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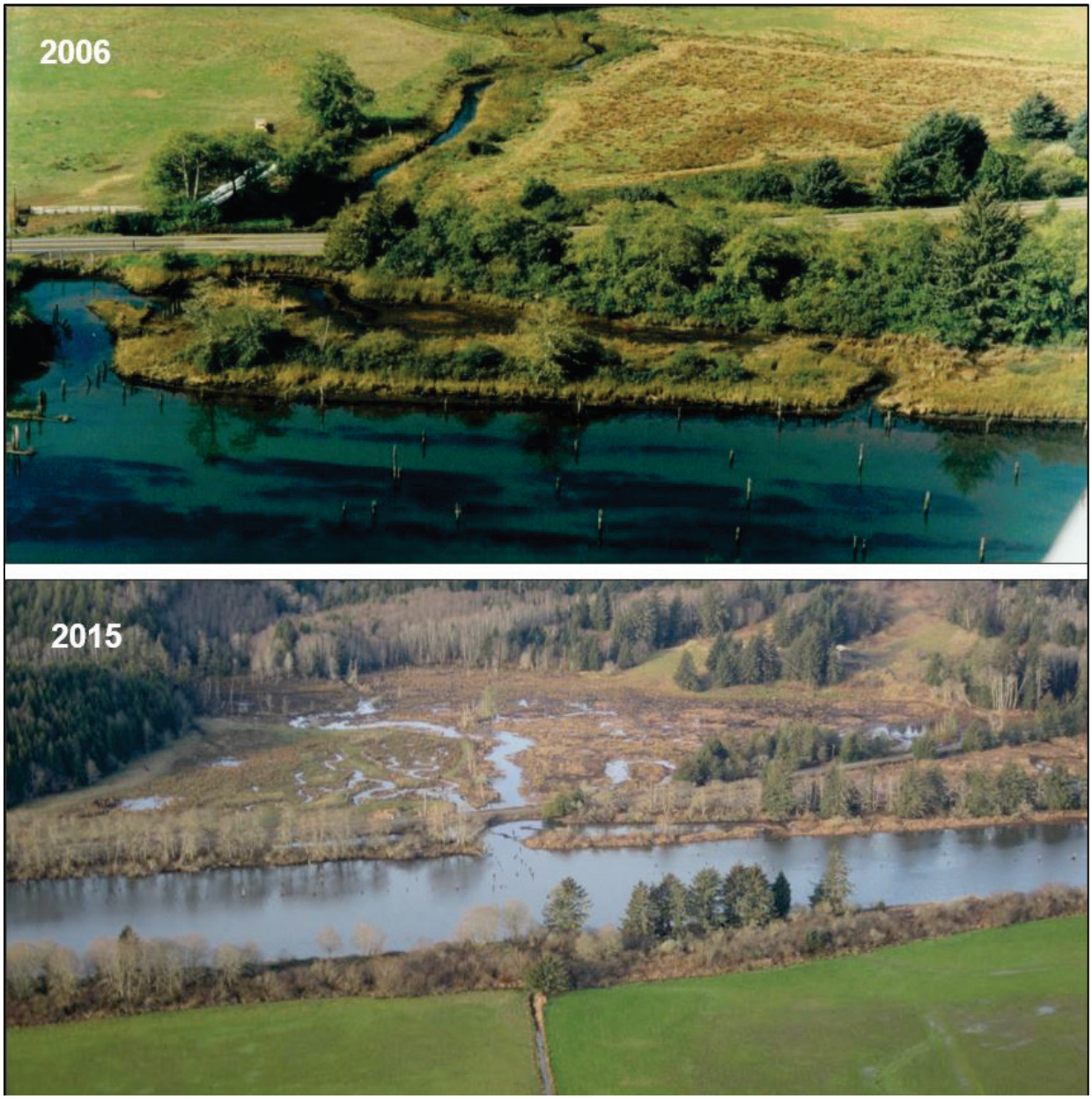
Natural Resource Stewardship and Science

Landsat-based Monitoring of Landscape Change in Lewis and Clark National Historical Park

1985–2011

Natural Resource Data Series NPS/NCCN/NRDS—2019/1206





ON THIS PAGE
South Clatsop Slough before (2006) and after (2015) following 2007 estuarine habitat restoration project.
Photos courtesy of Columbia River Estuary Study Task Force.

ON THE COVER
Trees at Sunset Beach State Recreation Area parking lot before and after the December 1-3, 2007 Great Coastal Gale.
Photograph by: NPS/LEWI Resources

Landsat-based Monitoring of Landscape Change in Lewis and Clark National Historical Park

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Natural Resource Data Series NPS/NCCN/NRDS—2019/1206

Catharine Copass[1], Natalya Antonova[2]

[1]National Park Service
North Coast and Cascades Network
Olympic National Park
600 East Park Avenue
Port Angeles, WA 98362

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

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Fort Collins, Colorado

The National Park Service, Natural Resource Stewardship and Science office in Fort Collins, Colorado, publishes a range of reports that address natural resource topics. These reports are of interest and applicability to a broad audience in the National Park Service and others in natural resource management, including scientists, conservation and environmental constituencies, and the public.

The Natural Resource Data Series is intended for the timely release of basic data sets and data summaries. Care has been taken to assure accuracy of raw data values, but a thorough analysis and interpretation of the data has not been completed. Consequently, the initial analyses of data in this report are provisional and subject to change.

All manuscripts in the series receive the appropriate level of peer review to ensure that the information is scientifically credible, technically accurate, appropriately written for the intended audience, and designed and published in a professional manner.

Data in this report were collected and analyzed using methods based on established, peer-reviewed protocols and were analyzed and interpreted within the guidelines of the protocols. This report received formal peer review by a subject-matter expert who was not directly involved in the collection, analysis, or reporting of the data.

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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 Lewis and Clark National Historical Park (LEWI) in 2016 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 ten categories of landscape change that occurred at LEWI and surrounding areas from 1985 to 2011: Agricultural Clearing, Clearing, Coastal, Development, Fire, Mass Movements, Progressive Defoliation, Riparian, Tree Toppling, and Windthrow Salvage. Agricultural Clearing captures an initial and permanent transition from vegetated to cleared for agricultural purposes. 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. The Mass Movement category includes both landslides and debris flows. Progressive Defoliation is a change type in which the vegetation cover remains but vigor has declined due to inundation, insect infestation, disease or drought. Change due to Tree Toppling is evidenced by fallen, broken or topped trees, generally due to wind but sometimes to root rot. 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 LEWI study area is 70,587 ha (174,428 ac), of which 2% (1,436 ha, 3,548 ac) is within the park legislative boundary. Approximately 23,365 ha (57,736 ac) (33 %) of the study area underwent detectable change at some point during the 26 year period of analysis. The annual average area affected by landscape change within the study area was about 857 ha (2,118 ac). Within the park boundary, the annual average area undergoing change was about 7 ha (17 ac).

Clearing was the major change type within the study area over the last 26 years, followed by Windthrow Salvage, Tree Toppling and Development. Inside LEWI, Tree Toppling was the most significant agent of landscape change, affecting 161 ha (398 ac) representing 75% of the total change detected.

The inter-annual variability in the total area experiencing landscape change was considerable. 2008 was a peak year due to “The Great Coastal Gale” which occurred the previous winter and impacted a total of 4,413 ha (10,905 ac) of change directly through Tree Toppling and indirectly through subsequent Windthrow Salvage in managed forests.

Acknowledgments

We wish to thank Chris Clatterbuck and Carla Cole at LEWI for contributing ideas and local knowledge of the park and the surrounding study area. Steve Acker, USFS, provided thoughtful review.

LandTrendr data were provided by Robert Kennedy and his team, including Justin Braaten, Sam Hooper, Joe Hughes and Tara Larrue (College of Earth, Ocean and Atmospheric Science, Oregon State University).

This work is funded by the NPS Inventory and Monitoring Division. Robert Kennedy's work was funded via Task Agreement P12AC15058 through the Cooperative Ecosystem Study Unit Cooperative Agreement H8W07110001.

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
LEWI	Lewis and Clark National Historical Park
LDMP	Landscape Dynamics Monitoring Protocol
MMU	Minimum Mapping Unit
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 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.

Image Chip – an area of interest and its neighborhood extracted from a time series stack of Landsat images and displayed side by side for easy viewing by TimeSync application.

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 coherent groups of a minimum of 9 Landsat pixels that meet rules of adjacency 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.

Random Forests – An ensemble learning method for classification (and regression) that constructs multitudes 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 organization of pixel data 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 a row and column number. Pixels are 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.

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 variability 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 3 March 2018).

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. Destruction and regeneration of vegetation are important ecosystem changes, both of which are captured by LandTrendr, however at this time the LDMP focuses on disturbances that remove vegetation.

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 clearing, development, fire, mass movement, progressive defoliation, riparian flooding, tree toppling and windthrow salvage.
- Determine trends in the size, location, and spatial distribution of each landscape change category.

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 Lewis and Clark National Historical Park study area. Annual Variability and Agriculture are two additional categories that are mapped but not included in this analysis.

Landscape Change Type	Definition
Agricultural Clearing	Includes first-time removal of vegetation for agricultural activities. Subsequent changes due to crop planting and harvest are included in the Agricultural category.
Clearing	Reflect a range of forest management practices, such as clearcuts, select cuts and thinning, and chemical removal of broadleaf vegetation.
Coastal	Captures partial to complete vegetation removal due to storm surges or other factors unique to the coastal foredune and strand.
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.
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.
Progressive Defoliation	Assigned to polygons where the forest remains but has undergone slow change in spectral values representing a loss of vegetation vigor. Several patterns of decline in tree health can be seen.
Tree Toppling	Forest areas where trees have been broken off or toppled by some action other than Avalanche or Clearing, generally due to wind but sometimes due to root rot.
Wetland Restoration	Category covers cleared areas that show change due to active restoration projects.
Windthrow Salvage	Unique category 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.

In this report, we present the first assessment of landscape change at Lewis and Clark National Historical Park (LEWI, or Park) using the LDMP. The assessment spans 26 years, from 1985 to 2011, and establishes baseline conditions for natural and anthropogenic changes both inside and outside LEWI. 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 xi.

Study Area

The Lewis and Clark National Historical Park landscape change monitoring study area includes seven park units within the legislative boundary (Figure 1). Three units are located in Washington State on the north side of the Columbia River: Cape Disappointment, Middle Village/Station Camp and Clark's Dismal Nitch. Four units are located in Oregon: Fort Clatsop, Sunset Beach State Recreation Area, Yeon, and the Salt Works. The units range in size from 698 ha (1,725 ac) of Cape Disappointment to the 0.10 ha (0.25 ac) of the Salt Works (Table 2). Most of the lands within LEWI administrative boundary were not managed by the National Park Service until after 2004 and some remain under management of state agencies and private owners. The State Parks shown in orange in Figure 1 are not included in the legislative boundary for LEWI, however shared management objectives and cooperative projects are sometimes pursued in these Parks.

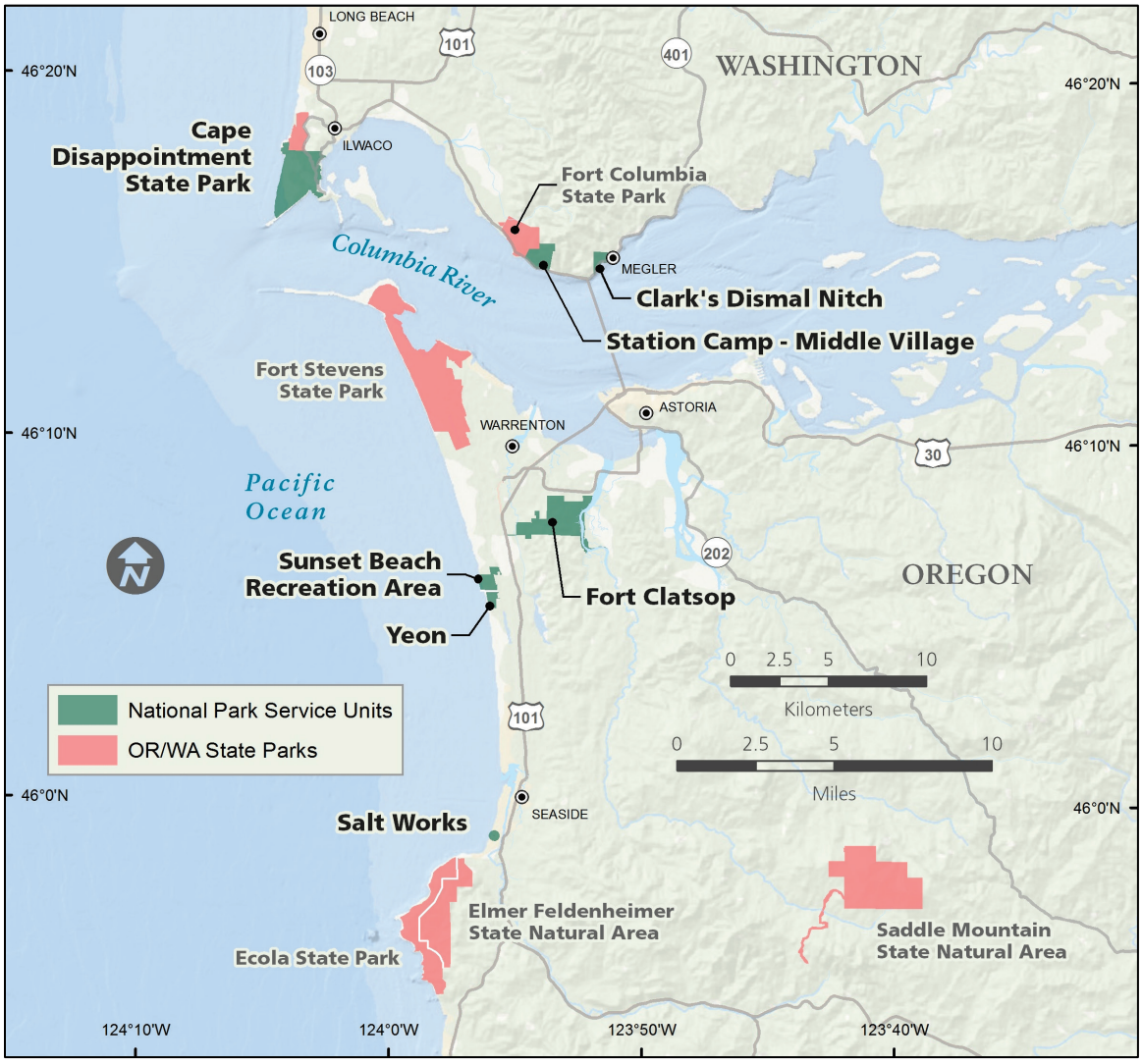


Figure 1. Location of the seven units within the legislative boundary of Lewis and Clark National Historical Park, Washington and Oregon.

Table 2. Size and location of the seven units within the legislative boundary of Lewis and Clark National Historical Park, Washington and Oregon.

Unit Name	Nearest Town	Hectares	Acres
Cape Disappointment	Ilwaco, WA	698.18	1725.22
Dismal Nitch	Megler, WA	77.54	191.61
Fort Clatsop	Warrenton, OR	522.44	1290.98
Middle Village/Station Camp	Megler, WA	143.78	355.29
Salt Works	Seaside, OR	0.10	0.25
Sunset Beach	Warrenton, OR	90.73	224.19
Yeon	Warrenton, OR	42.36	104.67

The overall study area integrates park unit boundaries with their broader ecological zones. An 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 managers, the study area was reduced slightly and aligned with watershed boundaries. The southern boundary of the study area includes the lower Necanicum, Lewis and Clark and Youngs Rivers. The resulting area includes 70,587 ha (174,424 ac) of land and water, about 2% (1,435 ha, 3,546 ac) of which fall inside the unit boundaries (Figure 2). The study area boundary along the Pacific Ocean reflects the approximate high tide zone, as indicated on aerial photos by accumulations of woody debris and or presence of vegetation. This report refers to this area as “large study area.” To better capture change immediately impacting park boundaries, we added a mid-size study area that extends about two kilometers beyond the park unit boundaries (Figure 2). This report refers to this area as “2 km study area.” Unless otherwise indicated, results reported for the large study area include the 2 km study area.

The landscapes within the units of Lewis and Clark National Historical Park feature forests dominated by Sitka spruce (*Picea sitchensis*) with Douglas-fir (*Pseudotsuga menziesii*), western hemlock (*Tsuga heterophylla*), and red alder (*Alnus rubra*) common. The native Shore pine (*Pinus contorta var. contorta*) has been widely planted for dune stabilization. Salt marshes and tidal wetlands are found along the coast, the Columbia River, and the Lewis and Clark River.



Figure 2. Two study areas used for monitoring landscape change in and around Lewis and Clark National Historical Park, Washington and Oregon. The large study area outlined in purple and the 2 km study area centered on the Park units is indicated with hatching.

Land Management Characteristics

The landscapes within the large study area encompass a high degree of heterogeneity of ownership types (Figure 3, Antonova 2018). The largest category of land management is Private Industrial Timber Lands, followed by the All Other category, which includes all other private land ownership. The Oregon Department of Forestry and Oregon State Parks also manage a large percent of the study area (Table 3). The Local Government category includes a variety of city and county parcels, managed for a variety of uses. Other State Lands includes Oregon Department of Military lands and state natural and conservation lands in both Washington and Oregon. The Other Federal Lands

category includes lands managed by the Army Corps of Engineers, The Bureau of Land Management, the Department of Defense and the Fish and Wildlife Service.

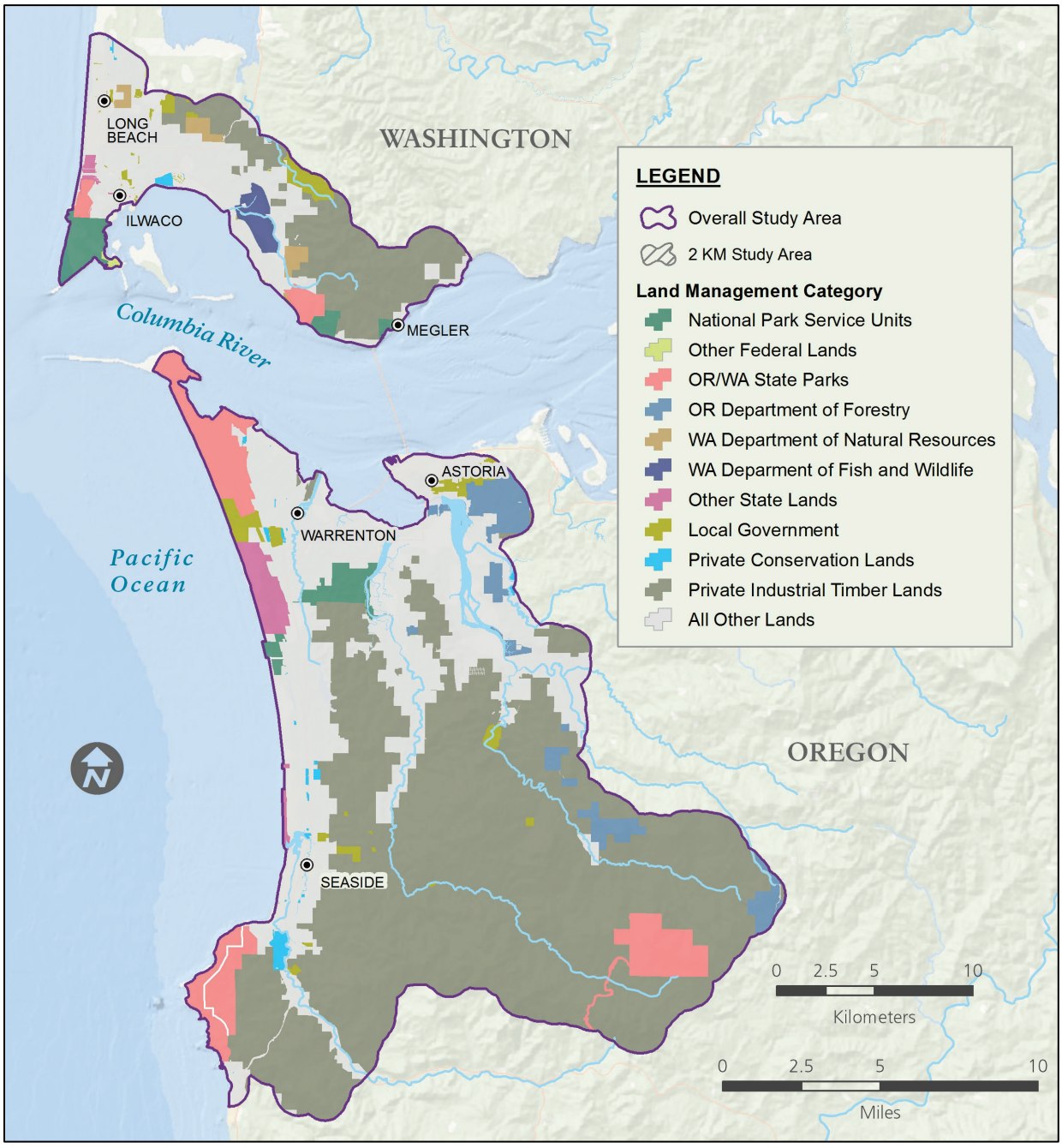


Figure 3. Land management categories within the Lewis and Clark National Historical Park large study area, Washington and Oregon. The land management layer was compiled by NPS staff using existing geospatial layers (NPS 2014) and updated with more current information using county, state and federal spatial layers (NPS 2012, WA DNR 2017a,b, Pacific County 2018).

Table 3. Area and percent of total area under various land management categories within the Lewis and Clark National Historical Park large study area, Washington and Oregon.

Land Manager	Agency or Category	% Study Area	Acres	Hectares
Federal	Bureau of Land Management	0.002	3.9	1.6
	National Park Service[1]	2.034	3547.4	1435.6
	US Department of Defense	0.058	100.7	40.7
	US Fish and Wildlife Service	0.020	34.9	14.1
	Total	2.114	3686.9	1490.4
State	State Parks	5.860	10221.4	4136.5
	OR Department of Forestry	2.847	4966.4	2009.8
	WA Dept. of Natural Resources	0.582	1014.7	410.6
	WA Dept. of Fish and Wildlife	0.610	1064.1	430.6
	Other State Lands	1.190	2075.5	839.9
	Total	11.089	19342.1	7827.4
County and City Government	–	1.838	3206.6	1297.7
Private	Conservation Lands	0.450	784.2	317.3
	Industrial Timber Lands	53.823	93881.5	37992.5
	All Other	30.686	53524.1	21660.4
	Total	84.959	148189.8	59970.2

[1] Most of the lands within NPS legislative boundary were not managed by the park service until after 2004 and some lands within the boundary continue to be managed by state agencies and private owners.

Population and Housing

The LEWI large study area is sparsely populated (Figure 4). The four major population centers within the study area, Astoria, Seaside, and Warrenton in Oregon and Ilwaco in Washington, support a combined population just under 30,000 (Table 4, US Census). The population in Pacific County in Washington and Clatsop County in Oregon increased by 10% from 1990-2010. The city of Warrenton, Oregon increased by 30% in that period which includes its merger with the town of Hammond in 1991. The population also increased in Ilwaco and Seaside (Figure 4, Table 4).

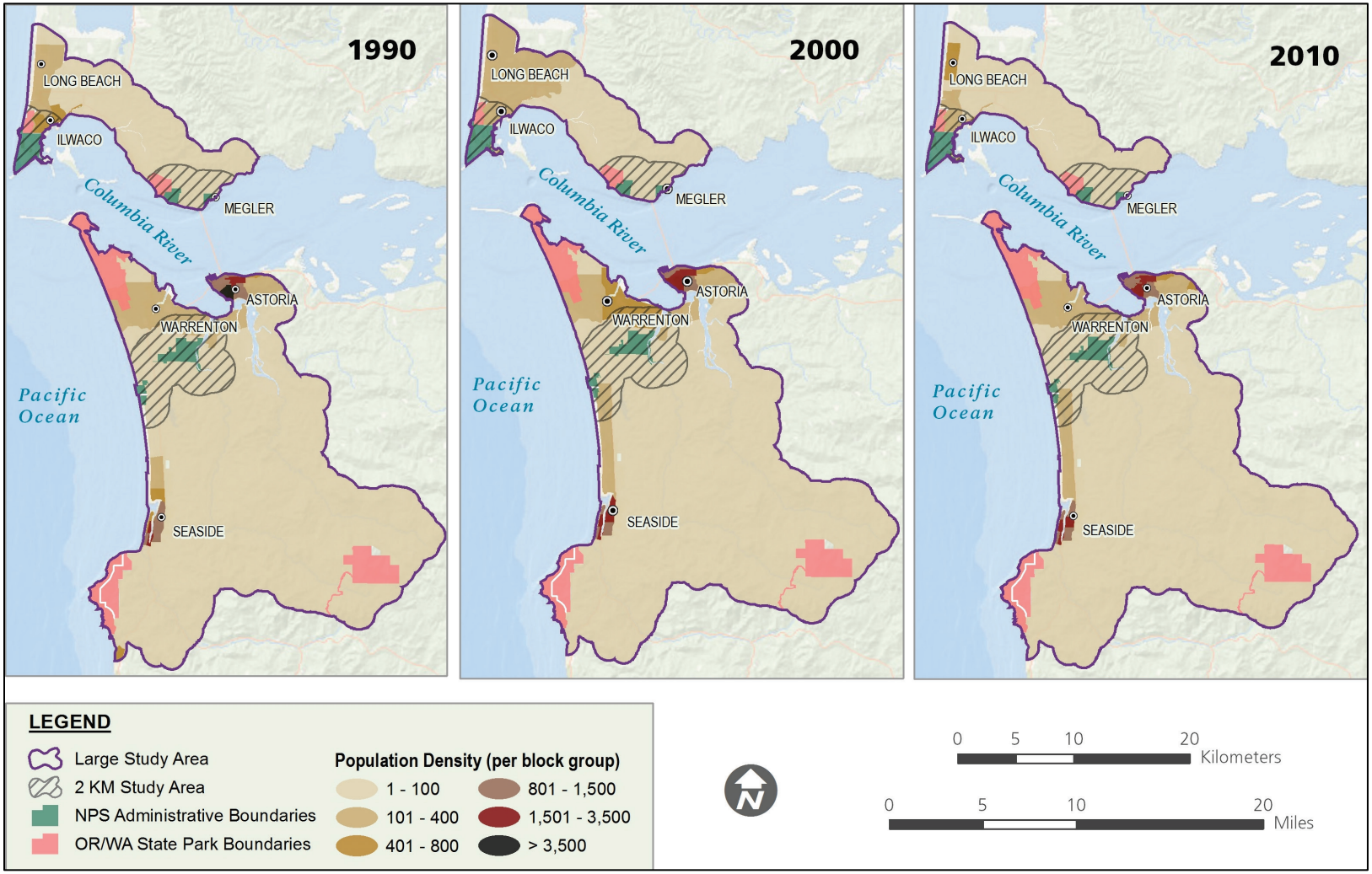


Figure 4. Changes in population density between 1990 and 2010 in the Lewis and Clark National Historical Park large study area, Washington and Oregon (NPScape 2018). Note that the population density within the block group that includes Warrenton appears to have decreased between 2000 and 2010 even though the total population increased (Table 4). This is an artifact of the 2010 block group having included unpopulated areas that influenced the calculation of population density.

Table 4. Population numbers and percent change in population for overall county areas and specific cities in and around the Lewis and Clark National Historical Park large study area, Washington and Oregon.

	Population			% Change		
Jurisdiction	**1990**	**2000**	**2010**	**1990-2000**	**2000-2010**	**1990-2010**
Pacific County	18882	20984	20920	10.02	-0.31	9.74
Clatsop County	33301	35630	37039	6.54	3.80	10.09
City of Astoria	10465	9813	9477	-6.64	-3.55	-10.43
City of Warrenton	3458	4096	4989	15.58	17.90	30.69
City of Seaside	5626	5907	6457	4.76	8.52	12.87
City of Ilwaco	838	950	936	11.79	-1.50	10.47

Great Coastal Gale of 2007

A storm named the "Great Coastal Gale" by regional meteorologists (Read 2008) significantly impacted the LEWI large study area during this monitoring period. Occurring over December 1-3, 2007, the first storm brought lowland snow followed quickly by a second more powerful storm which featured rapidly warming temperatures, heavy precipitation and 24 hours of sustained winds of over 30 mph with gusts around 70 mph. Wind measurements at the Astoria airport included a near record peak gust of 94 mph (Read 2008). The storms caused significant widespread property damage along the Oregon and Washington Coast, flooding and notable wind damage to the region's forests in the form of broken and toppled trees (Figures 5, 6, 7).

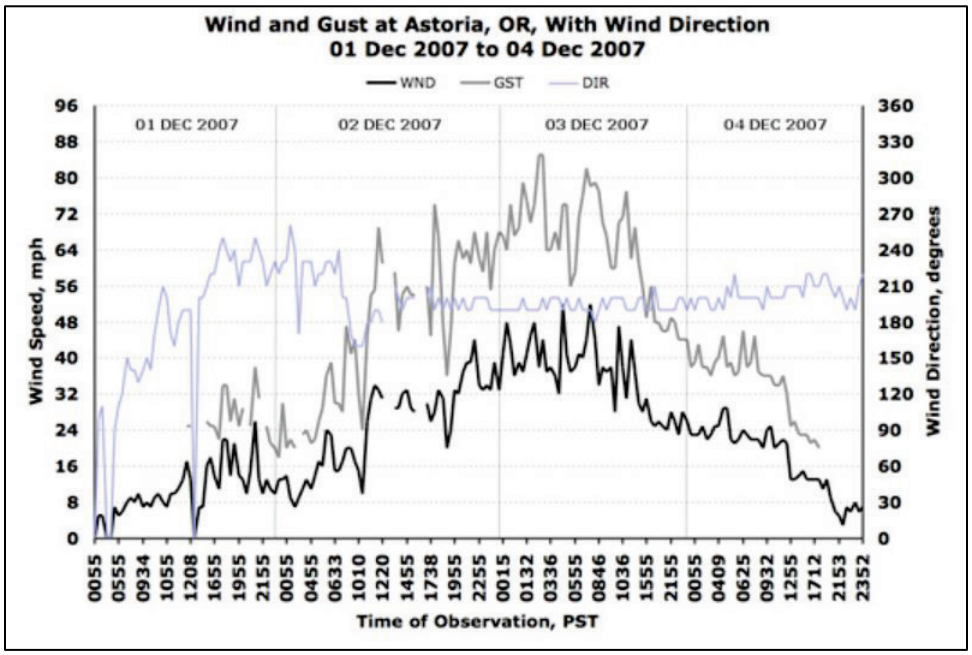


Figure 5. Wind profile during The Great Coastal Gale, December 1 through December 4, 2007. Image reprinted from "Great Coastal Gale of Dec 13, 2007" by W. Read (2008).



Figure 6. Forest before and after the Great Coastal Gale of December 1-3, 2007. Photo credit: NPS/LEWI Resources.



Figure 7. Lewis and Clark National Historical Park employee surveying building damage following the December 1-3, 2007 Great Coastal Gale. Photo credit: NPS/LEWI Resources.

Methods

The NCCN Landscape Change Detection and Monitoring Protocol (LDMP: Antonova et al. 2012) provides a detailed explanation of the methods used to detect changes in the 1985-2011 LEWI landscape. The methods include: running LandTrendr change detection algorithms with processed Landsat imagery, processing results into landscape patches, and labeling the patches by change type.

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 8 shows the day and year of Landsat images used in the analysis for LEWI.

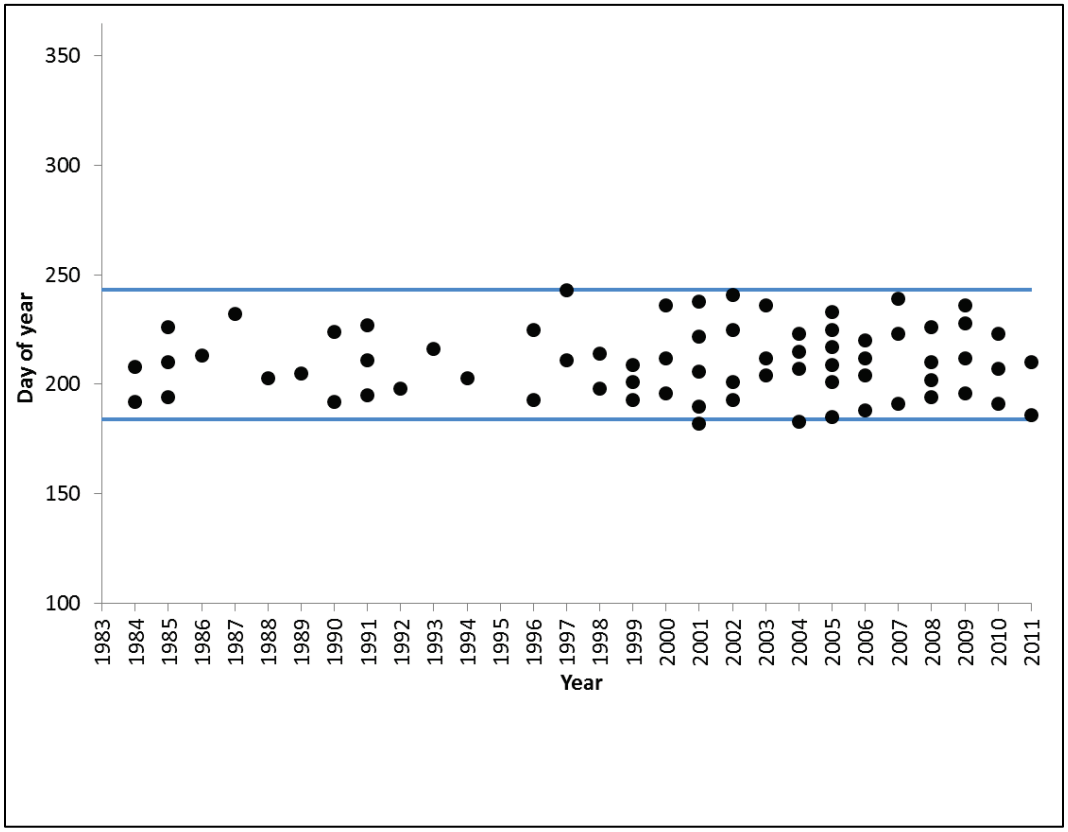


Figure 8. Day and year of Landsat images used for analysis for the Landsat scene 4728, which covers Lewis and Clark National Historical Park, Washington and Oregon. The blue lines bracket July 1st to August 31st.

Typically, at least several usable images per scene are captured in each year, however, no images were available for 1995. Landscape changes which occur during the years with missing imagery are detected in the next available image and given that date. Even in years where imagery is available,

pixels within the image can be unusable due to clouds or artifacts from the sensor. This occurred in 2005, a year when all useable pixels within available images were collected in the beginning of summer resulting in changes that occurred later in the season to be labeled with 2006.

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 9). 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 clearings, the year of change onset would come from the event that removed the most vegetation, i.e. event with highest magnitude.

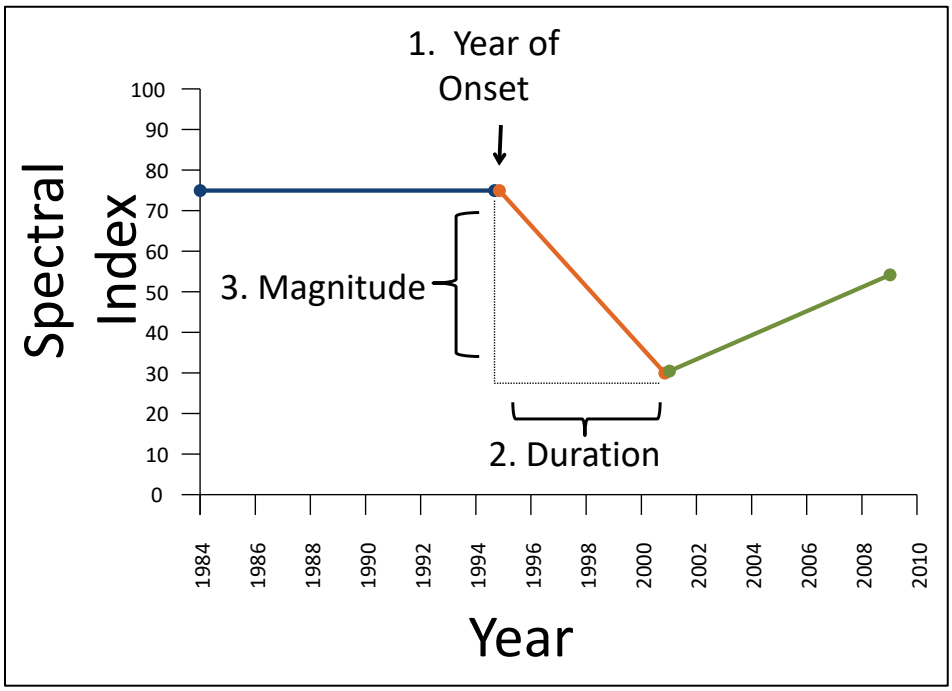


Figure 9. An idealized LandTrendr trajectory tracing a Landsat pixel through periods of stability, change and recovery. The period from 1984 to 1994 is a stable segment (blue line). A change event begins in 1994 (1) and lasts until 2001 (2), causing a drop of 45 spectral units (3). The change is followed by a recovery period from 2001 to 2010 (green line).

LandTrendr 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.

LandTrendr pixel outputs are grouped into patches based on the year the change began and the duration of change. 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.

Labeling Patches

The NCCN GIS analyst viewed and labeled each patch using the Google Earth Engine time slider bar to view aerial imagery before and after the change occurred. LEWI staff were consulted for several types of changes, which prompted the creation of a three change types specific to LEWI monitoring needs. Polygons that had low confidence in the label were reviewed by the NCCN ecologist and LEWI staff.

Change Type Characteristics

The LDMP provides a thorough description of the change types (Antonova et al. 2012) and types are summarized in Table 1. In this section, in order to facilitate interpretation of the results provided below, we provide additional details about and descriptions of the change types, particularly the change types specific to the LEWI monitoring dataset.

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 not capture change of interest to the NCCN, it is eliminated from the analysis and results.

Agricultural Clearing

Landscape change that converts forests or otherwise undisturbed vegetation into new agricultural areas is assigned this label.

Coastal

Storm surges from coastal storms periodically inundate the vegetated areas of the beach, causing declines in vegetation that have a similar spectral signature as Progressive Defoliation. The coastal change type recognizes the different cause of these declines in vegetation greenness.

Development

Development must show the addition of a permanent structure such as a road, house or other building. This category also includes gravel pits and other permanently cleared areas not used for agriculture.

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.

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.

Tree Toppling

While we recognize that the overwhelming cause of toppled trees in the LEWI dataset is one significant storm (Figure 10), we retained the label used in previous NCCN landscape change monitoring projects which broadly covers toppling not only due to windthrow but also root rot and other pathogens.



Figure 10. Example of Tree Topple caused by windthrow along the Fort to Sea Trail in Lewis and Clark National Historical Park following December 1-3, 2007 storm. Photo credit: NPS/LEWI Resources.

Wetland Restoration

This category is unique to the LEWI study and captures several areas undergoing active restoration to wetland communities within the NPS park boundary (Figure 11).

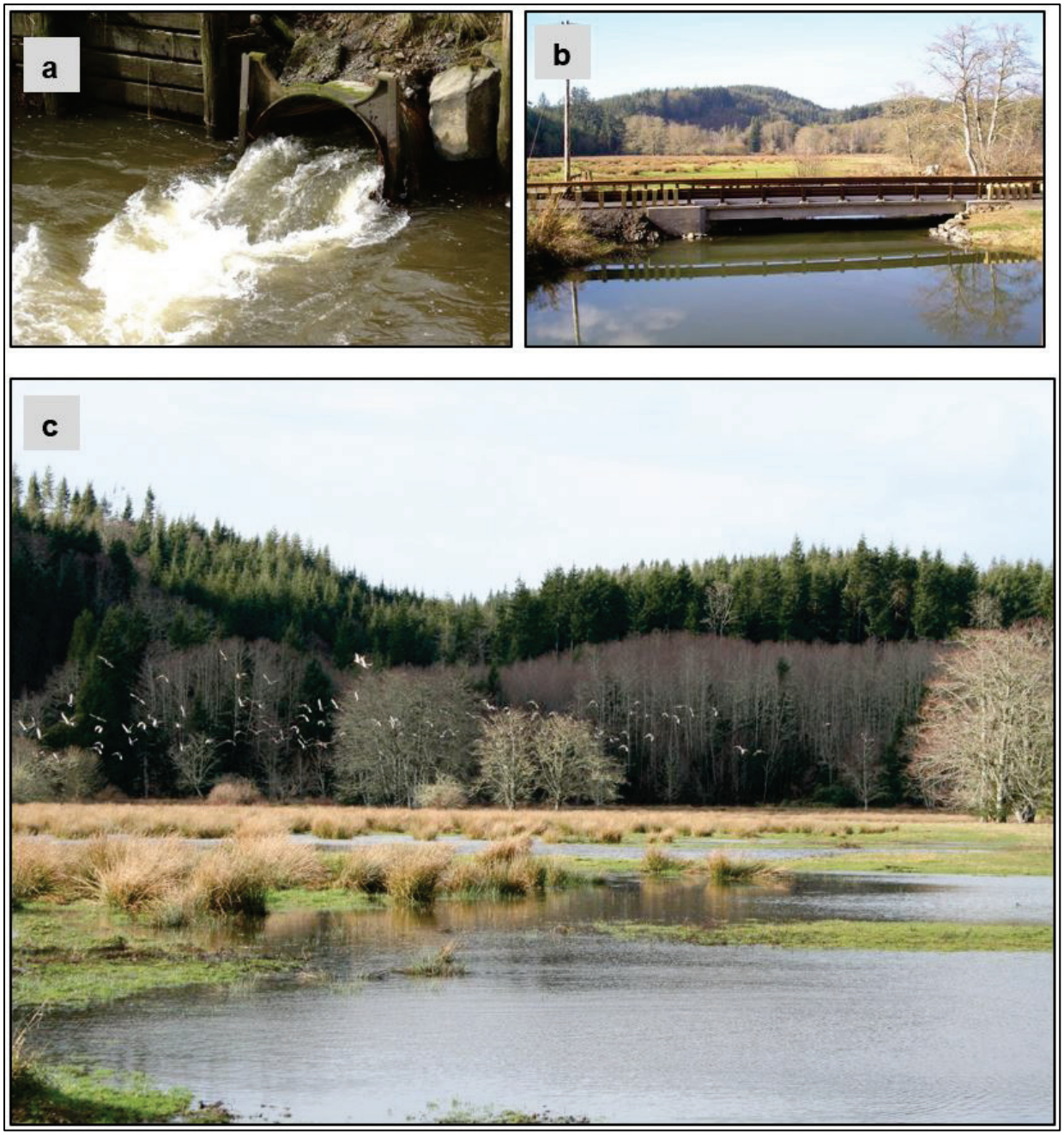


Figure 11. Old South Clatsop Slough Culvert (a) replaced by Bridge in 2007 (b). High tide in January 2008 after bridge replacement (c). Photo credit: NPS/LEWI Resources.

Windthrow Salvage

The windthrow salvage category captures a distinctive sequence of landscape change in forests following the Great Coastal Gale of 2007. Forested areas were toppled in the extreme winds. Toppled patches were subsequently salvage logged (Figure 12). The spectral signal in these patches matched that for "Clearing" but we wanted to document that windthrow was the proximal cause of the landscape change.



Figure 12. Salvage of trees toppled during the December 1-3, 2007 storm. Photo credit: NPS/LEWI Resources.

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 phenological variability and capture the greatest vegetation vigor. Changes to the spectral trajectory can 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.

Results

A total of 3180 patches were mapped within the LEWI large study area. Of these patches, 97 (3%) and 273 (9%) were classified as Annual Variability and Agricultural respectively. These patches were excluded from the summaries below.

We summarize and present results for inside the park administrative boundary, 2 km and the large study area. Results for the large study area include those for the 2 km area but not the park.

Inside the LEWI Legislative Boundary

Total Area Affected by Landscape Change

Landscape change affected about 15% of the area within the LEWI boundary during the 26 year period of analysis. This was a total of 214 ha (529 ac) changed. The annual average area that underwent change was 7.29 ± 31.30 ha (18.01± 77.34 ac) and the rate of landscape change on an annual basis was 0.01% ± 0.02% in the Park.

Types, Location, and Timing of Landscape Change

There were four types of landscape change detected within the LEWI boundary. Two types of change reflect human manipulation of the landscape (Clearing and Wetland Restoration) and two were highly episodic natural processes (Tree Toppling and Coastal). The overwhelming majority of change occurred in 2008 with 161 ha (398 ac) of Tree Toppling caused by the Great Coastal Gale in December 2007. The Toppling due to the storm represented 75% of the total change in the entire study period. The second greatest year of change within LEWI was 1998 with 21 ha (52 ac) of change in the Coastal category (Table 5, Figure 13). We mapped 26 ha (64 ac) of Clearing and 2 ha (5 ac) of Wetland Restoration (Table 5).

Table 5. Total hectares affected by change types within Lewis and Clark National Historical Park (LEWI) legislative boundary and percent of park area changed by each type 1985-2011.

Type	LEWI	% LEWI
Clearing	25.61	1.78
Coastal	25.36	1.77
Tree Toppling	161.11	11.22
Wetland Restoration	1.89	0.13
Grand Total	**213.97**	**14.90**

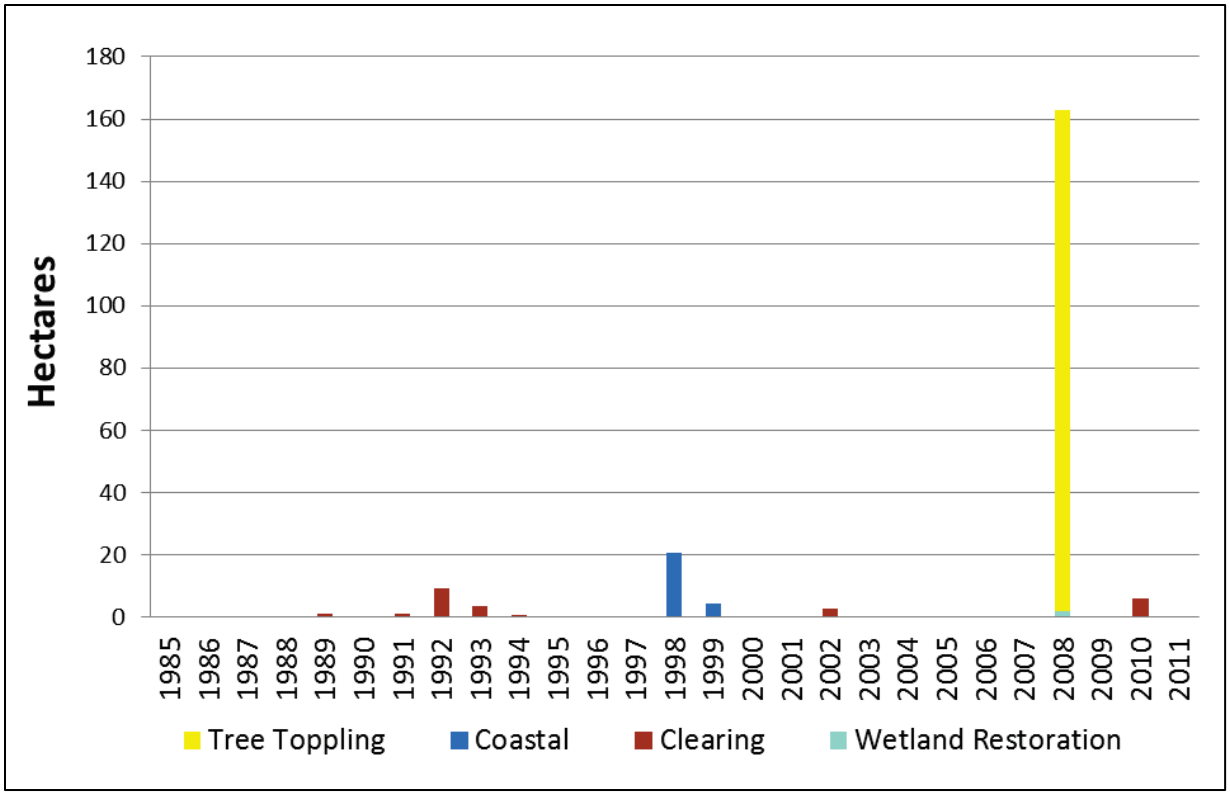


Figure 13. Total area disturbed by year within Lewis and Clark National Historical Park, Washington and Oregon. Changes labeled as Annual Variability or as Agriculture are not included.

Figure 14 indicates the location of the landscape changes. Tree Toppling largely occurred within the Fort Clatsop unit and the Sunset Beach/Yeon property adjacent to the coast. Coastal change occurred within the Cape Disappointment unit. Clearing was detected within Clark's Dismal Nitch but occurred before the area was included within the LEWI legislative boundary. Two Clearings in the northeastern corner of Fort Clatsop were detected in 2011 and were related to wetland restoration projects. The time frame of this study did not capture the eventual transition of these patches to the Wetland Restoration category.

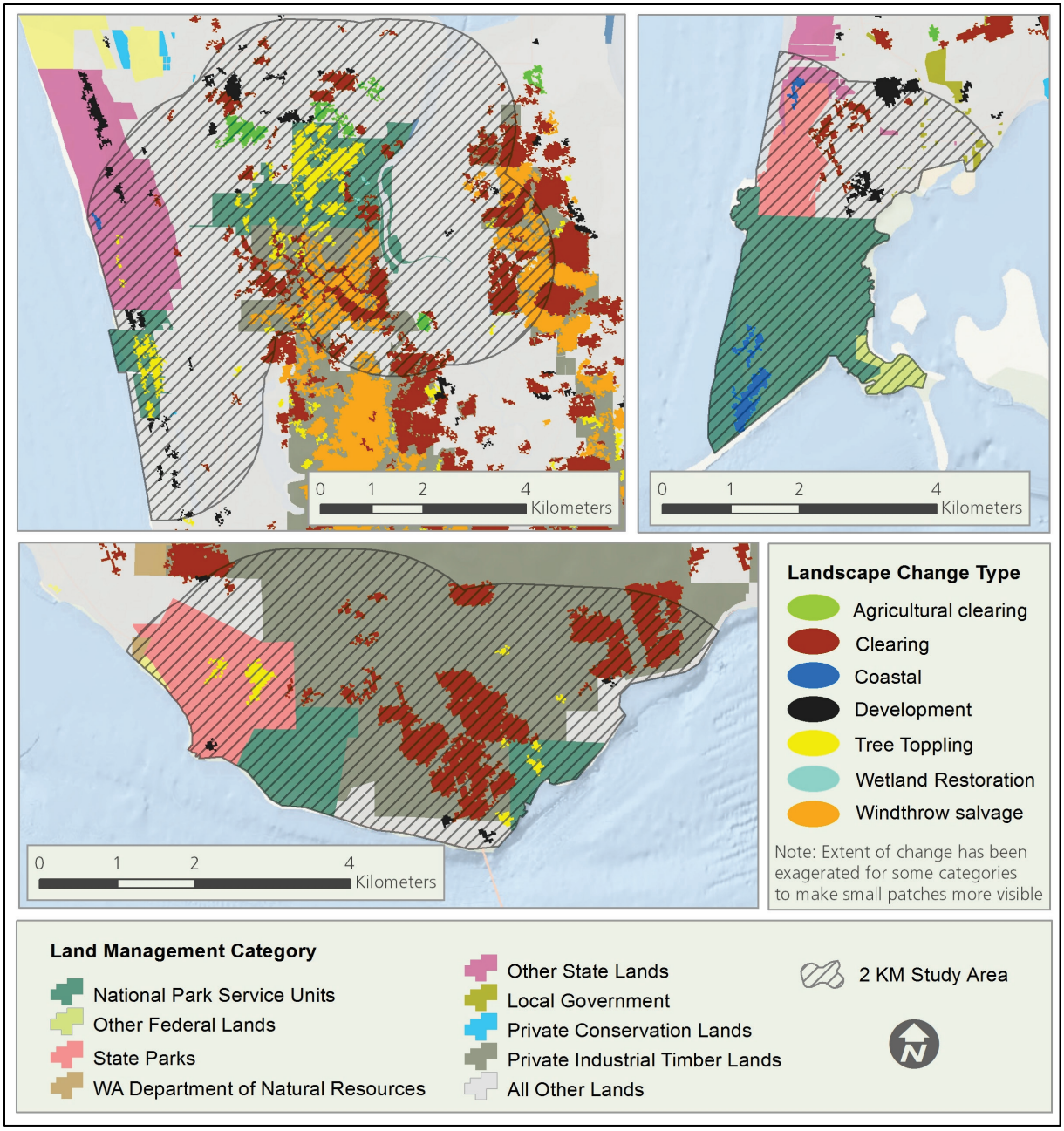


Figure 14. Location and types of landscape change mapped within the legislative boundary, Lewis and Clark National Historical Park, Oregon and Washington.

The map of the onset of change (Figure 15) shows the temporal distribution of change in the dataset, with older Clearings and Coastal occurring earlier in the time series and Tree Toppling and Wetland Restoration occurring more recently.

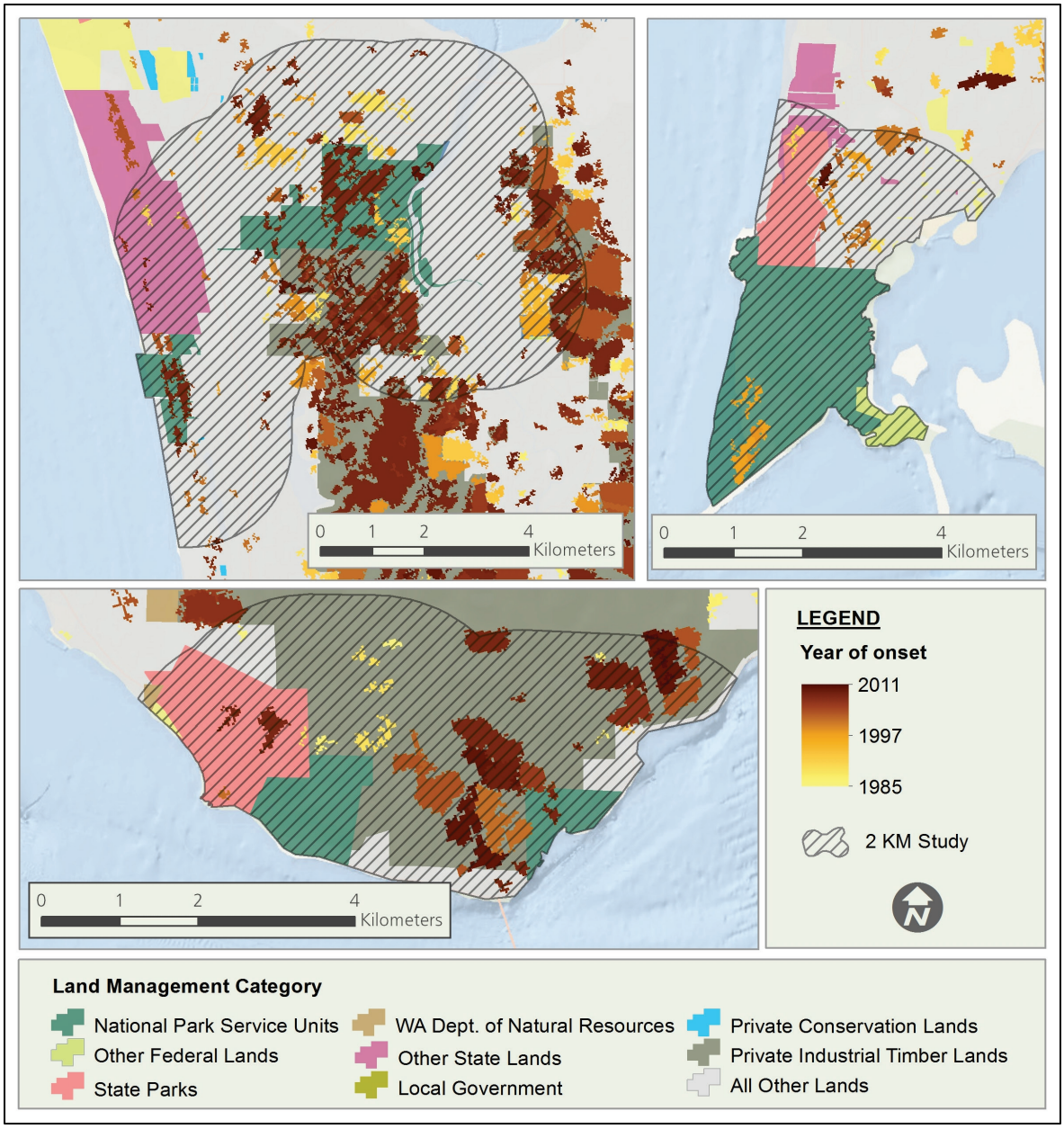


Figure 15. Map of the timing of landscape change inside the Lewis and Clark National Historical Park, Oregon and Washington.

Results in the Large and 2 km Study Areas

Total Area Affected by Landscape Change

Thirty three percent of the large study area and 15% of the 2 km study area changed during the 26 year period of analysis. This represents a total of 23,151 and 1,280 ha (57,207 and 3,163 ac) of change respectively. The annual average area affected by landscape change in the large study area was 857 ± 1,039 ha (2,118 ± 2,567 ac). Within the 2 km study area the annual average area changed was 47.4 ± 84.6 ha (117.1 ± 209.1 ac). The annual rate of landscape change was 1.2% ± 1.5% and 0.54% ± 0.97% in the large study area and 2 km study areas respectively.

Within the large study area, Clearing contributed the greatest amount to the total change detected over the last 26 years (Table 6, Figure 16). Windthrow Salvage and Tree Toppling were the second and third largest categories of change, significantly behind Clearing in the amount of area affected.

Table 6. 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.

Change 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 16. Clearing within the study area. Photo credit: NPS/Chris Clatterbuck.

The inter-annual variability of landscape change was considerable (Figure 17). In the large and 2 km study areas, the greatest amount of change was documented in 2008, when 5,294 ha (13,082 ac) and 418 ha (1,033 ac) were disturbed, more than double any other year in the study. Above average disturbance in the entire study area occurred in years 2007, 2004 and 2008. For the 2 km study area, 2007, 2004 and 2010 were the next biggest years of disturbance. The year with smallest change was 2005, with 34 ha (84 ac) affected (Figure 17), which is likely due to lack of late season imagery for analysis.

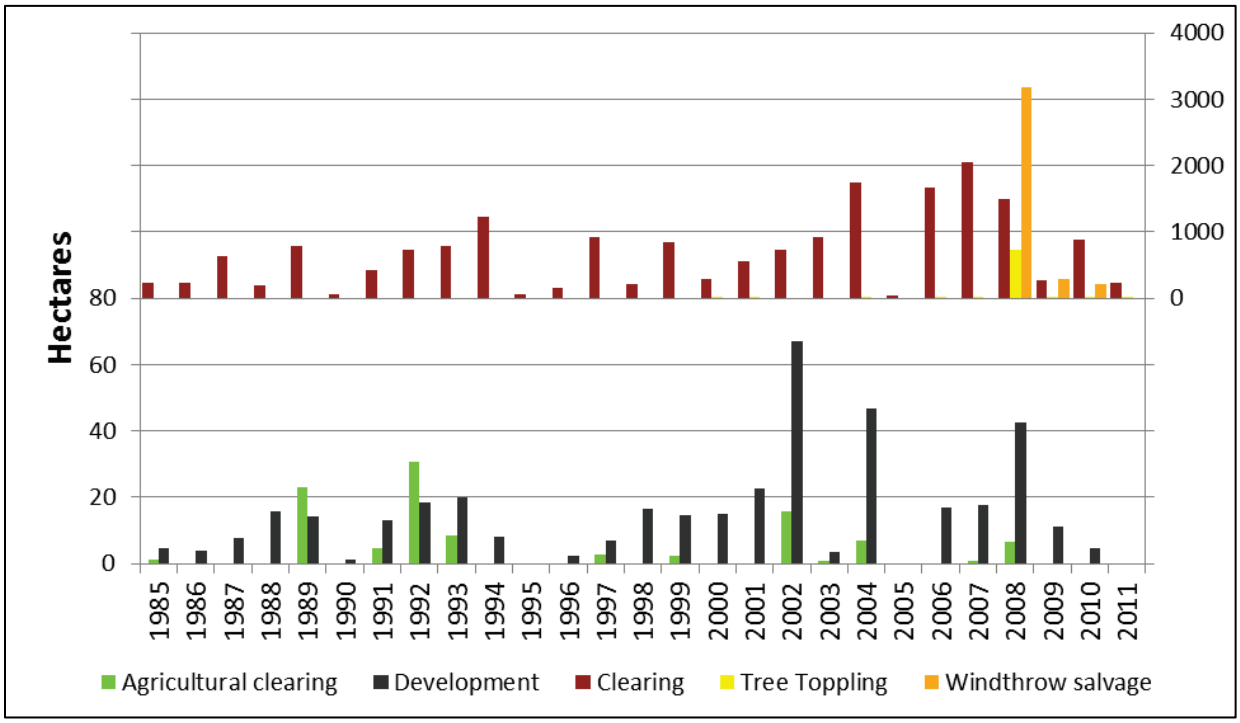


Figure 17. Hectares changed by landscape change types in the large study area, outside the Lewis and Clark National Historical Park boundary, Washington and Oregon.

Clearing was the predominant source of change during the analysis period. The peak year for Clearing was 2007, with high years also detected in 2004, 2006 and 2008 (Figure 17). The average annual area of Clearing was 678.4 ± 556.3 ha (1,676.4 ± 1,374.6 ac). Although a few patches of Tree Toppling were detected prior to Great Coastal Gale, the highest amount detected was in 2008, with 571 ha (1,411 ac) toppled during that single storm. Windthrow Salvage only occurred in 2008, 2009 and 2010, following the storm.

Agricultural Clearing totaled 104.4 ha (258 ac) and was detected in twelve of the 26 years, with a peak year occurring in 1992 and another notable year in 1989. The two largest Agricultural Clearings occurred in 1989 and 1992 just to the north of what is currently the Fort Clatsop unit. A total of 389.9 ha (963.5 ac) of the large study area was changed due to Development. Development had peak years in 2002 and 2004 as well as another peak in 2008, just after the regional housing bubble burst (Figure

17). Average annual change due to Agricultural Clearing was 3.9 ± 7.5 ha (9.6 ± 18.5 ac) and the average annual change for Development was 14.6 ± 15.2 ha (36.1 ± 37.6 ac).

Natural processes caused a total of 25.6 ha (63.3 ac) of disturbance in the large study area during the analysis period. There were five Mass Movements detected resulting in approximately 6 ha (15 ac) of change. These were located in the southeastern part of the large study area. A total of 41 ha (101 ac) of Coastal change happened in seven different years. Progressive Defoliation, a minor but detectable natural change type, caused 4 ha (10 ac) of change within two patches that appear to be inundated shrublands (Table 6 and Figure 18).

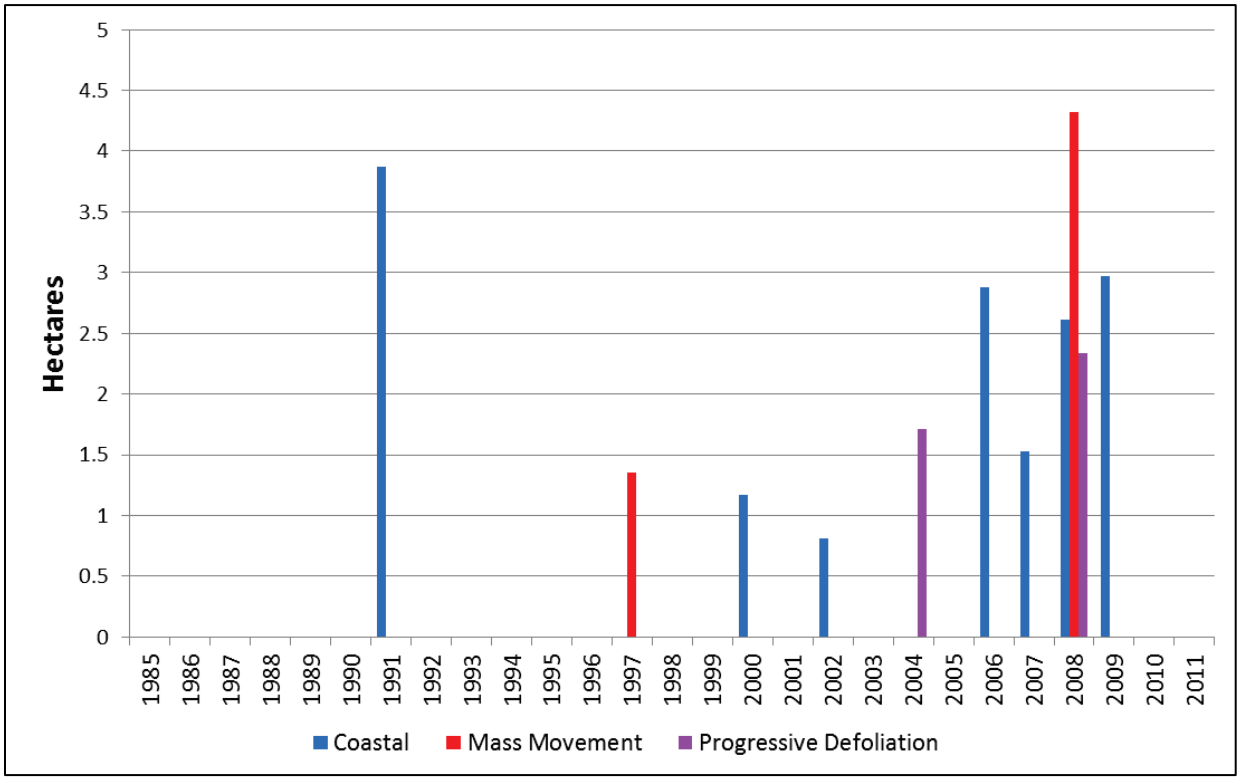


Figure 18. Hectares changed by natural landscape change types in the large study area outside the Lewis and Clark National Historical Park boundary, Washington and Oregon.

Timing of Landscape Change

A map of the year of the onset of change provides an overview of the distribution of disturbances within the time series (Figure 19). Change later in the time series dominates the change found outside the LEWI boundary. The eastern third of the large study area in Oregon features changes older than 1990s, the central third is dominated by recent change and the third of the large study area along the coast appears to be relatively unchanged throughout the entire period. The LEWI units on the north side of the Columbia River and their surrounding areas are relatively unchanged by recent disturbance. The strip of land along the coast appears to be stable throughout the entire period.

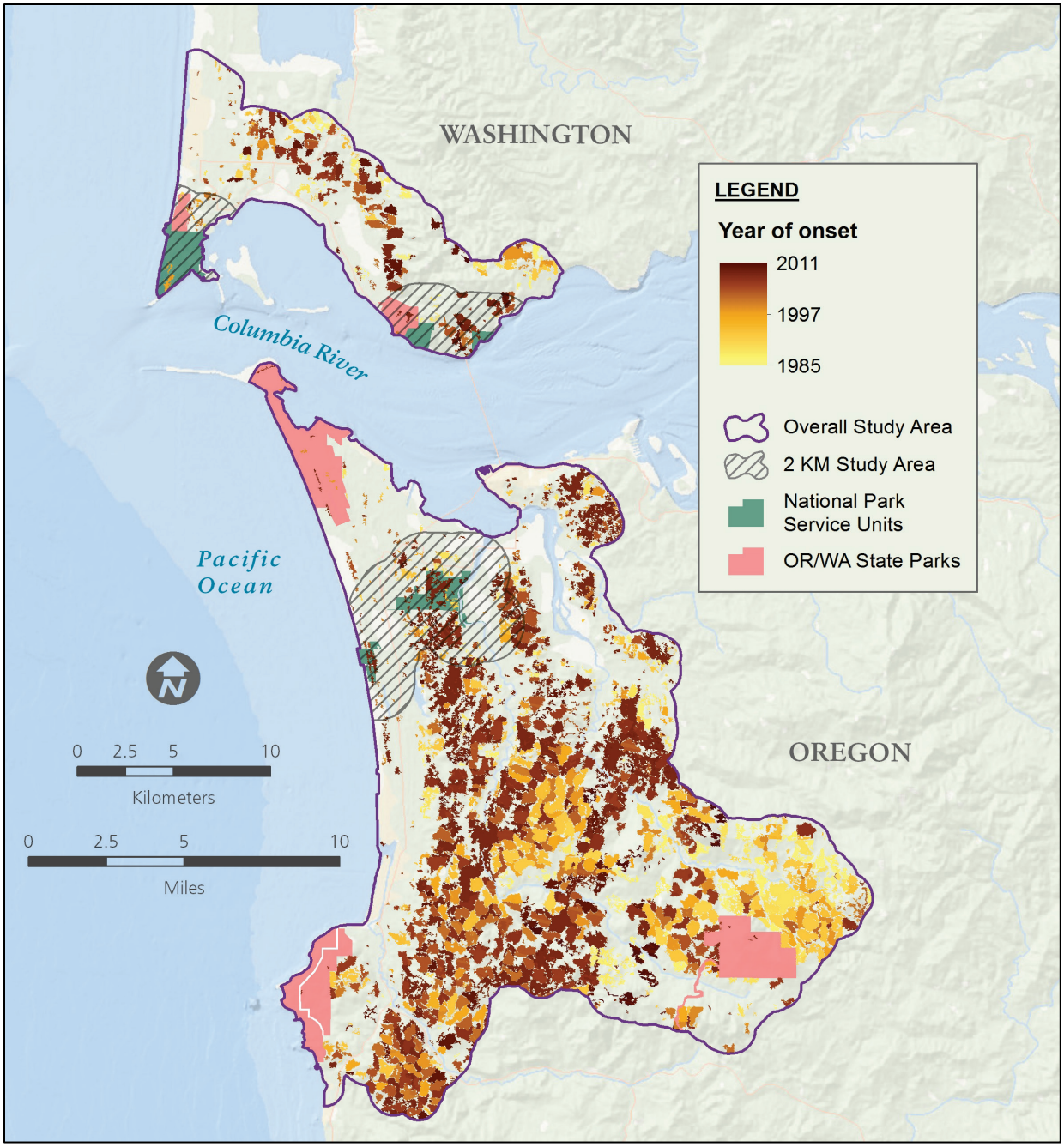


Figure 19. Map of landscape changes from 1985 to 2011 by year of onset, Lewis and Clark National Historical Park large study area, Washington and Oregon. Changes labeled as Annual Variability and Agriculture are not included.

Land Management Category and Landscape Change

Clearing dominated the change within the large study area over the last 26 years with a total of 18,342 ha (45,324 ac) (Table 7). A map of landscape change by type (Figure 20) shows the distribution of this type within the large study area. The Clearing landscape type prevailed to the north of the Washington units and to the east and south of the Oregon units, predominately on the

Private Industrial Timber Lands (1,115 ha (2,755 ac) in Washington and 14,687 ha (36,292 ac) in Oregon), with some occurring on the Oregon Department of Forestry (436.6 ha, 1,078.9 ac, Table 7). Within Private Industrial Timberlands, 49.6% of the acreage underwent Clearing or Windthrow Salvage between 1985 and 2011. On Oregon Department of Forestry lands, this rate was 42.3%. Landscape change due to Development occurred most notably north and west of the Fort Clatsop unit in the cities of Warrenton and Astoria, as well as north of the Cape Disappointment unit in Washington (Figure 20).

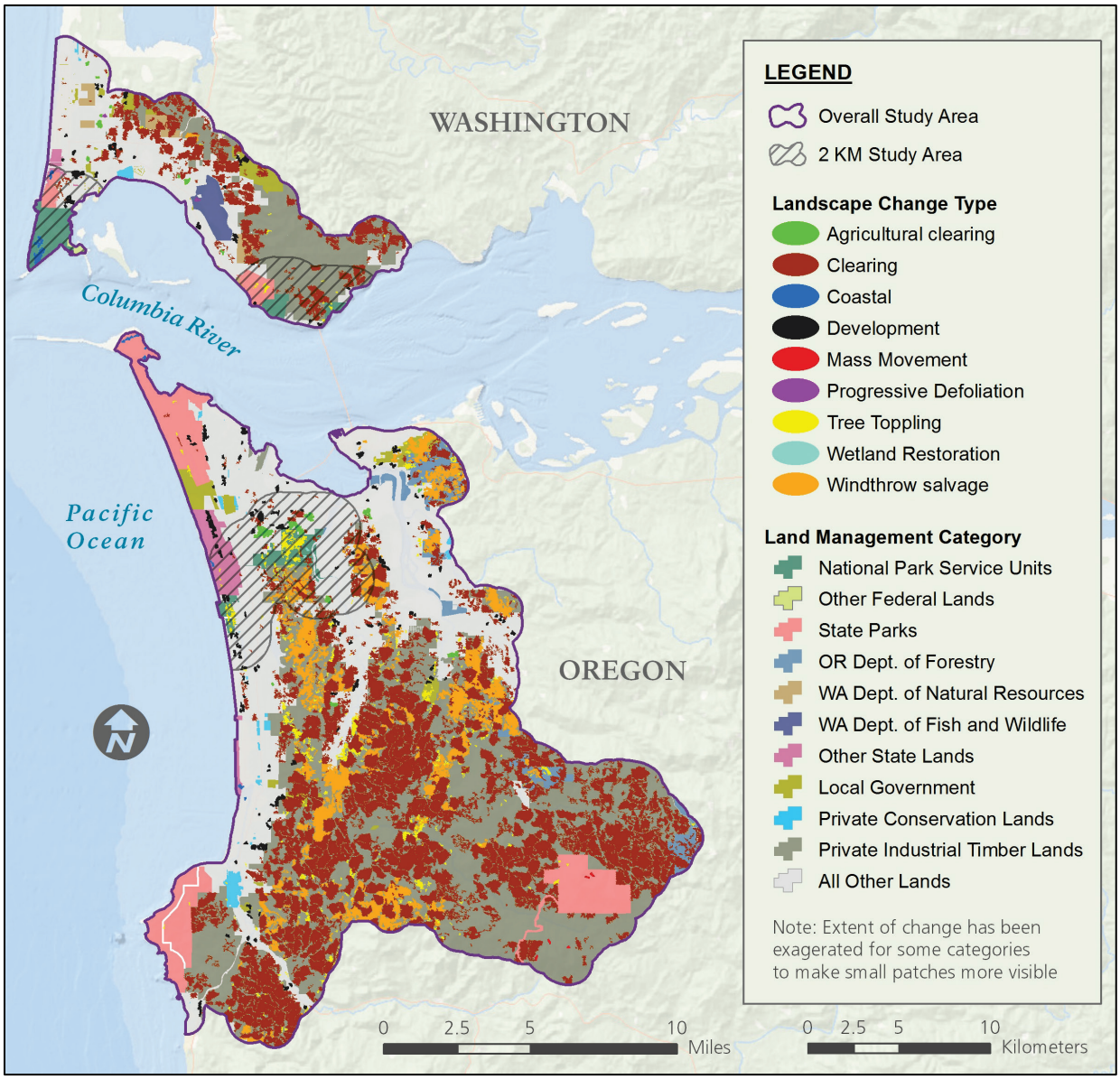


Figure 20. Map of landscape changes from 1985 to 2011 by change category overlaid on land management categories, Lewis and Clark National Historical Park large study area, Washington and Oregon. Changes labeled as Annual Variability or as Agriculture are not included.

Table 7. Area (ha) changed by Land Management category.

Land Manager	Agency or Category	Agricultural Clearing	Clearing	Coastal	Development	Mass Movement	Progressive Defoliation	Tree Toppling	Wetland Restoration	Windthrow Salvage	Total
Federal	National Park Service[1]	–	25.6	25.4	–	–	–	161.1	1.9	–	214.0
State	State Parks	–	9.2	13.5	5.6	–	–	25.8	–	–	56.2
	OR Dept. of Forestry	–	436.6	–	–	–	–	39.8	–	415.1	891.5
	WA Dept. of Natural Resources	–	105.4	–	–	–	–	0.8	–	–	106.2
	WA Dept. of Fish and Wildlife	–	–	–	–	–	2.3	–	–	–	2.3
	Other State Lands	–	3.2	1.5	28.6	2.2	–	5.4	–	–	38.7
	Total	–	554.4	15.0	34.2	2.2	2.3	71.8	–	415.1	1094.9
Local Government	City and County	–	94.2	–	23.8	–	–	39.9	–	108.7	266.8
Private	Conservation Lands	–	–	–	–	–	–	0.81	–	–	0.81
	Industrial Timber Lands	–	15802.2	–	4.8	3.1	–	459.1	–	3044.7	19314.3
	All Other	104.4	1865.8	0.8	332.7	–	1.7	56.9	–	112.1	2474.4
	Total	104.4	17668.0	0.8	337.5	3.1	1.7	516.8	–	3156.8	21789.5
Grand Total	**–**	**104.4**	**18342.2**	**41.2**	**395.5**	**5.7**	**4.0**	**789.7**	**1.9**	**3680.6**	**23365.2**

[1]Not all lands within LEWI legislative boundary were managed by NPS during the period of analysis and some areas continue to be managed by state parks or private inholders.

Comparison of Change Among Study Areas

The 2 km study area was designed to evaluate landscape change found immediately adjacent to the LEWI boundary. Comparing the results for just inside the 2 km area and the area within the large study area beyond that boundary shows that lands immediately adjacent to the LEWI boundary have proportionally more Agricultural Clearing and Development compared to the large study area further past the park boundary (Figure 21).

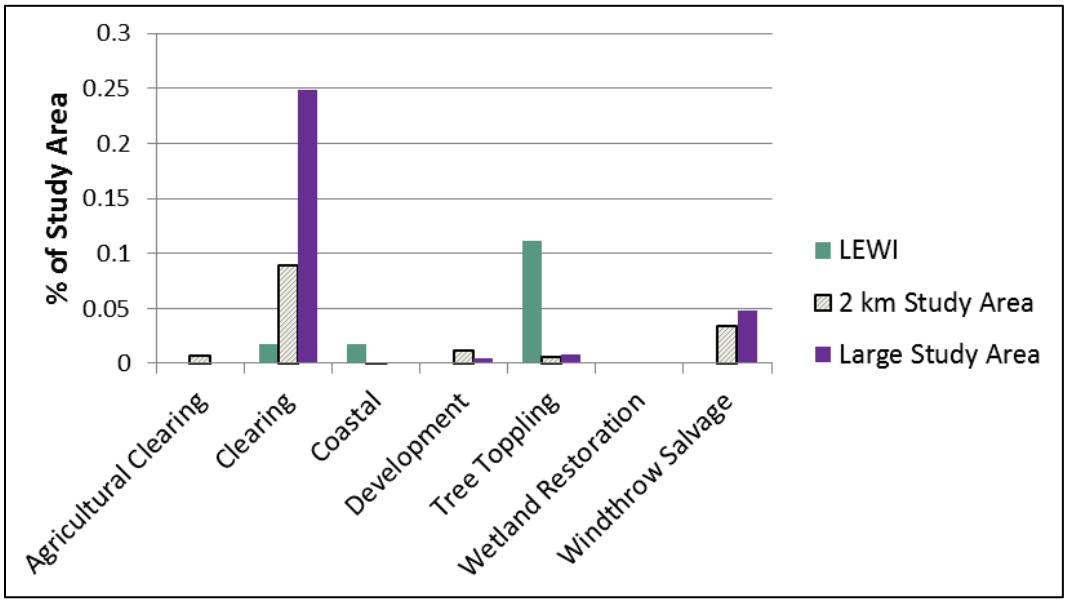


Figure 21. Percent of Park, 2 km and large study areas affected by landscape change types. Note that the large study area DOES NOT include patches within the 2 km study area or the Park.

Characteristics of Landscape Changes

Number of Patches

The number of landscape change patches occurring in the different study areas is presented in Table 8. We detected 1968 patches of Clearing within the large study area. Windthrow Salvage had 342 patches followed by Tree Toppling with 249 patches. One hundred seventy nine patches were mapped as Development and 23 as Agricultural Clearing.

Within LEWI, Tree Toppling was the most frequently occurring category with 15 patches detected. All other change types within the park had fewer than 10 patches.

The year with the greatest number of patches was 2008, mostly consisting of Clearing. The next largest year was 2009 with the Windthrow Salvage category contributing the largest number of patches.

Table 8. The number of patches[1] and percent of total contributed by each landscape change type inside and outside the Lewis and Clark National Historical Park (LEWI) boundary, Washington and Oregon from 1985 to 2011.

Change Type	Large Study Area	%Large Study Area	Inside LEWI	% Inside LEWI	2 km Study Area	% 2 km Study Area
Agricultural Clearing	23	0.83	0	0	7	2.83
Clearing	1968	70.8	9	28	138	55.87
Coastal	10	0.36	6	19	2	0.81
Development	179	6.44	0	0	44	17.81
Mass Movement	5	0.18	0	0	0	0
Progressive Defoliation	2	0.07	0	0	0	0
Tree Toppling	249	8.96	15	47	22	8.91
Wetland Restoration	0	0	2	6	0	0
Windthrow Salvage	342	5.32	0	0	34	13.77
Grand Total	**2778**	**–**	**32**	**–**	**247**	**–**

[1] A single patch does not necessarily represent a single event.

Size of Patches

The five largest patches detected were all Windthrow Salvage from 2008, with the largest patch covering nearly 400 ha (988 ac). The largest patch within the LEWI boundary was a 99 ha (245 ac) Tree Toppling inside the Fort Clatsop unit. The average size of the Windthrow Salvage patches (10.8 ha (26.6 ac)) was slightly bigger than the average Clearing patches (9.3 ha (23 ac)) (Table 9). This is due to the significant number of very large patches in the Windthrow Salvage category (Figure 17). The median value of Clearing patches is slightly larger than that of Windthrow Salvage patches. The extent of Windthrow Salvage patches is likely exaggerated due to our methods of merging together all adjacent pixels with the same year of change onset. This results in some Tree Toppling pixels that were not cleared to be included within the cleared patches.

Table 9. Patch size characteristics of different landscape change types from 1985 to 2011 within the Lewis and Clark National Historical Park study area, Washington and Oregon.

	Patch size (ha)		
Change Type	**Mean**	**Median**	**Variance**
Agricultural Clearing	4.54	2.25	28.90
Clearing	9.28	2.78	195.66
Coastal	2.57	1.44	6.6
Development	2.21	1.35	4.88
Mass Movement	1.13	1.26	0.05
Progressive Defoliation	2.02	2.02	0.10
Tree Toppling	2.99	1.44	50.76
Wetland Restoration	0.94	0.94	0.002
Windthrow Salvage	10.76	2.16	1497.85

Agricultural Clearing patches averaged 4.4 ha (10.9 ac) in size. The two largest patches in this category were 23 and 17 ha (57 and 42 ac) permanently cleared in 1992 and 1989 just to the northwest and north of the Fort Clatsop unit (Figure 22), which were previously State Forest Lands. The largest Coastal patch of 4.8 ha (11.8 ac) from 1998 corresponds to a major storm event in winter of 1997-8 when vegetation was removed along the coast of Cape Disappointment State Park (Kaminsky et al. 1998). There was a moderate storm event the following winter. We mapped about 25 ha (61.8 ac) of vegetation loss at Cape Disappointment resulting from these two storms.

As mentioned earlier in the report, the largest Tree Toppling patch covering almost 100 ha (247 ac) was mapped at Fort Clatsop unit of LEWI following the 2007 storm. The next largest at 30 ha (74 ac) also occurred within the administrative park boundary, inside the Sunset Beach unit. All other Tree Toppling patches larger than 10 ha (25 ac) that were not subsequently cleared by 2011 occurred on private timber lands.

Only one of the largest four Development patches included actual building of housing. The largest Development patch of over 15 ha (37 ac) occurred in 2004 on Oregon Department of Military lands. Forest was cleared and the area remains open as of 2017 NAIP photos. The second largest patch was cleared in 1998 to the east of city of Seaside. It remains open with no structures. The third and fourth largest Development patches at 12 and 10 ha (30 and 25 ac) each are associated with city of Ilwaco, Washington. One was cleared north of the city and is now partially developed. The second was cleared in 1998 for a city reservoir.

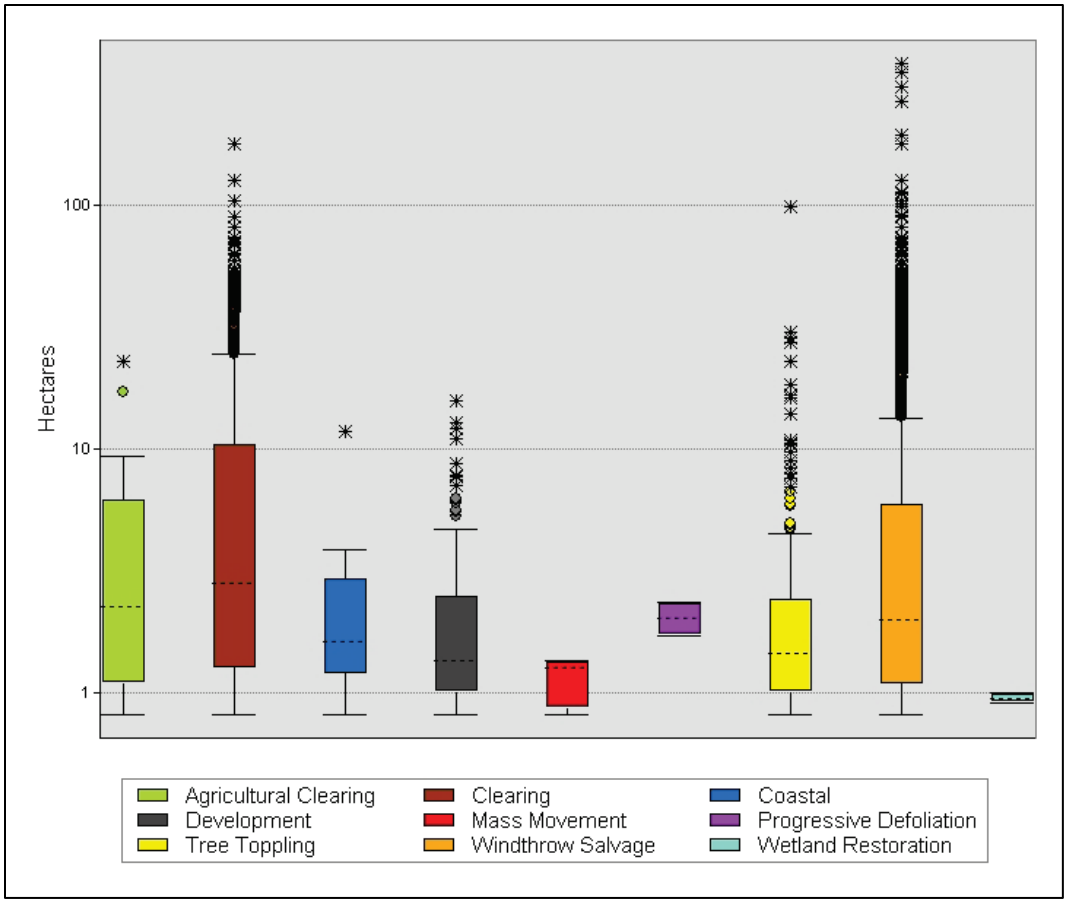


Figure 22. Patch size by change category within the Lewis and Clark National Historical Park large study area. Dashed lines represent median, boxes represent quartiles (middle 50% of data points), whiskers are 1.5 interquartile range (1.5 times the box length). Circles represent "mild" outliers that occur between 1.5 and 3 times the box length. Stars represent "extreme" outliers that occur beyond 3 times the box length.

The largest Clearing of 177 ha (437 ac) occurred on private timber lands in Oregon. The next five largest, ranging from 73 to 127 ha (180 to 314 ac), all occurred in 2008 on Oregon private timber lands.

The five largest Windthrow Salvage patches, ranging from 193 to 381 ha (477 to 941 ac), occurred on private timber lands. The next two patches of just over 100 ha (247 ac) were on Oregon Department of Forestry and City of Astoria lands east of the city.

Summary of Impact of Great Coastal Gale of 2007

The results of our monitoring of LEWI provide a summary of the impact of the Great Coastal Gale, the legacy effects of which will dominate the landscape both inside and outside the park for decades.

We were able to differentiate windthrown areas that were salvaged from Clearings using Landsat image chips and spectral trajectories of patches. Although the 2009 aerial photos (the first available high resolution aerial photos available after the 2007 storm) showed a large number of patches that

appeared to be cleared, the spectral signatures and the 2008 Landsat image chips showed gradual loss of cover indicating a more complex story. Figure 23 demonstrates the validation process for Windthrow Salvage patches using a) before and after NAIP aerial photos, b) the spectral trajectory of the pixels within the patch, and c) the annual Landsat image chips. The before and after aerial photos in Figure 23a show two patches that were cleared between 2005 and 2009.

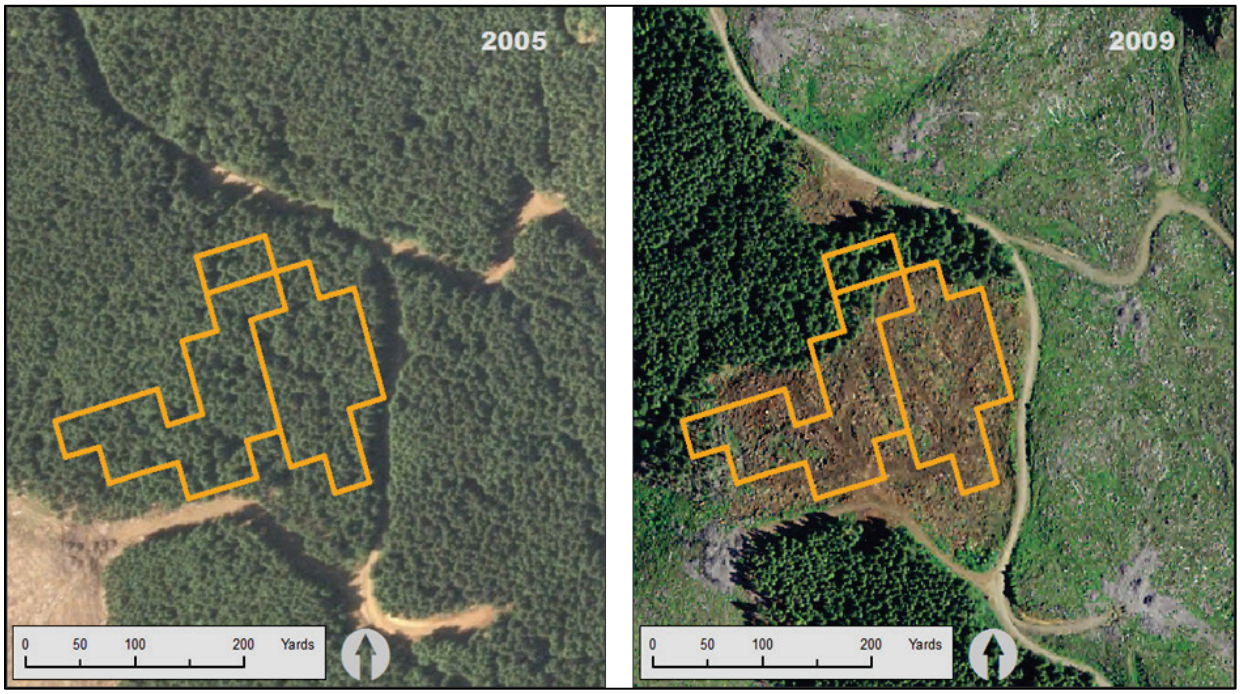


Figure 23a. Comparison of "before and after" aerial photos of the Clearing change type.

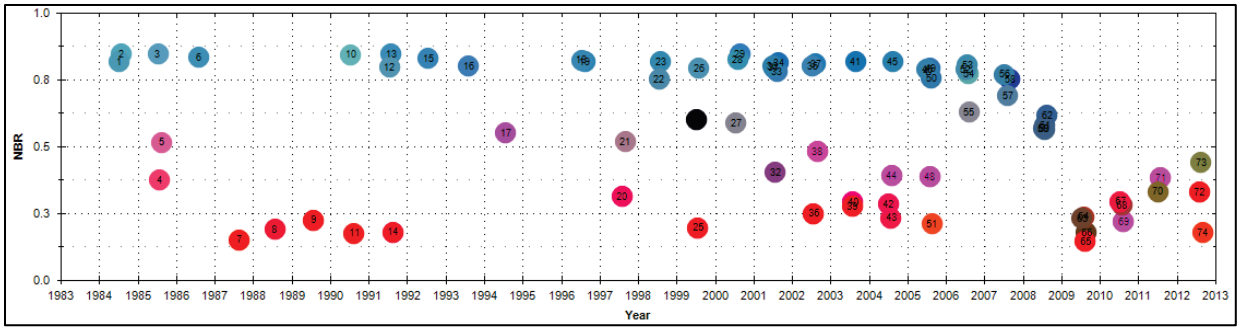


Figure 23b. Spectral trajectory of a Windthrow Salvage patch showing gradual loss of vegetation cover between 2007 and 2010. Bright red and magenta colors indicate cloudy images.

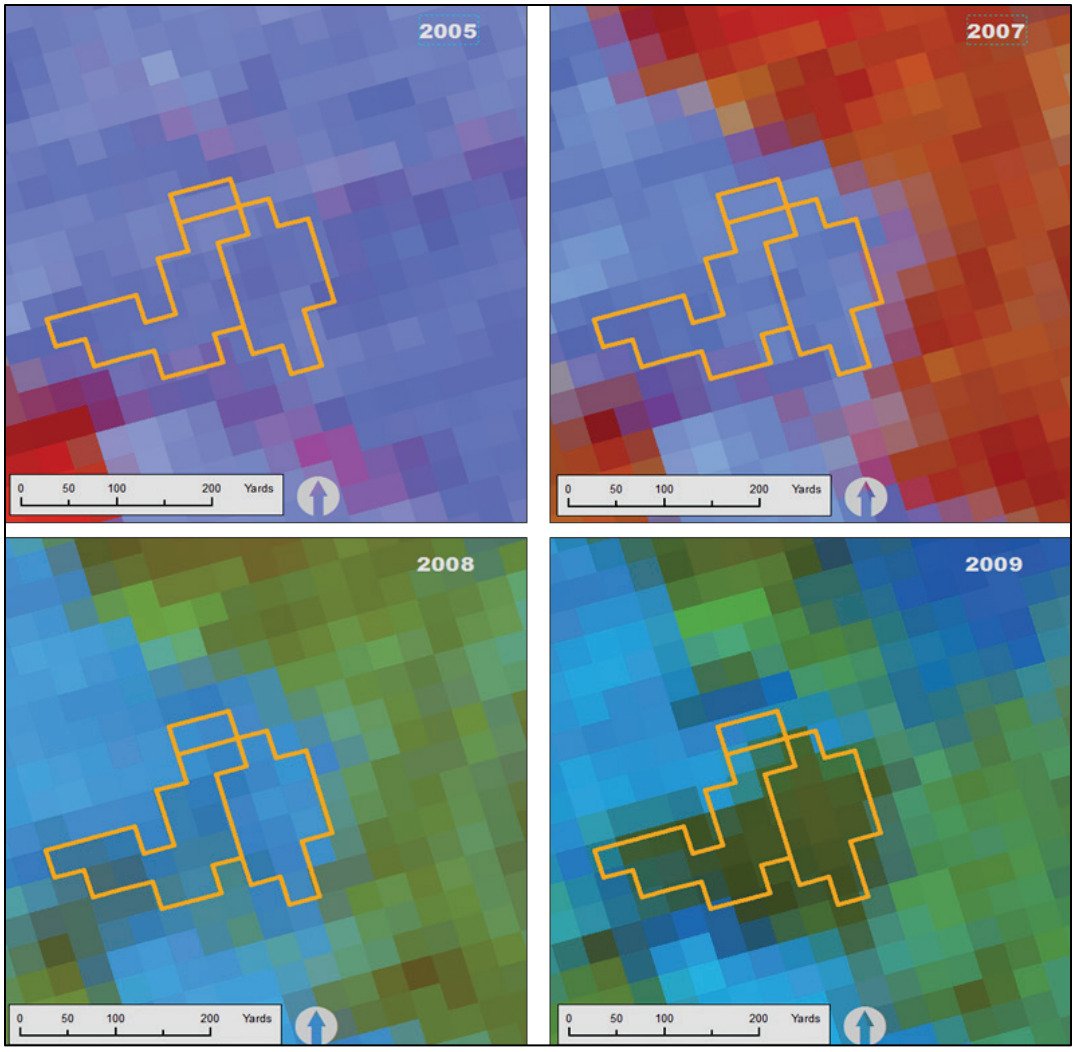


Figure 23c. Annual Landsat image chips of a Windthrow Salvage patch showing gradual loss of vegetation cover over a period of two years.

The spectral trajectory of the same area in Figure 23b indicates the patch was canopy conifer forest through summer of 2007 (dark blue/green color in the tasseled-cap transformation). Following the December 2007 storm, the spectral index (Normalized Burn Ratio (NBR)) values drop slightly in the summer 2008 images indicating a decrease in greenness and wetness. Images from the summer of 2009 show further decrease in NBR signaling complete removal of vegetation (bare soil shown in reddish brown colors).

Our methods detected a total of 4,413 ha (10,905 ac) of change from this one 2007 storm event (Table 10). One hundred and sixty one hectares of trees were toppled inside the LEWI boundary (mostly in the Fort Clatsop unit) and were left on the ground, reflecting NPS management policies to let natural processes dominate. Outside the park boundary, the storm had significant ecological and economic impacts on private and public forests. A total of 3,680 ha (9,093 ac) of forests within the state and private timberlands were windthrown and then subsequently salvaged during 2008, 2009

and 2010 (captured as Windthrow Salvage category in this report). An additional 570 ha (1,409 ac) of forest remained as Toppling as of 2011.

Table 10. Summary of hectares of change due to the 2007 Great Coastal Gale, Lewis and Clark National Historical Park (LEWI), Oregon and Washington.

Change Type	In LEWI	Large Study Area
Tree Toppling	161.12	571.22
2008 Windthrow Salvage	–	3172.80
2009 Windthrow Salvage	–	294.81
2010 Windthrow Salvage	–	212.97
Total	**161.12**	**4251.8**

The map of change shows the highly localized impacts of the storm on forests in the region (Figure 24). Wind measurements from weather stations in the area show both high sustained winds and near record or record peak gusts. However we did not detect Tree Toppling or Windthrow Salvage to the same extent in the northern part of the study area as compared to south of the Columbia River. Further studies could evaluate the role of forest management practices, stand age and topography in this result.

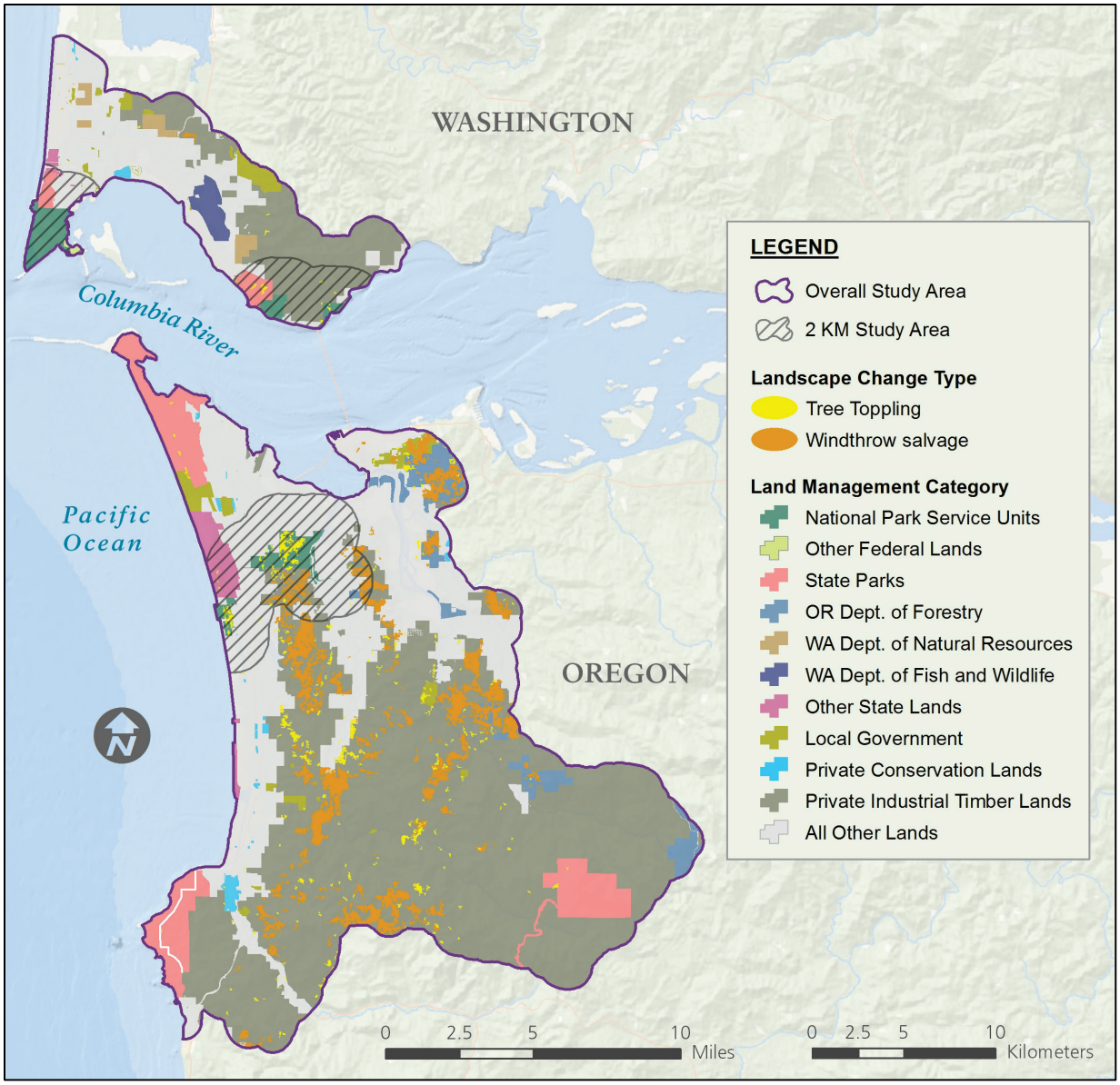


Figure 24. Tree Toppling and Windthrow Salvage due to the 2007 Great Coastal Gale, Lewis and Clark National Historical Park large study area, Oregon and Washington.

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

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Natural Resource Stewardship and Science
1201 Oakridge Drive, Suite 150
Fort Collins, CO 80525