicating that fire occurred regularly and frequently, particularly in the chaparral and mixed-conifer communities, where many plant species have life history attributes tied to fire for reproduction or as a means of competing with other biota. Many plants evolved fire-adapted traits, such as thick bark, and fire-stimulated flowering, sprouting, seed release, and/or germination (Chang 1996).

Short-term climatic variation had a significant impact on past burn patterns, fire regimes, and fire severity. Historically, specific fire-years throughout the southern Sierra Nevada's west slope–usually during dry years–have been identified (Brown et al. 1992; Swetnam 1993b; Swetnam et al. 1992b; Swetnam et al. 1998). Analysis of millennial-length fire histories for giant sequoias also document long-term variation (1,000–2,000 years) in the fire regime associated with climatic fluctuations (Swetnam 1993b).

Landscape Mosaics

Landscape mosaics are primarily influenced by abiotic constraints (elevation, soil, microclimate, topography), biotic processes (demography, competition, dispersal) and disturbance regime (Urban 2000). Landscape mosaics consist of contiguous patches of different types (Figure 3), which are areas that are relatively homogeneous in character (e.g., wetlands, high-elevation lakes). Vegetation forms a primary and dynamic component of landscape mosaics, and its relationship to climate and fire in the Sierra Nevada as well as its importance to wildlife habitat make it an important landscape component to monitor.

Other important elements of landscape mosaics include corridors (connectors or barriers). These are primarily linear features in the landscape. Barriers prevent flow across the landscape. The flows could be physical, such as water, or biological, such as animal migration. In contrast, connectors provide paths that promote flow through the landscape. Some landscape features, such as a river or a road, may be both a barrier and a connector depending on the process or organism of interest. These corridors are important to animal populations as they either link patches of habitat (as streams link lakes for amphibians), or they fragment habitat (as trails fragment invertebrate habitat in wetlands).

1.3.2 Stressors

Five systemic stressors pose the greatest threat to Sierra Nevada Network parks and landscapes:

- Climate change (rapid, anthropogenic)
- Altered fire regimes
- Non-native invasive species
- Air pollution
- Habitat fragmentation and human use

Climatic change may have the greatest potential to affect ecosystems at the landscape scale in part because of its pervasiveness and extent across ecosystems as well as synergistic effects with other stressors.

Recent simulations of climate change models suggest that by the years 2050 to 2100, average annual temperature in the Sierra Nevada could increase by as much as 3.8º C (6.8º F) (Snyder et al. 2002). Even more modest temperature increases (2.5º C, 4.5º F) would significantly alter precipitation, snow pack, surface water dynamics (e.g., flow), and hydrologic processes in the Sierra Nevada. The most pronounced changes would probably be earlier snowmelt runoff and reduced summer base flows and soil moisture (IPCC 2007), a lower snowpack volume at mid-elevations (Knowles and Cayan 2001), and increased winter and spring flooding (Dettinger et al. 2004).

Other anticipated effects from warming temperatures include potential shifts in distributions of plants and animals (especially those with narrow niches or at the edges of their ranges), changes in phenological events (nesting, timing of bloom), and exacerbation of other systemic stressors—altered fire regimes, air pollution, and non-native plant invasions.

Climate change and associated predicted changes in fire extent, severity, and occurrence are expected to be the primary drivers of landscape change in the Sierra Nevada in the foreseeable future. The altered fire regimes that have resulted from fire exclusion are currently considered one of the most important stressors on our natural systems. Therefore, it is imperative that we document and understand how climate change will affect fire regimes which will in turn to help interpret changes in plant community composition, structure and function; water chemistry and dynamics; and animal populations' abundance and distribution.

We know from historic photos and other research on vegetation change and fire history that, over the past 150 years, there have been significant changes in landscape mosaics (patterns of vegetation) in the Sierra Nevada. Changes in these landscape mosaics can be readily observed in repeat photographs (Figure 3). Sierra Nevada research on vegetation change (Parsons and DeBenedetti 1979; Roy and Vankat 1999; Vankat 1970; Vankat and Major 1978) and fire history (Caprio and Swetnam 1995; Kilgore and Taylor 1979; Swetnam 1993a; Swetnam et al. 1992a) has demonstrated strong links between vegetation structure and composition, fire, and climate.

Figure 3. Repeat photos of Middle Fork of the Kaweah River, Sequoia National Park. Evident in these photos is the change from shrub land to conifer forest over large areas—likely related to a decrease in fire frequency (1900 photo– George Smith, 1993 photo–Nate Stephenson).

Air pollution (ozone, deposition of nutrients, pesticides from agricultural areas) threatens Sierra Nevada ecosystems. Research suggests chronic ozone pollution can lead to shifts in forest structure and composition (Miller 1973). Since then, injury has been well-documented in remote pine forests of southern California (Arbaugh et al. 1998; Bytnerowicz et al. 2002) and the Sierra Nevada (Duriscoe 1987). In 1999 the National Park Service ranked Sequoia National Park among the "worst ozone polluted national parks" in the country (National Park Service 1999). If current ozone concentrations remain relatively constant or increase, they may affect the genetic composition of pine and sequoia seedling populations, and contribute to increased susceptibility to fatal insect attacks, death rates, and decreased recruitment (Miller 1973, Ferrell 1996, Miller 1996).

Large portions of the three large Sierra Nevada parks (Kings Canyon, Sequoia, and Yosemite) are buffered to some extent from the effects of habitat fragmentation and land-use change that occur in the Central Valley of California to the west of the parks, in the Sierra Nevada foothills, and on Sierra Nevada national forest lands. Nonetheless, edges of parks bordering these lands, as well as areas/corridors extending into parks, are affected by non-native species invasions, effects of urbanization, agriculture, and deforestation (such as reduced wildlife habitat outside parks and loss of connections among habitats), deterioration of air quality, and deterioration of natural soundscapes and dark night skies. Other forms of land use change include dams and diversions, and within SIEN parks, Hetch-Hetchy Dam on the Tuolumne River in Yosemite is the largest scale example of water impoundment and fragmentation of aquatic habitat.

1.3.3 Motivation for remote sensing of landscape dynamics

Because landscape patterns and the patchwork of vegetation communities integrate biotic and abiotic factors in their structure and composition over time, land cover type, condition, and spatial pattern are key aspects of ecological monitoring. For this reason, SIEN park and network staffs identified a need for long-term monitoring of landscape change at different spatial scales, from landscape to local.

Remote sensing of land use patterns offers a relatively rapid and cost effective method to assess large and small spatial scale changes in the landscape. Remote sensing has been used for almost two decades to assist in addressing ecological and landscape questions and issues (Goward et al. 1994; Hall et al. 1991; Lambin and Strahler 1994; Plummer 2000; Running et al. 1986; Zhu and Evans 1994). These include land cover classification, ecosystem function, change detection, monitoring process such as flooding and disease spread, among others.

The use of remote sensing data to monitor landscape dynamics is desirable because: 1) SIEN units are predominantly (94%) designated Wilderness and three out of four of the units are large, complex landscapes with difficult access issues for ground-based monitoring; 2) Remote-sensing data provide an opportunity to detect changes in SIEN parks in relation to some of the five primary threats affecting Sierra Nevada ecosystems; and 3) Remote-sensing data when used with other ground-based monitoring data (weather, vegetation, fire effects) and modeling can help establish relationships among major drivers and processes and landscape patterns and provide early warning of changes that may at times be mitigated by management actions. Remote sensing data are also relatively consistent across time and space, providing a means of objectively tracking and comparing spatial and temporal patterns.

1.4 History and desired objectives of remotely sensed landscape monitoring

Although remote sensing tools are attractive for ecological monitoring, the translation of ecological goals into terms appropriate for remotely-sensed measurement is often an iterative and challenging process (Kennedy et al. 2009). After the SIEN landscape protocol work group (network and park staff from Sequoia & Kings Canyon and Yosemite National Parks) initially identified primary monitoring objectives, they engaged the Oregon group in an agreement to hone those objectives and design a protocol by which some of the objectives could be met.

The detailed history of that process is provided separately in Appendix 1, but is summarized here briefly. Through direct meetings and post-meeting written reports, the Oregon group and the SIEN staff collectively identified the types of landscape transition associated with different monitoring objectives, the spatial and temporal grain of remote sensing imagery measurement needed to capture those transitions, potential analytical tools needed to process imagery to capture those changes, and the reference data available to corroborate or validate them. Although a wide range of options were available to natural resources managers in the SIEN, the best overall compromise in terms of consistency, cost, and availability was determined to be the Landsat Thematic Mapper (TM) sensors. Initial plans were to adapt an analytical tool known as the POM approach (for “probability of membership”) developed by the Oregon group for the North Coast and Cascades Network (NCCN; (Kennedy, Cohen, Kirschbaum et al. 2007). Like many methods of remote sensing change detection, the POM approach characterized change on the landscape according to how that change was manifested in the so-called spectral space of the Landsat sensor (Figure 4; see Glossary for terms). The challenge to both the POM and most other change detection techniques is identifying the signal of real, persistent landscape change against a backdrop of noise and uninteresting change (Figure 5).

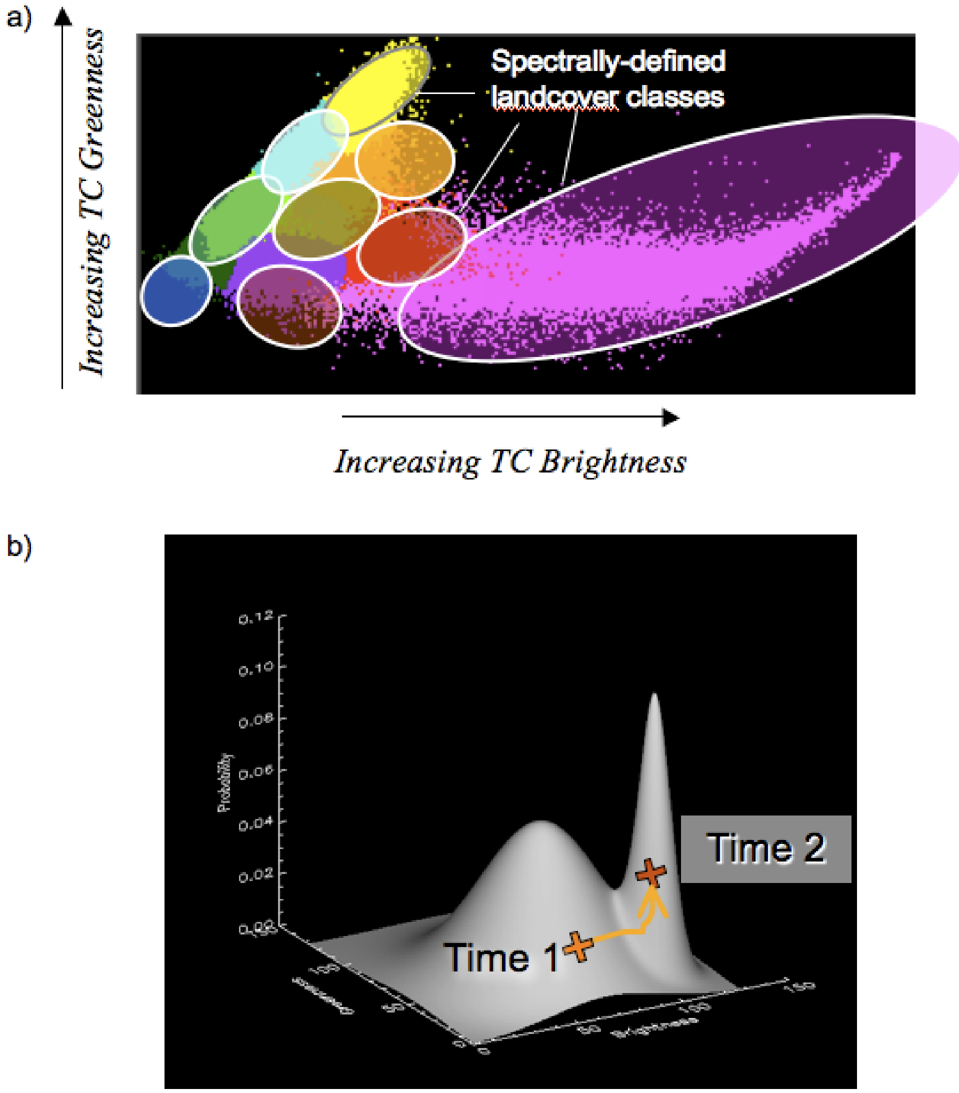

Figure 4. Basis for the POM (probability of membership) approach to change detection. a) Landcover classes are defined according to their location in the tasseled-cap spectral space (here showing brightness and greenness; wetness not shown). Each ellipse corresponds to a contour of equal-probability on a Gaussian probability surface for a single class. b) A theoretical example of spectral change using only two classes as an example. A pixel moves from the probability surface of one class to another from time 1 to time 2. By comparing the relative probabilities of the two time periods (Z-axis values in this figure), the change in the pixel's probability of memberships in these two classes can be quantified and used to indicate that it has likely changed class membership.

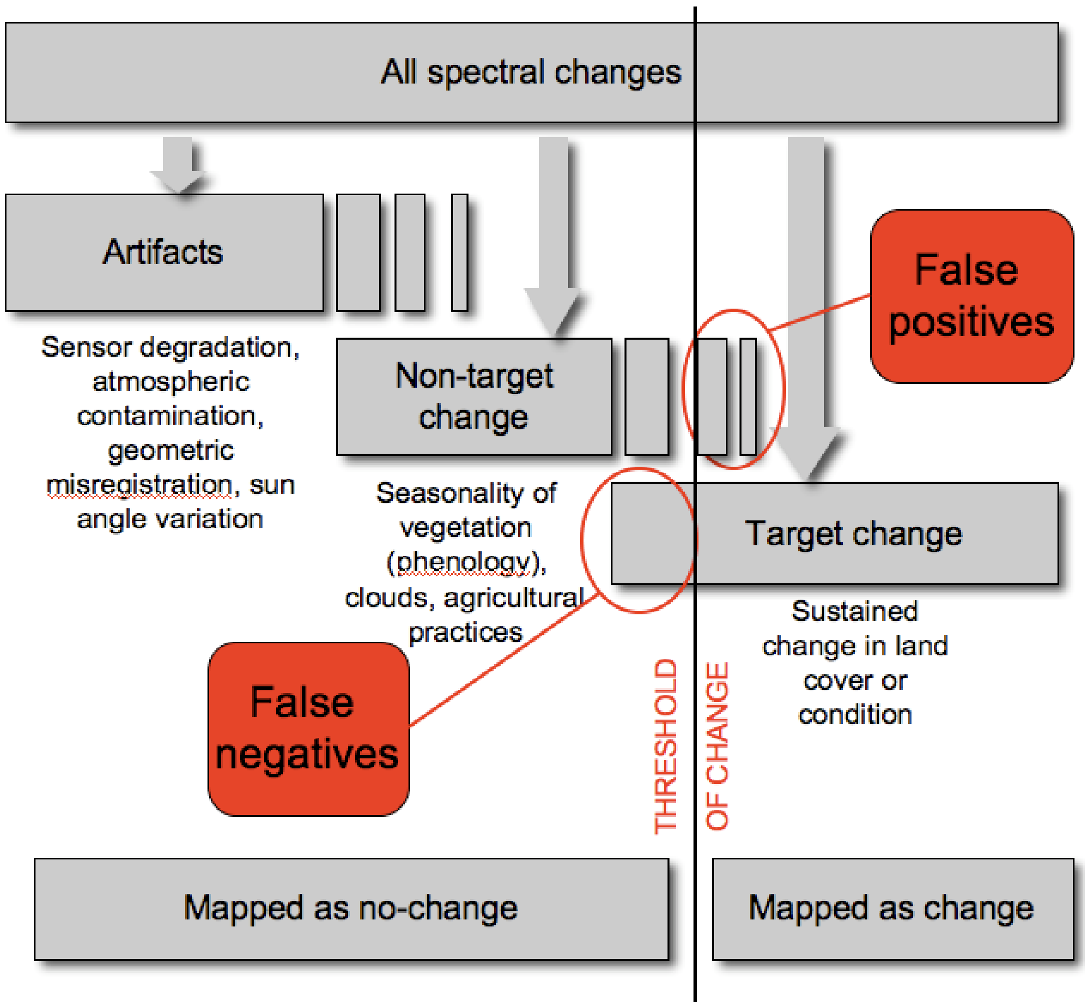

Figure 5. Remote-sensing based maps of sustained change in land cover or condition are typically made by identifying areas with spectral change, and identifying a threshold of spectral change above which real change on the landscape is assumed to have occurred. However, spectral change itself can be caused by artifacts and non-target surface change, meaning that any threshold chosen is likely to produce both false positive and false negative errors.

Over the course of the project, it became clear that a new technique developed by the Oregon group was more robust and directly relevant for the SIEN than the POM alone. This new technique, known as LandTrendr (for "Landsat based detection of trends in disturbance and recovery") leverages the dense time series of Landsat images to improve separation of real from false change (Figure 6), and allows capture of both long term trends and short-duration events (Kennedy et al. In press). A complementary interpretation tool known as TimeSync (Cohen et al. In press) allows quick and statistically robust validation opportunities, which is particularly important when field data and other reference data are sporadic and expensive to obtain. The LandTrendr approach can be used alone to capture change, or as a precursor to the POM approach. Details of all three methods are described in Section 3 below.

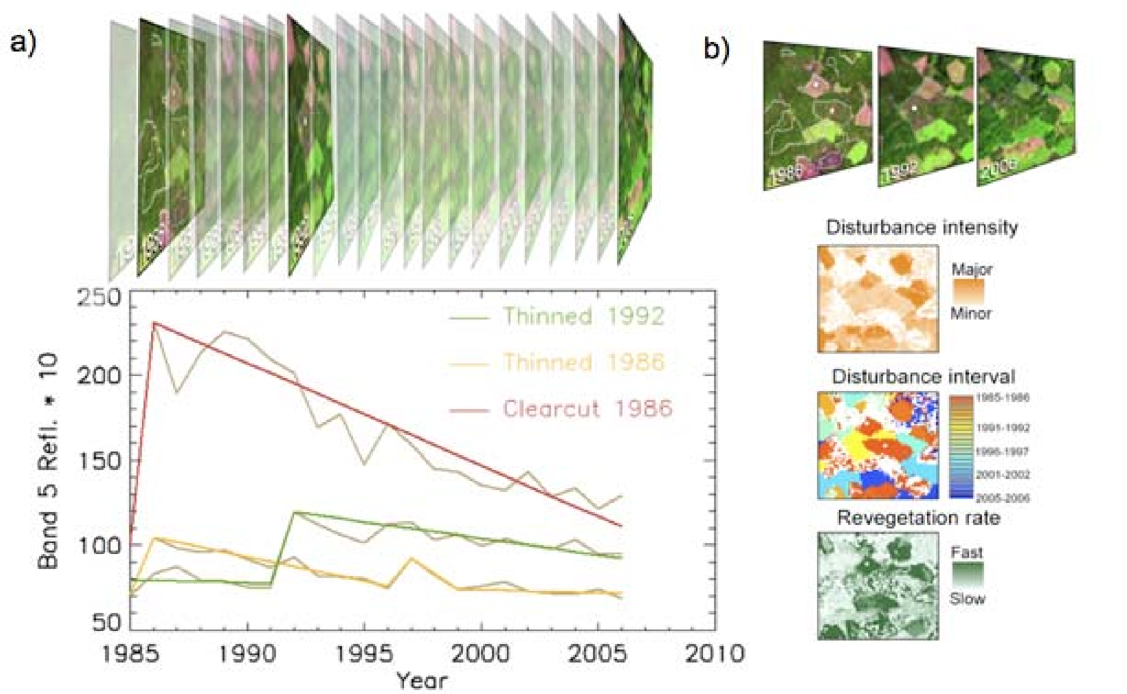

Figure 6. The core process in the LandTrendr algorithms. a) Spectral values of a single index are extracted for a pixel in a dense stack of images (grey traces). Signal extraction techniques are used to identify the years (on the x-axis) that form logical endpoints (or vertices) of segments describing consistent processes over time, and to find the vertex values (the y-axis component of the vertices) 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.

Based on the iterative evaluation of methods, data, and reference sources, a final set of monitoring objectives was selected to be met under the current protocol:

1. Determine temporal and spatial changes in landscape mosaics across SIEN parks every 5-10 years (time frame dependent upon pace of change and available funds). Landscape mosaics may include:
    - Vegetation type and cover
    - Other land cover types such as streams and lakes, bare ground, rock, roads, and developed areas
2. Determine fire regime characteristics across SIEN parks on an annual basis, and monitor trends through time in selected characteristics. These may include fire size, fire severity, fire frequency, and fire season.
3. Monitor changes in vegetation response to fire over variable time frames (1 to many years) post-fire and among different types of fire regime characteristics (low to high severity, different seasons, different frequencies).
4. Detect spatial and temporal changes in vegetation condition (or health) across SIEN parks – which may indicate change from other agents of change such as insects, pathogens, air pollutants, and drought.

The following sections and the associated SOPs document options to address these objectives.

2. 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 TM make it appropriate for 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 SIEN 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 Goward 2004; Cohen and Spies 1992). Landsat's temporal sampling 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 (Asner and Lobell 2000a; Brown et al.

2000; Chuvieco et al. 2004; Cohen and Spies 1992; Healey et al. 2006; Trigg and Flasse 2001).

When maps from satellite imagery are created, the robustness of those maps must be evaluated using some form of validation or corroboration. In remote sensing parlance, this is considered an “accuracy assessment” step (Congalton and Green 1999), which we detail in SOP 5 (TimeSync) and SOP 7 (Field validation). Ideally, accuracy assessment statistics should be based on a probability-based sampling designs (either random or stratified random). This is easy to achieve with theTimeSync approach, which uses imagery itself and is unconstrained by cost of access to points. Thus, we advocate a random-sample validation approach using TimeSync for initial accuracy assessment of any map products (SOP 5). Field validation can then be focused on confirming the TimeSync interpretation, or on opportunistic sampling of flagged, unusual or important change events.

3. Methods

The four objectives of this protocol involve mapping change on landscapes across parks and adjacent areas using yearly stacks of Landsat Thematic Mapper imagery. There are several possible combinations of mapping and validation that can be considered, depending on the SIEN’s final needs and resources. Mapping can be achieved using either LandTrendr or LandTrendr followed by the POM approach, but not all monitoring objectives can be mapped using either method alone (Table 2). Each method’s maps can then be evaluated using TimeSync alone, or TimeSync in conjunction with other reference data or with newly acquired field data. Ultimately, the SIEN will determine which combination of methods will be used.

Table 2. Linking monitoring objectives with remote sensing methods.

<table>
<tr><th>Monitoring objectives</th><th>LandTrendr / TimeSync</th><th>LandTrendr & POM / TimeSync</th></tr>
<tr><td>Determine temporal and spatial changes in landscape mosaics every 5-10 years: veg cover, other land cover</td><td rowspan="2">Yes</td><td>Yes</td></tr>
<tr><td>Determine fire size and severity annually</td><td></td></tr>
<tr><td>Monitor vegetation response to fire over variable time frames post-fire</td><td>Yes</td><td>Yes</td></tr>
<tr><td>Detect spatial and temporal changes in vegetation condition or health</td><td>Yes</td><td></td></tr>
</table>

3.1 Details of remote sensing tools

All three primary remote sensing tools in this protocol utilize Landsat Thematic Mapper (TM) imagery. The LandTrendr approach extracts information on trends and abrupt events for each pixel in a stack of annual images. It uses a single spectral index at a time to extract this information on change. The POM (probability of membership) approach describes spectral change in richer terms more closely aligned with land cover class distinctions. As a two-date change detection approach, the original POM approach was subject to substantial false positive mapping, but these problems are substantially diminished when the LandTrendr algorithms are used to produce temporally stable images upstream of the POM implementation. Thus, in this protocol, the POM approach is linked to LandTrendr (Figure 7).

Both approaches produce maps of change that must be evaluated using the TimeSync tool, which allows an expert interpreter quick and organized means of viewing an entire time series of the landscape at individual points. The TimeSync interpretations can then be backed up by opportunistic visits in the field, if resources permit.

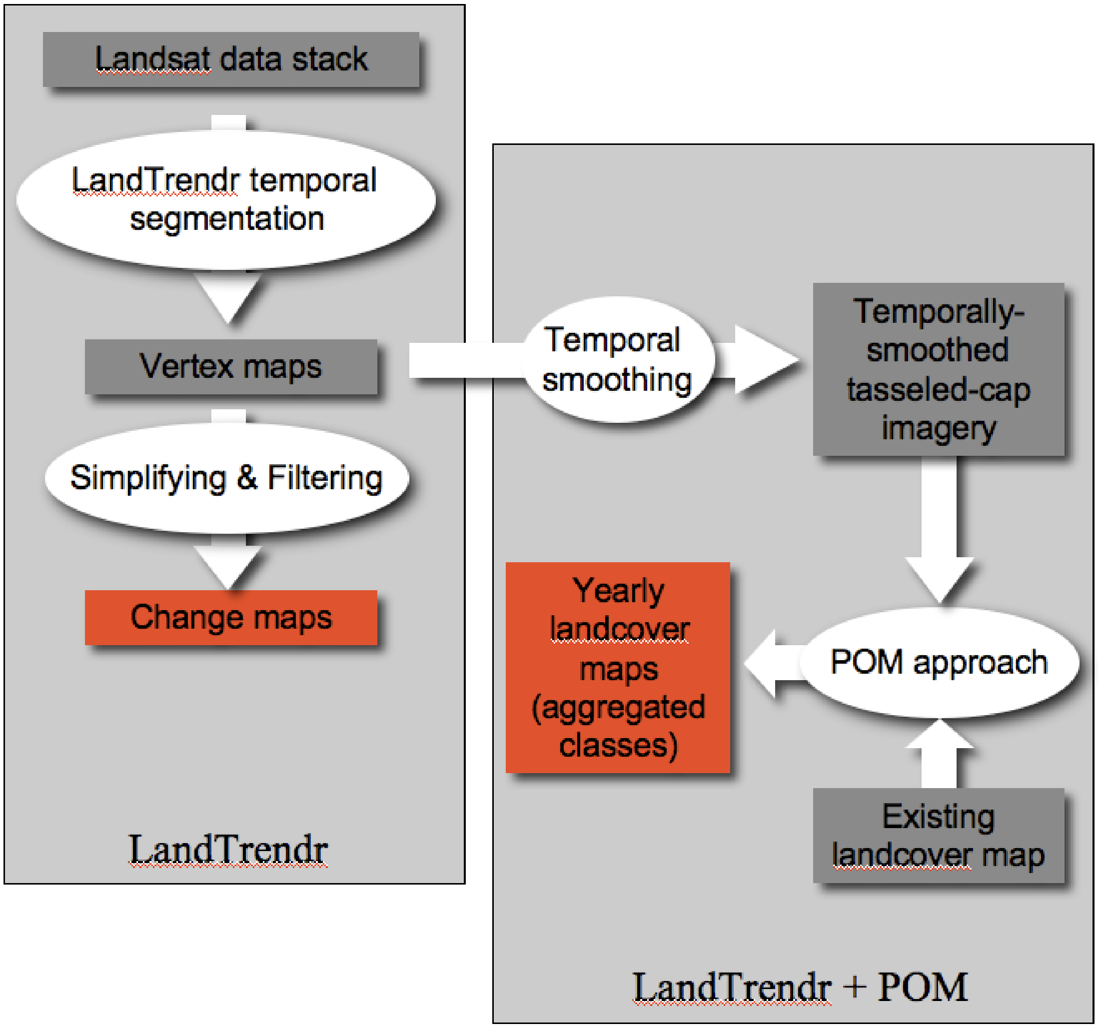

Figure 7. Schematic showing the relationship between LandTrendr processing alone and LandTrendr + POM processing. LandTrendr methods involve image preprocessing and segmentation of the temporal trajectory of spectral data on a pixel by pixel basis (see Figure 2, SOPs 1, 2 and 3), resulting in maps of the vertices of the temporal segments that efficiently describe each trajectory. These "vertex maps" can then be summarized in different ways to produce a suite of change maps (SOP 4). The vertex maps can also be used to smooth tasseled-cap imagery (SOP 3), which can then be used in the standard POM approach for landcover labeling over time (SOP 6).

3.2 LandTrendr

The foundation of LandTrendr change maps is a segmentation process that simplifies the temporal trajectories of pixels in a stack of Landsat Thematic Mapper imagery (as in Figure 6). The details of the method are described in Kennedy et al. (In press) In the standard incarnation of LandTrendr, the segments of the simplified time series are labeled as disturbance or growth based solely on a the direction of change in 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. In the LandTrendr + 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 8. Each step has a series of sub-steps described in detail below.

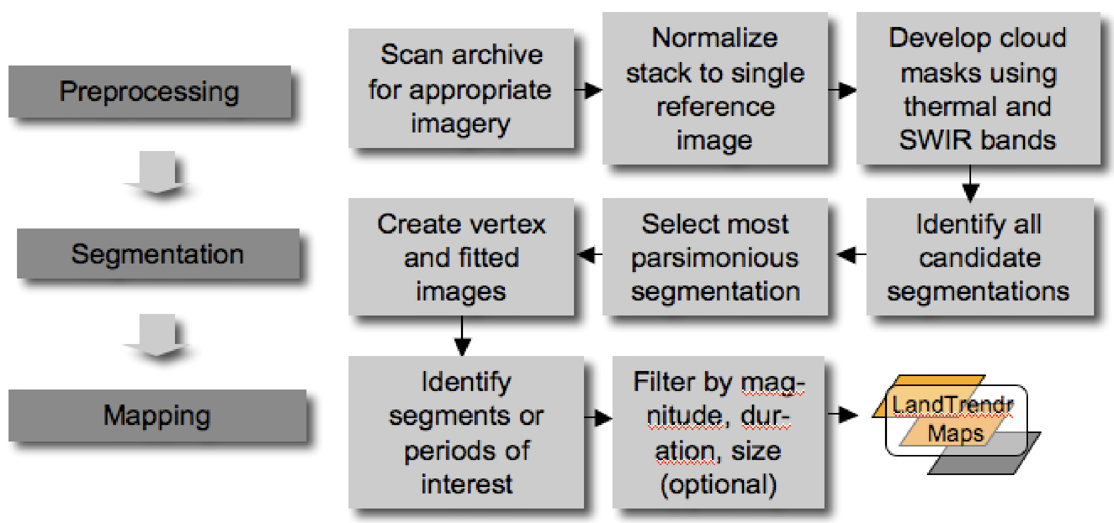

Figure 8. The overall workflow of LandTrendr.

<u>*3.2.1 Preprocessing*</u>

Pre-processing is a key step in any remote sensing monitoring study (Kennedy et al. 2009). It describes a set of steps to convert essentially raw imagery into a form useful for analysis in monitoring: image acquisition, radiometric normalization, and cloud-screening. Details of the methods used to conduct pre-processing are described in SOPs #1 and #2. For the purposes of later evaluating options for cost and task distribution, we highlight a few key issues here:

- Images are chosen to favor consistency of phenology over absence of clouds. This is because the method allows on-the-fly mosaicking of multiple partly cloud images per year, greatly reducing the impact of clouds.
- Normalization of images is favored over absolute atmospheric correction. Radiometric normalization is thus an important step that requires significant expertise to conduct.
- Cloud and shadow screening are based on a simple scoring approach that also involves significant human interpretation of images.

For the parks of the SIEN, the Oregon group has set the stage for pre-processing by building Landsat stacks for the years 1985 to 2007. Further monitoring will require acquisition, normalization, and cloud screening only of new images at the recent period of the image stack, but should not require construction of new stacks of imagery.

3.2.2 Segmentation

We consider segmentation to be the process of identifying periods within a time-series where a consistent process is occurring, either stability, increase, or decrease in a selected spectral index (Figure 5a). Details of the mathematical rules behind LandTrendr segmentation are described in Kennedy et al. (In press), but an overview is provided here for reference. 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 Cicone 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 Wagtendonk 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 2000b; Brown et al. 2000; Healey et al. 2006; Royle and Lathrop 2002; Skakun et al. 2003). 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 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 aseries of parameters that describe the weights of these different tuning coefficients, including the number of desired segments (SOP #3). Tests of the effects of these parameters are described in Kennedy et al. (in press).

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 9).

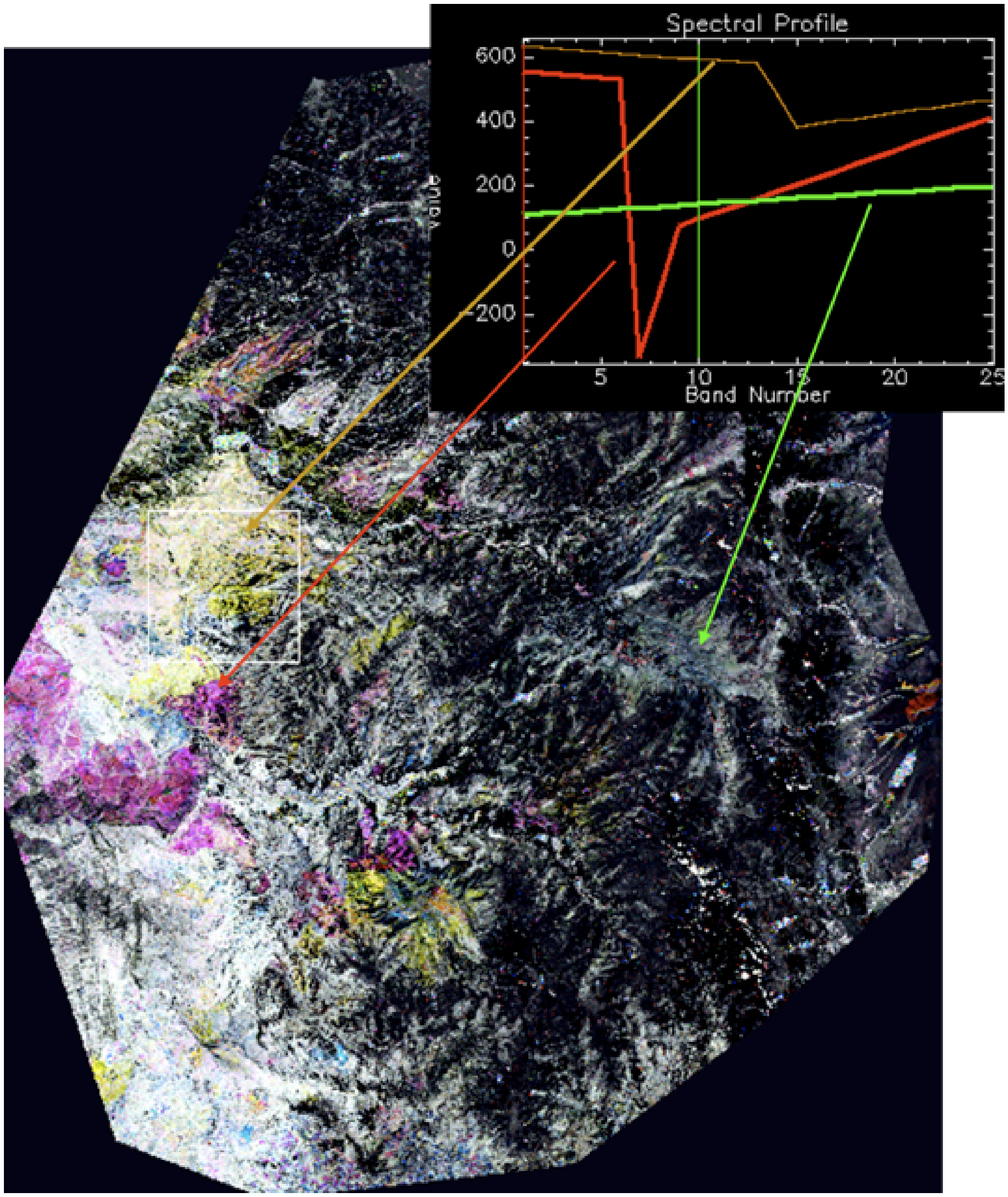

Figure 9. A false-color composite (1985: Red, 1995: Green, 2008: Blue) image of fitted trajectories of the normalized burn ratio (NBR) for the area including Yosemite NP. On the map, areas of relative stasis appear in shades of black, grey and white, but areas that have experienced change take on colors (such as purple or yellow) depending on the timing and intensity of the change. The fitted spectral trajectories for three pixels are shown in the inset: a high severity fire (red), a more moderate intensity fire (brown), and an area of growth (green).

3.2.3 Change mapping

There are three types of change-map that LandTrendr currently supports: segment-based, sequence-based, and sliced-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. 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 is labeled recovery, and if the segment moved from higher to lower value, it is 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 10a). 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 10b). 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).

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 from maps any segment information that is indistinguishable from noise.

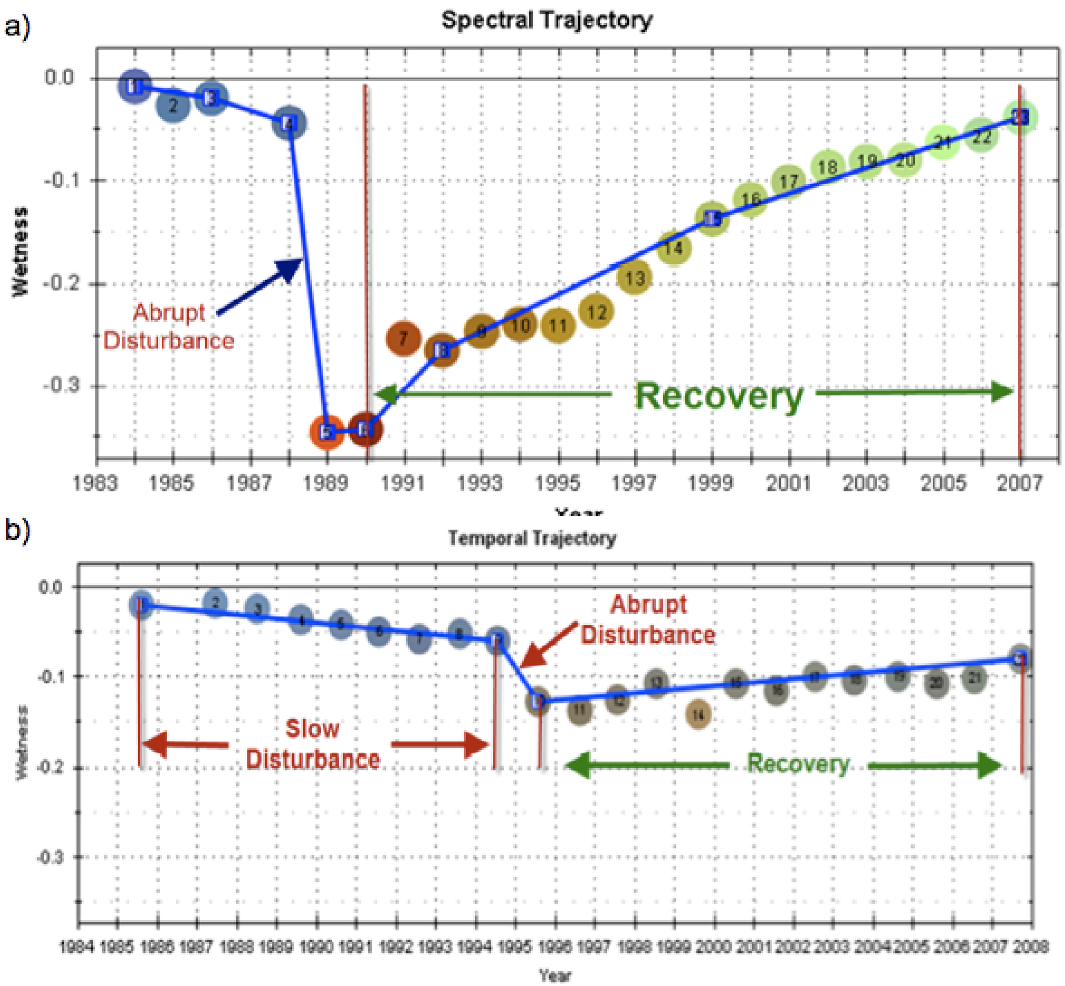

Figure 10. In many cases, the segmentation of a trajectory results in adjacent segments of the same type (disturbance or recovery) that differ only slightly in slope. a) In this example, the post-disturbance recovery period includes three straightline segments whose coalescing would simplify the information 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 and distinct information. Here, a slow disturbance is followed by an abrupt disturbance; coalescence in this case would remove useful information about two distinct processes.

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. (This is done using the TimeSync utility described below). 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. 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." Alternatively, if photointerpreted estimates of percent cover are unavailable, then a simple linear fit of a maximum and minimum cover condition can be used as a first-approximation.

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, characteristics of the remaining segments associated with each pixel's temporal trajectory are mapped. The segment characteristics being mapped include: starting year, duration (length of the segment in years) and magnitude (the change in NBR from the beginning to the end of the segment). To describe these characteristics, we create two raster stack images corresponding to magnitude and duration, respectively, with as many layers in each image as there are years. The magnitude and duration of a given segment's change are recorded in the layer of the image corresponding to the start year of the segment. 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 within a year that are smaller than 11 pixels in size (approximately 1ha). 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 11).

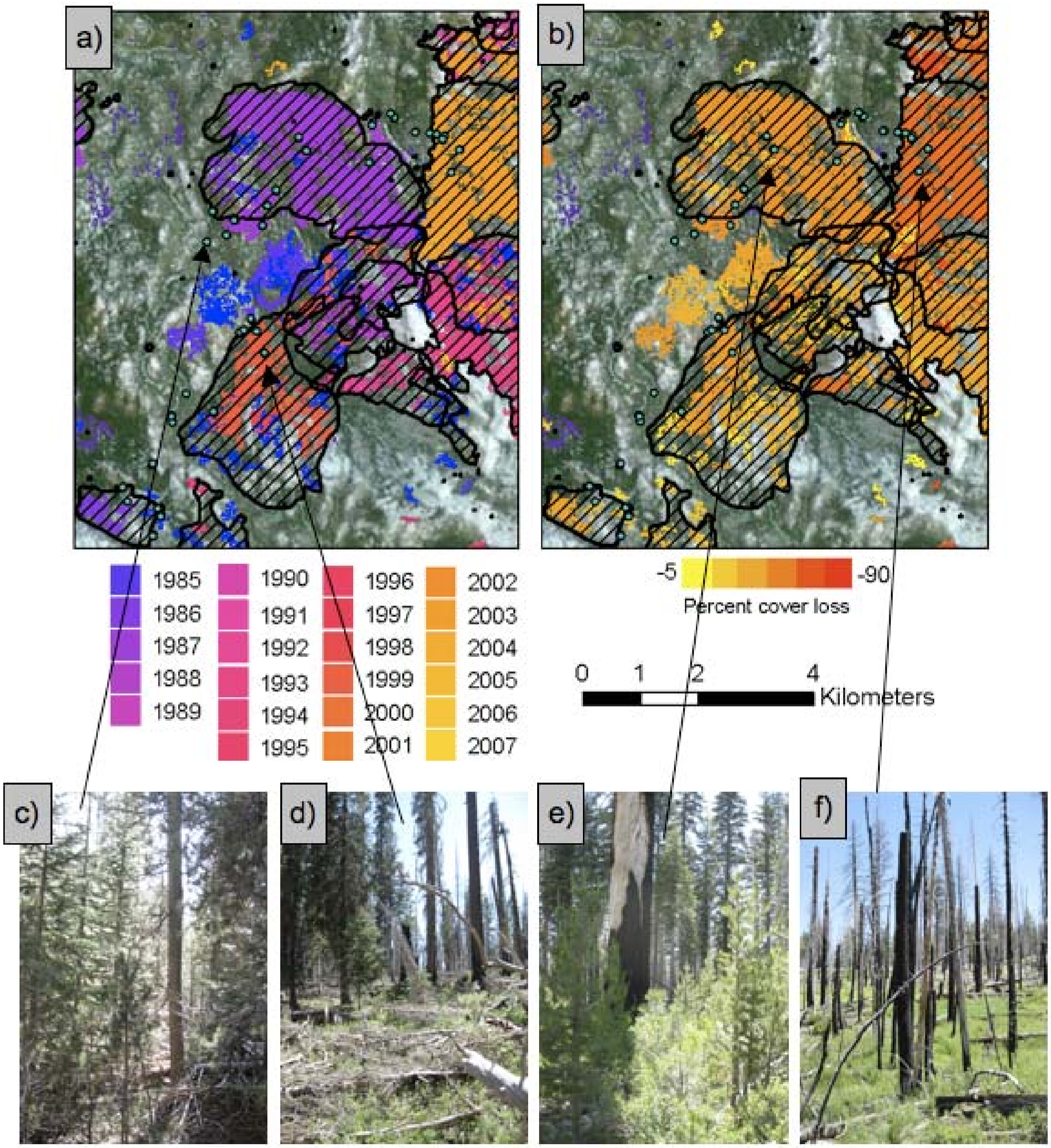

Figure 11. Fire disturbances in Yosemite mapped with the segment-based approach. a) Year of disturbance (colors) with fire polygon data from the park overlaid for reference. b) Estimated fire-wide average loss of percent vegetative cover between the years bracketing the fire. c-f) Field-visited locations showing the range of both fire-severity and post-fire recovery, ranging from unburned (c) to recently burned with substantial cover loss (f).

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. 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 (Figure 12), but the SIEN parks could add any number of additional change classes as new processes or events become interesting.

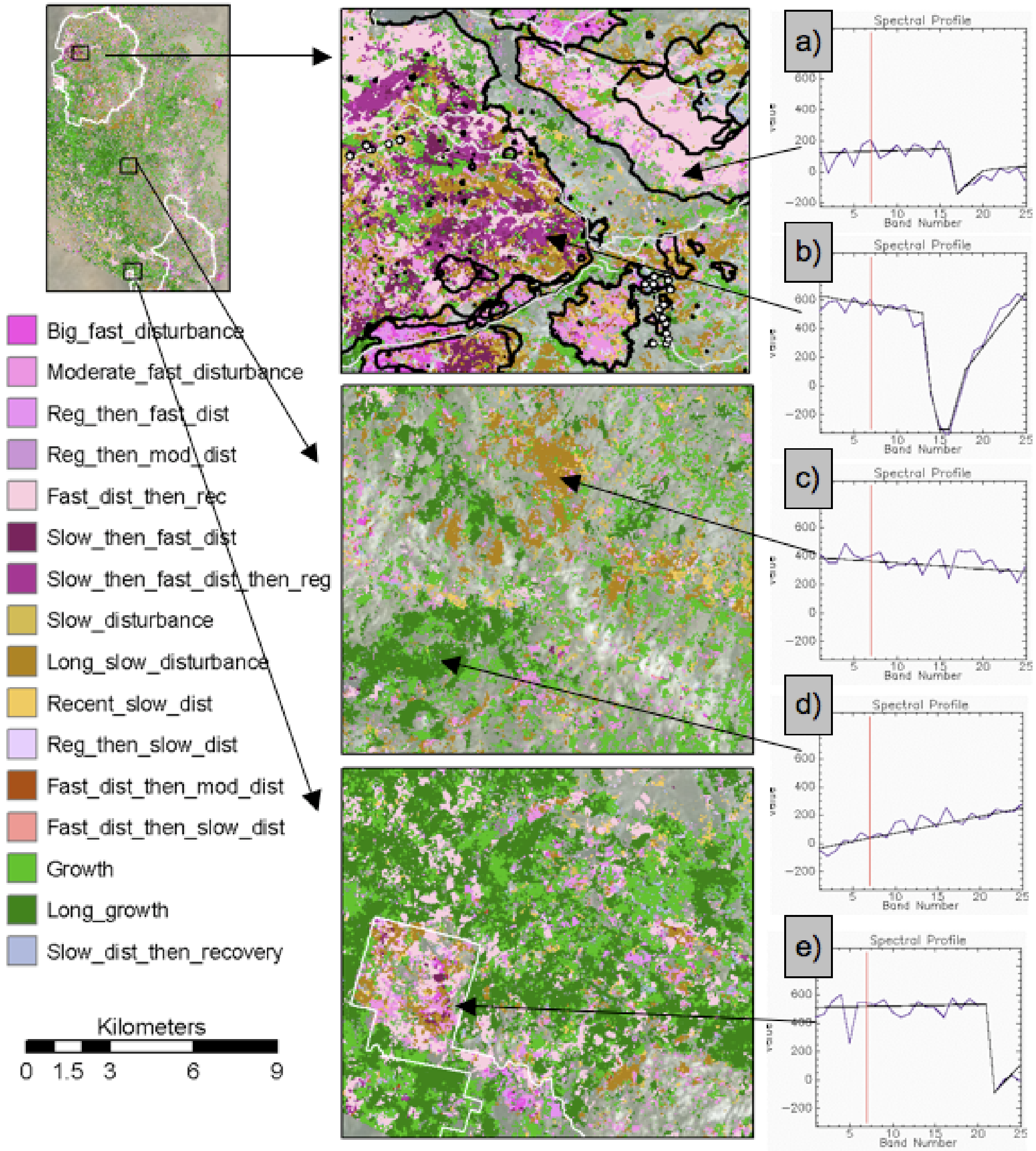

Figure 12. Segment-based mapping for the area spanning parts of both Yosemite and King's Canyon National Parks. Generic change label rules are applied to fitted images (such as that shown in Figure 8) to produce classified images that capture landscape dynamics. Maps capture the distinction between fire areas that burned relatively stable forest (a) from those that saw pre-fire mortality (b), such as that likely caused by insect activity (c). The signal of growth is also captured (d), as well as to the relatively subtle effects of prescribed fires (e)

Slice-based mapping

Both of the two prior mapping approaches provide overviews of when and where disturbance and recovery processes have occurred through the entire record of the imagery. Maps may include processes that occurred next to each other geographically but which occurred many years apart. For some monitoring or display purposes, it maybe more useful to provide a simple snapshot of all the dynamics occurring on the landscape at a particular point in time, or to observe such yearly snapshots over time. Thus, the final change mapping approach is to extract from the fitted trajectories the year-over-year direction and magnitude of change occurring in each pixel (Figure 13).

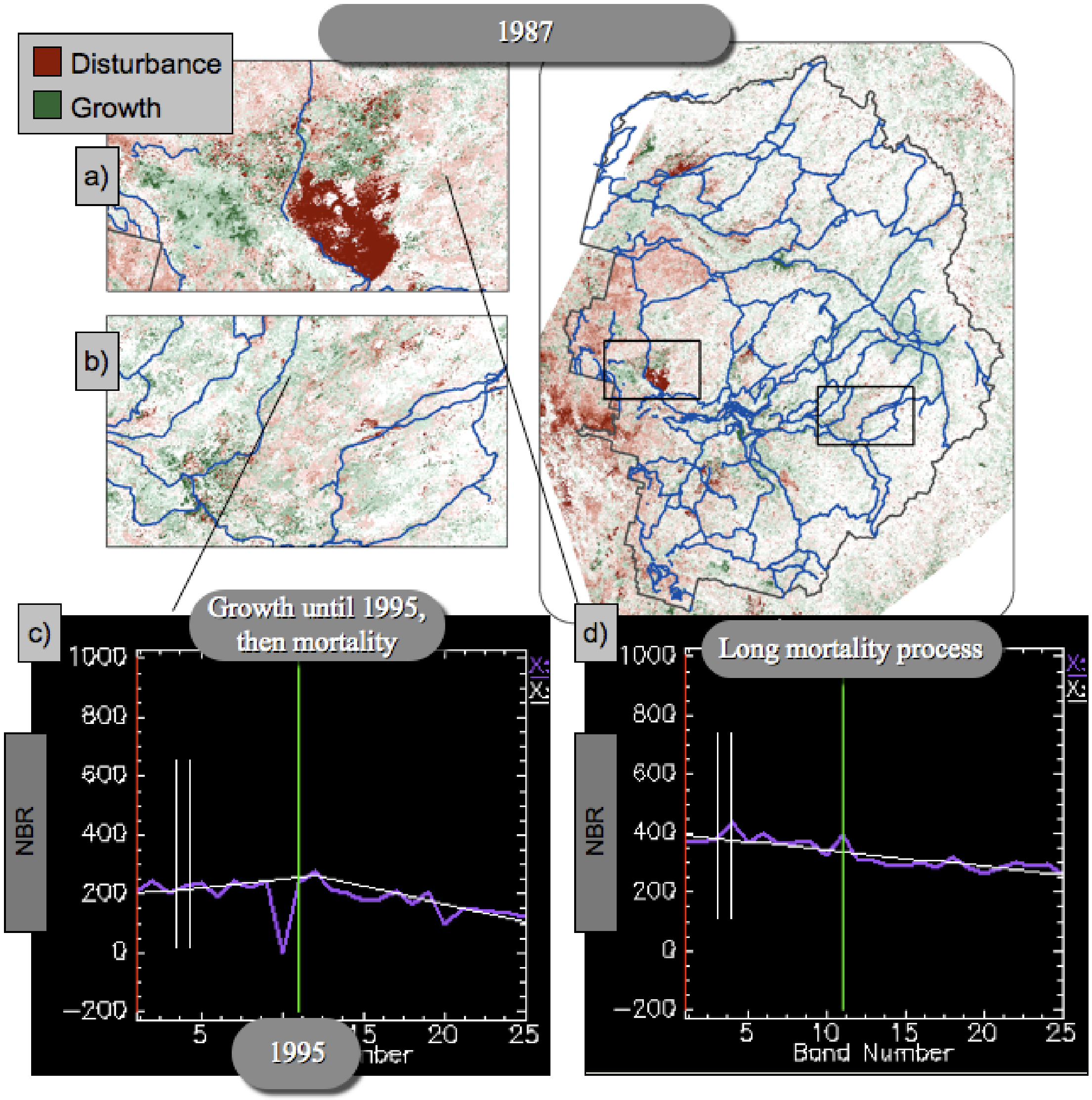

Figure 13. Slice-based mapping of disturbance and growth from 1986 to 1987 for Yosemite National Park. a) A fire from 1986 to 1987 appears as an area of deep red (steep decline from 1986 to 1987), while adjacent areas show signs of subtle growth. b) An area of general vegetative growth. c) The spectral trajectory of the normalized burn ratio index for one pixel from inset (b), with white parallel vertical lines indicating the period over which the slope is calculated for the maps above. d) The same as (c), but for an area of slow decline (usually associated with insect mortality).

3.3. LandTrendr + POM

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. To label changes in land cover, we must build links between LandTrendr and the probability-of-membership (POM) approach.

The process of integration involves three broad steps (Figure 14). 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 cover 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.

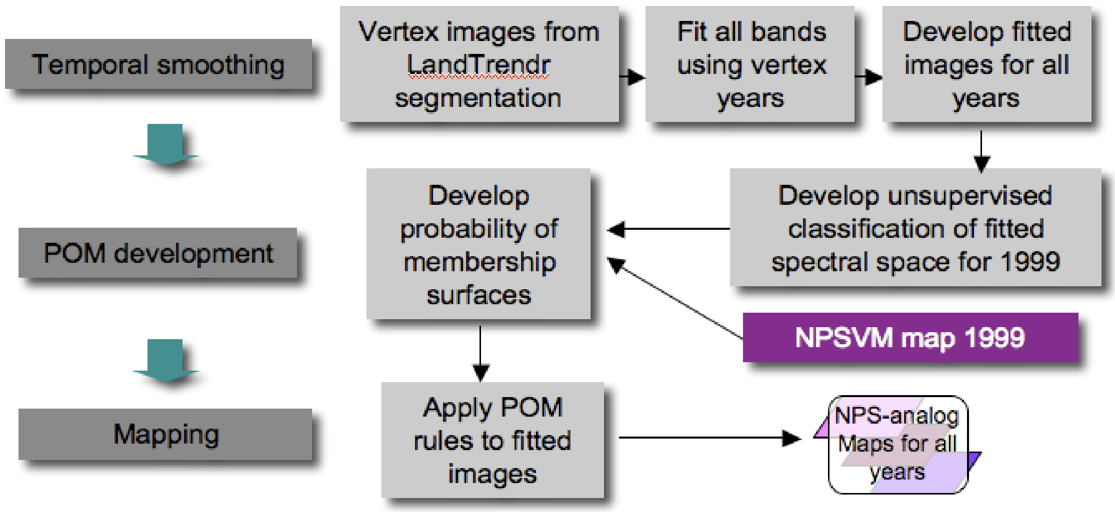

Figure 14. The overall workflow of LandTrendr + POM for a park with a 1999 landcover map from the NPS Vegetation Mapping (NPSVM) program.

3.3.1 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 15). Vertex years from the NBR fitting are fed to the LandTrendr fitting algorithms (described in the segmentation section above) to determine the most parsimonious path through other spectral band, 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.

3.3.2 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 compromise 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 which 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 using unsupervised classification. A standard *k*-means non-parametric partitioning algorithm (Richards 1993) is used to create a set of image "spectral classes" that optimally divide the spectral space. The number of classes is determined by the user, and 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

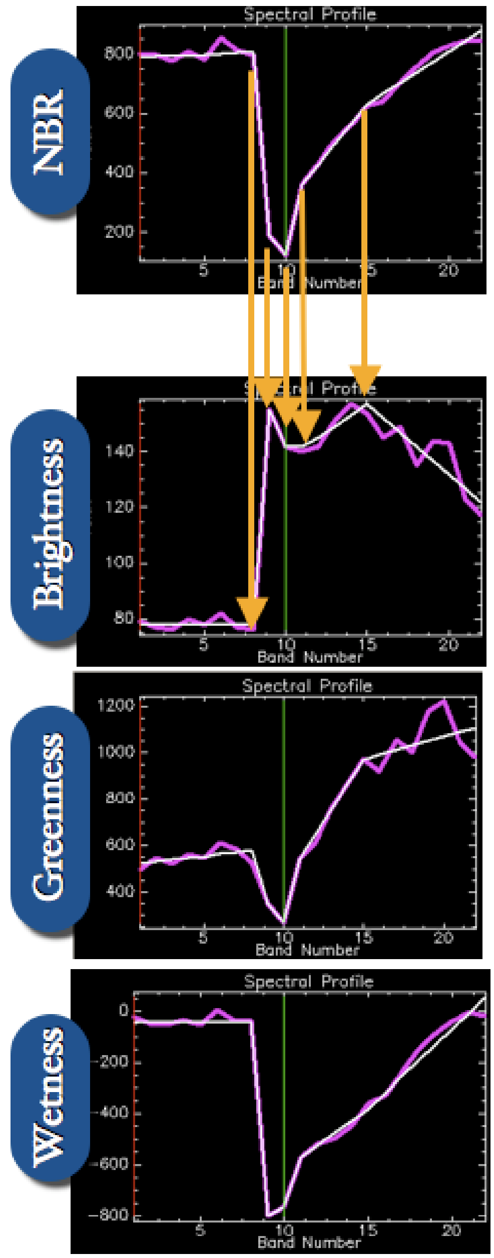

Figure 15. Once LandTrendr algorithms have been applied to a core index (here, the NBR, at top), other spectral indices (here, the tasseled-cap indices) can be smoothed using a constrained segmentation driven by the vertex years of the original segmentation.

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 probability of membership (POM) in each class for all parts of the spectral space are calculated (SOP 6).

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 section 3.3.1, a new landcover map can be created for the year of that pseudo-image (Figure 16).

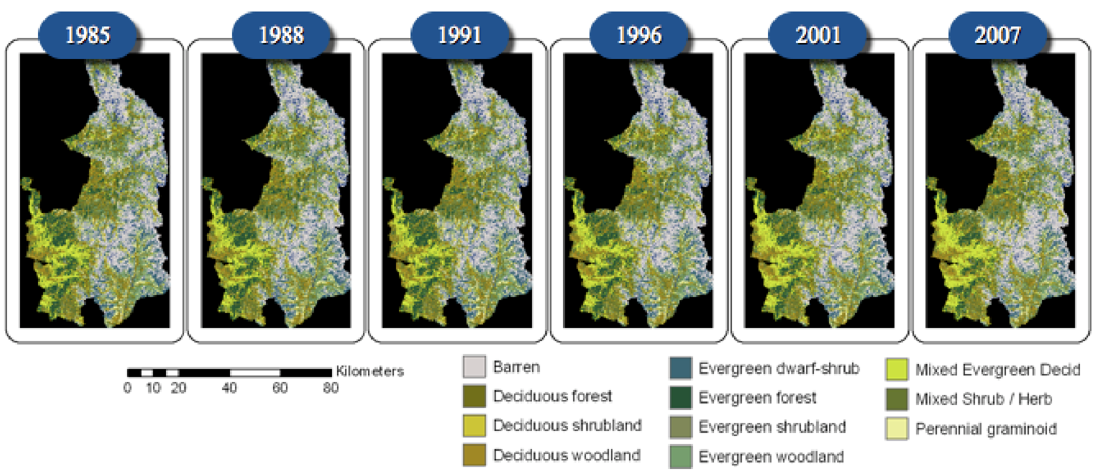

Figure 16. Landcover classes for SEKI derived using the LandTrendr + POM approach for a selection of years (maps for all years from 1985 to 2008 are created).

3.4 *TimeSync*

Because no single dataset exists that covers the entire spatial and temporal domain of the LandTrendr maps, expert-interpretation of the satellite imagery itself must be used as the first tier of corroboration. The TimeSync tool, developed by the Oregon group, serves this purpose and has been recently described in detail (Cohen et al. In press). Once a set of image stacks has been assembled for use in LandTrendr, it can also be ingested in the TimeSync tool, along with point coordinates for desired interpretation points. For each interpretation point, TimeSync displays image chips (small, square chunks of the image with user-selectable sizes ranging from 40 by 40 to 250 by 250 pixels) 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 (Figure 17). Initially, a single straight-line segment is drawn by the software between the first and last points in the trajectory; by evaluating the image chips, the trajectories of the pixel in different spectral bands, and a high-resolution image, the interpreter determines whether any trends or abrupt events have occurred. If so, the interpreter clicks on the point in the trajectory that captures the onset or end of that segment and uses a built-in Access database to describe the segment. This process is repeated for as many segments as the interpreter believes are needed to describe the trajectory.

The TimeSync tool has several key features that make it attractive:

- 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 much more easily ignored.
- Because the method uses the satellite imagery itself, interpretation plots can be placed anywhere on the landscape, allowing unbiased sampling of processes and unbiased evaluation of overall map accuracy.
- With built-in database functionality and automated loading of entire stacks of imagery, the method allows for very fast interpretation of plot data

Although the foundation of the TimeSync interpretation process is Landsat imagery, all points can be exported to a high-resolution image server to improve interpretation of the land use near the point of focus. Because the TimeSync utility was developed to serve as a generalized means of interpreting change across a time series, we document the use of GoogleEarth as a standard platform for such high resolution imagery. However, any geographic server that allows points to be displayed over high resolution imagery could be used, allowing the SIEN parks flexibility in how to implement that component of the protocol.

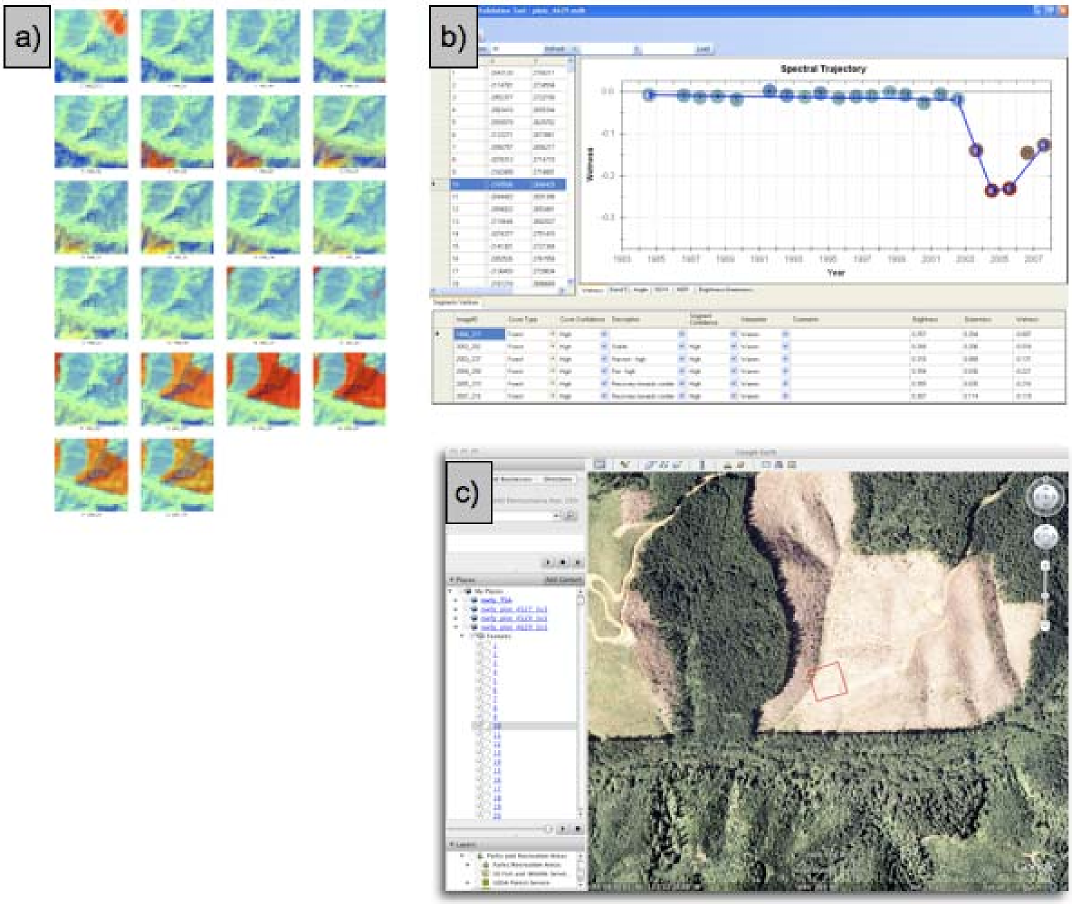

Figure 17. The TimeSync validation tool. a) Image chips for 20+ years of Landsat TM imagery centered around the target point. False-color tasseled-cap imagery is shown, where conifer vegetation is shown in blue tones and soil in reds and orangs. b) Connected with the center point in the images in a) is a database record populated by the interpreter that captures behavior of the pixel and labels it according to type. This database can then be linked with LandTrend maps or other point data. c) Plots can also be viewed on high-resolution digital photography (here an example from GoogleEarth) to aid in interpretation and to develop percent cover estimates to build models from the Landsat data space.

3.5. Field corroboration

Although an impetus for satellite-based mapping is to observe change across the large areas of the SIEN parks quickly and efficiently, on-the-ground validation of such maps may be useful as a means of interpreting and checking the maps. Provided below is a basic template for such field observation, designed with the idea that it could be added relatively cheaply to existing field observations conducted around the parks for other monitoring protocols or research. Details of several key pieces of this example approach are provided in SOP 7.

Key issues to consider during field sampling in support of Landsat-derived changes maps include:

- Because TimeSync interpretation is performed in an unbiased manner across the maps, field validation can be focused on validating the TimeSync interpretations and on assessing the validity of the algorithms rather than on validating the map. Thus, field plots can be placed near trails or other field campaigns.
- Evidence of change weakens with time, and measurements at a single point in time cannot strictly validate change because the conditions before the change are unknown. Moreover, validation of the existence of a long-duration process (such as encroachment of shrubs or slowly spreading mortality of trees in a forest stand) is particularly challenging, as these processes occur to some degree everywhere.
- For the purposes of remote sensing, the geospatial characteristics of the plot location and size are critical. Measurements made at plots must be linked to maps by GPS, and they must represent the conditions of at least an entire pixel footprint (approximately 30 by 30m). Moreover, we recommend use of GPS-ready cameras or of post-field GPS processing of photos to allow linkage of photos to maps.
- Measurements in the field should include estimates of percent cover of key structural types known to affect the remote sensing signal, and should be expressed in terms of projected cover.

4. 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 (see SOP 8).

Data storage needs are large. The parks of the SIEN cover three Landsat scenes (path 42, row 34 and row 35, as well as path 41, row 35). Simply processing each image through SOPs 1 and 2 requires as much as 125Gb of disk storage for data stacks spanning approximately 25 years.

NOTE TO SIEN STAFF:
THIS SECTION WILL REQUIRE FURTHER DISCUSSION ONCE DETERMINATION OF WHICH ANALYSES WILL ACTUALLY BE UNDERTAKEN BY THE SIEN.

5. Analysis and reporting

We arrange our discussion of analysis and reporting according to the SIEN's four monitoring objectives to be addressed in this protocol (Table 2 above). For each, we describe the analysis options and which of the methods described in section 3 would be applied to allow that analysis. At a minimum, however all methods require standard LandTrendr pre-processing and segmentation using the NBR for stacks of Landsat images in three scenes (path/rows: 42/34, 42/35, and 41/35). This processing has already been conducted by the Oregon group in support of protocol development for the years 1985 to 2007. Additionally, all methods require TimeSync interpretation.

5.1 Detecting change in vegetation condition and health

Many of the known stressors in the SIEN adversely affect vegetation over the long term, and can manifest themselves first as long term reduction in vigor or as spreading partial mortality within vegetative communities. By tapping into the 25+ year record of the Landsat archive, the LandTrendr algorithms are well-suited to capture such long-duration trends.

5.1.1 Map types needed

The following sequence of methods produces maps that can be used to capture long-term degration of vegetation condition and health:

- Standard pre-processing and LandTrendr segmentation using NBR on all three Landsat scenes needed for the SIEN
- Segment-based mapping of disturbance, filtering at the pixel scale with low threshold value, grouping into patches and filtering of patches < 11 pixels (~1 ha)
- Selection of disturbance events whose segments have duration greater than three years (to avoid abrupt disturbance events)
- Masking out false change in barren and water pixels, using either park-derived land cover maps or maps derived from imagery itself
- TimeSync interpretation of random points within this long-duration stratum to determine a patch-level average NBR magnitude threshold above which most changes are interpretable and real in both Landsat imagery and photos
- Filtering by patch-level magnitude and mosaicking

The resultant map represents long-duration degradation of vegetation that can be corroborated using TimeSync and, if resources allow, field validation. An example illustrating the effects of needleminer on lodgepole pine is shown in Figure 18 below. In this example, high levels of mortality are obvious in field visits (as evidenced by photos), but we note that field validation of low-magnitude mortality processes can sometimes be difficult to distinguish from normal background mortality in vegetative communities without repeat measurements over years.

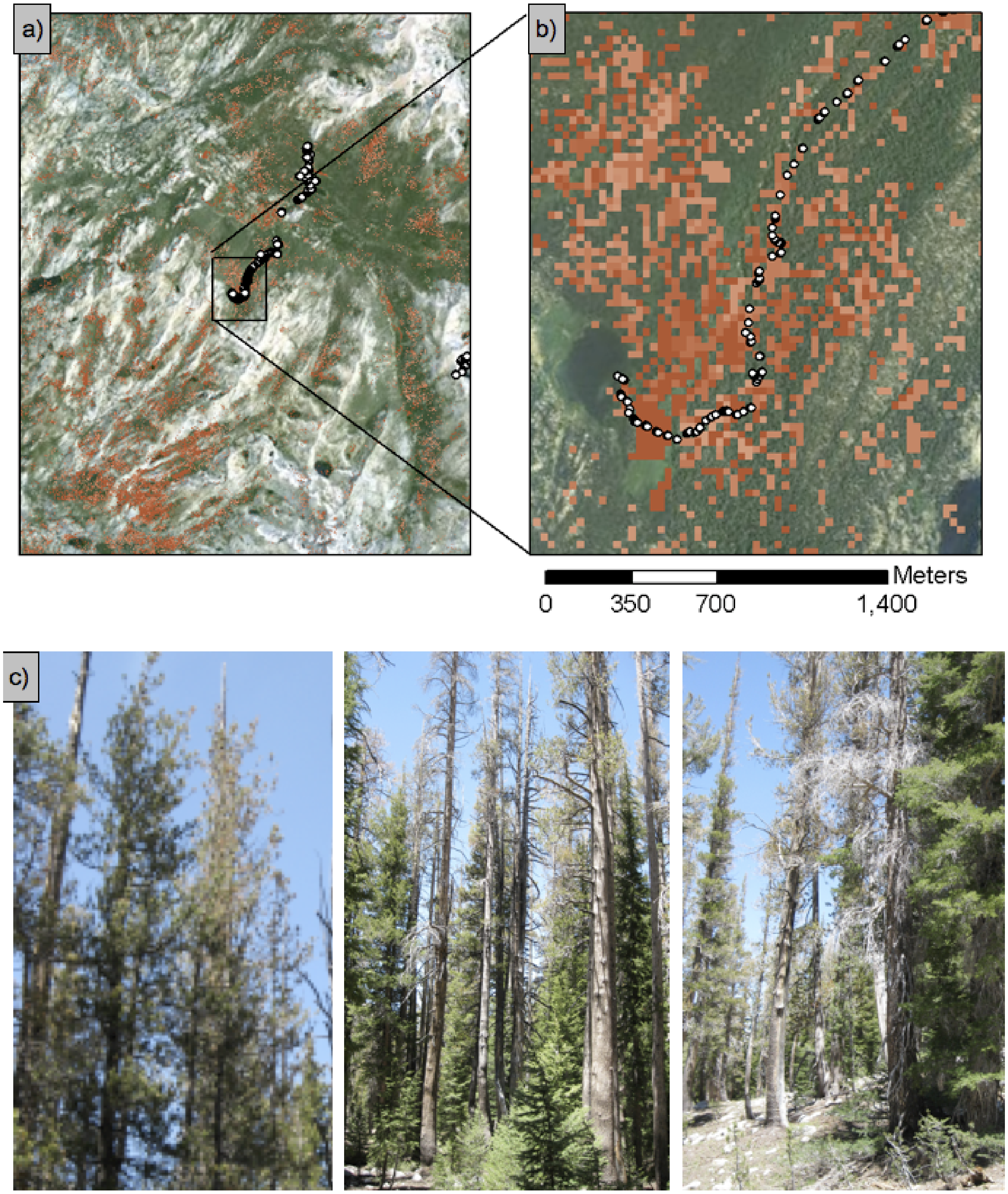

Figure 18. Insect-related mortality in lodgepole pine forests south of Tuolumne Meadows. a) and b) Airphoto of Tuolumne Meadows with areas of red indicating pixels showing loss of vigor. White dots show locations of field photos, three of which from the area of red pixels are shown in (c). Substantial mortality and loss of vigor caused by needleminer attack is evident throughout this area.

5.1.2 Analysis and reporting

Three characteristics of the long, slow disturbance signal captured in these maps are relevant metrics to track: presence/absence by vegetation, magnitude of loss, and timing.

The area affected by long-term mortality processes is a basic monitoring metric that can be derived from these maps. The metric would be calculated by intersecting the YOSE vegetation map (for example, that map produced for nominal year 1997) with all pixels experiencing the long, slow disturbance signal. The proportion of each vegetation type affected by insects could then be expressed in a single graph. Vegetation mortality caused by insects and other stressors is not uniform even within a single patch, and the range of severity is thus a metric that may be expected to change over time as stressors become more or less acute. Generally, the greater the level of vegetation mortality, the greater the spectral manifestation of that mortality. Derivation of this metric would be similar to the prior metric, but would retain for each vegetation class the distribution of spectral change magnitude values. Rather than a single graph illustrating the proportional area affected by slow change across all vegetation types, a graph of the distribution of magnitudes of change would be constructed for each vegetation.

Finally, both the prior metrics have a temporal dimension that can be tracked over time to understand whether the amount or severity of such mortality is changing. As this graph is re-calculated over time, the range of proportions within different community types will change, and such metrics could be used to begin discussions with the SIEN as to what proportions of mortality by vegetation community type merit heightened monitoring or perhaps management response.

5.2 Detecting fire size and severity

Fire detection using Landsat or related imagery is well established both in the SIEN parks (van Wagtendonk et al. 2004) and more generally for the nation (www.MTBS.gov). In addition to simple detection of fire events, the relative impact of the fire on vegetation is often considered to be related to the degree of spectral change before and after a fire event, particularly when the NBR index is used. Because we recommend the use of the NBR as a primary spectral index on which to base LandTrendr runs, tracking fire size and severity in this protocol is straightforward.

5.2.1 Map Types Needed

The following sequence of methods produces maps that can be used to capture fire events and their severity:

- Standard pre-processing and LandTrendr segmentation using NBR on all three Landsat scenes needed for the SIEN
- Segment-based mapping of disturbance, filtering at the pixel scale with low threshold value, grouping into patches and filtering of patches < 11 pixels (~1 ha)

- Masking out false change in barren and water pixels, using either park-derived land cover maps or maps derived from imagery itself
- Separation of disturbance events whose segments have durations either greater or less than three years in duration, resulting in a two-stratum map
- TimeSync interpretation of random points within each stratum to determine a patch-level average NBR magnitude threshold above which most changes are interpretable and real in both Landsat imagery and photos
- Filtering by patch-level magnitude and mosaicking
- Optional masking to constrain fire pixels to fire boundaries determined by other means, if so desired

Figure 19a shows an example of disturbance magnitude mapped with LandTrendr relative to known fire boundaries in SEKI. It is notable that the LandTrendr approach may be able to detect more subtle effects of fire than the standard two-date NBR differencing approaches typically used to map fire, including by the MTBS program. This is because low-intensity fires (such as those used in prescribed burns) only manifest themselves as post-fire mortality, not by their instantaneous effect on the canopy (Figure 20).

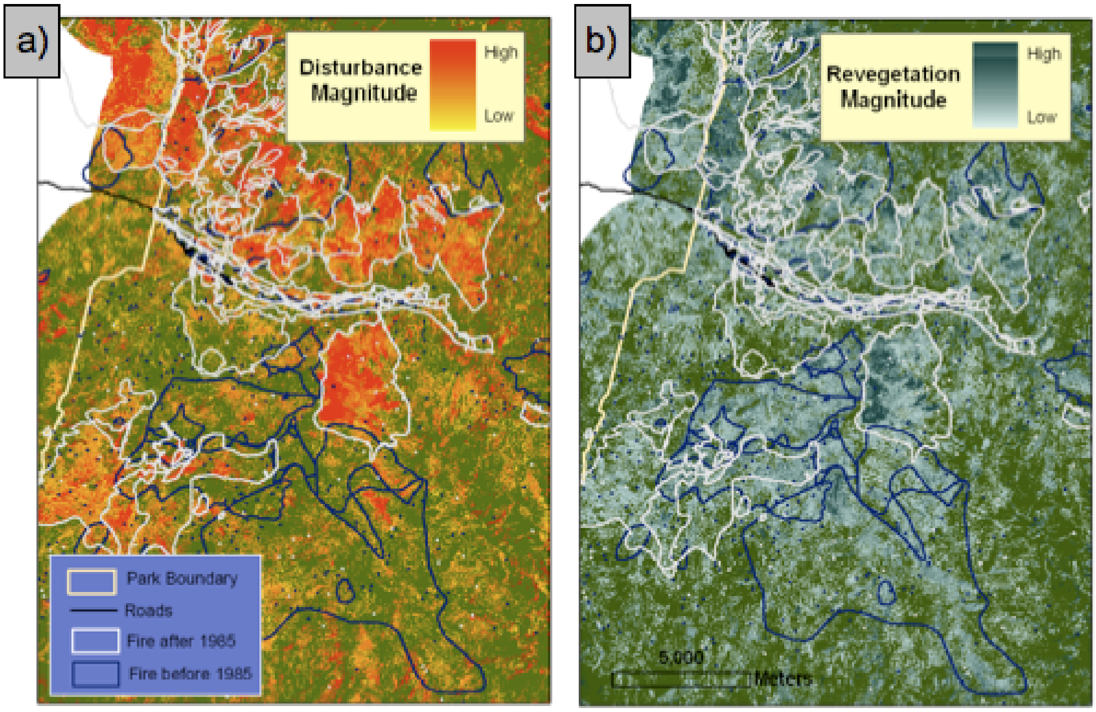

Figure 19. Disturbance and recovery dynamics of fire in Kings Canyon. a) Map of estimated disturbance magnitude, with known fire boundaries in white (during the Landsat record) and blue (preceding the Landsat record). b) Map of estimate recovery or revegetation magnitude. Note that fires preceding the Landsat record still show spectral evidence of recovering vegetation.

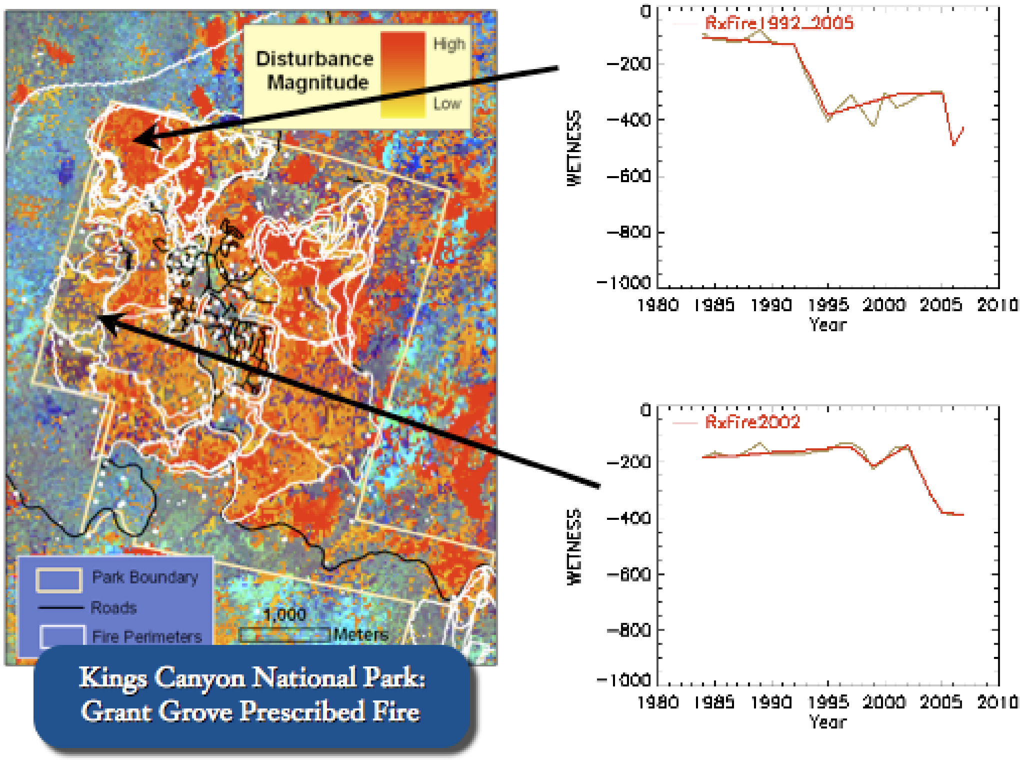

Figure 20. Prescribed burn magnitudes mapped for Grant Grove, Kings Canyon NP. Burns are captured through their prolonged effect on the spectral signal, rather than the immediate post-fire change in spectral values.

5.2.2 Analysis and reporting

Fire detection can be summarized both in terms of fire presence/absence and in terms of magnitude of change introduced by the fire. Two metrics can be easily derived by intersecting fire perimeters with disturbance magnitude images: Total area affected by fires at a yearly time step, and variability in the severity of a single fire. Ideally, such numerical estimates of fire magnitude must be matched with on-the-ground measures of fire severity, either immediately after or some years after the fire. This represents an ideal potential interaction point between this protocol and ongoing fire effects research within the SIEN parks.

5.3. Vegetation response to fire

Because of the consistent repeat measurements afforded by Landsat imagery in the years after a fire event, response of vegetation to fire over time may be an area where this protocol can contribute substantial new monitoring information. As noted in Table 2, both LandTrendr and LandTrendr followed by the POM mapping can be brought to bear on this objective.

5.3.1 Map types needed

The following sequence of methods produces maps that can be used to responses of vegetation to fire with LandTrendr and TimeSync alone:

- Standard pre-processing and LandTrendr segmentation using NBR on all three Landsat scenes needed for the SIEN
- Slice-based mapping of both disturbance and growth maps for each year in the archive
- Masking out false change in barren and water pixels, using either park-derived land cover maps or maps derived from imagery itself
- Clipping of disturbance and growth slices to fire perimeter maps (either developed through Park-preferred approaches or through LandTrendr NBR methods described in the prior objective)
- TimeSync interpretation of random points within each fire to corroborate post-fire trajectories.

Development of the POM approach requires additional steps:

- Rules defined by the Parks to simplify vegetation classes in native park land cover maps (for example, those developed under the NPS Vegetation Mapping program) to aggregated class groupings
- Creation of fitted Tassled-cap image stacks using the NBR segmentation outputs from the prior step
- Development of POM land cover class probability lookup tables
- Application of POM to fitted Tasseled-cap stacks to create yearly land cover maps
- TimeSync interpretation of randomized points within land cover classes, followed by opportunistic or targeted field validation

5.3.2 Analysis and reporting

The fundament spatial unit of reporting is the individual fire event, again as delineated either by Park-preferred methods or using the results of the second monitoring objective above. Within each fire perimeter, either LandTrendr slice-based maps or POM-derived land cover maps can be tracked over time to characterize the post-fire vegetation patterns.

A 1987 fire in Yosemite provides a useful example (Figure 21). During the fire, the central portion was burned more severely than the margins, but three years after the fire showed significant growth of vegetation (Figure 21b). In contrast, areas on the margin of the fire showed less mortality during the fire (as indicated by the shallower drop in NBR), but continued to show post-fire mortality three years later (Figure 21c).

Three fire events in 1995 and 1996 in SEKI provide a useful example. Although located adjacent to each other, the three fires showed different pre-fire cover class distributions, and different post-fire recovery patterns (Figure 22). Similar summaries of other fires in SEKI show similar variability in pre-fire conditions, fire effects, and post-fire recovery of landcover (Figure 23). The maps and analysis in these two examples are an unprecedented glimpse into the actual progression of cover types that is afforded by the combination LandTrendr fitting and POM mapping.

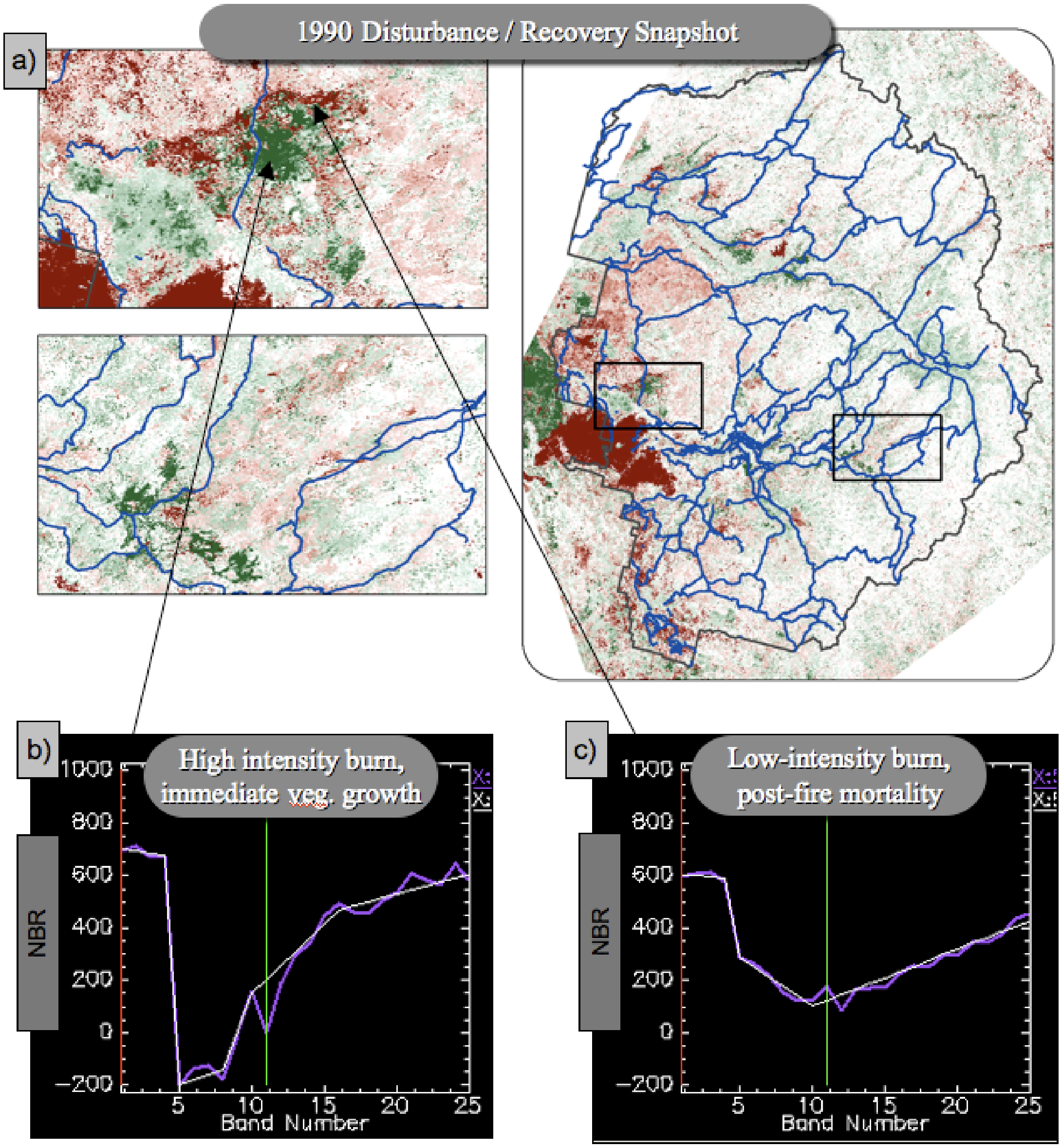

Figure 21. Post-fire dynamics captured with the slice-based approach to mapping change. a) Disturbance and recovery magnitude slices for the period 1989 to 1990 for Yosemite National Park. b) The centra portion of a 1987 fire experience substantial loss in vegetation (steep drop in NBR), but showed fairly 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.

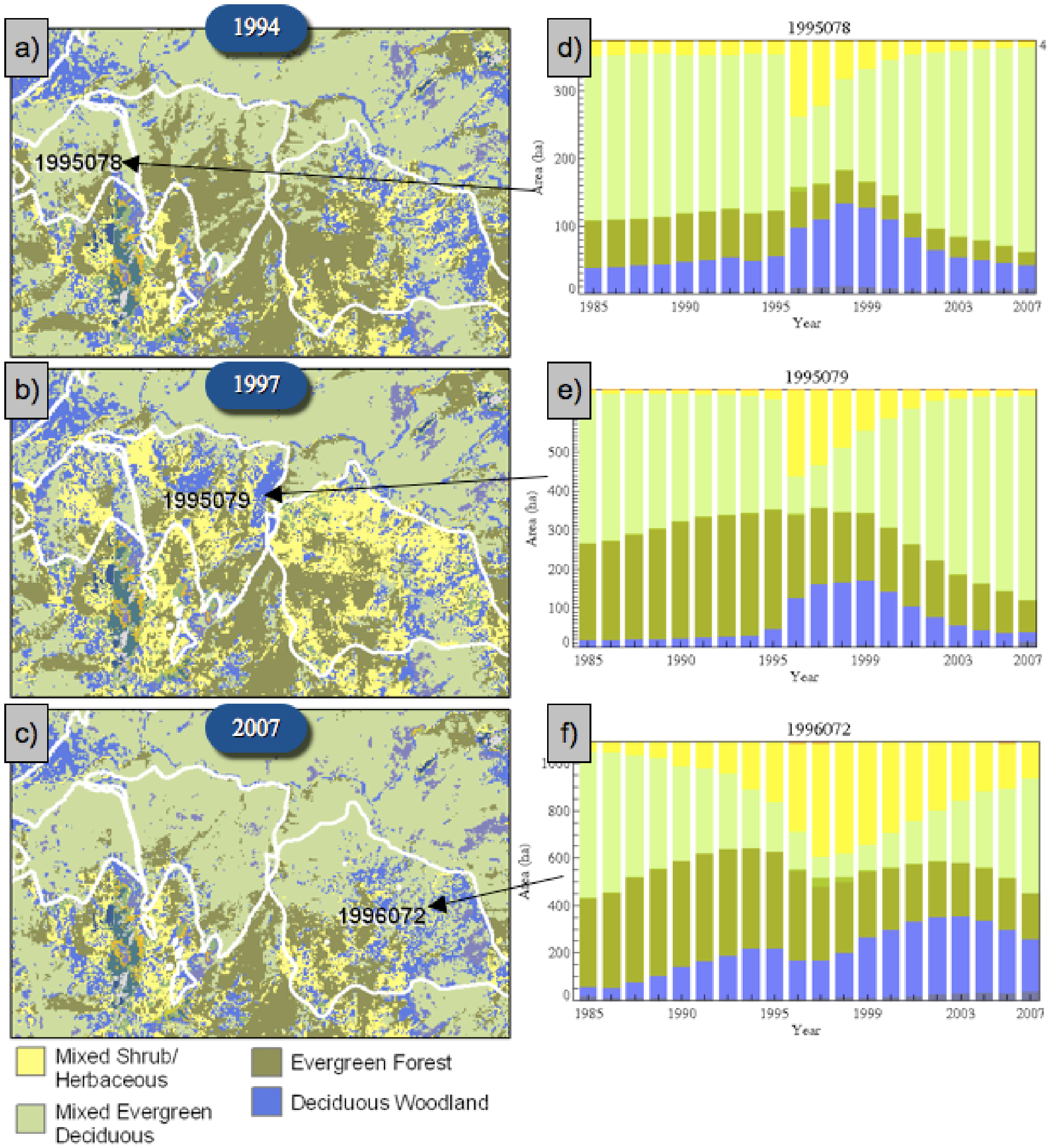

Figure 22. Pre- and post-fire landcover dynamics for three fires in SEKI a)-c) Landcover for 1994, 1997, and 2007,representing the periods before any of the fires, immediately after the fires, and 10+ years after fire. d)-f) Proportional makeup of land within the fire perimeters for the three fires indicated by arrows. Fires occur in 1995 for d) and e), and in 1996 for f).

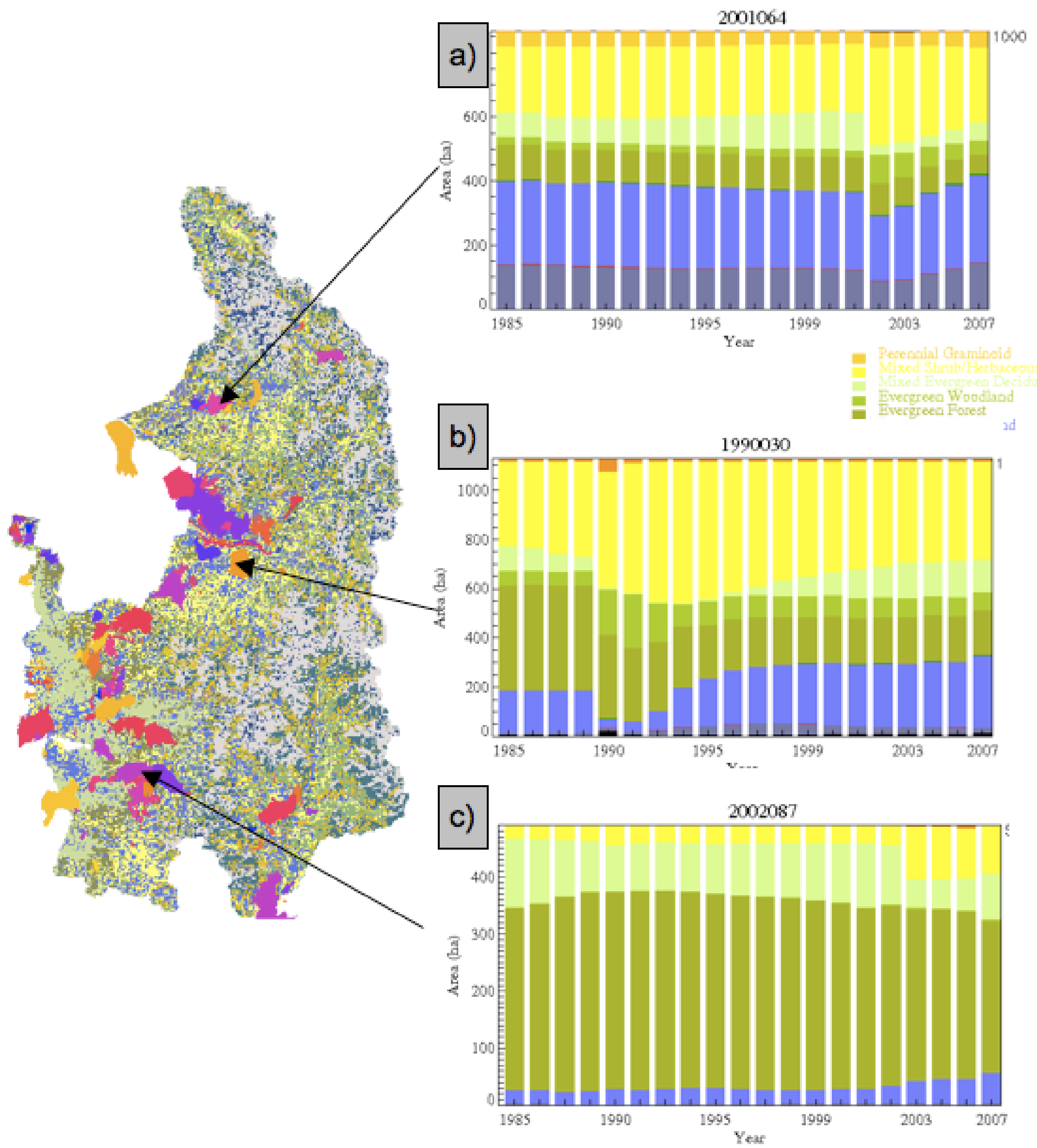

Figure 23. Landcover series for three other fires in SEKI occurring in 2001 (a), 1990 (b), and 2002 (c). Note the variability in pre-fire cover classes, in fire-related change in cover, and post-fire cover class changes.

5.4. Change in landscape mosaics

Characterizing mosaics of vegetation cover types on the landscape usually involves calculating various spatial or patch statistics from land cover maps. Tracking these mosaics over time requires yearly landcover maps that are stable where no change is occurring and are dynamic where change does occur. Exactly this type of map is produced using the LandTrendr and POM combination.

5.4.1 Map types needed

Map types needed are identical to those described for LandTrendr and POM in section 5.3.1.

5.4.2 Analysis and reporting

At the simplest level, annual summaries of the area of each park in each land cover type can capture the overall trends in vegetation type over time. Additionally, if the SIEN parks identify landscape spatial metrics that can be derived from land cover maps, these summary statistics can also be calculated and reported annually.

5.5 Encroachment

Although not explicitly defined as a monitoring objective for this protocol, encroachment of woody vegetation at treeline may be an indicator of effects of changing climate on Park ecosystems. Climate change and alteration of fire regimes may cause change in successional trajectories in the parks of the SIEN, particularly for vegetative communities at the margins of their temperature or moisture tolerance.
Encroachment of lodgepole pine into meadows at Yosemite may be one such indicator. Based on mapping and field observations made in the summer of 2009, it appears that LandTrendr-based change mapping can capture lodgepole encroachment in at least some situations. The effect is very subtle and occurs at a sub-pixel scale, but the contrast between dark lodgepole crowns and the relatively bright, sparse substrate in many meadows provides a means of capturing this slow process. In this case, the LandTrendr algorithms must be run using tasseled-cap brightness as the spectral index, rather than the normalized burn ratio that is used for all other change mapping recommended for the parks of the SIEN. Additionally, segmentation is constrained to a maximum of three segments, and the goodness-of-fit *p*-value threshold is relaxed from 0.05 to 0.15.

Using these altered parameters, the signature of decreasing brightness was indeed captured at several meadow areas where encroachment was observed in the field (Figures 30 and 31). These results indicate that the potential for mapping encroachment exists, but the fine-grained and subtle nature of this effect would require that further field validation and, likely, modification of segmentation parameters would be needed to evaluate the actual utility of this approach for mapping.

The signature of decreasing brightness also occurred elsewhere. Based on field visits and photos, the signal of decreasing brightness occurs in woody vegetation near treeline east and south of Mammoth Peak (Figure 24). While it is impossible to document what causes this change with a single field visit, the observation of consistently decreasing brightness provides a means of focusing potential future field-observation or historical photo analysis.

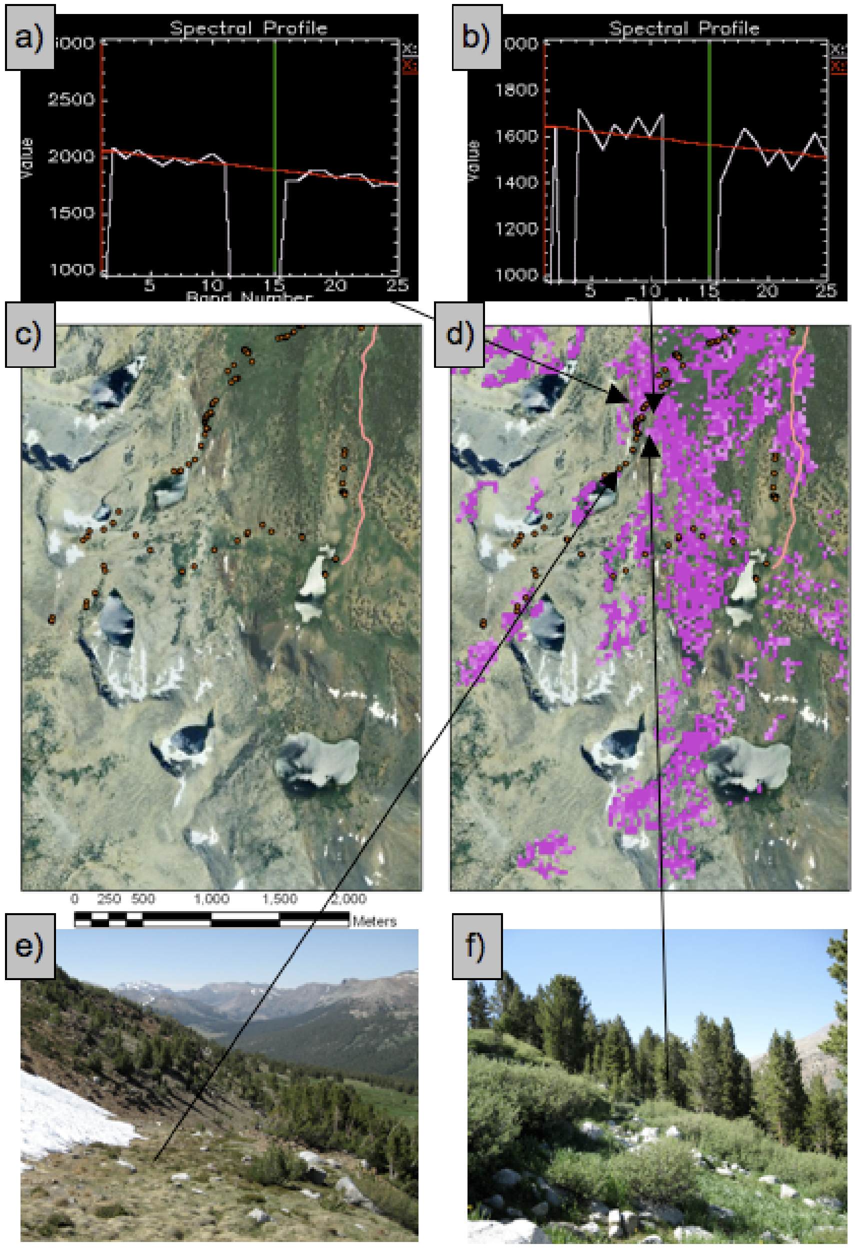

Figure 24. Signals of apparent decreasing brightness, and likely vegetation densification or encroachment, at the upper margin of shrubs and woody vegetation in Yosemite National Park. a) and b) Fitted trajectories of decreasing brightness for the two pixels indicated by arrows. Drops in the trajectory below the axis capture snow and cloud masked periods, which are not considered in the fitting. c) and d) Airphoto of treeline near Mammoth Peak, with dots indicating locations of photos taken in the field shown in orange and pixels of decreasing brightness indicated in purple. e) and f) show field photos for two location indicated with arrows.

6. Personnel requirements and training

6.1 Categories of effort

There are three major categories of effort needed to carry out any component of this protocol, each with different skillsets required of personnel: 1. Remote sensing image processing and mapping core outputs; 2. TimeSync validation of maps; and 3. Spatial analysis and reporting.

6.1.1 Remote sensing image processing and mapping core outputs

Carrying out basic remote sensing and image processing methods requires significant background in remote sensing theory, expertise in IDL coding and debugging, and familiarity with the ENI and Erdas Imagine image processing software packages. Within this category, application of the LandTrendr methods alone demands somewhat less expertise than adding the POM land cover mapping.

Based on the authors' experience in other networks and on conversations with SIEN personnel, such expertise is not typical either at individual parks or at the network level, and thus would require either hiring of individuals with these skillsets, significant investment of training for existing personnel, or contracting the remote sensing processing to another institution to carrry out.

6.1.2 TimeSync validation of maps

TimeSync validation requires a mix of remote sensing skills and knowledge of the local conditions likely to be found in the parks. Because the TimeSync code is stand alone, there is no need to detailed training on remote sensing software packages nor on the preprocessing phases of the protocol.

6.1.3 Spatial analysis and reporting

Spatial analysis and reporting are likely the area where existing staffs at parks and the network level are likely to be sufficient for this protocol. The require skillsets are largely overlapping with those of a "typical" GIS analyst, assuming some basic training in the background and theory leading to the creation of the specific LandTrendr outputs and maps. This skillset could be acquired through a focused training, such as that now being planned by the Oregon group with the NPS (cross network) for early 2011. Beyond this basic background for interpretation of results, methods for analysis and reporting involve spatial data processing, intersection with existing layers, and simple statistical summaries, all of which can be achieved using existing GIS software packages.

6.2 Estimated effort involved in implementing monitoring objectives

Much of the effort required to carry out this protocol can be considered modularly, providing the SIEN a fair degree of choice and flexibility in determining desired outputs and effort involved. As Table 2 indicates, three of four objectives could be addressed using basic LandTrendr mapping methods alone (section 3.2) and TimeSync validation (3.3). Fire effects would be augmented if the POM methods were carried out in addtion to the LandTrendr methods, and vegetation mosaics could only be achieved using the LandTrendr + POM steps. TimeSync validation would be the primary source of validation for both methods, but would require more effort to validate land cover type transitions (i.e. referencing POM-derived landcover maps) than LandTrendr change maps alone.

In Table 3, we estimate the person-time effort required to meet each component is considered separately. We separate a “Startup phase,” which is necessary to lay the foundations for further processing, from the “Ongoing monitoring phase,” which would be necessary in perpetuity. For the monitoring phase, estimated person-month effort represents that necessary for each instance of map creation, validation and reporting, whether annually or more infrequently. Thus, yearly updating of maps would require three times more effort than updating maps every third year.

In Table 3, we have *not* included any estimates that involve field validation. While we have presented options for field validation in SOP 7, we stress that the cost of conducting a full field validation of any of the map products described in section 5 would likely be prohibitive, and thus that any validation would necessarily be opportunistic

Table 3. Estimated person-time effort (in months) involved in implementing components of this protocol. Time estimates are based on effort needed by an expert in each category who is focused primarily on the tasks without startup time needed to switch from other tasks, and should be expanded upwards if training is needed or these tasks are carried out only sporadically.

Methdology	**Startup phase**		**Ongoing mapping phase**	
LandTrendr mapping	Complete to 2008		New images, preprocessing, segmentation, mapping	1.5
TimeSync for LandTrendr	Percent cover estimation	2	Vegetation health / condition	1.5
			Fire detection/severity	1
			Fire effects	1
Analysis & Reporting	NA		Vegetation health / condition	1-2
			Fire detection/severity	2
			Fire effects	1-2
POM mapping	Develop class aggregations, develop likelihood spaces	3	Mapping*	1
TimeSync for POM	NA		Fire effects	1.5
			Vegetation mosaics	2-4
Analysis & Reporting	NA		Fire effects	2
			Vegetation mosaics	2-3

*Assumes LandTrendr mapping has already occurred above

It is important to note that the estimates in Table 3 represent those needed by individuals already in possession of expertise in the skills needed to carry out the tasks. They do not take into account time needed for training in those skills if such expertise does not exist within the network. More importantly, perhaps, they also assume that the individuals carrying out these tasks are fully engaged in the tasks on a regular basis.

6.3 A model for structuring implementation

The modular nature of the protocol and the uncertainty of continued remote sensing expertise in the network suggest a split-responsibility structure for implementation of this protocol. Image processing and map production could largely be carried out by a remote sensing entitity: either contractors or the Oregon group. TimeSync interpretation could be conducted either completely within the network, or collaboratively between the network and that remote sensing entity. Finally, analysis and reporting could then be the focus of personnel time in the network proper.

This structure is attractive not only because it requires little new expertise development in the parks, but also because the most specialized components of the protocol (remote sensing and mapping) may eventually be wrapped into larger regional- or national-scale land cover change or forest mapping efforts. By focusing NPS effort on interpretation and analysis at the park-specific scale, little investment would be wasted if these larger efforts eventually come on line.

Appendix 1. Project history

SIEN staff developed an initial set of potential monitoring objectives, described in detail in the task agreement between OSU and SIEN. These objectives included:

1. Determine how vegetation type and cover is changing over time. Use remote sensing data and technology to detect changes in vegetation type and cover from a baseline on a 5-10 year interval.
2. As often as necessary, use remote sensing to detect the extent and severity of fire events and incorporate these into change detection maps. This detection will occur in every year there is at least one fire of significant size (to be determined).
3. Determine how snow cover within the parks is changing both inter-annually and intra-annually. The objective is to monitor how snow cover duration may be changing over time and how it is changing within the season (e.g. detect if timing of the initiation or melt of snow cover is changing over time.). This will be monitored on a 2-5 year interval.
4. Determine probable causation to changes detected in vegetation type and cover based on pilot studies of past disturbance events including fire and insect damage.
5. Conduct a spatial analysis of how the landscape dynamic is changing over time using available pattern analysis software. The objective is to analyze how vegetation and land cover classes are changing in their distribution and abundance over time. Metrics of patterns including total area, number of patches, mean patch size, mean inter-patch distance, and overall patch class diversity will be used to characterize and track changes in landscape dynamics.
6. Determine changes in vegetation health over time. Various remote sensing derived metrics of vegetation health can be used to monitor how vegetation health may be changing. These include NDVI, EVI, FPAR, and LAI, and possibly others. These metrics can be used in conjunction with the normally derived vegetation type and cover change detection to monitor vegetation condition. This will be monitored on a 2-5 year interval.
7. Using the change detection analysis, determine how vegetation phenology is changing over time. Phenology can include leafout, leaf senescence, and vegetation growth or activity (as detected with metrics such as NDVI). The objective is to determine how vegetation types are responding to changes in climate and other disturbances (i.e. is growing season expanding?).

Additional secondary objectives relate to other long-term monitoring protocols: 1) Monitor changes in forest patch size dynamics and forest condition (in collaboration with forest dynamics protocol); 2) Monitor changes in meadow extent and spatial arrangement in conjunction with the meadow ecological integrity protocol; and 3) Monitor ice-out of alpine and other high elevation lakes in conjunction with the lakes protocol. However, some of these objectives were not expected to be feasible due to limitations of resources to obtain the temporal or spatial resolution of imagery needed.

Initial project objectives

The primary goal at the onset of the project was to adapt protocols developed for the North Coast and Cascades Network (NCCN) to the objectives of the SIEN. Development of new methods on parallel project ultimately changed this objective, but a review of the timeline of the project is useful here for context.

The NCCN protocol was based on Landsat Thematic Mapper (TM) imagery, and utilized a probability-based change detection approach to capture and label change on the landscape (Kennedy, Cohen, Kirschbaum et al. 2007). As with most satellite-based monitoring strategies, the methods were based on digital-image change detection, which involves tracking cover condition of pixels on the landscape by observing changes in their spectral reflectance (their “color” in many parts of the electromagnetic spectrum) over time. Unlike most existing change detection approaches focused on single events or processes, the NCCN approach was required to meet diverse needs of monitoring over time: 1. Tracking changes to and from any type of cover, rather than just one or a few, and labeling those changes in terms useful for the parks; 2. Tracking both subtle and abrupt changes rather than just extreme changes; and 3. Allowing consistency over time and the ability to re-evaluate historical data in the future to allow for retrospective discovery of currently-unknown processes. A key consideration in any such undertaking is how to adequately validate the maps of change that result from the algorithms applied to the imagery. The availability and collection of reference data is also a critical consideration in the design of a monitoring program based on remote sensing data (Kennedy et al. 2009).

An initial meeting in November 2007 was held at Sequoia National Park to frame SIEN goals in terms of remote sensing, to assess available reference data, and to introduce the Oregon group to the key issues on the landscape. Additionally, this meeting served as the first occasion for interaction between the Oregon group and the CSU-Monterrey/NASA-Ames research group (primary contacts: Rama Nemani and Forrest Melton), which is developing a parallel effort using MODIS based imagery. A summary document of that meeting was produced by the Oregon group, and substantially improved by NPS staff (Appendix 2: “SIENLandscapeMeetingReport_kennedy_finalreview_v1.1.doc).

Also at this meeting, the Oregon group presented overviews of the basic methods at play in Landsat-based change detection. The first was the POM (probability of membership) change approach on which the NCCN protocol is based (Kennedy, Cohen, Kirschbaum et al. 2007). That method converted spectral change between two images into changes in probability of membership in broadly defined “physiognomic” classes – landcover descriptions of sufficiently generic character to be separable in the Landsat spectral data space. This method was considered the desired method at the onset of the protocol development because of its ability to characterize all types of cover change, and to describe both the condition before and after the change (Figure 4). The second method was developed by Kennedy and infers change from overall trajectories of change across many years of imagery, rather than from differences in only two dates of imagery (Kennedy, Cohen and Schroeder 2007; Kennedy et al. In press). The trajectory based approach is known as LandTrendr (Landsat-based detection of trends in disturbance and recovery; Figure 5).

The POM and LandTrendr methods derive their information on change in fundamentally different ways. The POM approach examines change across the multidimensional spectral space of the tasseled-cap indices (Crist and Cicone 1984), but does so using only two dates of imagery. If spectral changes exceed a threshold value determined by the user, then they are considered real change (Figure 6). Because many non-target types of change can cause spectral change, any threshold value chosen is likely to include both false positives (areas identified as change that have not actually changed on the ground) and false negatives (areas that have actually changed on the ground that do not appear in change maps). Such two-date change detection forms the core of most traditional change detection techniques (Coppin et al. 2004). The LandTrendr method infers change as deviation from long-term trends using only 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 5a). 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. However, the LandTrendr algorithms only can describe the changes using a single spectral index at a time. To the extent that land cover classes require two or more dimensions of spectral space to be labeled, compression to a single index makes such labeling more difficult. Most changes of interest to the SIEN parks can be detected with single indices that contrast the short-wave infrared bands against the near infrared band, such as the normalized burn ratio (NBR; (van Wagtendonk et al. 2004); labeling the change in terms of land cover class, however, requires three or more dimensions, which is the strength of the POM approach. Taken in sequence, then, the LandTrendr followed by POM approaches can significantly capture and describe change.

Framing monitoring objectives in terms of remote sensing

Framing SIEN's desired monitoring objectives in terms relevant for remote sensing was a key goal of the meeting. The seven major landscape dynamics monitoring objectives were first grouped thematically, then described according to transition type, cause, location on the landscape, and stressors (Table 2). The fundamental role of remote sensing in monitoring landscape dynamics is to detect the transition of land cover type or condition noted in the second column of Table 1, e.g. the transition of grass to shrub, or within-cover-type loss of vegetation density. Note that the underlying cause or ultimate stressor of interest cannot be derived solely from the remote sensing observations alone, but rather must be inferred from spatial and statistical analysis of when or where transitions occur.

Core transition types were then articulated in terms that allow identification of potential remote sensing tools (Table 3). For each transition type, the underlying metric of measurement was first identified. While some transition types would require tracking the fate of individual shrubs or trees, many transition types could be identified as changes in proportional contributions of different cover types within the larger footprint of remotely-sensed pixels. For each metric, the appropriate spatial and temporal grain and extent was then determined. The grain refers to the minimum separation of measurements in either space or time, and the extent refers to the largest area or time that must be observed to capture enough examples of the process to infer change. For example, the transition of shrub to tree likely needs to be observed frequently to avoid missing disturbance processes that could later confound interpretation (a fine temporal grain), but would need to be tracked for many years for the signal of change to be detectable (a long temporal extent).

Table 3 aids in determining which transition types could possibly captured using the Landsat-based protocols described here. Proportional changes in grass, shrub, and tree cover, as well as within-cover-type changes in vigor or amount, are all possible transition types that one could be expect would be detectable using Landsat imagery. Shrub or tree counts require measurements at a finer spatial grain, and issues of within-year timing of vegetation or snow (phenology or snow extent) require the use a sensor such as MODIS, with a coarser spatial grain but much finer temporal grain. A separate protocol (the NASA-Ames landscape dynamics protocol) for the use of MODIS data has been developed by Forrest Melton, Rama Nemani, and others at CSU Monterrey. The SIEN staff have also recently initiated a task agreement with UC Merced to have Sierra Nevada Research Institute staff extend methods they have used in Yosemite to model snow covered area and snow water equivalence at the watershed scale to the other major SIEN watersheds. Therefore, this protocol focuses on methods to detect and map the transition types shown in Table 3 except for phenology and snow-related changes.

Table A1.1. Articulating monitoring objectives of the SIEN parks in terms appropriate for remote sensing

Monitoring objectives	Type of transition	Underlying Cause	Location on landscape	Related stressors of interest
Fire effects and response; Vegetation type change	Grass to shrub	Post-disturbance succession / Encroachment	Lower elevation woody/herbaceous ecotone	Climate change, Fire
		Encroachment	Sub-alpine woody/herbaceous ecotone	Climate change
	Shrub to grass	Competition, mortality	Lower elevation woody/herbaceous ecotone	Climate change, Fire, Non-native Grasses
	Shrub to tree	Post-disturbance Succession; Encroachment	Mid-elevation forests; Lower sub-alpine ecotone	Climate change, Fire, Habitat fragmentation
	Tree to soil/grass	Disturbance	Chaparral, mid-elevation forests	Habitat fragmentation, Fire, Non-native Grasses
Vegetation health / condition; insect effects; Fire effects and response	Within-cover-type loss of vegetation density or vigor	Ozone, drought, disease or insect related stress; non-lethal disturbance	All vegetated areas	Climate change, Altered fire regime, Pollution, Non-native species introduction
	Within-cover-type gain in vegetation density or vigor	Nitrogen fertilization, Altered fire regime, CO_2 Fertilization	All vegetated areas	Climate change, Altered fire regime, Pollution
Vegetation phenology	Within-cover-type change in timing of greenup or browndown	Climate-related change in growing season	All vegetated areas	Climate change
Snow cover	Contraction of maximum snow extent	Changes in precipitation type and potentially quantity; increased spring temperatures	Alpine and sub-alpine and mid-elevations (pretty much all snow covered areas)	Climate change
	Decrease in snow water storage	Changes in precipitation type and potentially quantity; increased spring temperatures	Alpine and sub-alpine and mid-elevations (pretty much all snow covered areas)	Climate change and altered fire regimes
	Shrinkage of glaciers/ice-fields	Changes in precipitation type and potentially quantity; increased spring temperatures	Alpine and sub-alpine	Climate change

Table A1.2. Articulating transition types in terms appropriate for remote sensing

Type of transition	Metric	Spatial Grain / Extent 1	Temporal Grain / Extent 1	Spectral Separability	Discussion
Grass to shrub; Shrub to grass	Areal proportional cover	30m / Park-wide	2-5 yrs /	Moderate to High	Spectral variability of background may obscure subtle signals; Geometric misregistration can introduce error at edges of patches
	Shrub count / proportional cover	1-5m / Sub-sample of park	< 10 yrs	Low	Individual shrubs detectable in airphoto or IKONOS-type imagery, but large areas expensive to analyze; shadows and view angle effects can hinder quantification of change
Shrub to tree; Tree to shrub	Areal proportional cover	30m / Park-wide	2-10 yrs / 10+ yrs	Low	Temporal grain may affect signal-noise ratio and separation of otherwise spectrally similar types
		1-5m / Sub-sample of park	10 + yrs / 10+ yrs	Low	Stereo-airphotos likely the best tool to detect differences in type between trees and shrubs
Tree to soil/grass	Binary cover/ proportional cover	30m / Park-wide	2-5 yrs, / 2-5 yrs	High	Complete loss of tree cover fairly easy to capture with Landsat-type sensors
Within-cover-type loss or gain of vegetation density or vigor	Proportional cover	30m / Park-wide	1-2 yrs / 10+ yrs	Low to moderate	Capture of insect or disease-related defolation or partial mortality more feasible with trajectory-based approaches than with two-date approaches
	Peak NDVI	250m / Park- to region-wide	Biweekly / 5+ yrs	Moderate to High	Year to year variation in peak MODIS NDVI or EVI likely feasible using EcoCast framework
Within-cover-type change in timing of greenup or browndown	% of Pixels within Phenoregion above/below threshold	250m / Park to region-wide at different elevation bands	1 yr / 5+ yrs	Moderate to High	Pixel-level data not appropriate. These products likely to result from the EcoCast framework
Contraction of maximum snow extent	Binary cover/ proportional cover	500m / Park to region-wide	8 days to seasonal / 10+ yrs	High	Original products from MODIS or from Bob Rice (UC Merced) et al. ; Detection of snow proportions in forested regions more difficult than in unforested areas

Decrease in snow water storage	Snow water equivalent	500m / Park to region-wide	8 days to seasonal / 10+ yrs	Low to moderate	Not a standard MODIS product, but available from Roger Bales et al.; Validation hampered by paucity of ground measurement stations
Shrinkage of glaciers/ice-fields	Volume of ice / extent of glacier	1-2m (Lidar or airphoto)	Annual / 10+ years	Moderate	Lidar data expensive but may be most direct method for glacial volume; airphoto-based interpretation of glacier and ice-field extent challenging because snow-cover extent and type variation from year to year

Identifying reference data

Although Table 2 describes the potential of Landsat and other remote sensing sources to track transitions on the landscape, the actual robustness of a map based on remotely-sensed data requires a conceptual or statistical linkage with reference observations that are less “remote” than the satellite. The availability of reference data often sets an upper bound on the ability of any change detection or monitoring program (Kennedy et al. 2009).

NPS staff aided the Oregon team in identifying potential reference data that could be used to serve as validation or training of remotely sensed mapping products (Table 3). OSU then further collated and evaluated information on the available vegetation plot datasets (See Appendix 2: “OSU Evaluation of Vegetation Plot Data”). As is commonly the case, many field-measured reference data were not acquired with the needs of remote sensing in mind: locational accuracy, measurement footprint, and variables measured on the ground are frequently different than needed to link with remotely-sensed spectral data. More importantly, few datasets exist with consistent measurements at the same place for different points in time, which are needed to corroborate maps of change desired under this protocol. Those that do (for example, the Fire Effects and Forest Demography plots) are typically small in number, making them rich in thematic information but limited in ability to validate maps that cover the entire landscape.

Ultimately, all datasets are limited in their utility as *core* validation data for the transition types of interest (Table 4). However, most could be used as opportunistic (spatially or temporally) corroboration if other primary validation data gathered specifically for the purposes of remote sensing were available.

Table A1.3. Reference data likely available for use in the SIEN parks.

Reference dataset	Description	Information content	Spatial properties	Temporal properties	Discussion
Digital orthoquads (DOQs)	Black and white photos	Cover type	High resolution and generally park-wide	Many decades: Up to four historical repeat cycles	A useful reference source for basic cover type information; subtleties in cover condition or species type generally not detectable
National agriculture imagery program (NAIP) imagery	Color orthorectified imagery from recent years	Cover type; cover condition	High resolution and park wide	2000-era forward	Generally very high quality imagery that can be used to assess near-current conditions for the parks. Roughly comparable to B&W DOQs in past eras.
IKONOS imagery	Satellite-based 1m and 4m color-infrared imagery	Cover type	High resolution; individual scenes composited to cover larger areas of parks	Recent, generally only one set (no repeats)	Coarser resolution than NAIP imagery and of similar era, but advantages of near-infrared band information and more onsistent view-angle across scene, which minimizes distortions in mosaicking.
Lidar height and canopy data	Active laser-based maps of surface contours and vegetation heights	Vegetation structure; underlying topography	Partial coverage of YOSE and SEKI	One-time collection in the 2000-era	Lidar data are likely to be an extremely useful reference source for monitoring in the future, as they provide unprecedented detail about vegetation structure that complements airphoto- and satellite-data. With only a single period and partial coverage in the parks, it is unclear the extent to which this source can be evaluated for utility.
Forest Health Monitoring (FHM) maps	Sketch-maps from overflights delineating boundaries of insect and fire events	Forest mortality rates and likely causal agents	Polygon-based; spatial precision unknown	Yearly; Availability of pre-2004 data unknown	Useful for ascribing cause to observed changes in forest condition, although polygon-type data do not compare directly with pixel-based measures.

Table A1.3. Reference data likely available for use in the SIEN parks.

Reference dataset	Description	Information content	Spatial properties	Temporal properties	Discussion
National resource inventory (NRI) plot data	Field-based measurements of resource conditions	Vegetation type presence/absence; basal area for trees, total canopy cover for most other sites.	1/10th Ha measured; ~ 627 plots in SEKI randomly selected from major UTM grid intersections; ~1000 in YOSE (362 in 1989-1993) slected within 1000ft elevation bands	One-time measurement in late 80s to early 90s	Small size of plots may make connection with remote sensing difficult, but rich information content may make up for this potential challenge.
Veg mapping plots	Cover type measured in support of recent park-wide vegetation mapping programs	Cover type by species and by vegetation layer [1]	604 sites in YOSE, of which ~236 are within park. Plot size scaled to vegetation: 0.1 ha for tree dominated, 400m^2 for shrubs, 100m^2 for herbaceous; 423 plots in SEKI; 57 plots in DEPO	Single measurements	Experience in other parks suggests that plots developed for the vegetation mapping project may not be directly linked with Landsat imagery on a pixel basis, but this question should likely be addressed directly.
Vegetation mapping accuracy assessment plots	Accuracy assessment of YOSE 1997 vegetation map	Elevation, aspect, slope, topog. position, cover class and height by vegetative strata, cover class by most important species by veg. strata, and veg type assignment	2200 sites, 1123 in YOSE; widespread; spatial precision not recorded; Trimble Geo III data not post-processed; 2281 0.5 ha sites in SEKI, spatial location subject to error, plus 123 rapid assessment plots (dominant cover only)	Single measurements	Because entire polygons were evaluated and data recorded from representative areas within polygon of interest, data may be useful for validating imagery to the extent vegetation type or cover by canopy species is needed. However, many polygons are variable and difficult to represent in one area. See also comments in prior row.

Table A1.3. Reference data likely available for use in the SIEN parks.

Reference dataset	Description	Information content	Spatial properties	Temporal properties	Discussion
NPS Fire Effects Plots	Established from mid-1980s to present before management-ignited burns	Fuel reduction; tree sizes, species composition, mortality; shrub and herbaceous plant composition and cover; etc.	Widespread, most common in white fir, giant sequoia-mixed conifer, or ponderosa pine. SEKI has135 and YOSE 69 FMH plots beginning 1980s	Re-visited immediately pre- and post-burn and1,2, 5, 10, and then every 10 years after burns	More complete methods and metrics are documented in the NPS Fire Monitor Handbook (NPS 2001)
USGS tree demography plots	Forest demography at 23 plots in Sequoia and Yosemite.	Changes in overstory tree density and species composition by diameter class and condition	Mostly 1-hectare plots; a couple 2.5 hectares; limited spatial coverage; include ponderosa pine-mixed conifer, white fir-mixed conifer, giant sequoia, red fir, subalpine plots.	Repeated annual measurements at same plot since inception of plot (first plots 1980s)	Likely a very useful means of interpreting trends observed in historic satellite data; small sample size will likely preclude use as training for remote sensing products. Plots established under different programs, now under the USGS Global Change Research Program.
Post-fire CBI plots	Field measurements of composite burn index after wildfire events	Changes in seedling tree density and species composition by height class, percentage plot surface fuels burned, numer of live and dead pole and overstroy trees, estimates of pre and post-fire tree and shrub cover.	Confined to the burned area, usually sampled on fires >300 ac. Multiple 30m circular plots per fire, stratified by fire severity.[2]	Sampled the year after the fire.	May be useful for comparison with satellite-derived estimates of fire severity.

Table A1.3. Reference data likely available for use in the SIEN parks.

Reference dataset	Description	Information content	Spatial properties	Temporal properties	Discussion
Various legacy fire effects datasets	Plots established in 1960s, 70s or 80s as early fire effects research	Forest structure, understory vegetation data, tree mortality and establishment, fuel loads. [Pre- burn and various post-burn periods]	Various sized plots, not randomly selected.	Usually have pre-and post-burn data. Some also sampled multiple years after fires, including recent resamples.	Kilgore plots (1969); N=25 (SEKI) Sydoriak plots (1970s): N=120 (YOSE) Pitcher plots (1980s): N=3 (SEKI) Various other research plots.
CA DWR snowcourse network and remote automated network	Point data for long-term monitoring of snow condition	Snow depth, snow water equivalent, and air temperature and other meteorological variables (varies by site)	Snowcourses- snow depth and snow water content; SNOTEL- daily ppt and snow water content and some record temp, snow depth.	snowcourses - read 1-2 times/mo. Jan-Jun (often back to 1920-30s); SNOTEL-- many record hourly data, most began in mid 1970s	

[1] Cover in six classes by species and by vegetation layer (emergent tree layer; canopy tree; subcanopy tree; tall, short and dwarf shrub layers, herbaceous). Single cover class recorded for total vegetative cover for plot. Height classes (usually) assigned by layer. Vegetation type assigned later.

[2] Five severity classes (from no fire to high severity) are defined and an attempt is made to locate three plots in each class within all vegetation alliances in the burn perimeter. Selection criteria for plot location is random but plot are placed in 30x30 m pixel surrounded by pixels with similar severity values (plots are circular 30 m dia. so this reduces edge effects).

Table A1.4. Evaluating which reference data may be useful for capturing transition types noted in Table 1.

Type of transition	Reference data	Discussion
Grass to shrub, Shrub to grass	DOQ, NAIP, IKONOS	Grass cover difficult to distinguish from soil in B&W DOQs, but shrubs generally detectable if of sufficient size relative to grain of image. Grass cover may be distinguishable using NAIP and IKONOS imagery, depending on time of year of image acquisition.
	Lidar data	Vertical accuracy should allow distinction between grass and shrubs with current-era technology, but single date of imagery means that this approach must be matched with a different historical source.
	NRI plots, other plot data	Grass and shrub cover presumably noted in plot records, but single date of collection means that a different source must be used for second date. Large number of plots stratified across park systems may allow for opportunistic capture of shrub encroachment.
Shrub to tree	DOQ, NAIP, IKONOS	Distinction between trees and shrubs only possible if horizontal footprint is greater for trees.
	Lidar data	The vertical dimension of lidar data is ideal for distinguishing between trees and shrubs. Because the current availability is limited to one acquisition, however, this source must be combined with a different historical source for validation of historical trends.
	NRI plots, other plot data	If NRI plot data are not repeat measurements, the plot data will only be able to develop models of percent cover at a single point in time (rather than to directly capture change in cover over time).
Tree to soil/grass	All data	Capturing complete loss of tree cover is fairly straightforward with all reference data types.
Within-cover-type loss or grain of vegetation density or vigor	DOQ, NAIP, IKONOS	Vegetation density on an areal basis (I.e. % cover) can be captured with most high resolution image sources, but vigor will be essentially impossible with B&W airphotos. The NIR band of IKONOS may be useful to infer vigor, but changes in vigor over time may be difficult to quantify.
	NRI plots, other plot data	If NRI plot data are not repeat measurements, the plot data will only be able to develop models of percent cover at a single point in time (rather than to directly capture change in cover over time).

Table A1.4. Evaluating which reference data may be useful for capturing transition types noted in Table 1.

Type of transition	Reference data	Discussion
Within-cover-type change in timing of greenup or browndown	All data	None of the reference data listed in Table 4 would be useful for phenological comparisons.
Contraction of maximum snow extent Decrease in snow water storage	CA DWR recording stations	Recording data are sparse; this topic will require more discussion between OSU, SIEN, NASA-AMES and Roger Bales' group at UC-Merced.
Shrinkage of glaciers/ice-fields	Repeat photography work and ground measurements by Hassan Basagic.	Lidar data were recently acquired for some Yosemite glaciers. MS thesis on SEKI and YOSE glacier changes (Basagic 2008)

Incorporating trajectory-based methods

Three developments in the early part of 2008 led the Oregon group and SIEN staff to determine that a hybrid POM Change + LandTrendr approach would enjoy the highest likelihood of meeting the SIEN landscape monitoring objectives. The Oregon group's continued work with other NPS networks (Southwest Alaska [SWAN], Northern and Southern Colorado Plateau [NCPN, SCPN]) reached a point where it could be shown that the LandTrendr (trajectory-based) and POM (two-date probability of membership) approaches could be combined. Second, the Oregon group received funding from the USDA Forest Service to move the LandTrendr methods into an operational mapping context for monitoring within the range of the Northwest Forest Plan, greatly improving the robustness and repeatability of the methods. Finally in the spring of 2008, Kennedy was awarded a NASA New Investigator Program grant, which was specifically designed to apply and improve trajectory-based change detection methods to all of the park networks mentioned here (SIEN, SWAN, NCPN, SCPN, and NCCN), with a focus on characterizing landscape change in the face of likely climate-change. Because of the promise of the trajectory-based methods to capture more subtle events as well as evolving processes on the landscape, SIEN staff and the Oregon group decided expand the role of this protocol development to include both LandTrendr and POM methods. The greater effort needed to fully develop these methods would be absorbed through economies of scale of the Oregon group working on similar core methods (LandTrendr and POM) for all of the aforementioned projects, though it was also recognized that the added development time would push deadlines back to some degree.

The development of the trajectory-based approaches to mapping also led to an advance in validation that held promise for the parks as well. A core challenge in any remote-sensing based monitoring project is acquiring reference data of sufficient number and quality to be used in both training and testing change-mapping algorithms (Kennedy et al. 2009). Although reference data available in the SIEN parks are generally plentiful (Table 2), no single dataset exists that covers the entire area of interest, for the entire period of record (1985-present), at a yearly time-step, and with sufficient plot size and measurement type to serve as validation. Recognizing that this problem exists everywhere, the Oregon group developed a software tool (called "TimeSync") that allows a trained interpreter to efficiently interpret and label change dynamics using the Landsat imagery itself (for every year available), and that can be easily linked to high resolution airphoto data such as that available in Google Earth or other ESRI-based products (Cohen et al. In press) Such interpretations can be distributed on the landscape in a completely randomized, unbiased manner as needed to provide a first-level of validation. The robustness of this first tier of interpretation and validation can then be evaluated with the richer site-specific datasets. These existing datasets need not be distributed ideally or collected with remote sensing in mind, as they simply provide a check on the underlying interpreation skill of the first-tier TimeSync interpretations. Detailed examples of this process are given in Cohen et al. (in press).

Testing methods

In the summer and fall of 2008, the Oregon group tested the potential of the LandTrendr + POM approaches in the SIEN. To do so, we first improved and applied the LandTrendr + POM methods to Sequoia and Kings Canyon (SEKI) National Parks, utilizing the existing park vegetation map as the base for the POM-component of the methods. In September, we then conducted a limited field-sampling campaign to test field-validation methods, and separately tested the utility of the TimeSync approaches to identify effects on the ground. A conference call with SIEN staff in January 2009 covered these efforts, solidifying the collective decision to base the protocol on the LandTrendr + POM methods.

Further feedback and coordination with other networks

In the spring and summer of 2009, the Oregon group received final important feedback from park networks in two venues. First, Kennedy met with representatives from the NCPN, SCPN, NCCN, SWAN, and SIEN networks on the sidelines of the George Wright meeting in Portland, Oregon, in March 2009 to assess the extent to which cross-network goals and objectives could be incorporated into the underlying LandTrendr + POM methods. During those meetings, the group determined that some of the core change mapping outputs from the LandTrendr methods could have great utility to all of the networks, even if not connected to the landcover descriptions inherent in the LandTrendr + POM methods. The simplicity of knowing where on the landscape changes were occurring could be extremely valuable, even if not labeled explicitly in terms of landcover, as a means of focusing or redirecting monitoring efforts on the ground. Second, Kennedy met with staff from both SEKI and YOSE in July 2009, during a field campaign by his staff in YOSE in support of his NASA project. At those meetings, it became clear that the parks needed guidance within the protocol on how to analytically link maps of change to the core monitoring objectives of the SIEN parks.

This latter concern has been echoed in conversations between the Oregon group and all NPS networks thus far engaged, and represents a core challenge to the parks in implementing any potential landscape dynamics protocol based on remote sensing. The expertise to carry out such work is rarely found outside of remote-sensing centers and specialized academic centers, and would test the limits of time, funding, and expertise in most of the networks. Although no specific solution was devised, it was clear to members of all of the interested networks that some cross-network sharing of expertise or contracting would likely create economies of scale in implementing this protocol. One model considered was a sharing structure where each park network would have control over the interpretation and analysis of maps in the context of their own parks, but would join forces with other networks to farm out the detailed remote sensing processing expertise to an external body.

Project history summary

The project began with the goal of applying an existing methodology (the POM change detection method) to the parks of the SIEN, and eventually evolved to include entirely new methods (LandTrendr and TimeSync) to map and validate change. The new methods hold promise for more robustly detecting more subtle or ongoing change than the original POM approach alone. Because these core methods underlie much of the work the Oregon group conducts with other park networks and other natural resource agencies, the SIEN parks have benefited from economies of scale in development costs and implementation. The consistency of the core methods may also provide a means by which the SIEN parks can implement the highly-specialized components of the protocol, as they are likely to be shared with several other park networks and could be envisioned as core processing component whose burden could be distributed across networks, given an appropriate sharing structure.

Given the assessments summarized in Tables 1-4, the Oregon team constructed estimates of relative cost, time and benefit for several different analytical methods using Landsat TM data that would be under consideration for the network (Table 5). As noted above, the POM Change method was that described by Kennedy in the protocol for the NCCN (Kennedy, Cohen, Kirschbaum et al. 2007), which was considered the initial choice for the SIEN at the onset of the project. The LandTrendr method (Kennedy et al. In press)was developed by Kennedy and Yang on parallel projects, and was introduced in the November 2007 meeting as a potentially complementary approach because of its enhanced ability capture slow changes and to distinguish more subtle change events. Table 5 set the foundation for continued discussions between the SIEN and the Oregon group regarding which methods and questions to test in support of this protocol.

Table A1.5. Initial estimates of cost and benefit associated with several potential methods to begin addressing the goals of the SIEN using Landsat Thematic Mapper data as the image source.

Analytical Methods	**Reference data**	**Estimated costs/time**	**Expected benefit**	**Discussion**
POM Change	Landsat	Low to Moderate	Low	Extension of NCCN/SWAN approach would capture some events of interest, but would leave ambiguity of process for more subtle events associated with slow vegetation change, including encroachment, and with very subtle change.
POM Change	Landsat + Two Dates of High Resolution imagery	Moderate	Moderate	As above, but inclusion of higher resolution imagery may reduce some of the uncertainty in processes.
POM Change	Landsat + Field plot data	Moderate to High	Low to moderate	Field data typically difficult to match with remote sensing data unless collected specifically for this purpose. Even if field data useful, POM change approach may leave much ambiguity for many subtle goals of SIEN.
POM Change	Field plot data + Lidar data	High	Low to moderate	Inclusion of lidar data may add significant information content to reference data, but also at relatively high cost of analysis.
LandTrendr	Landsat	Moderate	Moderate	LandTrendr is suited to questions of encroachment, and better for detection of subtle events than the POM change approach. Without robust reference data, many of the subtle changes and trends detected with LandTrendr will not be interpretable.
LandTrendr	Landsat + Periodic High Resolution Imagery	Moderate	Moderate to High	Basic structure for inclusion of high-resolution imagery along with LandTrendr is already established, but would need to be tailored to SIEN. The use of such imagery would enhance the usability and interpretability of the rich LandTrendr outputs.
Novel	Landsat + Field plot data	Moderate to High	Moderate to High	Similar to the prior example, but status and utility of field plot data may increase costs and may not add significantly to use of Landsat data alone.
Novel	Field plot data + Lidar data	High	Moderate to High	Integration of Lidar data may be time-consuming, but potential for full understanding of system may result.

Cost labels descrbed:	Low: Use established methods with relatively little novelty; Moderate: Established methods + development of new approaches; High: Significant investment in new approaches, even if established methods used as base
Benefits labels described	Low: Some of the desired monitoring objectives likely achieveable with this approach with low to moderate confidence in results; Moderate: More objectives achieved, and better confidence in results; High: Most objectives achieved and confidence in results relatively high.

Based on the integrated assessment of the imagery, analytical techniques, and reference data, the Oregon group and the SIEN determined that the Landsat-based protocol described herein would best address these restated objectives:

1. Determine temporal and spatial changes in landscape mosaics across SIEN parks every 5-10 years (time frame dependent upon pace of change and available funds). Landscape mosaics may include:
    - Vegetation type and cover
    - Other land cover types such as streams and lakes, bare ground, rock, roads, and developed areas
2. Determine fire regime characteristics across SIEN parks on an annual basis, and monitor trends through time in selected characteristics. These may include fire size, fire severity, fire frequency, and fire season.
3. Monitor changes in vegetation response to fire over variable time frames (1 to many years) post-fire and among different types of fire regime characteristics (low to high severity, different seasons, different frequencies).
4. Detect spatial and temporal changes in vegetation condition (or health) across SIEN parks – which may indicate change from other agents of change such as insects, pathogens, air pollutants, and drought.

We would also like to seek funds or encourage outside research projects to help us establish linkages between observed landscape-level changes and potential causes for these changes. These studies might focus on particular areas where significant changes in landscape mosaics have occurred and test for relationships with agents of change such as fire, insects, air pollutants or weather-related factors.

The following two objectives are being addressed through projects with other cooperators and will not be discussed further in this protocol:

1. Monitor changes in snow covered area and snow water equivalence for major river watersheds in SIEN parks intra-annually and among years (Bales et al. in progress).
2. Monitor changes in phenological events (leafout, leaf senescence, and vegetation growth) in broad vegetation zones across SIEN parks (Melton and White in progress).

These objectives may be addressed with separate protocols, or could be added to this landscape protocol in the future if it seems appropriate from a staffing and project management perspective to integrate them.

Finally, the secondary objectives were evaluated and at this time SIEN staff have determined –

- Changes in forest patch dynamics and forest vegetation (tree) condition would be included under objectives 1, 3, and 4 above.
- Changes in meadow extent would be too costly to monitor with currently available funding and technology, as it would require higher spatial resolution imagery than we can afford.
- Changes in timing of ice-out of alpine and subalpine lakes would involve a higher level of spatial and temporal resolution imagery than we can currently afford.

Appendix 2:

"SIENLandscapeMeetingReport_kennedy_finalreview_v1.1.doc).

Glossary of terms

Band: Sensors on satellites, such as the Landsat Thematic Mapper instrument, measure reflected electromagnetic energy in discrete portions, or "bands", of the electromagnetic spectrum. The Landsat Thematic Mapper records information in the blue, green and red bands of the visible spectrum, and also in three regions of the infrared bands.

Ecosystem: a dynamic complex of plant, animal, and micro-organism communities and their non-living environment interacting as a functional unit (Convention on Biological Diversity 2005)

Landscape: a mosaic where a cluster of local ecosystems is repeated in similar form over a kilometers-wide area (Forman 1997)

Landscape element: each of the relatively homogeneous units, or spatial elements recognized at the scale of a landscape mosaic. This refers to each patch, corridor, and area of matrix in the landscape (Forman 1997)

Mosaic: a pattern of patches, corridors, and matrices, each composed of small similar aggregated objects (Forman 1997)

Patch: a relatively homogeneous nonlinear area that differs from its surroundings (Forman 1997)

Spectral space: the multivariate mathematical representation of reflected electromagnetic energy measured by the sensor.

Tasseled-cap [indices, transformation]: A mathematical transformation of the six original (non-thermal) bands of the Landsat Thematic Mapper sensor that captures most of the information in those six bands with three indices: the brightness, greenness, and wetness indices. Of those, wetness is something of a misnomer, as it responds not only to moisture and water, but to other chemical signatures unrelated to moisture.

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