



Protocol for Landsat-based Monitoring of Landscape Change in North Coast and Cascades Network Parks

Version 2.1

Natural Resource Report NPS/NCCN/NRR—2022/2448





ON THIS PAGE

Bear Creek Fire at North Cascades National Park Service Complex in 2021

Photo credit: NPS

ON THE COVER

Damage to the Carbon River Road at Mount Rainier National Park following 2006 floods

Photo credit: NPS

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Natural Resource Report NPS/NCCN/NRR—2022/2448

Catharine Copass¹, Natalya Antonova²

¹North Coast and Cascades Network
National Park Service
Olympic National Park
600 E Park St
Port Angeles, WA 98362

²North Coast and Cascades Network
National Park Service
North Cascades National Park
810 State Route 20
Sedro Woolley, WA 98284

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Standard Operating Procedures

The standard operating procedures for the Landscape Change Monitoring Protocol can be accessed at the Integrated Resource Management Applications (IRMA) Data Store project reference as they become available: [DataStore - Project - \(Code: 2097545\) \(nps.gov\)](https://irma.nps.gov/DataStore/Reference/Profile/2097545)
(<https://irma.nps.gov/DataStore/Reference/Profile/2097545>).

Revision History Log

The following table lists all changes that have been made to this Protocol Narrative since the original publication date. Rows will be added in the future as revisions occur.

Revision log:

Previous Version #	Revision Date	Author	Changes Made	Reason for Change	New Version #
1.0	Nov 2012	Antonova, Copass, Kennedy, Yang, Braaten, Cohen	Methods updated following development of LandTrendr algorithm	Methods based on version 1.0 did not produce desired results	2.0
2.0	July 2022	Copass, Antonova	Minor clarifications to enhance readability, migration of LandTrendr workflow to Google Earth Engine	Cooperator switched coding language and platform for image processing	2.1

Executive Summary

Landscape change refers to a large suite of ecological and geomorphological processes occurring across broad spatial scales. As part of its Vital Signs Monitoring, the North Coast and Cascades Network (NCCN) of the National Park Service (NPS) developed a protocol for monitoring landscape change by detecting and mapping landscape disturbances originating from both natural and anthropogenic causes. This protocol is presently implemented for four NCCN parks: Mount Rainier (MORA), North Cascades (NOCA), and Olympic (OLYM) National Parks; and Lewis and Clark National Historical Park (LEWI). Protocol implementation involves using images from the Landsat family of satellites to detect landscape change using a set of algorithms called LandTrendr (Landsat-based Detection of Trends in Disturbance and Recovery) developed by Oregon State University's Environmental Monitoring, Analysis, and Process Recognition (eMapR) Lab.

LandTrendr tracks the spectral trajectory of Landsat image pixels through time. The main processing steps in generating landscape change data using LandTrendr include uploading the study area outline to Google Earth Engine and processing the Landsat imagery using LandTrendr scripts by smoothing the spectral index signature of each pixel into coherent segments describing periods of stability or change. The primary outputs from LandTrendr are mapped pixels where change occurred, attributed with the year when the change began (year of onset), the duration of spectral change (measured in years), and the magnitude of the spectral change.

Change pixels are identified within the NPS boundaries of the four parks, plus a 16 km (10 mi) buffer modified using watershed boundaries surrounding the larger parks (MORA, NOCA and OLYM), and watershed-based areas surrounding the various units that comprise LEWI. Pixels are then grouped into polygons, or patches, based on their year of onset and adjacency. The minimum patch size for inclusion is nine pixels, or 0.8 ha (2 acres). Patches are then manually labeled by an ecologist who selects from a list of target change types: Avalanches, Clearings, Development, Fires, Mass Movements, Progressive Defoliation, Riparian, and Tree Toppling. Due to time limitations, manual labeling of patches is limited for the larger parks (MORA, NOCA and OLYM) to areas within NPS boundaries plus USDA Forest Service designated Wilderness Areas and British Columbia Provincial Parks and Ecological Reserves. For the remaining patches in the study areas surrounding the larger parks, change type labels are assigned using a machine-learning classification algorithm, Random Forests (RF), after which an ecologist validates a subset of the results to determine the accuracy of the RF classification. For LEWI, all patches within the study area are labeled manually.

Data summaries are generated every four years for the entire LEWI study area and the manually labeled areas within and surrounding MORA, NOCA and OLYM. Detection of trends for the target natural and anthropogenic change types is planned every 12 years. With the development of the Landscape Change Monitoring Protocol, NCCN is one of the first natural resource management agencies in the country to use the dense Landsat time-series data for monitoring.

Acknowledgments

This work would not have been possible without the efforts and contributions of many people. The authors would like to thank Dr. Robert Kennedy for his role in the development of the original version of the protocol, his continued involvement and support of the NCCN Landscape Change Monitoring Program, and for overseeing the implementation of LandTrendr on Google Earth Engine. Justin Braaten developed scripts for running LandTrendr in Google Earth Engine and the workflows for processing LandTrendr downloads. He was instrumental in developing standard operating procedures, training NCCN staff, and providing technical support needed for the implementation of these workflows locally. We thank Peter Clary for his work on customizing the desktop version of the TimeSync application for NCCN use. Eric Nielsen helped with Random Forests implementation. John Boetsch and Rachel Mazur reviewed the updated version of the protocol.

Acronyms

ArcGIS™: A group of geographic information system (GIS) software products produced by ESRI

CFMASK: The C Function of Mask - algorithm that populates cloud, cloud confidence, cloud shadow, and snow/ice pixels in the processing of Landsat Level-1 data products in Google Earth Engine

EBLA: Ebey's Landing National Historic Reserve

ESRI: Environmental Systems Research Institute

ETM+: Enhanced Thematic Mapper

GEE: Google Earth Engine

GIS: Geographic Information System

I&M: Inventory and Monitoring, as implemented by the NPS Inventory and Monitoring Division

IDL: Interactive Data Language, a scientific programming language used across disciplines to extract meaningful visualizations from complex numerical data

IRMA: Integrated Resource Management Applications

Landsat: A global land-imaging project consisting of a series of satellites that routinely gather land imagery from space

LandTrendr: Landsat-based Detection of Trends in Disturbance and Recovery

LCMP: Landscape Change Monitoring Protocol

LEWI: Lewis and Clark National Historical Park

MMU: minimum mapping unit

MODIS: Moderate Resolution Imaging Spectroradiometer

MORA: Mount Rainier National Park

NAIP: National Agriculture Imagery Program

NASA: National Aeronautics and Space Administration

NBR: Normalized Burn Ratio

NCCN: North Coast and Cascades Network

NIR: Near-Infrared

NOCA: North Cascades National Park Service Complex

NPS: National Park Service

OLI: Operational Land Imager

OLYM: Olympic National Park

OSU: Oregon State University

RF: Random Forests or randomForest

SAJH: San Juan Island National Historical Park

SWIR2: Shortwave Infrared

TC: Tasseled Cap

TM: Thematic Mapper

USGS: United States Geological Survey

Introduction

Rationale

Landscape change refers to a large suite of ecological and geomorphological processes occurring across broad spatial scales. Processes are listed as one of the core “park resources and values” subject to management provisions of the Organic Act of 1916 and further refined in the NPS General Authorities Act of 1978. These “park resources and values” are described in section 1.4 of the NPS Management Policies (National Park Service 2006) as including,

“The park’s scenery, natural and historic objects, and wildlife, and the processes and conditions that sustain them, including, to the extent present in the park: *the ecological, biological and physical processes that created the park and continue to act upon it*; scenic features; natural visibility, both in daytime and at night; natural landscapes...”

Monitoring ecological and geomorphological processes also allows for the tracking of park ecosystem health (Weber et al. 2005). One of the primary goals of the NPS Inventory and Monitoring (I&M) program is to “monitor park ecosystems to better understand their dynamic nature and condition and to provide reference points for comparisons with other altered environments” (<https://www.nps.gov/im/index.htm>). Although landscape condition data existed, it had not been converted into tangible analyses of how landscapes are changing within the NCCN parks prior to the initiation of this protocol. Therefore, the Landscape Change Monitoring Protocol (LCMP) was initiated with the main goal of conducting such analyses.

LCMP has four goals that address various aspects of landscape change from the ecological and park management perspectives. The first goal is to develop a baseline of information on the type, location, frequency, and severity of landscape changes occurring within the parks. The LCMP is unique among other NCCN monitoring efforts in that it takes advantage of a long record of data, from 1987 to present, to determine these baseline conditions.

A second goal of the LCMP is to measure how rates of change vary among disturbance types and to understand how changes in climate will affect landscape processes. In the coming decades, changing temperature and precipitation regimes are expected to alter the frequency, magnitude, and distribution of landscape changes within both natural and altered environments (Dale et al. 2001). Projected changes include annual temperature increases between 0.11 – 1.8 degrees C (0.2 – 1.0 degrees F) per decade, and greater variation in seasonal precipitation patterns, with more precipitation falling as rain rather than snow in the early winter, and less summer precipitation (Mote and Salathé 2010). Increased temperatures coupled with shifts in the timing of precipitation could impact natural landscape processes in NCCN parks in a variety of ways, including more windthrow events and riparian flooding due to increasing intensity or frequency of atmospheric rivers; increased riparian disturbances following increasing frequency of rain-on-snow events (Mantua et al. 2010); increased avalanche activity due to warming night temperatures; rise in windthrow events due to increase in winter soil moisture or tree icing causing tree toppling events; expanding areas of insect

damage; or an increase in the frequency or severity of wildland fires due to decreasing summer soil moisture causing drought stress (Littell et al. 2010).

Landscape change events such as tree topplings, landslides, floods, and fires can have significant impact on visitor experiences and park facilities. Therefore, a third goal of the LCMP is to provide park managers with information about trends in the size, frequency, and severity of these events, so they can plan for the future. Planning for large-scale events would allow managers to proactively allocate funding and facility maintenance rather than react to events that require an immediate management response (e.g., an avalanche blocking the road or a large wildfire).

A fourth goal of the LCMP is to act as a context indicator for changes documented by the other NCCN vital signs (see <https://www.nps.gov/im/nccn/index.htm> for further information). For example, if a long-term forest monitoring plot (Acker et al. 2010) experiences significant tree mortality, the products from the LCMP can provide context for the interpreting the extent of similar disturbances across park areas. Similarly, trends detected by the monitoring protocols for landbirds (Siegel et al. 2007), elk (Griffin et al. 2011 and 2012) or fish assemblages (Brenkman and Connolly 2008) can be correlated with the park areas affected by vegetation change due to progressive defoliation or tree toppling events, landslides, or riparian change.

Finally, the LCMP will provide both a trigger and a mechanism for updating two major inventories. Mass movements and changes in riparian corridors could inform updates to the Landform Inventory. Similarly, the LCMP will alert practitioners to changes in vegetation cover that could trigger a need to update park vegetation maps.

History

Monitoring landscape-level change requires a method with a resolution that captures broad spatial and temporal scales. To develop the LCMP, NCCN engaged in cooperative work with Dr. Robert Kennedy's Environmental Monitoring, Analysis, and Process Recognition (eMapR) Lab at Oregon State University (OSU). The eMapR lab had extensive experience using landscape-level remote sensing applications to document change in the Pacific Northwest. The lab staff used the Landsat platform as their primary remote sensing tool, which is what NCCN adopted. The spectral and spatial characteristics of Landsat Thematic Mapper (TM) and Landsat Enhanced Thematic Mapper (ETM+) made it appropriate and useful for park-wide monitoring of diverse land cover types. With a pixel size of approximately 30 meters, TM and ETM+ images captured adequate spatial detail for NCCN's eight target landscape change types. The spectral character of the sensor allowed discrimination of vegetated from non-vegetated surfaces, hardwoods from conifers, and structurally complex canopies from more uniform canopies (Cohen and Spies 1992, Cohen and Goward 2004).

Initial Protocol Development

The first version of the protocol was initiated in 2002 and oriented to monitoring goals that were achievable using Landsat TM and ETM+ data (Table 1).

Table 1. The original North Coast and Cascades Network landscape change monitoring goals grouped by change interval needed for detection (from Kennedy et al. 2007a).

Monitoring Interval	Landscape Change Agent *
Yearly	Avalanche chute clearing
	Landslides
	Fire
	Insect/disease defoliation in forest
	Riparian disturbance
	Clearcuts
	Rural development
	Windthrow
Every 10 Years	Alpine tree encroachment
	Hardwood/conifer forest composition
	Forest structure

* Note that “change agent” is now called “change type” to clarify that the goal is to measure change, regardless of the cause.

The resulting annual monitoring protocol used a simple two date change detection method (Kennedy et al. 2007a). In this method, after geometric and radiometric corrections were made, a baseline Landsat image was transformed using the Tasseled Cap (TC) algorithm (Crist and Cicone 1984). Using an unsupervised classification, the baseline TC image was classified into nine physiognomic classes including water, conifer forest, broadleaf vegetation, bare soil, and snow. The spectral signatures derived from the nine physiognomic classes were then used to calculate the probability of membership (POM) in each of the classes. The difference in POM between the two time periods was translated into change classes that could be interpreted from the TC images. The change classes encompassed broad transitions of pixels within and between physiognomic classes, for example vegetation to water, or conifer forest to broadleaf, or a generalized decrease in vegetation. The target landscape change to be monitored was indirectly linked to the change classes through interpretation of the change in physiognomic class. For example, windthrow could cause decreases in the broadleaf class, the conifer class and/or the mixed vegetation class.

Validation of change involved the process of determining how accurately the physiognomic change classes were detected and labeled. The change classes were validated using 1.5 km boxes randomly placed throughout the study area. Each pixel within the box was labeled as either “no change” or assigned to one of the change classes. The interpreter then used both the tassell cap images and the differenced image to confirm the change. Interpretation was greatly facilitated by being able to see the conditions before and after the change, which was generally only possible with repeat high resolution aerial photography. Therefore, a significant cost of the first version of the protocol was to purchase aerial photography for the NCCN parks approximately every seven years.

The protocol was to be implemented annually in each of the parks. The first version of the protocol (Kennedy et al. 2007a) included highly detailed image processing, change detection and validation

standard operating procedures (SOPs). However, a protocol for going from broad change classes to specific disturbance agents was never developed, a major omission in the original protocol.

Protocol Implementation

Between 2005 and 2008, the NCCN implemented the Landsat-based monitoring protocol at MORA, NOCA and OLYM. A detailed description of the results of this first implementation can be found in Antonova et al. (2010). Challenges arose from applying the change detection methodology described above. Although the method detected landscape changes of interest to the monitoring program, results were overwhelmed by false change and non-target change brought about by annual changes in cloud cover, shadows associated with cloud cover and topography, and phenology. It became apparent that it would be very difficult to select a pair of Landsat scenes for each park each year that would minimize the effects of differences in sun angle, phenology, and cloud cover. Additionally, implementation revealed that the validation of change classes, because it relied on human interpretation of satellite imagery that had undergone statistical modification, measured how well the interpreter mimicked the computer algorithm more than how well the algorithm mapped real change. An additional challenge was consistent application of the validation process among staff performing the interpretation. Finally, a methodology for labeling change agents was not developed in the first version of the protocol.

Second Version of the Protocol

Concurrent with the first implementation of the protocol, new developments in the field of remote sensing technology were taking place (Melesse et al. 2007). Numerous new satellite platforms were being introduced and tested for various natural resource applications by other agencies and other networks in the NPS (Reed et al. 2009, Bayer and Schei 2009). With Landsat ETM+ developing problems, NCCN evaluated a number of these instruments, keeping in mind that the key to any monitoring system is consistency over time. No other platforms could out-perform the stable, consistent utility of the Landsat system.

Advancements in change detection methods were concurrently emerging. In 2009, the Landsat archive was released to the public free of charge. The availability of these scenes facilitated the development of a change detection method that uses multiple Landsat images. OSU developed a set of algorithms called LandTrendr (Landsat-based Detection of Trends in Disturbance and Recovery) that tracked spectral changes in each pixel through the time-series of images (Kennedy et al. 2007b). Significant improvements to the image processing and the change detection steps followed shortly after (Kennedy et al. 2010), as well as the development of a new tool called TimeSync, which greatly facilitated the validation process (Cohen et al. 2010).

One of the major advantages of the LandTrendr algorithm is that it can accept multiple images (generally four to five) taken throughout the summer season so that pixels associated with clouds, cloud shadows and defects in one image can generally be replaced by unaffected pixels from another image from that same year.

LandTrendr traces the spectral trajectory of each pixel through the stack of imagery and breaks the trajectory into a series of segments. The segments are defined by vertices that represent changes in

spectral state that surpass a predefined threshold for change (Figure 1). Variations brought about by sensor drift, phenology or other artifacts are smoothed in a process of statistical line-fitting. The primary outputs from LandTrendr are the year at which the change occurred, the duration of change (measured in number of years it took for the full spectral impacts of the change to occur), and the magnitude of the change (Figure 1).

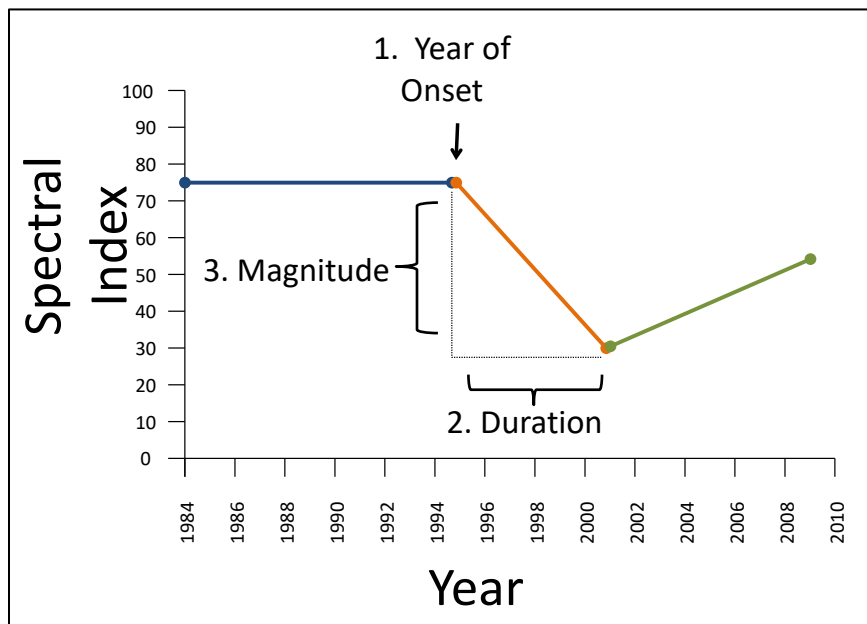


Figure 1. An idealized LandTrendr trajectory tracing a Landsat pixel through periods of stability, disturbance, and recovery. The period from 1984 to 1994 reflects a stable segment. A disturbance begins in 1994 and lasts until 2001, causing a 40% reduction in the spectral index. The disturbance is followed by a recovery period from 2001 to 2010.

The NCCN landscape protocol was updated to utilize the improved LandTrendr change detection methodology (Antonova et al. 2012). Under the new protocol, the names of the landscape change types originally proposed for monitoring (Table 1) were updated (Table 2). A machine-learning classification algorithm called the Random Forests (RF) (Breiman 2001) was used to label the change types, and the protocol also included a field component to validate the results. The second version of the protocol featured study area modifications. Results from 1985–2009, 2010, and 2011 were published for MORA (Antonova et al. 2014) and NOCA (Antonova et al. 2013), OLYM (Copass et al. 2016), and LEWI (Copass and Antonova 2019), respectively.

Table 2. Updated labels for the target landscape change types monitored by the NCCN from the second version of the protocol.

Landscape Disturbance (v. 2.0)	Landscape Change Agent (v. 1.0)
Avalanche	Avalanche chute clearing
Clearing	Clearcuts
Development	Rural Development
Fire	Fire
Forest Collapse	Windthrow
Forest Decline	Insect/disease defoliation in forest
Mass Movement	Landslides
Riparian	Riparian disturbance

Protocol Updates in Current Version

This latest version of the protocol includes minor updates and editing to improve clarity. The minor updates reflect refinement of the change types, updates to the study areas, changes to data processing due to deploying the LandTrendr algorithm in Google Earth Engine (GEE), and a more detailed description of trend detection methods.

Measurable Objectives

The two primary objectives of this protocol remain the same:

1. Detect and map target annual landscape changes for NCCN parks that are larger than 0.8 ha (2 acres) in size and resulting from avalanches, clearing, development, fire, mass movement, progressive defoliation, tree toppling, or riparian flooding.
2. Determine trends in the size, magnitude, location, and spatial distribution of each landscape change type.

We added a smaller study area at LEWI with changes mapped using a smaller minimum mapping unit (MMU), which added a third objective to the protocol.

3. Detect and map target landscape changes for LEWI that are larger than 0.45 ha (1.1 acres) within a 2-km buffer of the NPS unit boundaries.

We also adjusted the list of parks covered by the protocol and names of change types. Detailed descriptions of changes can be found in the following sections.

Updates to the LandTrendr algorithm (Mapping Overlapping Change)

The earlier version of the LandTrendr algorithm that was developed using the Interactive Data Language (IDL) and used by the second version of the protocol only mapped the “greatest” change within the analysis time step for each pixel. For example, if multiple floods occurred within a riparian corridor within a 10-year period, only the flood with the greatest magnitude of change was documented by LandTrendr for each pixel. As part of the migration of LandTrendr to Google Earth Engine, the algorithm was updated to document all pixel changes above a predetermined threshold, no matter the magnitude. For the riparian corridor flooding example above, this provides the ability

to map the extent of all changes affecting the area within the 10-year period, not just the “greatest” change. Figure 2 demonstrates this difference for an area along a creek at Mount Rainier National Park.

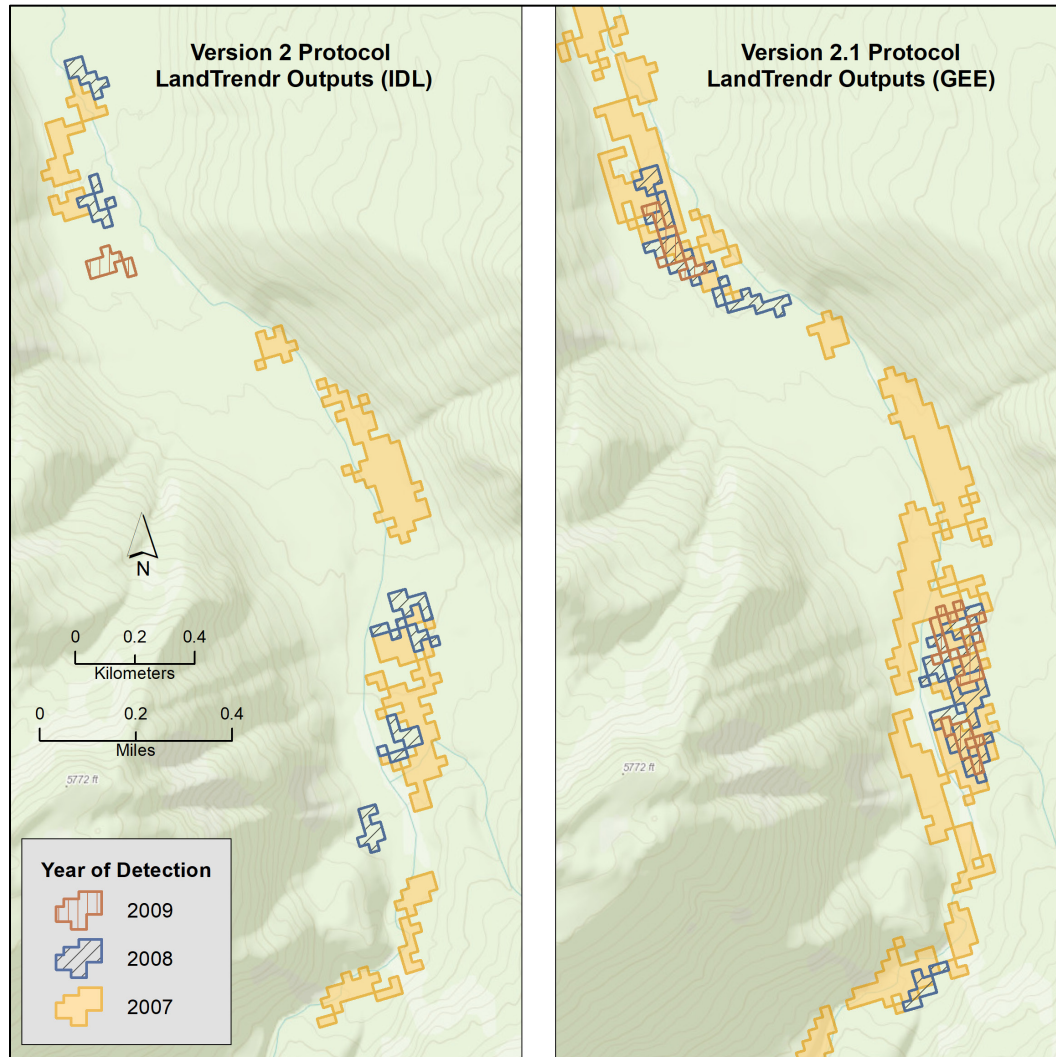


Figure 2. Comparison between outputs generated using Interactive Data Language (IDL) and Google Earth Engine (GEE) algorithm versions of LandTrendr. In the left panel, the change polygons represent the “greatest” change for that area within the time frame of the analysis. Mapped polygons are attributed with the year of detection, and they do not overlap. The panel on the right shows how the new version of LandTrendr documents all changes within the same time frame. Polygons from multiple years can overlap and therefore more accurately represent the progression of landscape change events occurring within the parks.

An additional advantage of the updated algorithm’s ability to map overlapping change is better representation of the extent. When only “greatest” change was mapped, there were often not enough adjacent pixels from the same year to form a polygon of at least 0.8 ha (2 acres) in size, which is our MMU. With the updated algorithm, we can now better map the extent of annual change, resulting in

better representation of the overall extent of landscape change in NCCN parks. The difference in extent between the two versions can be seen in Figure 2. The right panel shows greater area being affected by the floods in all shown years. The GEE version of the data was different enough from the previous IDL version to warrant a complete replacement of the 1985–2009 data set. This work was completed in 2021 and the data set was also updated to include the years 2010–2017.

Updates to the Study Areas

Following the data analysis with the second version of the protocol, it was determined that LandTrendr would no longer be used for two NCCN parks and an additional study area would be added for a third. SAJH and EBLA were dropped from the LandTrendr analysis because most of the landscape-scale changes, like tree clearing and rural development, occur at scales too small to be detected by the family of Landsat satellites. In 2021–2022, change detection methods using higher resolution imagery and parcel data will be assessed at EBLA and added to this protocol as an SOP. SAJH needs will be assessed in 2023 in coordination with a review of the Prairies Vegetation Monitoring Protocol.

Based on feedback from park staff, the study area for LEWI was re-delineated using watershed boundaries, and a second study area was added using a two-kilometer buffer around all NPS park units in Oregon and Washington (Figure 3). It was also determined that a separate analysis will be done within this smaller study area by filtering the existing LandTrendr data using a minimum mapping unit of five pixels (0.45 ha or 1.1 ac) to better detect and map the Development and Clearing change types close to park boundaries.

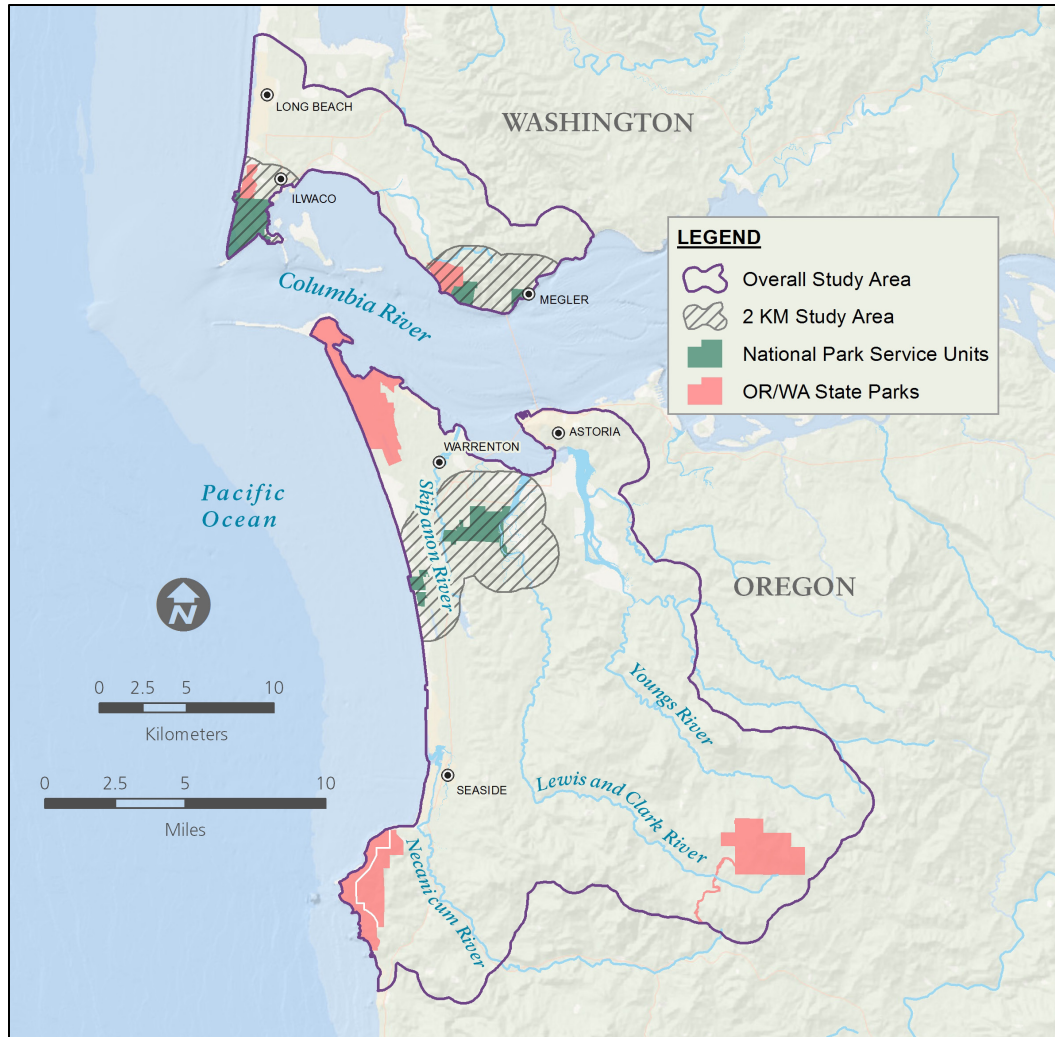


Figure 3. Two study areas used for monitoring landscape change in and around Lewis and Clark National Historical Park, Washington, Oregon. The large study area that uses nine Landsat pixels as the minimum mapping unit is outlined in purple. The 2 km study area centered on the park units and uses five pixels as the minimum mapping unit is indicated with hatching.

Updates to Labeling Techniques

The second version of the protocol relied on the RF classification to label landscape change patches throughout the study area. After assessing the accuracy of the RF model labels (Antonova et al. 2013, 2014 and Copass et al. 2016), we switched to manually labeling of patches inside the park boundary to improve their accuracy. Manual labeling was performed using the same techniques that were used for validation of the RF model labels (Antonova et al. 2012).

Updates to the Long-Term Trend Analysis

The second version of the protocol described general approach to the long-term trend analysis as specific techniques were not yet developed or tested at the time of the protocol publication. With the help of eMapR lab staff at OSU, detailed analysis methods were developed in 2019 (see Methods section) and tested on the 1985–2009 iteration of the data.

Following this analysis, it became clear that due to the low frequency and sporadic qualities of naturally caused disturbances, it would be a long time before trends could be detected for the target natural change types if only data within the park boundaries is used.

Natural Change Types

To augment the amount of data available for the analysis of target natural change types within the park boundaries, data from the NPS-managed lands is now combined with the data from the United States Forest Service (USFS) designated Wilderness Areas adjacent to the parks. These wilderness areas are managed similarly to the NPS lands, with landscape changes mostly caused by natural processes. NOCA's data set will also be augmented by data coming from the British Columbia (BC) Provincial Parks and Ecological Reserves (Figure 4).

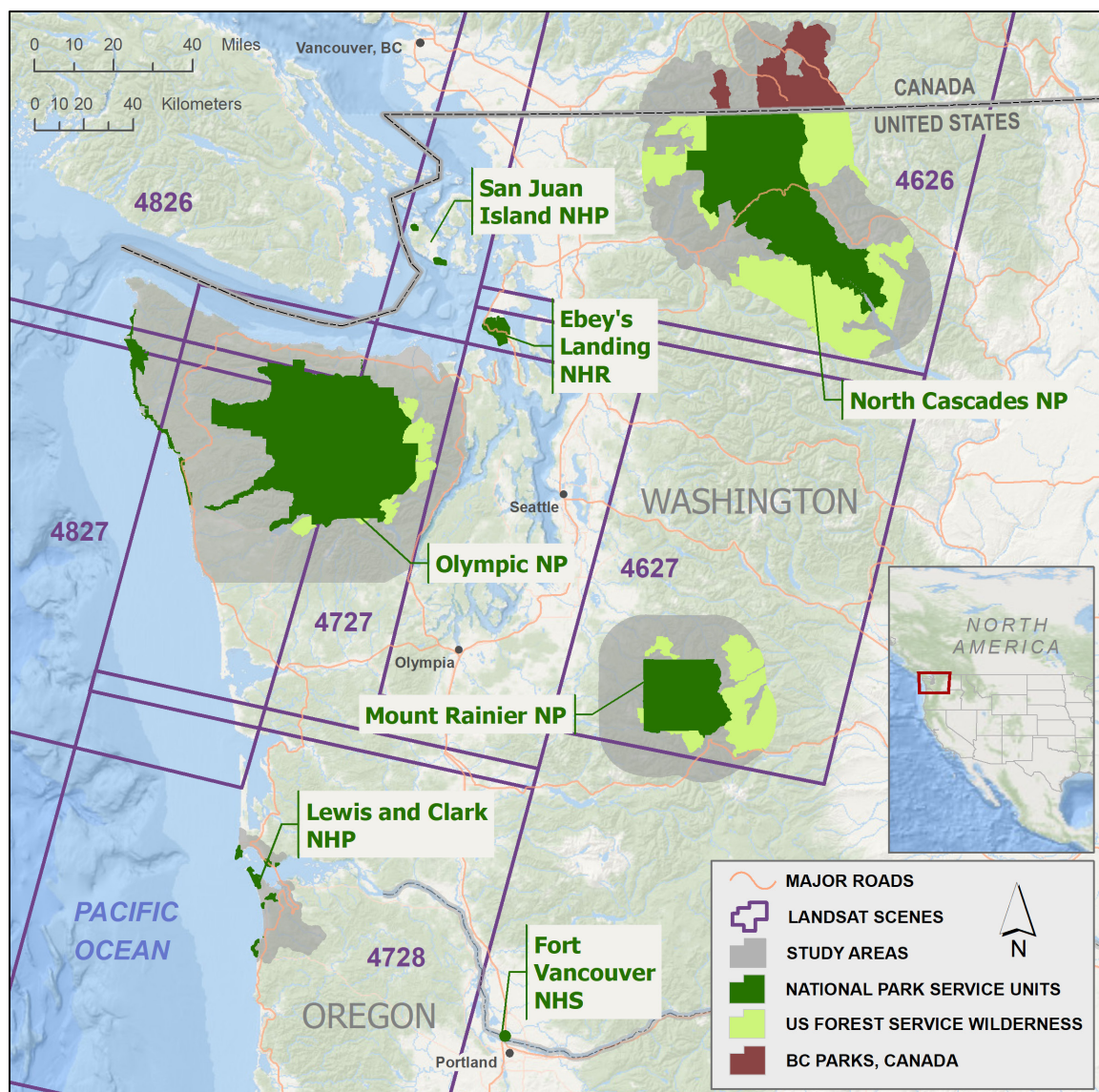


Figure 4. NCCN Landscape Change study areas. LandTrendr will be used to assess landscape change for NOCA, OLYM, MORA and LEWI. Analysis of natural disturbances will include patches from the USFS wilderness areas and BC parks in Canada in addition to patches from the NPS-managed lands.

Collectively, this augmented set of data is now called the “Protected Areas Data Set.” To maintain consistency, all data within the USFS designated Wilderness Areas and BC parks will be labeled by hand using same techniques as for the NPS-managed lands. The “Protected Areas Data Set” will only be used for long-term trend analysis and summaries of data for both natural and anthropogenic change types will still be provided for areas within the park boundaries and the overall study areas.

Anthropogenic Change Types

Analysis of trends for the anthropogenic change types (Clearing and Development) will not change and by default will mostly be based on patches from outside the protected areas with labels derived from the RF classification.

Updates to Analysis and Reporting Schedule

The analysis and reporting schedule developed in the previous version of the protocol was never fully implemented. Because the original time step covered 25 years (1985–2009), it produced a large amount of data that took longer to label than a 4-year routine analysis would allow. Following the first round of data summaries and reporting for MORA and NOCA (1985–2009), OLYM (1985–2010), and LEWI (1985–2011), we moved forward with the assessment and implementation of the LandTrendr in GEE, which replaced the existing MORA, NOCA and OLYM products and added eight more years of data to the data sets. We then performed the initial analysis of trends, which provided some insight into the best reporting and data analysis practices moving forward.

Labeling for areas within the MORA, NOCA and OLYM park boundaries, surrounding USFS designated Wilderness Areas, and BC parks will be done every four years starting with FY2023, i.e., all three parks will be updated simultaneously every four years. This is a better schedule than processing one park a year because it facilitates comparison among parks and concurrent analysis of trends. Summaries for areas inside the park boundaries will be provided to park staff on the same schedule.

In the intervening years, one year will be used to update and report on the LEWI data set. The other two years will be used to make progress on labeling areas outside MORA, NOCA, and OLYM park boundaries, developing science communication products, and exploring new technology.

The aim for long-term trend analysis for target natural change types at MORA, NOCA and OLYM and target human-caused change types outside park boundaries will be every 12 years, following the third rotation. A break will be taken from labeling change to analyze data for the three large parks and work on a report or journal publication. This timeline may be modified if the first round of analysis indicates it is needed.

Updates to Landscape Disturbance Types

During protocol implementation, ecologists came across several new change types in addition to the target eight shown in Table 2. Some were caused by single, extreme weather events in individual parks, and some were added at the request of park staff to document management actions inside and outside park boundaries, specifically at LEWI.

Table 3 shows the current list of mapped change types along with their descriptions and associated parks. Change types with few detections or resulting from a single event will be summarized for reporting purposes, but trends will only be calculated if they start occurring on a regular basis. Descriptions of NCCN target change types listed in Table 3 can be found in Appendix A of Copass et al. (2016).

Table 3. Landscape change types monitored within NCCN parks using the current version of the protocol, their associated parks, and inclusion in the data summaries and trend analyses.

Landscape Change Type	Definition	Parks	Summary	Trend Analysis
Agricultural Clearing	Includes first-time removal of vegetation for agricultural activities. Subsequent changes due to crop planting and harvest are included in the Inter-annual change type.	LEWI	X	–
Avalanche *	Long, linear change areas which originate in snow receiving zones or valley walls. Typically remove some but not all the vegetation.	MORA, NOCA, OLYM	X	X
Clearing *	Reflect a range of forest management practices, such as clearcuts, select cuts and thinning, and chemical removal of broadleaf vegetation. Differs from Development in that the vegetation can recover following removal.	All	X	X
Coastal	Captures partial to complete vegetation removal due to storm surges or other factors unique to the coastal foredune and strand.	LEWI, OLYM	X	–
Development *	Areas which show a complete, persistent removal of vegetation and transformation to a built landscape with evidence of urbanization such as houses or other structures.	All	X	X
Fire *	Includes both human-caused and natural events. Often corroborated from outside sources, wildland fires vary in intensity from full canopy removal to partial burns which leave behind a mixture of dead and singed trees.	All	X	X
Glacial Retreat	Captures changes associated with the loss of glacial ice at the terminus of the glacier.	MORA, NOCA, OLYM	X	–
Inter-annual Variability	Used to label change polygons that are artifacts of the inter-annual differences in cloud cover and sun angle (topographic shadow) that were not removed during image processing or that are the result of the inter-annual differences in vegetation phenology and soil moisture, which this protocol was not designed to reliably detect due to low temporal resolution of the Landsat imagery. This change type also captures changes associated with inter-annual agricultural activities, such as planting and harvesting of crops. Inter-annual Variability patches are not used for trend analysis and data summaries because they are not targeted by this protocol.	All	–	–
Mass Movement *	Includes a variety of vegetation-removing changes that expose rock and bare ground: landslides, which are found on valley walls and away from streams; creeps, which are slow downward movements of slope-forming soil or rock; and debris flows that are associated with steep gullies and involve water. Mass Movements usually occur on the slopes perpendicular to the valley bottom, making them distinguishable from the Riparian change type.	All	X	X

* Target types (also shown in gray).

Table 3 (continued). Landscape change types monitored within NCCN parks using the current version of the protocol, their associated parks, and inclusion in the data summaries and trend analyses.

Landscape Change Type	Definition	Parks	Summary	Trend Analysis
Post Disturbance	Captures changes in vegetation that continue to occur following the initial disturbance. Typically, only seen 1 year after the disturbance, but can be up to 10 years following a low intensity fire. Possible labels include Post Avalanche, Post Clearing, Post Fire, Post Mass Movement, and Post Tree Toppling. Omitted from data summaries and trend analyses because they are not targeted by this protocol.	All	–	–
Progressive Defoliation *	Assigned to polygons where the forest remains but has undergone slow change in spectral values representing loss of greenness and wetness. Several patterns of decline in tree health can be seen.	All	X	X
Riparian *	Patches along a river or stream on a valley bottom, typically with an average patch slope of less than 15 degrees. Steeper slopes are often associated with headwaters.	All	X	X
Tree Toppling *	Forest areas where trees have been broken off or topped by some action other than Avalanche or Clearing, generally due to wind but sometimes due to root rot.	All	X	X
Wetland Restoration	Covers cleared areas that show change due to active restoration projects at LEWI.	LEWI	X	–
Windthrow Salvage	Unique change type to LEWI that captures areas affected by the 2007 Great Coastal Gale where the windthrown trees were subsequently salvaged and therefore now show a similar spectral signature as Clearing.	LEWI	X	–
Winter Ice	Vegetation damaged by heavy, long-lasting snowpack or ice followed by wind, generally characterized by broken tree branches.	OLYM	X	–

* Target types (also shown in gray).

Methods

The overarching goal of this protocol is to detect and map landscape change in the NCCN parks and surrounding areas delineated either by a 16-km (10-mi) buffer (MORA, NOCA, OLYM) or watershed boundaries for LEWI. This section outlines the overall workflow and details the anticipated products of the protocol (Figure 5). The overall workflow can be divided into two major parts. The first part includes processing Landsat imagery and running the LandTrendr change detection algorithm. The first part is carried out in the Google Earth Engine (Gorelick et al. 2017) application programming interface (API) and ends with results delivered to NPS/NCCN servers. NPS then filters results by using a minimum mapping unit to generate change polygons, labels the polygons by change type, performs validation, and generates summary statistics and reports. The GEE portion of the workflow is completed by NPS using the Department of Interior Authority to Operate (ATO) the GEE API on federal equipment.

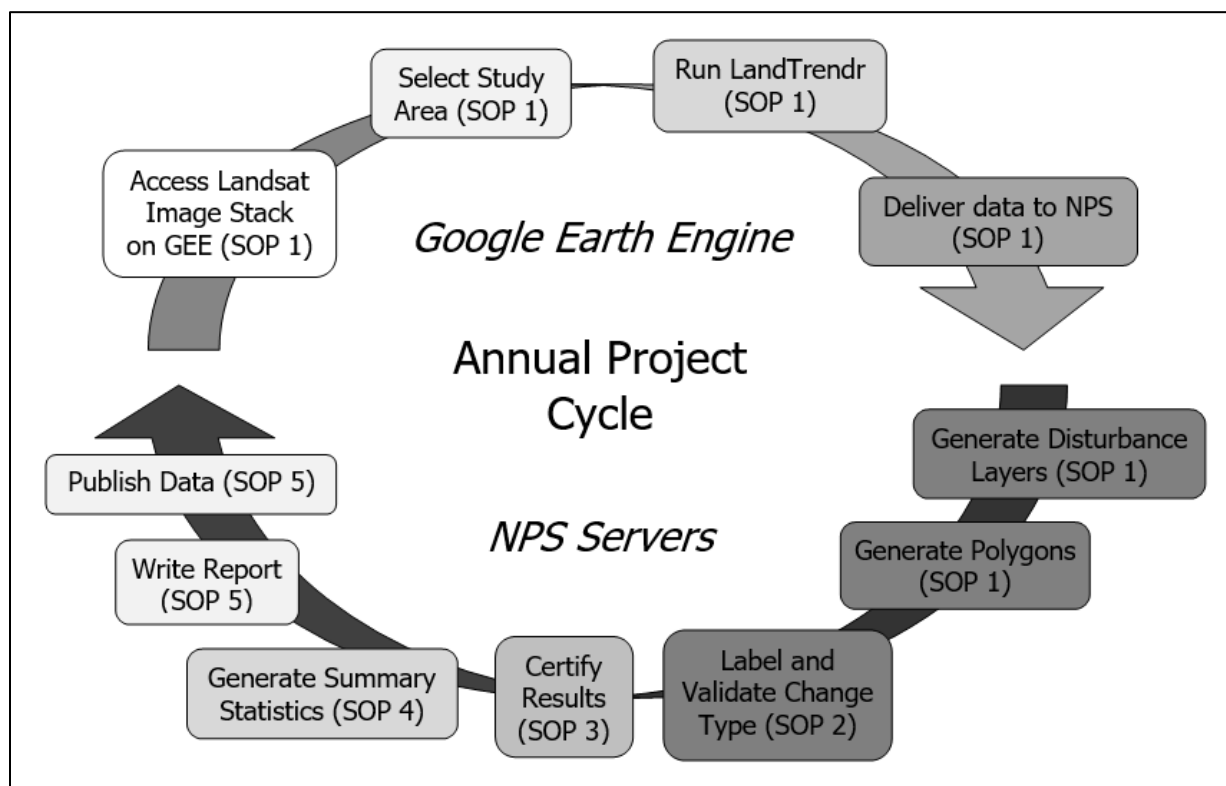


Figure 5. The annual project cycle with associated Standard Operating Procedures (SOPs). The upper arrow tracks project phases performed in the Google Earth Engine; the lower arrow tracks protocol steps done on NPS Servers.

Accessing the Landsat Image Stack on Google Earth Engine

The previous version of the NCCN Landscape Change protocol relied on the image processing algorithms that required significant pre-processing time and computational resources, as well as access to the proprietary programming language IDL (Kennedy et al. 2010). Transferring

LandTrendr processing to the GEE platform does not significantly change the outputs when compared to the earlier processing techniques (Kennedy et al. 2018) and offers significant benefits, including simpler and faster image processing times and seamless analysis of study areas, rather than one Landsat scene at a time.

Image Selection and Acquisition

The priority for image selection is to acquire quality Landsat images as close as possible to the median Julian date (approximately mid-July) of the likely candidates in the entire stack of Landsat images following the 1984 launch of Landsat 5 satellite. A consistent image date minimizes signal noise related to annual changes in sun angle, which cause topographic shadows, and vegetation phenology. Topographic shadows and phenological variability in source imagery potentially exert a confounding effect on the year-to-year spectral signal, and their effect must be reduced as much as possible. The catalog of images on the GEE platform includes more than 7 million surface reflectance images from the Landsat family of sensors, including Landsat Thematic Mapper (TM/ETM+) and Operational Land Imager (OLI). The density of images available on the Landsat archive in GEE means that pixels affected by topographic shadows and phenological variability can be replaced by pixels from images adjacent in time. Similarly, dense image stacks allow replacement of pixels affected by clouds and cloud shadows. The same approach can be taken to replace pixels from the Landsat ETM+ images have striping or gaps on their edges caused by a 2003 sensor malfunction.

Cloud Screening

The first step in image processing is to screen out the clouds and cloud shadows that can confound change detection. One of the advantages of the GEE platform is that image screening criteria and cloud mask processing are standardized across the image collection and utilize up-to-date, sophisticated protocols without having to involve expert interpreters. GEE applies a method called CFMask (C Function of Mask) that uses Top of Atmosphere reflectance and Brightness Temperature to separate Potential Cloud Pixels and clear-sky pixels (Zhu et al. 2015). Separate cloud probability masks are then produced for clouds over land and water. The combination of the Potential Cloud Pixel layer with the probability mask produces the final cloud cover layer. The potential cloud shadows layer is produced using the Near Infrared Band that is checked against the predicted possible cloud shadow locations generated from the cloud mask. CFMask also produces a snow mask if snow is present in each Landsat image.

Atmospheric Correction and Normalization

Atmospheric correction of satellite images is a critical image-processing step in which the influence of Earth's atmosphere is removed or greatly reduced. The goal of this processing step is to generate images that are spectrally similar to each other by reducing variability in reflectance values associated with atmospheric scattering due to aerosols and solar angle at the time of acquisition.

Landsat images stored in GEE are processed using the Landsat Ecosystem Disturbance Adaptive Processing System (LEDAPS) originally developed by the National Aeronautics and Space Administration (NASA) to map forest disturbance across the continent (Masek et al. 2008). Landsat images are first calibrated to at-sensor radiance using low level data, called digital numbers, or DN,

then atmospherically corrected to surface reflectance, composited, and reprojected into the map projection of the study area. The corrections are based on the Second Simulation of a Satellite Signal in the Solar Spectrum (6S; Kotchenova et al. 2006; Vermote et al. 1997) radiative-transfer model used by the Moderate Resolution Imaging Spectroradiometer (MODIS) Land Science Team. The original model was adopted by United States Geological Survey (USGS), and a second version was published in 2012 (Masek et al. 2012, Vermote et al. 2016).

In addition, OLI image bands 2 through 6 and 7 are transformed to the spectral properties of ETM+ bands 1 through 5 and 7, respectively, using slopes and intercepts from reduced major axis regressions reported in Table 2 of Roy et al. (Roy et al. 2016). This standardizes images across multiple sensors.

Because LandTrendr requires a single annual spectral value for each pixel, one composite image is created for each year from multiple available images. To calculate annual composites, a medoid approach is used as follows: For a given image pixel, the medoid is the value for a given band that the pixel value from the image whose overall spectral response (across all bands) is numerically closest to the median spectral response of the same pixel location from all images considered that year. The medoid compositing method was used to reduce variability that can be frequently introduced when using either maximum or minimum values (unpublished analysis from OSU), and to retain actual pixel values, as opposed to a summary statistic when using mean or median.

Medoid compositing is performed for each year in the collection and includes images from any sensor contributing to the annual set of summer-season observations (June 1 through September 30) for the year being processed. The result is a single multi-band image, per year, free of clouds and cloud shadows, and representing median summer-season surface reflectance. After all image processing is complete, the composite stack of Landsat images (from here on referred to as “image stack”) is ready for further analysis (Figure 6).

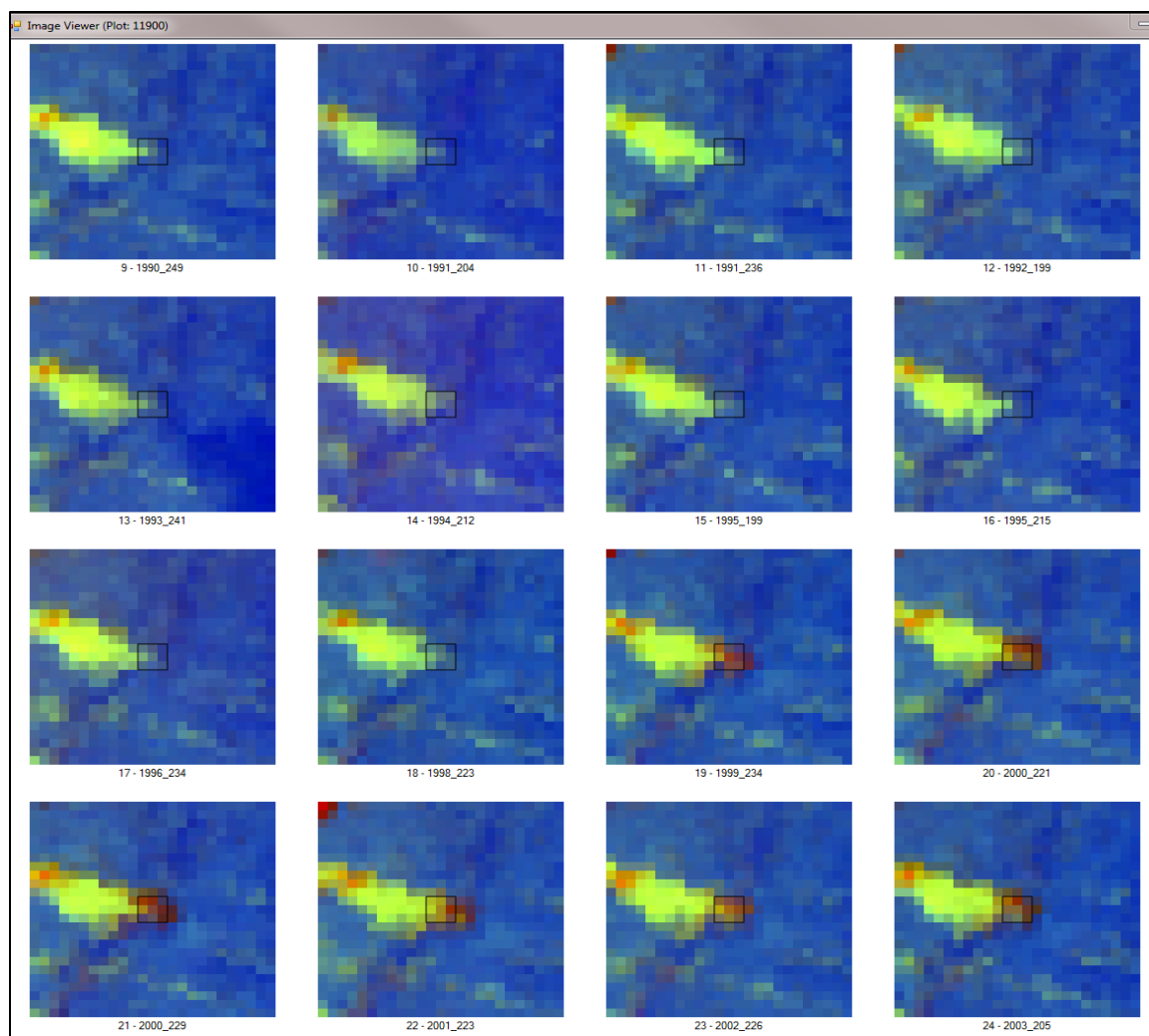


Figure 6. A subset of series of image chips from 1990 to 2003 for an area at North Cascades National Park Complex prior to and after an avalanche in 1999.

Access to the Image Stack on the Google Earth Engine Platform

Accessing the medoid image stack and running the LandTrendr scripts requires an account on the GEE platform. The procedures for signing up for a GEE account and setting up the user home directory are described in SOP 1. This only needs to be done once for each user. Each user requires a separate account, which can then be used to complete unlimited number of LandTrendr runs.

Study Area Selection

To run LandTrendr on GEE, the user needs to define a study area for each run. A shapefile containing the outline of one or more study areas is imported to GEE as an “Asset”, the term used for data entities stored on GEE. Procedures for preparing the shapefile for the upload to GEE are described in SOP 1. Since the image stacks stored in GEE are seamless, the user does not need to process individual Landsat scenes separately, as was the case for the prior protocol. The entire study area is processed at the same time.

LandTrendr-Based Change Detection

LandTrendr is a combination of change detection and results-processing algorithms. The acronym has come to refer to the larger process of detecting and mapping change. LandTrendr evaluates one spectral index at a time. The core LandTrendr algorithms follow the trajectory of a spectral index of an image pixel through the time series of Landsat images. Statistical line fitting techniques are used to draw a smooth trajectory through the series of values of the spectral index of a pixel. Primary outputs from LandTrendr are the vertices (breakpoints in the time series) that separate periods of distinct activity. From these, several key metrics are extracted: the years in which major changes occurred, the duration of the change, and the magnitude of change in units the spectral index used.

Spectral Index

Landsat satellite data comes in seven bands, with each band representing some portion of the visible to infrared spectrum. Spectral indices are a useful tool for reducing the complexity of multispectral space. Although any spectral index could be used, the normalized burn ratio (NBR) index has been determined by the OSU team to be one of the most useful for detecting change in vegetation cover in the Pacific Northwest (Key and Benson 2006), and is the index used for this protocol. NBR is defined as the difference between near infrared (NIR) and the second short-wave infrared band (SWIR2, centered at approximately 2.2 microns) reflectance divided by their sum.

$$\text{NBR} = (\text{NIR} - \text{SWIR2}) / (\text{NIR} + \text{SWIR2})$$

Although the index was originally developed for studies related to wildland fire, the index is more broadly used for characterizing vegetated systems because vegetation has low reflectance in the SWIR2 and high reflectance in the NIR. Additionally, the inclusion of SWIR2 appears to be particularly useful in working in forested regions. The wide range of values generated by the index allows for detection of subtle difference in vegetation types and condition (Cohen and Goward 2004). NBR has been used in national parks as a means of observing fire severity (van Wagtenonk et al. 2004) and has been used by the OSU in various change detection applications (Kennedy et al. 2010, Cohen et al. 2010, Gelabert et al. 2021, Senf and Seidl 2021, Ye et al. 2021). NBR has been shown to be more sensitive than the Tasseled Cap wetness index for detecting lower intensity changes (Cohen et al. 2010).

Segmentation

Even after efforts to normalize images in the time series, residual year-to-year variations remain in each pixel's temporal history. These variations are caused by the random effect of image acquisition date and can include: phenological differences, sun angle variations, and residual atmospheric effects. These noise effects can confound change detection, and therefore it is necessary to identify the underlying temporal progression of each pixel's spectral history.

The LandTrendr process is built on an approach to achieve this simplification through the fitting of straight line-segments through each spectral trajectory. This temporal segmentation process simplifies each pixel's spectral history to its salient shape. The resultant segments can then be evaluated to determine when the spectral values are increasing, decreasing or stable.

Segmentation is described in detail in Kennedy et al. (2010) and is summarized here. For each pixel, the NBR values are extracted for each year in the stack of the annual medoid composites (Figure 7).

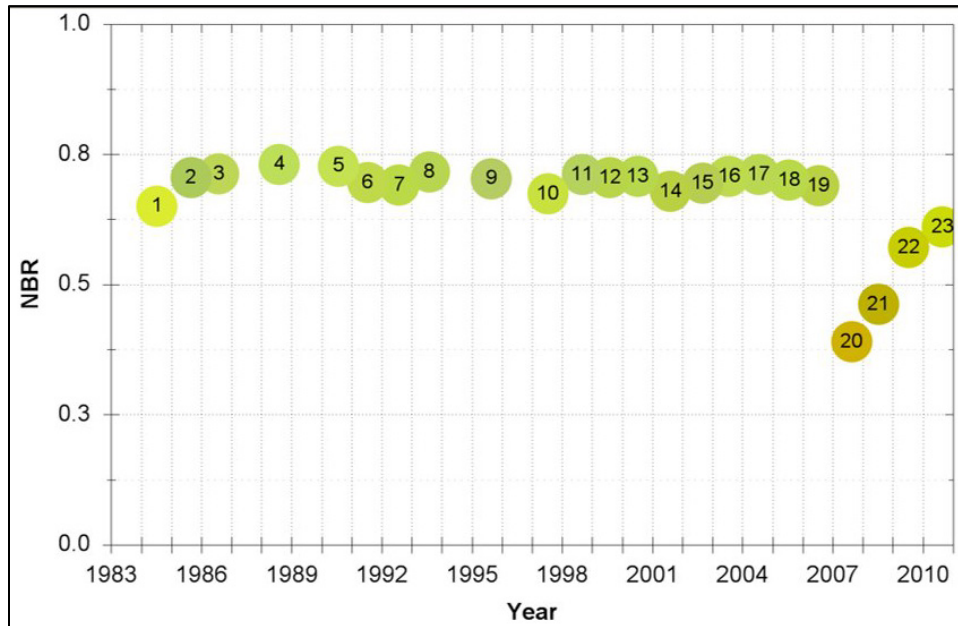


Figure 7. Extracted NBR (Normalized Burn Ratio) values from the Landsat stack. The numbers in each circle correlate to the ordered sequence of Landsat image chips in the stack. The colors reflect landcover type; dark blues represent conifer forest (not shown), browns represent exposed soil following a disturbance (circles 20–21), and greens depict broadleaf vegetation prior to disturbance and post-recovery (circles 1–19 and 22–23).

The first LandTrendr algorithm identifies years that appear to represent turning points – either upward or downward – in the overall spectral trajectory of a pixel. These turning points are referred to as vertex years in the trajectory, since they describe vertices between two sequential segments (Figure 8). Selection of these candidate vertex years is a critical step that is achieved using one of several different approaches. One approach is to evaluate slope change with and without each vertex.

Another approach analyzes the deviation of the point from the longer-term, straight-line trend. Priority for retention of a vertex can also be given to years that precede or follow large changes, if change signals have a consistent directional character. A target number of candidate vertex years is chosen, next a second set of algorithms 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. A third algorithm then identifies and removes the vertex whose removal caused the least penalty to the 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 (Figure 8). Finally, another algorithm is used to determine which number of segments represented the best overall description of the trajectory. The result from LandTrendr is an annual time series of NBR fitted to vertices of spectral-temporal segmentation.



Figure 8. Comparison of the spectral profile of an unfitted trajectory for a disturbance (left) and the smoothing effect of the LandTrendr line fitting algorithm (right).

The decision points for all these steps are controlled by a set of segmentation control parameters, which are detailed in Kennedy et al. (2010). Based on comparison with validation points across the west-side Pacific Northwest forests, the OSU team identified a stable set of segmentation parameters used in all forest-related efforts in the region. These values were updated in Kennedy et al. (2018) but largely remained the same (Table 1 in Kennedy et al. (2018)). NCCN then modified these parameters slightly after our own testing to better match environments in NCCN parks and to accommodate longer time series that are now available to run LandTrendr on. The parameters used for this protocol are shown in Table 4. Procedures for running LandTrendr scripts on GEE are detailed in SOP 1.

Table 4. The LandTrendr segmentation parameters used in this protocol.

Parameter	New Value	Old Value	Description
Kernelsize	dropped	1	Size in pixels of the fundamental analysis. Each pixel is handled separately. Originally used to save computational burden; no longer necessary.
pvalThreshold	0.05	0.05	Statistical p-value of goodness-of-fit test needed for a fitted trajectory to be considered good. Higher values allow noisier trajectories.
maxSegments	8	6	Maximum number of segments into which to divide a given trajectory. Increased to accommodate longer trajectories and new ability to map overlapping events.
recoveryThreshold	0.25	0.25	A noise filtering parameter that prevents segments with unrealistically fast recovery to be considered valid.
spikeThreshold	0.9	0.9	Used to filter year-to-year spikes or dips; this value allows moderate filtering.
Distweightfactor	dropped	2	A parameter used to give preference to vertices that lie near change events; this allows capture of more subtle change effects. Hardwired into GEE LandTrendr code.

Table 4 (continued). The LandTrendr segmentation parameters used in this protocol.

Parameter	New Value	Old Value	Description
vertexCountOvershoot	3	3	The initial regression-based detection of potential vertices can overshoot ($\text{max_segments}+1$) vertices by this value; angle-based culling is used to return to the desired number of vertices if overshoot occurs. This parameter allows better capture of subtle changes by allowing initial discovery of more vertices than necessary.
bestModelProportion	0.75	0.75	Allows more complicated segmentation results to be selected as best even if not strictly the highest-scoring model.
minObservationsNeeded	8	6	Minimum observations needed to perform output fitting. Usually equals maxSegments but could be higher as number of years in time series increases (e.g., $\frac{2}{3}$ or $\frac{3}{4}$ of run time step).

Spectral indices other than NBR are used in LandTrendr algorithms to increase the amount of spectral information available to describe change. Rather than using these indices to repeat the process of both identifying vertices and then fitting the time series data, the first step is skipped, and the other indices are forced to fit to the vertices found using NBR. These “fit-to-vertices” images allow for a richer description of change in a manner that constrains all other spectral indices used for visualizing or validating results to move in unison with NBR. For this protocol, the Tasseled Cap spectral indices (brightness, greenness, and wetness) are fit to the NBR temporal segmentation (Crist and Cicone, 1984)

After the LandTrendr run described above is completed, spatial layers generated by the run are downloaded to NPS servers by NCCN staff (SOP 1). From this point in the protocol forward, NCCN carries out the remaining steps on the NCCN servers using scripts created by the OSU team (Figure 5).

Generate Disturbance Layers

Unpacking GEE Outputs

The output files produced by the LandTrendr run in GEE are intermediate and need to be “unpacked” using one of the Python scripts created by the OSU team (SOP 1). The unpacked segmentation files contain information about the LandTrendr segmentation and fitting to vertex processes. The vertex years and vertex values of this “best description” of the trajectory provide the basis for all further mapping. 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. Detailed descriptions of each file can be found in Appendix A of SOP 1. These files are further filtered to extract useful information based on parameters chosen by the user.

The LandTrendr outputs at this point are information rich and must be processed to filter out unwanted information using a series of Python scripts. The fitted image could itself be used to display spatial patterns in the trajectories of pixels across an image and compared visually with other datasets to understand if a particular known phenomenon is being captured by the segmentation

process. However, the information is not summarized in a manner that can be interpreted quickly or quantitatively. To make use of the data, rule-based approaches must be applied to the vertex data to distill the information into simpler forms that can be mapped easily. In essence, the most salient or distinctive features are extracted from a given trajectory while ignoring the noise in the signal. This requires a sequence of processing steps.

Filtering Disturbance

A thresholding filter process is used to remove segment information that is indistinguishable from noise. The thresholding process is based on the minimum disturbance threshold, defined as standard deviation times 1000. Tests conducted by the OSU staff determined that 1.25 standard deviation is a reasonable value to use for the thresholding process. For NBR, this translates into the value of 125 and that is the value used for this protocol.

Extracting Annual Change as Rasters

After threshold filtering, the next scripts generate a series of raster files that are used in the next step which is creating polygons for use in change attribution. These multi-band GeoTIFF raster files have one band for each year for which a change onset was detected, starting at the second year of the time series. Each file describes some aspect of a change segment (e.g., disturbance year, or magnitude, as noted below), and information in each file corresponds to the other files. If no change onset is detected for a given year and pixel, then the pixel value for the year/band across all files is “null.” For a pixel in which a change onset is detected, the files contain attributes about the change, including the year of change onset detection, the magnitude of change, the duration of change, the pre-change segment spectral value, and the post-change segment spectral value. The spectral values include the NBR index on which LandTrendr segmentation was run, as well as Tasseled Cap brightness, greenness, and wetness (fit to the vertices of the LandTrendr-segmented index). Description of the annual change raster files and associated metadata files can be found in Appendix B of SOP 1.

Generating Polygons

Extracting Polygons

At this point the LandTrendr change detection results are still at the pixel level. The next processing step groups pixels into patches of meaningful change that can be linked to the change types of interest to the NCCN. Although landscape changes are detected at the scale of one pixel, monitoring change at the one-pixel scale is not feasible. First, monitoring at the finest scale of the Landsat pixels greatly increases the noise in the data. Second, it is much more challenging to validate results at that scale due to the relatively coarse resolution of the aerial photography used for validation. Thus, a spatial filtering step is used to limit changes to those that meet or exceed a minimum mapping unit. The MMU represents the smallest number of pixels joined together to create a landscape change patch. During the development stage of the protocol, various sizes of the MMU were tested to determine which one would achieve a tolerable balance between detecting enough of the changes of interest and validating the changes detected. A nine-pixel MMU – approximately 0.8 ha (2.5 acres) – was selected as the optimal size for the NCCN monitoring.

In some cases, especially when a smaller area of analysis is involved, a smaller MMU has been used to detect change. For example, a five-pixel MMU has been used to create more detailed maps of change associated with riparian areas or individual watersheds and to map development in areas directly adjacent to LEWI to inform elk movements across the landscape (analysis of elk data at LEWI through 2021 is in progress). While not part of the recurring analysis conducted for the protocol, these small projects can be used to answer specific park management questions.

A Python script is used to filter annual change rasters into patches equal or greater to the MMU. The same script is used to define how disturbance patches are formed. NCCN change types are focused on “abrupt” change, i.e., it is assumed that adjacent pixels which have the same year of onset are part of the same landscape change event. Therefore, patches are defined as groups of adjacent pixels, using an eight-neighbor rule, in which the year of change onset is the same for every pixel. The eight-neighbor rule allows all eight pixels surrounding a target pixel to be evaluated for inclusion in a polygon, rather than just the four pixels in the cardinal directions. Outputs are written into a polygon feature class layer corresponding to each year of disturbance, as well as into a combined data set that includes all the patches in the time series. Each patch is assigned a unique identifier. Thus, the result of this phase is vector-format file that documents each unique change event as a separate polygon.

Extracting Spectral and Landscape Attributes

Various spectral and landscape variables can be extracted for each patch to be used later in the process for the trend analysis. A Python script is used to run zonal statistics to generate spectral attributes from annual rasters. A list of these attributes can be found in Appendix C of SOP 1. Landscape attributes, such as slope and elevation, can also be added to the script by following steps outlined in SOP 1.

Labeling Landscape Change Type

A main objective of this protocol is not only to know the year, location, and magnitude of landscape changes, but also to identify and label each change with a change type (Table 3). The number and change type of detected patches vary considerably between the NPS and USFS designated Wilderness Area lands and the rest of the study area; areas dominated by private and state ownership have five to ten times the number of patches, largely due to different land management practices, which makes it impossible to review all patches every few years. Therefore, labeling these patches requires different approaches.

Manual Labeling of Patches

Within the NPS, USFS designated Wilderness Areas and BC Park boundaries (Figure 4), the NCCN approach is to manually label each polygon using historical aerial photography. Manual labeling has been used successfully by the Great Lakes Network (Gafvert and Kirschbaum 2015; Kirschbaum and Gafvert 2010, 2012, 2013, 2014, and 2017; Kirschbaum et al. 2016) and by NCCN during the implementation of the second version of this protocol (Antonova et al. 2012, 2013 and 2014; Copass et al. 2016; Copass and Antonova 2019). Analysis by NCCN showed that aerial photography can successfully be used for labeling landscape change for most change types mapped by NCCN, reducing the need for expensive field visits (Copass et al. 2019). Although the GEE version of the LandTrendr algorithm generates about twice as many patches per period of analysis as the IDL

version used previously, due to addition of overlapping disturbances, manual labeling is still feasible. Based on the 1987–2017 LandTrendr data set generated in GEE, the average number of patches to be labeled each year inside the park boundary is 161 ± 111 at NOCA, 34 ± 34 at MORA and 107 ± 89 at OLYM.

High Elevation Mask

A portion of the change patches, mostly inside the park boundaries, are located at higher elevations and are a result of ephemeral changes in phenology, soil moisture and snow cover. NCCN has developed a high elevation mask for NOCA, MORA, and OLYM study areas based on the detailed park vegetation maps (Nielsen et al. 2021a, b, c). Vegetation associations used for the masks are listed in Table 5. Areas covered by the masks are shown in Figures 9–11. NOCA high elevation mask also includes data from version 3 of the GAP analysis (USGS GAP 2016) where detailed park map is not available (Figure 9). GAP classes used in the mask are listed in Table 6. These masks were tested during labeling of the 1987–2017 data set by looking at the patches covered by the mask and making sure the masks did a satisfactory job of both including changes of interest and filtering out changes of no interest to NCCN. In addition to high elevation areas, water bodies are also included in the mask. Application of the mask significantly reduces the number of patches that must be labeled manually. Patches filtered out by the mask in their entirety are labeled as Inter-annual Variability and flagged as having been assigned that label via the application of the mask. Patches that intersect the mask but are not completely within the mask are examined during the labeling process to avoid filtering out patches of interest.

Table 5. NPS vegetation map classes included in the high elevation masks for NOCA, MORA and OLYM.

Map Class	Association Name	Park
C26 Conifer krummholz and treed cliff	<i>Abies lasiocarpa</i> -(<i>Pinus albicaulis</i>)/ <i>Juniperus communis</i> Krummholz	All
H51W Subalpine herbaceous wetland	<i>Carex</i> spp.- <i>Caltha chionophila</i> -(<i>Leptarrhena pyrolifolia</i>)	All
H54 Moist talus vegetation	<i>Athyrium distentifolium</i> ssp. <i>americanum</i> - <i>Cryptogramma acrostichoides</i>	NOCA, OLYM
H57 Green fescue dry meadow	<i>Festuca viridula</i> - <i>Eucephalus ledophyllus</i> , <i>Eucephalus engelmannii</i>	MORA, NOCA
H62 Alpine sparse herbaceous vegetation	<i>Luetkea pectinata</i> -(<i>Carex spectabilis</i>)	All
H63 Alpine buckwheat pumice vegetation	<i>Eriogonum pyrolifolium</i> - <i>Aconogonon davisiae</i>	MORA
H64 Alpine lupine pumice vegetation	<i>Phlox diffusa</i> - <i>Lupinus lepidus</i> -(<i>Pedicularis contorta</i>)	MORA
S48 Subalpine heather shrubland	<i>Phyllodoce empetriiformis</i> -(<i>Vaccinium deliciosum</i>)/ <i>Lupinus latifolius</i>	All
S49 Alpine heather shrubland	<i>Phyllodoce glanduliflora</i> -(<i>Cassiope mertensiana</i>)	All
R72 Colluvial Barren	–	All
R73 Bedrock Barren	–	All
W81 Fresh water	–	All
W82 Exposed snow and ice	–	All

Table 6. GAP map classes included in the high elevation masks for NOCA.

Map Code	National Vegetation Classification Subclass	Subclass Code	Park
551	North Pacific Alpine and Subalpine Bedrock and Scree	3501	NOCA
554	North Pacific Montane Massive Bedrock, Cliff and Talus	3209	NOCA
531	North American Alpine Ice Field	3502	NOCA

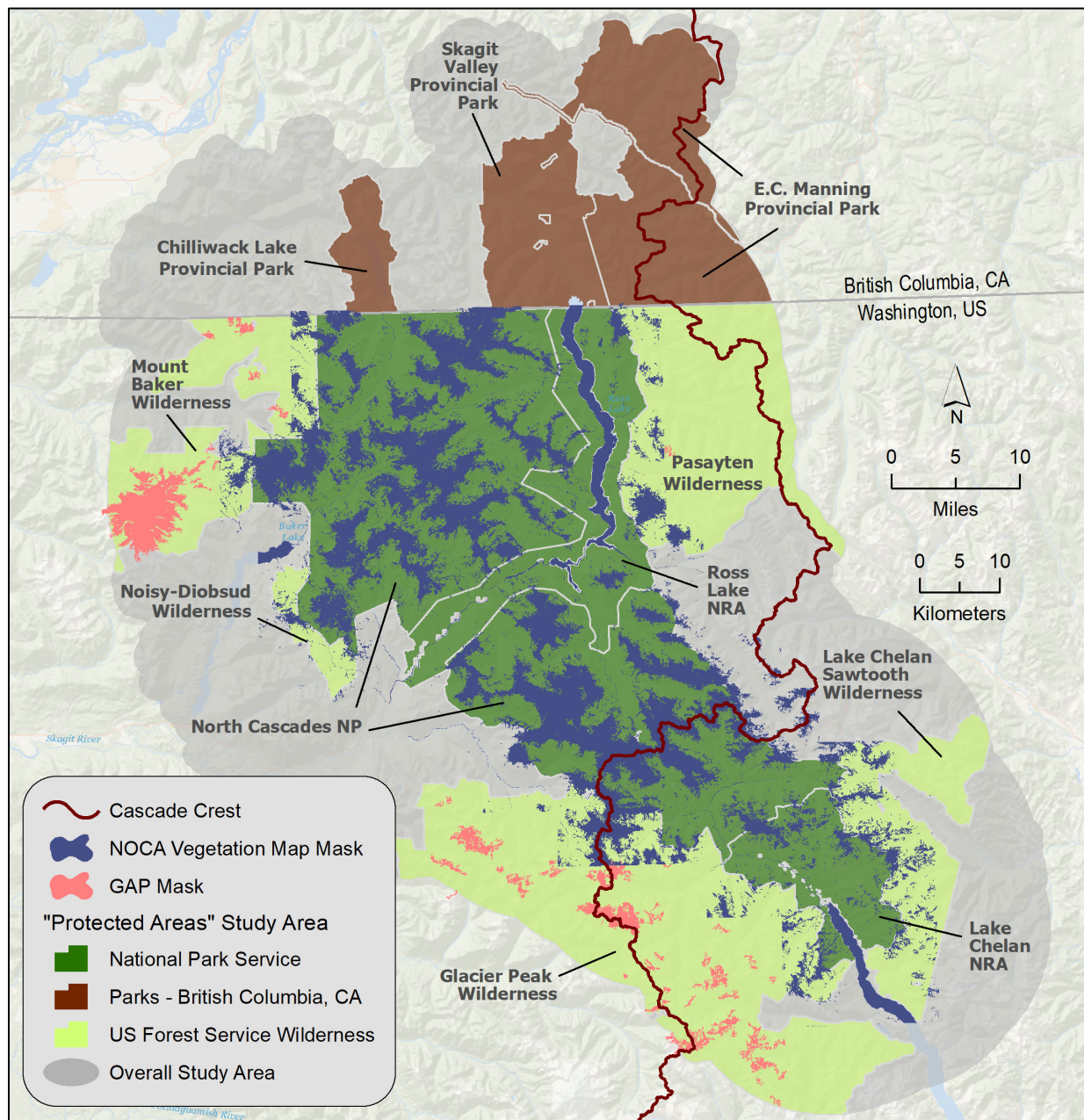


Figure 9. High elevation mask developed for NOCA using park vegetation map (Nielsen et al. 2021) and version 3 of the GAP data.

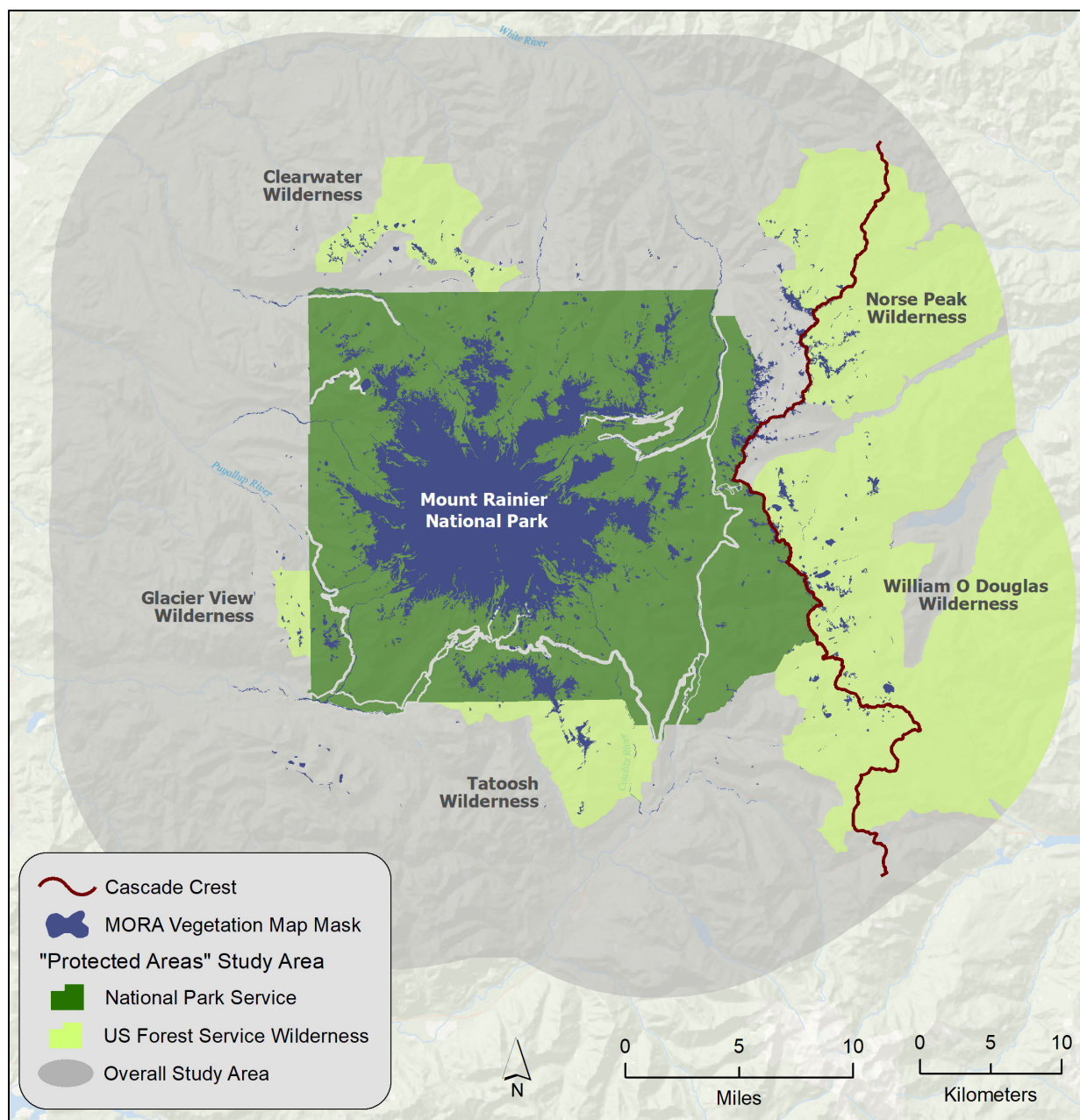


Figure 10. High elevation mask developed for MORA using the park vegetation map (Nielsen et al. 2021).

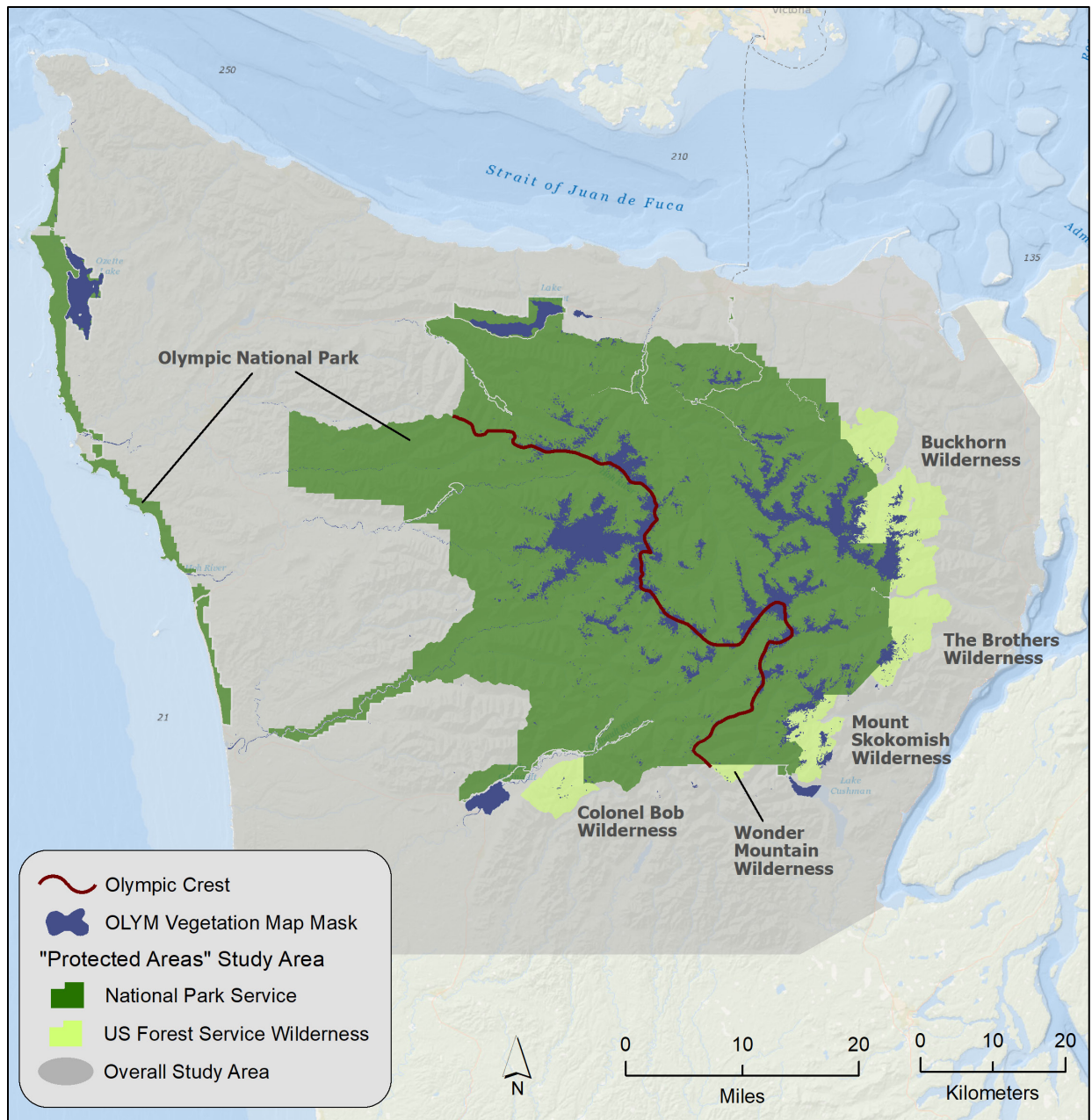


Figure 11. High elevation mask developed for OLYM using the park vegetation map (Nielsen et al. 2021).

Random Forests Classification

Labeling all patches within the overall study areas by hand is not feasible. Instead, a method for automatically labeling the polygons by change type using a machine-learning classification algorithm called Random Forests (Breiman 2001) was developed for each park. Methods for developing the models are described in the second version of the protocol (Antonova et al. 2012) and are also briefly summarized in SOP 2. Applying the RF model speeds up the labeling process considerably for areas outside the boundaries of the parks and the USFS designated Wilderness Areas.

Validation

Validation is the process of determining how well the change detection method captures and labels change. Underpinning this protocol are two layers of validation. The first layer is overall validation of the LandTrendr method and its ability to detect and map change. This validation has been performed by OSU when LandTrendr was first developed (Cohen et al. 2010). The GEE implementation of LandTrendr was then compared to the original version with satisfactory results (Kennedy et al. 2018).

The second layer is validation of the change type labels that are assigned to change patches by the NCCN interpreters using aerial photos and patch spectral trajectories (manual labeling) and by the Random Forests attribution model. Figure 12 depicts both types of validation.

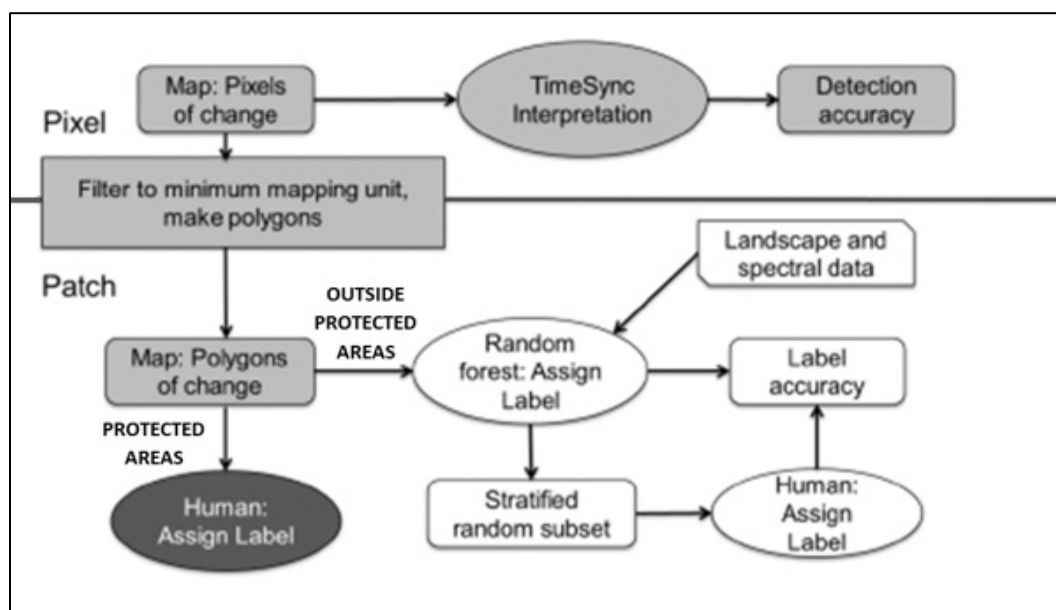


Figure 12. Schematic of the two layers of validation underpinning the protocol. Pixel level results above the line have been validated by Oregon State University. Patch level results are validated by NPS staff during protocol implementation. Changes inside park boundaries, USFS wilderness areas and BC Parks (protected areas) are labeled by hand in the office. Changes outside protected areas are labeled by the Random Forests (RF) model and validated in the office using a random subset of changes stratified by change type.

Validation of LandTrendr Method

Cohen et al. (2010) present a thorough examination of LandTrendr validation issues. There are two primary challenges with validating a long time series of data: 1) there are three types of LandTrendr outputs that need to be validated, including vertices (years), intensity and duration; and 2) reference datasets (e.g., plot data or aerial photographs) with matching variables are extremely rare. Because comparison with field or aerial photo data is virtually impossible, validation relies on comparing automated vs. human interpretation of change using Landsat images.

Oregon State University has developed an application called TimeSync to aid the human interpretation steps of the validation process. TimeSync facilitates visualization of the time series of Landsat images and validation data collection. The TimeSync application consists of four components: an image chip window, a trajectory window, Google Earth (<http://earth.google.com/>), and a structured query language (SQL) server database. The SQL server database is populated with spatial information for patches that need to be validated. TimeSync displays each patch in the spatial-temporal context of the entire stack of corresponding annual image chips. TimeSync also displays the averaged spectral value of all pixels in the patch (using NBR or a variety of other spectral indices) for each image chip (Figure 6) over the time series. By providing the interpreter with both spatial and temporal depth, detection of subtle events is vastly improved relative to single- or two-date interpretation, and ephemeral non-informative changes are easily ignored.

Cohen et al. (2010) used TimeSync to validate LandTrendr results over forested areas in Oregon and Washington. In this validation exercise, interpreters compared trajectories they created by hand using the time series with trajectories that LandTrendr generated. They compared the dates of change initiation, number of segments, and whether the change was a disturbance or recovery. Disagreements in the form of false positives (detecting a change when none occurred-commission) and false negatives (change occurred but was not detected-omission) were also evaluated.

When compared to manual change detection using TimeSync and the NBR index, LandTrendr had a slight tendency toward omission, with rates of omission varying with intensity of change. Intensity was defined for each pixel as the percent cover loss relative to the starting cover value. In contrast, LandTrendr, when using the same NBR index, overestimated the number of recovery and stable segments relative to TimeSync. LandTrendr omitted 10% of all high intensity (76–100 % cover loss) TimeSync-identified changes. Omission rates increased to 22% for medium (36–75 % cover loss) and 56% for low intensity (1–35 % cover loss) changes.

Following the transition of LandTrendr to GEE, a comparison between the IDL and GEE outputs were made based on how the two versions mapped abrupt forest disturbances (Kennedy et al. 2018). The two algorithms agreed 90% of the time. The assumption is that the error rates for NCCN use of both IDL and GEE LandTrendr are comparable.

Landscape Change Type Validation

Manually Assigned Labels

The second version of this protocol provided for field validation of patches labeled manually in the office using patch spectral trajectories and before and after aerial photos, when available (Antonova et al. 2012). Consequent analysis of this work showed that, for most landscape change types, office labeling performs as well or better than field sampling for identifying the change type (Copass et al. 2019). For more difficult types, similar challenges exist in the field as in the office, and office validation often offers additional benefits of having spectral information readily accessible to aid interpretation. In some cases, however, field observations revealed the cause of the change detected by satellites but difficult to see in aerial imagery; for example, a debris flow killing off trees by burying tree trunks in mud. For the updated version of the protocol, NCCN staff will not generally

field validate labels that were manually assigned in the office. Occasionally, we may choose to do a field visit for a patch that office validation assigned low confidence to, either due to missing or poor-quality aerial photos or because the change type was not obvious. Field visits will be prioritized for patches inside the park boundary and within areas that are accessible from the maintained trails or roads. Patches with lower confidence of label assignment will be blindly reviewed and labeled by additional NCCN and/or park staff to increase confidence.

Incidental Field Observations

NPS staff and visitors frequently report and document disturbances. For example, the major storm events at MORA in 2006 and OLYM in 2007 created a wealth of photos and data for specific disturbance events that were linked to change polygons generated by LandTrendr. These observations are used by the protocol to increase the robustness of the manual labeling methods.

Random Forests Assigned Labels

For areas outside the parks, USFS designated Wilderness Areas, and BC park boundaries, we will assess how accurately the RF model classifies landscape change types. The RF-generated error matrix that is produced by the statistical package during the model development stage will be used as one assessment of the labeling accuracy. The second type of assessment will be used by validating RF labels by comparing them to hand-labeled patch assignments. A random subset of 30 of patches in all change types will be selected from the RF-labeled pool of patches and labeled blindly in the office (Lea and Curtis 2010). If fewer than 30 polygons are labeled by the RF model for a particular change type, all instances of this change type will be validated using the manual method. During the first implementation of the protocol, it was determined that some disturbances can be represented by multiple patches. This is especially true for narrow, long disturbances such as avalanches and riparian changes. To avoid validating the same disturbance event multiple times, an oversample of additional 10 patches will be generated. If, during the validation of the first 30 samples, two or more of them come from the same event, only one sample representing the event will be retained and additional samples will be drawn from the oversample. The two types of labels will then be compared using an accuracy assessment confusion matrix (SOP 2). Once the error rate stabilizes, the validation for areas outside the Protected Areas will no longer be performed.

Data Management, Analysis and Reporting

This section describes the procedures for data management, analysis, and reporting. Effective data management ensures data quality, security, longevity, and availability, and is critical first step towards analysis and reporting. Additional information and context for this section may be found in NCCN Data Management Plan (Boetsch et al. 2009) which describes the overall information management strategy for the network.

Data Organization

This long-term monitoring protocol generates large quantities of spatial and tabular data, images, and analysis products. A well-organized digital file structure is critical to avoid confusion and potential data duplication. At NCCN, each project has a folder structure designed to store all the protocol's data products, documentation, and administrative history. Once all work has been completed for a specified time step for each park, all files will be transferred to the permanent project folder on the NCCN file share.

A normalized relational SQL Server database is used to store and manage LCMP data. This database has indicators to represent where data is in the data life cycle. The NCCN data management staff maintain the metadata and documentation that articulates the data dictionary and revision history of the data model.

The database is composed of three core tables including specifications on the run of LandTrendr in the GEE environment (e.g., scope of time, MMU, spectral index, etc.), data on the patches (e.g., year of when a change was detected, where that change occurred, and its size and magnitude, etc.) and change type (e.g., change type label, confidence in that labeling, etc.).

The user applications contain forms for data entry, loading, and verification, queries for quality assurance / quality control (QA/QC) that certify data that pass those QA/QC tests, data exports, and code for creating custom features designed to maintain efficient workflow. The applications will have documentation that describes the procedures for management and versioning, as well as easy-to-understand user instructions.

Data Entry and Verification

During the office validation, data will be entered directly or loaded into the project database application. The data entry forms in the front-end application will be patterned to follow the steps of validation process, including identification of the landscape change label, determination of certainty and alternative types. Built-in quality assurance components, such as pick lists and validation rules to test for missing data or illogical combinations, will be included in the forms. Metadata fields related to the timing and the identity of person entering the data and editing data will be captured automatically by the application and submitted to the database along with the project's data.

Verification of patch change types will be done in parallel with determining change type labeling confidence and, if needed, assigning an alternative change label. This work will be done by visually comparing the patch attributes in ArcGIS those in the project's database.

Spatial data are validated according to the procedures specified in SOP 2 using the latest version of ArcGIS software (ESRI, Inc.).

Data QA/QC and Certification

After the data have been entered and processed, they need to be reviewed for structural integrity, completeness, and logical consistency. The front-end database application facilitates this process by showing the results of pre-built queries that check for data integrity, data outliers and missing values, and illogical values. The GIS Specialist may then fix these problems and document the fixes. Not all errors and inconsistencies can be fixed, in which case a description of the resulting errors and why edits were not made is documented and included in the metadata and certification report.

Below are examples of tests applied to the data prior to certification:

- Verify that all fields are populated.
- Verify that spelling of change types and other attributes is consistent throughout the data set and with the instructions outlined in the protocol.
- Verify that date values are within the time steps of the analysis.
- Verify that polygon centroid coordinates were within the study area of interest.
- Verify that change type values are consistent with their location, for example, all Clearing and Development change polygons within the wilderness areas (NPS and USFS) are labeled correctly.
- Verify that if an alternative disturbance type exists, the confidence value is 1 or 2.
- Verify that all records with change type “Fire” have disturbance year and name assigned.

The data are considered certified after all the identified data issues are either corrected or documented. Data do not need to be completely free of errors to be certified but are of a level of quality needed for analysis. After the dataset is certified, it can be used in analysis, reporting, and published. More details of the QA/QC and certification processes are further documented in SOP 3.

Documenting, Distributing, and Archiving the Data

All data produced by the Landscape Change Monitoring protocol should have accompanying metadata. For the protocol’s spatial products, North American Profile of ISO 19115:2003 should be used for metadata creation ([North American Profile of ISO 19115:2003, Geographic information - Metadata — Federal Geographic Data Committee \(fgdc.gov\)](https://www.fgdc.gov/standards/projects/incits-11-standards-projects/NAP-Metadata)) (<https://www.fgdc.gov/standards/projects/incits-11-standards-projects/NAP-Metadata>). All SQL database objects (e.g., tables, fields) need to be defined and documented in a data dictionary.

Both spatial and non-spatial metadata records are uploaded to the NPS Integrated Resource Management Applications (IRMA) Data Store, where they are available to the public. All metadata records are updated as needed whenever additional data are collected and added to the data set.

Data Store References that meet the record retention criteria are imported into the eTIC internal system where they are archived in accordance with NPS Director's Order 19. The criteria for a Data Store reference to be harvested for record retention is:

- The reference has been explicitly marked 'Created by or for the NPS'
- At least one digital file is associated to the reference
- There is a Reference Title
- There is an associated Unit Code
- The Reference Status has been Active at one point in the lifecycle. It can currently be set to DRAFT, but it must have been previously set to Active.
- Original Publication date or content begin date is greater than 5 years

Recommended Reporting Schedule

For areas within the NOCA, MORA, and OLYM park boundaries and adjacent USFS designated Wilderness Areas and BC parks, we plan to generate a change detection data set every three to four years. A change detection data set for the entire LEWI study area will also be generated every three to four years. Because of the large number of patches and additional work involved in labeling and validating patches outside the protected areas, we plan to generate a change detection data set for the overall NOCA, MORA and OLYM study areas every ten years. This could also be done more frequently for a subset of areas if needed to meet specific management consideration and data needs. Nationally available datasets that use the LandTrendr algorithm are quickly becoming available and should be assessed for use in summary statistics (USDA Forest Service 2021).

Recommendation for Routine Data Summaries and Statistical Analyses to Detect Change

Analysis of trends in continuous predictor variables (time, climate indices) is performed using regression models. The data generated by this protocol include both response variables that are likely to have non-constant variance across the domain of the predictor (i.e., heteroskedastic responses) and count data with a similar non-constant variance. Therefore, we use a Generalized Linear Model (GLM) rather than simple linear regressions (ordinary least squares, OLS). The GLM approach effectively minimizes the squared error over a transformed version of the data. For the disturbance patch count response, this would typically be a Poisson model, and for the disturbance area response, an exponential model.

The data are also likely overdispersed, because some years in the time series have many events and other years have none. Both count and area responses in this study have many years with zero detected disturbance, resulting in zero inflation. Both overdispersion and zero inflation are forms of heteroscedasticity and can be addressed by using models with an additional parameter. We apply a Negative Binomial model, a generalization of Poisson that allows for cases where the mean and variance are not equal (over- or under-dispersed cases). Sometimes, however, the Negative Binomial model will not converge; in this case a more robust, but less powerful, Tweedie model is employed. Tweedie is a family of models that continuously interpolates between Normal, Poisson, Gamma, and Inverse Gamma distributions. All Tweedie models in this analysis use a power variance index of 1.5,

corresponding to a Compound Poisson with mass at zero and constrained to be non-negative. Negative Binomial models are implemented in the R package ‘MASS.’ Tweedie models are implemented in the R package ‘statmod.’

R scripts have been created that generate negative binomial and Tweedie models of disturbance metrics by year. Additionally, the R scripts generate graphs for visual exploration. All models are separated by change type; these are run separately with all changes throughout all parks, separated by park, and separated by park and east/west side of the Cascade and Olympic crest (Figures 9–11).

In summary, routine data summaries produced by this protocol include:

- Total number events
- Total area disturbed
- Average area disturbed per event
- Average magnitude (in NBR units) of disturbance event

Graphs created by each by change type include:

- Histograms of disturbance area
- Disturbed area by year
- Change magnitude by year
- Number of disturbance events by year
- Average area disturbed per event by year
- Total area disturbed by year

Trend analysis of target natural landscape change types will be conducted every twelve years and coincide with the analysis of the Development and Clearing change types produced by labeling patches in the larger study area.

Recommended Report Format with Examples of Summary Tables and Figures

In the past, this protocol has created reports summarizing the long-term data sets (Antonova et al. 2013, 2014; Copass et al. 2016, Copass and Antonova 2019). From here forward, we will focus on Resource Briefs and other science communication products, which are more appropriate to convey information to park management and the public, and journal publications to convey information to the scientific community. The summary tables and maps in the LEWI report on the 1985–2011 time series provides examples of typical outputs from this protocol, which will be used, as appropriate, in our communication materials (Table 7, Figure 13).

Table 7. Example of a summary table from the LEWI 1985–2011 report (Copass and Antonova 2019). Area (ha) affected by each disturbance type within the large and 2 km study areas from 1985 to 2011. Results reported for the large study area include the 2 km study area.

Type	Large Study Area	% Large Study Area	2 km Study Area	% 2 km Study Area
Agricultural Clearing	104.42	0.15	60.08	0.69
Clearing	18316.66	26.49	770.61	8.88
Coastal	15.82	0.02	5.4	0.06
Development	395.41	0.57	96.81	1.14
Mass Movement	5.67	0.01	–	–
Progressive Defoliation	4.05	0.01	–	–
Tree Toppling	628.6	0.91	49.77	0.57
Windthrow Salvage	3680.58	5.32	297.69	3.43
Grand Total	23151.22	33.48	1280.35	14.75

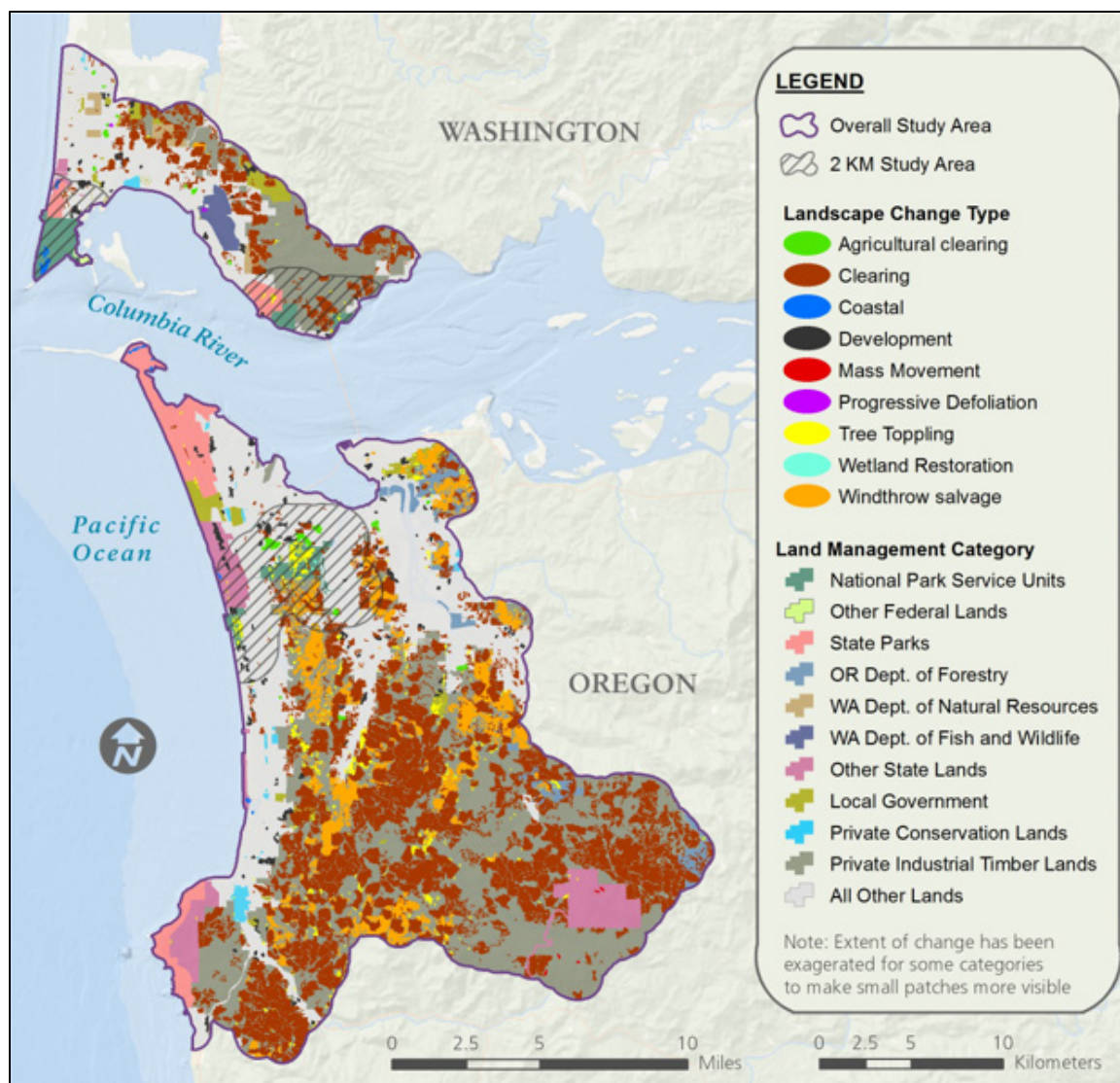


Figure 13. Example map of landscape change types overlaid on land management categories. This map shows landscape changes of interest to NCCN from 1985 to 2011 within LEWI study area in Washington and Oregon.

We will use R scripts to create summary graphics for the time series data for various subsets of the data (see Statistical Analyses section) (Figure 14).

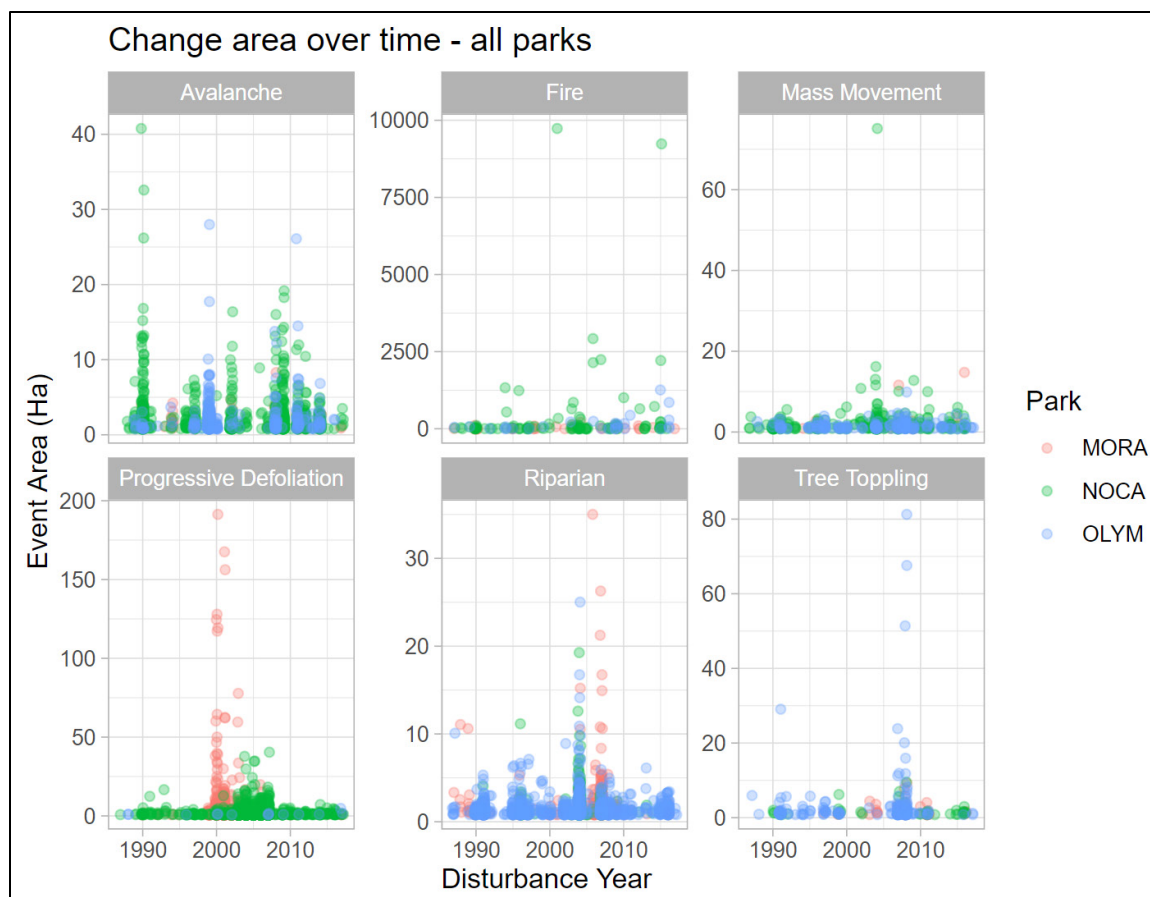


Figure 14. Example summary graphic generated by the protocol R script.

Science communication materials for each park will be updated as more data get processed. Story Maps or similar products focused on disturbances occurring because of individual extreme weather events, such as the Great Coastal Gale of December 1–3, 2007 at LEWI or the strong windstorm of March 2–3, 1999, will be generated as those disturbances are documented in the long-term data set. An example of such a Story Map can be viewed here: [The Great Coastal Gale of 2007 \(nps.gov\)](https://www.nps.gov/maps/stories/the-great-coastal-gale-of-2007.html) (<https://www.nps.gov/maps/stories/the-great-coastal-gale-of-2007.html>).

New Methodologies

As with any long-term monitoring project that relies on use of a specific technology, there will always be a chance that the Landsat imagery or the LandTrendr processing algorithms will at some point become unavailable, either because they are no longer functioning or supported. However, with the launch of Landsat 9 in September of 2021 and the Landsat imagery stack moving to the Google Earth Engine platform where it is accessible to the global scientific community, it is our belief that the technology this protocol relies on will be available for at least several decades into the future. Should that change, new methods will have to be developed or adopted using other available sources of remotely sensed data that will mimic or improve upon the current information provided by Landsat. Such efforts are already under way for parts of Washington State and rely on high resolution National Agricultural Imagery Program (NAIP) photography to detect change ([Data | High Resolution Change Detection \(arcgis.com\)](#)) (<https://hrcd-wdfw.hub.arcgis.com/pages/data>). Labeling the change polygons with NCCN target change types and producing data summaries and trend analyses will still require investments on the part of the network.

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1201 Oakridge Drive, Suite 150
Fort Collins, CO 80525