



# **Landscape Disturbance Status and Trend Analysis Report for the North Coast and Cascades Inventory and Monitoring Network, 1987–2017**



Hayes Fire Flames and Smoke, Olympic National Park, 2016.

NPS

# **Landscape disturbance status and trend analysis report for the North Coast and Cascades Inventory and Monitoring Network, 1987–2017**

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# Contents

|                                                                                                                                                                | Page |
|----------------------------------------------------------------------------------------------------------------------------------------------------------------|------|
| Figures.....                                                                                                                                                   | v    |
| Tables.....                                                                                                                                                    | vii  |
| Abstract.....                                                                                                                                                  | ix   |
| Executive Summary.....                                                                                                                                         | x    |
| Acknowledgments.....                                                                                                                                           | xi   |
| Acronyms.....                                                                                                                                                  | xii  |
| Glossary.....                                                                                                                                                  | xiii |
| Introduction.....                                                                                                                                              | 1    |
| Study Area.....                                                                                                                                                | 3    |
| Potential Natural Vegetation.....                                                                                                                              | 4    |
| Methods.....                                                                                                                                                   | 9    |
| Detecting Disturbances Using the NCCN Landscape Change Monitoring Protocol.....                                                                                | 9    |
| Summaries of Disturbance Activity (1987–2017) Within National Park Boundaries.....                                                                             | 10   |
| Analyzing Trends in Annual Disturbance Area, Patch Size, and Number of Events<br>(1987–2017).....                                                              | 11   |
| Assessing Differences in Disturbance Activity (Annual Disturbance Area, Patch<br>Size, and Number of Events) Between Two Periods: 1987–1999 and 2000–2017..... | 11   |
| Assessing Stand Ages Affected by Different Change Types.....                                                                                                   | 14   |
| Results.....                                                                                                                                                   | 15   |
| Cumulative Area Affected by Disturbances Across All Parks (1987–2017).....                                                                                     | 15   |
| Cumulative Area Affected by Disturbances Within Each Park Boundary (1987–<br>2017).....                                                                        | 17   |
| Temporal Trends in Annual Disturbance Area, Mean Patch Size, and Number of<br>Events by Change Type.....                                                       | 21   |
| Differences in Disturbance Activity (Area, Mean Patch Size, and Number of Events)<br>Between 1987–2000 and 2001–2017.....                                      | 25   |
| Distribution of Stand Ages Affected by Disturbance (1987–2017).....                                                                                            | 25   |
| Prevalence of Overlapping Disturbances (i.e., More Than One Disturbance<br>Occurring in the Same Place).....                                                   | 29   |

## Contents (continued)

|                                                                                                                                                                     | Page |
|---------------------------------------------------------------------------------------------------------------------------------------------------------------------|------|
| Discussion .....                                                                                                                                                    | 36   |
| Fire Was the Most Extensive Disturbance Affecting NPS Land and Adjacent<br>Federally Protected Areas.....                                                           | 36   |
| Increasing Mean Annual Patch Size of Fire Disturbances Reflects Relatively Large<br>Wildfire Events During the Latter Half of the Period Examined (1987–2017) ..... | 37   |
| Defoliation Activity Peaked in the Mid-2000s Consistent with Regional Insect<br>Outbreaks.....                                                                      | 39   |
| No Significant Trends in Disturbance Activity for Other Disturbances .....                                                                                          | 39   |
| Minimal Overlapping Disturbances Across the Study Areas .....                                                                                                       | 40   |
| Stand Ages Affected by Disturbance .....                                                                                                                            | 40   |
| Limitations and Areas of Future Research .....                                                                                                                      | 41   |
| Literature Cited .....                                                                                                                                              | 42   |
| Appendix.....                                                                                                                                                       | 48   |

# Figures

|                                                                                                                                                                                                                        | Page |
|------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------|------|
| <b>Figure 1.</b> The North Cascades National Park Service Complex study area (NOCA study area), Olympic National Park study area (OLYM study area), and Mount Rainier National Park study area (MORA study area). .... | 4    |
| <b>Figure 2.</b> Potential Natural Vegetation (PNV) zones within North Cascades National Park Service Complex, WA. ....                                                                                                | 6    |
| <b>Figure 3.</b> Potential Natural Vegetation (PNV) zones within Olympic National Park, WA. ....                                                                                                                       | 7    |
| <b>Figure 4.</b> Potential Natural Vegetation (PNV) zones within Mount Rainier National Park, WA. ....                                                                                                                 | 8    |
| <b>Figure 5.</b> Mean monthly vapor pressure deficit (kPa). ....                                                                                                                                                       | 13   |
| <b>Figure 6.</b> Disturbances within the North Cascades National Park (NOCA) study area (1987–2017). ....                                                                                                              | 19   |
| <b>Figure 7.</b> Disturbances within the Olympic National Park (OLYM) study area (1987–2017). ....                                                                                                                     | 20   |
| <b>Figure 8.</b> Disturbances within the Mount Rainier National Park (MORA) study area (1987–2017). ....                                                                                                               | 21   |
| <b>Figure 9.</b> Temporal trends in disturbance within all three study areas combined. ....                                                                                                                            | 23   |
| <b>Figure 10.</b> Temporal trends in disturbance within the North Cascades National Park Service Complex (NOCA) study area. ....                                                                                       | 23   |
| <b>Figure 11.</b> Temporal trends in disturbance within the Olympic National Park (OLYM) study area. ....                                                                                                              | 24   |
| <b>Figure 12.</b> Temporal trends in disturbance within the Mount Rainier National Park (MORA) study area. ....                                                                                                        | 24   |
| <b>Figure 13.</b> Stand ages within the North Cascades National Park Service Complex (NOCA) study area. ....                                                                                                           | 26   |
| <b>Figure 14.</b> Stand ages within the Olympic National Park (OLYM) study area. ....                                                                                                                                  | 27   |
| <b>Figure 15.</b> Stand ages within the Mount Rainier National Park (MORA) study area. ....                                                                                                                            | 28   |
| <b>Figure 16.</b> The Kolmogorov–Smirnov test statistic (D) and the departure index (M) for each combination of study area and change type. ....                                                                       | 29   |
| <b>Figure 17.</b> Overlapping disturbances within the North Cascades National Park Service Complex (NOCA) study area. ....                                                                                             | 31   |
| <b>Figure 18.</b> Overlapping disturbances within the Olympic National Park (OLYM) study area. ....                                                                                                                    | 32   |

## Figures (continued)

|                                                                                                                                                                                                                                             | Page |
|---------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------|------|
| <b>Figure 19.</b> Overlapping disturbances within the Mount Rainier National Park (MORA) study area. ....                                                                                                                                   | 33   |
| <b>Figure 20.</b> Potential Natural Vegetation (PNV) zones within the North Cascades National Park Service Complex (NOCA) study area. ....                                                                                                  | 49   |
| <b>Figure 21.</b> Potential Natural Vegetation (PNV) zones within the Olympic National Park (OLYM) study area. ....                                                                                                                         | 50   |
| <b>Figure 22.</b> Potential Natural Vegetation (PNV) zones within the Mount Rainier National Park (MORA) study area. ....                                                                                                                   | 51   |
| <b>Figure 23.</b> Conceptual diagram of LandTrendr pixel time series segmentation, borrowed from Kennedy et al., 2018 ( <a href="https://emapr.github.io/LT-GEE/landtrendr.html">https://emapr.github.io/LT-GEE/landtrendr.html</a> ). .... | 52   |
| <b>Figure 24.</b> Temporal trends in disturbance within the eastern portion of the North Cascades National Park Service Complex (NOCA) study area. ....                                                                                     | 57   |
| <b>Figure 25.</b> Temporal trends in disturbance within the western portion of the North Cascades National Park Service Complex (NOCA) study area. ....                                                                                     | 57   |
| <b>Figure 26.</b> Temporal trends in disturbance within the eastern portion of the Olympic National Park (OLYM) study area. ....                                                                                                            | 58   |
| <b>Figure 27.</b> Temporal trends in disturbance within the western portion of the Olympic National Park (OLYM) study area. ....                                                                                                            | 58   |
| <b>Figure 28.</b> Temporal trends in disturbance within the eastern portion of the Mount Rainier National Park (MORA) study area. ....                                                                                                      | 59   |
| <b>Figure 29.</b> Temporal trends in disturbance within the western portion of the Mount Rainier National Park (MORA) study area. ....                                                                                                      | 59   |

# Tables

|                                                                                                                                                                                                                                                                                                                                                                                                                                        | Page |
|----------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------|------|
| <b>Table 1.</b> Area (ha) and percent (%) of Potential Natural Vegetation zones within NOCA, MORA, and OLYM park boundaries. ....                                                                                                                                                                                                                                                                                                      | 5    |
| <b>Table 2.</b> Description of each change type (Copass and Antonova 2022).....                                                                                                                                                                                                                                                                                                                                                        | 9    |
| <b>Table 3.</b> Description, units, and scale of climate variables. ....                                                                                                                                                                                                                                                                                                                                                               | 12   |
| <b>Table 4.</b> Cumulative area disturbed (ha), percentage of total area disturbed (%), and number of disturbance events of each change type within boundaries of North Cascades National Park Service Complex, Olympic National Park, and Mount Rainier National Park, combined. ....                                                                                                                                                 | 15   |
| <b>Table 5.</b> Cumulative area disturbed (ha), percentage of total area disturbed (%), and number of disturbance events of each change type by geographic region (west or east side; Figure 1) for within boundaries of North Cascades National Park Service Complex, Olympic National Park, and Mount Rainier National Park, combined.....                                                                                           | 16   |
| <b>Table 6.</b> Cumulative area disturbed (ha), percentage of total area disturbed (%), percentage of park area disturbed (%), and number of disturbance events of each change type within the North Cascades National Park Service Complex, Olympic National Park, and Mount Rainier National Park. ....                                                                                                                              | 18   |
| <b>Table 7.</b> Summary results of statistically significant trends in disturbance activity (i.e., annual disturbance area, mean patch size, and number of events) from 1987 to 2017 across three scales: (1) all study areas combined, (2) within each study area, and (3) within each study area and georegion (east versus west side of the study areas). ....                                                                      | 22   |
| <b>Table 8.</b> The amount of disturbed area (ha) and percentage of disturbed area (%) that experienced a single disturbance (number of disturbances = 1) or multiple disturbances (number of disturbances > 1) from 1987 to 2017 within the North Cascades National Park Service Complex (NOCA) study area, Olympic National Park (OLYM) study area, Mount Rainier National Park (MORA) study area, and all study areas combined..... | 30   |
| <b>Table 9.</b> Types of overlapping disturbances and corresponding areas within the NOCA, MORA, and OLYM study areas. ....                                                                                                                                                                                                                                                                                                            | 34   |
| <b>Table 10.</b> Total area (ha) and percentage (%) of the study area of each potential natural vegetation (PNV) zone within the North Cascades National Park Service Complex (NOCA) study area, the Olympic National Park (OLYM) study area, and the Mount Rainier National Park (MORA) study area.....                                                                                                                               | 48   |
| <b>Table 11.</b> Cumulative area disturbed (ha), percentage of total area disturbed (%), and number of disturbance events for each change type within all study areas combined (i.e., NOCA, OLYM, and MORA study areas).....                                                                                                                                                                                                           | 53   |

## Tables (continued)

|                                                                                                                                                                                                                                                                                                 | Page |
|-------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------|------|
| <b>Table 12.</b> Cumulative area disturbed (ha), percentage of total area disturbed (%), and number of disturbance events of each change type by geographic region (west or east side of the study areas) within all three study areas combined (i.e., NOCA, OLYM, and MORA study areas). ..... | 53   |
| <b>Table 13.</b> Cumulative area disturbed (ha), percentage of total area disturbed (%), and number of disturbance events of each change type within each study area (NOCA, OLYM, and MORA).....                                                                                                | 55   |
| <b>Table 14.</b> The amount (ha) and percentage (%) of area each fire regime group (FRG) occupies within all three park study areas combined, and the percentage (%) of cumulative area burned (1987–2017) that occurred within each fire regime group. ....                                    | 60   |
| <b>Table 15.</b> The amount (ha) and percentage (%) of area each fire regime group (FRG) occupies within each park study area, and the percentage (%) of cumulative area burned (1987–2017) that occurred within each fire regime group. ....                                                   | 60   |

## Abstract

Disturbance is a key characteristic of landscapes that significantly influences ecosystem functions such as carbon storage, water storage, and nutrient cycling, as well as ecosystem structure and productivity. This report summarizes disturbance patterns and trends for three national parks—North Cascades National Park Service Complex, Olympic National Park, and Mount Rainier National Park—and adjacent federally protected wilderness areas in the Pacific Northwest. We assessed changes greater than 0.8 ha across a 31-year period from 1987 through 2017 as detected using freely available satellite imagery, an automated change detection algorithm, and human review to identify and label disturbance areas in the following categories: Fire, Riparian Change, Avalanche, Defoliation, Mass Movement, Blowdown, Coastal Change, Ice Damage, Development, and Clearing. Fire was the predominant disturbance category for all parks combined, affecting 78% of cumulative disturbed area, followed by Defoliation which affected approximately 12% of total disturbed area. Generalized linear models indicated significant increases of annual disturbed area affected by Fire at Mount Rainier and Olympic National Park. Mean disturbance patch size also increased for Mount Rainier and all park study areas combined. Additionally, the number of Defoliation disturbance events at North Cascades National Park Service Complex and in all park study areas combined increased in the latter half of the study period (2000 to 2017) compared with the first half, as well as annual area affected by Defoliation in the eastern portion of North Cascades. These results, maps, and summaries provide useful baseline information about the frequency, extent, and magnitude of landscape change processes in and adjacent to our parks that can be used for guiding natural resource planning and understanding disturbance patterns in remote wilderness areas.

## Executive Summary

Monitoring landscape-scale trends in disturbance activity within national parks is increasingly important in a changing climate. Information about changes to the frequency, extent, intensity, and distribution of disturbance events can be used to guide park management and resource use. This information can also provide insight about the condition and trajectory of natural resources and interrelated environmental indicators (e.g., water quality or wildlife habitat) and potential increased risks to park infrastructure. Here, we assessed qualitative and statistical trends in disturbance activity from 1987 to 2017 within the North Cascades National Park Service Complex (NOCA), Olympic National Park (OLYM), and Mount Rainier National Park (MORA) and adjacent federally protected areas. We used remote sensing techniques following the North Coast and Cascades Inventory and Monitoring Network (NCCN) Landscape Change Monitoring Protocol to identify the extent, magnitude, and number of disturbance patches annually. Disturbance patches were then manually labeled with one of the following disturbance categories: Fire, Riparian Change, Avalanche, Defoliation, Mass Movement, Blowdown, Coastal Change, Ice Damage, Development, or Clearing. Trends in annual disturbance area, mean patch size, and number of events for each disturbance type were analyzed using generalized linear models within each park study area and across all study areas combined. We also tested for significant differences in disturbance activity between the first and second half of the study period (i.e., 1987 to 1999 and 2000 to 2017) as the climate has warmed.

Overall, fire was the most extensive disturbance affecting the study area, accounting for 78% of cumulative disturbance area from 1987 to 2017. While the observed fire size and frequency within study areas aligned with expectations of historical fire regimes, our findings highlight that, among disturbances, fire is likely to have the greatest effects on park infrastructure, recreation, and resources. Defoliation, Avalanche, and Riparian Change were the next most extensive disturbances, affecting 12, 4, and 4% of cumulative disturbance area from 1987 to 2017, respectively. Statistical models indicated significant increases in annual area affected by Fire from 1987 to 2017 within the MORA and OLYM study areas and increases in annual mean patch size within the MORA study area and all study areas combined. Annual Defoliation area also increased within MORA and the western portion of NOCA over the study period, though visually these models indicated poor fit due to non-linear trends in Defoliation activity. No other disturbance types had significant trends for the full study period of 1987 to 2017.

The annual number of Defoliation events was greater in the second half of the study period (2000–2017) within the NOCA study area and all study areas combined, and the annual area of Defoliation events was greater in the eastern portion of NOCA during the second half of the study period. We found that 80% of cumulative disturbance activity occurred in the eastern portions of parks, suggesting these areas may continue to be more disturbance prone in the future under regional warming and drying scenarios. Finally, we found that Defoliation activity peaked from 2001 to 2007 consistent with regional insect outbreaks. These findings highlight the spatial and temporal patterns of disturbance activity within three of the largest NCCN parks and have important implications for natural resource planning and management within the National Park Service.

## Acknowledgments

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## Acronyms

**ADS:** Aerial detection survey

**GLM:** Generalized linear model

**GNN:** Gradient nearest neighbor

**I&M:** Inventory and Monitoring Program

**LandTrendr:** Landsat-based detection of trends in disturbance and recovery

**LEMMA:** Landscape Ecology Modeling Mapping and Analysis

**MORA:** Mount Rainier National Park

**NOCA:** North Cascades National Park Service Complex

**NPS:** National Park Service

**NCCN:** North Coast and Cascades Inventory and Monitoring Network

**OLYM:** Olympic National Park

**PNV:** Potential natural vegetation

**SPEI:** Standardized precipitation evapotranspiration index

**SWE:** Snow water equivalent

**TEUI:** Terrestrial Ecological Unit Inventory

**USFS:** United States Forest Service

**VPD:** Vapor pressure deficit

## Glossary

**Disturbance:** Any relatively discrete event in time that disrupts the structure of an ecosystem, population, or community (definition from Pickett and White, 1985).

**Disturbance regime:** Spatial and temporal dynamics of disturbances that occur over long time periods (definition from Turner 2010), often describing the characteristic patterns of disturbance size, frequency, and severity.

**Normalized burn ratio (NBR):** a vegetation index produced from surface reflectance images using bands in the near-infrared (NIR) and shortwave infrared (SWIR) wavelengths that are sensitive to photosynthetic vegetation and moisture content of soil and vegetation. High values of NBR typically indicate abundant and healthy vegetation while low NBR values indicate low vegetation cover.

**Potential natural vegetation (PNV):** Environmentally constrained vegetation expected to occur in the absence of disturbance.

# Introduction

The mission of the National Park Service (NPS), which encompasses over 85 million acres across 433 park units, is to protect natural and cultural resources of the National Park System for the benefit of current and future generations (NPS Organic Act of 1916). In 1998, the NPS established the Natural Resource Inventory and Monitoring (I&M) Program to determine the presence, distribution, and condition of natural resources and track how they are changing over time. The I&M Program includes 32 ecoregional networks each with a unique array of natural resources and priorities for what environmental indicators (also referred to as ‘vital signs’) should be monitored (Gross et al., 2012). Environmental indicators provide a measure of natural resource health and integrity and enable park managers to detect trends and potential threats to natural resources using reliable scientific information that can inform early-intervention management strategies. Examples of environmental indicators include weather and climate, atmospheric pollutants, water quality and quantity, presence of invasive species, and terrestrial wildlife and vegetation community dynamics (Weber et al., 2009).

Monitoring landscape dynamics is one of the highest ranked priorities across all I&M networks (Gross et al., 2012), however only a few networks currently implement this type of monitoring. One such network is the North Coast and Cascades Inventory and Monitoring Network (NCCN) which includes the three largest national parks in Washington state: the North Cascades National Park Service Complex (NOCA), Olympic National Park (OLYM), and Mount Rainier National Park (MORA). Dense and highly productive forests blanket the rugged terrain of the Olympic and Cascade Mountains within these three park units which encompass key natural resources including structurally complex old-growth forests, subalpine meadows, and alpine glaciers.

An important dimension of landscape dynamics is the pattern and process of changes created by disturbance, specifically the magnitude, spatial extent, and temporal frequency of such disturbances. A disturbance is a relatively discrete event that alters the physical environment and disrupts the ecological structure of an ecosystem, and that can be caused by biotic (e.g., insects or disease) or abiotic (e.g., avalanches or landslides) agents of change (Pickett and White, 1985). Disturbances increase landscape heterogeneity and are critical ecological processes that shape ecosystem structure, composition, and function (Turner, 2010). Organisms within many ecosystems are adapted to particular disturbance regimes—defined as the characteristic patterns of disturbance—including dimensions of frequency, size, and severity. However, there is uncertainty in how disturbance regimes and disturbance interactions might change in response to climate (Turner, 2010) and how ecosystems may recover following disturbance in a changing post-disturbance climate (e.g., Davis et al., 2019). Monitoring disturbance activity within the National Park System establishes a baseline for future comparisons and informs spatial and temporal patterns of disturbance that can help inform park management and resource use as disturbances can affect park infrastructure (e.g., wildfires that damage park buildings), recreational access (e.g., floods that damage roads), and management costs (e.g., use of park resources to suppress wildfires). Monitoring disturbance activity also provides key information about the condition of natural resources and other interrelated environmental indicators

(e.g., air and water quality or wildlife diversity). For example, severe disturbances may reset stand succession and reduce the amount of old-growth forests present in parks or may affect habitat quality for important wildlife species (e.g., elk, marbled murrelet, or wolverines). Finally, relating disturbance patterns to climate drivers can provide important insights on the current and likely future effects of changing climate on the character and nature of park lands.

The NCCN Landscape Change and Monitoring Protocol was co-developed with Oregon State University (OSU) to detect the extent, duration, and magnitude of disturbance events greater than 0.8 ha within and adjacent to NCCN park units using remote sensing techniques (Antonova et al., 2012; Copass and Antonova, 2022; Kennedy et al., 2007). This protocol uses annual Landsat satellite imagery (<https://developers.google.com/earth-engine/datasets/catalog/landsat>) and the Landsat-based detection of trends in disturbance and recovery (LandTrendr) algorithm (Kennedy et al., 2007) to identify areas that experience a decline in spectral greenness over time (i.e., a loss in vegetation). Disturbance patches are identified as contiguous areas greater than 0.8 ha that experience a decline in spectral greenness above a certain threshold (Antonova et al., 2012; Copass and Antonova, 2022; Kennedy et al., 2007). Disturbance patches are then reviewed and manually labeled by park staff, using disturbance classes that include both anthropogenic (e.g., development) and natural disturbances (e.g., avalanches, fire, blowdown). The goal of developing and implementing this protocol was to document baseline disturbance activity within NCCN parks and to track how that activity may be changing over time to inform park planning and provide ecological context for other ecosystem indicators being monitored within NCCN (Copass and Antonova, 2022). This is particularly important as climate projections for the Pacific Northwest predict warmer temperatures, reduced snowpack, and lengthened summer dry seasons (Case et al., 2021; Mote and Salathé, 2010). Changes to precipitation are expected to be small, however, confidence in the magnitude and direction of expected changes to precipitation are less certain (Case et al., 2021; Mote and Salathé, 2010). The use of remote sensing techniques to detect disturbances allows for broad-scale disturbance mapping at annual time steps which is time and cost-effective relative to field methods, is easily reproducible, and allows for retrospective disturbance mapping dating back to the earliest available aerial imagery.

Here, we describe qualitative and statistical trends in annual disturbance activity over a 31-year period (1987–2017) within the three largest NCCN parks (NOCA, OLYM, and MORA) and adjacent protected areas in Washington state (USA) and British Columbia (Canada) using the dataset produced by the NCCN Landscape Change and Monitoring Protocol (Copass and Antonova, 2022). These findings describe where on the landscape disturbances are occurring and trends in annual disturbance area, mean patch size, and number of disturbance events over the 31-year period examined.

## Study Area

The study area for this analysis includes NOCA, OLYM, MORA, and all federally protected areas within a 16 km radius of park boundaries (Figure 1). Federally protected areas include United States Forest Service (USFS) designated wilderness areas and provincial parks within British Columbia, Canada (Figure 1). The expanded definition of the study area was intended to bolster the sample size with additional disturbance data from adjacent, similarly managed natural areas, and to provide context for observations within park areas. Throughout the report, references to NOCA, OLYM, MORA, or “the park” are specific to areas within the national park boundaries, whereas references to NOCA study area, OLYM study area, MORA study area or “the study area” denote areas within the national park boundaries and adjacent protected areas. Throughout the report, NOCA refers to the combined area of North Cascades National Park and Ross Lake and Lake Chelan National Recreation Areas. Each park study area was further divided into ‘east’ and ‘west’ sides to capture differences in precipitation gradients that may affect disturbance activity. In the MORA and NOCA study areas, the Cascade Range crest was used to divide the east and west sides of the park study areas (Figure 1). In the OLYM study area, the delineation of east and west was derived from 6-digit hydrologic unit code (HUC) watersheds and maps of watershed precipitation. Watersheds with above median precipitation were assigned to the western side of the OLYM study area while watersheds with below median precipitation were assigned to the eastern side of the OLYM study area. The eastern portions of all three study areas experience drier conditions relative to the western portions due to orographic effects of the Olympic Mountains and the Cascade Range.

Summary information about disturbances is reported for areas within the national park boundaries, with complementary information provided in the Appendix for all protected areas. To use the full sample size available in the dataset, the formal trend analyses included disturbances within all protected areas.

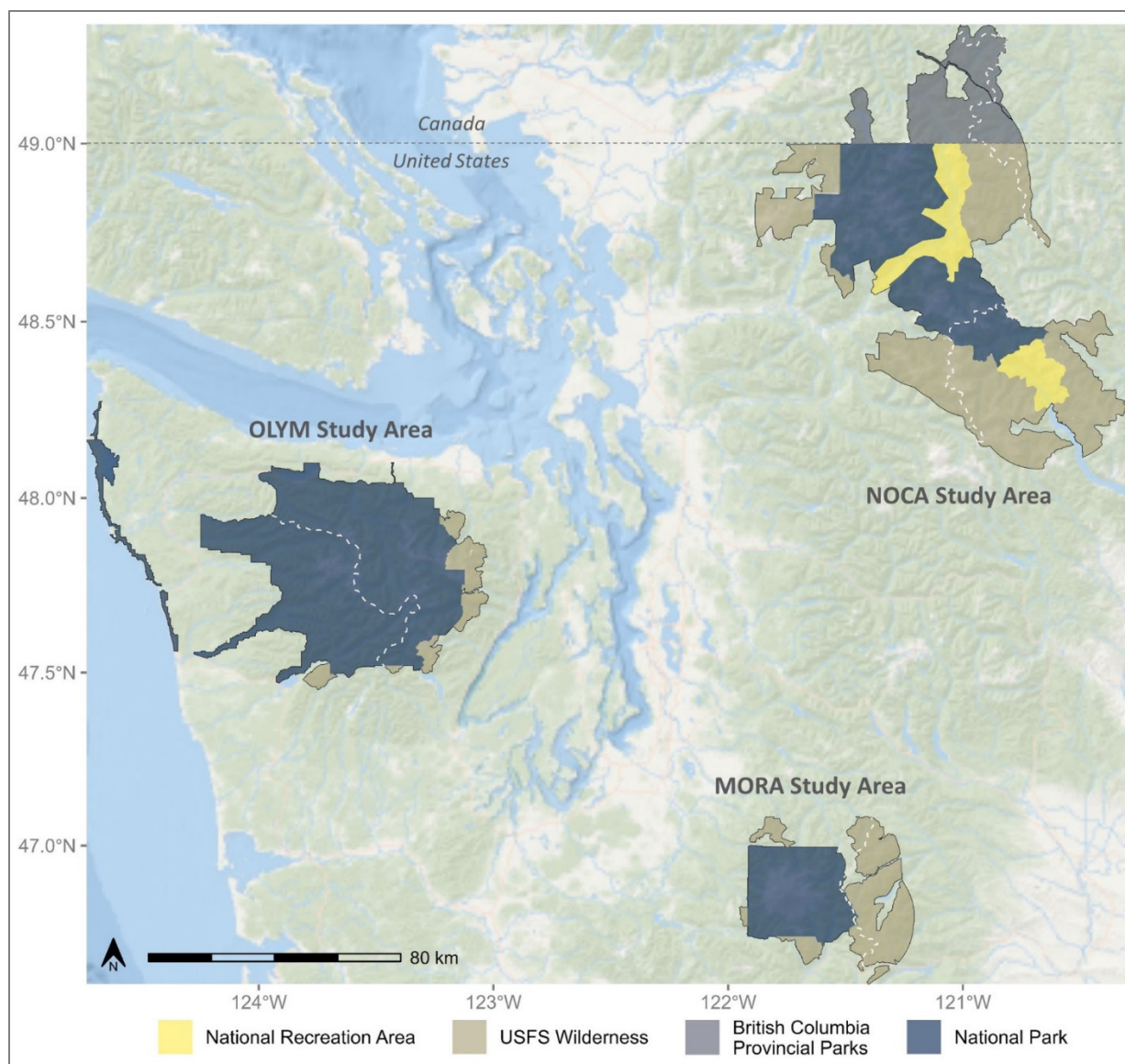


**Figure 1.** The North Cascades National Park Service Complex study area (NOCA study area), Olympic National Park study area (OLYM study area), and Mount Rainier National Park study area (MORA study area). The dashed white lines represent the east-west dividing line for each study area. Data ESRI.

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## Potential Natural Vegetation

We used potential natural vegetation (PNV) maps sourced from the USFS Pacific Northwest Region's Terrestrial Ecological Unit Inventory (TEUI) data viewer (<https://teui-region6-usfs.hub.arcgis.com/pages/data-viewer/>) to describe vegetation across the study area. The PNV zones represent vegetation expected to occur in a particular location based on historical climate and biophysical environment (i.e., soils, topography, geology) in the absence of disturbance and often encompass unique sets of ecosystem structure, composition, and function. In this analysis, PNV zones are a useful representation of vegetation because they are consistent over the period examined

(1987–2017) and map well onto management zones as they are situated within a specific climate and biophysical context.

The most common PNV zones across all parks were Pacific silver fir, mountain hemlock, western hemlock, parklands (i.e., high-elevation forests near treeline, often with low tree cover and highly variable openings), and subalpine fir/Engelmann spruce (Table 1, Figures 2–4). Olympic National Park had a relatively higher abundance of Sitka spruce, concentrated along the Pacific coast and river floodplains leading from the coast towards the west side of the Olympic Mountains (Table 1; Figure 3). North Cascades National Park Service Complex had a higher abundance of drier vegetation zones, the most common of which included the Douglas-fir and white fir/grand fir zones (Table 1; Figure 2).

**Table 1.** Area (ha) and percent (%) of Potential Natural Vegetation zones within NOCA, MORA, and OLYM park boundaries. The percentage of total area (%) was calculated by dividing the area of each PNV by the total area within each park boundary.

| Potential Natural Vegetation Zone | NOCA   |       | OLYM    |       | MORA   |       |
|-----------------------------------|--------|-------|---------|-------|--------|-------|
|                                   | (ha)   | (%)   | (ha)    | (%)   | (ha)   | (%)   |
| Pacific Silver Fir                | 55,585 | 23.31 | 150,922 | 43.01 | 36,714 | 46.97 |
| Western Hemlock                   | 53,416 | 22.40 | 66,852  | 19.05 | 8,142  | 10.42 |
| Parklands                         | 66,923 | 28.07 | 40,054  | 11.42 | 14,904 | 19.07 |
| Mountain Hemlock                  | 37,479 | 15.72 | 55,443  | 15.80 | 14,630 | 18.72 |
| Sitka Spruce                      | 2,527  | 1.06  | 27,568  | 7.86  | 804    | 1.03  |
| Subalpine Fir/ Engelmann Spruce   | 9,543  | 4.00  | 8,125   | 2.32  | 2,241  | 2.87  |
| Douglas-Fir                       | 7,034  | 2.95  | 277     | 0.08  | 50     | 0.06  |
| White Fir - Grand Fir             | 4,212  | 1.77  | 549     | 0.16  | 251    | 0.32  |
| Hardwoods                         | 689    | 0.29  | 825     | 0.24  | 195    | 0.25  |
| Grasslands - Meadows              | 266    | 0.11  | 197     | 0.06  | 218    | 0.28  |
| Shrublands                        | 482    | 0.20  | 7       | 0.00  | 11     | 0.01  |
| Lodgepole Pine                    | 263    | 0.11  | 45      | 0.01  | 11     | 0.01  |
| Ponderosa Pine                    | 12     | 0.01  | 0       | 0.00  | 0      | 0.00  |

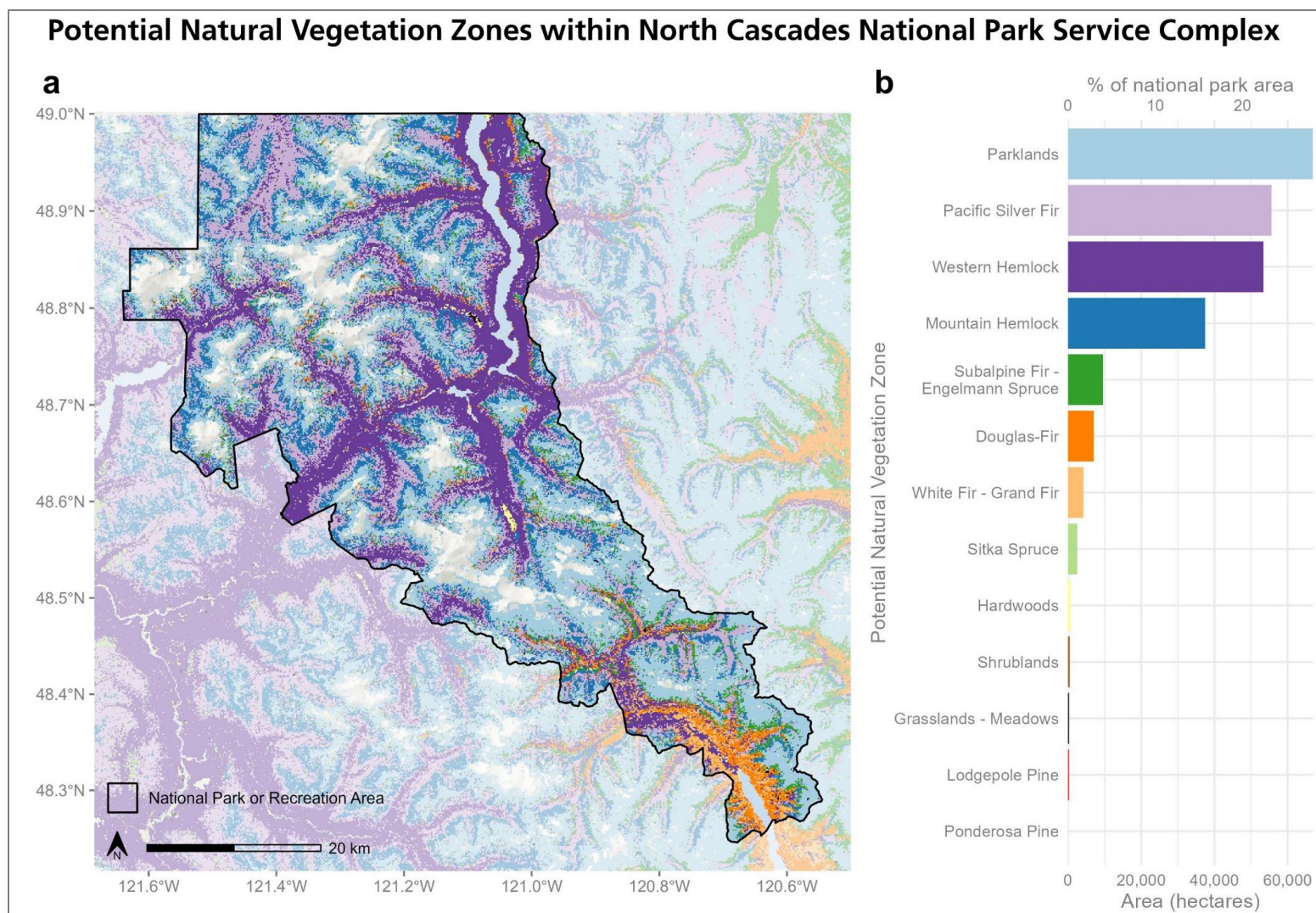


**Figure 2.** Potential Natural Vegetation (PNV) zones within North Cascades National Park Service Complex, WA. **(a)** Distribution of PNV zones within the park boundary. **(b)** Area (ha) and percentage (%) of the park occupied by each PNV zone. The colors on the bar graph correspond to the mapped PNV zones. Data from US Forest Service.

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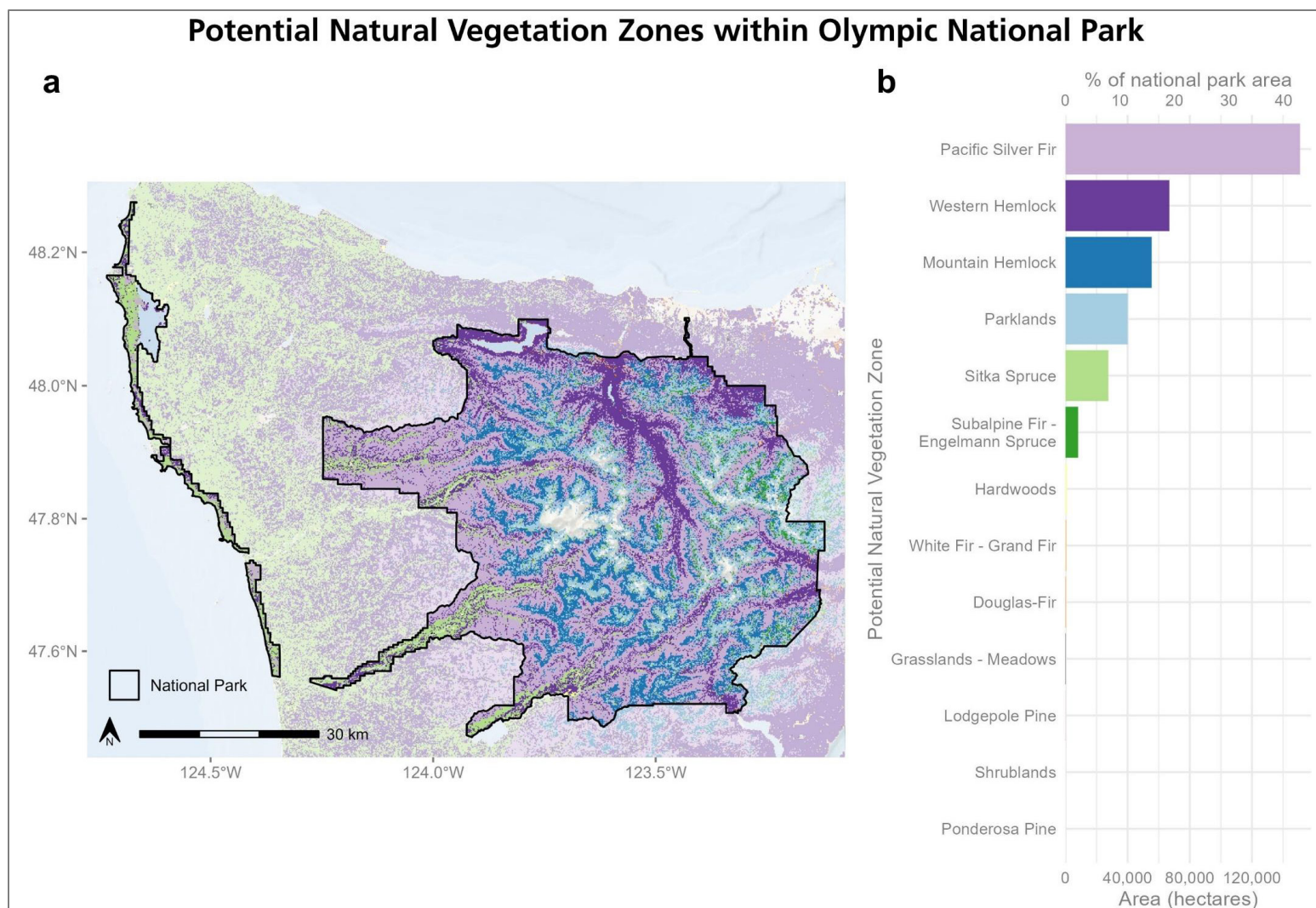


**Figure 3.** Potential Natural Vegetation (PNV) zones within Olympic National Park, WA. **(a)** Distribution of PNV zones within the park boundary. **(b)** Area (ha) and percentage (%) of the park occupied by each PNV zone. The colors on the bar graph correspond to the mapped PNV zones. Data from US Forest Service.

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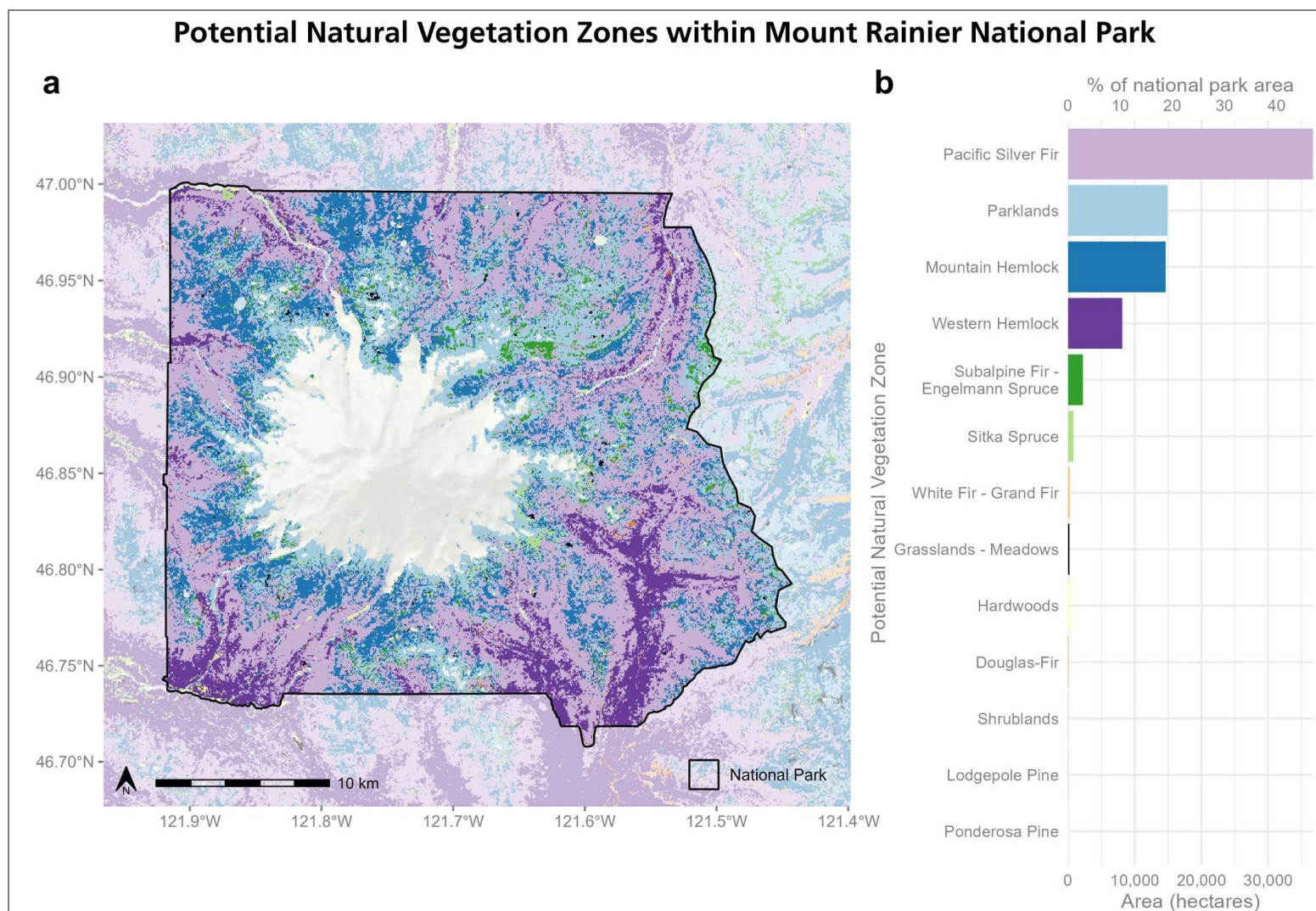


**Figure 4.** Potential Natural Vegetation (PNV) zones within Mount Rainier National Park, WA. **(a)** Distribution of PNV zones within the park boundary. **(b)** Area (ha) and percentage (%) of the park occupied by each PNV zone. The colors on the bar graph correspond to the mapped PNV zones. Data from US Forest Service.

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## Methods

### Detecting Disturbances Using the NCCN Landscape Change Monitoring Protocol

Disturbance patches from 1987 to 2017 in the study area were detected using the NCCN Landscape Change Monitoring Protocol version 2.1 (Copass and Antonova, 2022) (published dataset available here: <https://irma.nps.gov/DataStore/Reference/Profile/2310252>; NCCN et al., 2025 <https://irma.nps.gov/DataStore/Reference/Profile/2294375>). The protocol uses Landsat satellite imagery (Collection 1) with the LandTrendr algorithm in Google Earth Engine (GEE) to track the spectral trajectory of pixels within the study area and segment them into periods of relative stability and change (Gorelick et al., 2017; Kennedy et al., 2018, 2010; see supplementary figure in the Appendix). Disturbance patches were identified as groups of pixels (connected vertically, horizontally, or diagonally) that experienced spectral change that began in the same year and had a minimum size of 0.8 hectares. Python scripts developed by the Oregon State University Environmental Monitoring, Analysis, and Process Recognition Lab (eMapR) were used to automate the identification of disturbance patches. Information for each disturbance patch identified from the LandTrendr output layers included the detection year, duration (i.e., number of years it took for maximum spectral change to occur), and the average magnitude of spectral change. After disturbance patches were identified by LandTrendr, they were manually labeled as one of ten potential change types using historical aerial photography: Avalanche, Blowdown, Coastal Change, Clearing, Defoliation, Development, Fire, Ice Damage, Mass Movement, and Riparian Change (Table 2). Defoliation disturbances include insects, disease, or other unknown causes of tree mortality including drought. Manually labeling disturbances using aerial photography has been shown to be successful within the NCCN (i.e., overall agreement greater than 85% between office and field-assigned categories; Copass et al., 2019), reducing the need for field validation of each patch. For more detailed information on how disturbance patches were identified using LandTrendr in GEE and manually labeled, see Copass and Antonova (2022). Although the Landscape Change Monitoring Protocol provides information on disturbance magnitude, we did not include magnitude in our results because magnitude represents the raw difference in pre- and post-disturbance spectral signature and is not relativized to the pre-disturbance conditions (i.e., the same severity of disturbance ecologically may have different magnitudes depending on how green or densely vegetated the pre-disturbance environment was). Additionally, there were no statistically significant trends in mean annual disturbance magnitude.

**Table 2.** Description of each change type (Copass and Antonova 2022).

| Change Type                 | Description                                                                                                                                                   |
|-----------------------------|---------------------------------------------------------------------------------------------------------------------------------------------------------------|
| Avalanche                   | Long, linear change areas which originate in snow receiving zones or valley walls. Typically removes some but not all the vegetation.                         |
| Blowdown                    | 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. |
| Coastal Change <sup>A</sup> | Captures partial to complete vegetation removal due to storm surges or other factors unique to the coastal foredune and strand.                               |

<sup>A</sup> Disturbances removed from the trend analysis due to low sample size.

**Table 2 (continued).** Description of each change type (Copass and Antonova 2022).

| Change Type              | Description                                                                                                                                                                                                                                                                                                                                                                                                                                                                  |
|--------------------------|------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------|
| Clearing <sup>A</sup>    | Reflect a range of forest management practices, such as clearcuts, select cuts and thinning, and chemical removal of broadleaf vegetation. Differs from Development (see below) in that the vegetation can recover following removal.                                                                                                                                                                                                                                        |
| Defoliation              | Assigned to polygons where the forest remains but has undergone slow change in spectral values representing loss of greenness and wetness. Several agents of decline in tree health may be associated with this change type (e.g., insects, disease, drought, or other unidentifiable agents of change).                                                                                                                                                                     |
| Development <sup>A</sup> | 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.                                                                                                                                                                                                                                                                                                      |
| Fire                     | Includes both human-caused and natural events. Often corroborated from outside sources, wildland fires vary in intensity from full canopy removal to partial burns which leave behind a mixture of dead and singed trees.                                                                                                                                                                                                                                                    |
| Ice Damage <sup>A</sup>  | Vegetation damaged by heavy, long-lasting snowpack or ice followed by wind, generally characterized by broken tree branches.                                                                                                                                                                                                                                                                                                                                                 |
| Mass Movement            | Includes a variety of vegetation-removing changes that expose rock and bare ground: landslides, which are found on valley walls and away from streams; creeps, which are slow downward movements of slope-forming soil or rock; and debris flows that are associated with steep gullies and involve water. Mass Movement usually occurs on the slopes perpendicular to the valley bottom, making these disturbance events distinguishable from the Riparian Change category. |
| Riparian Change          | Patches along a river or stream on a valley bottom, typically with an average patch slope of less than 15 degrees. Steeper slopes are often associated with headwaters.                                                                                                                                                                                                                                                                                                      |

<sup>A</sup> Disturbances removed from the trend analysis due to low sample size.

### Summaries of Disturbance Activity (1987–2017) Within National Park Boundaries

Summaries of total area affected by each change type and the number of events were reported for areas within each park boundary (NOCA, OLYM, MORA) and across all parks combined.

Complementary summaries for the full study areas are provided in the Appendix. Singular fire events had multiple LandTrendr-detected disturbance patches associated with them due to the heterogeneous arrangement of unburned, low, and severe burn severities within a fire perimeter. LandTrendr is more likely to detect fire disturbance in areas that experience greater overstory tree mortality and may miss areas of lower burn severity where the difference in pre- and post-fire spectral indices is less substantial. To ensure this process did not inflate the number of fire events throughout the report, we assigned each fire disturbance patch to an individual fire event using external wildfire monitoring datasets (e.g., Monitoring Trends in Burn Severity) and only summed the number of fire events as opposed to summing number of fire patches (i.e., a singular event may be comprised of multiple patches). However, area affected by fire only included LandTrendr detected disturbance patches (i.e., outside datasets were not used to calculate area affected by fire). For all other disturbance types, the number of annual disturbance events was based on a tally of individual patches as defined in the NCCN Landscape Change Monitoring Protocol (i.e., based on adjacency rules and minimum mapping unit size). We acknowledge that in doing so, the number of events may be inflated for some

disturbances, especially those that are less severe, occur in smaller patches, and unfold over multiple years (e.g., bark beetle outbreaks under the Defoliation category).

### **Analyzing Trends in Annual Disturbance Area, Patch Size, and Number of Events (1987–2017)**

We used generalized linear models (GLMs) to assess trends in annual disturbance area, mean patch size, and number of events for each disturbance type over the period examined (1987–2017). Any disturbance patches whose centroid fell within the NOCA, OLYM, or MORA study areas were used in the trend analysis, excluding Development, Clearing, Ice Damage, and Coastal Change disturbances due to low sample size. In some instances, patches near the study area boundary were partially located outside of the study areas. Because we were interested in assessing trends in mean patch size, these patches were included in the trend analysis but were clipped to the study area boundaries in other summaries throughout the report. Response variables were modeled using a Tweedie distribution, because response data were continuous and strongly right-skewed. The explanatory variable in each model was the year in which disturbance was detected by LandTrendr (detection year). For fire patches, detection year was replaced with disturbance year as determined by crosswalking fire patches with other wildfire monitoring datasets. This avoided patches from the same fire event being assigned different detection years due to LandTrendr annual analysis window ending mid-September while some wildfires are still burning. Models were run for each disturbance type across 3 slices of the dataset: (1) across all study areas combined (total of 18 models), (2) within each study area (NOCA, OLYM, and MORA) (total of 54 models), and (3) within georegions of each study area (east versus west side of the study area; Figure 1) (total of 106 models). We considered test results with a  $p < 0.05$  as strong evidence of a trend and considered model results with  $p < 0.10$  as suggestive evidence of a trend. To account for the potential of false-positives across our models, we adjusted p-values using the Holm-Bonferroni correction method (Eichstaedt et al., 2013).

### **Assessing Differences in Disturbance Activity (Annual Disturbance Area, Patch Size, and Number of Events) Between Two Periods: 1987–1999 and 2000–2017**

To test whether annual disturbance activity (area disturbed, mean patch size, and number of events) differed between the first half (1987–1999) and the second half (2000–2017) of the period examined, we used a two-sided two-sample t-test (R Core Team 2022) when the assumptions of normality and equal variances were met; when assumptions were not met, we used a non-parametric Wilcoxon rank sum test. Normality and equal variances were assessed using a Shapiro-Wilk normality test and an F test from the stats package, respectively (R Core Team 2022). Tests were performed for each disturbance type across 3 slices of the dataset: (1) across all study areas combined (total of 18 tests), (2) within each study area (NOCA, OLYM, and MORA) (total of 54 tests), and (3) within georegions of each study area (east versus west side of the study area) (total of 106 tests). We adjusted p-values using the Holm-Bonferroni correction method within each slice of data to address the potential for false-positives across test results (Eichstaedt et al., 2013).

Because climate is a key driver of disturbance, we used climate variables to determine an ecologically relevant breakpoint between the first and second half of the study period. We visually assessed annual trends in vapor pressure deficit (VPD), snow water equivalent (SWE), and 12-month

standardized precipitation evapotranspiration index (SPEI) for each of the study areas (Table 3, Figure 5). Monthly SWE and VPD data were sourced from the Climatology Lab at the University of California (<https://www.climatologylab.org/terraclimate.html>) at a 4 km resolution. Monthly SWE represents the amount of water available in the snowpack at the end of each month. Vapor pressure deficit describes the difference between the actual amount of moisture in the air relative to the potential amount of moisture the air can hold. Higher values of VPD indicate drier conditions (i.e., a higher deficit of moisture in the air). Standardized precipitation evapotranspiration index data were downloaded from the National Oceanic and Atmospheric Administration (<https://www.drought.gov/data-maps-tools/us-gridded-standardized-precipitation-index-spei-nclimgrid-monthly>) and sourced from nClimGrid-Monthly datasets at a 4 km resolution to represent drought conditions across each park study area. SPEI is a drought index that models the impact of precipitation and potential evapotranspiration on water demand and can be used to detect drought over varying temporal windows ranging from 1 to 48 months. Here, we used a 12-month window based on the water year (i.e., October 1st) to represent annual drought anomalies. The SPEI index is unitless and values between -1 and 1 represent normal conditions; values greater than 1 indicate wetter than normal conditions; and values less than -1 indicate drier than normal conditions. We calculated the mean 12-month SPEI value across the spatial extent of each study area (NOCA, OLYM, and MORA) for each year. Qualitatively, mean VPD increased by 0.05 kPa within each of the study areas from 2000–2017 relative to 1987–1999 (Figure 5a); this transition was used to justify a breakpoint of the year 2000 (i.e., comparing 1987–1999 disturbance activity to 2000–2017 disturbance activity).

**Table 3.** Description, units, and scale of climate variables.

| Variable                                                   | Unit     | Description                                                                                                                                                                                                                                                                                   | Spatial Resolution | Temporal Scale |
|------------------------------------------------------------|----------|-----------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------|--------------------|----------------|
| Vapor pressure deficit (VPD)                               | kPa      | The difference between the amount of moisture in the air relative to the amount of moisture that air could hold at saturation. Higher VPD indicates drier conditions (i.e., the amount of moisture in the air is much less than the total amount of moisture that air is capable of holding). | 4 km               | Monthly        |
| Snow water equivalent (SWE)                                | mm       | The amount of water available in the snowpack. Monthly SWE values indicate the end-of-month SWE.                                                                                                                                                                                              | 4 km               | Monthly        |
| Standardized precipitation evapotranspiration index (SPEI) | unitless | A drought index modeled using precipitation and potential evapotranspiration. Values greater than 1 indicate wetter than normal conditions; values less than -1 indicate drier than normal conditions; values between -1 and 1 indicate within normal conditions.                             | 1/24 degree        | 12-month       |

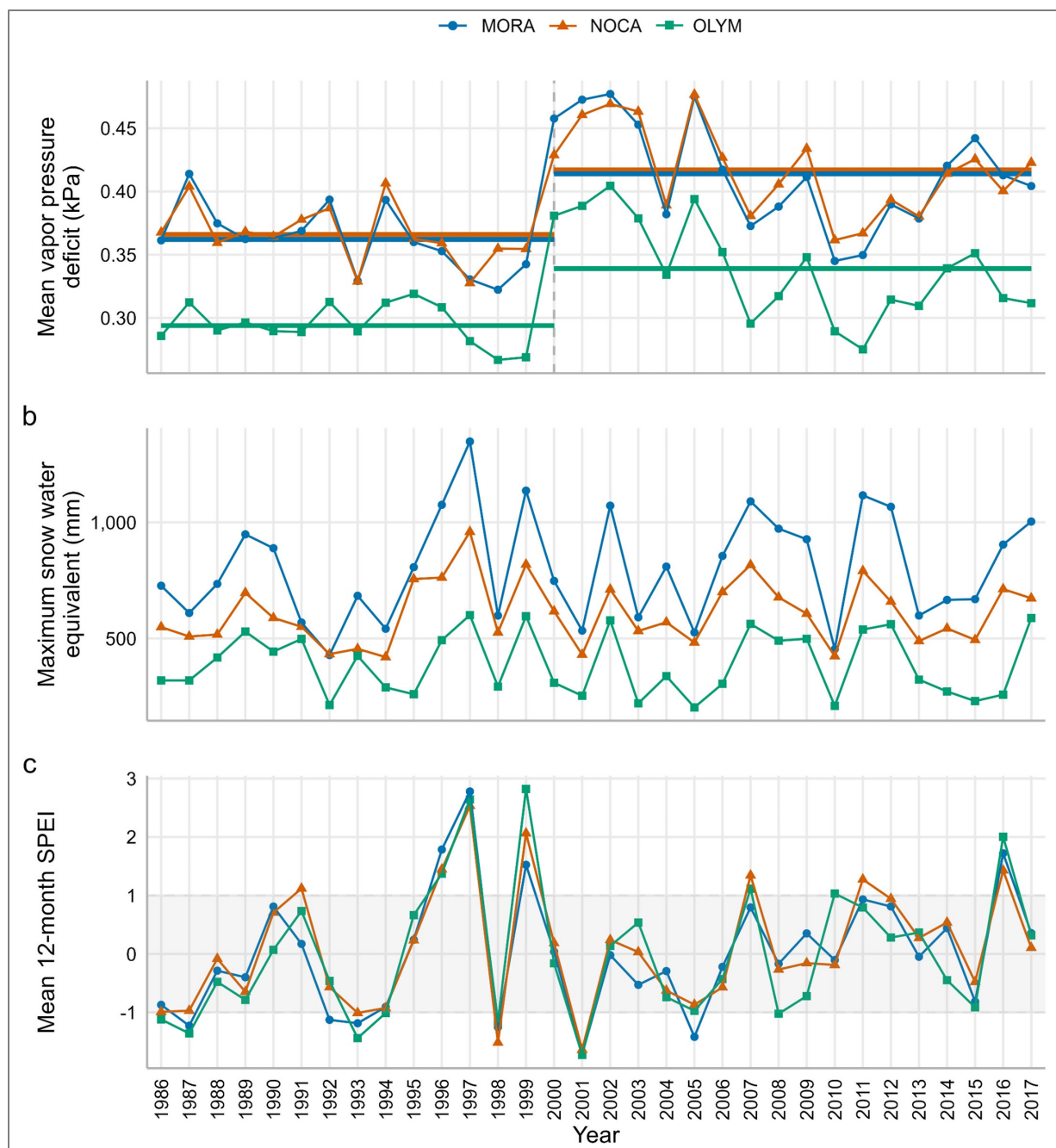


**Figure 5.** Mean monthly vapor pressure deficit (kPa). **(a)**, maximum monthly snow water equivalent (mm) **(b)**, and 12-month standardized precipitation evapotranspiration index (SPEI) **(c)** across each of the study areas (NOCA, OLYM, and MORA) from 1986 to 2017. The vertical dashed line at year 2000 in panel **a** represents the threshold used to separate the time period and the horizontal lines indicate the pre- and post-2000 mean VPD value for each study area. The shaded area in panel **c** represents within normal drought conditions (i.e., SPEI values between -1 and 1). Data from University of California and National Oceanic and Atmospheric Administration.

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## Assessing Stand Ages Affected by Different Change Types

Annual stand age rasters (1986–2017) were sourced from Gradient Nearest Neighbor (GNN) maps developed by the Landscape Ecology, Modeling, Mapping and Analysis (LEMMA) group at Oregon State University (OSU) (<https://lemma.forestry.oregonstate.edu/>). Gradient Nearest Neighbor stand age rasters provide continuous modeled estimates of dominant stand age across Washington state at a 30-meter pixel resolution. Gradient Nearest Neighbor datasets relate satellite imagery to field data to produce full spatial coverage estimates of forest structure conditions based on interpolation, and have been applied in other regional studies across the PNW (e.g., DeMeo et al., 2018; Haugo et al., 2015; Laughlin et al., 2023a). The stand age rasters capture important differences in forest structure and complexity that relate to stand age, though stand age estimates for a given pixel may be inaccurate. Because these data are limited to Washington state, these analyses exclude area disturbed in British Columbia, Canada. These rasters were clipped to the three study areas using the terra package in R (Hijmans R, 2023).

To assess whether certain stand ages were more likely to be affected by different disturbances, we compared the distribution of stand ages across the study areas to the distribution of stand ages affected by disturbances. We used the 1986 stand-age distribution within the study areas as the reference distribution for comparison, as this represents the stand age of the study area unaffected by disturbances analyzed in this study (1987–2017).

To test whether the two distributions (disturbed vs. non-disturbed) differed from one another statistically, we used the Kolmogorov–Smirnov (K–S) test in the stats package in R (R Core Team, 2024) and considered test results with a p-value less than 0.05 as strong evidence of a trend and considered model results with  $p < 0.10$  as suggestive evidence of a trend. We also qualitatively looked at the test statistic (D) which describes the maximum difference in the empirical cumulative distribution function (ECDF) curves between the two distributions (i.e., the greater the test statistic (D), the greater the difference between the two distributions). While the K–S test is useful in determining whether two distributions statistically differ from one another, it does not describe the nature of the difference.

To determine the magnitude and direction of difference between the two distributions, we calculated the departure index (Menning et al., 2007) using the distribution of stand ages affected by disturbance as the test distribution and the distribution of stand ages within the study areas as the reference distribution. When the departure index (M) is positive, it indicates that the distribution of stand ages affected by disturbances is right-shifted relative to the distribution of stand ages within the study areas (i.e., areas affected by disturbances tend to be older relative to the reference distribution). When the departure index (M) is negative, it indicates that the distribution of stand ages affected by disturbances is left-shifted relative to the distribution of stand ages within the study areas (i.e., areas affected by disturbances tend to be younger relative to the reference distribution). Larger departure index values in either a positive or negative direction indicate greater differences between the two distributions. These tests were performed within each study area for each disturbance type, except for Clearing, Development, Coastal Change, and Ice Damage disturbance types due to low sample sizes.

## Results

### Cumulative Area Affected by Disturbances Across All Parks (1987–2017)

Across all three parks, a total of 22,169 ha (i.e., ~3% of NPS area) were disturbed over the 31 years examined (1987–2017). Fire accounted for 65.7% of the area disturbed within the NPS lands (14,557 ha), followed by Riparian Change (2,746 ha; 12.39%), Avalanche (1,958 ha; 8.83%), Defoliation (1,341 ha; 6.05%), Mass Movement (822 ha; 3.71%), Blowdown (698 ha; 3.15%), Clearing (26 ha; 0.12%), Development (10 ha; 0.05%), Ice Damage (7 ha; 0.03%), and Coastal Change (2 ha; 0.01%) (Table 4). The cumulative number of disturbance events ranged from 2 (Coastal Change) to 1,579 (Riparian Change) (Table 4).

**Table 4.** Cumulative area disturbed (ha), percentage of total area disturbed (%), and number of disturbance events of each change type within boundaries of North Cascades National Park Service Complex, Olympic National Park, and Mount Rainier National Park, combined.

| Change Type     | Area Disturbed (ha) | % of Total Area Disturbed | Number of Disturbance Events |
|-----------------|---------------------|---------------------------|------------------------------|
| Fire            | 14,557              | 65.66                     | 92                           |
| Riparian Change | 2,746               | 12.39                     | 1,579                        |
| Avalanche       | 1,958               | 8.83                      | 848                          |
| Defoliation     | 1,341               | 6.05                      | 681                          |
| Mass Movement   | 822                 | 3.71                      | 424                          |
| Blowdown        | 698                 | 3.15                      | 264                          |
| Clearing        | 26                  | 0.12                      | 21                           |
| Development     | 10                  | 0.05                      | 7                            |
| Ice Damage      | 7                   | 0.03                      | 7                            |
| Coastal Change  | 2                   | 0.01                      | 2                            |
| <i>Total</i>    | <i>22,169</i>       | <i>100</i>                | <i>4,411</i>                 |

Approximately 51% of the total disturbance area within park boundaries occurred in the eastern portions of the parks (11,200 ha out of 22,169 ha; Tables 4 and 5). The primary disturbances in the eastern portions of the park boundaries were Fire (78.7% of the disturbed area) and Defoliation (10.9% of the disturbed area) (Table 5). In the western portions of the parks, the primary disturbances were Fire (52.4% of disturbed area), Riparian Change (22.7% of disturbed area), and Avalanche (12.2% of disturbed area) (Table 5). In the broader study areas, approximately 80% of the total area disturbed occurred in the eastern portion of the area (59,620 ha out of 75,206 ha), 82% of which was Fire (see supplementary tables in the Appendix).

**Table 5.** Cumulative area disturbed (ha), percentage of total area disturbed (%), and number of disturbance events of each change type by geographic region (west or east side; Figure 1) for within boundaries of North Cascades National Park Service Complex, Olympic National Park, and Mount Rainier National Park, combined.

| Change Type     | West          |                           |                              | East          |                           |                              |
|-----------------|---------------|---------------------------|------------------------------|---------------|---------------------------|------------------------------|
|                 | Area (ha)     | % of Total Area Disturbed | Number of Disturbance Events | Area (ha)     | % of Total Area Disturbed | Number of Disturbance Events |
| Fire            | 5,744         | 52.37                     | 61                           | 8,813         | 78.68                     | 8                            |
| Riparian Change | 2,495         | 22.74                     | 1,434                        | 251           | 2.24                      | 145                          |
| Avalanche       | 1,341         | 12.23                     | 575                          | 617           | 5.51                      | 273                          |
| Defoliation     | 117           | 1.07                      | 74                           | 1,224         | 10.93                     | 607                          |
| Mass Movement   | 709           | 6.47                      | 354                          | 113           | 1.01                      | 70                           |
| Blowdown        | 530           | 4.83                      | 191                          | 168           | 1.50                      | 73                           |
| Clearing        | 20            | 0.18                      | 17                           | 6             | 0.05                      | 4                            |
| Development     | 8             | 0.07                      | 5                            | 2             | 0.02                      | 2                            |
| Ice Damage      | 2             | 0.02                      | 2                            | 5             | 0.05                      | 5                            |
| Coastal Change  | 2             | 0.02                      | 2                            | 0             | 0.00                      | 0                            |
| <i>Total</i>    | <i>10,969</i> | <i>100</i>                | <i>2,715</i>                 | <i>11,200</i> | <i>100</i>                | <i>1,576</i>                 |

### **Cumulative Area Affected by Disturbances Within Each Park Boundary (1987–2017)**

Sixty-four percent of the total area disturbed in all three parks from 1987 to 2017 occurred in NOCA (14,259 ha out of 22,169 ha; Tables 4 and 6). Fire accounted for 76.0% of the disturbed area within NOCA (10,843 ha), followed by Defoliation (1,305 ha; 9.15% of disturbed area), Avalanche (1,106 ha; 7.8%), Mass Movement (496 ha; 3.5%), and Riparian Change (438 ha; 3.1%) (Table 5). Blowdown accounted for less than 1% of the NOCA's disturbed area (Table 6).

Thirty-one percent of the total area disturbed within the three park boundaries from 1987 to 2017 occurred in OLYM (6,852 ha out of 22,169 ha; Tables 4 and 6). Fire accounted for 51.8% of the disturbed area within OLYM (3,551 ha), followed by Riparian Change (1,604 ha; 23.4%), Avalanche (782 ha; 11.4%), Blowdown (568 ha; 8.3%), and Mass Movement (297 ha; 4.3%) (Table 6). Defoliation, Ice Damage, and Coastal Change accounted for less than 1% of the disturbed areas within the Olympic National Park (Table 6).

The remaining 5% of the total area disturbed within the three park boundaries from 1987 to 2017 occurred within MORA (1,058 ha out of 22,169 ha; Tables 4 and 6). Riparian Change accounted for 66.5% of the disturbed area within the park (704 ha), followed by Fire (162 ha; 15.4%), Blowdown (86 ha; 8.2%), Avalanche (71 ha; 6.7%), and Mass Movement (30 ha; 2.8%). Defoliation accounted for less than 1% of disturbed area within the Mount Rainier National Park (Table 6).

Summary statistics for NOCA, OLYM, and MORA study areas are documented in the supplementary tables in the Appendix.

Distribution patterns of different disturbance types in NOCA, OLYM and MORA study areas are shown in Figures 6–8.

**Table 6.** Cumulative area disturbed (ha), percentage of total area disturbed (%), percentage of park area disturbed (%), and number of disturbance events of each change type within the North Cascades National Park Service Complex, Olympic National Park, and Mount Rainier National Park.

| Change Type     | North Cascades National Park Service Complex |                           |                            |             | Olympic National Park |                           |                            |             | Mount Rainier National Park |                           |                            |             |
|-----------------|----------------------------------------------|---------------------------|----------------------------|-------------|-----------------------|---------------------------|----------------------------|-------------|-----------------------------|---------------------------|----------------------------|-------------|
|                 | Area (ha)                                    | % of Total Disturbed Area | % of Park Area Disturbed ^ | # of Events | Area (ha)             | % of Total Disturbed Area | % of Park Area Disturbed ^ | # of Events | Area (ha)                   | % of Total Disturbed Area | % of Park Area Disturbed ^ | # of Events |
| Fire            | 10,843                                       | 76.04                     | 3.94                       | 61          | 3,551                 | 51.83                     | 0.98                       | 23          | 162                         | 15.29                     | 0.17                       | 8           |
| Riparian Change | 438                                          | 3.07                      | 0.16                       | 231         | 1,604                 | 23.41                     | 0.44                       | 1,012       | 704                         | 66.53                     | 0.74                       | 336         |
| Defoliation     | 1,305                                        | 9.15                      | 0.47                       | 651         | 33                    | 0.48                      | 0.01                       | 26          | 4                           | 0.40                      | <0.01                      | 4           |
| Avalanche       | 1,106                                        | 7.76                      | 0.40                       | 454         | 782                   | 11.41                     | 0.21                       | 360         | 71                          | 6.68                      | 0.07                       | 34          |
| Blowdown        | 43                                           | 0.30                      | 0.02                       | 26          | 568                   | 8.29                      | 0.16                       | 196         | 86                          | 8.18                      | 0.09                       | 42          |
| Mass Movement   | 496                                          | 3.48                      | 0.18                       | 219         | 297                   | 4.33                      | 0.08                       | 193         | 30                          | 2.82                      | 0.03                       | 12          |
| Clearing        | 21                                           | 0.15                      | 0.01                       | 16          | 4                     | 0.05                      | <0.01                      | 4           | 1                           | 0.11                      | <0.01                      | 1           |
| Ice Damage      | 0                                            | 0.00                      | 0.00                       | 0           | 7                     | 0.10                      | <0.01                      | 7           | 0                           | 0.00                      | 0.00                       | 0           |
| Development     | 7                                            | 0.05                      | <0.01                      | 3           | 4                     | 0.05                      | <0.01                      | 3           | 0                           | 0.00                      | 0.00                       | 1           |
| Coastal Change  | 0                                            | 0.00                      | 0.00                       | 0           | 2                     | 0.03                      | <0.01                      | 2           | 0                           | 0.00                      | 0.00                       | 0           |
| Total           | 14,259                                       | 100                       | 5.18                       | 1,661       | 6,852                 | 100                       | 1.88                       | 1,826       | 1,058                       | 100                       | 1.11                       | 438         |

^ Percentage of park area disturbed was calculated by summing the annual disturbance footprint area, then dividing by total park area. This value thus likely overestimates the aggregate footprint area disturbed within parks, as pixels that experienced multiple disturbances over the 31-year period would be counted more than once.

## Disturbances within the North Cascades National Park Service Complex Study Area

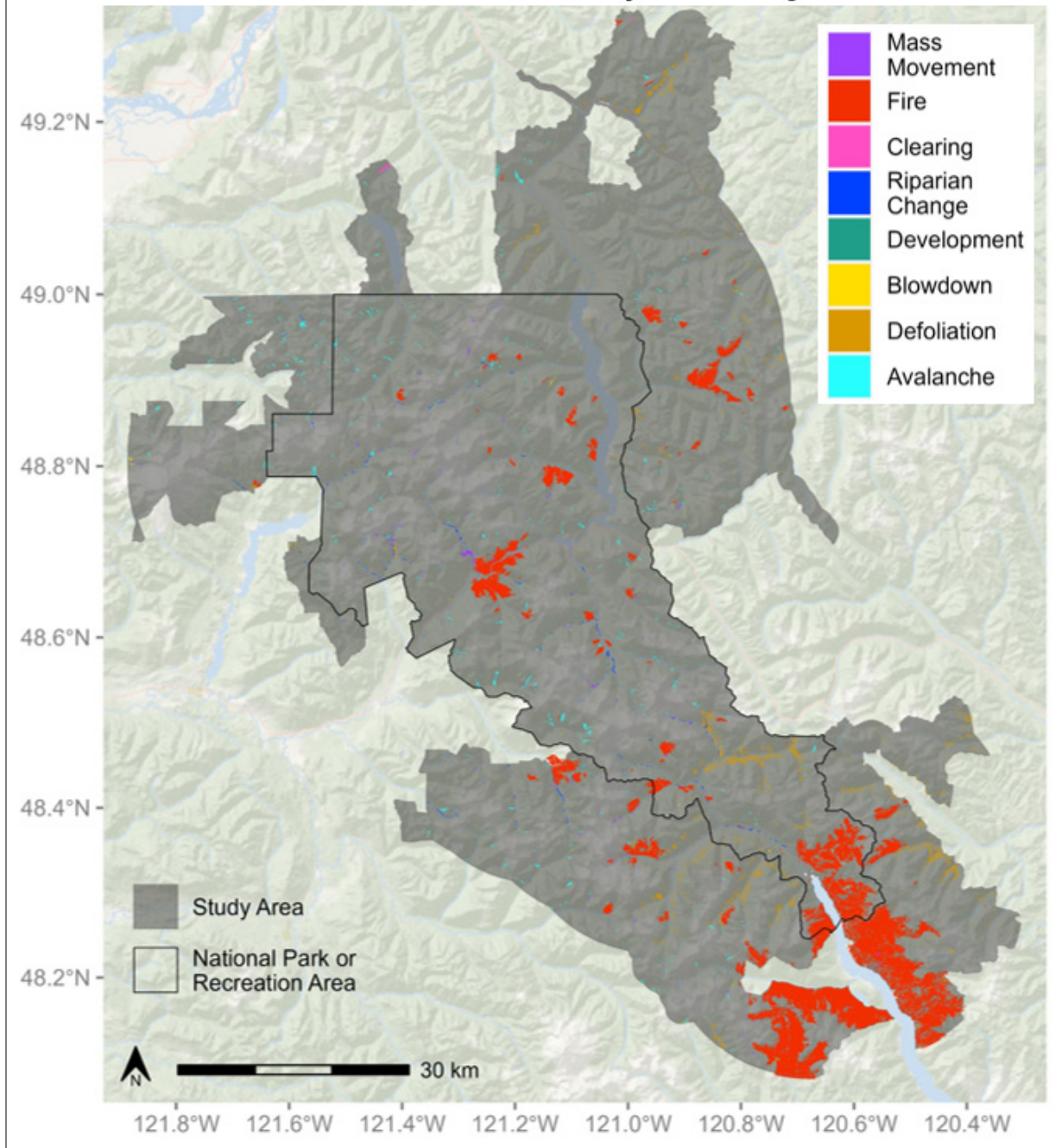


**Figure 6.** Disturbances within the North Cascades National Park (NOCA) study area (1987–2017). Most orange disturbance patches in the southern half of the study area are Defoliation events (i.e., not Blowdown). Data from ESRI.

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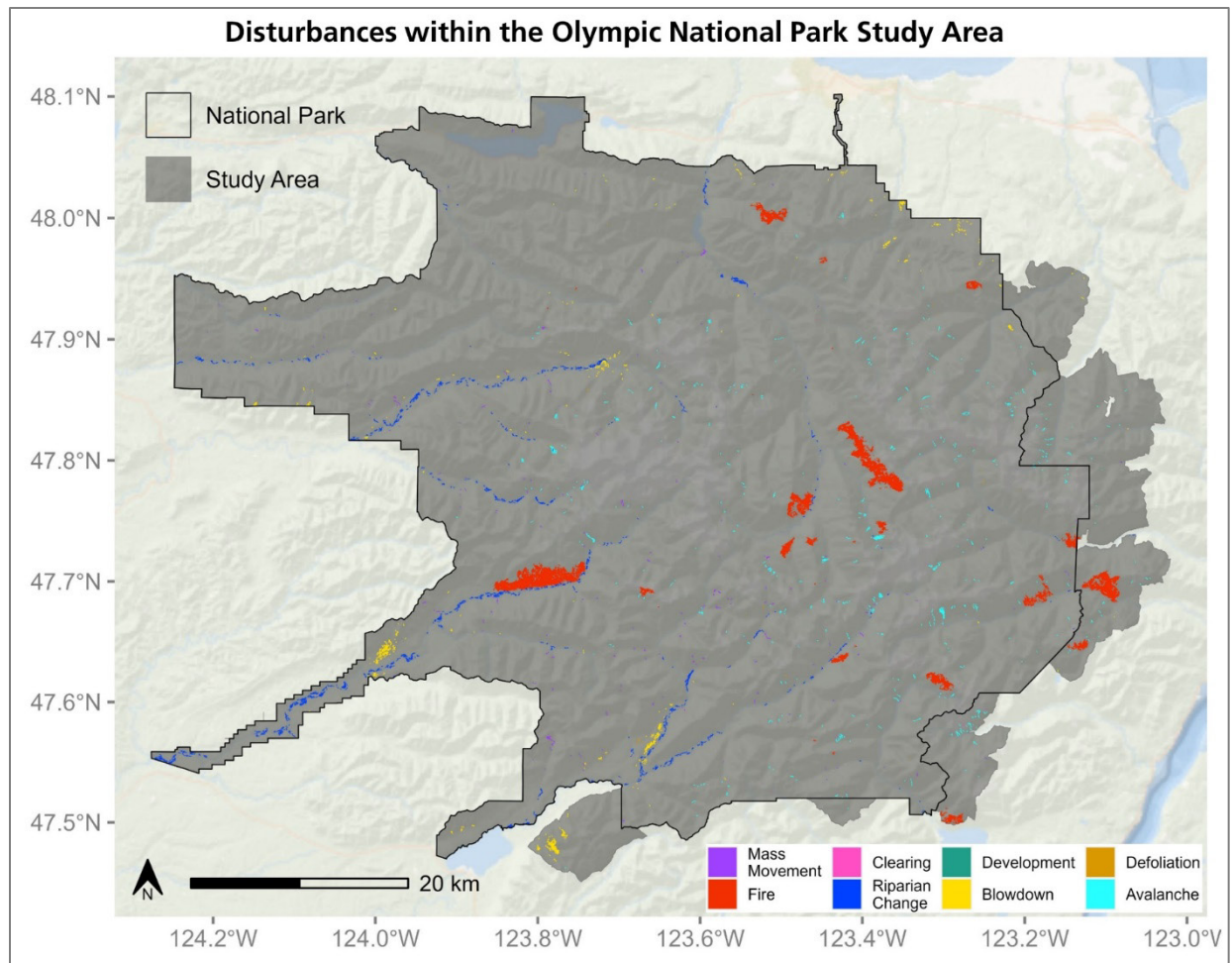


**Figure 7.** Disturbances within the Olympic National Park (OLYM) study area (1987–2017). Note: The coastal portion of the OLYM study area is not included in this map, as there were very few disturbance patches. Data from ESRI.

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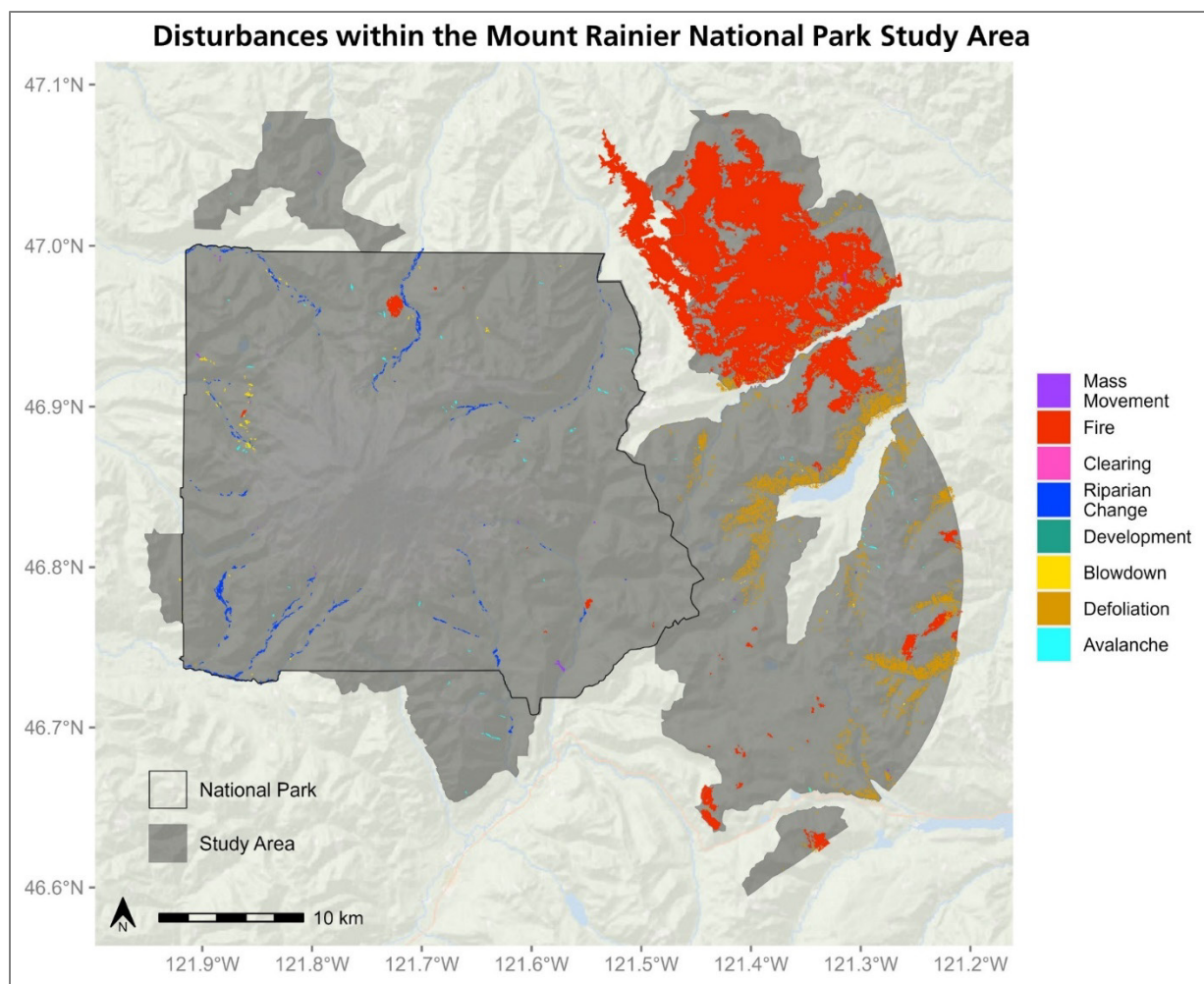


**Figure 8.** Disturbances within the Mount Rainier National Park (MORA) study area (1987–2017). Data from ESRI.

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### Temporal Trends in Annual Disturbance Area, Mean Patch Size, and Number of Events by Change Type

At the scale of all three study areas (i.e., NOCA, OLYM, and MORA study areas combined), the mean annual patch size of Fire events increased over the period examined ( $p < 0.01$ ; Table 7; Figure 9). Two large fire years occurred in 2015 and 2017, with greater than 12,000 hectares total burned each year (Figure 9). Visually, annual Defoliation area and number of events appeared to peak in the early- to mid-2000s (Figure 9) though no statistically significant trends were detected.

Within the NOCA study area, no statistically significant trends in disturbance activity were observed (Figure 10). Within the OLYM study area, there was a statistically significant increase in area disturbed by Fire over the period examined ( $p < 0.01$ ; Table 7; Figure 11). Within the MORA study area, there was a statistically significant increase in area and mean patch size of Fire ( $p < 0.01$ ; Table 7; Figure 12) and an increase in annual area affected by Defoliation ( $p < 0.01$ ; Table 6; Figure 12) over the period examined.

**Table 7.** Summary results of statistically significant trends in disturbance activity (i.e., annual disturbance area, mean patch size, and number of events) from 1987 to 2017 across three scales: (1) all study areas combined, (2) within each study area, and (3) within each study area and georegion (east versus west side of the study areas).

| Scale                       | Study Area | Disturbance | Variable(s)                                      | P-value          | Trend |
|-----------------------------|------------|-------------|--------------------------------------------------|------------------|-------|
| All study areas combined    | –          | Fire        | Mean annual patch size                           | < 0.01           | +     |
| By study area               | OLYM       | Fire        | Annual area disturbed                            | <0.01            | +     |
|                             | MORA       | Fire        | Annual area disturbed,<br>Mean annual patch size | <0.01,<br>< 0.01 | +     |
|                             | MORA       | Defoliation | Annual area disturbed                            | <0.01            | +     |
| By study area and georegion | NOCA west  | Defoliation | Annual area disturbed,<br>Number of events       | <0.01,<br><0.01  | +     |

At the scale of each study area and georegion (i.e., east versus west side of study areas), the annual area and number of Defoliation events increased from 1987 to 2017 within the west side of the NOCA study area ( $p < 0.01$ ; Table 7; see supplementary figure in the Appendix). No other significant trends were detected at the scale of study area and georegion.

There were no statistically significant trends for disturbance magnitude at any scale, and results are not included in the report.

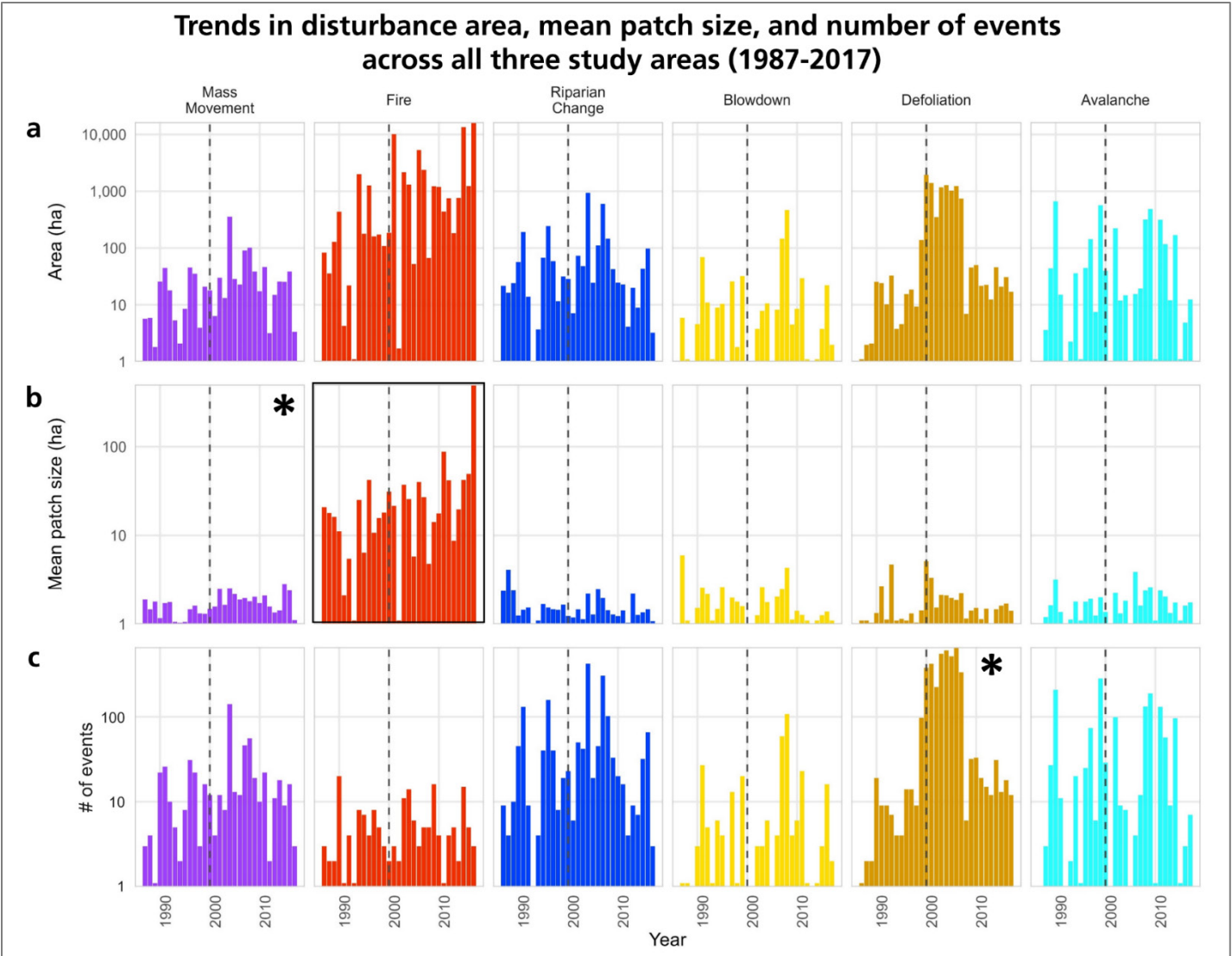


**Figure 9.** Temporal trends in disturbance within all three study areas combined. **(a)** Trends in annual disturbance area (ha), **(b)** mean annual patch size, and **(c)** annual number of events. Black rectangles indicate statistically significant trends over the period examined (1987–2017) and asterisks (\*) indicate significant differences between 1987–1999 and 2000–2017 (separated by a vertical dashed gray line). The y-axis is on the base 10 log scale. To avoid negative values (i.e., when values are less than 1) and artificial zeros (i.e., when values are equal to 1) on the base 10 log scale, all response variable values greater than 0 and less than or equal to 1 were replaced with a value of 1.1 for visualization purposes only.

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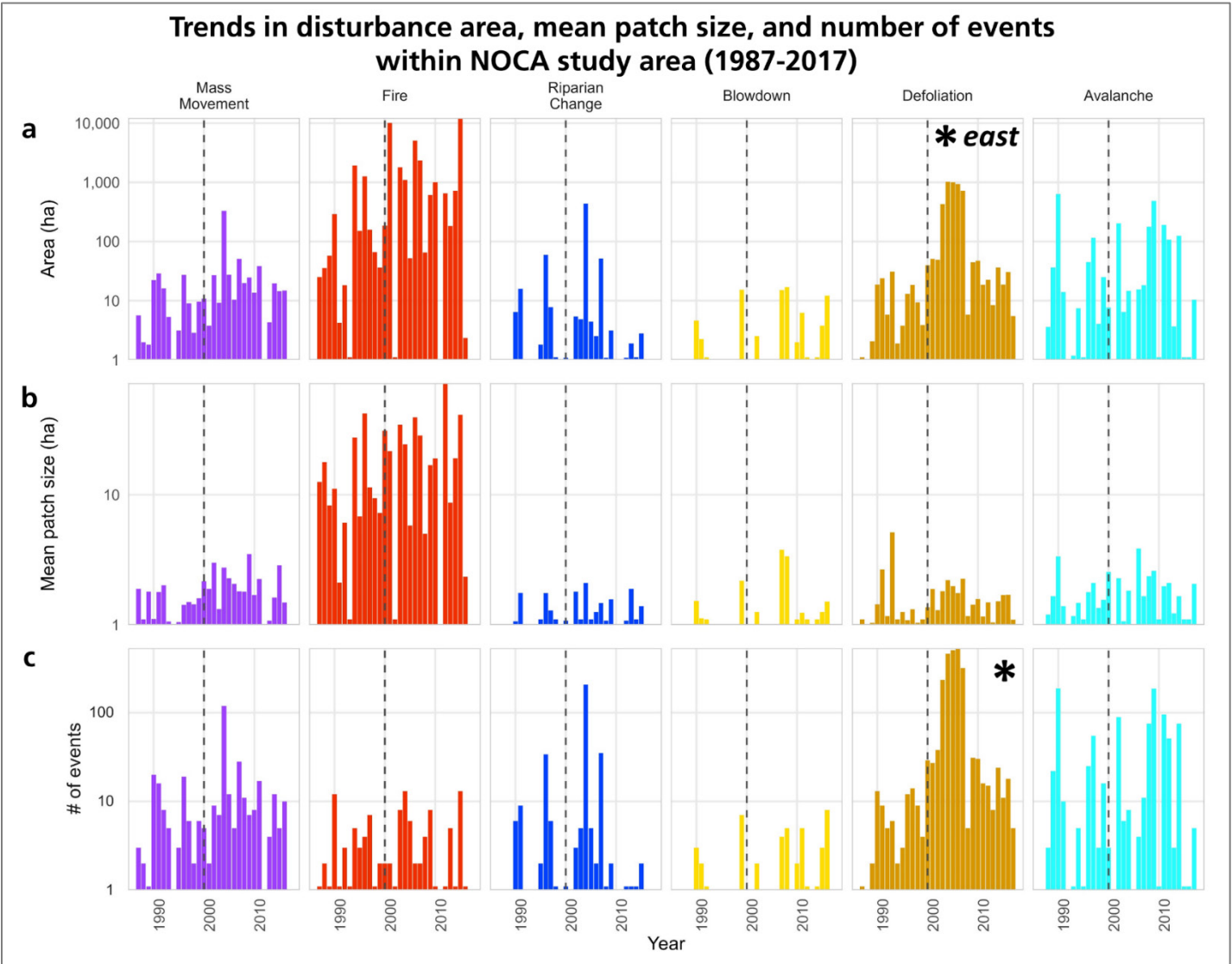


**Figure 10.** Temporal trends in disturbance within the North Cascades National Park Service Complex (NOCA) study area. **(a)** Trends in annual disturbance area (ha), **(b)** mean annual patch size, and **(c)** annual number of events. Asterisks (\*) indicate significant differences between 1987–1999 and 2000–2017 (separated by a vertical dashed gray line). The “\* east” indicates a significant difference in the east georegion of the NOCA study area. The y-axis is on the base 10 log scale. To avoid negative values (i.e., when values are less than 1) and artificial zeros (i.e., when values are equal to 1) on the base 10 log scale, all response variable values greater than 0 and less than or equal to 1 were replaced with a value of 1.1 for visualization purposes only.

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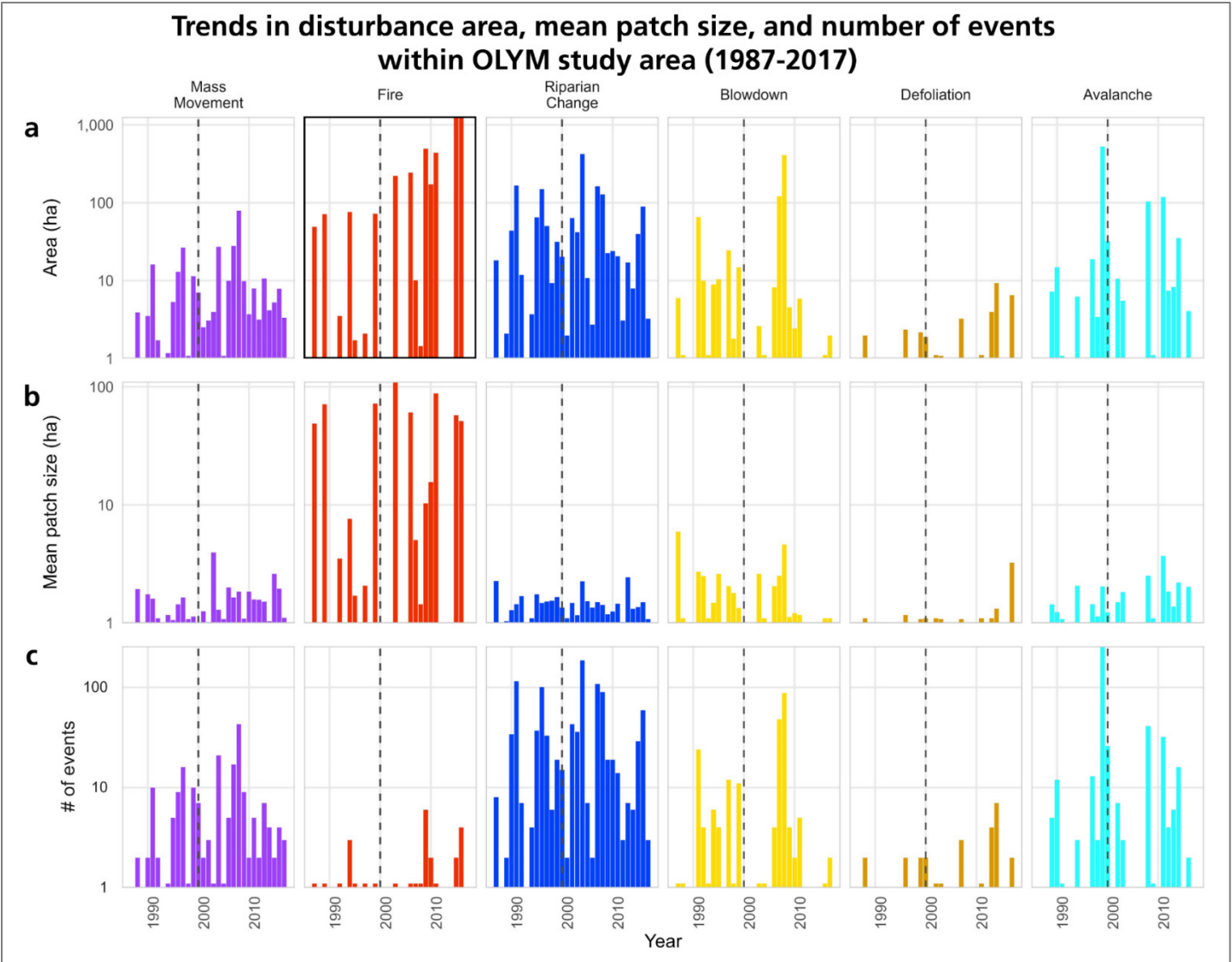


**Figure 11.** Temporal trends in disturbance within the Olympic National Park (OLYM) study area. **(a)** Trends in annual disturbance area (ha), **(b)** mean annual patch size, and **(c)** annual number of events. Black rectangles indicate statistically significant trends over the time period examined (1987–2017) for that disturbance and variable. The gray dashed vertical line separates pre- and post-2000. The y-axis is on the base 10 log scale. To avoid negative values (i.e., when values are less than 1) and artificial zeros (i.e., when values are equal to 1) on the base 10 log scale, all response variable values greater than 0 and less than or equal to 1 were replaced with a value of 1.1 for visualization purposes only.

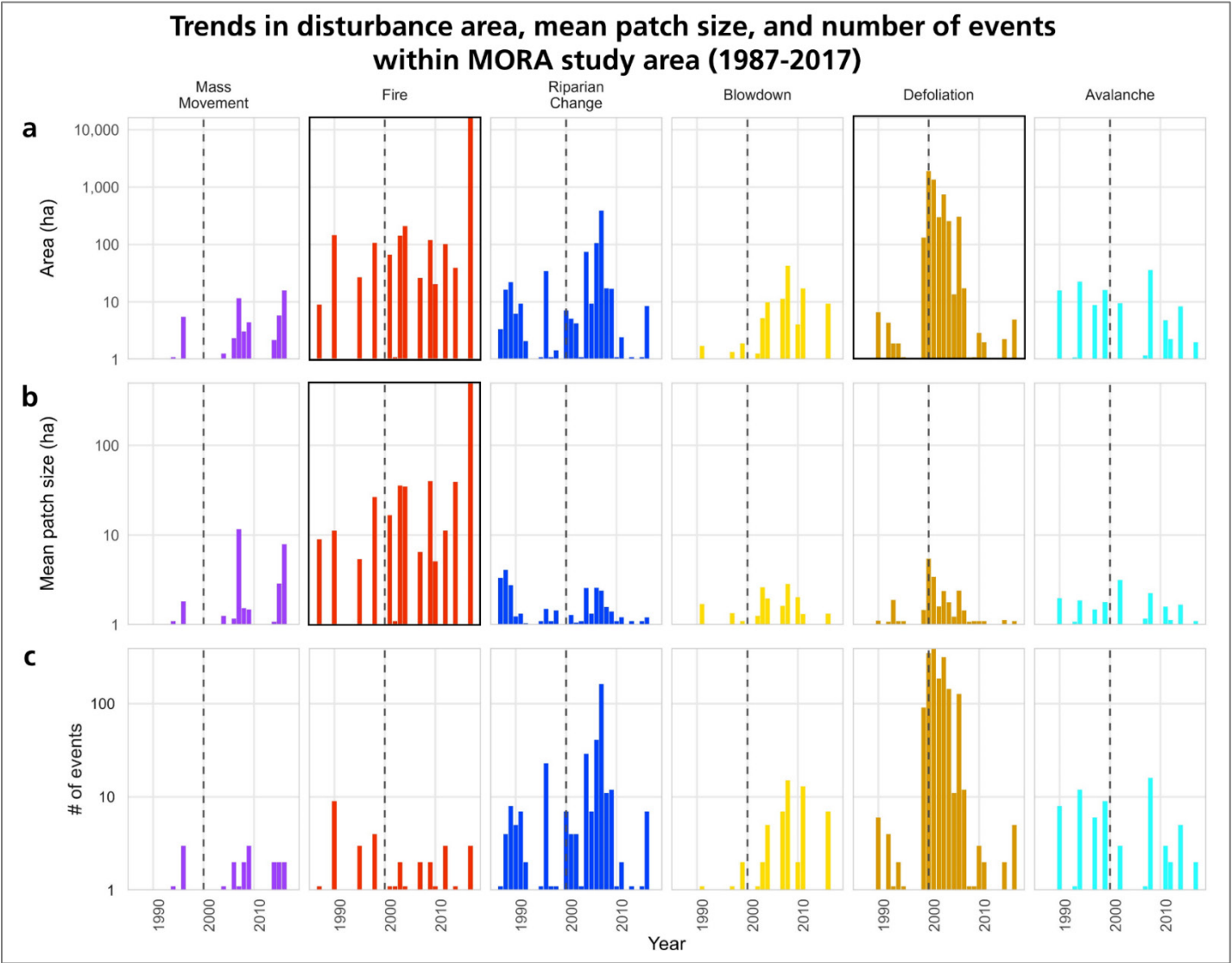


**Figure 12.** Temporal trends in disturbance within the Mount Rainier National Park (MORA) study area. **(a)** Trends in annual disturbance area (ha), **(b)** mean annual patch size, and **(c)** annual number of events. Black rectangles indicate statistically significant trends over the time period examined (1987–2017) for that disturbance and variable. The gray dashed vertical line separates pre- and post-2000. The y-axis is on the base 10 log scale. To avoid negative values (i.e., when values are less than 1) and artificial zeros (i.e., when values are equal to 1) on the base 10 log scale, all response variable values greater than 0 and less than or equal to 1 were replaced with a value of 1.1 for visualization purposes only.

### **Differences in Disturbance Activity (Area, Mean Patch Size, and Number of Events) Between 1987–2000 and 2001–2017**

The number of Defoliation events was greater from 2000–2017 relative to 1987–1999 across all study areas combined ( $p = 0.002$ ) and within the NOCA study area ( $p = 0.0004$ ) (Figures 9 and 10). Area affected by Defoliation events was greater in 2001–2017 within the eastern portion of the NOCA study area ( $p = 0.0002$ ) (see the supplementary figure in the Appendix). The mean patch size of Mass Movement events was greater from 2000–2017 relative to 1987–1999 at the scale of all three study areas combined ( $p = 0.002$ ). No other disturbances showed significant differences in area, mean patch size, or number of events between the two periods.

### **Distribution of Stand Ages Affected by Disturbance (1987–2017)**

The median estimated stand age of the NOCA, OLYM, and MORA study areas in 1986 was 142, 225, and 174 years, respectively (Figures 13, 14, and 15). In all three study areas, Riparian Change occurred more often in younger stands and had the greatest magnitude of difference from the 1986 distribution of stand ages across all study areas (the departure index 'M' ranging from -0.32 to -0.1; the K–S statistic (D) ranging from 0.28–0.44; Figures 13, 14, 15, and 16). Blowdown tended to occur more commonly in older stands within the MORA and NOCA study areas but occurred in younger stands within the OLYM study area (Figures 13, 14, 15, and 16). Mass Movement events tended to occur in younger stands in the NOCA study area (M of -0.1), though did not differ substantially from the 1986 stand age distribution in MORA or OLYM study areas (M of -0.001 and -0.02, respectively) (Figures 13, 14, 15, and 16). Avalanches tended to occur in younger stands in OLYM and MORA study areas (M of -0.11 and -0.05). Defoliation appeared to affect a narrower range of stand ages within NOCA and MORA study areas, though the peak disturbed stand age was similar to the peak stand age of these areas (Figures 13 and 15). Within the OLYM study area, Defoliation tended to occur in younger stands (M of -0.08; Figures 14 and 16). Fire tended to occur in younger stands in OLYM and NOCA study areas (M of -0.07 and -0.06, respectively; Figures 13, 14, and 16).

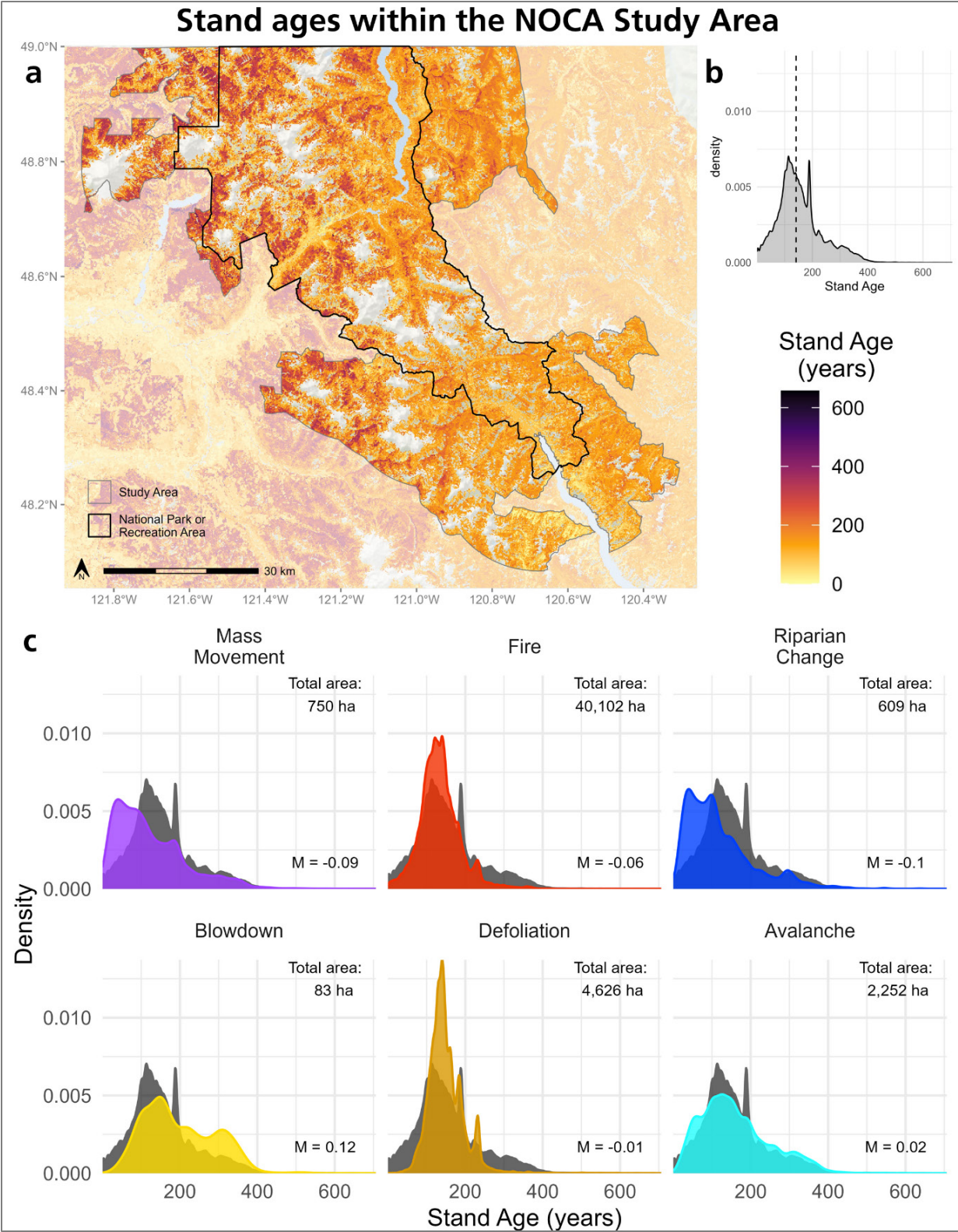


**Figure 13.** Stand ages within the North Cascades National Park Service Complex (NOCA) study area. **(a)** Map of estimated stand age for NOCA study area sourced from 2017 Gradient Nearest Neighbor (GNN) data. Park boundaries are outlined in black. **(b)** Distribution of stand ages within the NOCA study area in 1986, with the median stand age plotted as a vertical dashed line. **(c)** Density distribution of stand ages affected by each change type within the NOCA study area from 1987 to 2017. The dark gray distribution in each panel is the same distribution from panel **b**. The total area affected by each disturbance and the departure index (M) between the two distributions are labeled. Data from Oregon State University (<https://lemma.forestry.oregonstate.edu/data>).

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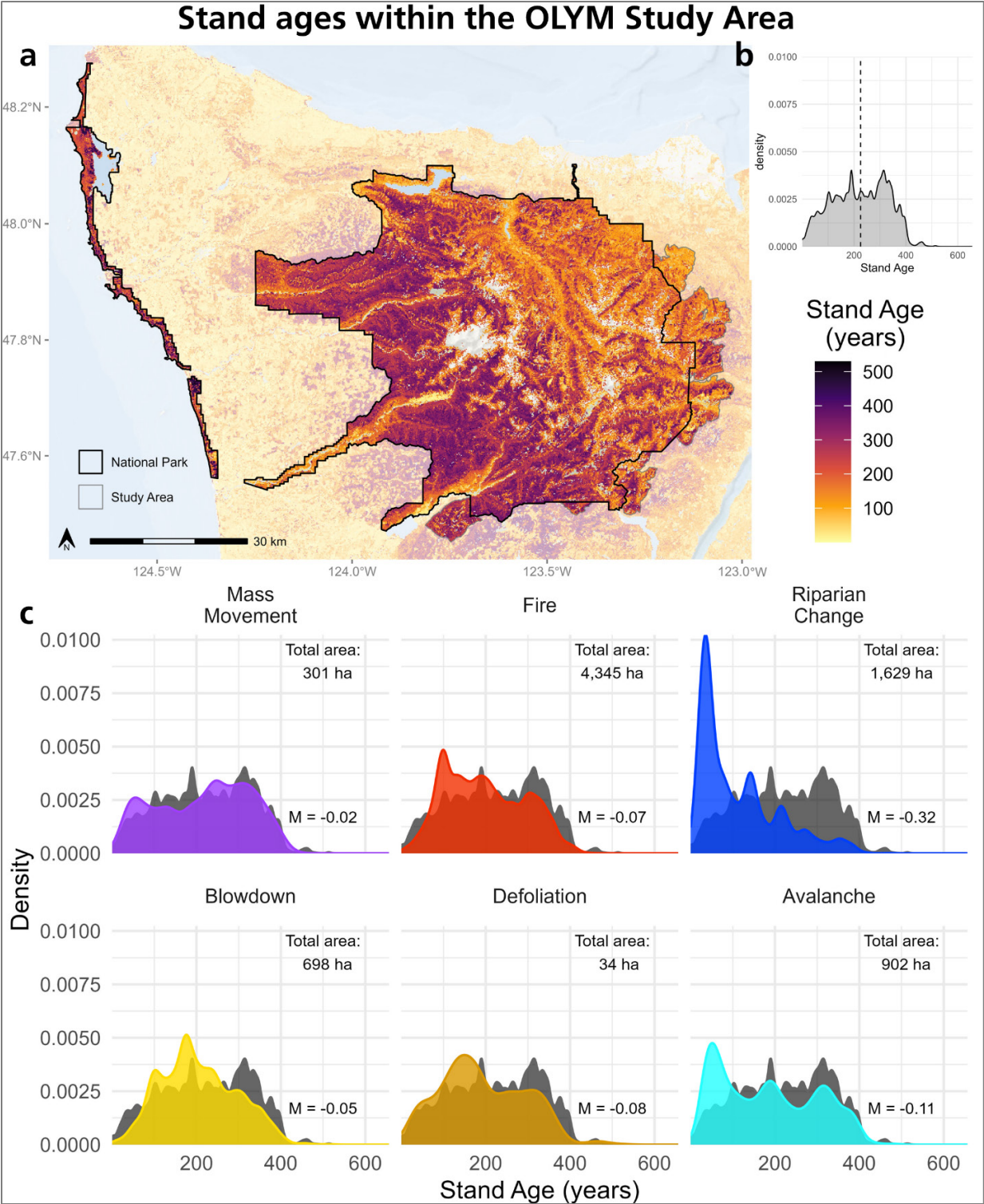


**Figure 14.** Stand ages within the Olympic National Park (OLYM) study area. **(a)** Map of estimated stand age for OLYM study area sourced from 2017 Gradient Nearest Neighbor (GNN) data. Park boundaries are outlined in black. **(b)** Distribution of stand ages within the OLYM study area in 1986, with the median stand age plotted as a vertical dashed line. **(c)** Density distribution of stand ages affected by each change type within the OLYM study area from 1987 to 2017. The dark gray distribution in each panel is the same distribution from panel **b**. The total area affected by each disturbance and the departure index ( $M$ ) between the two distributions are labeled. Data from Oregon State University (<https://lemma.forestry.oregonstate.edu/data>).

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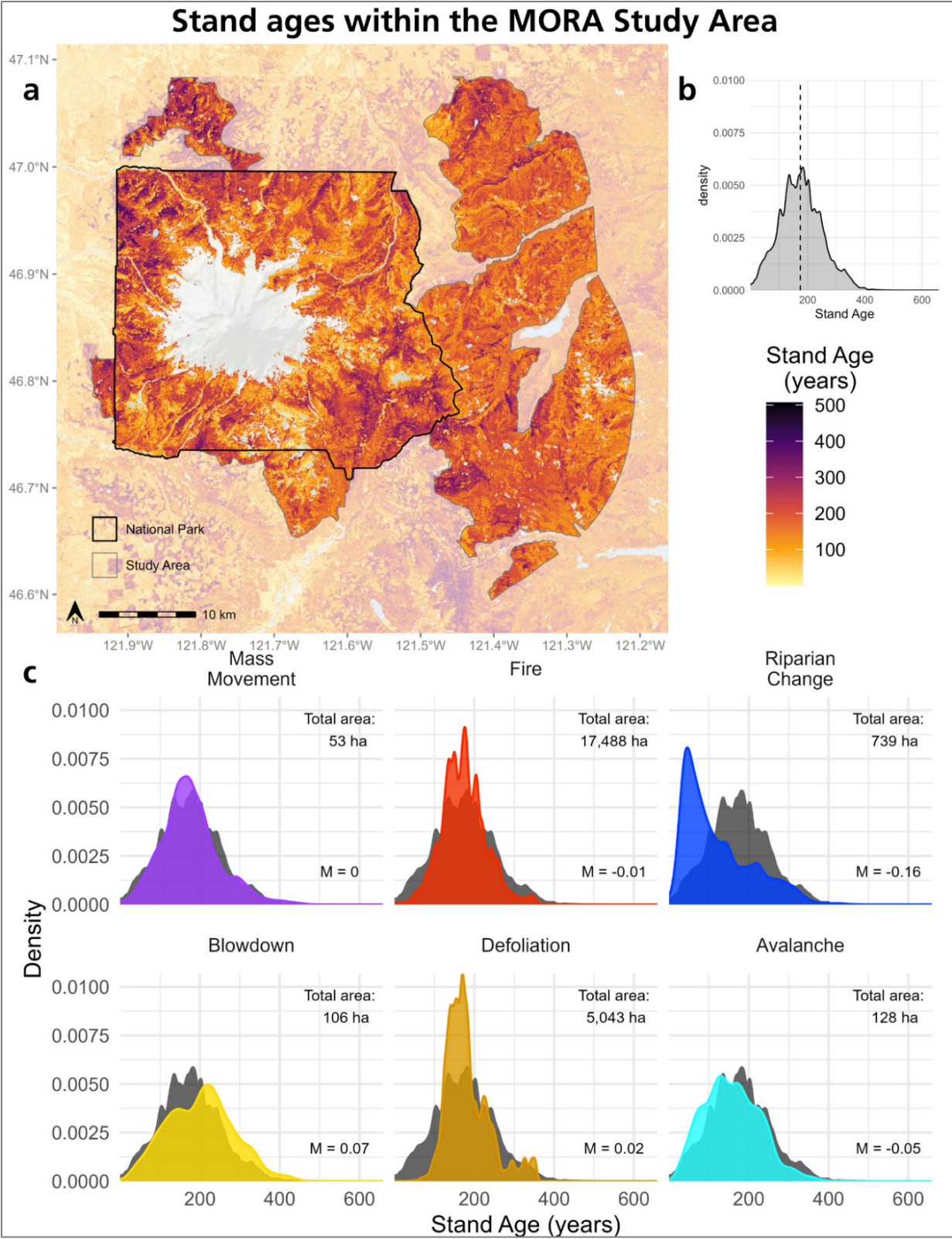


**Figure 15.** Stand ages within the Mount Rainier National Park (MORA) study area. **(a)** Map of estimated stand age for MORA study area sourced from 2017 Gradient Nearest Neighbor (GNN) data. **(b)** Distribution of stand ages within the MORA study area in 1986, with the median stand age plotted as a vertical dashed line. **(c)** Density distribution of stand ages affected by each change type within the MORA study area from 1987–2017. The dark gray distribution in each panel is the same distribution from panel **b**. The total area affected by each disturbance and the departure index ( $M$ ) between the two distributions are labeled. Data from Oregon State University (<https://lemma.forestry.oregonstate.edu/data>).

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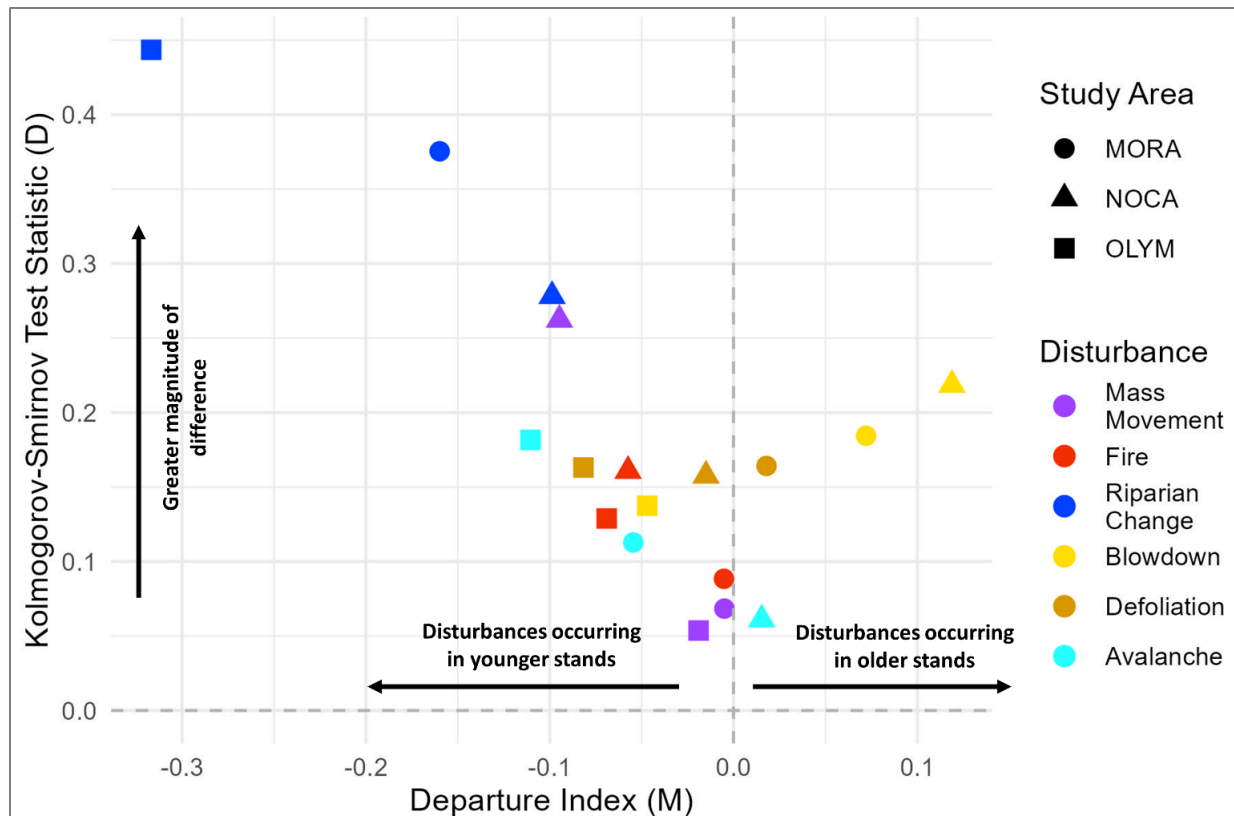


**Figure 16.** The Kolmogorov–Smirnov test statistic (D) and the departure index (M) for each combination of study area and change type. These statistics compare the distribution of stand ages affected by each change type to the distribution of stand ages in the study areas. Greater values of D indicate a greater difference between the two distributions. Negative values of M indicate disturbed areas are younger than the distribution of stand ages in the study areas, with more negative numbers indicating a greater magnitude of difference. Positive values of M indicated disturbed areas are older than the distribution of stand ages in the study areas, with more positive numbers indicating a greater magnitude of difference.

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### Prevalence of Overlapping Disturbances (i.e., More Than One Disturbance Occurring in the Same Place)

Approximately 91% of the total disturbed area experienced only one disturbance over the 31-year period examined (1987–2017) (Table 8, Figures 17, 18, and 19). The remaining 8% experienced two disturbances (Table 8).

**Table 8.** The amount of disturbed area (ha) and percentage of disturbed area (%) that experienced a single disturbance (number of disturbances = 1) or multiple disturbances (number of disturbances > 1) from 1987 to 2017 within the North Cascades National Park Service Complex (NOCA) study area, Olympic National Park (OLYM) study area, Mount Rainier National Park (MORA) study area, and all study areas combined.

| Number of Disturbances | NOCA Study Area     |                     | OLYM Study Area     |                     | MORA Study Area     |                     | All Study Areas Combined |                     |
|------------------------|---------------------|---------------------|---------------------|---------------------|---------------------|---------------------|--------------------------|---------------------|
|                        | Disturbed Area (ha) | % of Disturbed Area | Disturbed Area (ha) | % of Disturbed Area | Disturbed Area (ha) | % of Disturbed Area | Disturbed Area (ha)      | % of Disturbed Area |
| 1                      | 38,216              | 89.7                | 7,101               | 97.1                | 20,512              | 93.5                | 65,829                   | 91.2                |
| 2                      | 4,242               | 10.0                | 206                 | 2.8                 | 1,319               | 6.0                 | 5,766                    | 8.0                 |
| 3                      | 168                 | 0.4                 | 8                   | 0.1                 | 106                 | 0.5                 | 285                      | 0.4                 |
| 4                      | <1                  | <0.1                | <1                  | <0.1                | 2                   | <0.1                | 2                        | <0.1                |

## Overlapping disturbances within the NOCA Study Area

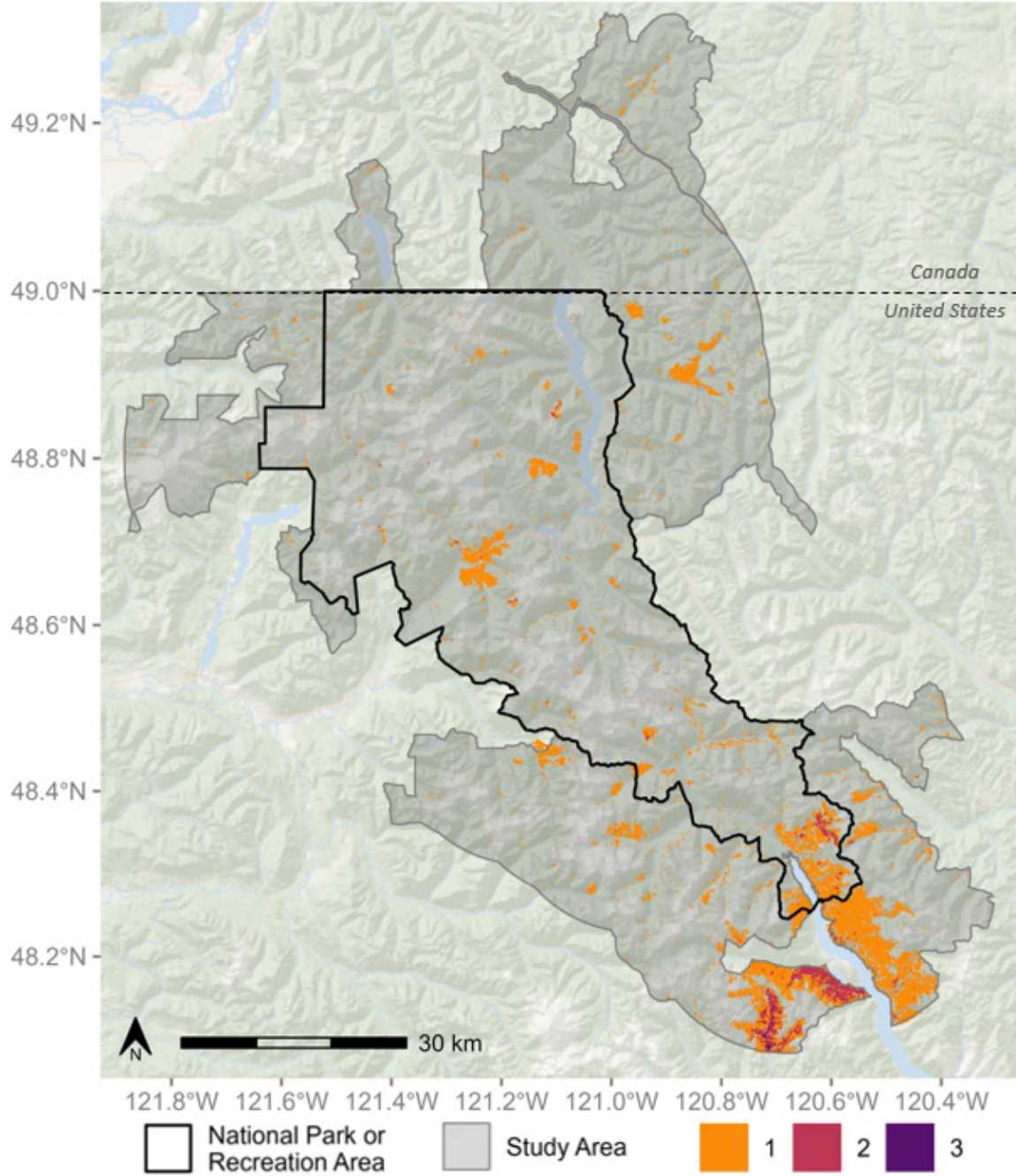


**Figure 17.** Overlapping disturbances within the North Cascades National Park Service Complex (NOCA) study area. Values of one indicate the occurrence of 1 disturbance over the 31-year period examined (1987–2017); values greater than 1 indicate the occurrence of multiple disturbances.

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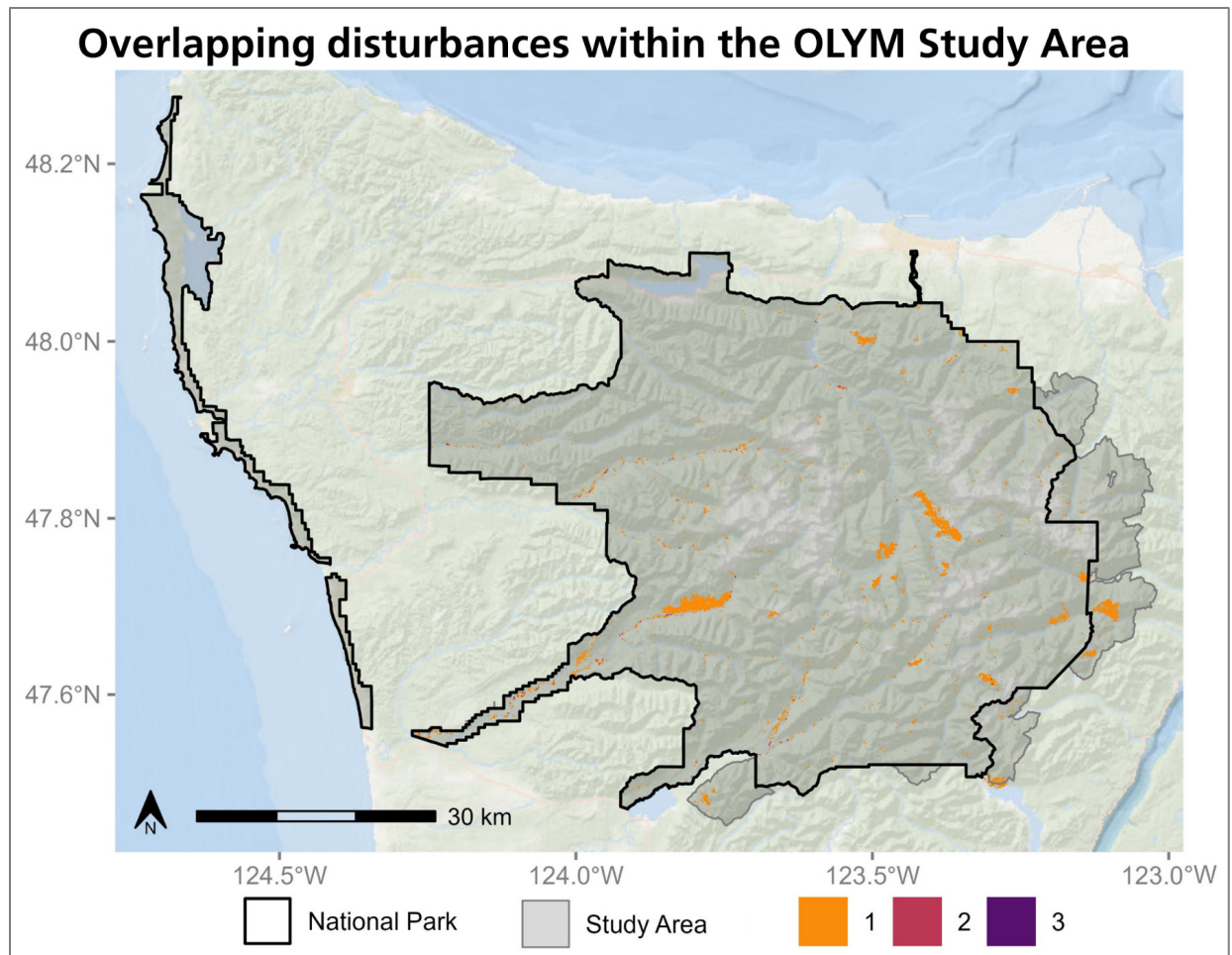


**Figure 18.** Overlapping disturbances within the Olympic National Park (OLYM) study area. Values of 1 indicate the occurrence of 1 disturbance over the 31-year period examined (1987–2017); values greater than 1 indicate the occurrence of multiple disturbances.

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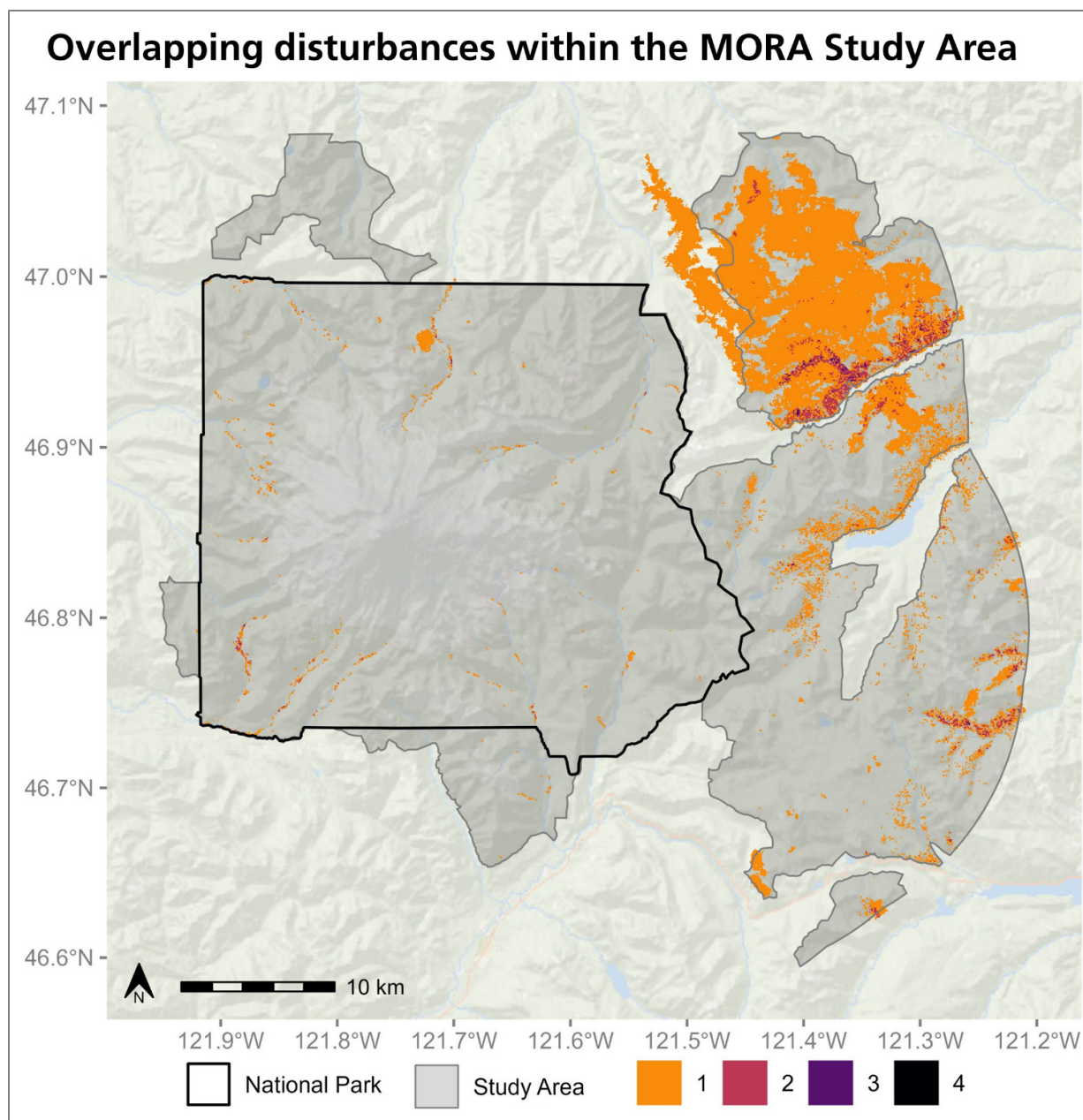


**Figure 19.** Overlapping disturbances within the Mount Rainier National Park (MORA) study area. Values of 1 indicate the occurrence of 1 disturbance over the 31-year period examined (1987–2017); values greater than 1 indicate the occurrence of multiple disturbances.

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Out of the three study areas, NOCA had the greatest amount of overlapping disturbances, with 4,410 ha over the period examined (Table 8), accounting for approximately 10% of the total study area. Approximately 81% of the overlapping disturbances within NOCA were Fire followed by Fire (Table 9). Defoliation followed by Fire was the second most frequent combination and accounted for 9% of the area affected by overlapping disturbances (Table 9).

**Table 9.** Types of overlapping disturbances and corresponding areas within the NOCA, MORA, and OLYM study areas. *Note: Disturbance combinations that accounted for less than 1% of the total overlapping disturbance area within each study area were removed from the table.*

| Study Area | Initial Disturbance | Second Disturbance | Third Disturbance | Area (ha) | % of Overlapping Disturbance Area Within Respective Park |
|------------|---------------------|--------------------|-------------------|-----------|----------------------------------------------------------|
| NOCA       | Fire                | Fire               | –                 | 3,561     | 80.8                                                     |
|            | Defoliation         | Fire               | –                 | 404       | 9.2                                                      |
|            | Defoliation         | Fire               | Fire              | 153       | 3.5                                                      |
|            | Defoliation         | Defoliation        | –                 | 55        | 1.3                                                      |
|            | Avalanche           | Fire               | –                 | 45        | 1.0                                                      |
| OLYM       | Riparian Change     | Riparian Change    | –                 | 171       | 79.6                                                     |
|            | Avalanche           | Avalanche          | –                 | 8         | 3.8                                                      |
|            | Riparian Change     | Riparian Change    | Riparian Change   | 7         | 3.4                                                      |
|            | Mass Movement       | Mass Movement      | –                 | 5         | 2.5                                                      |
|            | Riparian            | Fire               | –                 | 4         | 2.1                                                      |
|            | Fire                | Fire               | –                 | 4         | 1.8                                                      |
|            | Avalanche           | Fire               | –                 | 3         | 1.4                                                      |
|            | Blowdown            | Blowdown           | –                 | 3         | 1.2                                                      |
|            | Blowdown            | Riparian Change    | –                 | 2         | 1.1                                                      |
| MORA       | Defoliation         | Fire               | –                 | 968       | 67.9                                                     |
|            | Defoliation         | Defoliation        | –                 | 229       | 16.0                                                     |
|            | Defoliation         | Defoliation        | Fire              | 88        | 6.2                                                      |
|            | Riparian Change     | Riparian Change    | –                 | 67        | 4.7                                                      |
|            | Fire                | Fire               | –                 | 36        | 2.5                                                      |
|            | Defoliation         | Defoliation        | Defoliation       | 14        | 1.0                                                      |

The OLYM study area experienced 214 hectares of overlapping disturbances (Table 8), accounting for less than 3% of the total study area. The most frequent overlapping disturbances within the OLYM study area were Riparian Change followed by Riparian Change, accounting for 80% of all overlapping disturbances, followed by overlapping Avalanche events (Table 9).

Within the MORA study area, a total of 1,427 ha of overlapping disturbances occurred during the period examined (Table 8), accounting for under 7% of the total disturbed area. The primary overlapping disturbances within MORA were Defoliation followed by Fire (968 ha, accounting for 67.9% of overlapping disturbances) and Defoliation followed by Defoliation (229 ha, accounting for 16.0% of overlapping disturbances) (Table 9). Most of these overlapping disturbances occurred on

the US Forest Service lands. Within the park, the most frequent overlapping disturbance was Riparian Change.

## Discussion

This study highlights spatial and temporal patterns of disturbance activity within the North Cascades National Park Service Complex, Olympic National Park, Mount Rainier National Park, and adjacent federally protected areas. First, we found that Fire was the most extensive disturbance category affecting the study areas, accounting for 78% of the cumulative disturbance area from 1987 to 2017. While the observed fire activity across study areas was consistent with expectations of historical fire regimes, our findings suggest that fire is likely to have the greatest effect on park infrastructure, recreation, and resources in the future. Second, 80% of cumulative disturbance activity across the broader study area was concentrated in the eastern portions of the study areas; when limited to park lands, this figure was 51% of cumulative disturbance. These drier, eastern areas may continue to be more disturbance prone in the future under continued climate warming and drying. Third, Defoliation activity peaked in the early to mid-2000s consistent with regional insect outbreaks. These findings have important implications for natural resource planning and management within the National Park Service and surrounding areas.

### **Fire Was the Most Extensive Disturbance Affecting NPS Land and Adjacent Federally Protected Areas**

Fire was the most extensive disturbance affecting NPS land and adjacent federally protected areas, accounting for 78% of all cumulative disturbance area from 1987 to 2017 (see supplementary tables in the Appendix). Approximately 85% of the cumulative fire-disturbed area occurred east of the Cascade crest in the NOCA and MORA study areas and in the eastern portion of the OLYM study area (see supplementary tables in the Appendix). The eastern portions of all three study areas are situated within the rain shadows of the Olympic Mountains and Cascade Range, resulting in reduced precipitation and drier conditions relative to the west side of the study areas (Raymond et al., 2014). The moisture gradient is more pronounced east of the Cascade Range crest, which also appears to correspond to greater area burned in the NOCA and MORA study areas relative to the OLYM study area (i.e., 92% of fire-disturbed area occurred in NOCA and MORA study areas; see supplementary tables in the Appendix). Greater area burned east of the Cascade Range crest is consistent with expectations of historical fire regimes, which are characterized by frequent (average fire return interval of 0 to 35 years), low-severity fire in dry, low-elevation forests and moderately-frequent (average fire return interval between 35 and 100+ years), mixed-severity fire in moist mixed conifer forests (Reilly et al., 2021; see supplementary tables in the Appendix). For example, 38.8% of the cumulative area burned within the NOCA study area occurred within historically frequent, low severity fire regimes despite these fire regimes only accounting for 7.5% of the NOCA study area (see supplementary tables in the Appendix).

Increasing wildfire activity has been observed across many forest types in the western United States in recent decades and is attributed to a warmer and drier climate (Abatzoglou and Williams, 2016; Coop et al., 2020; Parks and Abatzoglou, 2020). In dry, fire-dependent forests, the legacy of fire suppression and fire exclusion has led to dense and spatially homogenous forests that promote fire spread, leading to larger and more severe fires (e.g., Hessburg et al., 2005). Fires ignited in dry,

lower-elevation forests of the study area may spread towards higher elevation forests (Halofsky et al., 2020; Reilly et al., 2021), including moist mixed conifer forests or cold, high-elevation forests that are characterized by infrequent (e.g., average fire return intervals greater than 200 years; see supplementary tables in the Appendix) and high severity fire regimes. These infrequent, high-severity fire regimes in cold, high-elevation forests of the eastern Cascades historically burned less frequently due to cooler and wetter climatic conditions and a short summer-dry season (Reilly et al., 2021). When these forests do burn, they are more likely to experience high-severity fire due to the dominance of fire-sensitive species and denser forest structure (Agee, 1993; Reilly et al., 2021). However, with warmer and drier climatic conditions projected across the entire study area (Case et al., 2021; Mote and Salathé, 2010), summer-dry periods may become longer in these high-elevation forests which may increase fire potential especially when fires spread upslope from dry, low-elevation forest ignitions (Halofsky et al., 2020).

Despite recent large fire years in eastern Washington and Oregon, dry and moist mixed conifer forests across the region remain in a considerable fire deficit of all fire severity classes (i.e., low, moderate, and high) relative to historical conditions (Donato et al., 2023; Haugo et al., 2019). For example, the average area burned across all forest types of eastern Washington would have ranged from 89,000 to 115,000 ha per year under historical fire frequencies in contrast to a contemporary average area burned of 26,000 ha per year (Donato et al., 2023). However, while the region remains in a fire deficit, individual fire events are burning at uncharacteristically high proportions of high severity within both dry and moist mixed conifer forests (Haugo et al., 2019), which may result in undesirable ecological and social outcomes. To reduce the risk of uncharacteristically severe fire within dry forests, contemporary forest management is focused on restoring forest structure conditions at landscape scales by reducing fuel loads and fuel continuity through silvicultural treatments, prescribed burning, and managed wildfire (Churchill et al., 2022, 2013; Hessburg et al., 2021). Dry and moist mixed conifer forests account for ~30% and 50% of area within the NOCA and MORA study area, respectively (see supplementary tables in the Appendix).

### **Increasing Mean Annual Patch Size of Fire Disturbances Reflects Relatively Large Wildfire Events During the Latter Half of the Period Examined (1987–2017)**

Large wildfire events are more likely to contain large individual patches (Buonanduci et al., 2024), and our finding that mean annual fire patch size increased from 1987 to 2017 within the MORA study area and at the scale of all study areas combined (Table 6; Figures 9 and 12) reflects the occurrence of relatively large wildfire events towards the end of our study period. For example, the Norse Peak Fire burned approximately 16,500 ha within the MORA study area in 2017 in contrast to a mean annual area burned of ~80 ha before 2017 (Figure 12). In the LandTrendr approach, individual pixels (30 m resolution) and disturbance patches represent contiguous areas of spectral change and may contain a mix of burn severities that include both living and fire-killed trees. Areas that contain living trees or that are situated within the maximum seed dispersal distance of living trees (i.e., within 150 meters for most conifer species; Harvey et al., 2016a; Kemp et al., 2016) are likely to have access to seed sources that aid in post-fire forest re-establishment. Without knowing the burn severity of fire-disturbed patches, it is difficult to anticipate ecological outcomes of larger patch sizes. However, even large, stand-replacing burn patches that experience near-100% mortality

often exhibit complex spatial patterns that result in a substantial amount of stand-replacing area being within proximity to a live seed source (e.g., Harvey et al., 2016b).

Additionally, many of the larger wildfire events occurred in the western Cascades including the 2015 Goodell Creek fire in the NOCA study area, the 2015 Paradise fire in the OLYM study area, and the 2017 Norse Peak fire in the MORA study area. In contrast to fire regimes in dry and moist mixed conifer forests of the eastern Cascades, fire regimes in moist temperate forests of the western Cascades are in part characterized by large (maximum area burned exceeding 1,000,000 ha; Donato et al., 2020) and infrequent (i.e., average severe-fire return intervals that range from 200 to > 450 years; Agee, 1993; Tepley et al., 2013) fire events that contain large stand-replacing burn patches (i.e., areas with >90% overstory mortality; Reilly et al., 2022). Because fire operates at longer time scales and broader spatial extents in the western Cascades, we are unable to determine ecological trends in fire activity over a 31-year time series (i.e., a much longer temporal record across a broader spatial extent would be required). However, the larger fire events observed in our study areas are not anomalous for the western Cascades (Donato et al., 2020; Agee, 1993) and the larger patch sizes do not necessarily indicate ecological concern. For example, abundant post-fire conifer regeneration in the western Cascades has been observed at distances as far as 400 meters from a live seed source following stand-replacing wildfire (Laughlin et al., 2023b). It is uncertain how fire activity in the western Cascades may change in the future, however, climate warming and drying may increase fire potential as wildfires in the western Cascades are largely driven by climatic conditions (Halofsky et al., 2020).

While the observed fire activity across our study areas aligned with expected historical fire activity, our findings highlight that fire is the most extensive change type within and adjacent to NPS land and is likely to pose the greatest future risk to park infrastructure, recreation, and natural resources. Fires are contagious disturbances that have the potential to affect large extents in relatively short periods and may threaten human infrastructure (e.g., buildings and roads) and natural resources of particular interest such as old-growth forests and the immense carbon stores they contain that if lost are likely to be irrecoverable in the foreseeable future (Noon et al., 2021). Given that fire activity in the highly productive western Cascades is climate-limited (i.e., driven by climatic conditions suitable for burning as opposed to availability of fuels; Meyn et al., 2007), fire suppression remains an effective management strategy for protecting resources of interest such as old-growth forest (e.g., Halofsky et al., 2020; Kopper, 2022).

Economically, suppressing wildfires can be costly and resource-intensive and wildfire activity can negatively impact recreation and visitor use of national parks (Duffield et al., 2013; Kim and Jakus, 2019). With wildfire activity increasing globally under a warming and drying climate (Parks and Abatzoglou, 2020), wildfire will likely remain to be an extensive disturbance within and adjacent to NPS lands in the future. Based on our findings, we may anticipate future fire activity to be concentrated in the eastern Cascades of the study areas with the potential to spread west towards NPS lands under some conditions (Agee, 1993). For example, the 2017 Norse Peak fire was ignited by lightning in the eastern Cascades and later spread west over the Cascade Range crest during strong easterly winds.

## **Defoliation Activity Peaked in the Mid-2000s Consistent with Regional Insect Outbreaks**

Defoliation activity peaked in the mid-2000s, likely driven by regional mountain pine beetle and western spruce budworm outbreaks (Meigs et al., 2015). Frequency and extent of Defoliation was greater from 2001 to 2017 relative to 1987 to 2000 in terms of the number of events per year (across all three study areas combined, and within the eastern portion of NOCA) and annual disturbance area (within NOCA). Our GLM results also indicated that Defoliation activity increased within the MORA study area and the western portion of the NOCA study area (Table 6), however, it is important to note that GLMs model linear trends whereas trends in Defoliation activity appeared to be non-linear (i.e., increasing through the mid-2000s, then decreasing; Figures 9, 10, and 12). Additionally, trends in the western portion of the NOCA study area were likely driven by very little Defoliation activity followed by a modest increase in the mid-2000s. Approximately 97% of the cumulative Defoliation area occurred in the eastern portions of the study areas (see supplementary tables in the Appendix), primarily within the MORA and NOCA study areas (see supplementary tables in the Appendix). The peak in Defoliation activity corresponds to regional mountain pine beetle and western spruce budworm outbreaks across dry interior forests of the PNW during the mid-2000s during a particularly warm and dry period (Meigs et al., 2015; Figure 5). Drought and warmer temperatures can indirectly increase insect outbreaks by weakening tree defenses and promoting insect larvae survival through the winter and thus increasing insect populations (Preisler et al., 2012; Robbins et al., 2022). However, drivers of insect outbreaks vary depending on the insect and host species (Johnson and Haynes, 2023). While it is likely that insect outbreaks contributed to the observed peak in Defoliation activity during the mid-2000s, we did not identify the causes of Defoliation. Additional factors like drought-induced mortality and disease could also contribute to Defoliation activity. Future research identifying the underlying causes of Defoliation (e.g., insects, drought, or disease) and determining which host species are affected would improve our understanding of how Defoliation activity may change in the future within the study areas. Doing so would also provide more information on the ecological impact of Defoliation events, as the severity and duration of insect outbreaks vary with insect and host species (Andrus et al., 2025). This could be done by cross-validating the LandTrendr change detection polygons with the US Forest Service aerial detection surveys (ADS) that identify insect and disease activity.

## **No Significant Trends in Disturbance Activity for Other Disturbances**

The lack of statistical trends in disturbance activity for Mass Movement, Riparian Change, Blowdown, and Avalanche categories suggests that these change types are neither increasing nor decreasing over the examined period in our study areas. Excluding Fire and Defoliation, all other change types accounted for ~10% of the cumulative disturbance area from 1987 to 2017 (7,988 ha; see supplementary tables in the Appendix). Despite the lack of trends in these disturbances, our results provide information about where we might anticipate these disturbances to occur. For example, Riparian Change was more extensive within the OLYM study area, and Mass Movement, Riparian Change, Blowdown, and Avalanche disturbances affected more area in the western portions of each study area (see supplementary tables in the Appendix).

### **Minimal Overlapping Disturbances Across the Study Areas**

Overall, there was not a substantial amount of area that experienced more than one disturbance in the 31 years examined. Areas that did experience more than one disturbance were primarily overlapping fires within the eastern Cascades of the NOCA study area (Table 8; Figure 17), which may reflect the fire-prone nature of dry, low-elevation forests and the manifestation of the historical fire regime. For example, climatic conditions are typically conducive to burning during the summer months and fire activity is thus constrained by an ignition source and the availability of combustible fuels (Pausas and Keeley, 2019). In the absence of fire suppression, some areas experienced historical fire return intervals of less than 30 years (Kopper, 2022; Reilly et al., 2021) which may be reflected in our results. Alternatively, some of this area could be attributed to delayed mortality which can occur for up to 5 years following the fire (Reilly et al., 2023). Areas that initially experience high mortality are more likely to be detected by the LandTrendr algorithm immediately following the wildfire event while areas that experience low initial mortality may go undetected until subsequent delayed mortality in the years following the wildfire event (Reilly et al., 2023). In addition, unlike for the trend analysis, we did not aggregate fire patches by individual fire events for this portion of the analysis, which may have increased the prevalence of overlapping fire disturbed area. For example, instances of delayed mortality would not show up as the same fire event but rather two separate events.

### **Stand Ages Affected by Disturbance**

The stand age distribution of areas affected by disturbances mostly overlapped with the stand age distribution of the study areas, suggesting most disturbances were not selective towards a specific stand age and corresponding stand structure. One exception to this was Riparian Change, which appeared to disproportionately affect younger stands across all three parks (Figures 13, 14, and 15). One potential explanation for this is that forests adjacent to rivers and streams are more likely to experience flooding events that reset stand age (i.e., forests on floodplains are more likely to be younger because they are affected by riparian disturbances more frequently). This may also explain some instances of Avalanche and Mass Movement affecting younger stands in some of the study areas (Figures 13, 14, and 15). Alternatively, this result may be an artifact of how the stand-age rasters were produced by GNN. The GNN stand age rasters are a modeled product that relates satellite imagery and satellite-derived metrics to on-the-ground field measurements. It is important to note that GNN does not accurately estimate the exact stand age in years of a particular pixel, but instead captures important differences in stand structure that correlate with stand age. These models were developed primarily within coniferous forests where structural complexity increases with stand age (i.e., old-growth forests have a much more complex forest structure relative to young forests in ways that are detectable from satellite imagery; Martin et al., 2021). Riparian vegetation is often dominated by more deciduous species (e.g., red alder, cottonwood, aspen, or maple) that may appear less structurally developed relative to a conifer-dominated forest. Thus, it is possible that what we are detecting is Riparian Change occurring in more deciduous-dominated forests as opposed to younger forests.

Although the Kolmogorov–Smirnov tests showed significant differences between the distribution of stand ages in protected areas and the distribution of stand ages affected by disturbance ( $p < 0.05$ ), the

K–S test is sensitive to large sample sizes. Because of large sample sizes used in the stand age distributions, we instead focused on relative differences in the D statistic and the departure index from the Menning test (Menning et al., 2007) to assess differences between distributions.

### **Limitations and Areas of Future Research**

The LandTrendr approach is more likely to detect disturbances that correspond with more pronounced shifts in vegetative greenness over short periods (i.e., a greater difference between the pre- and post-disturbance spectral signature). This is due in part to the segmentation process that uses a given threshold to filter out interannual variability due to phenology, soil moisture, shadowing, haze, and other imagery anomalies. As a consequence, low-magnitude disturbances are likely to be excluded by the algorithm, leading to underestimation of total disturbance area in our results across a range of disturbance types. For example, our results likely underestimate the total amount of area affected by low-severity fire and insect or disease outbreaks. We did not explicitly examine the severity of each disturbance patch (i.e., the percent of overstory mortality), which could be a valuable area of future research to better understand the potential ecological outcomes of disturbance patches. We did assess disturbance magnitude (i.e., the raw change in pre- and post-disturbance spectral signature), which did not stand out as statistically significant in any of our tests. We chose not to report or analyze results pertaining to disturbance magnitude because magnitude thresholds were used to detect disturbance patches in the LandTrendr algorithm (Copass and Antonova, 2022) and because magnitude represents the raw difference in pre- and post-disturbance Normalized Burn Ratio (NBR) index used by the change detection protocol and is thus highly correlated with the amount of pre-fire vegetation (e.g., Miller and Thode, 2007). For example, two pixels could experience complete vegetation loss, though one pixel may have a much larger magnitude value only because it had greater pre-disturbance vegetation.

In addition, it could be useful to compare disturbance activity within our study areas which are protected from development and resource extraction to non-protected areas in the region to see if there are meaningful differences. There are some limitations to how narrow (linear) and multi-year disturbances are detected. For example, low-severity mortality caused by Defoliation may unfold over multiple years, which may inflate the number of events (i.e., every year new disturbance patches will be added, even though they are all arising from the same disturbance phenomenon in a given area). Inflation of the number of Riparian Change events may also occur due to multiple disconnected and narrow patches of change occurring along a riparian corridor during the same flood event. On the other hand, total area affected by these change types is likely underestimated due to the low-severity nature of the disturbance and its concomitant dampening of any observed spectral change. Furthermore, because disturbance patches are determined by year of detection and adjacency (i.e., areas smaller than 0.8 ha are missed from the LandTrendr approach), disturbance area estimates for patchy disturbances (such as Defoliation) and narrow features such as landslide scars and along riparian corridors may frequently be underestimated. Future increases in spatial resolution of underlying imagery may help to resolve this issue.

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## Appendix

### Potential Natural Vegetation Zones Within Each Study Area

Table 10 and Figures 20–23 summarize information on the potential natural vegetation (PNV) zones within the NOCA, MORA and OLYM study areas. The PNV zones represent vegetation expected to occur in a particular location based on historical climate and biophysical environment (i.e., soils, topography, geology) in the absence of disturbance and often encompass unique sets of ecosystem structure, composition, and function. Data were sourced from the USFS Pacific Northwest Region’s Terrestrial Ecological Unit Inventory (TEUI) data viewer (<https://teui-region6-usfs.hub.arcgis.com/pages/data-viewer/>).

**Table 10.** Total area (ha) and percentage (%) of the study area of each potential natural vegetation (PNV) zone within the North Cascades National Park Service Complex (NOCA) study area, the Olympic National Park (OLYM) study area, and the Mount Rainier National Park (MORA) study area. The percentage of the study area (%) was calculated by dividing the area of each PNV by the total area of each study area.

*Note: The Canadian portion of the NOCA study area is not included in this table, as PNV data are limited to the USA.*

| Potential Natural Vegetation Zone | NOCA    |       | OLYM    |       | MORA   |       |
|-----------------------------------|---------|-------|---------|-------|--------|-------|
|                                   | (ha)    | (%)   | (ha)    | (%)   | (ha)   | (%)   |
| Pacific Silver Fir                | 111,122 | 22.54 | 165,606 | 42.88 | 62,145 | 38.03 |
| Parklands                         | 172,934 | 35.07 | 44,694  | 11.57 | 35,017 | 21.43 |
| Mountain Hemlock                  | 80,808  | 16.39 | 60,837  | 15.75 | 41,263 | 25.25 |
| Western Hemlock                   | 66,849  | 13.56 | 74,538  | 19.30 | 11,609 | 7.10  |
| Subalpine Fir/ Engelmann Spruce   | 29,330  | 5.95  | 10,255  | 2.66  | 6,550  | 4.01  |
| Sitka Spruce                      | 4,210   | 0.85  | 27,875  | 7.22  | 873    | 0.53  |
| Douglas-Fir                       | 17,599  | 3.57  | 465     | 0.12  | 818    | 0.50  |
| White Fir - Grand Fir             | 7,531   | 1.53  | 794     | 0.21  | 4,041  | 2.47  |
| Hardwoods                         | 977     | 0.20  | 864     | 0.22  | 389    | 0.24  |
| Grasslands - Meadows              | 502     | 0.10  | 214     | 0.06  | 664    | 0.41  |
| Shrublands                        | 713     | 0.14  | 8       | 0.00  | 29     | 0.02  |
| Lodgepole Pine                    | 296     | 0.06  | 64      | 0.02  | 15     | 0.01  |
| Ponderosa Pine                    | 211     | 0.04  | 0       | 0.00  | 0      | 0.00  |

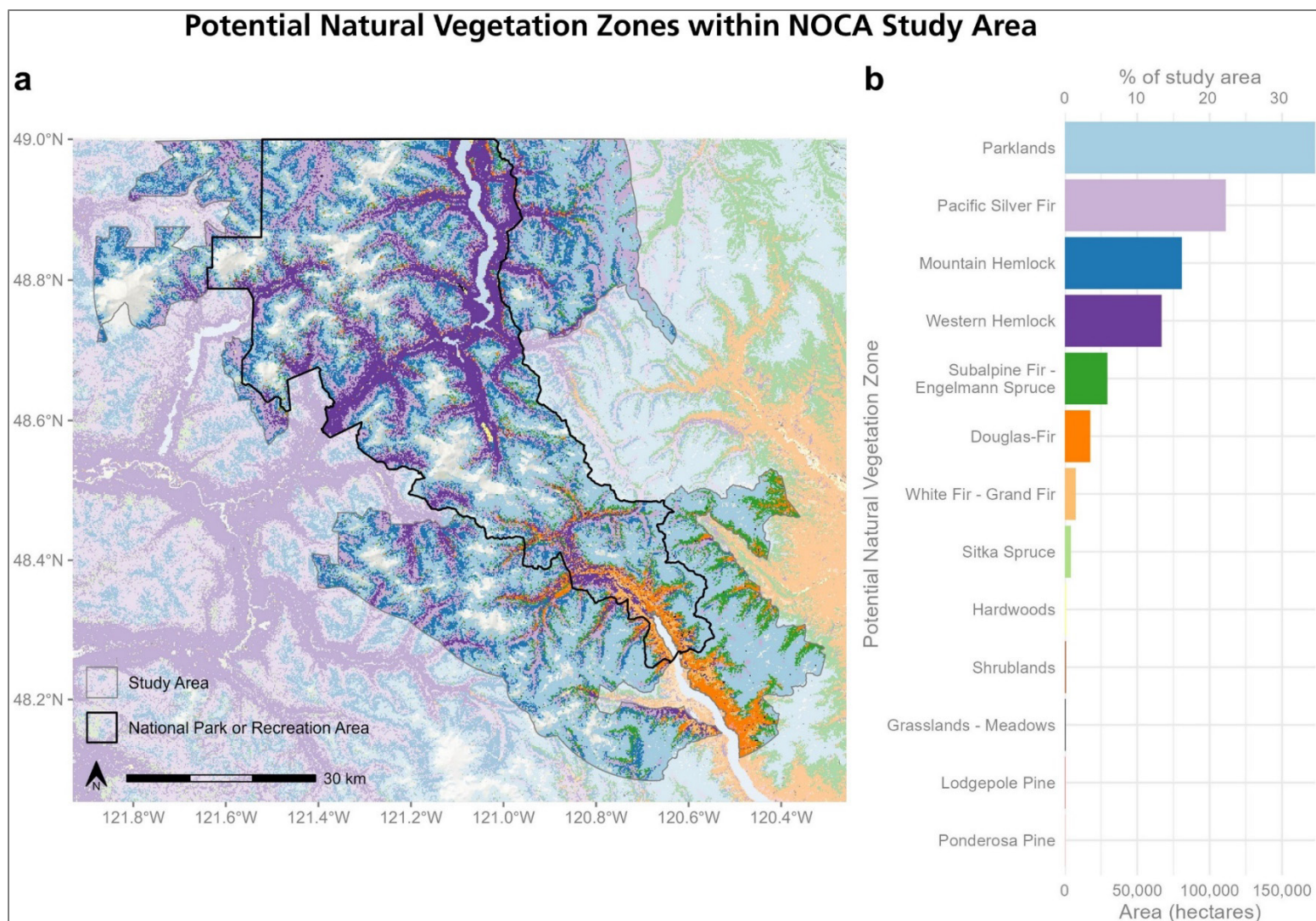


**Figure 20.** Potential Natural Vegetation (PNV) zones within the North Cascades National Park Service Complex (NOCA) study area. **(a)** Distribution of PNV zones within the NOCA study area. **(b)** Area (ha) and percentage (%) of the NOCA study area occupied by each PNV zone. The colors on the bar graph correspond to the mapped PNV zones. Data from US Forest Service.

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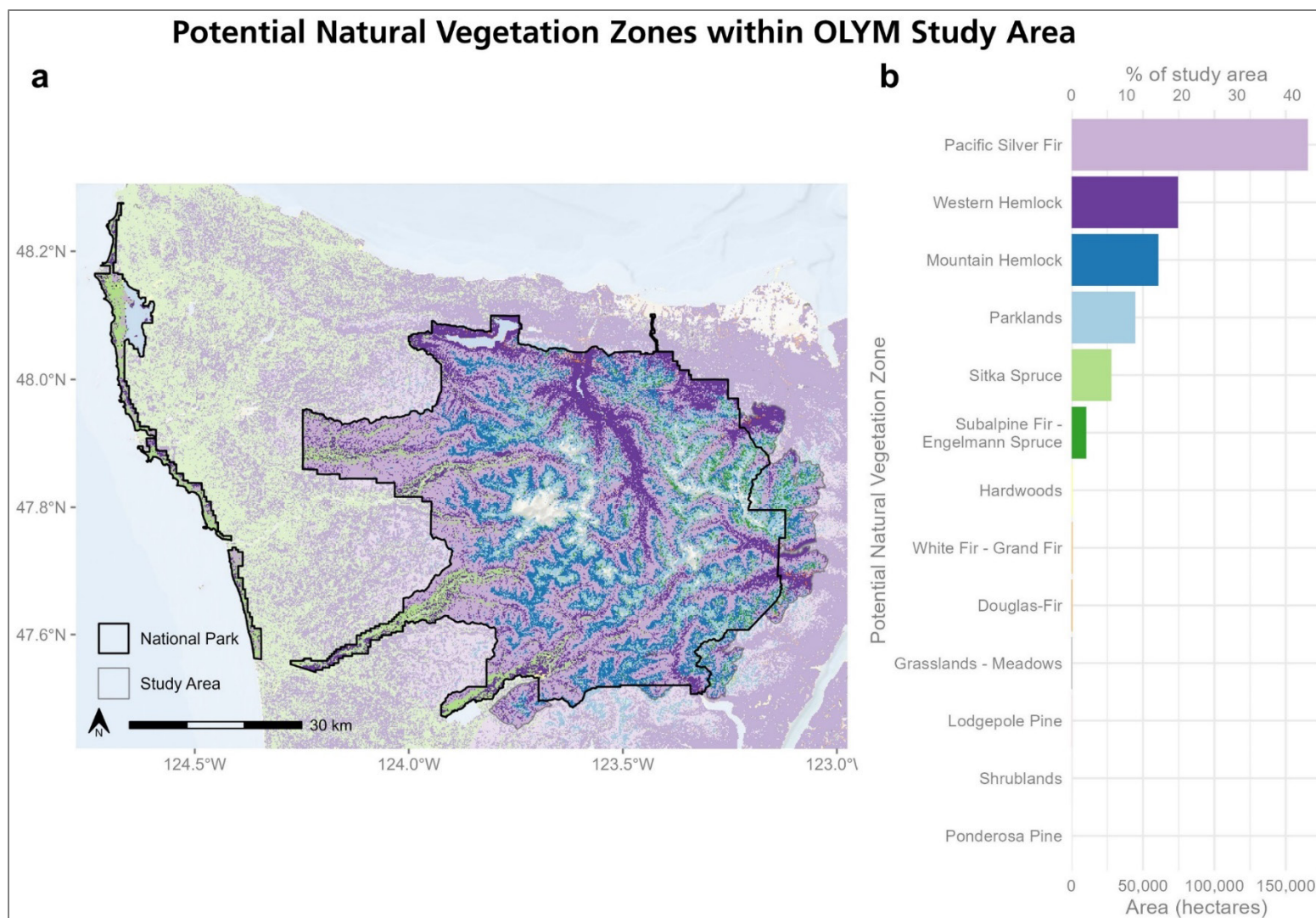


**Figure 21.** Potential Natural Vegetation (PNV) zones within the Olympic National Park (OLYM) study area. **(a)** Distribution of PNV zones within the OLYM study area. **(b)** Area (ha) and percentage (%) of the OLYM study area occupied by each PNV zone. The colors on the bar graph correspond to the mapped PNV zones. Data from US Forest Service.

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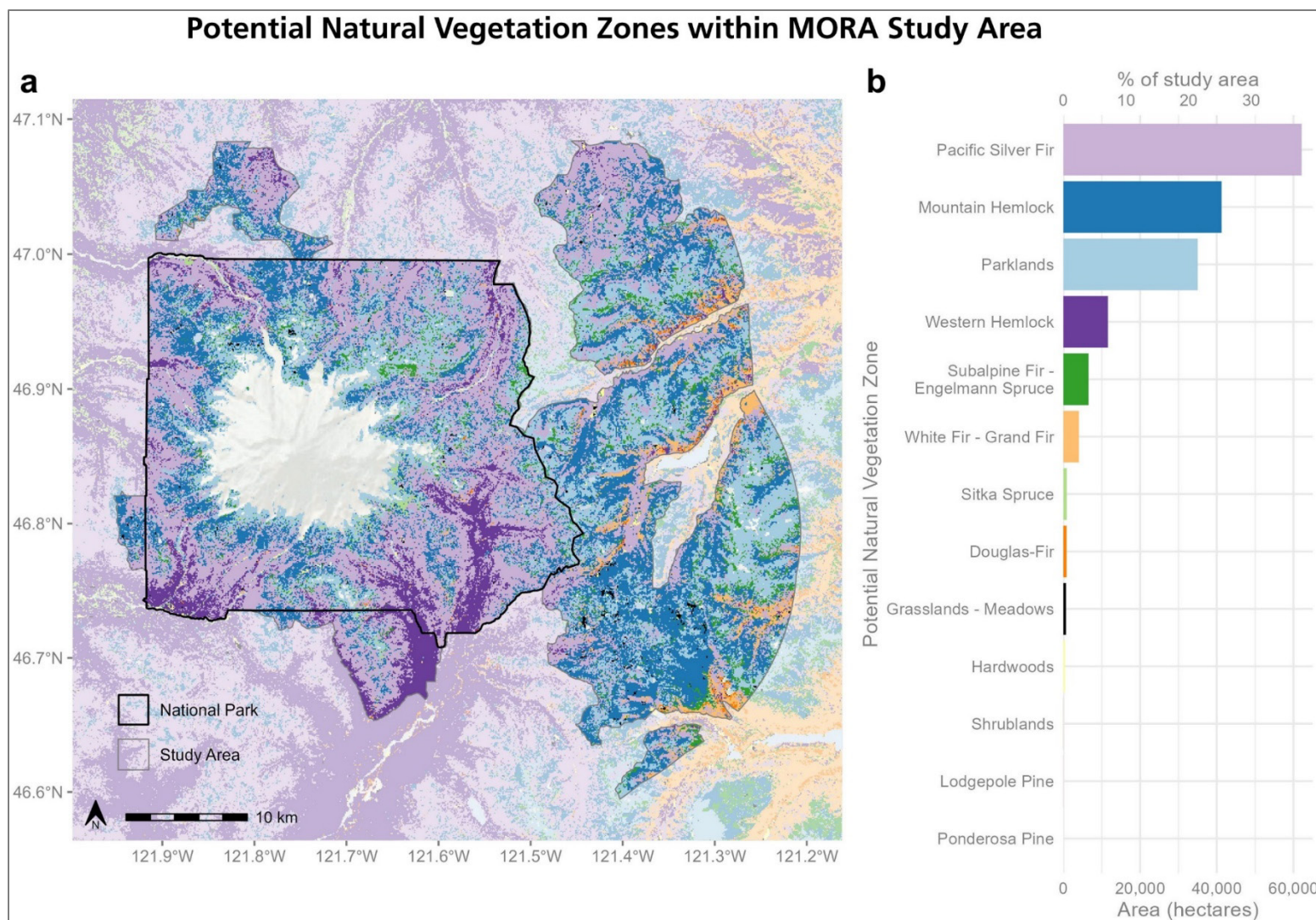


**Figure 22.** Potential Natural Vegetation (PNV) zones within the Mount Rainier National Park (MORA) study area. **(a)** Distribution of PNV zones within the MORA study area. **(b)** Area (ha) and percentage (%) of the MORA study area occupied by each PNV zone. The colors on the bar graph correspond to the mapped PNV zones. Data from the US Forest Service.

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### Conceptual Diagram of LandTrendr Pixel Time Series Segmentation

Figure 23 conceptualizes the process by which the LandTrendr algorithm summarizes the trajectory of each pixel in an image time series. Image data are reduced to a single band or spectral index and then divided into a series of straight line segments by breakpoint (vertex) identification.

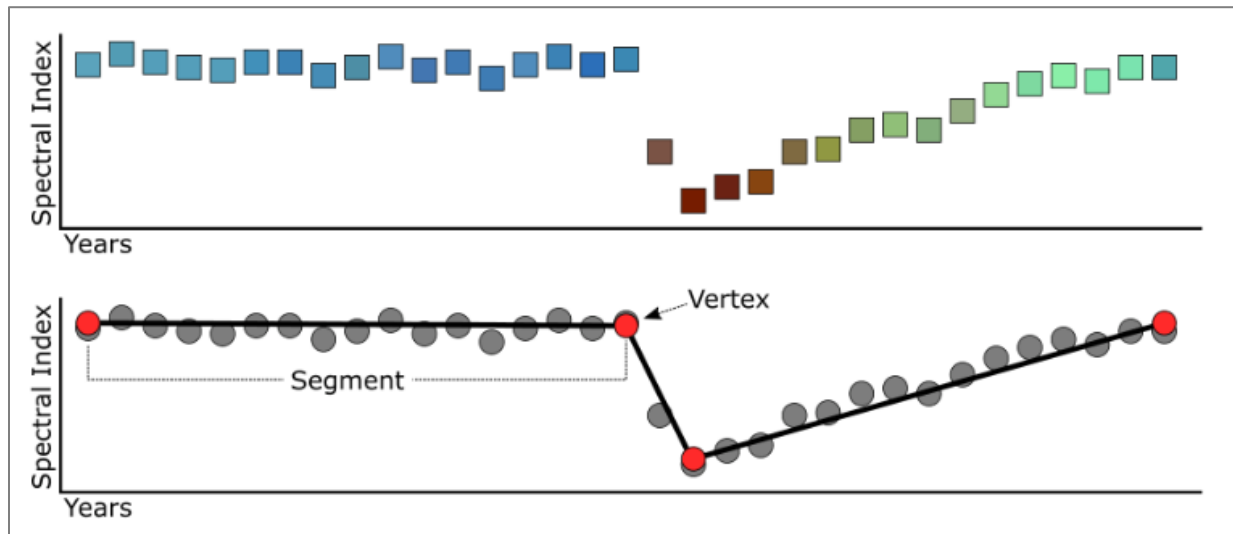


**Figure 23.** Conceptual diagram of LandTrendr pixel time series segmentation, borrowed from Kennedy et al., 2018 (<https://emapr.github.io/LT-GEE/landtrendr.html>). In the above figure, time in years is on the x-axis and the spectral index measuring a pixel's greenness is on the y-axis.

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### Cumulative Area Affected by Disturbances Across All Study Areas (1987–2017)

For each disturbance category, Tables 11 and 12 summarize disturbance area and frequency for the North Cascades, Olympic and Mount Rainier study areas and for the East and West georegions combined. Across all three study areas, a total of 75,206 ha was disturbed over the 31 years examined (1987–2017). Fire accounted for 77.56% of the area disturbed within the study areas (58,327 ha), followed by Defoliation (8,891 ha; 11.82%), Avalanche (3,032 ha; 4.03%), Riparian Change (2,936 ha; 3.9%), Mass Movement (1,093 ha; 1.45%), Blowdown (877 ha; 1.17%), Clearing (26 ha; 0.03%), Development (11 ha; 0.02%), Ice Damage (10 ha; 0.01%), and Coastal Change (2 ha; <0.01%). The cumulative number of disturbance events ranged from 2 (Coastal Change) to 3,864 (Defoliation).

**Table 11.** Cumulative area disturbed (ha), percentage of total area disturbed (%), and number of disturbance events for each change type within all study areas combined (i.e., NOCA, OLYM, and MORA study areas).

| Change Type     | Area Disturbed (ha) | % of Total Area Disturbed | Number of Disturbance Events |
|-----------------|---------------------|---------------------------|------------------------------|
| Fire            | 58,327              | 77.56                     | 166                          |
| Defoliation     | 8,891               | 11.82                     | 3,864                        |
| Avalanche       | 3,032               | 4.03                      | 1,368                        |
| Riparian Change | 2,936               | 3.90                      | 1,674                        |
| Mass Movement   | 1,093               | 1.45                      | 562                          |
| Blowdown        | 877                 | 1.17                      | 317                          |
| Clearing        | 26                  | 0.03                      | 23                           |
| Development     | 11                  | 0.02                      | 7                            |
| Ice Damage      | 10                  | 0.01                      | 10                           |
| Coastal Change  | 2                   | 0.00                      | 2                            |
| <i>Total</i>    | <i>75,206</i>       | <i>100</i>                | <i>7,993</i>                 |

**Table 12.** Cumulative area disturbed (ha), percentage of total area disturbed (%), and number of disturbance events of each change type by geographic region (west or east side of the study areas) within all three study areas combined (i.e., NOCA, OLYM, and MORA study areas).

| Change Type     | West          |                           |                              | East          |                           |                              |
|-----------------|---------------|---------------------------|------------------------------|---------------|---------------------------|------------------------------|
|                 | Area (ha)     | % of Total Area Disturbed | Number of Disturbance Events | Area (ha)     | % of Total Area Disturbed | Number of Disturbance Events |
| Fire            | 9,065         | 58.16                     | 76                           | 49,262        | 82.63                     | 92                           |
| Defoliation     | 293           | 1.88                      | 173                          | 8,597         | 14.42                     | 3,691                        |
| Riparian Change | 2,666         | 17.11                     | 1,512                        | 270           | 0.45                      | 162                          |
| Avalanche       | 2,031         | 13.03                     | 872                          | 1,001         | 1.68                      | 496                          |
| Mass Movement   | 816           | 5.23                      | 417                          | 277           | 0.47                      | 145                          |
| Blowdown        | 682           | 4.37                      | 222                          | 196           | 0.33                      | 95                           |
| Clearing        | 20            | 0.13                      | 19                           | 6             | 0.01                      | 4                            |
| Development     | 9             | 0.06                      | 5                            | 2             | 0.00                      | 2                            |
| Ice Damage      | 2             | 0.01                      | 2                            | 9             | 0.01                      | 8                            |
| Coastal Change  | 2             | 0.02                      | 2                            | 0             | 0.00                      | 0                            |
| <i>Total</i>    | <i>15,586</i> | <i>100</i>                | <i>3,300</i>                 | <i>59,620</i> | <i>100</i>                | <i>4,695</i>                 |

### Cumulative Area Affected by Disturbance Within Each Study Area (1987–2017)

Summary statistics for the full study areas are presented in Table 13. For the NOCA study area, Fire accounted for nearly 84% of total disturbed area, with 39,156 hectares and 106 events. For the

OLYM study area, the top three disturbances were Fire (54% of total disturbed area), Riparian Change (21% of total disturbed area), and Avalanche (11.6% of total disturbed area); total disturbed area was 7,757 hectares. For the MORA study area, Fire and Defoliation together represented over 95% of total disturbed area, with 14,975 hectares (72%) and 4,793 hectares (23%) affected, respectively.

**Table 13.** Cumulative area disturbed (ha), percentage of total area disturbed (%), and number of disturbance events of each change type within each study area (NOCA, OLYM, and MORA).

| Change Type     | NOCA          |                           |              | OLYM         |                           |              | MORA          |                           |              |
|-----------------|---------------|---------------------------|--------------|--------------|---------------------------|--------------|---------------|---------------------------|--------------|
|                 | Area (ha)     | % of Total Disturbed Area | # of Events  | Area (ha)    | % of Total Disturbed Area | # of Events  | Area (ha)     | % of Total Disturbed Area | # of Events  |
| Fire            | 39,156        | 83.91                     | 106          | 4,196        | 54.09                     | 27           | 14,975        | 72.05                     | 34           |
| Defoliation     | 4,064         | 8.71                      | 2,183        | 33           | 0.43                      | 27           | 4,793         | 23.06                     | 1,654        |
| Avalanche       | 2,003         | 4.29                      | 868          | 902          | 11.63                     | 432          | 127           | 0.61                      | 68           |
| Riparian Change | 597           | 1.28                      | 317          | 1,610        | 20.76                     | 1,014        | 730           | 3.51                      | 343          |
| Mass Movement   | 739           | 1.58                      | 347          | 301          | 3.88                      | 196          | 53            | 0.25                      | 19           |
| Blowdown        | 77            | 0.16                      | 40           | 695          | 8.96                      | 221          | 106           | 0.51                      | 56           |
| Clearing        | 21            | 0.04                      | 18           | 4            | 0.05                      | 4            | 1             | 0.01                      | 1            |
| Ice Damage      | 0             | 0.00                      | 0            | 10           | 0.13                      | 10           | 0             | 0.00                      | 0            |
| Development     | 7             | 0.01                      | 3            | 4            | 0.05                      | 3            | 1             | 0.00                      | 1            |
| Coastal Change  | 0             | 0.00                      | 0            | 2            | 0.03                      | 2            | 0             | 0.00                      | 0            |
| <i>Total</i>    | <i>46,664</i> | <i>100</i>                | <i>3,882</i> | <i>7,757</i> | <i>100</i>                | <i>1,936</i> | <i>20,785</i> | <i>100</i>                | <i>2,176</i> |

### **Temporal Trends in Annual Disturbance Area, Mean Patch Size, and Number of Events by Change Type and Georegion**

Figures 24–26 provide visual summaries of the area, mean patch size and number of events for each disturbance category between 1987 and 2017 and each georegion. Significant differences were found between 1987–1999 and 2000–2017 in the area affected by Defoliation in the eastern portion of the NOCA study area. Significant positive trends were found in area and number of events for the Defoliation category in the western portion of the NOCA study area between 1987 and 2017. No other significant trends were found for other disturbance categories of the NOCA study area georegions or the georegions of the two other study areas.

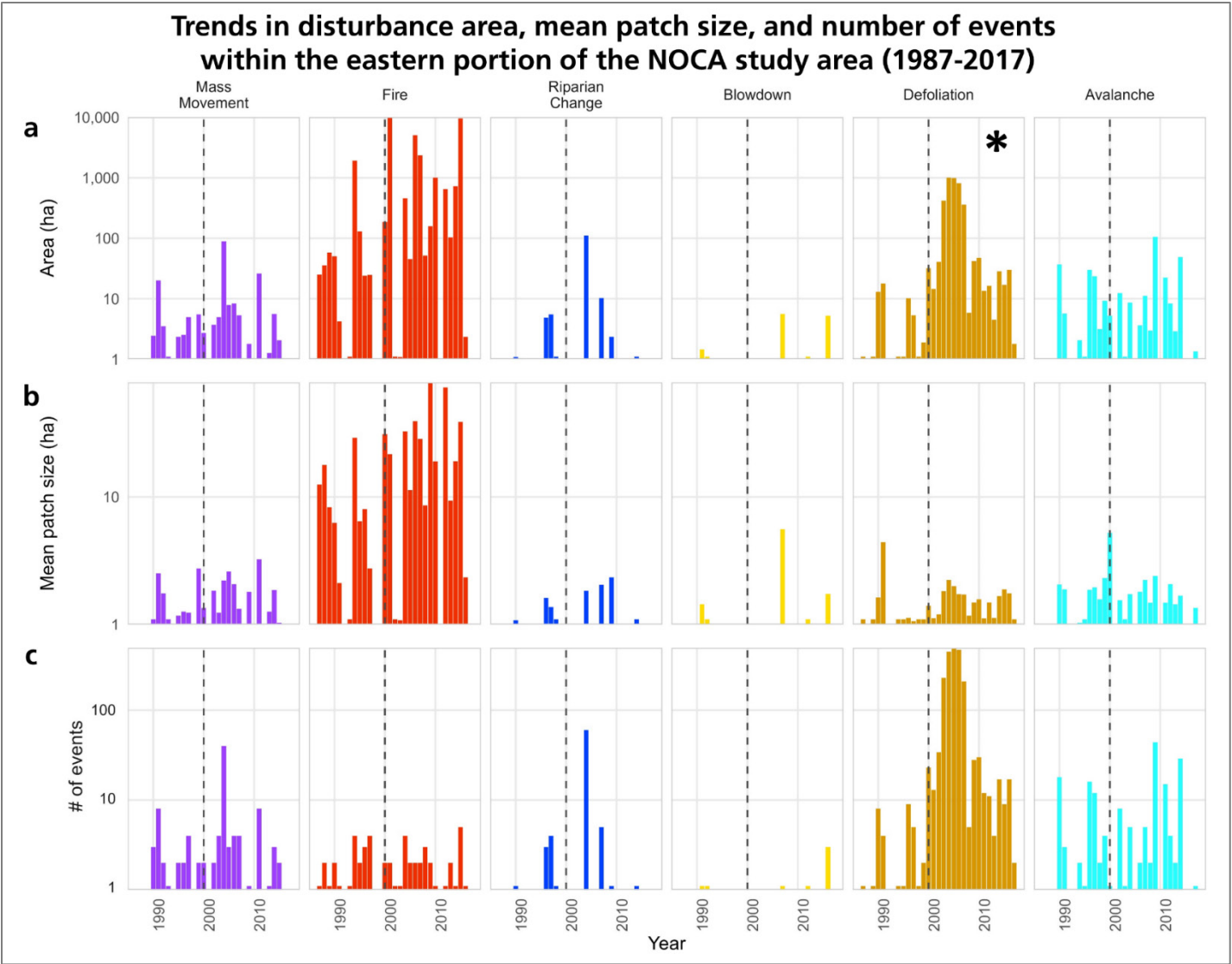


**Figure 24.** Temporal trends in disturbance within the eastern portion of the North Cascades National Park Service Complex (NOCA) study area. Trends in (a) annual disturbance area (ha), (b) mean annual patch size (ha), and (c) annual number of events. Asterisks (\*) indicate significant differences between 1987–1999 and 2000–2017 (separated by a vertical dashed gray line). The y-axis is on the base 10 log scale. To avoid negative values (i.e., when values are less than 1) and artificial zeros (i.e., when values are equal to 1) on the base 10 log scale, all response variable values greater than 0 and less than or equal to 1 were replaced with a value of 1.1 for visualization purposes only.

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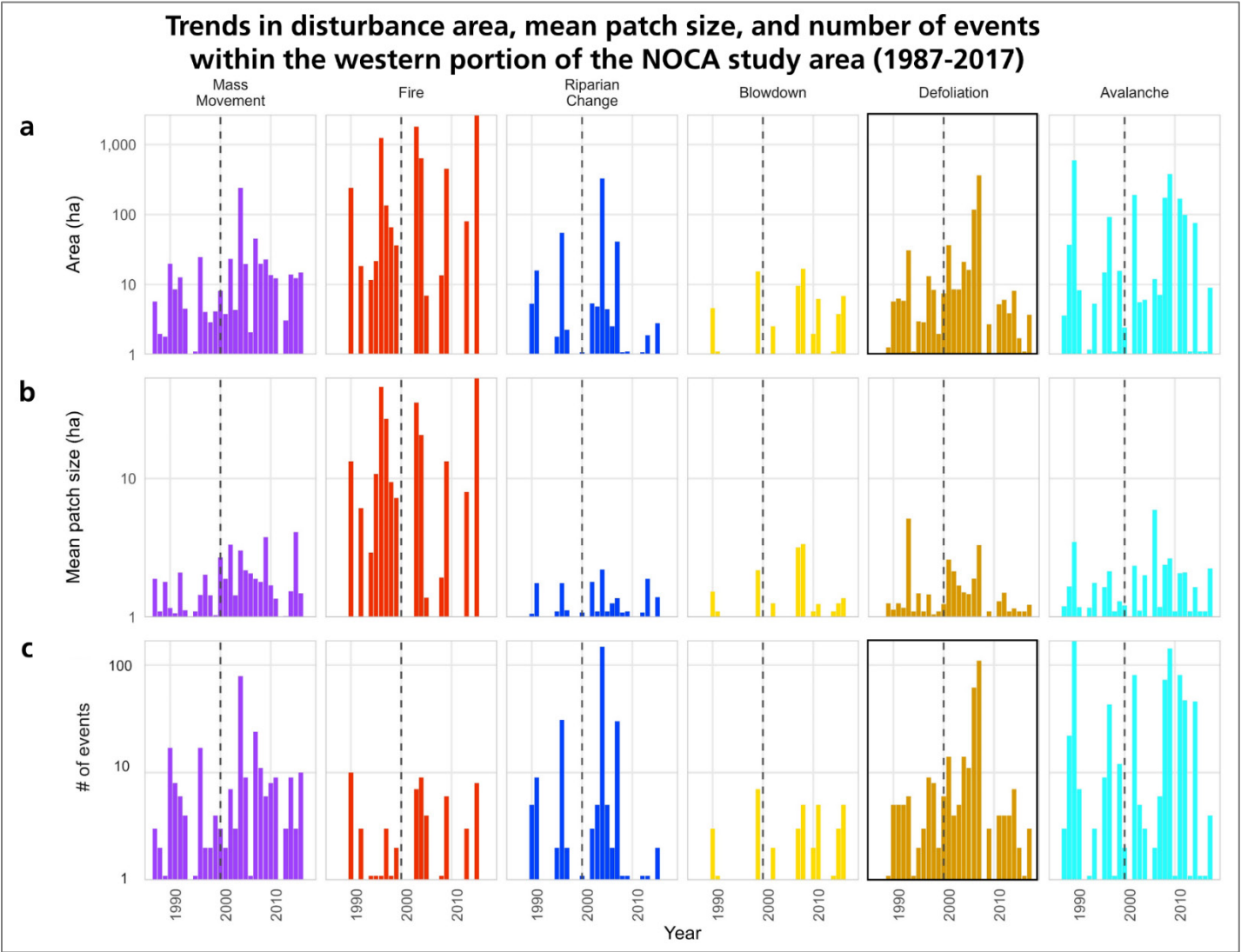


**Figure 25.** Temporal trends in disturbance within the western portion of the North Cascades National Park Service Complex (NOCA) study area. Trends in (a) annual disturbance area (ha), (b) mean annual patch size (ha), and (c) annual number of events. Black rectangles indicate statistically significant trends over the period examined (1987–2017). The vertical dashed gray line separates pre- and post-2000. The y-axis is on the base 10 log scale. To avoid negative values (i.e., when values are less than 1) and artificial zeros (i.e., when values are equal to 1) on the base 10 log scale, all response variable values greater than 0 and less than or equal to 1 were replaced with a value of 1.1 for visualization purposes only.

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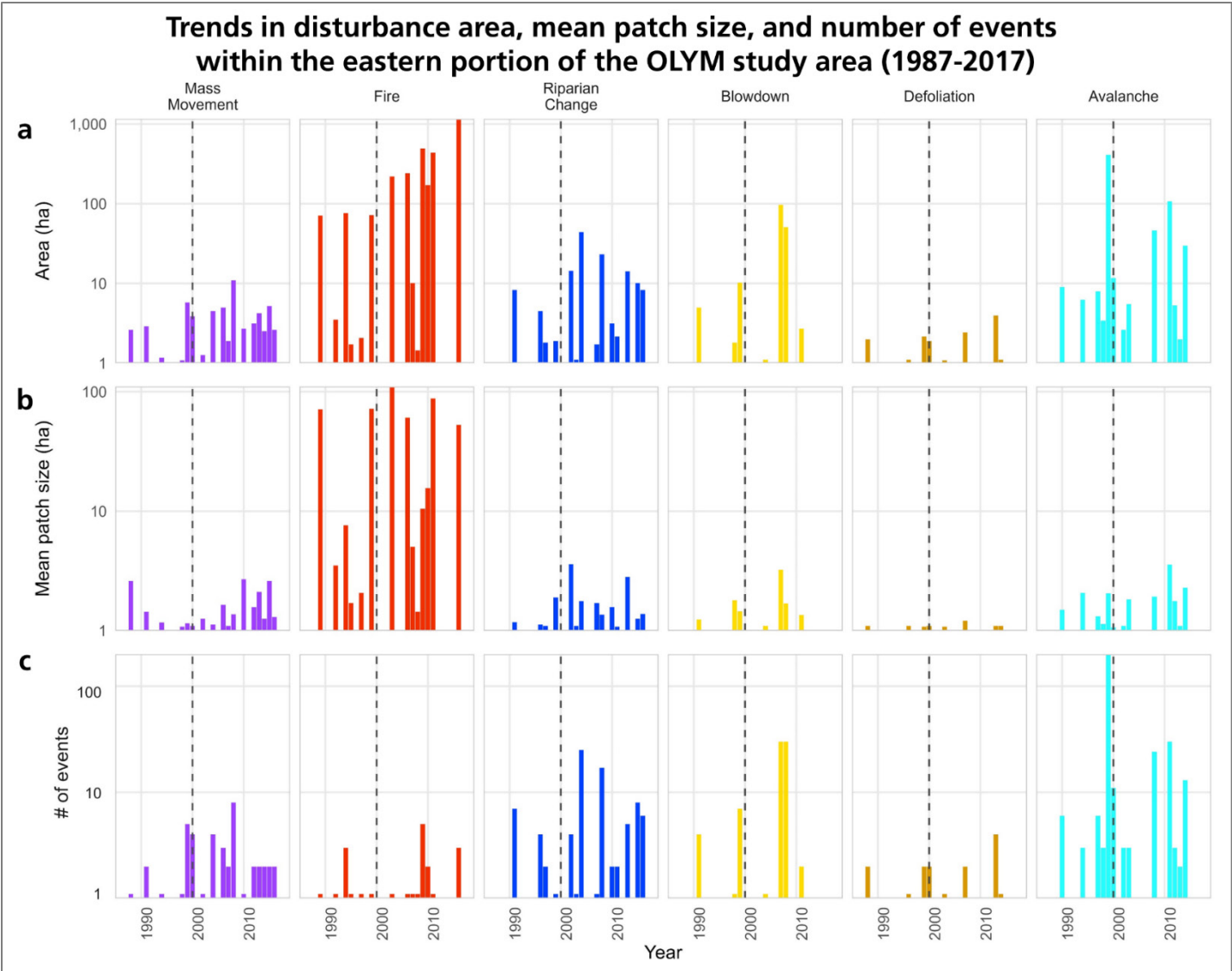


**Figure 26.** Temporal trends in disturbance within the eastern portion of the Olympic National Park (OLYM) study area. Trends in **(a)** annual disturbance area (ha), **(b)** mean annual patch size (ha), and **(c)** annual number of events. The vertical dashed gray line separates pre- and post-2000. The y-axis is on the base 10 log scale. To avoid negative values (i.e., when values are less than 1) and artificial zeros (i.e., when values are equal to 1) on the base 10 log scale, all response variable values greater than 0 and less than or equal to 1 were replaced with a value of 1.1 for visualization purposes only.

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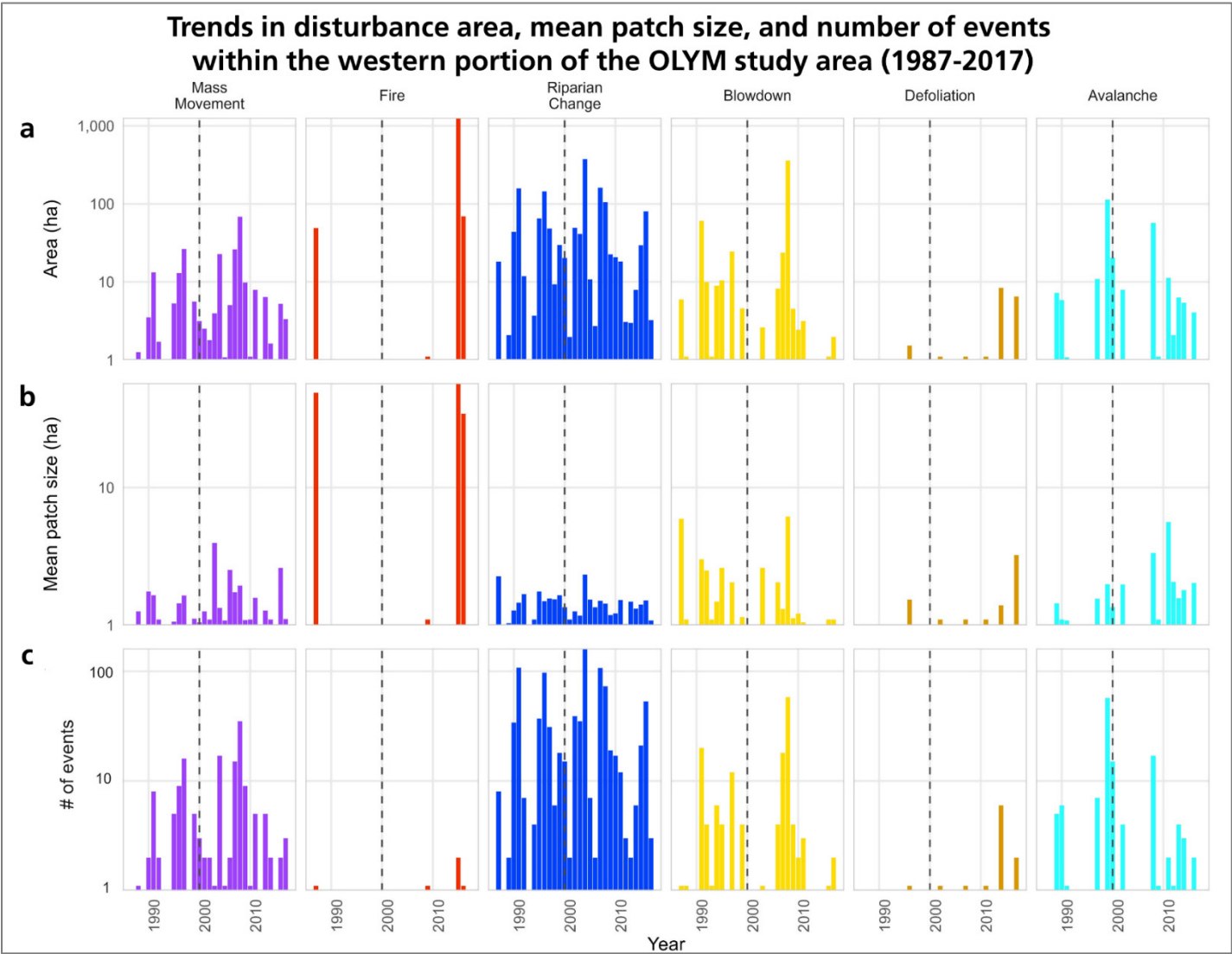


**Figure 27.** Temporal trends in disturbance within the western portion of the Olympic National Park (OLYM) study area. Trends in **(a)** annual disturbance area (ha), **(b)** mean annual patch size (ha), and **(c)** annual number of events. The vertical dashed gray line separates pre- and post-2000. The y-axis is on the base 10 log scale. To avoid negative values (i.e., when values are less than 1) and artificial zeros (i.e., when values are equal to 1) on the base 10 log scale, all response variable values greater than 0 and less than or equal to 1 were replaced with a value of 1.1 for visualization purposes only.

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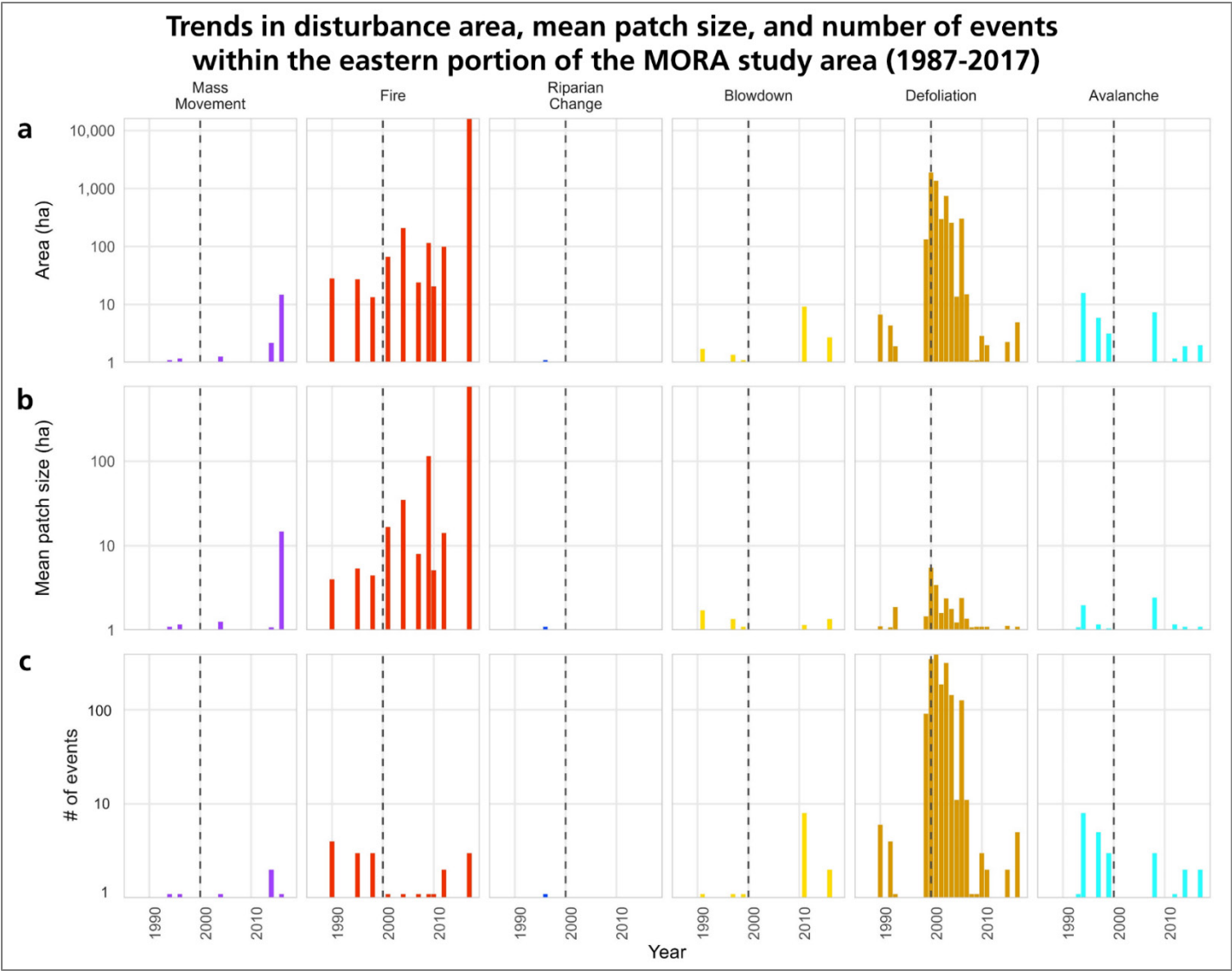


**Figure 28.** Temporal trends in disturbance within the eastern portion of the Mount Rainier National Park (MORA) study area. Trends in **(a)** annual disturbance area (ha), **(b)** mean annual patch size (ha), and **(c)** annual number of events. The vertical dashed gray line separates pre- and post-2000. The y-axis is on the base 10 log scale. To avoid negative values (i.e., when values are less than 1) and artificial zeros (i.e., when values are equal to 1) on the base 10 log scale, all response variable values greater than 0 and less than or equal to 1 were replaced with a value of 1.1 for visualization purposes only.

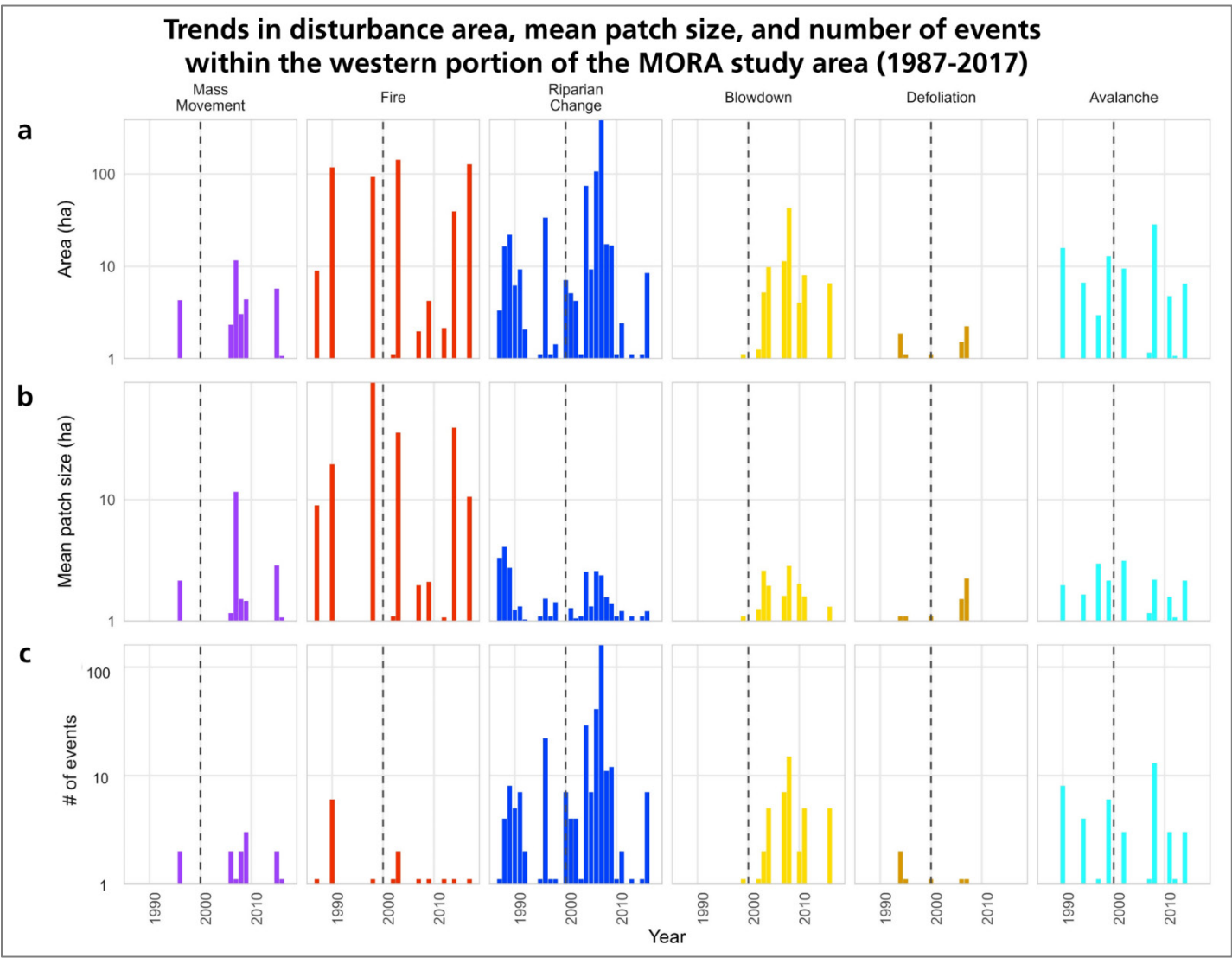


**Figure 29.** Temporal trends in disturbance within the western portion of the Mount Rainier National Park (MORA) study area. Trends in **(a)** annual disturbance area (ha), **(b)** mean annual patch size (ha), and **(c)** annual number of events within the western portion of the MORA study area. The vertical dashed gray line separates pre- and post-2000. The y-axis is on the base 10 log scale. To avoid negative values (i.e., when values are less than 1) and artificial zeros (i.e., when values are equal to 1) on the base 10 log scale, all response variable values greater than 0 and less than or equal to 1 were replaced with a value of 1.1 for visualization purposes only.

## Fire Regime and Disturbance

Tables 14 and 15 provide information on how different fire regime groups (FRGs) are distributed within the three combined and the individual study areas and the percentage of cumulative area burned within each FRG by the Fire disturbance category from 1987 to 2017.

**Table 14.** The amount (ha) and percentage (%) of area each fire regime group (FRG) occupies within all three park study areas combined, and the percentage (%) of cumulative area burned (1987–2017) that occurred within each fire regime group. Fire regime group data were sourced from LANDFIRE (<https://landfire.gov/fire-regime/frg>) which is only available for the U.S. Thus, the values below exclude the Canadian portion of the NOCA study area.

| Fire Regime Group (FRG) | Fire Return Interval (years) | Severity | Area (ha) | % of Entire Study Area | % of Cumulative Area Burned |
|-------------------------|------------------------------|----------|-----------|------------------------|-----------------------------|
| I                       | 0–35                         | low      | 36,568    | 3.7                    | 25.7                        |
| III                     | 35–100+                      | mixed    | 235,617   | 24.1                   | 33.4                        |
| V                       | 200+                         | high     | 705,937   | 72.1                   | 40.7                        |

**Table 15.** The amount (ha) and percentage (%) of area each fire regime group (FRG) occupies within each park study area, and the percentage (%) of cumulative area burned (1987–2017) that occurred within each fire regime group. Fire regime group data were sourced from LANDFIRE (<https://landfire.gov/fire-regime/frg>) which is only available for the U.S. Thus, the values below exclude the Canadian portion of the NOCA study area.

| Study Area | FRG | FRG Area (ha) | % of Study Area | % of Cumulative Area Burned |
|------------|-----|---------------|-----------------|-----------------------------|
| NOCA       | I   | 33,998        | 7.5             | 38.8                        |
|            | III | 97,946        | 21.5            | 27.0                        |
|            | V   | 322,656       | 70.9            | 33.9                        |
| OLYM       | I   | 253           | <1              | 0.3                         |
|            | III | 59,195        | 16.3            | 21.5                        |
|            | V   | 304,667       | 83.7            | 78.2                        |
| MORA       | I   | 2,317         | 1.5             | 1.4                         |
|            | III | 78,476        | 49.2            | 52.1                        |
|            | V   | 78,614        | 49.3            | 46.5                        |



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