



Landsat-based Monitoring of Landscape Dynamics in Olympic National Park

1985-2010

Natural Resource Data Series NPS/NCCN/NRDS—2016/1053



ON THE COVER

2012 revisit of a 2007 Tree Toppling, Quinault Rainforest, Olympic National Park
Photograph by: Bill Baccus

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Abstract

As part of Vital Signs Monitoring, the North Coast and Cascades Network (NCCN) of the National Park Service (NPS) developed a protocol for monitoring landscape dynamics using Landsat satellite imagery. The protocol was implemented at Olympic Park (OLYM) in 2014 using LandTrendr (Landsat-based Detection of Trends in Disturbance and Recovery) algorithms developed by the Laboratory for Applications of Remote Sensing in Ecology (LARSE) at Oregon State University.

We mapped eight categories of landscape change that occurred at OLYM and surrounding areas from 1985 to 2010: Avalanches, Clearing, Development, Fire, Mass Movements, Progressive Defoliation, Riparian, Tree Toppling, and Winter Ice. The Avalanche category captures long, linear change which partially or completely removes vegetation from the valley wall following a release of a large mass of snow down a mountain side. Clearings are areas under forest management where practices vary from thinning to clearcuts. The Development category captures changes associated with complete and persistent removal of vegetation and transformation to a built landscape. Changes due to Fire vary in intensity from full canopy removal to partial burns that leave behind a mixture of dead and singed trees. The Mass Movement category includes both landslides found on valley walls and debris flows associated with steep gradient streams. Progressive Defoliation is a change type in which the forest cover remains but vigor has declined due to insect infestation, disease or drought. Riparian changes are restricted to the valley floors alongside major streams and rivers and capture areas where either conifer or broadleaf vegetation previously existed and has been converted to river channel. Change due to Tree Toppling is evidenced by fallen, broken or topped trees, generally due to wind but sometimes to root rot. Winter ice is a category created to capture forest damage due to a unique combination of large quantities of snow and a windstorm at higher elevations. Only changes larger than 0.8 ha (2 ac) and for which the duration of the period of landscape change was less than 4 years were mapped.

The OLYM study area is 1,146,810 hectares, of which 32% (368,593 ha) is within the park boundary. Approximately 159,631 ha (13.9%) of the study area underwent detectable change at some point during the 26 year period of analysis, affecting about 0.98% of OLYM and about 20.1% of the area outside the park boundary. The annual average area impacted by landscape change within the study area was about 6,001 ha. Within the park boundary, the annual average area undergoing change was about 138 ha.

Clearing was the major change type within the study area over the last 26 years, followed by Tree Toppling and Development. Inside the park, Fire was the most significant agent of landscape change, with Tree Toppling and Riparian contributing significantly to total change.

The inter-annual variability in the total area experiencing landscape change was considerable. The greatest amount of change outside the park boundary was documented in 1988 and was associated with the Clearing category. Inside the park, 2008 was the year with greatest change, due to several winter storms that caused high levels of change in the Tree Toppling, Riparian and Mass Movement categories.

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We wish to thank Mark Huff and Lise Grace with the NCCN for assisting with the development of this report. LandTrendr data were provided by Robert Kennedy and his team, including Tara Larrue (College of Earth, Ocean and Atmospheric Science, Oregon State University), James Perkins (Boston University) and David Miller (Boston University). Katherine Beirne, Roger Hoffman and Bill Baccus contributed helpful feedback and images to this work.

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Acronyms

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

CESU - Cooperative Ecosystem Study Unit

DFW - Department of Fish and Wildlife

DNR - Department of Natural Resources

ESRI - Environmental Systems Research Group

GIS - Geographic Information System

I&M - Inventory and Monitoring

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

LARSE - Laboratory for Applications of Remote Sensing in Ecology

LDMP - Landscape Dynamics Monitoring Protocol

MMU - Minimum Mapping Unit

MORA – Mount Rainier National Park

NAIP - National Agricultural Imagery Program

NBR – Normalized Burn Ratio

NCCN - North Coast and Cascades Network

NPS - National Park Service

PNW - Pacific Northwest

PWRO - Pacific West Region Office

RF - Random Forests

TM - Thematic Mapper

Glossary

Duration – An output variable from LandTrendr, defined as the length of time it took for a given landscape change to occur and is expressed in years.

Ensemble classification method – An ensemble is a set of classifiers whose individual decisions are combined in some way to improve predictive performance.

Google Earth – a free program from Google that allows you to "fly" over a virtual globe and view the Earth through high-resolution graphics and satellite images.

Kappa Statistic – Used as a measure of agreement between a prediction and reality in a mapping context. In this project the prediction is derived from a classification model and is compared to reality as determined by photo-interpretation process. It can also be used to determine if the values contained in an error matrix represent a result significantly better than random.

Magnitude – The estimated change in percent vegetative cover following a landscape change event. Magnitude is calculated by differencing a pixel's Normalized Burn Ratio (NBR) index values prior to and following the landscape change event. The percent reduction is relative to the original cover value.

Patches – Used to describe polygons that meet rules of adjacency and minimum mapping unit of 9 Landsat pixels and are combined to represent one change event.

Pixel – short for picture element and is defined as smallest single component of a digital image. In this report it refers to Landsat pixels which are 30 m on a side.

Producer's Accuracy – The probability that a reference sample will be correctly mapped. The reference sample in this project is a photo-interpreted landscape change type. In other words, if you were to stand in a patch that had experienced a landslide, would that event be labeled as a landslide on the map? Producer's accuracy measures the errors of omission.

Random Forests – An ensemble learning method for classification (and regression) that constructs multitude of decision trees and outputs the class that is the statistical mode of the classes represented by individual trees.

randomForest – Statistical package in R that conducts Random Forests analysis.

Raster – A spatial data model that defines space as an array of equally sized cells arranged in rows and columns, and composed of single or multiple bands. Each cell contains an attribute value and location coordinates (ESRI).

Regression Trees - A data-analysis method that partitions data into sets, which are then modeled using regression methods.

Scenes – Refers to the rasters collected by Landsat as it passes over the Earth. Landsat scene size is approximately 170 km x 185 km (106 mi x 115 mi) and each scene has a unique identifier consisting of

row and column number. The raster data is organized into scenes to facilitate data organization and management and so that repeat data from the same part of the Earth can be retrieved more easily.

Spectral index – combination of surface reflectance at two or more wavelengths that indicate relative abundance of features of interest.

User's Accuracy – The probability that a mapped landscape change type matches the reference sample. The reference sample is photo-interpreted landscape change type in this project. In other words, if you look at the map and see a landslide, then visit that spot in the field, would you find a landslide? User's accuracy measures the error of commission.

Vector – A coordinate-based data model that represents the world using points, lines, and polygons.

Introduction

The overall purpose of natural resource monitoring in national parks is to develop scientifically sound information on the current status and long term trends in the composition, structure, and function of park ecosystems (Fancy et al. 2009). The North Coast and Cascades Network (NCCN) developed a Landscape Dynamics Monitoring Protocol (LDMP) in order to provide information on the type, location, frequency, and magnitude of landscape changes in ecosystems both in the park and the surrounding region (Antonova et al. 2012).

Individual landscape change events such as windthrow, landslides, floods, and fires can have significant impact on visitor experiences and park facilities. The information provided by the LDMP offers important insights regarding trends in the size, frequency or magnitude of these events. This knowledge can be used to better target and prioritize funding allocations and contribute to park facilities planning and maintenance. By providing maps of landscape change in conjunction with other information, results from this monitoring effort will contribute to assessments of park vulnerability to climate change via the development and validation of park resource vulnerability models. The LDMP also provides complimentary information to the NPScape program, which provides landscape-scale indicators that broadly address changes due to human population, housing density and landcover change (see NPScape website: <http://science.nature.nps.gov/im/monitor/npscape/>; accessed 21 September 2015).

The Landscape Dynamics Monitoring Protocol was developed in cooperation with the Laboratory for Applications of Remote Sensing in Ecology (LARSE) at Oregon State University, which utilizes the Landsat platform as their primary remote sensing tool. LARSE developed Landsat-based Detection of Trends in Disturbance and Recovery (LandTrendr) - a suite of change-detection algorithms which track the spectral trajectory of Landsat pixels through time.

The primary objectives of Landscape Dynamics Monitoring Protocol are to:

- Detect and map landscape changes that are larger than 0.8 ha (2 ac) resulting from vegetation removal due to avalanche, clearing, development, fire, mass movement, progressive defoliation, riparian flooding, tree toppling and winter ice.
- Determine trends in the size, magnitude, location, and spatial distribution of each landscape change category. The term “magnitude” is used to quantify percent change in vegetation cover removed.

Table 1 lists the landscape change types of interest to the NCCN covered by this report. The types were originally selected based on NCCN’s priorities and with input from NCCN employees following a series of workshops during the development of the original version of the protocol (Kennedy et al. 2007). The types were subsequently modified during the development of the second version of the LDMP (Antonova et al. 2012).

Table 1. Landscape change types monitored within the Olympic National Park study area. Annual Variability and Agriculture are two additional categories that are mapped but not reported on with this protocol.

Landscape Change Type	Definition
Avalanche	Long, linear change areas which originate in snow receiving zones or valley walls. Typically remove some but not all of the vegetation.
Clearing	Reflect a range of forest management practices, such as clearcuts, select cuts and thinning, and chemical removal of broadleaf vegetation.
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. Also includes first-time removal of vegetation for agricultural activities. Consequent changes due to crop planting and harvest are included in the Agricultural category.
Fire	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.
Mass Movement	Category 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 Movement is distinguished from the Riparian category because it occurs on slopes greater than 15 degrees.
Progressive Defoliation	Assigned to polygons where the forest cover remains but has undergone slow change in spectral values representing a loss of greenness and wetness. Several patterns of decline in tree health can be seen.
Riparian	Change areas of this type are restricted to the valley floor in areas where either conifer or broadleaf vegetation previously existed and has been removed, reduced and generally converted to active river channel, with water or river bars.
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.
Winter Ice	Vegetation damaged by heavy, long lasting snow and ice followed by severe winds; generally characterized by broken tree branches.

In this report, we present the first assessment of landscape change at Olympic (OLYM, or Park) using the LDMP. The assessment spans 26 years, from 1985 to 2010, and establishes baseline conditions for natural and anthropogenic changes both inside and outside OLYM. The report provides data summaries by year, change type and land ownership, accompanied by maps of landscape changes. A Glossary of terms used in this report is shown on page ix.

Study Area

The Olympic National Park landscape change monitoring study area includes the majority of the Olympic Peninsula and integrates ecological features with constraints of the Landsat imagery (Figure 1). The initial study area, a 16 km (10 mi) buffer around the Park boundary, was established in accordance with protocol guidelines and was designed to capture connectivity between the park and surrounding lands of particular importance for wildlife and fish populations. Following consultation with park ecologists, the study area was expanded to include the majority of the Olympic Peninsula, which borders the Pacific Ocean on the west, the Strait of Juan de Fuca on the north and the Hood Canal on the east. The southern boundary of the study area still ends at 16 km from the park boundary. The resulting area includes 1,146,810 ha of land and water, about 32% (368,593 ha) of which are inside the park boundary. The study area includes parts of three Landsat images, scenes 4727, 4827 and 4826, which cover 73, 21 and 6 percent of the study area respectively.

Olympic National Park is sometimes described as three parks in one because it encompasses three major ecosystems; a 117 km (73 mi) long strip of coastal wilderness, iconic temperate rainforests and mountainous subalpine and alpine landscapes. Mount Olympus at 2,430 m (7,965 ft) and surrounding peaks form a central hub on the Olympic Peninsula from which 11 major rivers radiate. The core of taller peaks at the center of the peninsula creates a strong rainshadow effect, driving vegetation patterns that shift from west to east in combination with lower to higher elevations. The western and central parts of the study area, including the park, are dominated by mesic Douglas-Fir and Western Hemlock and Silver Fir forests at lower and middle elevations transitioning into woodlands and meadows as elevation increases. In the eastern side of the study area drier Douglas-fir forests and woodlands predominate.



Figure 1. Study area used for monitoring landscape change in and around Olympic National Park, Washington.

Study Area: Land Management Characteristics

The landscapes within the study area represent a broad mix of ownership types. Olympic National Park covers about 32% of the study area (Hoffman 2014a). Ninety five percent of the Park is congressionally-designated wilderness (United States Congress 1988; Hoffman 2014b). The five percent of the Park that is not wilderness is concentrated in road corridors, parking lots and heavy visitor use areas including Hurricane Ridge, Elwha, Sol Duc, Hoh and Kalaloch (Figure 2).

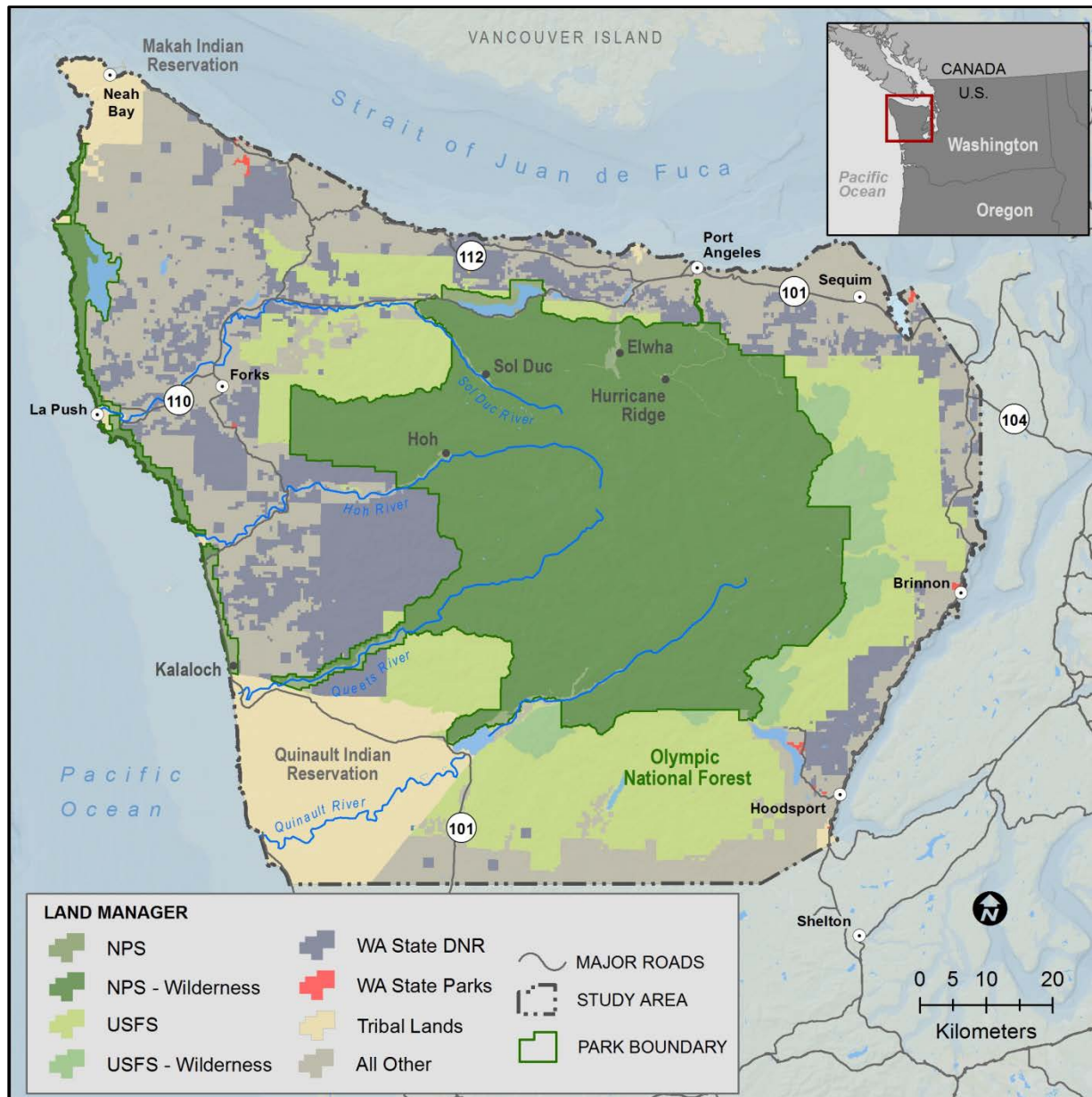


Figure 2. Major land management categories within the Olympic National Park study area, Washington.

The broad category “All-Other” comprises 24% of the study area; it includes all private, city, and county lands. Lands within this category are subject to a variety of uses, including commercial timber harvests, development, and agriculture. The United States Forest Service (USFS) manages 22% of the study area, primarily bordering the northwest, east, and south sides of OLYM. Of the USFS land, 3% of the study area is wilderness (Table 2, WA DNR 2007a). USFS wilderness areas neighbor the park on the east and south; these include the Buckhorn, The Brothers, Mt. Skokomish, Wonder Mountain, and Colonel Bob Wilderness areas. The Department of Natural Resources (DNR) manages about 13% of the study area (WA DNR 2007a and 2007b). Tribal lands comprise about 8% of the study area, with most coming from the Quinault Indian Reservation.

Table 2. Area and percent of total area under various land management categories within the Olympic National Park study area, Washington.

Land Manager	Area (ha)	% of Area
Olympic National Park- Non Wilderness	18761	1.637
Olympic N.P. - Wilderness	349832	30.523
Bureau of Land Management	65	0.005
Tribal Lands	94024	8.204
US Department of Defense	22	0.002
US Fish and Wildlife Service	118	0.010
US Forest Service- Non Wilderness	219293	19.134
US Forest Service- Wilderness	35313	3.081
WA DNR	152664	13.320
Washington State Parks	1107	0.097
WA State Other	33	0.003
All Other	274884	23.984

Study Area: Population and Housing

The OLYM study area is sparsely populated. Port Angeles, Sequim, and Forks, the three major population centers within the study area, support a combined population just under 30,000 (Table 3, WAOFM 2011). Unincorporated areas within Clallam, Mason and Jefferson counties have been growing steadily the past two decades (Figure 3), with rates of growth highest in the eastern part of Clallam County near Sequim.

Table 3. Population numbers and percent change in population for unincorporated county areas and cities in and around the Olympic National Park study area, Washington.

	Population			% Change		
	1990	2000	2010	1990-2000	2000-2010	1990-2010
County						
Clallam	32045	38328	42228	19.61	10.18	31.78
Grays Harbor	25000	25548	28438	2.19	11.31	13.75
Jefferson	13405	17965	20759	34.02	15.55	54.86
Kitsap	138676	159896	170022	15.30	6.33	22.60
Mason	31100	40963	50865	31.71	24.17	63.55
Pierce	339679	315359	366738	-7.16	16.29	7.97
City						
Forks	2838	3120	3532	9.94	13.21	24.45
Port Angeles	17710	18397	19038	3.88	3.48	7.50
Port Townsend	7001	8334	9113	19.04	9.35	30.17
Sequim	3617	4334	6606	19.82	52.42	82.64
Shelton	7241	8442	9834	16.59	16.49	35.81

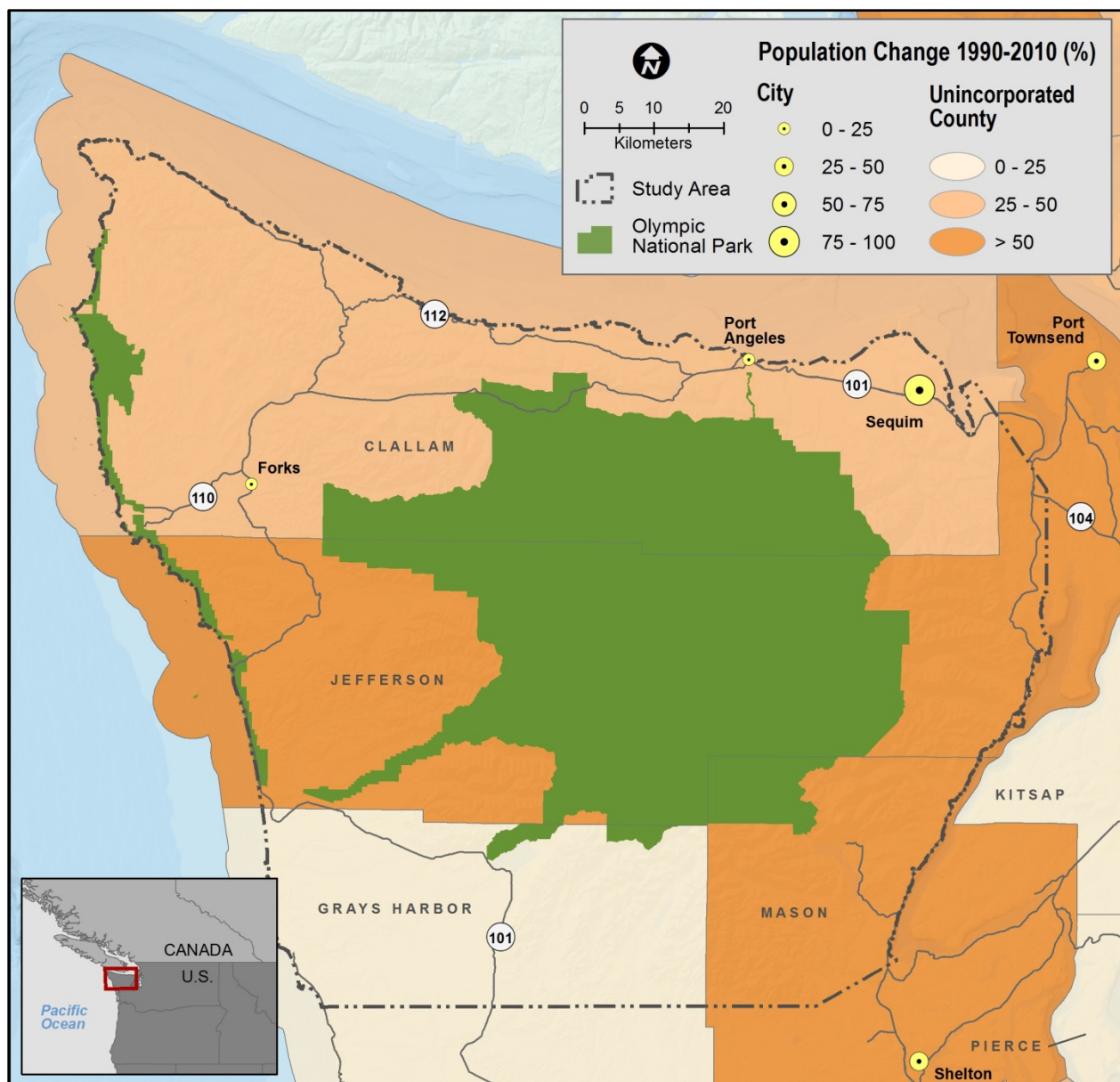


Figure 3. Percent population change for unincorporated county areas and cities in and around the Olympic National Park study area, Washington.

Methods

The NCCN Landscape Change Detection and Monitoring Protocol (LDMP: Antonova et al. 2012) provides a detailed explanation of the methods used to detect the 1985-2010 OLYM landscape changes. The methods include: running LandTrendr change detection algorithms with processed Landsat imagery, processing results into landscape patches, classifying the patches by change type, and validating the accuracy of the change type classification results from aerial photography.

Change Detection

LandTrendr change detection starts with downloading and processing Landsat imagery. The Landsat images chosen for inclusion in the change detection preferentially occur as close to mid-July as possible. A consistent date of imagery between years improves interpretation by minimizing the noise from annual changes in sun angle, which causes topographic shadows, and from differences in vegetation phenology. Figure 4 shows the day and year of Landsat images used in the analysis for the three OLYM scenes.

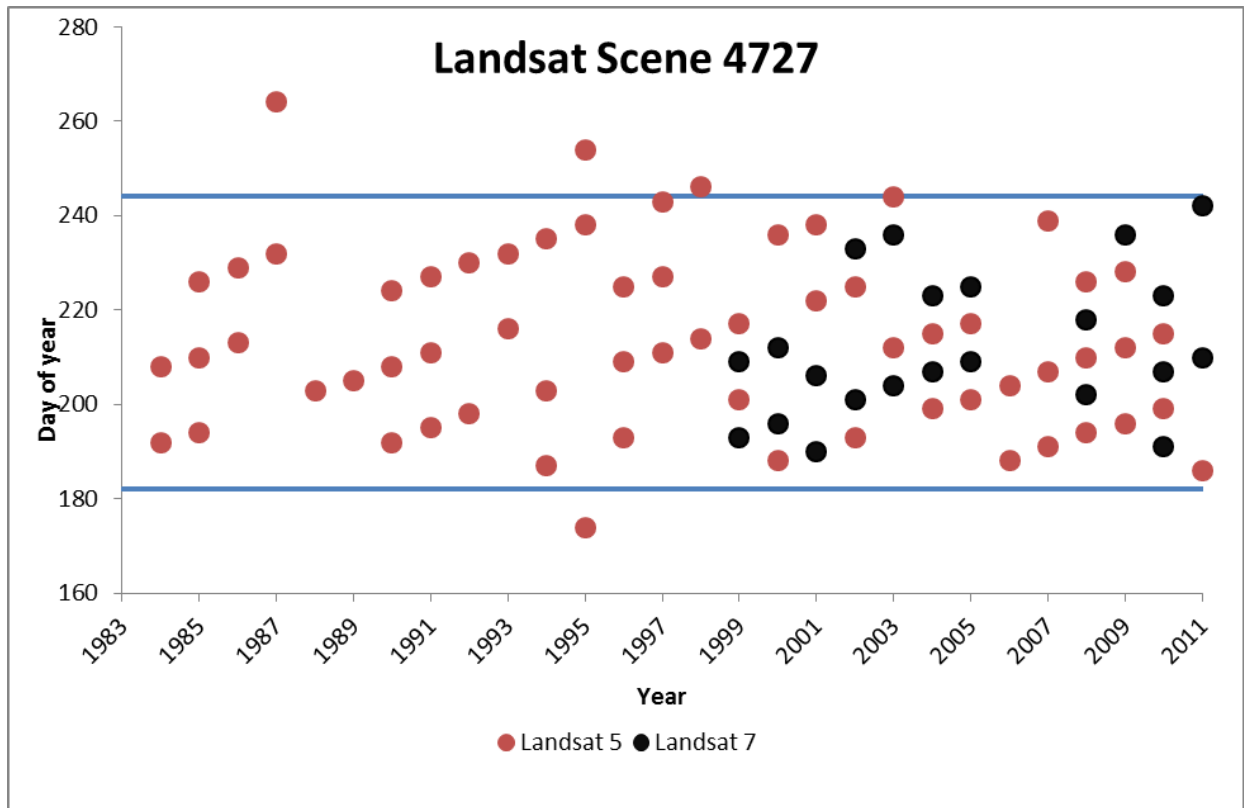


Figure 4a. Day and year of Landsat images used for analysis for the Landsat scene 4727, which covers the majority of Olympic National Park, Washington. Blue lines denote the time period between July 1st and September 1st.

Typically, at least several usable images per scene are captured in each year, however, a notable gap exists between 1996 and 1998 in scene 4827 (Figure 4c), which covers about 20% of the western part of the study area and mostly affects non-NPS lands (Figure1). Landscape changes occurring within

this three-year gap are attributed with the next consecutive year for which the imagery is available (1999). In general, fewer good images exist for the 4826 and 4827 scenes due to frequent cloud cover in these coastal portions of the study area. Landscape changes which occur during the years with missing imagery are given the date of the first available image.

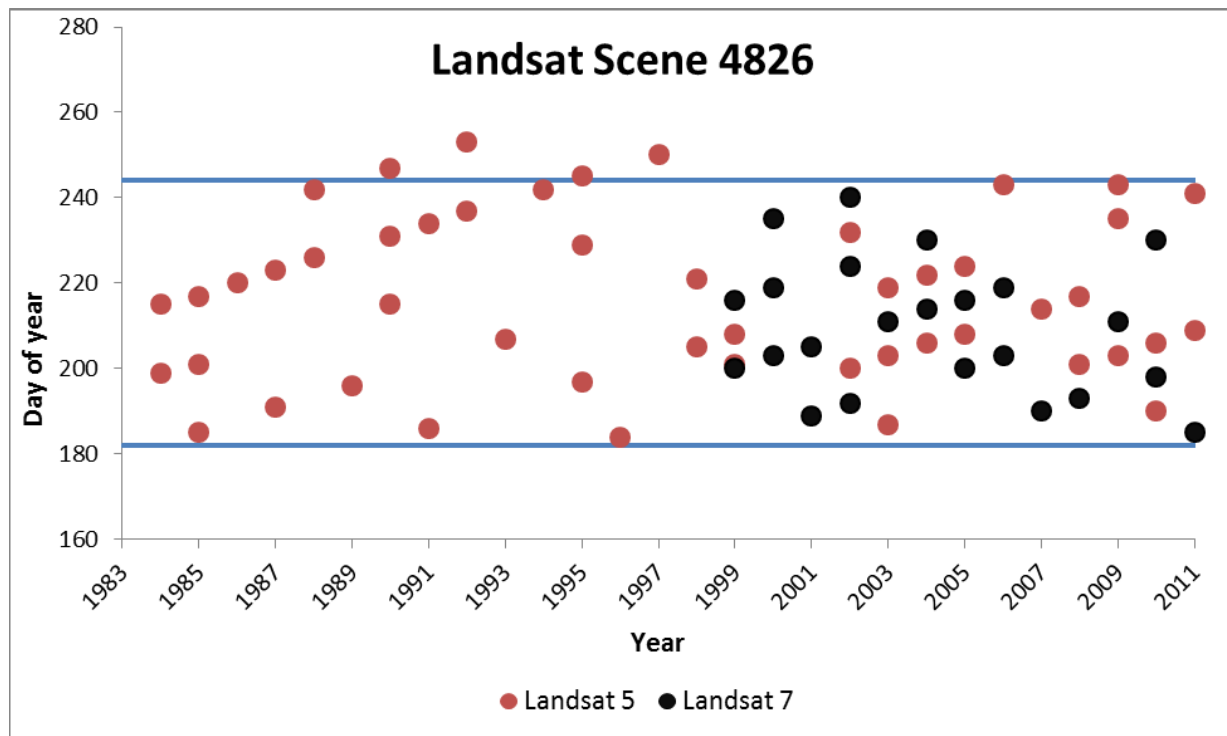


Figure 4b. Day and year of Landsat images used for analysis for the Landsat scene 4826, which covers the northwest corner of Olympic National Park, Washington. Blue lines denote the time period between July 1st and September 1st.

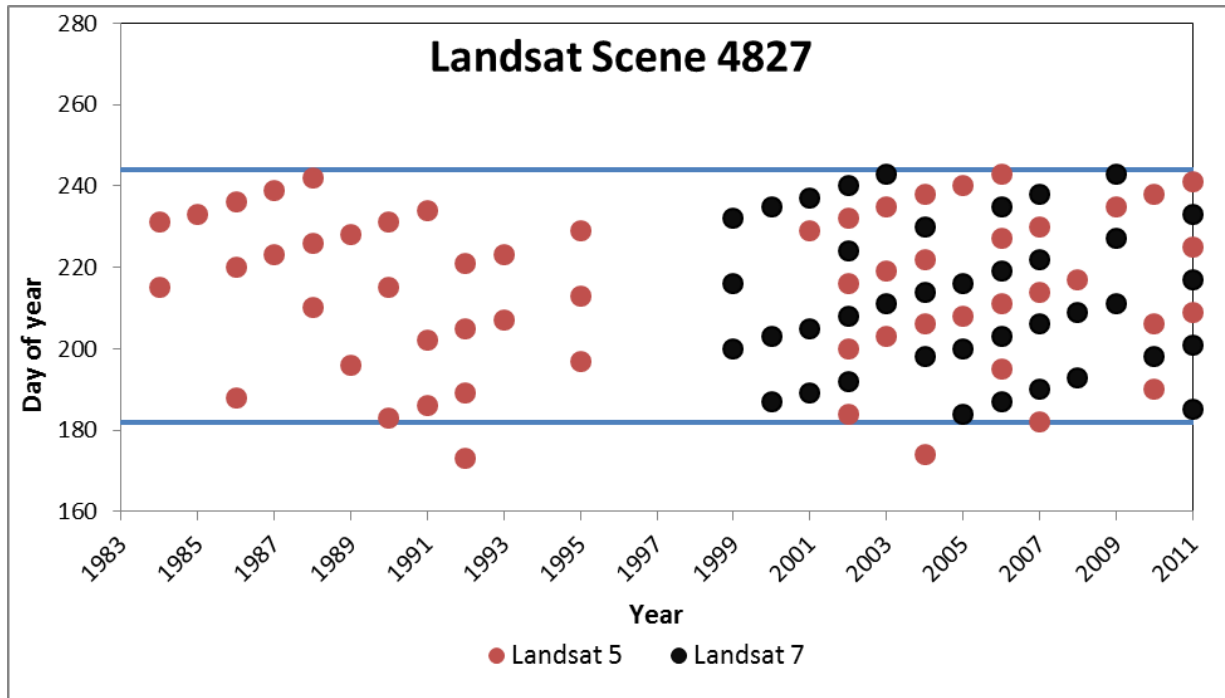


Figure 4c. Day and year of Landsat images used for analysis for the Landsat scene 4827, which covers the western edge of Olympic National Park, Washington. Blue lines denote the time period between July 1st and September 1st.

Next, statistical line-fitting techniques are used to create a smooth line tracking the spectral index of each pixel. The fitted line is separated into segments describing periods of stability or change. The primary outputs from LandTrendr are 30-meter resolution raster datasets with layers containing pixel-level data on the year of change onset, the duration of change expressed as the number of years, and the magnitude of the change expressed as percentage of vegetative cover that was removed by the event (Figure 5). For each pixel, only the year of the greatest disturbance within the time series is reported. For example, if a pixel is affected by repeated avalanches, the year of change onset would come from the event that removed the most vegetation, i.e. event with highest magnitude.

LandTrendr results only include pixels with magnitude > 10 , i.e. where more than 10% of the canopy cover has been removed (Kennedy et al., 2010). Changes with less than 10% of vegetative cover removed are indistinguishable from the background noise and therefore are considered “no-change.” This parameter has been optimized during LandTrendr development and was not modified for application to the LDMP.

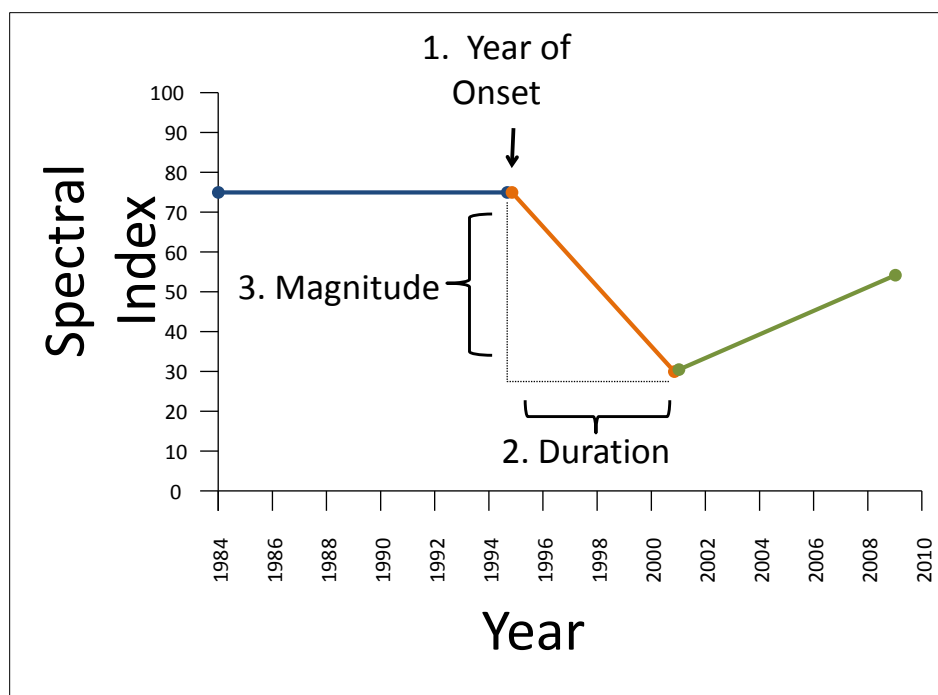


Figure 5. An idealized LandTrendr trajectory tracing a Landsat pixel through periods of stability, change and recovery. The period from 1984 to 1994 is a stable segment (blue line). A change event begins in 1994 (1) and lasts until 2001 (2), causing a drop of 45 spectral units (3). The change is followed by a recovery period from 2001 to 2010 (green line).

LandTrendr pixel outputs are grouped into patches based on the year the change began and the duration of change. For this protocol, the patches are first screened by duration, so that the first dataset only includes pixels that experienced rapid change occurring over a period of less than 4 years. These pixels are then grouped into patches in which a change event started or occurred in the same year. Patches must be nine-pixels (0.8 ha or 2 ac) or larger to be included in the monitoring dataset. Although using a nine-pixel patch size means that the results underestimate the total change within the study area, it was determined during protocol development that this minimum mapping unit (MMU) size was the smallest area that could still be accurately validated using the validation techniques described below. After the formation of patches, the data set is converted to vector format (polygons). A variety of attributes that describe each patch's shape, spectral characteristics and location on the landscape are extracted for each patch. A classification model is applied in order to attribute the patches with their change type (Table 1). Lastly, validation and accuracy assessment is performed.

Examples of landscape patches within the OLYM boundary that the NCCN LDMP detects and attributes are shown in Figure 6. These patches range from high intensity, large natural disturbances such as Fire and Riparian changes, to more subtle effects such as Progressive Defoliation in forested areas due to pathogens and insect infestations.



Figure 6. Examples of landscape changes documented from 1985 to 2010 within Olympic National Park boundaries, Washington. Photo credits: all NPS except Avalanche near Boulder shelter – J. Brew (Flickr).

Change Type Characteristics

A thorough description of the change types is provided in the LDMP (Antonova et al. 2012) and is summarized in Table 1. In this section, additional details are provided in order to facilitate interpretation of the results provided below.

Annual Variability

The Annual Variability category is used to categorize landscape changes caused by annual differences in cloud cover, sun angle, phenology, and soil moisture. Even though the LandTrendr algorithm includes procedures that minimize the inclusion of annual variations in the final dataset, we still found residual effects of these variations and labeled them explicitly. Because Annual

Variability category does capture change of interest to the NCCN, it is eliminated from the analysis and results. The spectral signatures of Annual Variability changes can be very different and an exhaustive sample is difficult to obtain for model development. The accuracy for this category is often lower and errors or omission are often distributed among all the very different change types.

Agriculture

The Agriculture category captures changes associated with annual agricultural activities, such as planting and harvesting of crops. Landscape change that has created new agricultural areas from previously forested or otherwise undisturbed areas are categorized as Development. The Agriculture category is shown on maps, but as with the Annual Variability category Agriculture is not included in the summary statistics because it represents interannual variability rather than lasting landscape change.

Fire

The Fire category includes both human-caused and natural events. Smaller and/or low intensity fires are often not captured in the change detection because they are too small or do not meet the spectral threshold. As for all other landscape change categories, results for Fire are reported using patches rather than events. First, individual fire events sometimes span days or weeks, and if the Landsat image used for the analysis is taken while the fire is in progress, the part of the fire which occurs after that date isn't captured until the following year, causing one event to be detected as two adjacent patches with different years. Second, because fires can vary in intensity over short distances, some burned pixels do not spectrally show the effects of fire until one or two years after the event, when the cumulative effect of the fire on the pixel exceeds the detection threshold. These two factors contribute to a single fire event often being represented by a large number of patches with different onset dates.

Mass Movement

The Mass Movement category includes landslides as well as debris flows and debris torrents. Debris flows or torrents are defined as fast moving, liquefied landslides of mixed and unconsolidated water and debris. For the purposes of the LDMP, if the mapped patch representing a debris flow or torrent had a calculated average slope of more than 15 degrees, it was included in the Mass Movement category. If the mapped patch had an average slope of less than 15 degrees and was located along the valley bottom, it was classed as Riparian. The 15 degree threshold is a modification of the 10 degree value used to define a Debris Torrent for the landform mapping project at MORA (Riedel and Dorsch 2016). After evaluation, the threshold was increased in order to accommodate the increase to the average for a patch contributed by parts of the often steeper valley walls included in the change polygons. The 15 degree threshold was used in the development of the sample for the Random Forests classification model (see below). Patches classified by the model as Mass Movements will not necessarily have an average slope of more than 15 degrees, as slope was not the only variable used in the classification.

Progressive Defoliation

The Progressive Defoliation category includes insect infestations, diseases, and losses in vegetation vigor due to drought or inundation. In general, these changes are long-term and progressive, i.e. the

declines happen over several years and spread incrementally to larger areas. This pattern of change presents challenges to detecting and mapping. To belong to the same patch, adjacent pixels must have the same year of onset. For this reason, the vegetation changes that are included in the Progressive Defoliation category only include pixels that changed rapidly (duration of less than 4 years) and were located adjacent to enough other pixels that changed in the same year to form a patch.

Riparian

Riparian disturbances are defined as patches along a river or stream on a valley bottom with an average patch slope of less than 15 degrees. These events are often linear and narrow and do not occupy the entire width of a Landsat pixel. Because changes in spectral characteristics are averaged over an entire pixel, if the average spectral change for a pixel does not meet the threshold of change, the pixel is not labeled as “changed.” In addition, many pixels in riparian zones that are designated as “changed” are removed from results during filtering because the size of patches do not meet the minimum mapping unit requirement.

Winter Ice

The Winter Ice category was developed specifically for the OLYM dataset to capture the effects of unique conditions in the winter of 1998-1999. The winter ice impacts were seen primarily in mid- to high-elevation forests, particularly on the east side of the Park. A heavy snowpack due to La Nina conditions (NRCS; NOAA), combined with variable temperatures added a considerable weight of snow and ice rime to the forest canopy. While the trees were heavily weighted by this thick casing of snow and ice, a wind event in early March 1999 blasted parts of the Park, causing widespread broken branches, broken tree boles and damaged trees which were detected in the imagery from 1999 to 2001.

Year of Onset

The “year of onset” assigned by the LandTrendr algorithms to individual patches can be delayed by a year or two from when the event actually happened. There are two reasons for this difference in timing. First, in some years, all or portions of the Landsat images are not useable due to cloud cover or topographic shadows. Second, the Landsat images for the analysis are prioritized by date closest to the middle of July in order to minimize snow cover and phenological variability and capture the greatest vegetation vigor. A number of landscape changes being monitored by NCCN occur in the winter months and are readily detected by the analysis when Landsat images from the following summer are examined. The detected change is then assigned the year of onset that corresponds to the year of the following summer. For example, change that occurred in a storm event of November 2007 is assigned a 2008 date. This can also occur for summer events which occur after July, as is usually the case with fires.

Random Forests Classification

The protocol uses Random Forests (RF) to classify the patches by their change types. RF is an ensemble classification method that expands the relatively simple concept of classification and regression trees. The RF classification produces many regression trees. To produce each tree, RF first

takes a random subset of the training data. As RF creates each tree, it uses a random subset of two thirds of the predictor variables for each split or decision node. The outcome is a single prediction - the tree which occurs with the most frequency represents the best classification model. Data are held in reserve to test the accuracy of the classification. This provides a statistical assessment of how well RF can predict the training data used in the modeling process, and is one view of the accuracy of the classification approach.

A training dataset of 714 patches was used to generate a RF classification model based on methods described in Kennedy et al. (2015). The model was then applied to the entire study area to assign each patch one of the landscape change types listed in Table 1 (or Agriculture and Annual Variability categories).

Validation

Validation is the process of determining how well the change detection method captures and labels landscape changes of interest to the NCCN. Underpinning the NCCN LDMP are two layers of validation (Figure 7). The first layer is pixel-based overall validation of the LandTrendr method and its ability to detect and map change. This method of validation has been performed and documented by LARSE (Cohen et al. 2010). The second layer is patch-based validation of the change category labels assigned to change patches by the Random Forests classification model.

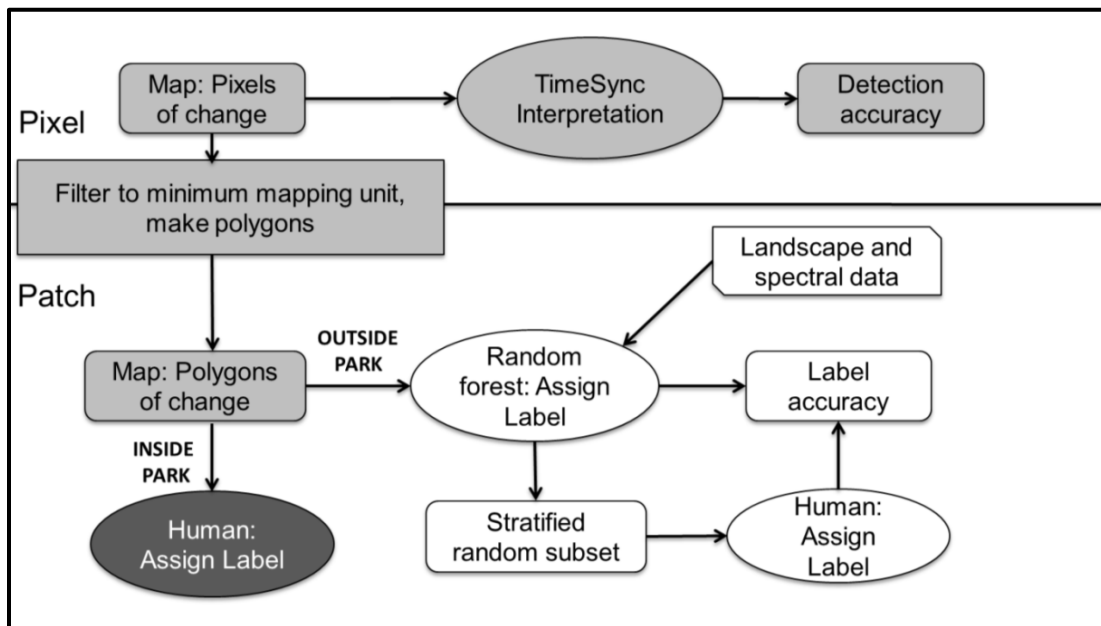


Figure 7. Steps in the validation process.

We assessed the classification accuracy of all 2069 patches located inside the park boundary and a randomly selected subset of 2379 patches outside the park boundary, representing approximately 10% of patches in this category. We performed validation in the office using multi-date aerial photography available from Google Earth in conjunction with the TimeSync application. TimeSync, developed by LARSE, displays trajectories of groups of pixels through time using one of the spectral

indices most sensitive to changes in vegetative cover. TimeSync also facilitates viewing of both the spectral trajectory of a target pixel and thumbnails of the Landsat imagery through the time series. Table 4 indicates the date and source of the most widespread imagery available in Google Earth for validation inside the OLYM study area. In addition to these, several other imagery sources were used, mostly in Port Angeles and Sequim areas.

Table 4. Google Earth primary image sources for validation of change. Most imagery is 1-meter resolution, except 2013 imagery and imagery covering urban areas, which are higher resolution. 1990 through 1994 and 2000 images are in black and white and the other dates are color imagery.

Date	Coverage	Image Source
1990-1994	Full	National Aeronautics Space Administration/ United States Geological Survey
Summer 2006	Full	United States Department of Agriculture – Farm Service Agency
Summer 2009	Full	United States Department of Agriculture – Farm Service Agency
Summer 2011	Full	United States Department of Agriculture – Farm Service Agency
Summer 2013	Full	United States Department of Agriculture – Farm Service Agency
2000-2015	Partial	City of Port Angeles, Digital Globe, United States Geological Survey

We compared the labels generated during the office validation to the labels generated by the RF model and calculated the overall classification accuracy, class error rates from both a user's and producer's perspective, and the Kappa statistic. User's accuracy is the probability that a patch classified into a given category actually represents that category on the ground and represents errors of commission. Producers' accuracy indicates how well training set patches of a given landscape change agent are classified and represents errors of omission. Users' accuracies are important to users going to a particular mapped location for a particular reason. Producers' accuracies estimate the true areas of types that may have been missed in mapping and could be important to people interested in the true area a type occupies.

Following the validation of randomly selected patches, we validated an additional 6381 patches outside the park boundary in all categories other than Clearing. All Clearing patches were examined visually using time series of aerial photos in Google Earth overlaid by a 4x4 km grid. Patches were relabeled if RF model prediction was found to be incorrect. Auxiliary data were used to validate Fire patches inside and outside the park boundary (LANDFIRE 2010, NPS 2013).

For this analysis we assume that the analyst performing the office validation is always correct, but in reality the analyst makes subjective choices that are at times based on different parameters than what the computer algorithm uses. For example, a large patch in which the trees are thinned and a small vacation trailer is erected is very likely to be labeled Clearing by the RF model because the trailer is too small to be detected by the algorithm. It will be labeled Development by the office validation.

Field-based validation was not performed for 1985-2010 OLYM analysis because we found office-based validation to be a more accurate method for validating legacy data (Antonova et al. 2011). First, office validation using TimeSync allowed the spectral characteristics associated with change to

be assessed quickly alongside the aerial photo view, and 2) for changes older than about 4 years, recovery processes often mask the agent of disturbance. In contrast, the time series of aerial photos accessible through Google Earth's "time" toolbar allowed one to view the patch as it appeared closer to the time of original change. This was particularly helpful for landscape changes which occurred prior to about the year 2000. Validation methods in the next implementation time step will include field visits to a stratified random subset of patches, and will supplement the office validation.

Results

A total of 24,739 patches were mapped within the OLYM study area. Of these patches, 1,695 (6.9%) and 456 (1.8%) were classified as Annual Variability and Agriculture respectively. These patches were excluded from the summaries below.

Total Area Affected by Landscape Change

Approximately 159,619 ha (13.9%) of the study area underwent detectable change at some point during the 26 year period of analysis. Landscape change affected about 1% of OLYM and about 20.1% of the study area outside the Park boundary. The annual average area affected by landscape change outside the Park boundary was $6,001 \pm 1,752$ ha. Within the Park boundary, the annual average area that underwent change was about 138 ± 221 ha. The rate of landscape change on an annual basis was $0.02\% \pm 0.03\%$ in the Park and $1.63\% \pm 0.48\%$ outside the Park boundary.

Timing of Landscape Change

The inter-annual variability in the total area that experienced landscape change was considerable and differed between inside and outside the park boundary (Figure 8). Within the OLYM boundary, 2008 was the year with the greatest change detected (1,024 ha). The second greatest year of change within the Park was 1999 with 537 ha (Figure 8a). Outside the park, the greatest amount of change outside the Park boundary was documented in 1988, when 9,369 ha were disturbed. This total was nearly repeated in 2006, when 9,221 ha changed. The year with smallest change was 1998, with 2,846 ha affected (Figure 8b).

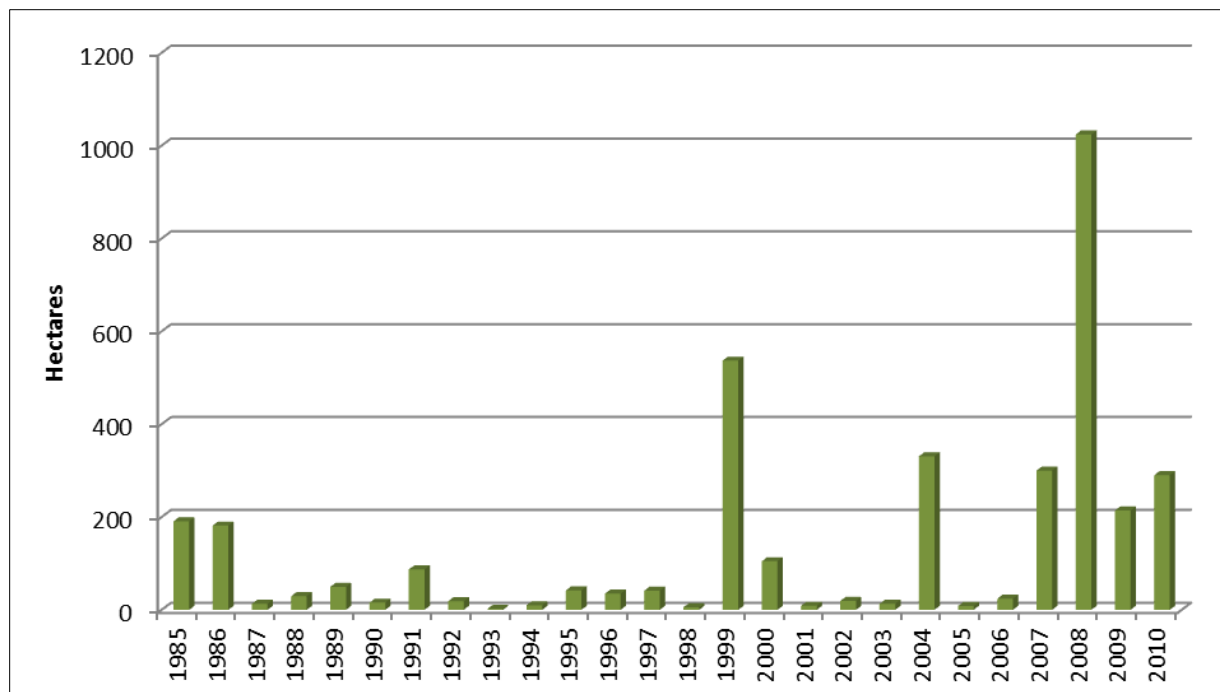


Figure 8a. Total area disturbed by year within Olympic National Park, Washington. Changes labeled as Annual Variability or as Agriculture are not included.

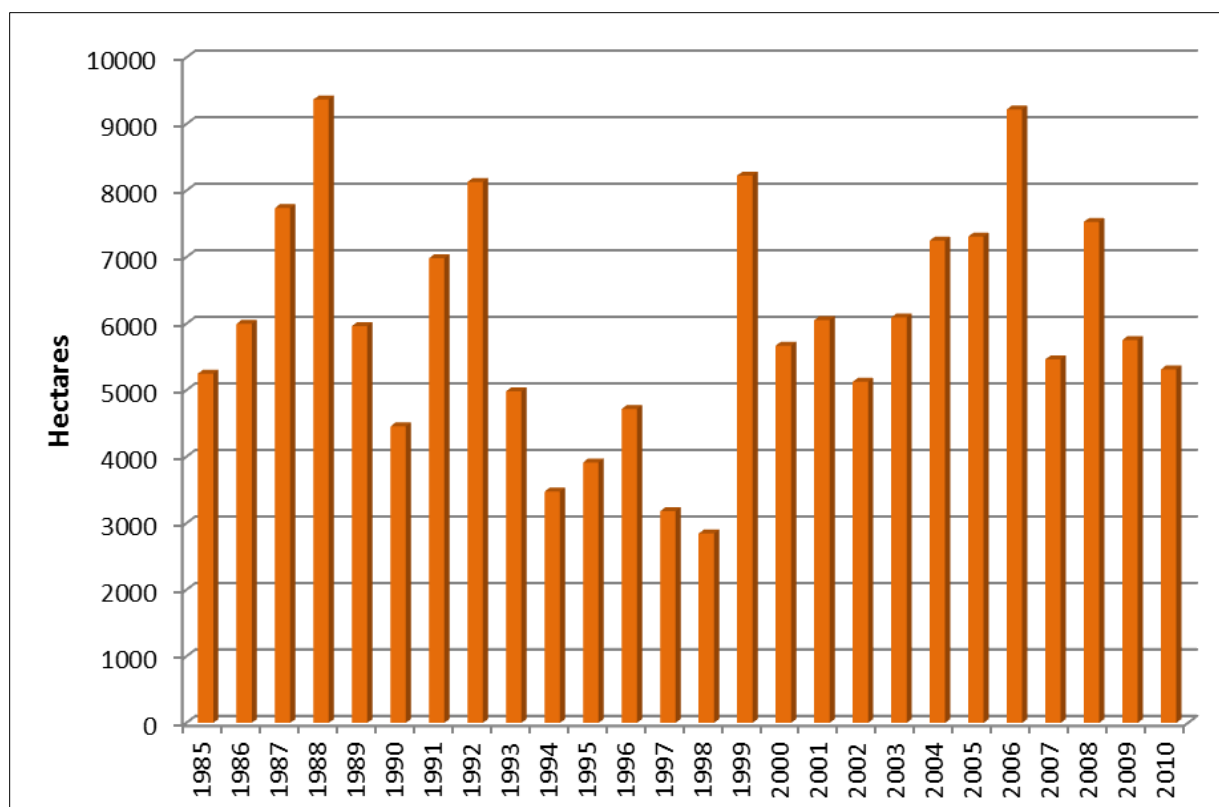


Figure 8b. Total area disturbed by year outside Olympic National Park, Washington. Changes labeled as Annual Variability or as Agriculture are not included.

A map of the year of the onset of change shows the distribution within the time series of disturbances across the study area (Figure 9). Clearing was widespread in earlier years outside of the park, but in later years was less likely to be found close to the park boundary. With a few notable exceptions, larger, more recent disturbances of multiple types were generally found away from the park boundary. Inside the Park boundary, with the exception of the 1985 Beaver Fire, most larger changes also occurred in more recent years.

Distribution of Landscape Change by Type

Within the entire study area, Clearing contributed the greatest amount to the total change detected over the last 26 years (Table 5). Tree Toppling and Development were the second and third largest categories of change, significantly trailing behind Clearing in the amount of area affected. Inside OLYM, Fire was the predominant type of landscape change, closely followed by Tree Toppling. Avalanches and Riparian changes were the third and fourth largest categories, and affected about half of the area of Fire and Tree Toppling (Table 5).

A map of landscape change by type (Figure 10) shows the extent to which Clearing dominated the change within the study area over the last 26 years. The Clearing landscape type rings the park and was most prominent on WA State DNR and All Other land categories, including private commercial timberland, when compared with USFS. Most other change categories are spatially segregated within

the study area. Landscape change due to Development occurred in the greater Sequim area, and to a lesser extent along the Highway 101 corridor and near the city of Forks (Figures 3 and 10).

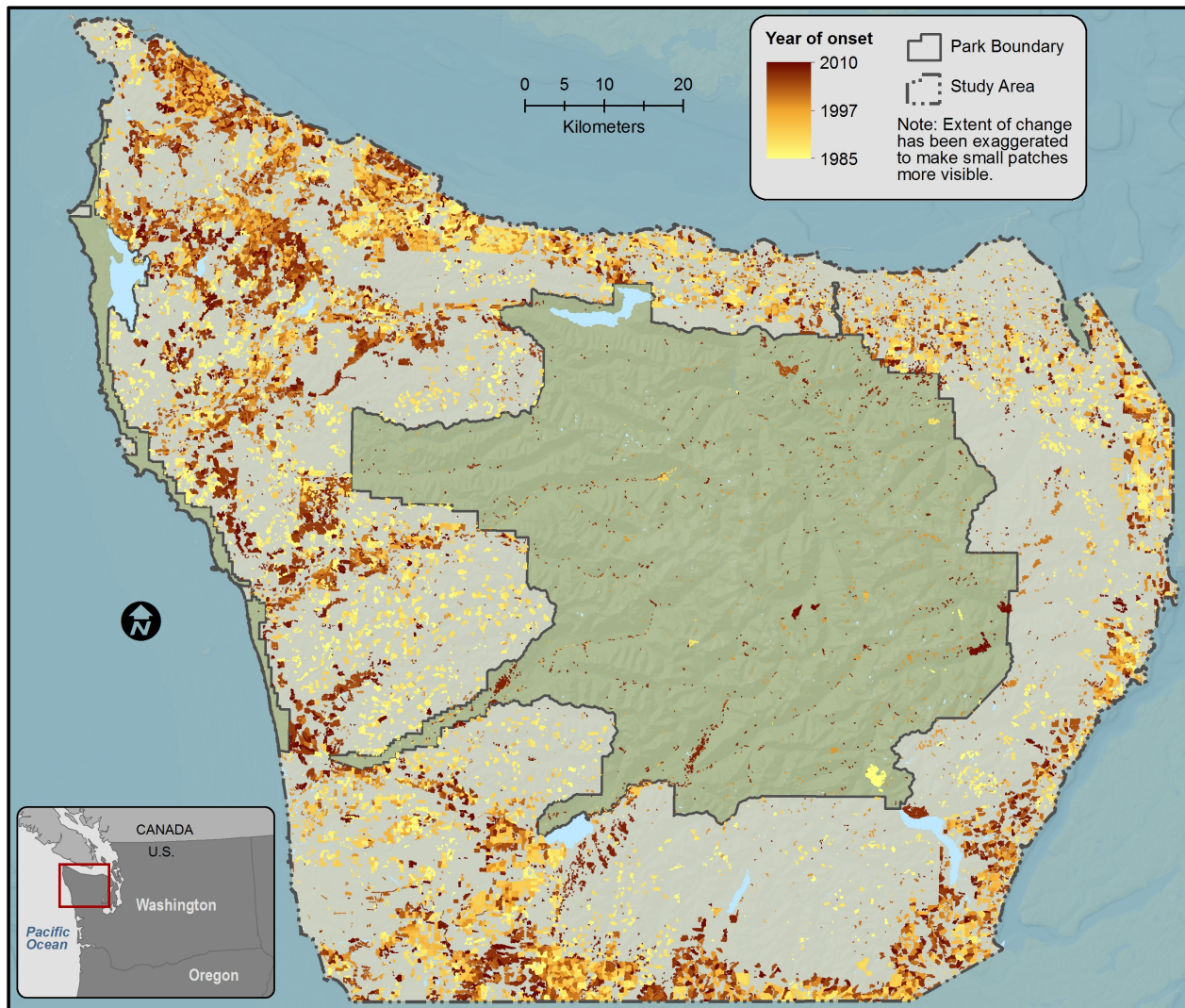


Figure 9. Map of landscape changes from 1985 to 2010 by year of onset, Olympic National Park study area, Washington. Agricultural category is not included.

Table 5. Area (in ha) affected by each disturbance type within the study area and inside and outside the Olympic National Park (OLYM), Washington, boundary from 1985 to 2010. Agriculture class is not included.

Type	Study Area	% Study Area	Inside OLYM	% OLYM	Outside OLYM	% Outside OLYM
Avalanche	713.88	0.06	581.85	0.16	132.03	0.02
Clearing	150327.03	13.12	0.81	0.00	150326.22	19.33
Development	2463.20	0.21	0.99	0.00	2462.21	0.32
Fire	1371.78	0.12	1019.16	0.28	341.46	0.04
Mass Movement	341.19	0.03	160.47	0.04	190.35	0.02
Progressive Defoliation	381.51	0.03	238.05	0.06	142.65	0.02
Riparian	878.04	0.08	430.38	0.12	438.84	0.06
Tree Toppling	2531.16	0.22	958.95	0.26	1572.21	0.20
Winter Ice	622.62	0.05	202.32	0.05	420.30	0.05
Grand Total	159630.40	13.93	3592.98	0.97	156026.26	20.06

The distribution of Tree Toppling trends strongly from the southwest to the northeast, tracking the orientation of the storms from the southwest (Read 2015). Changes due to Fire, Progressive Defoliation and Winter Ice occurred primarily on the east side of the study area. Riparian changes followed the large river corridors of the west side drainages, and are not detected along the steeper gradient rivers on the east side of the study area. The Park's wilderness coastal strip is notable for the lack of disturbance, a surprising result given the potential vulnerability of this near-coastal landscape to the impact of storms from the Pacific. It is possible that the MMU for this protocol was too small to detect any bluff erosion or landslides occurring in this zone.

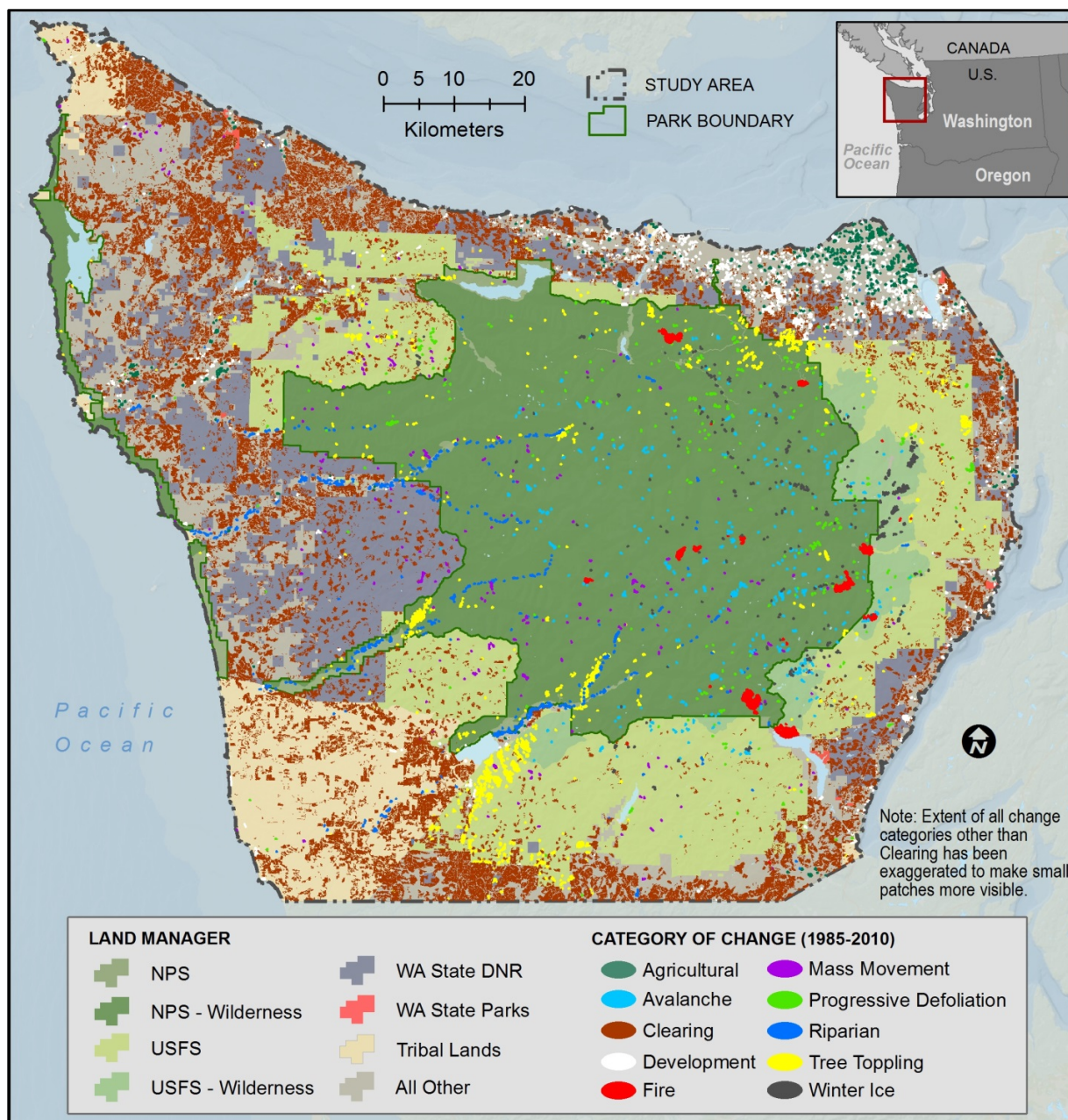


Figure 10. Map of landscape changes from 1985 to 2010 by change type and land management type within the Olympic National Park study area, Washington.

Trends in Landscape Change Types

Clearing was the dominated landscape change type outside the Park boundary from 1985 to 2010, and shows a varying pattern with highest levels in 1988 and 2006 (Figure 11a). Development shows a pattern similar to Clearing with high levels in the mid-1990s, 2000 and 2006 (Figure 11b). The contribution of Progressive Defoliation to total landscape change outside the park has increased in recent years, particularly during the early 2000s with a notable spike in 2008. Avalanche activity showed a spike in 1999 but is generally not detected consistently outside the park due to the mountainous terrain occurring largely within the park. Large fires were uncommon in most land

management categories, the notable exception being the 2007 Bear Gulch 2 fire in USFS land in the southeast corner of the study area. Riparian changes showed much higher than average values in 2004, 2007 and 2008. Mass Movement, Progressive Defoliation and Riparian change occur in more years and affect more of the landscape starting in in 1999-2010 as compared to 1985-1998.

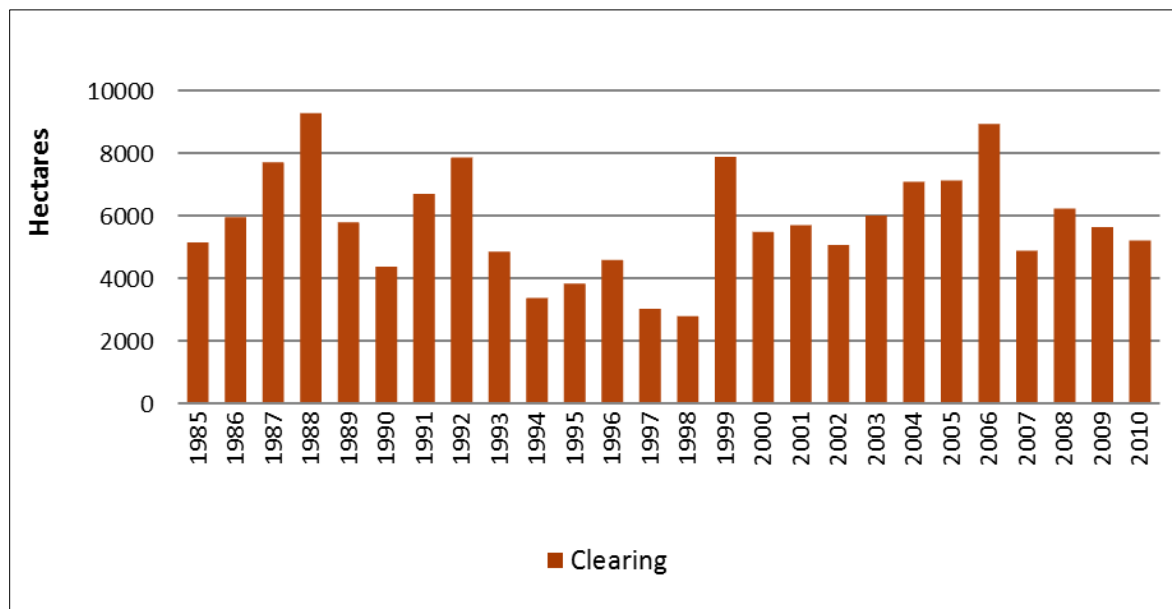


Figure 11a. Area in the Clearing landscape type outside the Olympic National Park boundary, Washington.

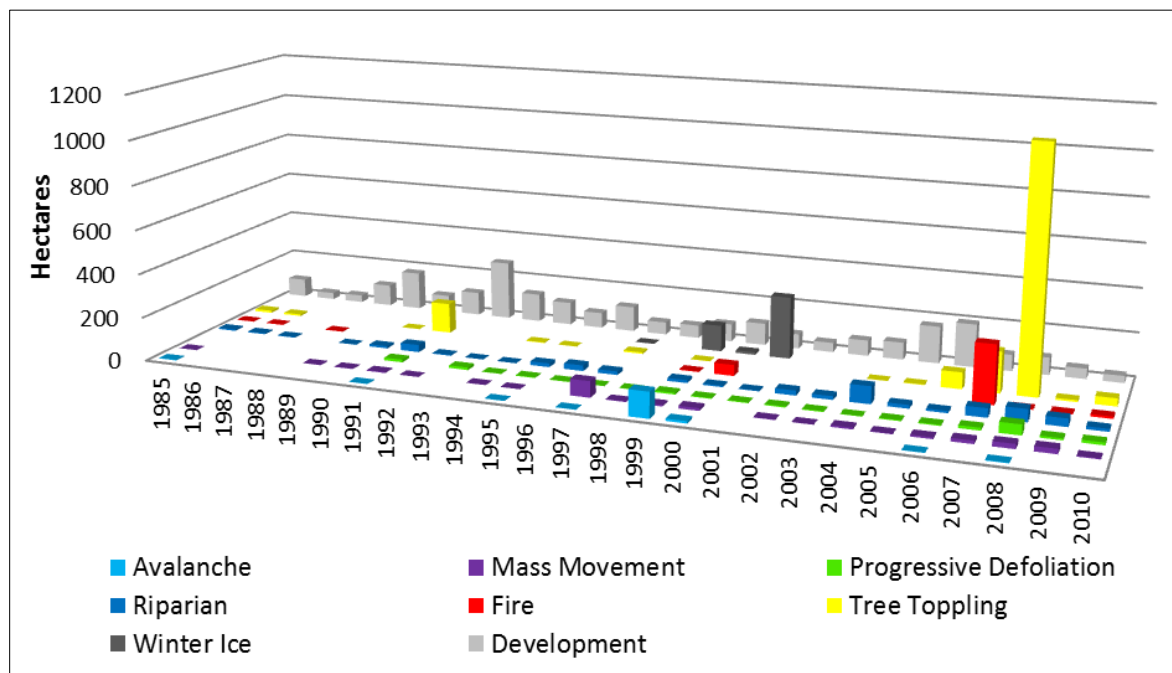


Figure 11b. Area disturbed by all change categories except Clearing outside the Olympic National Park boundary, Washington.

Within the Park, Avalanche, Tree Toppling, Fire and Riparian categories contributed the majority of the disturbed area in the years with above-average hectares changed (Figure 12). Notable fires within the time series included the Beaver Fire in 1985, the Griff Fire in 2004, the Buckinghorse, Heatwave Complex and Constance Fires in 2009 and the Hopper fire in 2010. The winter of 1999, which featured greater than average snowfall (NRCS), showed a significant spike in the area affected by Avalanches.

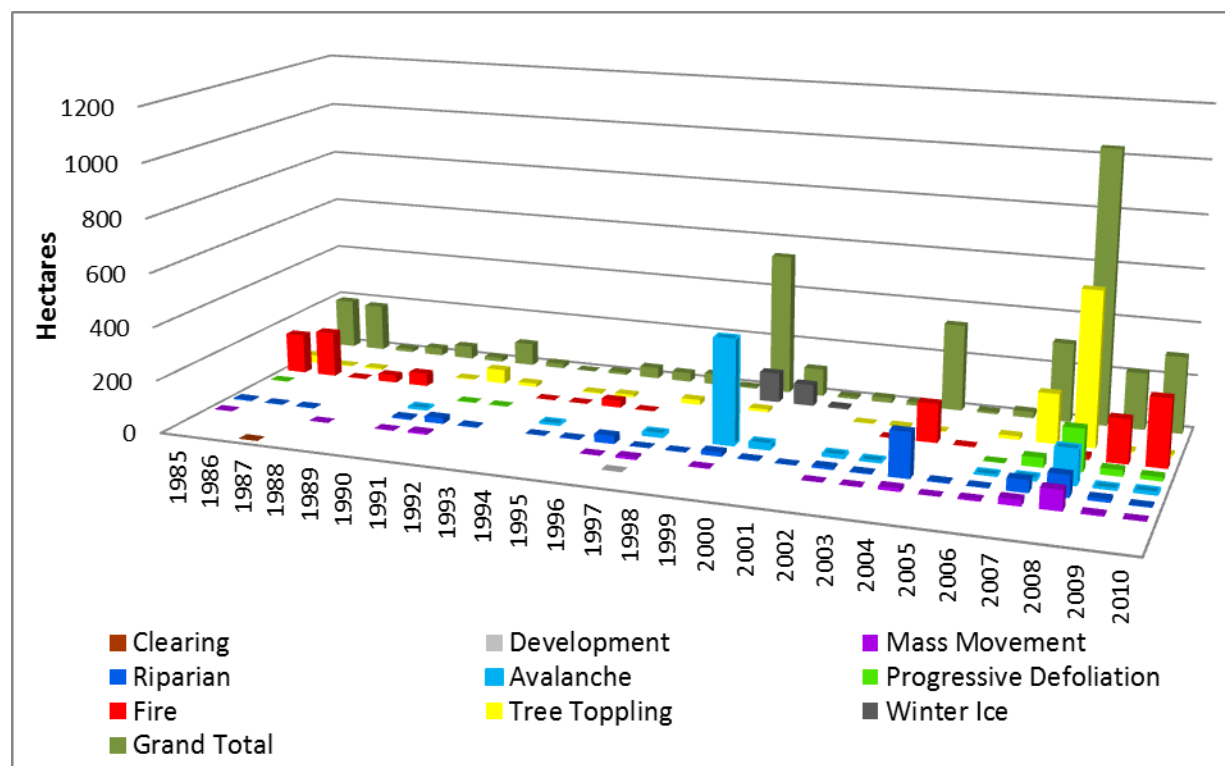


Figure 12. Time series of area disturbed by change category within the Olympic National Park boundary, Washington.

Characteristics of Landscape Changes

Number of Patches

The number of landscape change patches occurring in the study area is presented in Table 6. We detected 18,743 patches in the Clearing category within the study area, which had by far the largest number of patches. Development, with 1,102 patches, was the second highest category within the study area, followed by Tree Toppling with 811 patches and Riparian with 590 patches.

Within the Park boundary, Tree Toppling was the most frequently occurring category with 333 patches detected between 1985 and 2010. Avalanche with 293 patches and Riparian with 288 were the second and third most frequent categories. More patches were detected inside the Park boundary than outside in the Avalanche, Fire, Progressive Defoliation and Winter Ice categories. The Mass Movement category had the lowest number of patches in the Park.

Table 6. The number of patches¹ and percent of total contributed by each landscape change type inside and outside the Olympic National Park boundary, Washington from 1985 to 2010.

Type	Outside	% Outside	Inside	% Inside	Study Area	% Study Area
Avalanche	81	0.4	293	19.4	374	1.7
Clearing	18742	88.9	1	0.1	18743	83.0
Development	1101	5.2	1	0.1	1102	4.9
Fire	24	0.1	112	7.4	136	0.6
Mass Movement	124	0.6	106	7.0	230	1.0
Progressive Defoliation	106	0.5	206	13.7	312	1.4
Riparian	302	1.4	288	19.1	590	2.6
Tree Toppling	478	2.3	333	22.1	811	3.6
Winter Ice	125	0.6	164	10.9	289	1.3
Grand Total	21083		1504		22587	

¹ A single patch does not necessarily represent a single event. For example, 112 Fire patches inside the park boundary comprise about 13 individual fires.

The number of patches detected annually within the study area is shown in Figure 13. The year with the greatest number of patches was 2008, mostly consisting of Tree Toppling (Figure 13a). The next largest year was 1999 with the Winter Ice category contributing the largest number of patches. Riparian patches were most prevalent in 2004, with smaller contribution to the total numbers in 2007, 2008 and 2009. In general, patches within Riparian, and Progressive Defoliation categories occurred regularly, whereas patches within categories that can be caused by extreme weather events such as Avalanche and Tree Toppling tended to occur intermittently.

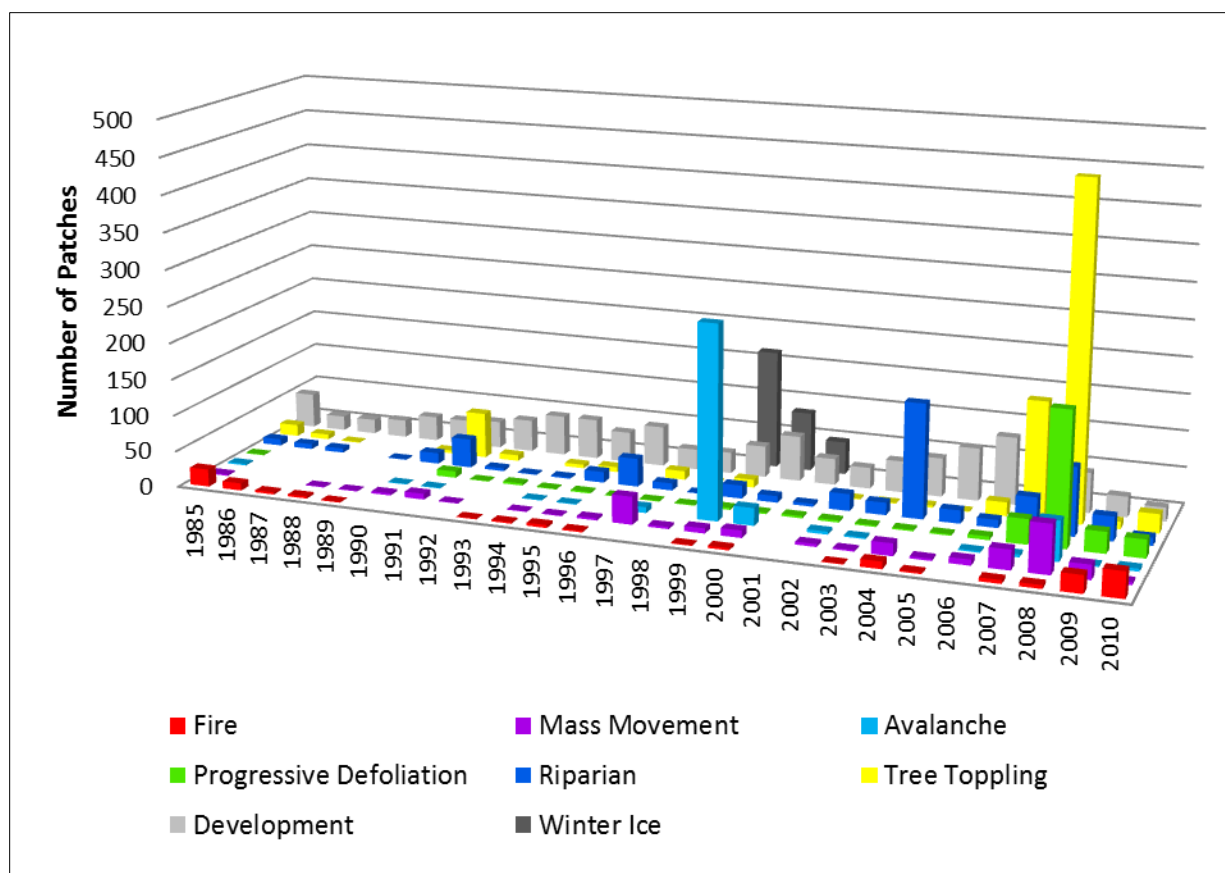


Figure 13a. Number of landscape change patches detected for all change categories except Clearing within the Olympic National Park study area, Washington.

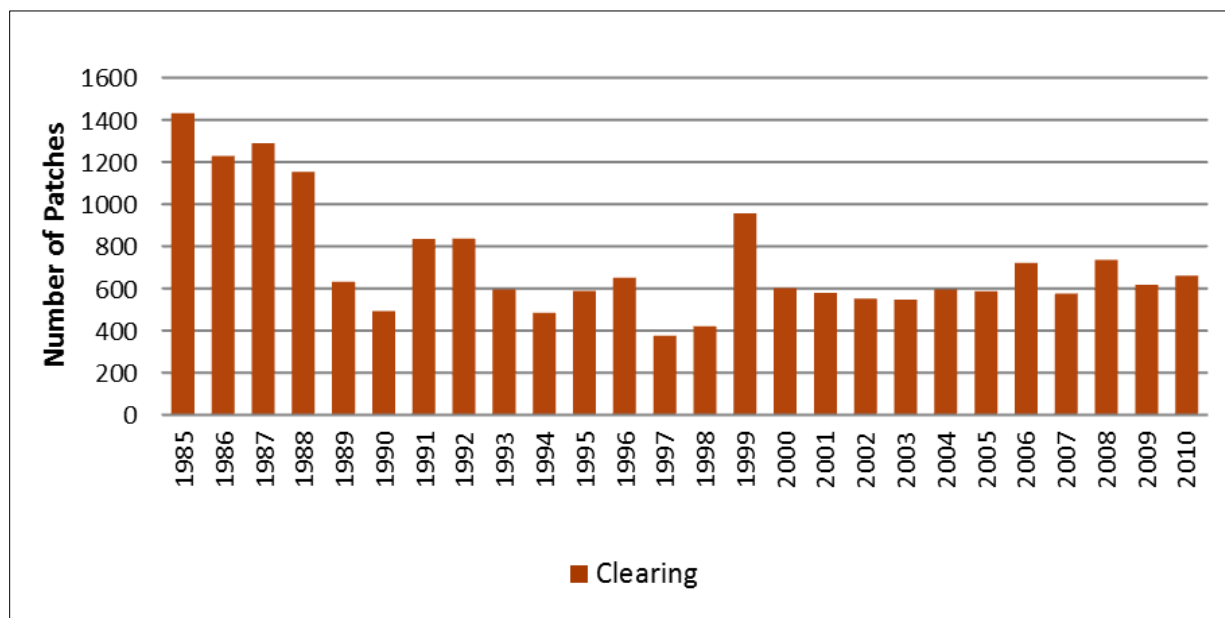


Figure 13b. Number of landscape change patches detected in the Clearing landscape type category within the Olympic National Park study area, Washington.

Figure 13b shows changes in the number of patches associated with Clearing in the study area between 1985 and 2010. The period between 1985 and 1988 shows twice as many annual patches as later years except for a spike in 1999. The 1999 spike is in part due to missing 1996-1998 imagery for Landsat scene 4827, which results in that scene's landscape changes for the entire 1996-1999 time period being assigned the 1999 label.

Size and Magnitude of Landscape Changes

The median patch size detected was relatively small, 0.99 ha. All categories except Clearing and Fire had a median size of less than 1.5 ha (Table 7, Figure 14). The Clearing category had the largest median patch size of 2.79 ha, followed by Fire with median patch size of 1.7 ha. The Fire category had the largest variance in patch size; Mass Movement and Riparian categories had the smallest. All landscape change categories except Avalanche had a large number of outliers with numerous patches being significantly larger than the median size.

Table 7. Patch size characteristics of different landscape change types from 1985 to 2010 within the Olympic National Park study area, Washington.

Type	Patch size (ha)		
	Mean	Median	Variance
Avalanche	1.91	1.26	4.08
Clearing	8.02	2.79	172.49
Development	2.24	1.35	20.18
Fire	10.00	1.62	647.83
Mass Movement	1.53	1.08	1.70
Progressive Defoliation	1.22	0.99	0.45
Riparian	1.47	1.17	1.14
Tree Toppling	3.12	1.44	60.91
Winter Ice	2.15	1.08	29.74

We examined each of the largest patches outside the Park boundary in the Mass Movement, Riparian, and Tree Toppling categories. The largest Mass Movement patch was 10 ha in size and was called the Falls Creek Landslide, located in the Quinault adjacent to the south shore road. The next two Mass Movements were from one event - the Grouse Creek Landslide in the Clearwater. Both of these large Mass Movements occurred in 1997. The largest Riparian change patch, just over 15 ha, occurred in 2004 in the Quinault just above the confluence of the West Fork Quinault and Rustler Creek. The second largest contiguous Riparian patch occurred in the Hoh in 2007 along a large oxbow outside the park. A 132 ha Tree Toppling patch in the Queets from 2004 and 82 ha Tree Toppling patch in the Quinault.

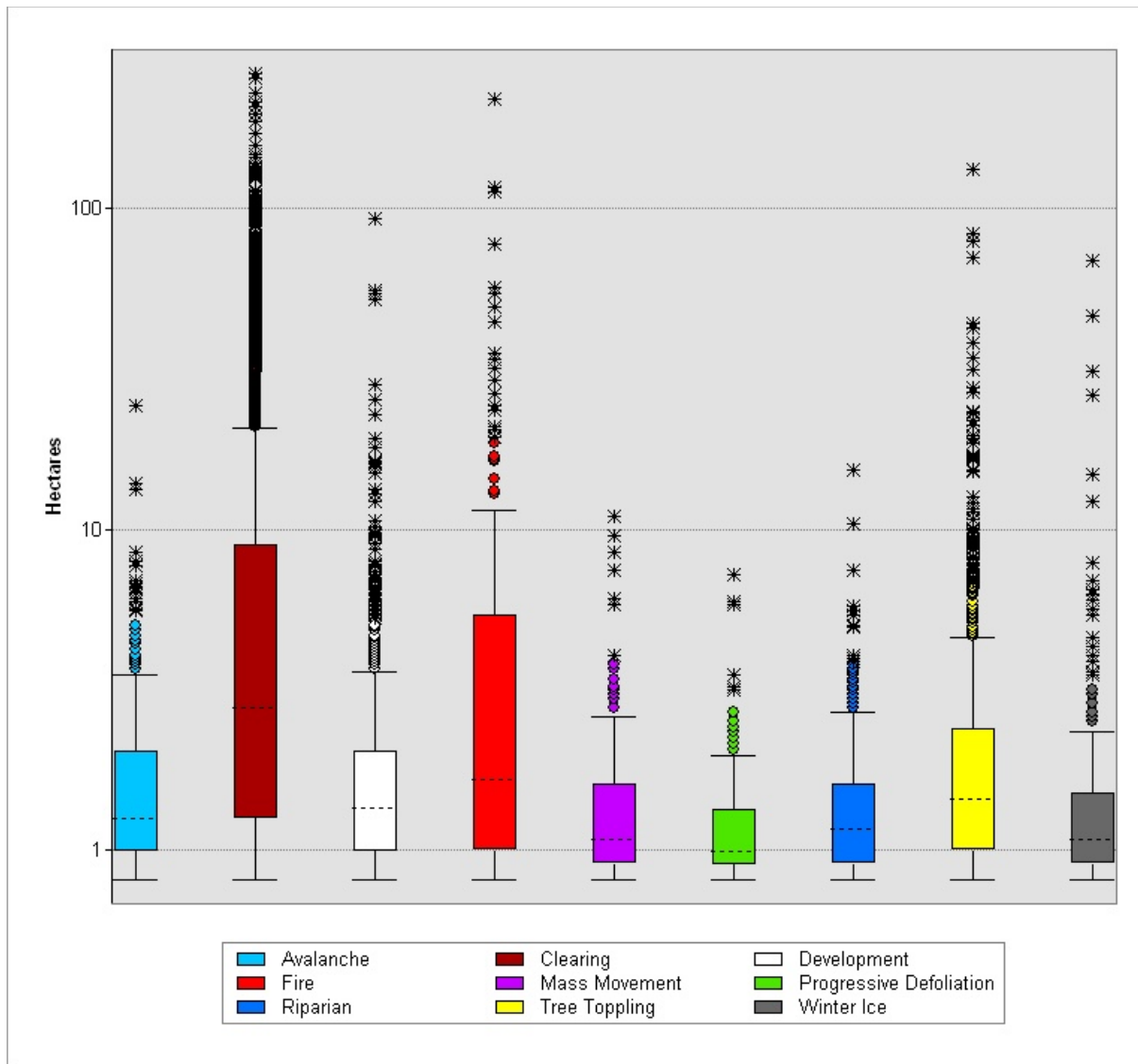


Figure 14. Patch size by change category within the Olympic National Park study area, Washington. Dashed lines represent median, boxes represent quartiles (middle 50% of data points), whiskers are 1.5 interquartile range (1.5 times the box length). Circles represent “mild” outliers that occur between 1.5 and 3 times the box length. Stars represent “extreme” outliers that occur beyond 3 times the box length.

A map of the magnitude of disturbance, which reflects the percent of the total vegetative cover removed, is shown in Figure 15. Landscape change across the study area varied significantly by change type. The majority of high magnitude patches were Clearing outside the park boundary. Clearing and Riparian categories had the highest median magnitudes above 55%, closely followed by Development and Fire, which had median magnitudes around 50% (Figure 16). Figure 17 shows the relationship between patch size and magnitude. Clearing and Fire are the change types that are both the largest and most severe with average percent canopy removed for all patches above 50%. Of the smaller patches, Riparian and Development also have averages above 50%. The lowest average magnitudes were found in the Tree Toppling and Progressive Defoliation categories.

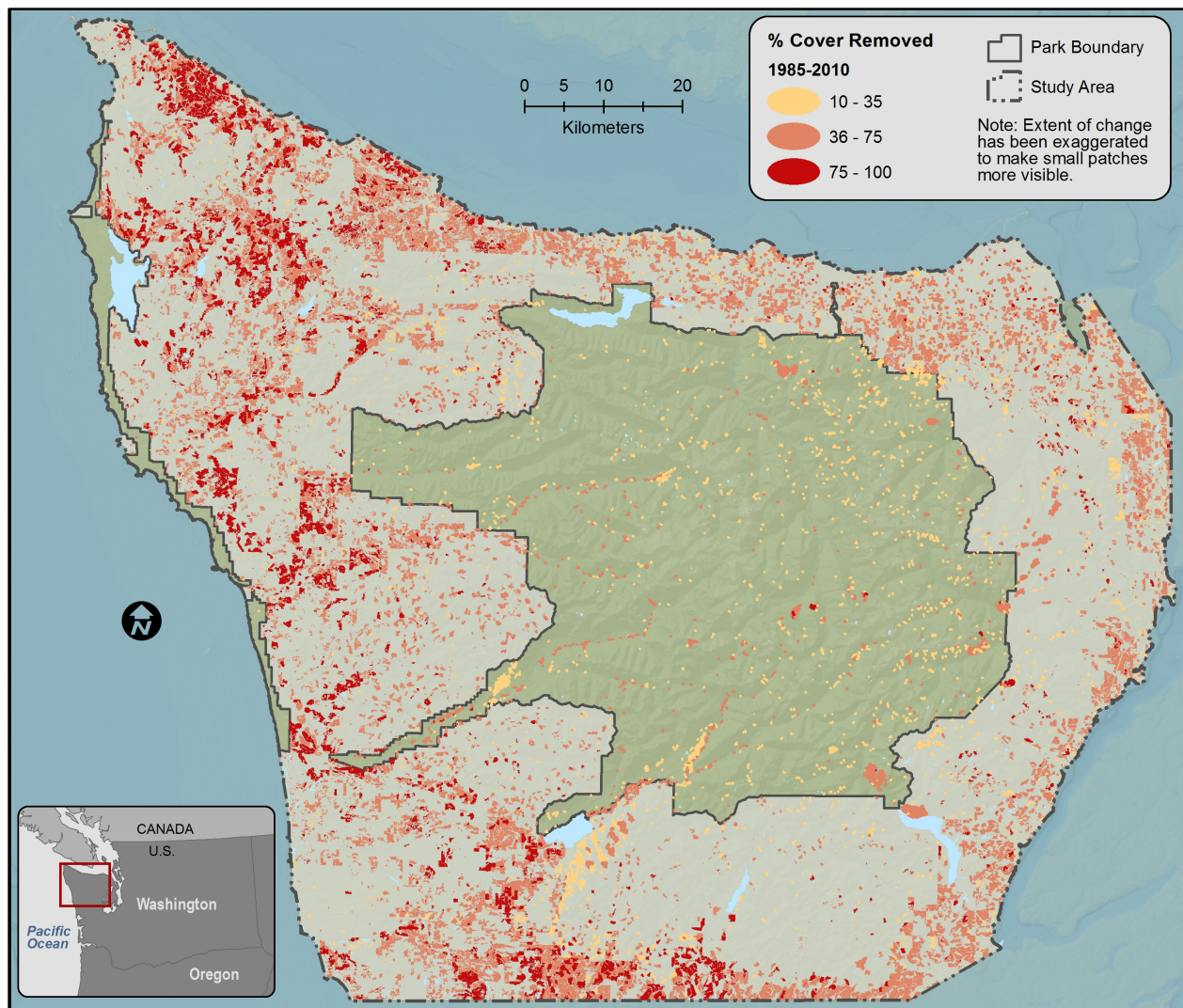


Figure 15. Map of landscape changes from 1985 to 2010 by magnitude (% vegetation cover removed) within the Olympic National Park study area, Washington. Agricultural category not included.

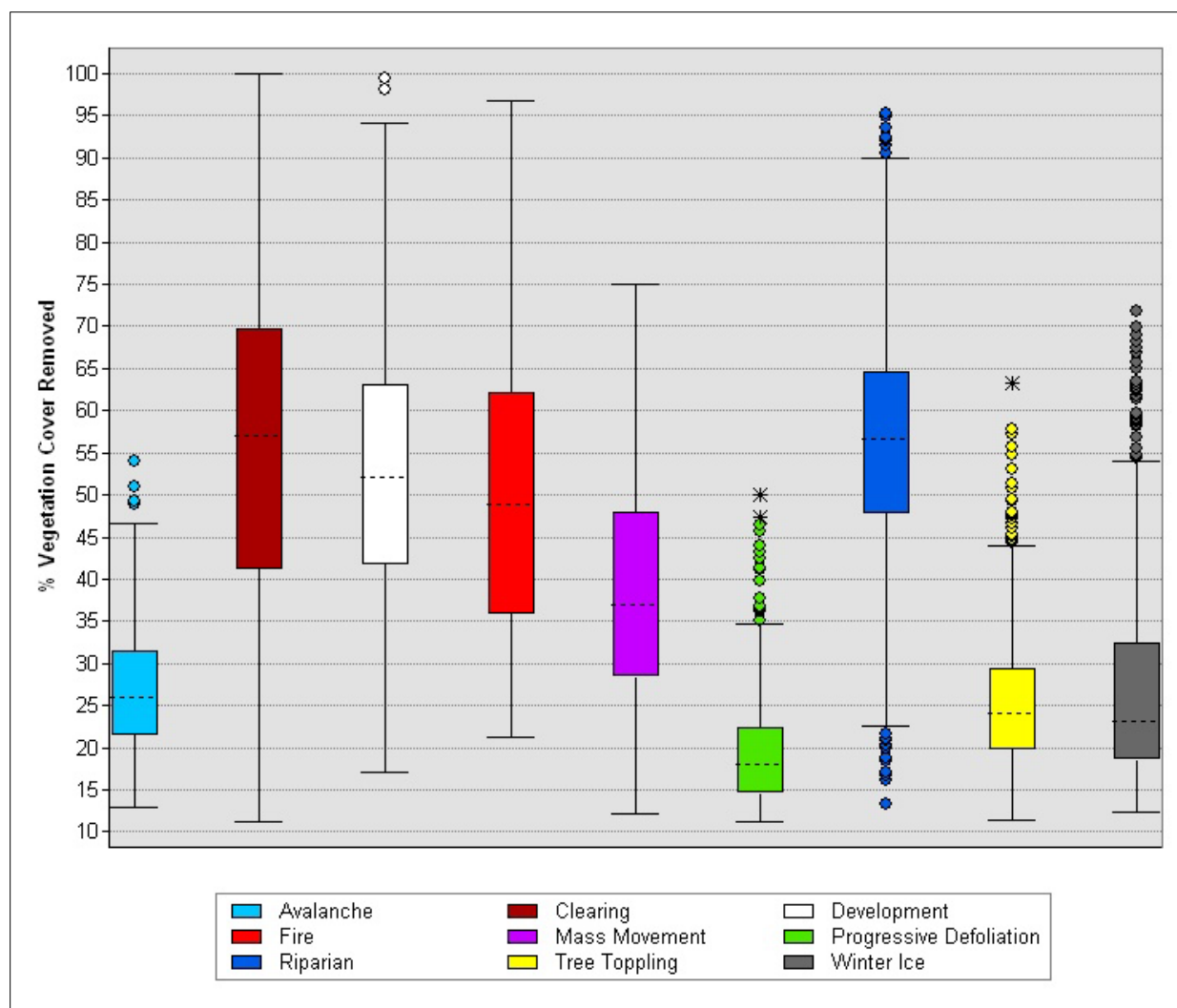


Figure 16. Magnitude (% vegetation cover removed within patch) by change category within the Olympic National Park study area, Washington. Dashed lines represent median, boxes represent quartiles (middle 50% of data points), whiskers are 1.5 interquartile range (1.5 times the box length). Circles represent "mild" outliers that occur between 1.5 and 3 times the box length. Stars represent "extreme" outliers that occur beyond 3 times the box length.

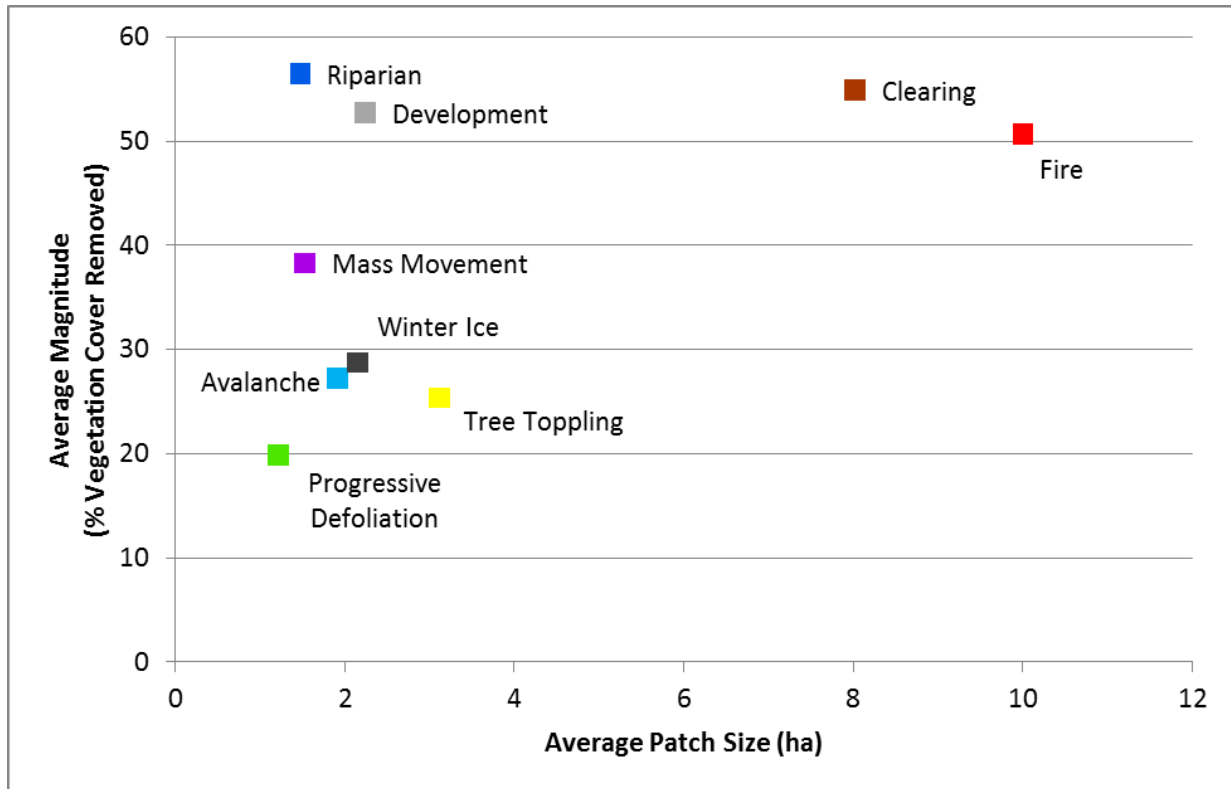


Figure 17. The relationship between average magnitude (% vegetation cover removed) and average patch size by agent type within the Olympic National Park study area, Washington.

Other Landscape Factors: Elevation and Slope

Most landscape change types inside the Park span a large range of elevations (Figure 18). Winter Ice and Riparian have a narrower distribution of median elevation values than the other types. Winter ice patches are found around elevation of 1,500 m. Riparian patches are found at a median elevation of 160 m. Tree Toppling and Mass Movements are generally low elevation phenomena. Avalanche, Fires and Progressive Defoliation found at mean elevations above 1000 m.

With the exception of Riparian and Tree Toppling patches, the change types within the Park are generally found at a median slope of 30, with slopes varying from around 5 degrees to as high as 55 degrees for Avalanche, Fire and Progressive Defoliation (Figure 19).

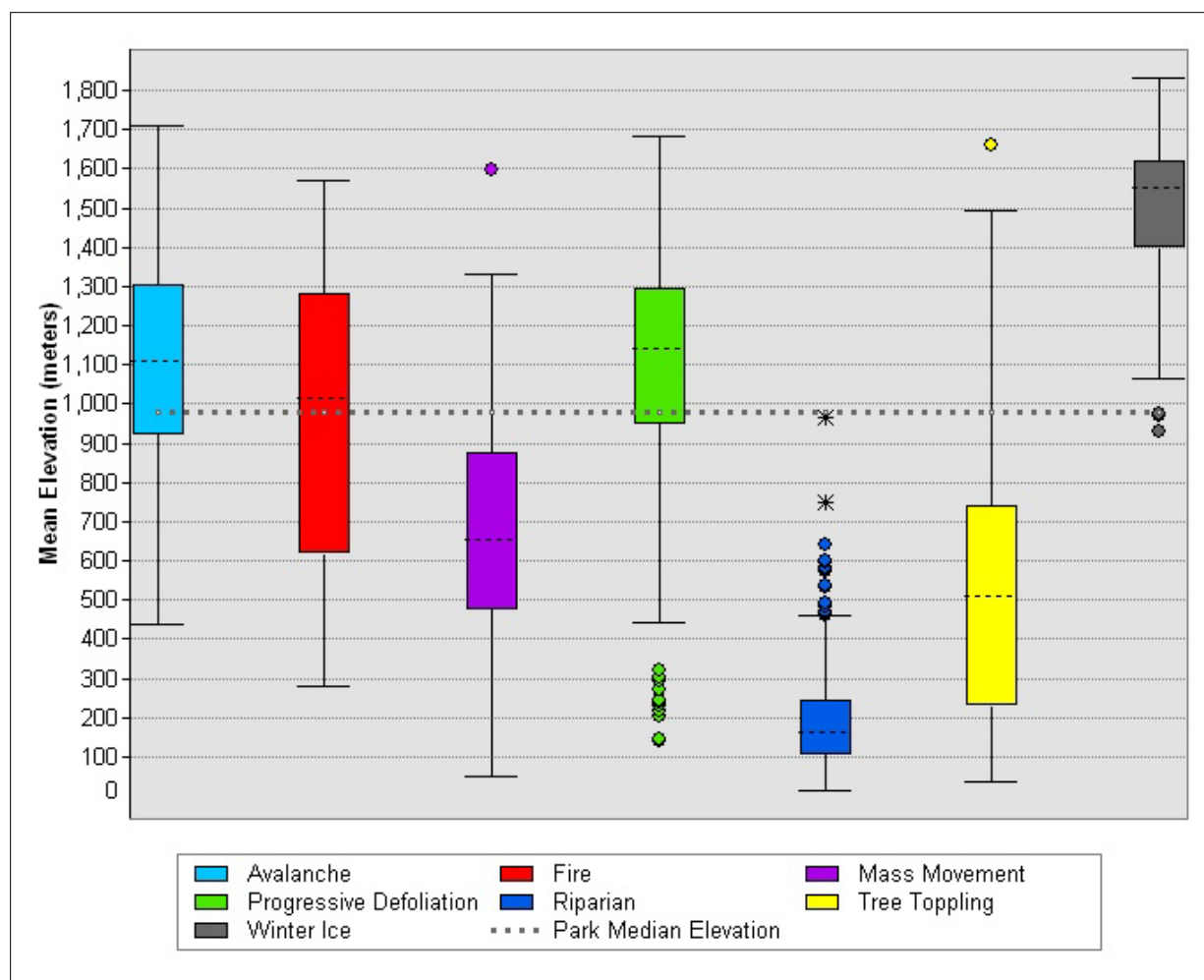


Figure 18. Distribution of elevation values for each landscape change category using patches detected between 1985 and 2010 inside the boundary of Olympic National Park, Washington. Dashed lines represent median, boxes represent quartiles (middle 50% of data points), whiskers are 1.5 interquartile range (1.5 times the box length).

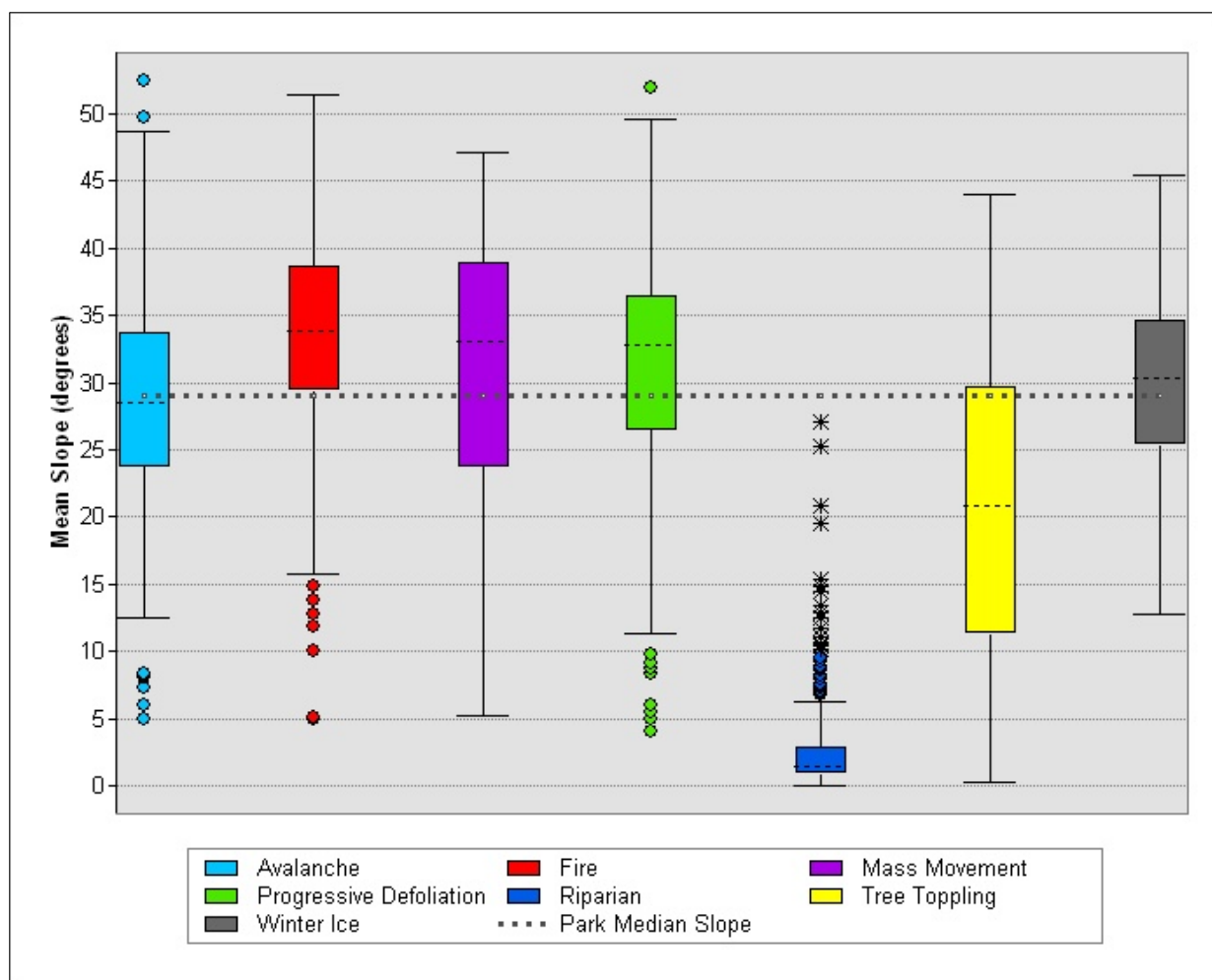


Figure 19. Range of slope values for patches in all change categories within the boundary of Olympic National Park, Washington. Dashed lines represent median, boxes represent quartiles (middle 50% of data points), whiskers are 1.5 interquartile range (1.5 times the box length). Circles represent “mild” outliers that occur between 1.5 and 3 times the box length. Stars represent “extreme” outliers that occur beyond 3 times the box length.

Land Management Category and Landscape Change

Not surprisingly, Land Management category correlates very closely with the percent of land area changed and the cumulative total areas of change detected (Figure 20). More than one third of lands within the All Other category, dominated by privately owned lands, changed during this period. Lands under Tribal and WA State DNR management underwent 15 to 20% change. Whereas, National Park Service and US Forest Service lands changed less than 5%. US Forest Service non-wilderness areas changed twice as much as US Forest Service wilderness.

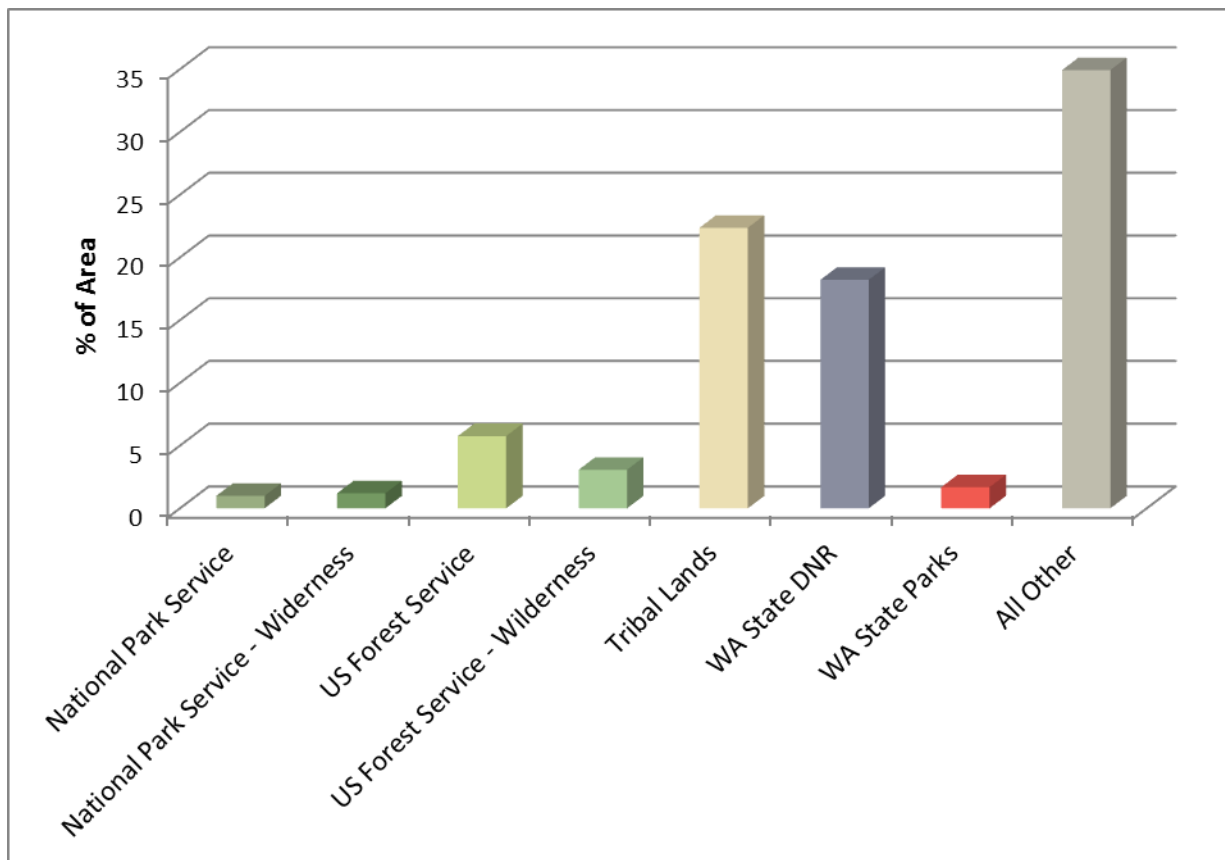


Figure 20. The percent of the total area by land management category that underwent change between 1985 and 2010 within the Olympic National Park study area, Washington. Agriculture is not included. “All Other” category includes private, municipal and county lands.

Clearing was the primary category of change during the time period studied (Figure 21). Over 60% of Clearing in the study area occurred in private lands (All Other category), affecting over 92,000 ha (Figure 21). Nearly 20% of Clearing occurred on WA State DNR (27,000 ha) and 13% on Tribal lands (20,000 ha). The Clearing on the National Park Service land was a 0.99 ha parcel in the Quinault that was cleared prior to transfer of ownership to the National Park Service. Even though fewer total acres were detected as Clearing on Tribal Lands as compared to WA State DNR lands, a larger proportion of the land in this management category (Figure 20) was detected as changed, with the majority (98% of all patches) labeled Clearing.

Total hectares altered by Clearing outside the park shows the trends in timber harvest among Federal, State, Tribal and private lands (Figure 22). The total area affected by Clearing did not decline throughout the study area. Clearing on private lands remains near an average of $3,694 \pm 1,297$ ha per year. The peaks in Clearing in 1988 and 2006 were associated with higher than average of the Clearing category on private lands. Low numbers in 1997 and 1998 followed by the peak of 1999 probably is not accurate; satellite imagery data were missing from 1996-1998 (see methods).

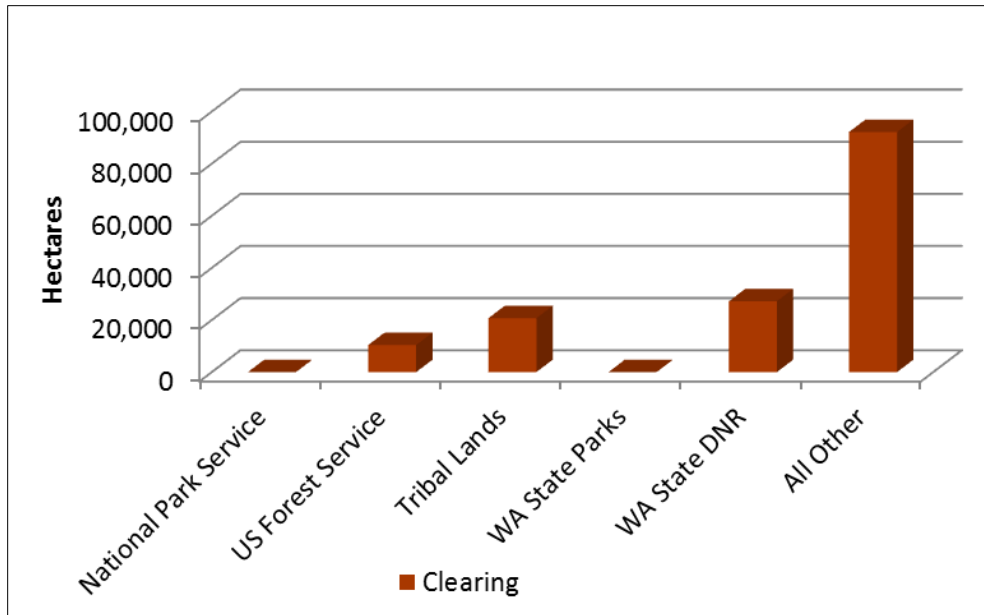


Figure 21. Total hectares disturbed by Clearing between 1985 and 2010 by land management category outside the Olympic National Park boundary, Washington. “All Other” category includes private, municipal and county lands.

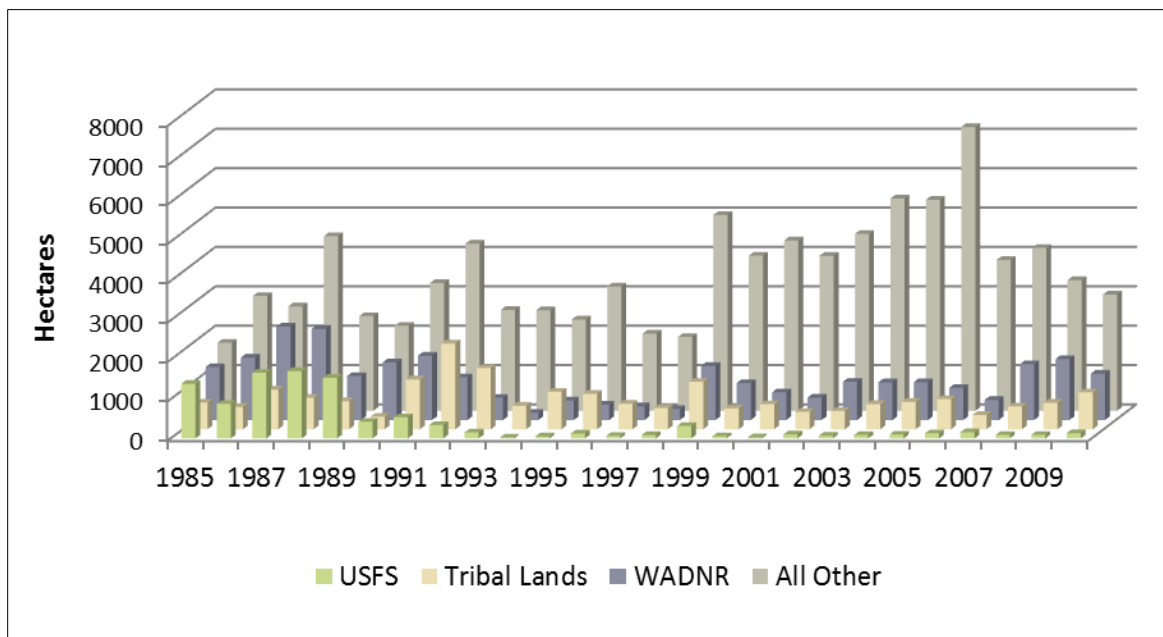


Figure 22. Total hectares disturbed in the Clearing category between 1985 and 2010 by year and land management category outside the Olympic National Park boundary, Washington. “All Other” category includes private, municipal and county lands.

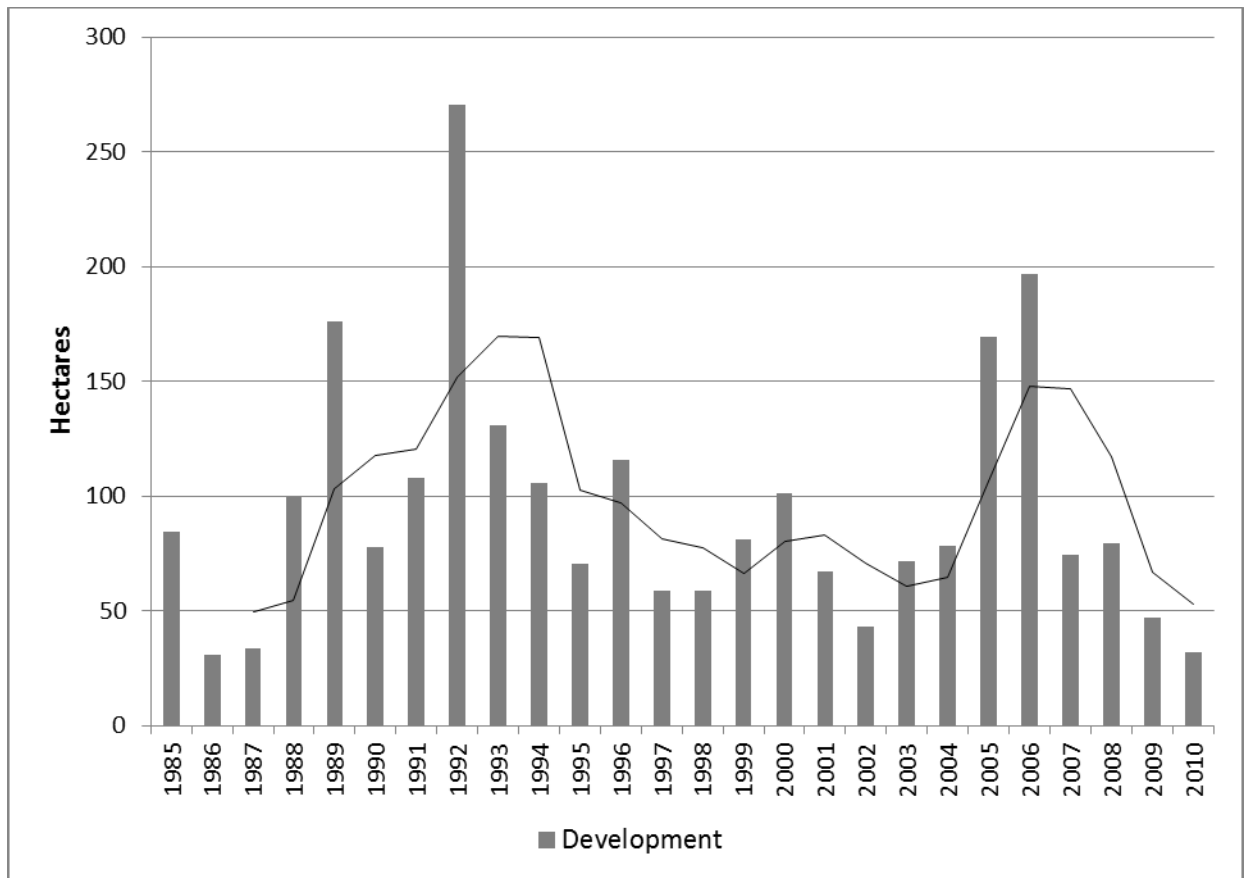


Figure 23. Landscape change due to Development from 1985 to 2010, overlain with a three-year running average.

Landscape change due to Development also varies considerably, with peak years in 1989, 1992 and 2005-2006.

Accuracy Assessment

We used classification models to label the category of change for patches in the study area. The results are described in the following section.

Random Forests Classification

The overall classification accuracy for the OLYM study area was 83.75%. The accuracy assessment matrix for the RF classification applied to change patches inside and outside the park boundary is shown in Table 8. The Clearing category had the lowest error rate of 5%. The Riparian, Fire, Winter Ice, Tree Toppling and Avalanche categories had error rates at or below 20%. Development had the highest error rate and was most often confused with both Clearing and Agriculture. Progressive Defoliation had an error rate of 28% and was most frequently confused with Tree Toppling, likely due to the similar effect these two types can have on the forest canopy. The Avalanche and Winter Ice categories were also confused because they occur in similar landscape positions and are due to similar forces (snow accumulation). The accuracies reported in Table 8 indicate the overall performance of the RF model used to label the patches.

Table 8. Accuracy assessment matrix for the Random Forests-derived labels for training polygons used to create the classification model. In this table, the values in the diagonal are where the predicted and actual values match. The values off-diagonal are where the model did not accurately predict the training data

Actual	Predicted											Error (%)
	Agriculture	Annual Variability	Avalanche	Clearing	Development	Fire	Mass Movement	Progressive Defoliation	Riparian	Tree Toppling	Winter Ice	
Agricultural	31	0	0	0	7	0	0	0	0	0	0	18
Annual Variability	0	52	0	0	0	3	0	2	0	1	4	16
Avalanche	0	0	49	1	0	1	2	2	0	0	6	20
Clearing	1	0	0	113	4	0	0	0	0	1	0	5
Development	8	0	0	12	40	0	0	0	0	0	0	33
Fire	0	2	0	0	0	53	3	1	1	0	0	12
Mass Movement	0	0	3	4	0	2	46	1	2	2	0	23
Progressive Defoliation	1	0	2	2	0	1	1	43	0	9	1	28
Riparian	0	0	0	0	1	0	3	0	63	2	0	9
Tree Toppling	0	1	1	1	0	2	2	5	0	51	1	20
Winter Ice	0	0	3	0	0	0	0	1	0	0	57	7

Office Validation

We report on office validation inside and outside the park boundary separately because we validated the entire population of patches inside the park boundary and a random subset of change patches outside the park boundary. For the office validation outside the park boundary, highest accuracies occur in the Riparian, Clearing, and Annual Variability classes (Table 9). Lower accuracy is found in the Progressive Defoliation class. Some of the high error rates for the natural process categories are simply due to low sample size. These disturbance types are infrequently found outside the park and RF accuracies are inherently reduced when the sample size is low.

Table 9. Accuracy assessment of polygons outside the Olympic National Park boundary, Washington. The sample plots where the analyst and the classification model assign the same patch type are found along the diagonal. Where there is disagreement, the patch type labels assigned by the analyst are found down the rows and represent the error in the classification modeling effort.

		Validation												
RF Model	Patch Type	Agricultural	Annual Variability	Avalanche	Clearing	Development	Fire ¹	Mass Movement	Progressive Defoliation	Riparian	Tree Toppling	Winter Ice	Grand Total	User's Accuracy
	Agricultural	39	8		19	8				3			77	50.6
	Annual Variability		17		1						1		19	89.5
	Avalanche			5	3			1					9	55.6
	Clearing		24		1813	29			5	2	19		1892	95.8
	Development	2	5		88	107				1			203	52.7
	Fire*		4		13		0				1		18	0.0
	Mass Movement				8			5					13	38.5
	Progressive Defoliation		1		14				11		7		33	33.3
	Riparian		1							45			46	97.8
	Tree Toppling				18	1					30		49	61.2
	Winter Ice		7	2	1				1			9	20	45.0
	Grand Total	41	67	7	1978	145	0	6	17	51	58	9	2397	
Producer's Accuracy	95.1	25.4	71.4	91.7	73.8	0	83.3	64.7	88.2	51.7	100			
Overall Accuracy	87.5													
Kappa Statistic	87.4													

¹ Fire patches were not part of the random sample of patches selected for office validation because locations of fires in the study area are generally known and data other than aerial photos are used to label this change type.

The landscape change types inside the park are very accurately mapped, with all types at greater than 50% accuracy and most mapped at or above 80% accuracy (Table 10). Lower accuracies were seen in categories with understandably easily confused signatures, both spectrally and visually in the aerial imagery. Winter Ice was confused with Avalanches as both occur in upper elevation areas affected by snow load and both cause forest damage of varying degrees. Progressive Defoliation was confused with Tree Toppling because when the toppling events are mild, the result is mostly a

decrease in canopy greenness, with tree boles exposed. Fire was confused with Tree Toppling for a similar reason.

Table 10. Accuracy assessment of polygons inside the Olympic National Park boundary, Washington.

		Validation											
	Patch Type	Annual Variability										Grand Total	User's Accuracy
			Avalanche	Clearing	Development	Fire	Mass Movement	Progressive Defoliation	Riparian	Tree Toppling	Winter Ice		
RF Model	Annual Variability	379	1					3	1	8	3	395	95.9
	Avalanche	28	248			1	5	2	1	4	10	299	82.9
	Clearing	2		0						3		5	0.0
	Development				1							1	100.0
	Fire	49	1			105	1	7		7		170	61.8
	Mass Movement	11	3			2	78		4	4	2	104	75.0
	Progressive Defoliation	53	4				2	180	2	26		267	67.4
	Riparian	2				3	4		279	6		294	94.9
	Tree Toppling	4	8	1		1	15	9	1	270		309	87.1
	Winter Ice	37	28				1	5		5	149	225	66.2
Grand Total		565	293	1	1	112	106	206	288	333	164	2069	
Producer's Accuracy		67.1	84.6	0.0	100	93.8	73.6	87.4	96.9	80.8	90.9		
Overall Accuracy		81.6											
Kappa Statistic		81.3											

Literature Cited

- Antonova, N., C. Copass, R. K. Kennedy, Z. Yang, J. Braaten, and W. Cohen. 2012. Protocol for Landsat-based monitoring of landscape dynamics in North Coast and Cascades Network Parks: Version 2. Natural Resource Report NPS/NCCN/NRR—2012/601. National Park Service, Fort Collins, Colorado.
- Antonova, N., C. Thompson, D. Wallin, R. Bryson, S. Clary, A. Hayes, I. Oehler, B. Pickard, M. Ponce-McDermott, and N. Schaller. 2011. Identifying the causes of landscape change in the North Coast and Cascades Network parks. Published Report-2184853, Task Agreement J8W07110003; PNW CESU Agreement H8W07110001. North Coast and Cascades Network, National Park Service, Sedro-Woolley, Washington.
- Baccus, W. T., C. In prep. NCCN annual climate summary – 2007: Olympic National Park. Natural Resource Data Series. National Park Service, Fort Collins, Colorado.
- Cohen, W. B., Z. Yang, and R. Kennedy. 2010. Detecting trends in forest disturbance and recovery using yearly Landsat time series: 2. TimeSync - Tools for calibration and validation. *Remote Sensing of Environment* 114:2911-2924.
- Fancy, S. G., J. E. Gross, and S. L. Carter. 2009. Monitoring the condition of natural resources in US National Parks. *Environmental Monitoring and Assessment* 151:161-174.
- Hoffman, R. 2014a. Olympic Wilderness boundary, Olympic National Park, Washington, wild_park_current.shp. Unpublished Geospatial Dataset. Olympic National Park, Port Angeles, Washington.
- Hoffman, R. 2014b. Boundary of the Olympic National Park, Washington, parkbndy.shp. Unpublished Geospatial Dataset. Olympic National Park, Port Angeles, Washington.
- Kennedy, R. E., W. B. Cohen, A. A. Kirschbaum, and E. Haunreiter. 2007. Protocol for Landsat-based monitoring of landscape dynamics and North Coast and Cascades Network Parks. 2-G1. U.S. Geological Survey Techniques and Methods, Reston, Virginia. Available from: <http://pubs.usgs.gov/tm/2007/tm2g1/pdf/tm2g1.pdf> (accessed 19 June 2012).
- Kennedy, R. E., Z. Yang, and W. B. Cohen. 2010. Detecting trends in forest disturbance and recovery using yearly Landsat time series: 1. LandTrendr - Temporal segmentation algorithms. *Remote Sensing of Environment* 114:2897-2910.
- Kennedy, R. E., Z. Yang, J. Braaten, C. Copass, and N. Antonova. 2015. Attribution of disturbance change agent from Landsat time-series in support of habitat monitoring in the Puget Sound region, USA. *Remote Sensing of Environment* 166:271-285.
- LANDFIRE. 2010. LANDFIRE public events geodatabase. Geospatial dataset. Available from: http://www.landfire.gov/public_data.php (accessed 26 July 2013).

- National Oceanic and Atmospheric Administration (NOAA). Historical El Nino/ La Nina episodes (1950-present). National Weather Service Climate Prediction Center. Available from: http://www.cpc.ncep.noaa.gov/products/analysis_monitoring/ensostuff/ensoyears.shtml (accessed 16 August 2016).
- National Resource Conservation Services (NRCS). Snow telemetry (SNOTEL) and snow course data and products. National Weather and Climate Center. United States Department of Agriculture. Available from: <http://www.wcc.nrcs.usda.gov/snow/> (accessed 16 August 2016).
- Read, W. A., 2015. The climatology and meteorology of windstorms that affect southwest British Columbia, Canada and associated tree-related damage to the power distribution grid. Ph.D Dissertation. University of British Columbia.
- Riedel, J., and S. Dorsch. 2016. Geomorphology of Mount Rainer: Landform mapping at Mount Rainer National Park, Washington. Natural Resource Report NPS/MORA/NRR—2016/1234. National Park Service, Fort Collins, Colorado.
- Thomas, J. W., J. F. Franklin, J. Gordon, and K. N. Johnson. 2005. The Northwest Forest Plan: origins, components, implementation experience, and suggestions for change. *Conservation Biology* 20:277-287.
- United States Congress. 1988. House. Senate. 100th Congress. 2nd Session. S.2165. Washington Park Wilderness Act of 1988. Government Printing Office, Washington, D.C.
- U.S. Department of Labor. 2011. Bureau of Labor Statistics, Local Area Unemployment Statistics, Washington, D.C. National Bureau of Economic Research. 2009. U.S. Business Cycle Expansions and Contractions, Cambridge, Massachusetts.
- Washington Department of Natural Resources (WA DNR). 2007a. NDMPL – Washington State Non-Department of Natural Resources major public lands. Geospatial dataset. Available from: <http://fortress.wa.gov/dnr/app1/dataweb/dmmatrix.html> (accessed 30 May 2013).
- WA DNR. 2007b. CADASTRE.PARCEL - Washington State Department of Natural Resources managed parcels. Geospatial dataset. Available from: <http://fortress.wa.gov/dnr/app1/dataweb/dmmatrix.html> (accessed 30 May 2013).
- Washington Office of Financial Management (WAOFM). 2011. April 1 Population estimates for the State, counties, and cities, 1990 to present. Available from: <https://data.wa.gov/Demographics/WAOFM-April-1-Population-by-State-County-and-City-/64z8-2nqn> (accessed 1 March 2016).

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