FOREST DISTURBANCE IN THE OLYMPIC EXPIERMENTAL STATE FOREST

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ABSTRACT

Forest Disturbance in the Olympic Experimental State Forest

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The Olympic Experimental State Forest (OESF) is a Washington State Department of Natural Resources (DNR) planning unit on the western Olympic Peninsula. The OESF includes 110,000 hectares of DNR-managed state trust land, as well as private, tribal, and federal lands, specifically Olympic National Forest and Olympic National Park. Land management practices within the OESF have changed over time among these different ownerships. Under the 1997 Habitat Conservation Plan, DNR manages State trust lands on the OESF in a manner that integrates revenue production with ecological values across the landscape. Natural disturbance regimes are used as a reference in managing forest conditions; it therefore benefits DNR to understand the spatial scales and frequencies of both natural and anthropogenic disturbances in the OESF. Through remote sensing and the LandTrendr methodology, this study uses NASA/USGS Landsat images from 1985 to 2012 to identify and compare forest disturbances among the major landowners groups over time. The average rate of disturbance has stayed the same in the OESF from 1985-2012:0.84% per year. On lands the DNR manages, the rate of disturbance decreased from 1.0% annually during the time period of 1985-1998, to 0.54% annually from 1999-2012, which shows that on DNR lands a reduced rate of disturbance coincides with the implementation of the HCP.

Table of Contents

List of Figures

List of Tables

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Introduction

Disturbance is a widespread phenomenon in nature and is common in all ecosystems. Disturbance is an important ecological process shaping ecosystems (Attiwill, 1994a; White & Pickett, 1985). Disturbance can be defined as any event that changes the trajectory or spatial extents of an ecosystem and is important in shaping ecosystem function and structure (White & Pickett, 1985). Forest disturbance can be a natural processes like fire, windstorms, diseases, and damage or mortality from insects. Disturbance can also stem from anthropogenic causes such as timber harvests, road building, housing development, agriculture, and infrastructure building projects. As a forest grows, a disturbance event can change a forest by a small event like a single tree fall or a large event (for example-timber harvest and fires). Disturbance events can also impact humans such as landslides damaging roads and windblown events damaging trees that would be harvested at a later time. These disturbance events can cause economic and physical harm to humans, their buildings, and infrastructure (roads, pipelines, power lines, etc.). These natural events in forest ecosystems may reduce the profitability of timber harvest (Cliff Mass, 2005). Humans have historically changed disturbance regimes in forests across the United States by fire suppression or timber production (Franklin & Johnson, 2012). Modern timber production uses clearcutting techniques which consists of harvesting nearly all of the trees and this changes the structure and species affected by the clearcutting.

Disturbance has been increasingly studied by ecologists because of the importance it has in shaping forest ecosystems. Ecologists have recognized that disturbance regimes have been greatly altered by humans in the last one hundred years. Temperate forests on the Pacific Coast specifically face disturbances of infrequent large wildfires and large and small scale windstorms that help achieve complex old growth forest ecosystems (Franklin & Johnson, 2012). These forests have been historically logged and their primary economic purpose is timber production. Natural disturbance events happen less frequently and on average a smaller scale than modern timber harvests in the Pacific Northwest. Historical timber production provided poor habitat for seral species and modern practices have changed historical disturbance regimes, which has caused the function and structure of forests to change (White & Pickett, 1985). Ecologists studying disturbances are alarmed because disturbance regimes across the planet are changing rapidly due to anthropogenic climate change and the consequences of this is unknown. Currently, the Western United States has experienced an increased frequency of large fires and this is strongly associated with higher than historically normal temperatures (Halofsky et al., 2011; Turner, 2010). Studying disturbances is important to better understand how future disturbance will shape ecosystems.

An important method used to detect forest disturbances is remote sensing technology. The 1960s and 1970s brought two technologies that have helped aid ecologists studying disturbance; Landsat Imagery and Geographic Information Systems (GIS). The launch of Landsat satellites enabled scientists to study the earth through satellite imagery. At the same time, electronic computing lay the foundation for GIS software which could model and map Earth. Scientists were able to use Landsat Imagery and GIS to model and study spatial and temporal trends in ecosystems (Cohen & Goward, 2004). Since the implementation of both of these technologies, computing power has increased exponentially and higher resolution of Landsat imagery has increased the effectiveness of these remote sensing methods to analyze disturbance patterns across the planet. These two technologies are used together and are used by researchers to study landscape disturbance regimes and forest cover rates. Using GIS and Landsat imagery has become an effective and common way of detecting trends and patterns of disturbance over time. LandTrendr software is an algorithm that creates disturbance maps and was developed by researchers at Oregon State University to detect disturbance in forests landscapes (Kennedy et al., 2009).

The Olympic Peninsula in Western Washington State has large temperate rainforests and various landowners who have different objectives in managing their forests. The Olympic Peninsula encompasses the Olympic National Park (ONP), Olympic National Forest (ONF), State lands (managed by Washington State Department of Natural Resources (DNR), Tribal lands and private landowners (many are owner my commercial timber companies). Washington State DNR established the Olympic Experimental State Forest (OESF) on the western half of the Olympic forest (**Figure 1-1-** Map of DNR Managed OESF Lands (WA DNR 2016).. The state of Washington approved a Habitat Conservation Plan (HCP) for multispecies habitat management for Federally-listed endangered species on Washington state lands in 1997. The establishment of the HCP was the state of Washington's requirement to comply with the Federal Endangered Species Act. The HCP's objective is to protect habitat for endangered species in state lands managed by DNR. The HCP designates the OESF as a state experimental forest and lays out its unique purpose among Washington state managed lands. The purpose of the OESF is to research natural phenomenon and to study natural processes in working forests. One of the objectives of the OESF is to study how disturbance affects their forest and how these patterns can be applied to other forests in Washington and the Pacific Northwest (WA DNR, 1997, 2016). This thesis paper will use LandTrendr software to determine annual disturbance trends in the forest from 1985-2012. Management practices have changed in the OESF since the 1980s and this paper will look at how disturbance has affected the OESF by answering these five questions:

Research Questions

1) What is the disturbance rate on forest lands in the Olympic Experimental State Forest (OESF)?
2) Has the disturbance rate on the DNR lands in the OESF since 1999, when the Habitat Conservation Plan was implemented?
3) What are differences in disturbance rates by different land ownership categories in the Olympic Experimental State Forest?
4) What is the disturbance rate across the different ecoregions in the OESF?
5) What is the disturbance rate across the different forest vegetation zones?

Chapter 1-Literature Review

Introduction

Disturbance is an event that changes the spatial and temporal trajectory of an ecosystem (Turner, 2010). For example, a temperate rain forest in Olympic Peninsula in Western Washington can grow for hundreds of years and will eventually be dominated by Western hemlock, its climax community. A climax community will hypothetically stay on the same trajectory or stay in equilibrium until a disturbance event happens (for example, a windthrow event that blows down trees and opens the forest canopy). These disturbance events create heterogeneity in a forest (White & Pickett, 1985). Forest openings allow early successional species that thrive in sunlight to germinate, grow, and reproduce (Peterson et al., 1997) A disturbance can be small or large in spatial extent, and potentially change the structure and species composition of the forest. Disturbances therefore shape a forest and have been increasingly studied by ecologists. This literature review will examine what disturbance is, the common terms used by ecologists and foresters, and existing disturbance research in forest ecosystems.

The Olympic Experimental State Forest (OESF) was created on the Olympic Peninsula to study to natural phenomenon in a working forest by the Washington State Department of Natural Resources (DNF). The creation and the history of forestry practices in OESF will be examined as will disturbance related research in the OESF and the Pacific Northwest. The paper will then focus on remote sensing techniques and how disturbance is determined using remotes sensing techniques. LandTrendr will be used as the primary methodology in this study and studies using this software will be reviewed. The chief OESF researcher had a database compiled in 2011 that attempted to include all disturbance related research in the OESF. The purpose of this bibliography was to examine how disturbance has shaped the OESF and how to incorporate disturbance's spatial and temporal variability in the management standards of the OESF (Foster et al., 2011).

Ecological Disturbance

White and Picket et al., (1985) describe disturbance as an event that changes the structure of an ecosystem, resource availability, and the physical environment of the ecosystem. The previously stated definition is often cited as the standard definition in most of the reviewed literature. Disturbance affects all ecosystems through all range of scale and alter the state and trajectory of an ecosystem (Turner, 2010; White & Pickett, 1985). Disturbances are a major factor in development and function of forests and disturbance is widespread across all ecosystems on the planet (Attiwill, 1994b; White & Pickett, 1985). Few communities exist in equilibrium where disturbance does not happen. Biological and physical processes act as agents of disturbance and the latter is most commonly associated with disturbance (Sousa, 1984). Disturbance events can be hard for researchers to detect because they occur over a wide range of size, frequency, seasons, and magnitude (Attiwill, 1994b). An example of a small scale disturbance event is when a single tree falls, creating small forest gaps (Attiwill, 1994b).

After a disturbance event, the ability of an ecosystem to absorb the changes and return to an equilibrium or previous state is called resilience. After a disturbance like a fire or windfall, a forest will go through a period of community succession, with some species more adapted to greater sunlight availability replacing others. In old growth forests in the Eastern United States, disturbance was causing gaps in the forest at about 1% per year and these gaps were vital to increase success of early successional species and other species that need more sunlight (Runkle, 1982).

Major sources of natural disturbances in forests across the world are fire, hurricanes or typhoons, windstorms, mass movements, flooding, droughts, and biotic disturbances such as pests and disease (Attiwill, 1994b; Wallin et al., 1996; White & Pickett, 1985). These were the main disturbance agents in OESF before European settlement (WA DNR, 2016). Disturbance can happen over different time periods, such as a windstorm that occurs over hours, or a pine beetle infestation that can kill trees over a period of years (Turner 2010). Mass movement events include landslides as well as debris flows or torrents (Copass & S., 2016). Debris flow is fast moving event that is combination of debris and water. These events can scour river and stream bed and also bury vegetation under sediment. Debris flow event in the Olympic can have effects on riparian habitat for over one hundred years (Benda et al., 2003). The term 'disturbance regime' describes how often a certain type of disturbance typically happens in an ecosystem. Fire disturbance regime describes, on average, how often a forest experiences a forest fire. The most common type of natural type of disturbance in the OESF are windstorms, landslides, fire, and pests (Peterson et al., 1997; WA DNR, 2016)

Windthrow

Windthrow or windfall events are fairly common in the OESF. Windthrow events occur from small to large spatial scales. A single tree could blow down from the wind because of factors like decay and insects, whereas a hurricane or wind storm can cause a large percentage of trees to blow down in a large area of forest (Attiwill, 1994b). Historically, windstorms typically occur in the winter in the Pacific Northwest (Cliff Mass, 2005). Native Americans have legends about strong windstorm including one from the Quillayute tribe (whose lands are in the OESF) where Thunderbirds (a giant mythological bird) are the cause of these strong winds. The

Quillayute tribe would move to a sheltered area in the winter to protect themselves from the storms (Mass, 2005).

The giant windfall of 1921 was a large-scale windthrow event and affected 20% of the forests on the Olympic Peninsula (Cliff Mass, 2005). There has been at least fourteen storms with hurricane strength winds on the Washington coast in the previous 200 years; two of these fourteen storms recorded winds with over 150 miles per hour (Cole Mass, 2008). These events have shaped the forest in the OESF and also cause timber productivity losses. Blowdowns on the Olympic Peninsula can lead to complete stand or partial stand replacement in the Olympic Peninsula. The common silvicultural practice for DNR in the OESF after windthrow events is to salvage the fallen trees and then replant (WA DNR, 2016). There is concern that with climate change there could be an increase in weather patterns that favor strong windstorms (Devine et al., 2012; Halofsky, 2013). Climate change could also lead to more disturbance in the future and this could lead to more insect and tree mortality, landslides, and fires (Halofsky, 2013).

Fire

Fire is often the most predominant disturbance type in many forests (Attiwill, 1994b). Fire has been suppressed by modern societies since the early 20th century (Wallin et al., 1996). Fire regimes varies across the Western United States and are dependent on vegetation and annual precipitation rates. In the Douglas Fir (*Pseudotsuga menziesii*) forest type the average is around 230 years in the Pacific Northwest, though historically this type of forest wasn’t abundant in the OESF (Agee, 1991, 1996). However, specifically in the western part of the Olympic Peninsula, fire regimes for the Western hemlock (*Tsuga hetrophylala*) forest type are about once every millennia and for Douglas fir forest types, about every 750 years (Agee 1991, 1996). These are very long intervals compared to most fire regimes in the Western United States and is because of the high rates of precipitation in the Olympic Peninsula. However, remote sensing data reveals that fire has become a more common factor in the loss of old-growth forests since the implementation of the Northwest Forest Plan (NWFP) in the 1990s, which could be linked to climate change (Healey et al., 2008)

The size and intensity of forest fires in the Olympic Peninsula is less than in most other parts of the Pacific Northwest, although large scale fire events of over thousands of acres have occurred. There are stories of large fires among the Native American tribes that live in the Coastal forest of the Pacific Northwest. The Quinault tribe has a legend of a massive fire in the western Olympic Peninsula: the fire came down from the Olympic Mountains and drove the tribe to the sea (Agee, 1991, 1996) Modern forest management has suppressed fire activity through fire suppression and timber harvesting (Agee, 1996). Fir is crucial in the stand development and species recruitment in northwestern forests and suppression and timber harvesting could change the composition of these forests (Agee, 1991).

There has only been one large fire (over 100 acres burned) in the OESF since 1985 and in was the Paradise fire. It was in the Hoh river drainage in the Olympic National Park. It was 2,798 acres and was caused by lightning in 2015 (WA DNR, 2018b). There has been a total of seven large fires in the Olympic Peninsula (outside the OESF) according to WA DNR data from 1973-2016, and only the Paradise fire was in the boundaries of the OESF. Since 2008, the DNR has recorded a total of 75 fires in the OESF region and all of were small fires (less than 100 acres). There may be missing data in the database because of the 75 fires only one is located in the ONP, which is about a third of total area in the OESF. The total amount of acres burned in these fires is 276 acres, this is quite small compared to other regions in the west that have large fire disturbance regimes. Of the 75 fires, 28 were noted as caused by logging activities such as deliberately burning debris from logging activities and one lightning caused fire (WA DNR, 2018b).

These data and other research suggest that the Olympics have a low rate of lightning-caused fire. Agee (1991) ran a simulation for lighting ignitions in four forests in the Pacific Northwest: the Western Olympics and Wind River in Washington, and McKenzie River and Siskiyou's in Oregon. The western Olympics had the smallest ignition rate at 0.2 per year per 175,000-ha. This could be a possible reason that Olympics have a low-frequency fire regime.

History of the Forests on the Olympic Peninsula

The Olympic Peninsula has a high amount of biodiversity because of its geographical location, mountains, and unique geological history (Peterson et al. 1997). The Olympic Peninsula was not affected by the giant ice sheet of Fraser glaciation period from ~15,000 years before present (Peterson, et al 1997). Because of this geologic history, seven of the eight plant taxa endemic to the Olympics survived the Ice Age and contribute to the uniqueness of the area**.**

The coniferous forest within the Olympic Peninsula is an important producer of wood products and the forests have been extensively harvest for timber in the last century. Washington state law in 1948 mandated all logged forests had to be replanted. Laws in the 1970s and 1980s further mandated how forests should be managed (WA DNR, 2018a). The harvest of virgin or old growth forests led to tension between economies that relied on timber product and groups that advocated for the existence of old growth forest that served as habitat for species such as the marbled murrelet (*Brachyramphus marmoratus*) and the northern spotted owl (*Strix occidentalis caurina*) (Kennedy et al., 2012; Moeur et al., 2011).

The northern spotted owl was listed as threatened under the Endangered Species Act in 1990 and this led to multiple lawsuits on how the federal government managed federally-owned forests in the Pacific Northwest (Moeur et al., 2011).. The concern for the old growth forests led to the Northwest Forest Plan (NWFP). The NWFP led to changes in timber harvest activities and has reduced forest timber harvest and disturbance levels across the northwest in federal lands. The purpose of the NWFP was to protect forests and the species that use them such as northern spotted owls and marbled murrelets (Kennedy et al., 2012; WA DNR, 1997).

The Olympic National Forest (ONF) was established in 1897 as the Olympic Forest Reserve, and as a National Forest in 1907, and encompasses over 256,400 acres on the Olympic Peninsula (Halofsky et al., 2011; Lesher et al., 1989). Prior to the 1990s, ONF management practices favored timber production in the forest. Timber harvest began in the 1920s and an estimated 1/3 of the total forest was harvested by 1990. The NWFP directly led to management change in the ONF in 1994. The NWFP shifted ONF management to ecosystem management. The current ONF focus is on ecological restoration and has objectives that focus on the protection and restoration of late successional or old growth forest (Halofsky et al., 2011). Timber harvest activities have significantly reduced since the NWFP implementation and this can be seen when reviewing Washington State timber harvest reports (WA DNR, 2017).

The Olympic National Park (ONP) was first established as a National Monument in 1909 under President Theodore Roosevelt (Lesher et al., 1989). The National Monument was established primarily to protect its native elk species-Roosevelt elk (*Cervus canadensis roosevelti*). The ONP was created out of the national monument in 1938. The park has expanded multiple times from 680,000 acres to the current size of approximately 936,011 acres (Halofsky et al., 2011; Lesher et al., 1989). One of the ONP expansions added a 110 km coastal strip (which is entirely in the OESF). Most of the park is in relatively pristine condition compared to lands outside of ONP, though there are some concentrated areas of human activity by park visitors. The purpose of the ONP is to conserve the scenery, the natural objects, and wildlife for the future (Halofsky et al., 2011).

The Olympic Experimental Forest (OESF) was created in 1992 by the Washington Department of Natural Resources (DNR) in order to learn how to integrate revenue production and ecological values in a working forest (WA DNR, 2016). The OESF is located on the Northwest section of the Olympic Peninsula in Washington State (Figure 1-1). The OESF mission statement only applies to DNR lands in the OESF, which are a part of Washington state trust lands. The primary purpose of Washington State trust lands is to generate revenue for public education for the state of Washington (WA DNR, 1997). The OESF has four other major types of land ownership: private lands (whose primary purpose is typically timber production), tribal lands, Olympic National Forest, and the Olympic National Park (WA DNR, 2016).

In 1997, Washington State created a Habitat Conservation Plan (HCP) for state trust lands that details how the DNR will restore, maintain, and enhance habitat for endangered species, which was authorized under the Endangered Species Act (ESA) to protect listed species that occupy the OESF (WA DNR, 1997). The HCP describes the conservation strategies for how the Washington Department of Natural Resources (DNR) will restore and enhance habitation for listed species such as the northern spotted owl and marbled murrelet, in conjunction with using best practices for timber harvest and activities on its forested lands. The HCP has four major strategies: riparian (management strategies for aquatic species, including salmonids and others), northern spotted owl, marbled murrelet (management strategies for restoring and maintaining their habitat), and multispecies (habitat management for unlisted species and species that have risk of local extinction). The HCP also describe how they will implement adaptive management and research and monitoring in the OESF (WA DNR, 1997, 2016).

The 1997 Washington state trust lands HCP was established in coordination with the Northwest Forest Plan of 1997 (WA DNR, 1997). Under the 1997 HCP, the DNR manages state trust lands on the OESF in a manner that integrates revenue production with ecological values across the landscape. One of the DNR's conservation objectives is to study natural disturbance regimes in the OESF. The DNR wants to study how scales and frequencies of both natural and anthropogenic disturbances affect the OESF (WA DNR, 1997). DNR has determined there is limited knowledge of what natural landscapes caused by disturbance looks like and DNR is trying to learn how the spatial and natural variability of disturbance should be incorporated in the management of their forest (Foster et al., 2011). DNR also set aside lands in the OESF that are used by endangered species and provide protection for riparian habitat (WA DNR, 2016). In 2011, the OESF commissioned a bibliography to record all instances of disturbance and research of disturbance in the OESF to establish a reference pool for future projects describing disturbance in the OESF (Foster et al., 2011).

The DNR's objectives to estimate and understand patterns in forest disturbances is the reason for this project and the author is trying to determine how disturbance has affected landscapes in the OESF. Disturbance is importance is natural ecosystems and are vital to the diversity of forest ecosystems and is important in forest stand development (Franklin et al., 2002). Large scale natural disturbances occur in the OESF, and have influenced the structure of the forest and have long lasting impacts to landscape in the OESF (WA DNR, 2013). In the last four decades silviculture practices have tried to use practices from disturbance ecology that are more aligned to natural disturbance process (Attiwill, 1994b; Franklin et al., 2002; Franklin & Forman, 1987).

Vegetation Types and Ecoregions

There are many different vegetation types in the OESF. A vegetation type is determined by the most shade tolerant species in an ecosystem (Lesher et al., 1989). Vegetation types affect the disturbance rate in area. The vegetation types in the OESF are Sitka spruce (*Picea sitchensis*), Western hemlock (*Tsuga heterophylla*), Pacific silver fir (*Abies amabilis*), mountain hemlock (*Tsuga mertensiana*), parkland, alpine, and subalpine fir (*Abies lasiocarpa*) (ECOSHARE, 2017). Kennedy et al. (2012) studied disturbance using LandTrendr in ecoregions across the OESF, but did not break out disturbance rates by vegetation types, so this is one of the primary questions of this thesis.

Geographers have classified ecological communities that are similar as "ecoregions." Omernik (1987) developed this framework with federal agencies and other North American countries, they mapped these ecoregions in North America (Omernik, 1987; US EPA, 2015). The purpose of having ecoregions is to develop a common system for research, monitoring and assessment of similar types of ecosystems. Ecoregions are hierarchal from I to IV, and there are four types of level IV ecoregions in the OESF. The Coastal Lowlands consist of marine estuaries, beaches, and lowland lands and western hemlock/Sitka spruce forests in the OESF region (US EPA, 2015). This is the smallest ecoregion in the OESF, which is less than 3% of total area. The Coastal Uplands consist of coastal headlands and higher gradient streams. The main forest in the OESF consists of Western hemlock, Sitka spruce, Western red cedar (*Thuja plicata),* and Douglas fir *(Pseudotsuga menziesii)* trees. The Low Olympic ecoregions consist of low mountains and previously glaciated areas. The main forests are Western hemlock, western red cedar, and Pacific silver fir. Low Olympics and Coastal Uplands is the most common ecoregion in the OESF. The High Olympic ecoregion is only found in the ONP and consists of glaciers, mountains, subalpine coniferous forests and meadow (US EPA, 2015).

Human Caused Disturbance

Disturbance caused by humans (timber harvest activities, dams, agriculture, and human settlements) have about the same impact at a spatial scale, but not at the same temporal scale to largest natural disturbance such as fire). Fire can be quite large across the landscape and usually takes place in a period of days happens from days to months while large scale human disturbance such as timber harvest takes place over years and does not progress as rapidly as a fire. According to Peterson (1997) anthropogenic activities are more frequent and fragment the landscape more than natural disturbance in the Pacific Northwest forest region. Human activities could lead to less diversity and reduce the spatial and temporal scale of natural disturbances such as fire (Peterson et al., 1997). Peterson (1997) noted that in clear-cuts caused by logging a lot of early succession species exist and this could cause species that are more adapted to prevalent disturbance.

High levels of disturbance has reduced connectivity between various habitats and this could cause the loss of species and especially in lowland vegetation and wetlands due to future climatic change. Peterson et al. (1997) concluded that by 1988 timber harvests had removed over 75% of old growth forest in the ONF and almost all old growth forest in tribal, state, and private lands. Species before human settlement that dominated the area such as Sitka spruce (*Picea sitchensis*) and Low elevation Douglas fir (*Pseudotsuga menziesii*) has been reduced drastically in the Olympic Peninsula. The forests in Olympic Peninsula get harvested at about every 50-80 years (Peterson et al., 1997). After a forest gets logged it can be followed by slash burning, this can somewhat mimic the disturbance of a fire, but is quite different as there is less snags (standing dead trees) and more soil disturbance (Agee, 1991; Ruggiero, et al. 1991). This has led to a simplification of a class in the forests through simplifying the structure and species composition. Peterson (1997) studied clear cuts in the Olympic Peninsula and found a proliferation of early successional and exotic species in clear cuts. They concluded that these early successional species will be more abundant in areas with a high amount of disturbed areas like in the Olympic Peninsula (Peterson et al., 1997).

Since the 1980s researchers have proposed that anthropogenic actions such as timber harvest can be used to mimic natural disturbance events (Agee, 1991, 1996; Attiwill, 1994b; Franklin et al., 2002; Franklin & Forman, 1987). Franklin (2002) looked at modern forest methods and how they shape the forest and compared them to natural forest. Franklin noted that structural development of forest is very complex and that disturbance processes contribute to forest development and structure. Modern timber practices such as clearcutting are not based on natural disturbance processes. Attiwill (1993) in a study of disturbances stated the greater the magnitude of a disturbance, the less likely the forest will recover. Diversity, structure, and the functions of forests are developed by natural disturbance that silviculture practices should be based on natural disturbance process.

Silviculture practices traditionally did not try to replicate natural disturbance and foresters simply tried to maximize production in the forest. Foresters currently use practices that help resemble natural disturbance patterns that encourage different patterns of forest and retain parts of the previous forest structure (Franklin et al., 2002). Current laws also regulate how foresters have to leave gaps and leave undisturbed space in wetlands and riparian areas (WA DNR, 2018a). DNR set areas in the OESF that are off limits to timber harvest activities to protect species and watersheds by providing habitat buffers. Under the 1997 HCP, the DNR reduces harvest on unstable slopes, restores and maintains habitat for northern spotted owls and marbled murrelets. DNR also thins forest stands in different densities to maintain a diverse forest structure. Current OESF forest practices managed by DNR leave standing and down snags, some uncut trees to help improve the structure and diversity of their forest stands and they also protect old growth forest stands from timber harvest where previous to HCP and other management practices implemented in the 1990s, the policy was to harvest older and larger forests (WA DNR, 1997, 2016).

Spatial Methods to Analyze Disturbance

Researchers often use remote sensing to help analyze disturbance in forests (Cohen et al., 2017). Remote sensing helps researchers show connections between natural disturbances and human disturbances. Land satellite (Landsat) data is a common remote sensing method for monitoring disturbance in forests (Cohen et al., 2017). Land Satellite Time series (LTS) data has been used over 40 years for remote sensing. Landsat data can be within 30 m range (Cohen et al., 2017). Landsat data is obtained freely from NASA and includes Landsat Thematic Mapper (TM) data. TM data has fine grain photos to detect small scale disturbance like patches in the forest and roads and large scale event like a large fire (over a hundred acres). A limitation of TM data is it only goes back to 1984 (Kennedy et al., 2012).

There are numerous software programs that use algorithms to analyze disturbance using Landsat data. Cohen et al. (2017) conducted a study using six Landsat scenes to determine the similarity and differences among seven different algorithms. The algorithm analyzes the pixel data and determines which areas have been disturbed. All of the software programs, that were reviewed, can detect long term disturbances (large scale insect kills, fires, clear cuts) and short term disturbances (windstorms or timber clear cuts). The researchers noted that of the seven algorithms, all were in general agreement about areas that had no disturbance but areas with disturbance the algorithms had a great amount of variability in the magnitude of disturbance. As in areas with low magnitude of disturbance (small insect kills, tree mortality, small scale wind blow down), the different software reviewed showed high variability. Not all of the programs agreed how large or scale of small magnitude disturbance. The researchers found agreement among areas that showed high magnitude of disturbance (Cohen et al., 2017).

The algorithm from these disturbances I will use in these studies is LandTrendr developed from Oregon State (Kennedy et al., 2010). The disturbance maps created from LandTrendr is what I am using for this study to determine what the disturbance rates are in the OESF. LandTrendr was developed in 2010 and is currently still being updated from Oregon State (Kennedy et al., 2010). LandTrendr developers developed maps for the NWFP region (Washington, Oregon, and California) to analyze how disturbance has shaped the NWFP, the. The researchers published these maps online[1] for public use.

Landscape Disturbance rates in the Pacific Northwest

Remote sensing technology has allowed researchers to study disturbance and land cover rates in forests in the Pacific Northwest. Researchers have been study disturbance with remote sensing technology at least since the 1990s. Turner et al. (1996) used the Landsat multiple scanner imager to analyze forest cover in the Hoh River basin (which is in the OESF) and the Dungeness River basin, Washington, and a river basin in Tennessee. The authors used formulae that analyzed satellite imagery to determine how much forest cover existed in each area. Their

[1] http://landtrendr.forestry.oregonstate.edu/content/download-data

analysis showed forest cover rates were higher in federally owned land than in state and private lands in the Olympic Peninsula. Turner el al. (1996) also noticed that harvesting trends in private lands owned by commercial timber lands in the Hoh River basin were influenced by economic forces. They did not find the same trends in the Dungeness river basin, and attributed this to more large commercial timber land in the Hoh basin than in the Dungeness (Turner et al. 1996). The researchers noted that in when timber prices increased, disturbance increased in the Hoh basin (Turner et al., 1996).   This study was conducted when the primary purpose of DNR lands was to generate revenue from timber harvesting and before the implementation of the HCP and NWFP. During this time period, federal lands had lower rates of disturbance than state and federal. Their primary conclusion was that land ownership has a strong effect on disturbance patterns and forest cover rates in their study.

Kennedy et al. (2012) conducted a study using LandTrendr to analyze disturbance rates in the Pacific Northwest, which they used LTS data from 1985 to 2008. Their goal of the study was to determine if the NWFP of 1994 changed disturbance rates across the forests of the Pacific Northwest and looked at land ownership. Kennedy used disturbance through the whole forest instead of annual disturbance rates. They found a high level of disturbance in the Olympic region compared to other areas (Kennedy et al., 2012). The models generated showed that the predominance disturbance in the Olympic region is timber harvest compared to other regions using the greatest disturbance map (Kennedy et al., 2012; Ohmann et al., 2012). Disturbance rate on native lands increased after 1993. Disturbance on non-protected federal lands decreased after implementation of the NWFP. Researchers noted that disturbance in state lands in Washington decreased after the implementation of the NWFP.

Disturbance Research in the OESF

Disturbance has been studied in the OESF by many different researchers. The DNR wanted to keep track of all disturbance related studies in the OESF and landscape that was simpler and created a bibliography for all disturbance related research in 2011(Foster et al., 2011). The bibliography also cites any disturbance related research to Olympic Peninsula.

National Park Service researchers used LandTrendr to study disturbance in the ONP and the lands surrounding it on the Olympic Peninsula, Mount Rainer, and North Cascades National Park. The National Park researchers worked with Dr. Kennedy, the lead developer of LandTrendr. The researchers mapped the different types of disturbance in the ONP and surrounding forests on the Olympic Peninsula from 1985-2010 (WA-DNR, 2017). The researchers used LandTrendr disturbance patterns focused on land imagery to determine what type of agent caused the disturbance. The researchers used the fast disturbance event by year data from LandTrendr. The researchers labeled the disturbance event in their study area and measured disturbance by total area disturbed by hectares. One of the most common types of disturbance noticed inside and outside the ONP was wind throw events. In 2007, nine of the top ten largest natural disturbance events in the ONP were wind throw events that ranged from 44 to 10 acres (Thompson et al., 2011). There was a large wind blow event in the Quinault and Queets river valley in 2005. This wind blow event was noted by ONP researchers using LandTrendr. This wind blow event was quite large and wide-spread and affected private lands, ONF, and ONP. The most common natural events in the study area were wind throw, fires, riparian disturbance, avalanche, winter ice events, defoliation, and mass movement. Outside ONP, landscape clearing caused by timber harvest was the most dominant and common form of disturbance and had high levels in the 1990s and 2000s. The study determined that private lands had highest rate of timber harvest followed by Tribal and DNR lands, ONF, and lastly ONP. (Copass & S., 2016) The challenges the researchers noticed in the study were that slow changes like insect and disease were hard to detect using the fast disturbance map in LandTrendr.

Conclusion

The OESF was established as a working research forest (WA DNR, 2016). DNR is studying how natural processes shape forest and how understand the process that shape disturbance can be used to help establish sustainable practices for forestry on their lands. The OESF has multiple landowner with different management objectives on their respective forest lands (WA DNR, 1997). Multiple management objectives throughout the OESF have shaped the structure and disturbance rate of the OESF (Turner et al., 1996). Disturbance is an important influence on forest ecosystems (White & Pickett, 1985). Disturbance shapes the function, structure, and diversity of the forest. The natural disturbance categories that affects the OESF are wind, fire, landslides, insects, and disease. The OESF has a low fire regime compared to many forests in the west, but has had large historical forest fires (over thousands of acres) in the past. Windblown events are quite important in shaping the OESF and are quite common and can range from very small to very large events.

Currently the largest disturbance agent in the OESF is timber harvest. Studies have showed that clearcutting practices shape diversity and the function of the forest. Modern methods use remote sensing to best detect disturbance. LandTrendr was developed to look at disturbance and has been used many times to study disturbance rates and help determine what caused the disturbance. LandTrendr has also been used to show Federal lands have reduced disturbance levels since the implementation of the NWFP. Furthermore, Washington DNR lands have reduced their disturbance levels since the 1990s.

Figure 1-1- Map of DNR Managed OESF Lands (WA DNR 2016).

Chapter 2-Methods

The maps and primary data for this thesis use the LandTrendr (Landsat-based detection of Trends in Disturbance and Recovery) approach to extract spectral trajectories of land surface change from yearly Landsat time-series stacks (LTS) and NASA Landsat imagery scenes (Cohen et al., 2017; Kennedy et al., 2012; Kennedy, Yang, & Cohen, 2010). LandTrendr data from 1985-2015, that covers the NASA LTS scenes 48/26, 48/27, and 47/27, were used for this analysis. LandTrendr was developed by Oregon State University as a method to analyze remote sensing data (Kennedy et al., 2010). LandTrendr software can detect the magnitude, duration, and detection of disturbance using land cover layers in ArcGIS. The LandTrendr output was analyzed using ArcGIS to determine the amount and timing of forest disturbance in the Olympic Experimental State Forest (OESF). The rates of disturbance will be compared by primary land ownership types in the OESF, which includes Washington DNR Lands, Private, Tribal, Olympic National Park (ONP), and Olympic National Forest (ONF). All disturbance in Olympic National Park (ONP) is assumed as natural disturbance since they do not allow logging and other large scale human disturbance. All the landowners have different primary goals for their lands, so we expect to observe some differences in forest disturbance rates.

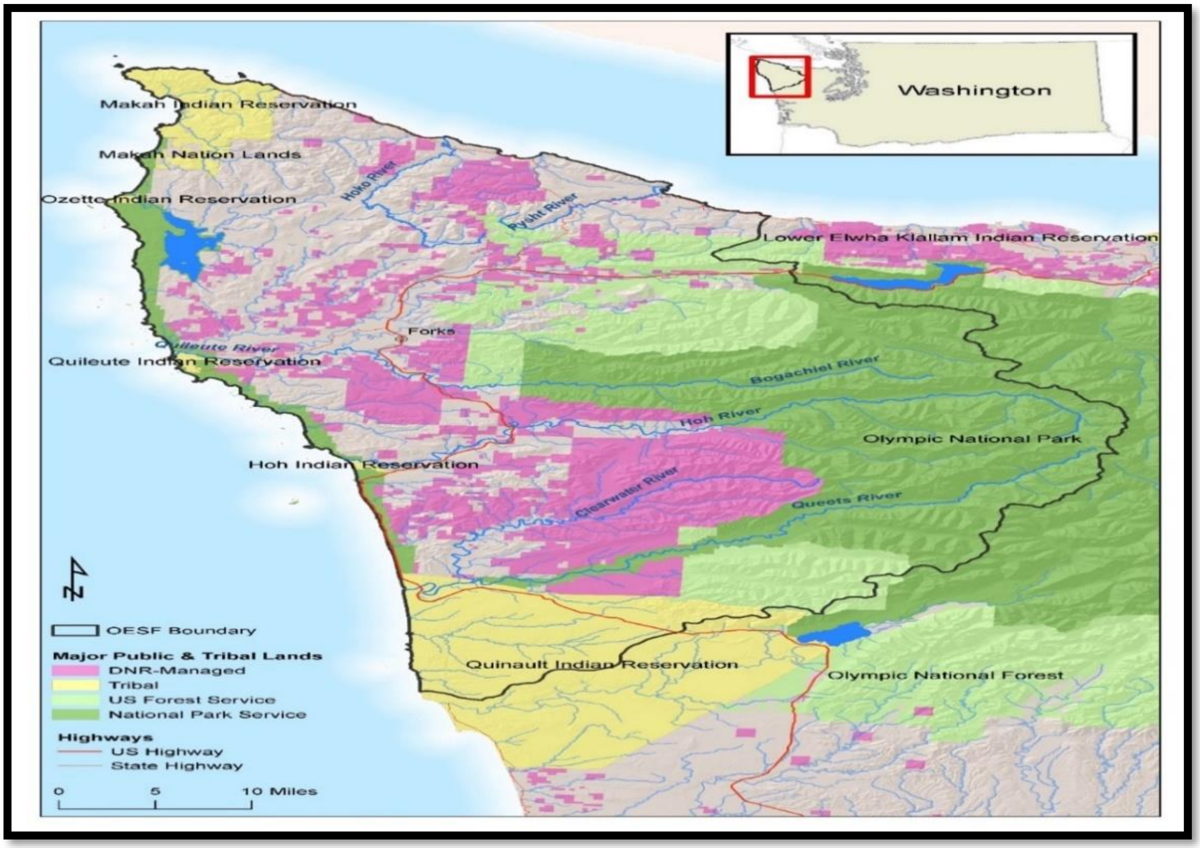

Figure 2-1-Map of the Olympic Experimental Forest and Landownership (OESF 2017).

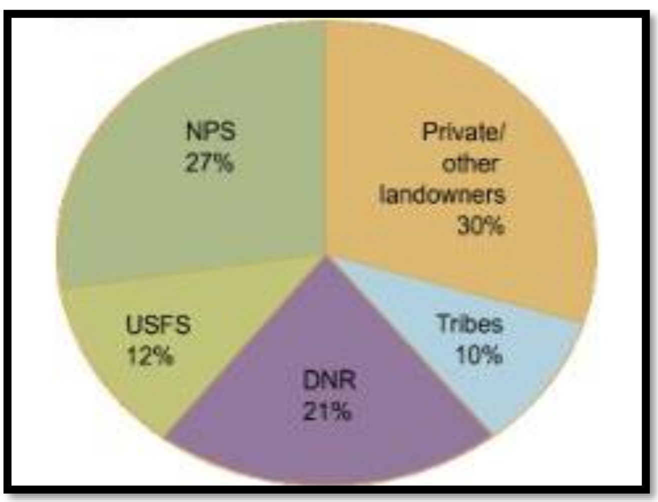

Figure 2-2- Percentage of Landowner's Area in the OESF (WA DNR 2016).

NPS (National Park Service), USFS (United States Forest Service), DNR (Washington State Department of Natural Resources), Tribes (Makah Tribe, Quinault Indian Nation, Quileute Tribe, and the Hoh Tribe.)

The OESF Study Area

The study area is the Olympic Experimental State Forest OES and lies in the northeast section of the Olympic Peninsula in Washington State (**Figure 1-1-** Map of DNR Managed OESF Lands (WA DNR 2016).; **Figure 2-1-Map** of the Olympic Experimental Forest and Landownership (OESF 2017).). The study compared different disturbance rates across the five main landowner in the OESF (from largest to smallest landownership group) - private, Olympic National Park (ONP), and Olympic National Forest (ONF; **Figure 2-2-** Percentage of Landowner's Area in the OESF (WA DNR 2016).). The area has a total of 1.3 million acres with acres with DNR lands consisting of 275,506 acres. The largest landownership group is private owners with about 370,000 acres, ONP is responsible for approximately 355,000 acres, ONF with about 158,00 acres, and tribal lands compose of about 133,300 acres There are four tribes with reservation and tribal managed lands in the OESF; Quinault Indian Nation (92,734 acres), Makah Tribe (92,734 Acres), Quileute Tribe (1,859 acres) and the Hoh Tribe (1,009 acres) (WA DNR, 2018b).

The OESF lies in the temperate rainforest of the Olympic Peninsula from coastal wetland to high alpine mountains and glaciers of the Olympic Mountains. The area has high amount of rain fall with annual precipitation of 80 to 180 inches a year (WA DNR, 2016). The elevation range is from sea level to 7980 feet. The DNR lands in the OESF comprise elevation from 12 feet to 3680 feet. The area lies within two level III EPA ecoregions (Coast range and North Cascades). The 4 Level IV ecoregions are Coastal Lowlands, Coastal uplands, Low Olympics and High Olympics (US EPA, 2015) (**Figure 2-3-** Map of ECO Regions in OESF(US EPA, 2015)). The High Olympic Ecoregion will be excluded from the forest study area since most of this terrain is alpine isand is protected in Olympic National Park.

The main forest disturbance in the OESF is timber harvest. The main natural disturbance factors in the regions are fires, insects, wind blows, landslides, and floods (WA DNR, 2016). The primary management objectives are different for the different landowners. The lands of the OESF are managed for the benefit of the State trust. Private forest lands are operated by private landowners who are supervised by state forest land regulations. The Forest Service lands are managed by the U.S. Forest Service under the Northwest forest plans. The National Park lands are protected from forest harvest activities (Halofsky et al., 2011). The tribal lands are managed under the four different tribes with different objectives.

The main forest zones in the OESF are Sitka spruce (*Picea sitchensis***),** Western hemlock (*Tsuga heterophylla*), Pacific silver fir (*Abies amabilis***),** mountain hemlock (*Tsuga mertensiana*), parkland, alpine, and subalpine fir (*Abies lasiocarpa*,) (listed from most dominant to least) (ECOSHARE, 2017; WA DNR, 1997, 2016). The Sitka spruce, western hemlock, and Pacific silver fir are the predominant vegetation zone in the DNR lands in the OESF (**Figure 2-4-** Map of Vegetation Zones in the OESF (ECOSHARE, 2017)).

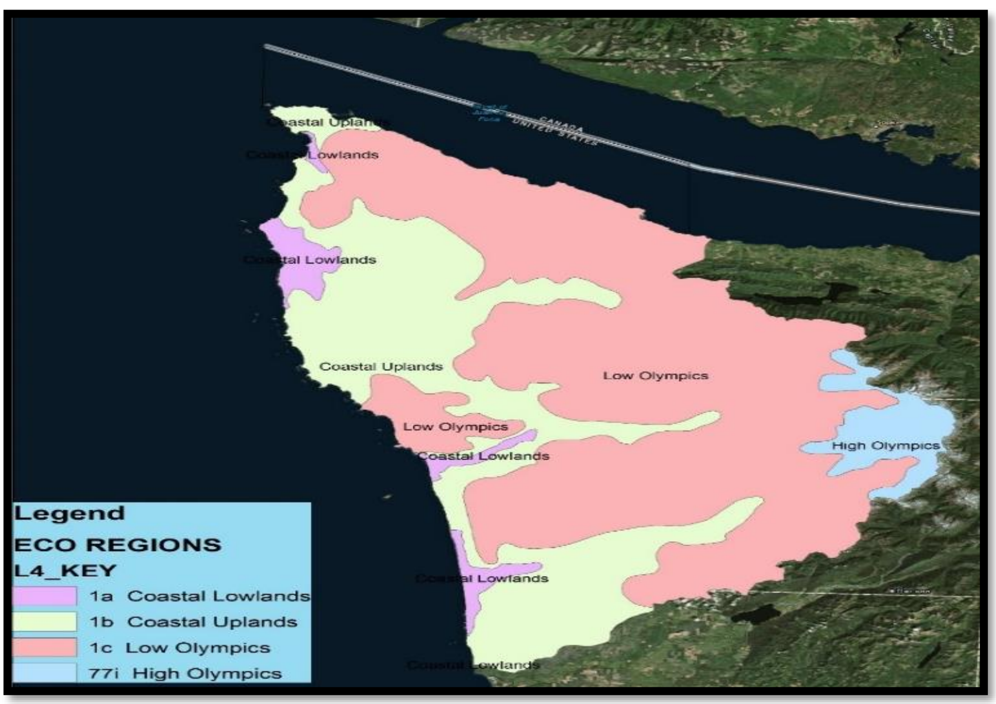

Figure 2-3- Map of ECO Regions in OESF(US EPA, 2015)

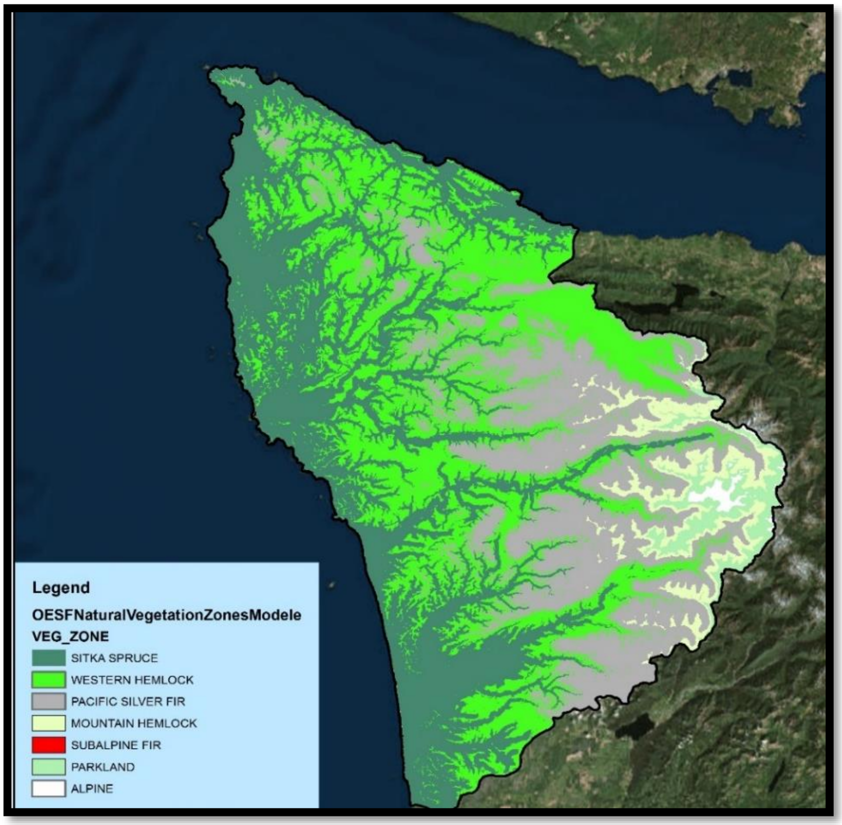

Figure 2-4- Map of Vegetation Zones in the OESF (ECOSHARE, 2017)

Study Design

The LandTrendr output was brought into ArcGIS and mapped on to the Olympic Experimental State forest. The disturbance data was sorted by year and landownership (State, private, ONF, ONP, and tribal lands). The maps are pixel based and each pixel indicates a disturbance. The data were sorted by year and magnitude. The magnitude is sorted by greatest disturbance by year. There are a variety of LandTrendr maps that were created by disturbance level (magnitude of disturbance) - greatest disturbance, second greatest disturbance, and third greatest disturbance. The maps with the third greatest disturbance is quite small and researchers suggest it isn’t very effective because of how little data there is in this map (Kennedy et al., 2012; Ohmann et al., 2012). This study used greatest disturbance by year.

If a disturbance pixel was present on the map, it means there is disturbance detected by the LandTrendr algorithm (Kennedy et al., 2010). Each pixel is nine square meters. Disturbance rates were calculated by the total area of disturbance (indicated by disturbance pixels) divided by total area. One of the problems with this LandTrendr data is that disturbances of less than 8 pixels are not very accurate and could reflect error. LandTrendr data was designed for to 3 x 3 pixel plots and not areas smaller than that (Kennedy et al., 2010). Thompson (2011) excluded disturbances less than 8 pixels sizes in their study rea. I did not exclude disturbance less than 8 pixels but assumed that the rate of smaller than 8 pixels is constant. Another problem researchers have notice using the algorithm is that the first and last year ran by the LandTrendr algorithm has less disturbance than expected and this could be an error in the program (Copass & S., 2016). I included this in my data because excluding it would reduce the amount of data in the study.

Each ownership group disturbance rate was determined using ArcGIS software and exported into Excel Worksheets to plot the data. The yearly rates were compared by land ownership, EPA Ecoregion, Vegetation Zones, Landownership and EPA Ecoregion, Landownership and Vegetation zone (**Figure 2-5** Flow chart of Study Design).

Two time periods were used to analyze whether disturbance rates have changed over time. The Northwest Forest Plan (NWFP) and the Habitat Conservation Plan (HCP) were implemented on DNR lands in 1999 (WA DNR, 2016), so annual disturbances were analyzed for two time periods: 1985-1998 and 1999-2012. To determine if trends in disturbance rates were the same or different across the two time periods, I used piecewise regression modeling, a type of multiple linear regression. In this study, disturbance rate was the dependent variable (Y) and 'year' was the first independent variable (X_1). For the piecewise regression (also known as segmented or 'broken-stick' regression) I used a dummy variable, X_2, to indicate whether data are in the first or second time period (Oosterbaan, 1994). The equation for the piecewise regression then uses the product of the dummy variable X_2 and the term (X_1 – 1998):

$$Y_i = \beta_0 + \beta_1 X_{i1} + \beta_2 (X_{i1} - 1998) X_{i2} + \varepsilon_i$$

which can be expressed as:

$$Y_i = \beta_0 + \beta_1 X_{i1} + \beta_2 X^*{}_{i2} + \varepsilon_i$$

where

Y_i is the disturbance rate in year i,

X_{i1} is the year,

X_{i2} is the dummy variable (0 if $X_{i1} \leq 1998$ and 1 if $X_{i1} > 1998$), and

X^*_{i2} represents the product (X_{i1} – 1998) X_{i2}

The results of the piecewise regression yields two separate linear functions, one (in the context of this study) for the first time period of 1985-1998, and another for the second time period of 1999-2012. The coefficient β_1 is the slope of the first linear relationship, and the sum of the two coefficients ($\beta_1 + \beta_2$) is the slope of the second linear relationship. If the coefficient β_2 is not significantly different than 0, that represents a similar linear trend during the two time periods. I used JMP software to fit the piecewise regression model for disturbance rates in OESF overall and by different landowners. I used an alpha of 0.05 to evaluate statistical significance.

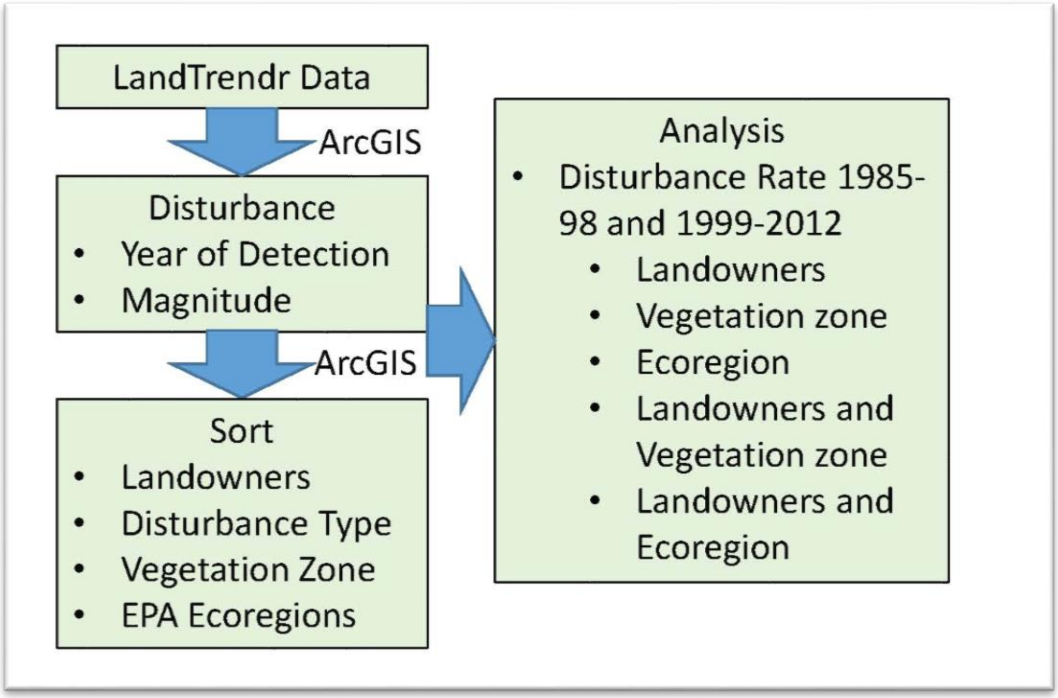

Figure 2-5 Flow chart of Study Design

Table 2-1- Data Type Used in Study

Data Layer	Data Type	Source
LandTrendr Disturbance by Year	Raster File	(Kennedy et al., 2012)
EPA Ecoregions	Shape File	(US EPA, 2015)
Vegetation Zones	Raster File	(ECOSHARE, 2017)
Landowners	Shape File	(WA DNR, 2018b)

I anticipated that forest disturbance rates would decrease on DNR lands during the second time period because of the 1997 HCP and active measures to set aside land from logging. I anticipated the ONF forest disturbance rate would decrease because the ONF reduced logging on their land since 1999. I predicted rates of disturbance on tribal lands would have increased because of previous research and the privately owned land disturbance rate would not change.

Forest disturbance is historically higher on state, tribal, and private lands than federally managed lands (ONP and ONF) (Kennedy et al., 2012). I expected ONP annual disturbance rates to be similar in both time periods. Forest disturbance in Olympic National Park can be assumed to be from natural causes since logging and human disturbance is managed at a minimum. The annual forest disturbance rate data was used to answer the questions posed in this thesis.

Chapter 3- Results & Discussion

Question 1. What is the Disturbance Rate in the Forest Lands in the Olympic Experimental State Forest (OESF)?

The overall disturbance rates in the OESF were similar during the two designated time periods of 1985-1998 and 1999-2012: 0.83% and 0.85%, respectively (**Error! Reference source not found.**). However, within the data there was considerable variation, and the trends varied within the two time periods (**Table 3-2-** Summary of Piecewise Regression Results for Each Landownership Type; **Figure C-2-** Overall Annual Disturbance Rates in the OESF with Piecewise Regression Analysis Line). The piecewise regression model explained 43% of the variation in disturbance rates across all landownership types and was statistically significant (**Table 3-2-** Summary of Piecewise Regression Results for Each Landownership Type). The highest overall disturbance level in the OESF was in 1987 at 2% and the rate decreased every year thereafter (**Figure 3-1-** Graph of Disturbance Rate among Primary Landowners in OESF.). The reason for the decreasing disturbance level was most likely because of the multiple lawsuits to conserve old growth successional forests and because two species (northern spotted owl and marbled murrelet) that used them were listed on the ESA in 1992 (Moeur et al., 2011; WA DNR, 1997). The period from the late 1980s to the implementation of the NWFP is nicknamed the 'Timber Wars,' as lawsuits related to the listing of the northern spotted owl halted timber production in the PNW region. Declining disturbance rates from 1985-1988 is most likely because of decreased timber harvests on OESF lands, since the predominant mode of disturbance in OESF is timber harvest (Kennedy et al., 2012; Ohmann et al., 2011). The 1985-1998 time period has a steeper decline in disturbance compared to the 1999-2012 period (**Figure C-2-** Overall Annual Disturbance Rates in the OESF with Piecewise Regression Analysis Line). The 1999-2012 yearly disturbance data decreased at a slower rate than previous years and rates of disturbance are more stable from year to year. The stability of the disturbance data could be because of fewer lawsuits and the implementation of the NWFP, which focused more on old growth forest preservation than previous OESF management plans.

Table 3-1- Annual Disturbance Rates in OESF by Landownership Group

	Disturbance Rates					
Year Group	**DNR**	**ONP**	**ONF**	**Private**	**Tribal**	**All**
85-98	1.01%	0.10%	0.63%	1.30%	0.98%	0.83%
99-12	0.54%	0.10%	0.15%	2.02%	0.77%	0.85%
Total	**0.77%**	**0.10%**	**0.39%**	**1.66%**	**0.87%**	**0.84%**

Table 3-2- Summary of Piecewise Regression Results for Each Landownership Type

Model	Year[1] (SE)	Product[1] (SE)	Sum[2]	Adj. R^2	F-Ratio	P-Value
OESF (all ownership)	-1.08‡(.23)	0.74‡ (.17)	-0.34	.43	11.14	.0003
DNR	-1.62‡(.32)	0.91‡ (.24)	-1.05	.53	16.07	<.0001
ONP	-0.112*(.05)	0.08*(.03)	-0.03	.096	2.44	.1079
ONF	-1.04‡(.17)	0.52‡ (.13)	-0.52	.67	28.06	<.0001
Private	-1.52**(.53)	1.31**(.41)	-0.21	.24	5.27	.012
Tribal	-0.91**(.29)	0.51*(.22)	-0.40	.29	6.44	.0055

[1]coefficient values are shown x1000 for readability
[2]the sum of the 'year' and 'product' coefficients, which represents the slope of the linear function in the second time period (see Methods)
$*p<0.05$, $** P<0.01$, $‡P<0.001$

Question 2. Has the Disturbance Rate Decreased in the DNR lands in the OESF since 1999, When the Habitat Conservation Plan (HCP) Was Implemented?

The overall disturbance rate on DNR lands in the OESF decreased from 1.01% from 1985-1998, to 0.45% from 1999-2012 (Error! Reference source not found.). This shift was expected because of the implementation of the HCP in 1999. The DNR had protected certain lands in the OESF from timber harvest in the HCP and has tried to reduce logging on the lands (WA DNR, 1997, 2016). Kennedy et al. (2012) have shown using LandTrendr data that disturbance in Washington State DNR lands in the PNW Region has stabilized. The piecewise regression model for DNR lands explained 53% of the variation in the disturbance rate, which decreased at a greater rate from 1985-1998 compared to 1999-2012 (**Table 3-2-** Summary of Piecewise Regression Results for Each Landownership Type; **Figure C-3-** DNR Annual Disturbance Rates in the OESF with Piecewise Regression Analysis Line. The most likely explanation for this difference is because of court cases reducing logging in the OESF (Kennedy et al., 2012; WA DNR, 2016). The disturbance rate per year was the highest in the 1980s with the highest rate in

1987 and on a decreasing trend after that date (**Figure 3-1-** Graph of Disturbance Rate among Primary Landowners in OESF.). The 1999-2012 data shows that the disturbance rate was more stable year to year with a slight decreasing trend (**Figure C-3)**. Since the implementation of the HCP, large percentage of the lands are off limits to timber harvesting and this would cause a decrease in overall disturbance rates since less land is available for timber harvest. This stability is most likely because of the implantation of HCP and forestry practices that reduced the rates of timber harvest.

Question 3. What are Differences in Land Disturbance Rate between the Different Landownership Groups in the Olympic Experimental State Forest?

Disturbance Rate in Federal Land Owners (ONP and ONF)

The lowest disturbance rate among the landownership groups (Private, DNR, Tribal, ONF, and ONP) were in the ONP (**Table 3-1-** Annual Disturbance Rates in OESF by Landownership Group**; Figure 3-1-** Graph of Disturbance Rate among Primary Landowners in OESF.). This was expected since their management policy is a natural regime. Currently very little human development exists in the ONP compared to other landowner categories and this is because of ONP policy (Halofsky et al., 2011). ONP policy is to allow natural processes to shape the forest and landscape in the National park. ONP disturbance rates from 85-98 and 99-12 was the exact same at 0.1%. This rate stayed relatively stable from year to year. The piecewise regression model for the ONP showed no statistical difference in the1985-99 and 1999-2012 year groups (**Table 3-2- Summary of Piecewise Regression Results for Each Landownership Type**). This stability was expected because of the ONP management policy that does not allow logging.

The next lowest landownership disturbance rate was the ONF. On the ONF, disturbance rates have declined since the 1990s (**Table 3-1-** Annual Disturbance Rates in OESF by Landownership

Group**)**. The rate from 1985-1998 was decreasing and then stabilized from 1999-2012 (**Figure 3-1-** Graph of Disturbance Rate among Primary Landowners in OESF.; **Figure C-5** ONF Annual Disturbance Rates in OESF with piecewise Regression Analysis Line). This trend in disturbance rate was expected since the timber harvest production is minimal on the ONF and their land management practices is to preserve old growth forest and was implemented in the mid-1990s (Halofsky et al., 2011; Kennedy et al., 2012). In addition, there also hasn't been any large fires on the ONF and the ONP during the years studied, which could cause spikes in disturbance rates, like the 2,798 acre Paradise fire in the ONP in 2015 (WA DNR, 2018b). The piecewise regression model explained 67% of the variation in disturbance rates on ONF lands, the best-fitting model compared to other landownership types (**Table 3-2- Summary of Piecewise Regression Results for Each Landownership Type).**

It is interesting to note that ONF annual disturbance rates dropped to around 0.15% from 1999-2012, and the ONP disturbance rate is around 0.10%. This rate could be assumed as the natural disturbance rate in the OESF, i.e. from 0.10% to 0.15% annual disturbance. The disturbance rate in the ONP was consistent across both time periods (1985-98 and 1999-2012). However, disturbance in the ONP could increase with climate change and it would be interesting to determine if the rate has increased from 2012-2017. Halofsky (2011) projected that as the climate warms, the disturbance regime will shift and increase because of stronger storms and more frequent fires. Natural disturbance rates may also increase because of increasing temperatures which lead to forest heat stress which could cause more of the forest to be susceptible to diseases and insects. Trees could die because of insect infestation and diseases (Chmura et al., 2011). The stronger storms could cause higher windstorms and higher precipitation events which could increase the amount of landslides, fires, and wind throw events leading to higher rates of disturbance.

Private Lands

Private land yearly disturbance rates increased from 1.30% in the 1985-1998 time period to 2.02% in the 1999-2012 year group (**Table 3-1-** Annual Disturbance Rates in OESF by Landownership Group). Private land disturbance rates were expected to be the highest disturbance rates in the study area. The increase in private land disturbance is one of the reasons why disturbance didn't decrease across all of the OESF in the 1999-2012 time period. Previous studies in Washington state showed that private landowners had the highest rate of disturbance in the State but the disturbance rate on private lands stayed relatively the same from 1985-2008; whereas, federal and state lands had decreased disturbance rates since the implementation of the NWFP (Kennedy et al., 2012). The piecewise regression model supported different trends during the two time periods, but only explained 24% variation in the data (**Table 3-2-** Summary of Piecewise Regression Results for Each Landownership Type; Figure C-6- **Private Annual Disturbance Rates in the OESF with the Piecewise Regression Analysis Line**).

Timber mill survey data was analyzed to see if timber mills received more lumber during 1999-2012 and overall, board feet has decreased compared to the 1985-1998 year group (WA DNR, 2017). In addition, logging rates in the two counties in the OESF has decreased since the 1980s (**Figure B-3-** Timber by Board Feet in Olympic Region by Landownership (Klallam County, Jefferson County, and Quinault Reservation, Washington)). However, this data is incomplete, since DNR stopped tracking timber harvested from Native American tribal land in 2002. The data was from Washington State DNR mill surveys and only includes county data, and not the specific area origin of the timber harvest. The data is sorted by county where the lumber is harvested.

The OESF lies in three counties, Jefferson, Clallam, and Grays Harbor County. All of the private lands in the OESF are in Jefferson and Clallam counties. These were the only counties used in the mill surveys for private, state, and federal lands. The Grays Harbor portion of the OESF is in the Quinault Indian Nation reservation. Timber production could have increased in the OESF and decreased in other lands in the county, but further investigation is warranted. Soulard et al. (2017) analyzed private timberlands using remote sensing in the Cascade Mountains of Washington from 1985-2014 and concluded that the highest rates of disturbance were from 2000-2007. They concluded this was because of the housing boom of the 2000s and the rates dropped after the 2008 housing bust (Soulard, et al., 2017). The increasing disturbance trend on private lands is similar to the trend in the annual disturbance in the OESF among private lands (**Figure 3-1-** Graph of Disturbance Rate among Primary Landowners in OESF.).

Tribal Lands

The disturbance level on tribal lands decreased from the mid-1980s and had a lower disturbance rate in the 1999-2012 year group than the 1985-1998 data set (**Table 3-1-** Annual Disturbance Rates in OESF by Landownership Group; **Figure 3-1-** Graph of Disturbance Rate among Primary Landowners in OESF.). Kennedy et al. (2012) in their study noted the increased yearly disturbance rate in tribal lands in Washington State but this finding was not seen in the OESF. The piecewise regression model explained 29% of the variability and showed a different slope in the two time periods (**Table 3-2-** Summary of Piecewise Regression Results for Each Landownership Type; **Figure C-7-** Tribal Annual Disturbance Rates in the OESF with the Piecewise Regression Analysis Line). Because DNR stopped taking mill surveys from tribal lands in 2002, it is impossible to determine if timber production increased on reservation lands (**Figure B-3-** Timber by Board Feet in Olympic Region by Landownership (Klallam County, Jefferson County, and Quinault Reservation, Washington)) (WA DNR, 2018).

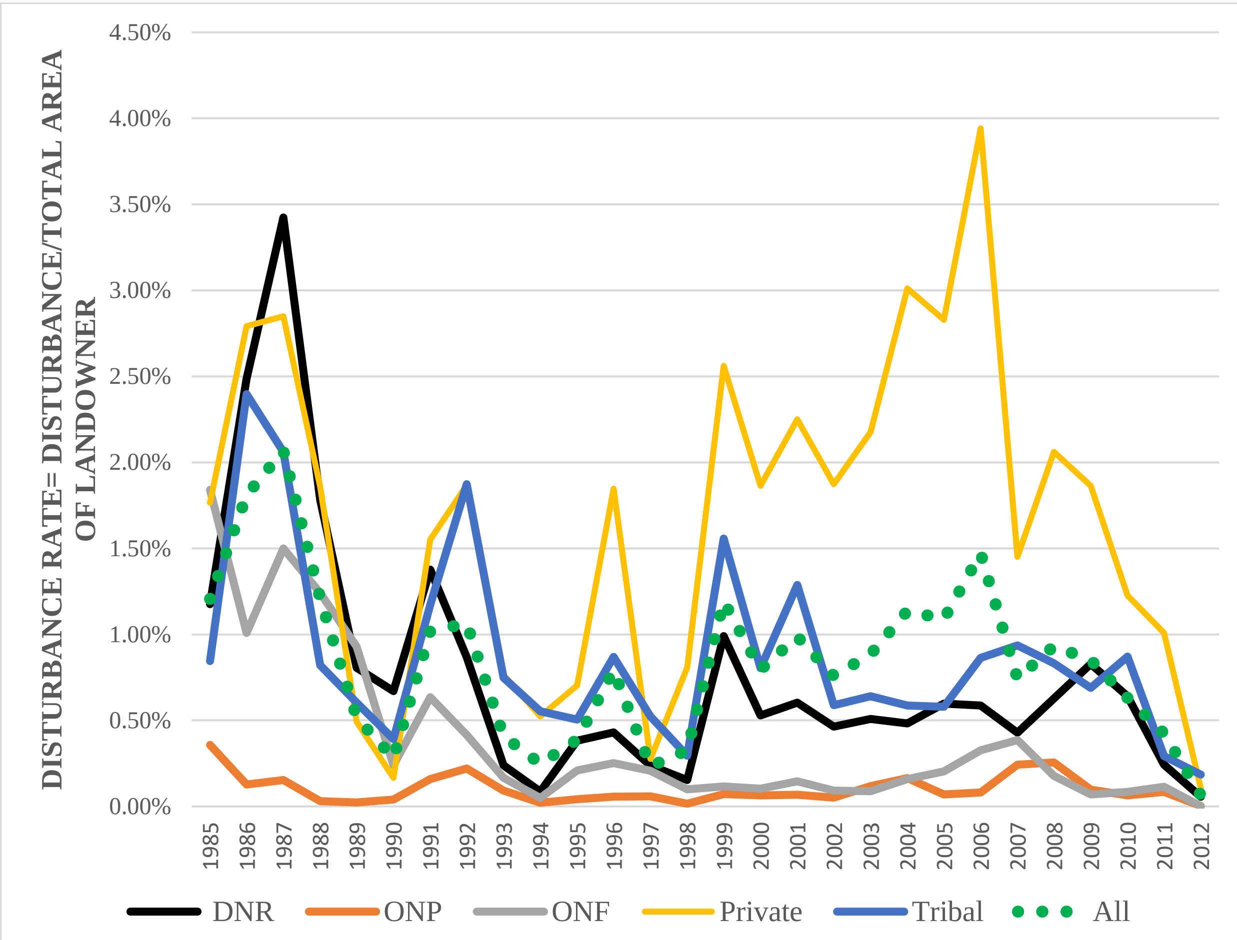

Figure 3-1- Graph of Disturbance Rate among Primary Landowners in OESF.

Question 4. What is the Disturbance Rate among the Different EPA Ecoregions in the OESF?

Each of the different EPA ecoregions have a different disturbance rate (

). The largest of the ecoregions are the low Olympics and coastal uplands. The high Olympics (which is excluded because its extent is only within the ONP) and coastal lowlands are the smallest ecoregions (**Figure B-4-** Level IV Ecoregions in the OESF by Area). The coastal lowlands region is also excluded because this region is not in ONF lands. The coastal lowland disturbance rate might not be accurate because of its small size, as acknowledged specifically by the creators of LandTrendr (Kennedy et al., 2010) (**Table 3-3-** Annual Disturbance Rate in OESF by EPA Level IV Ecoregions; **Figure 3-2-** Disturbance in Ecoregions in the OESF**2**). There are years where there is no disturbance in this ecoregion which could reflect errors in the data.

The coastal uplands ecoregion has the highest yearly disturbance rate among the different landowners, possibly reflecting its status as the most favorable ecoregion for timber production in the OESF. This ecoregion also has the highest disturbance rate for DNR lands (

Table D-2- Yearly Disturbance Rate among Coastal Uplands**)**. The disturbance rate in the coastal uplands ecoregion among private lands doubled in the 1999-2012 year group from the 1985-1998 year group and this could be why the overall annual disturbance rate increased in the coastal uplands (

Table D-2- Yearly Disturbance Rate among Coastal Uplands**; Table D-3- 3**). All the other landowners' disturbance rate decreased in the coastal uplands.

The low Olympic ecoregion experienced a decrease in overall disturbance in the 1999-2012 from 1985-98 year group (**Table D-3- 3**). The disturbance level in DNR lands decreased from 1.01 to 0.44% in this time period (**Table D-3-** Yearly Disturbance Rate among Low Olympic Ecoregion). The ONF yearly disturbance rate also decreased during the same time period. The ONP disturbance rate stayed the same in the two different time periods. Tribal lands also experienced a decrease in disturbance rates but private lands disturbance rate increased in the 1999-2012 year group in the low Olympic ecoregion.

Table 3-3- Annual Disturbance Rate in OESF by EPA Level IV Ecoregions

	Disturbance Rate			
Year Group	**Low Olympics**	**Coastal Uplands**	**Coastal Lowlands**	**All**
85-98	0.76%	1.00%	0.44%	0.83%
99-12	0.69%	1.19%	0.65%	0.85%
Total	0.73%	1.10%	0.55%	0.84%

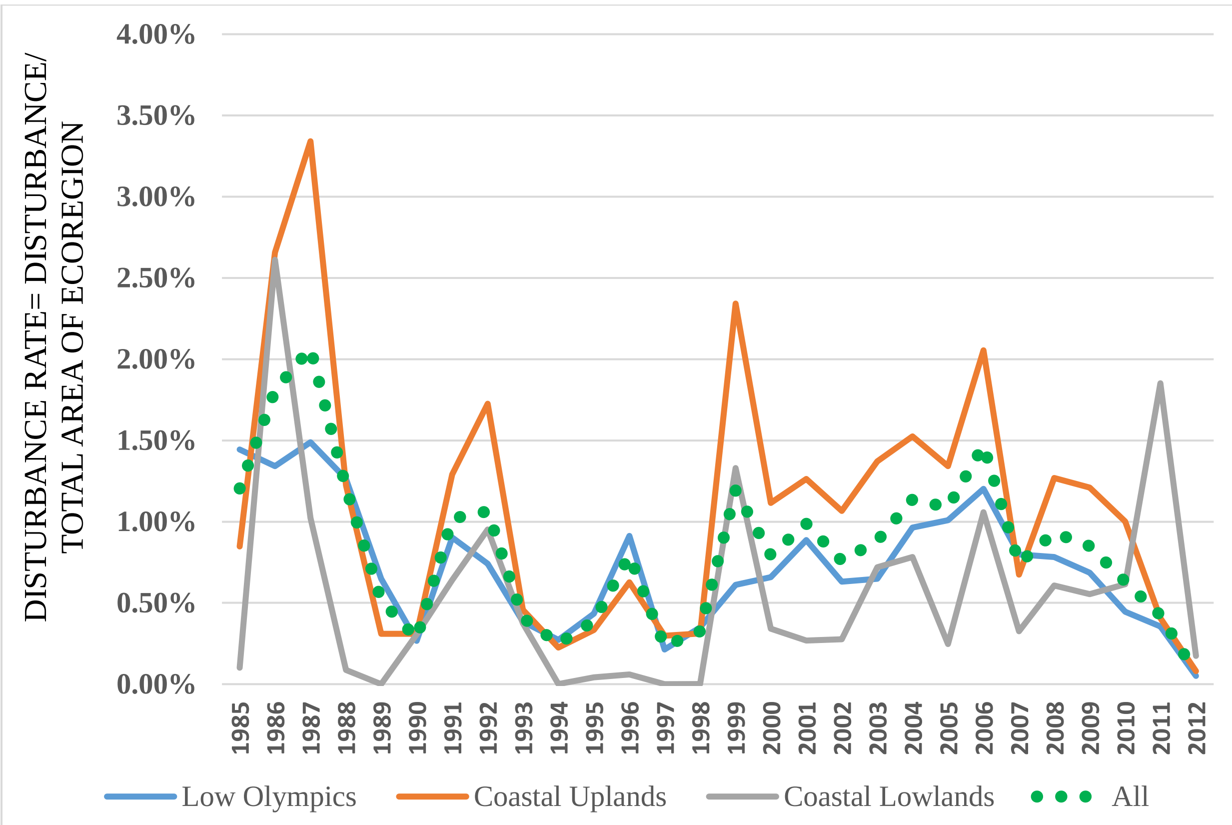

Figure 3-2- Disturbance in Ecoregions in the OESF

Disturbance in the High Olympics Ecoregion

Disturbance rates from the high Olympic ecoregion is excluded from this study because this area is predominated by glaciers and non-forest area which is not the focus of LandTrendr. However, the data shows an increase in disturbance rate and the disturbance patterns appear to be retreating glaciers in the High Olympic region (**Figure A-13-** Map of Disturbance in the High Olympics Ecoregion by YOD (Mount Olympus).). The disturbance rate has increased from 1999-2011 and the trend is increasing overall as from 1985-98 (

Table 3-4- Yearly Disturbance Rates in the High Olympic Ecoregion

Year **High Olympics Disturbance Rate**

; **Figure B-8-** Annual Disturbance Rate by High Olympic Ecoregion**8**). The effects of climate change could result in further downstream disturbance in watersheds that have glaciers such as the Hoh and Queets river drainage. Copass (2016) did not include High Olympic ecoregion in their study because of the high variability of disturbance data from year to year and the data is not very accurate. The algorithm is not reliable in alpine areas because of differences in yearly snow depth in the high Olympics (Copass et al., 2016). The high Olympic ecoregion in the OESF includes Mt Olympus, the highest and most glaciated peak in the Olympic Mountain Range. Scientists have said climate change poses a high risk to glaciers in the Olympics and that glaciers and snowfields are retreating (Halofsky et al., 2011). Retreating glaciers could increase riparian disturbance and rivers banks shifting due to the changes in hydrology patterns (Halofsky et al., 2011).

Table 3-4- Yearly Disturbance Rates in the High Olympic Ecoregion

Year	High Olympics Disturbance Rate
1985-1998	0.49%
1999-2011*	0.68%
Total	0.58%

**There was no disturbance data in this ecoregion for 2012.*

Question 5-What is the Disturbance Rate among the Different Forest Vegetation Zones?

There are eight vegetation zones in the OESF. Not all OESF landowners have all eight vegetation zones on their lands and only the ONP contains all eight vegetation zones. The primary vegetation zones in the OESF are Sitka Spruce, Western hemlock, and Pacific silver fir. The primary vegetation zones are found with all the landowners in the OESF. The Western hemlock and Sitka spruce is the vegetation zone where timber harvest primarily takes place in the OESF and they have the highest rates of disturbance (**Table 3-5-** Annual Disturbance Rate by Different Vegetation Zones; **Figure 3-3-Disturbance** in Primary Vegetation Zones). Disturbance rates in the Sitka spruce and Western hemlock vegetation zones mirrored the overall disturbance rate (**Figure 3-3-Disturbance** in Primary Vegetation Zones). This finding would be expected because these zones have the most favorable trees for timber harvest (WA-DNR, 2017). Silver Fir has a lower disturbance rate and this is also expected since this tree is not as favorable for timber harvest as are trees in the Sitka spruce and Western hemlock vegetation zones (USDA NRCS, 2017). The Pacific silver fir disturbance rate is close to vegetation zone's rates where there is no timber harvest and this could be a natural disturbance rate for Pacific silver fir (**Figure B-9- Disturbance by Vegetation Zones** .

Table 3-5- Annual Disturbance Rate by Different Vegetation Zones

	Disturbance Rate		
Year	**Low Olympics**	**Western Hemlock**	**Pacific Silver Fir**
85-98	0.93%	1.05%	0.46%
99-12	1.14%	1.09%	0.21%
Total	**1.03%**	**1.07%**	**0.33%**

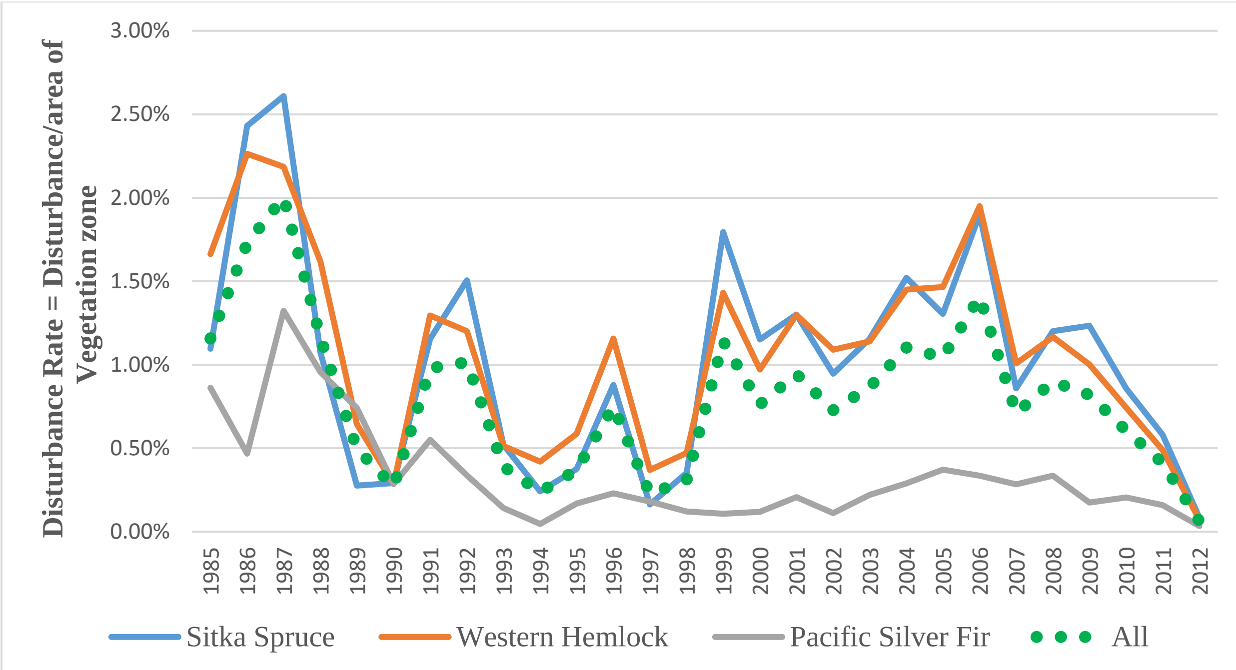

Figure 3-3-Disturbance in Primary Vegetation Zones

Conclusion

Using LandTrendr data, the overall disturbance rates in the OESF since the implementation of the 1997 HCP did not change, which was unexpected (**Table 3-1-** Annual Disturbance Rates in OESF by Landownership Group). However, this overall average hides considerable variation by land ownership, ecoregion, vegetation type, and year-to-year changes. On DNR managed lands, disturbance rates declined considerably from 1985-1998, and then declined but at a slower rate during 1999-2012 (Table 3-5). The overall rates in OESF were similar likely because of an increase in timber production on private lands in the OESF. The yearly disturbance rate on private lands increased during the duration of this study (**Table 3-1-** Annual Disturbance Rates in OESF by Landownership Group**; Figure 3-1-** Graph of Disturbance Rate among Primary Landowners in OESF.). The landownership type is the biggest factor in determining disturbance rates in the OESF and this has been shown in other studies (Kennedy et al., 2012; Peterson et al., 1997) . Each landowners different objectives for their forest land. Private land owner's main objective is for profit from timber sales (Peterson et al., 1997). The ONF objectives since the implementation of the PNW is to preserve old growth successional sorest and this is seen in their reduced disturbance rate. The ONP Policy is to support natural disturbance regimes and as a result, they have the least amount of disturbance. DNR's management in the OESF is to be ecological friendly and also incorporate revenues from timber productions and as a result their disturbance rate is between private and Federal (ONP and ONF) landownership types.

More research needs to be done to see what the natural disturbance rate is in the OESF. This is partially being done by researchers at the ONP (Copass & S., 2016). Future research needs to focus on whether this natural disturbance rate is increasing. Many studies suspect that climate change could increase the natural disturbance rates because of stronger storms and more fires. The increase of natural disturbance rates could have an effect on DNR lands in the OESF. As more LandTrendr data becomes available, this data should be examined to see if the natural disturbance levels on the OESF is increase or decreasing. Natural disturbance type can be sorted and measured by how much it covers. Categorizing natural disturbance rates by size can further help DNR determine how disturbance is shaping their forest and how they should best manage their land.

Appendix A- Maps

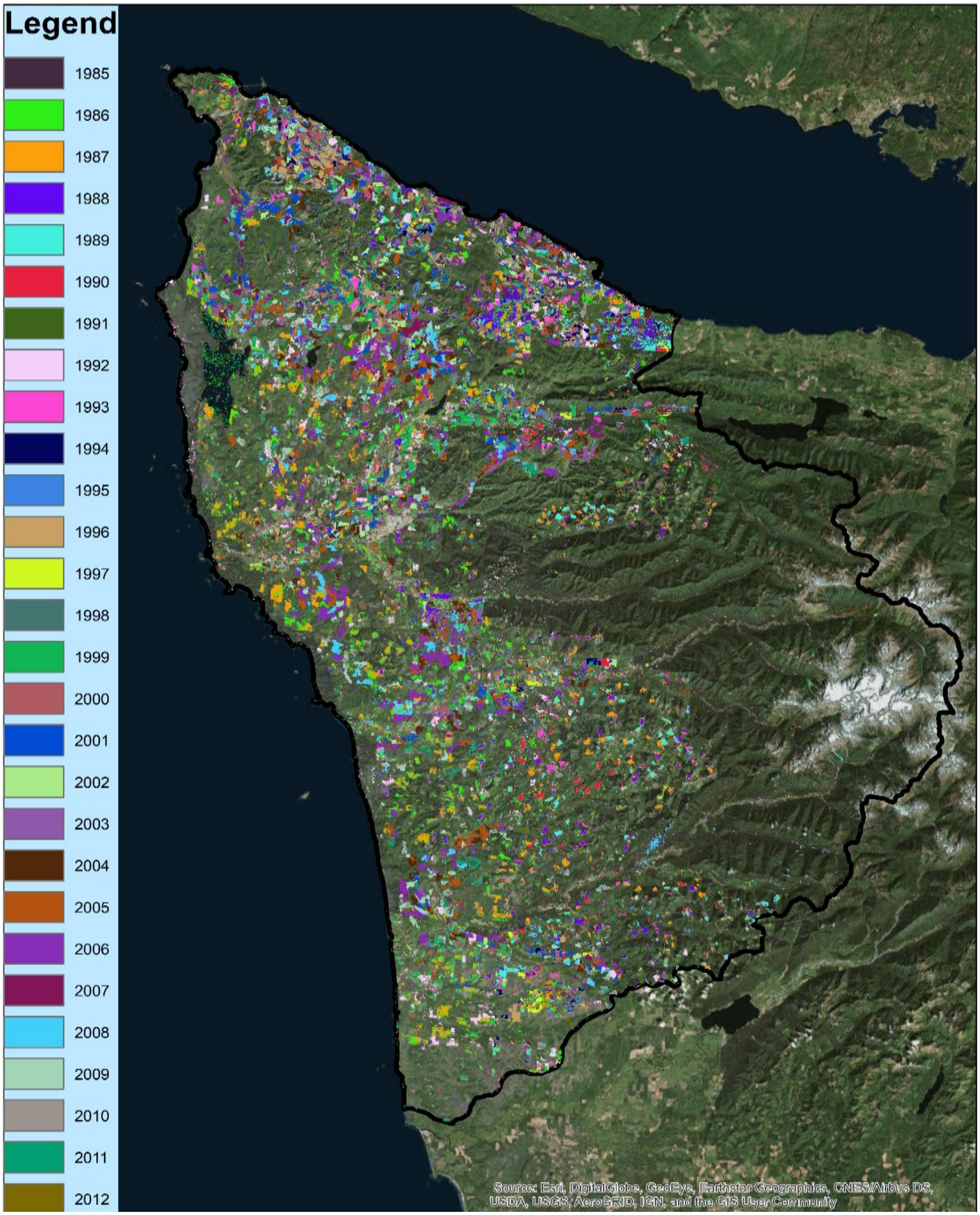

Figure A-1- Map of Disturbance in OESF

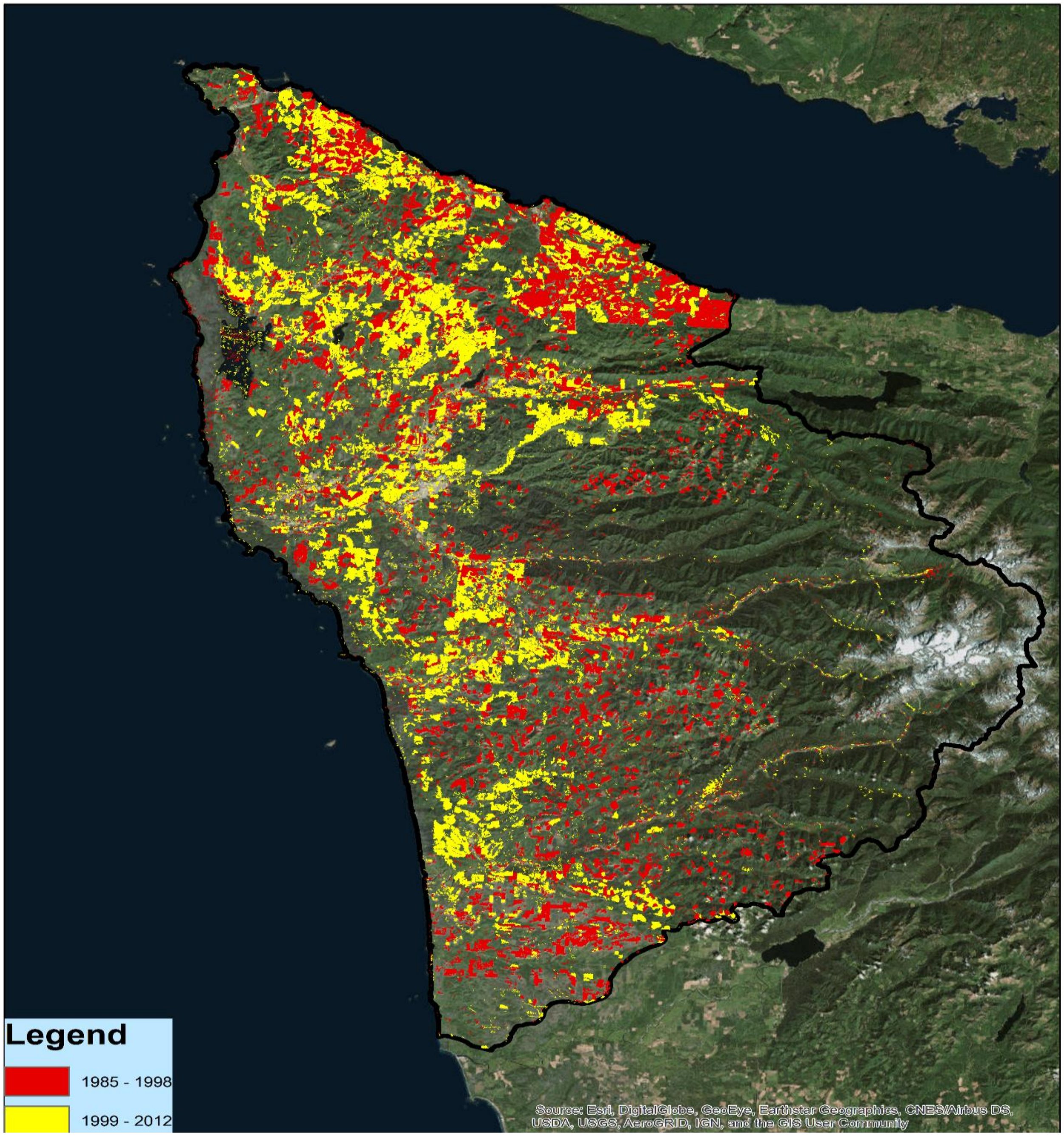

Figure A-2- Map of Disturbance in the OESF by Two Year Groups (1985-98 and 1999-2012)

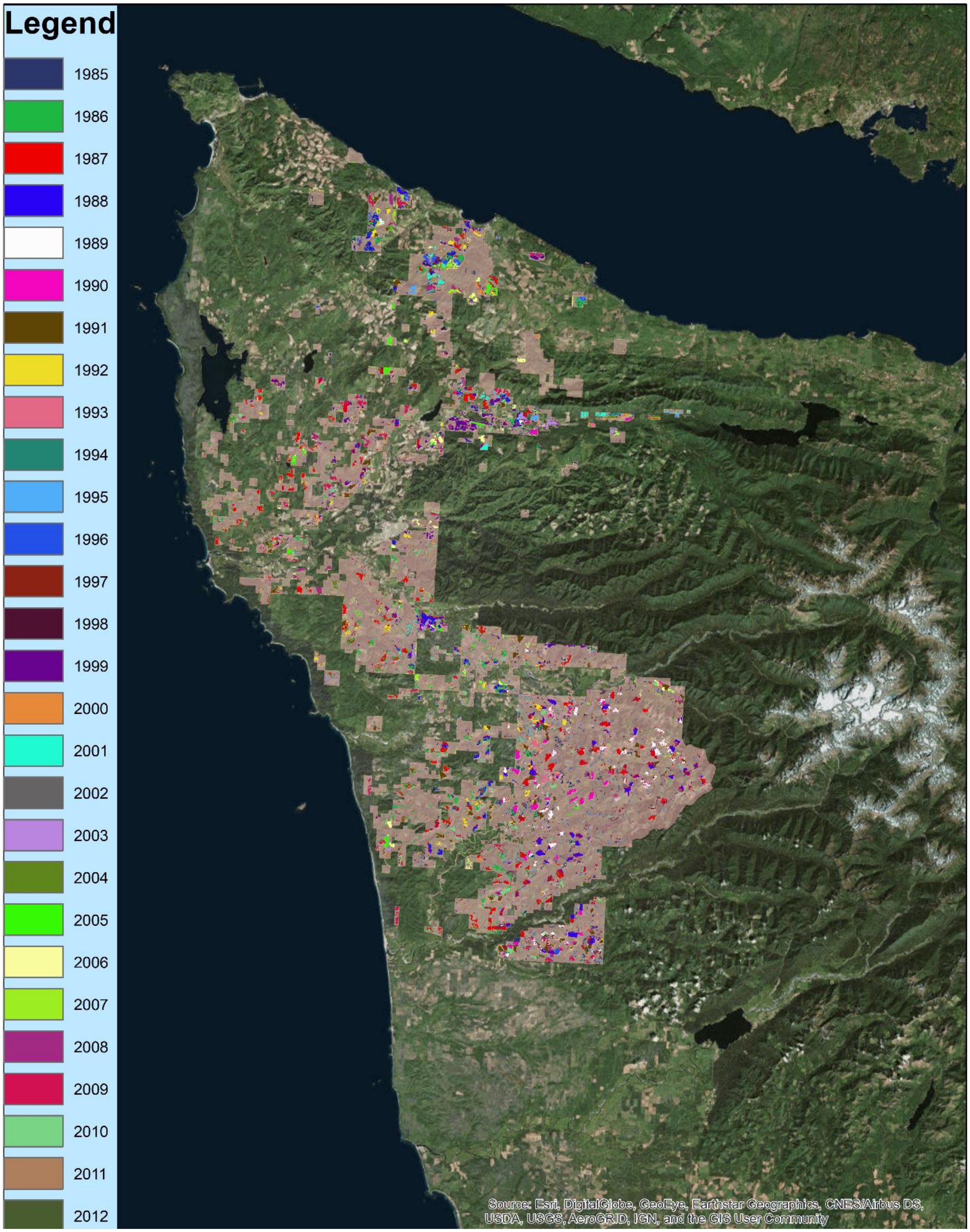

Figure A-3- Map of Disturbance in DNR Lands in the OESF by YOD

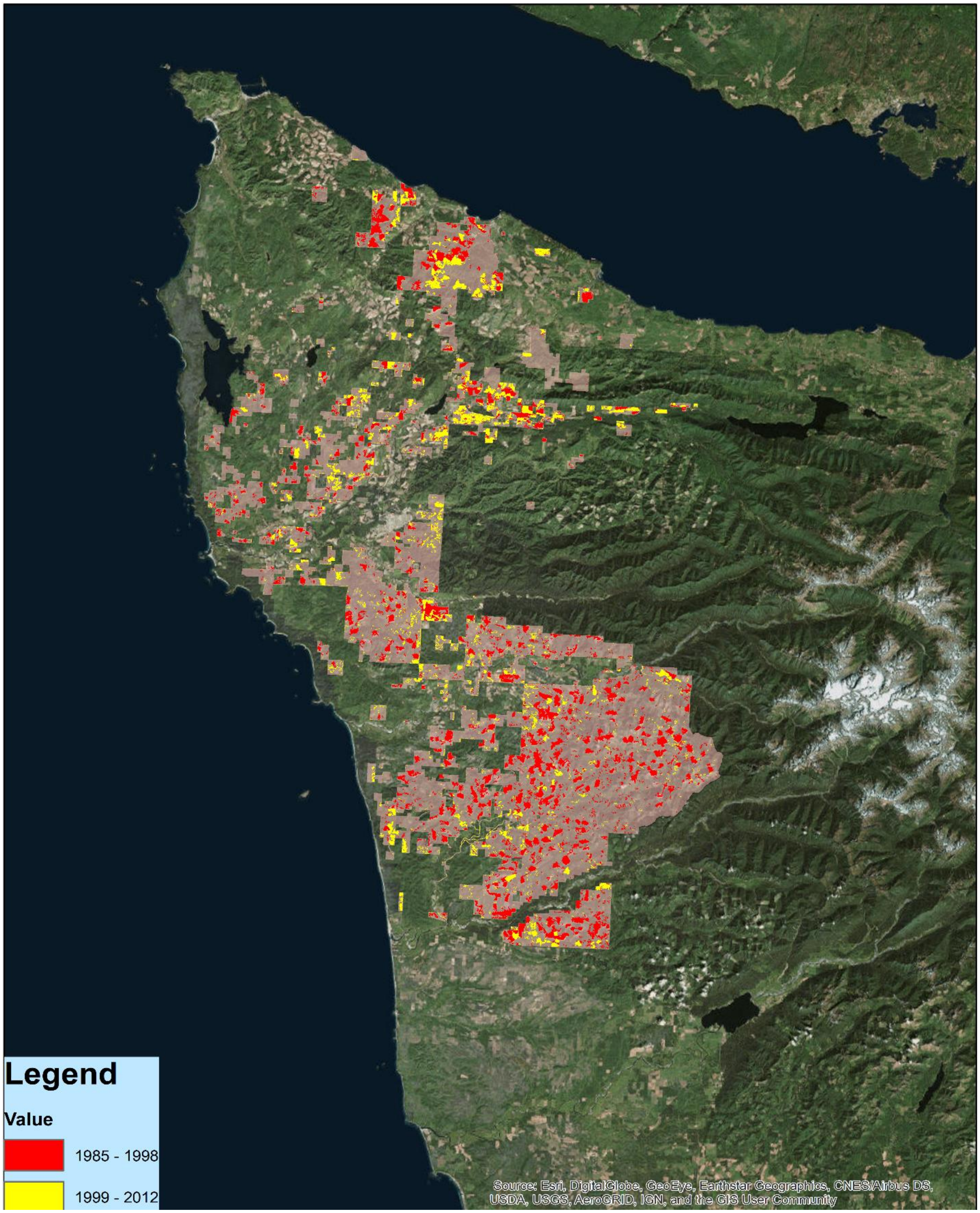

Figure A-4- Map of Disturbance in DNR lands in the OESF by Year Groups 1985-1998 and 1999-2012

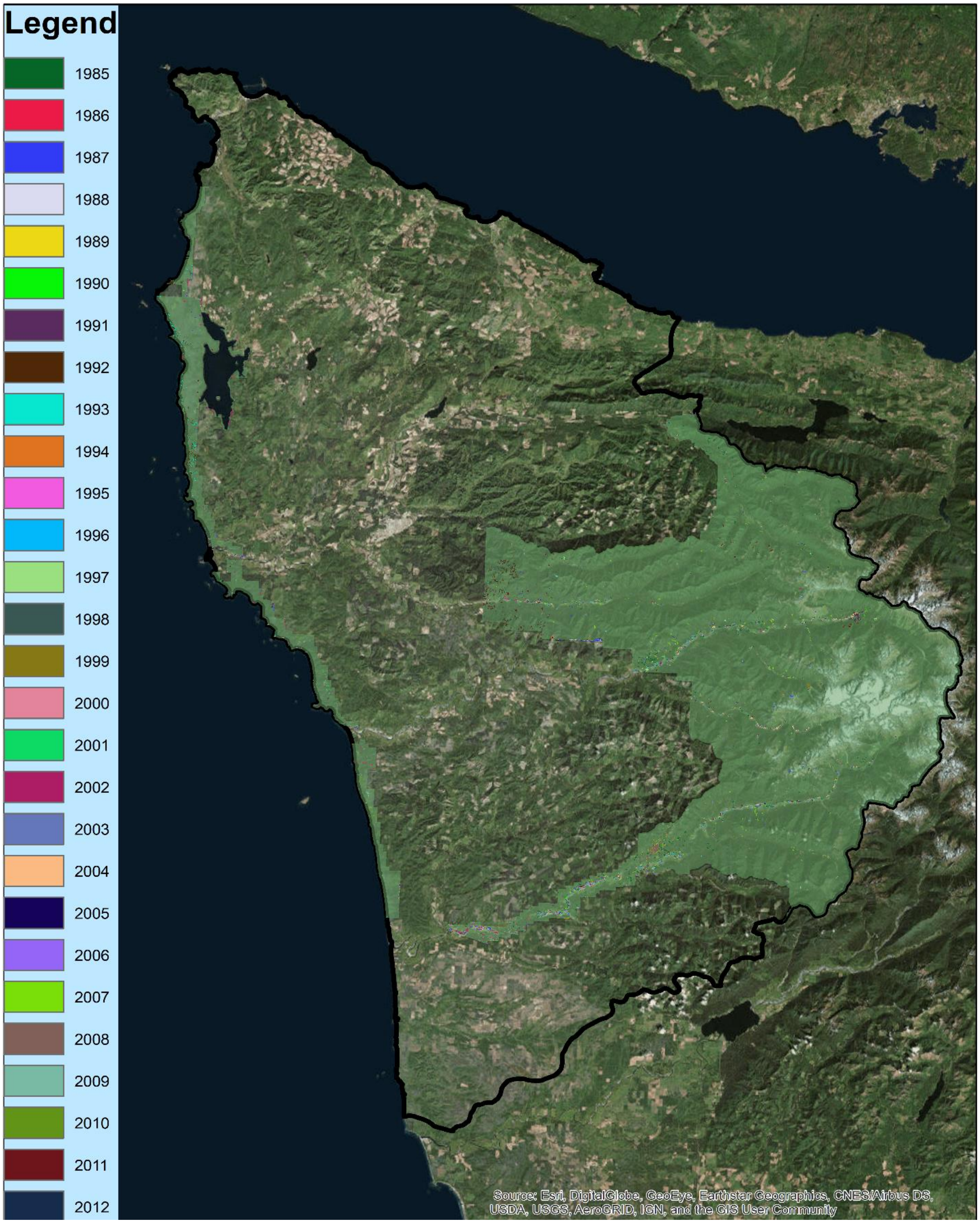

Figure A-5- Map of Disturbance in ONP Lands in the OESF by YOD

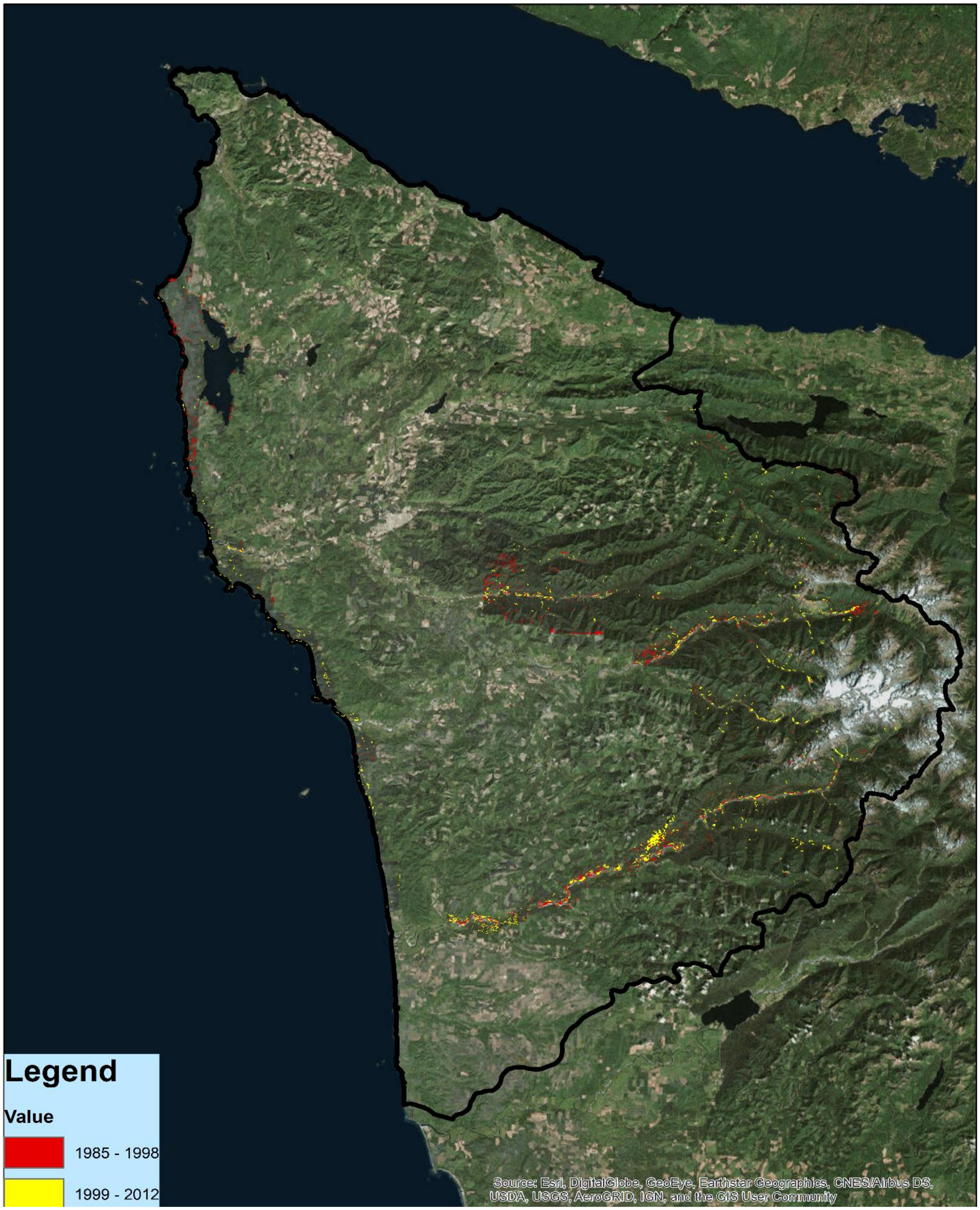

Figure A-6- Map of Disturbance in ONP Lands in the OESF by Year Groups 1985-1998 and 1999-2012

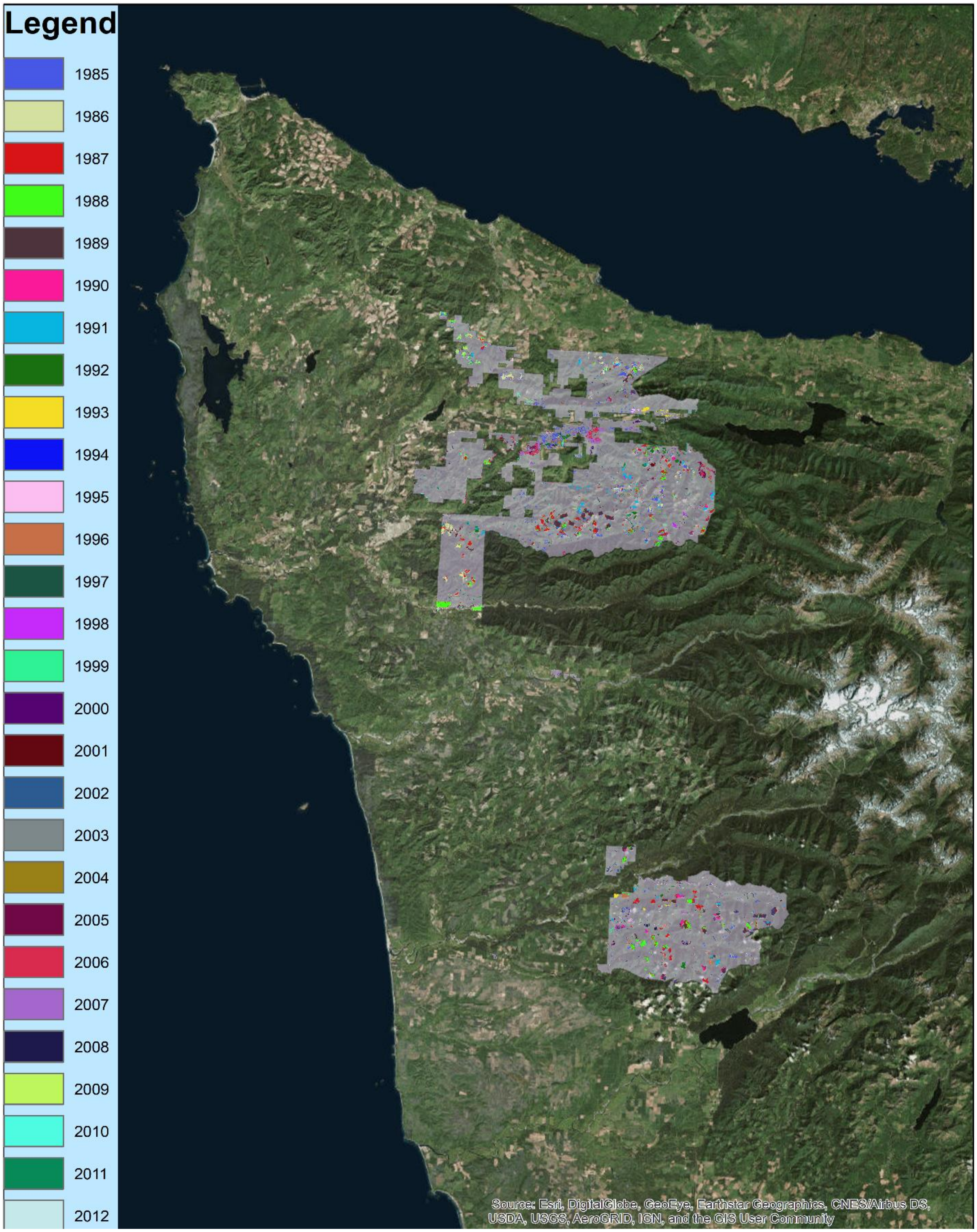

Figure A-7- Map of Disturbance in ONF Lands in the OESF by YOD

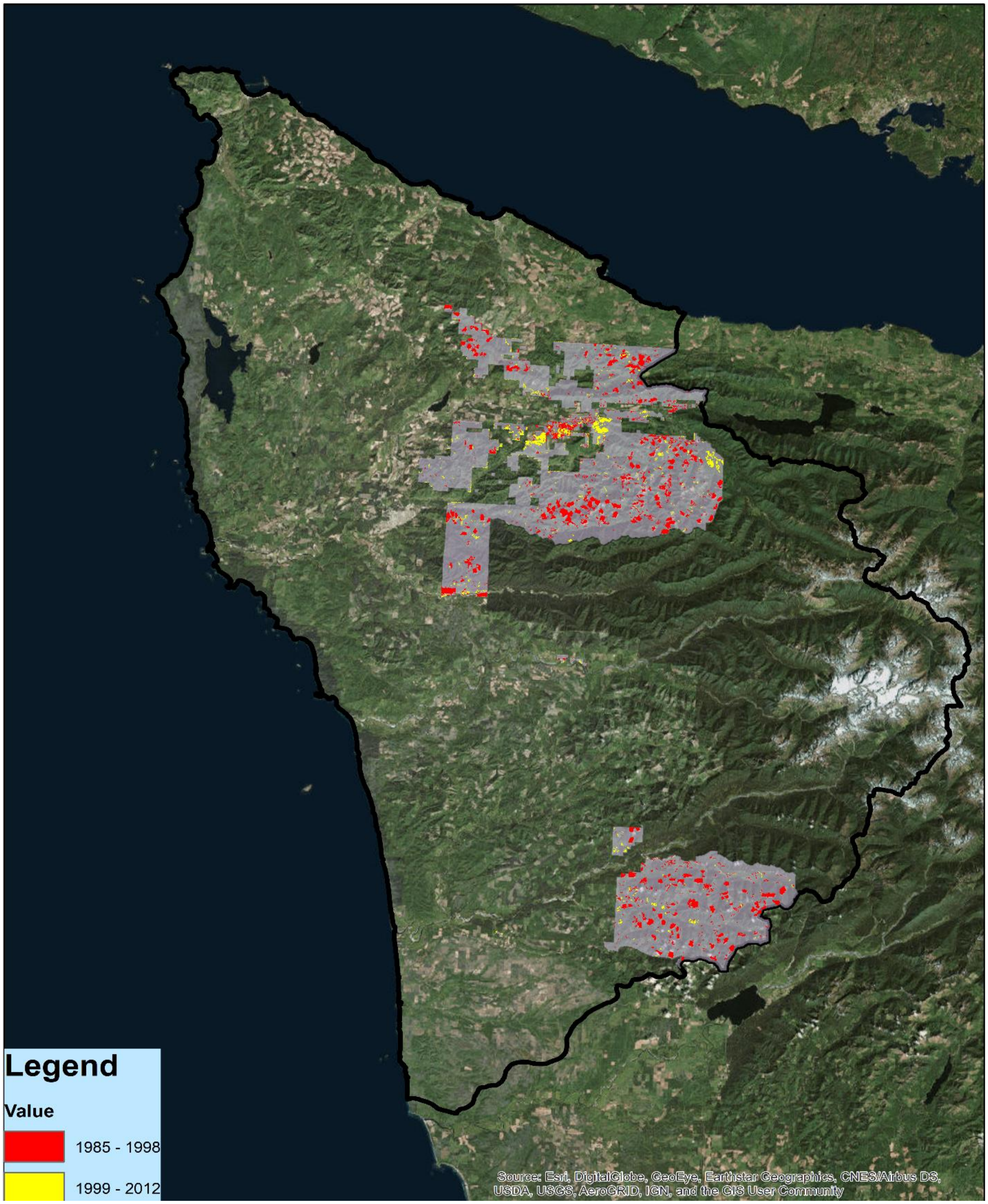

Figure A-8- Map of Disturbance in ONF Lands in the OESF by Year Groups 1985-1998 and 1999-2012

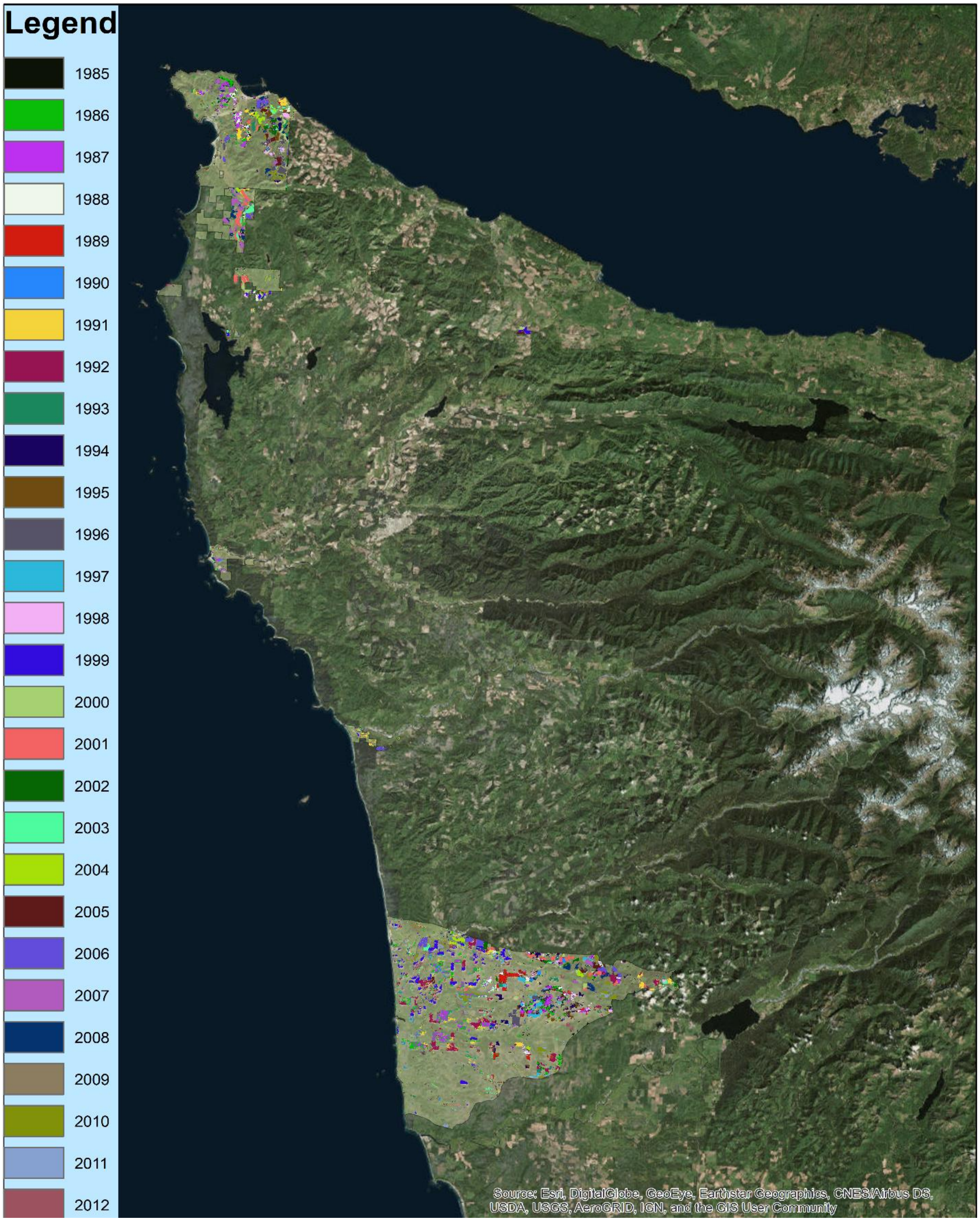

Figure A-9- Map of Disturbance in Tribal Lands in the OESF by YOD

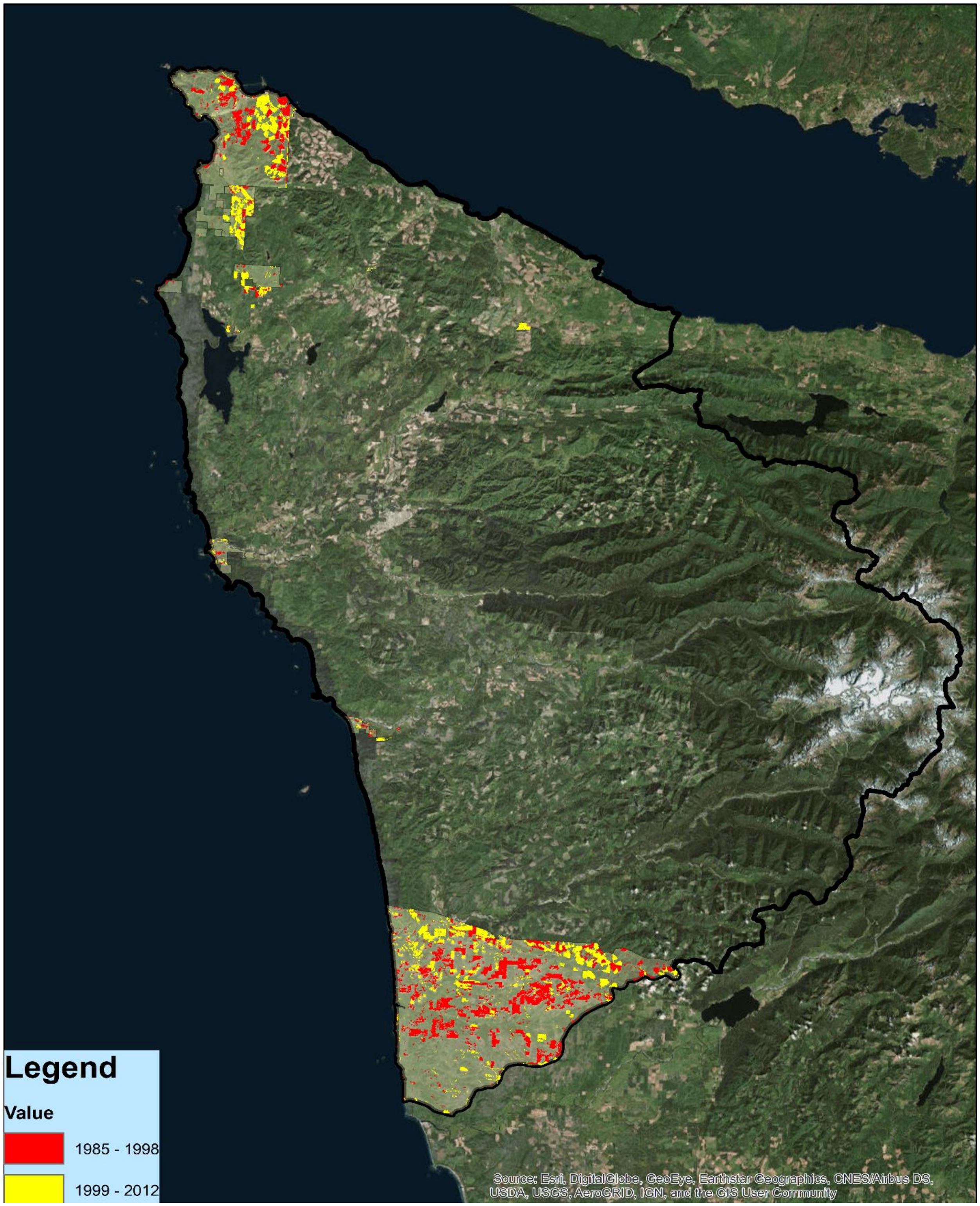

Figure A-10- Map of Disturbance in Tribal Lands in the OESF by Year Groups 1985-1998 and 1999-2012

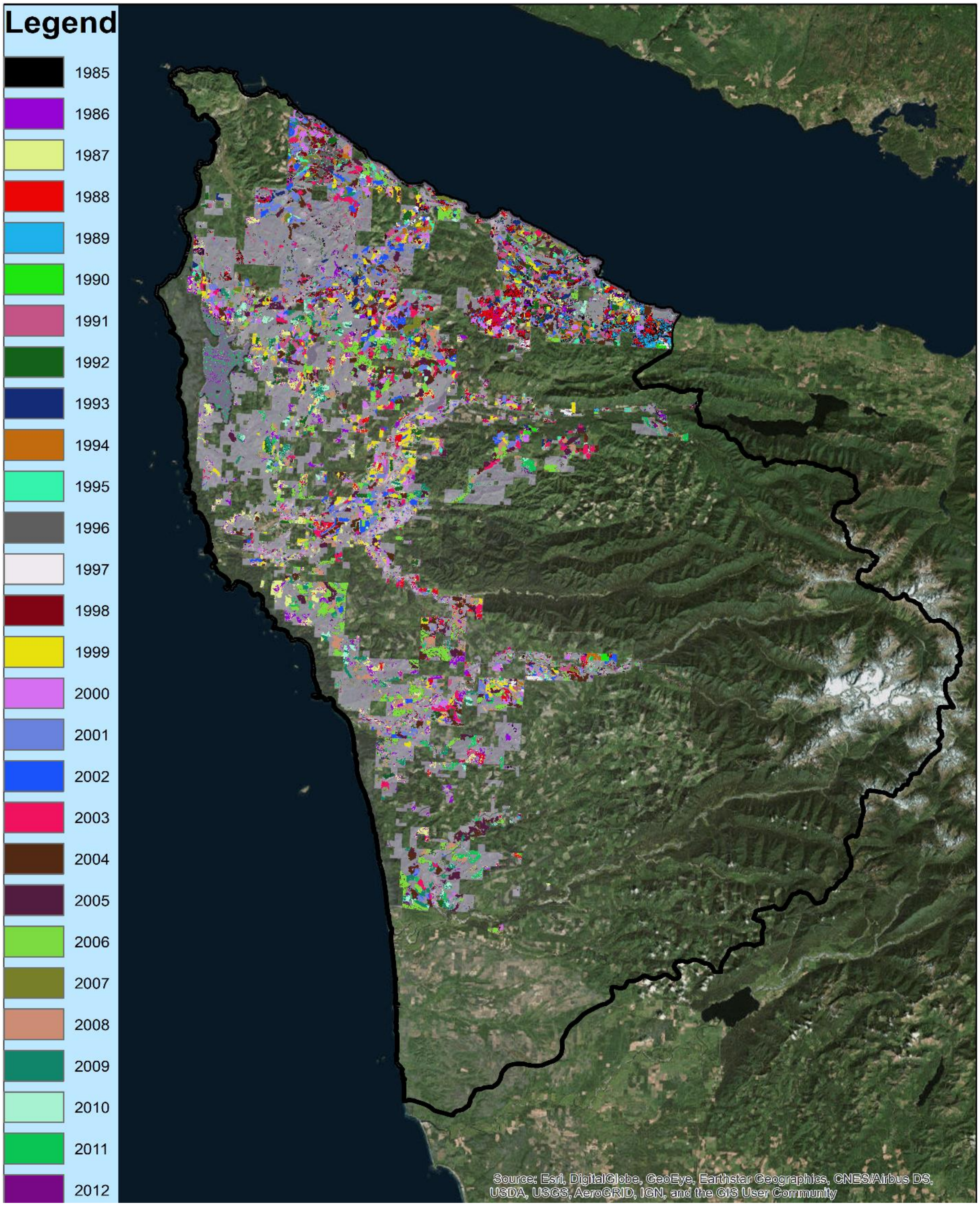

Figure A-11- Map of Disturbance in Private Lands in the OESF by YOD

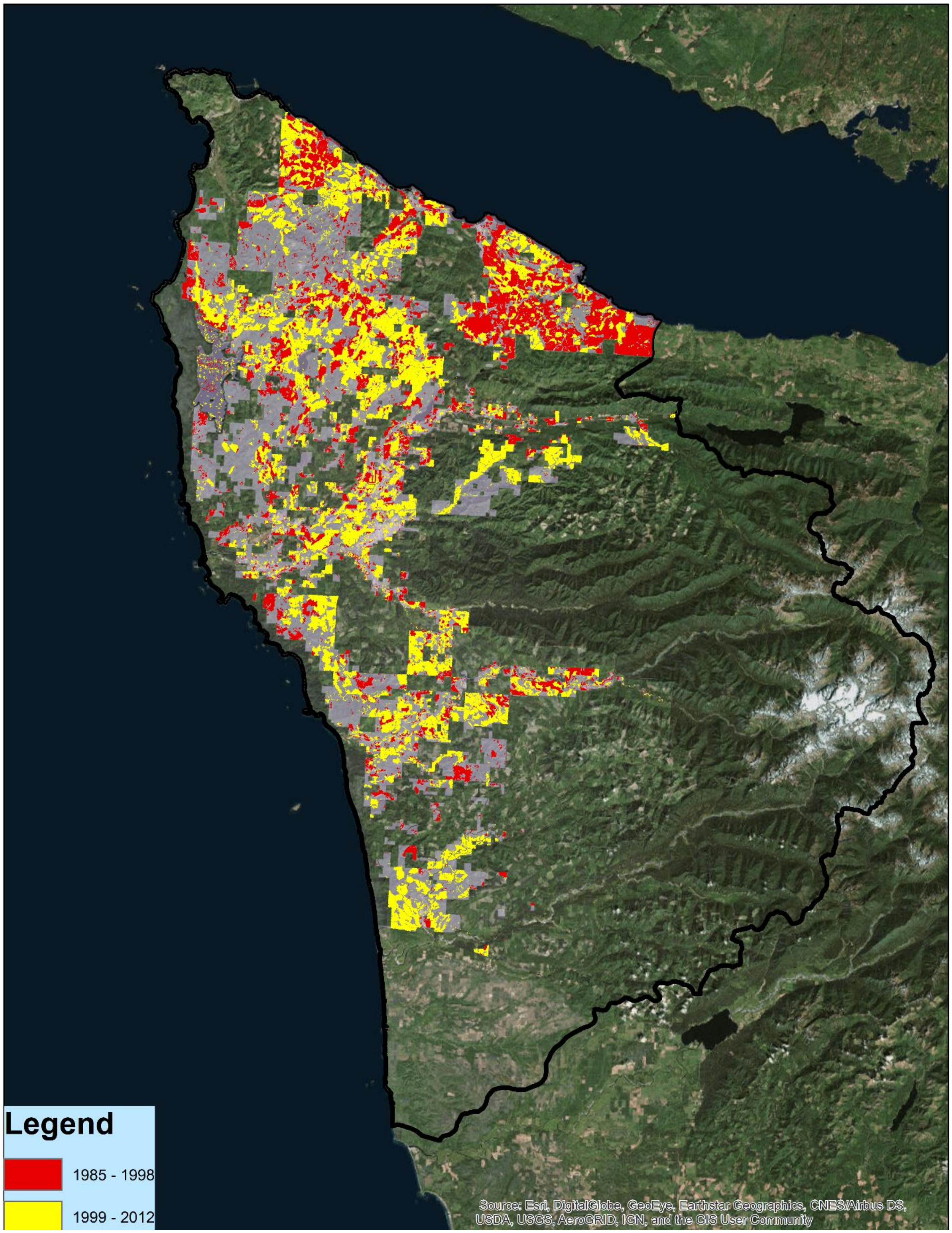

Figure A-12- Map of Disturbance in Private Lands in the OESF by Year Groups 1985-1998 and 1999-2012

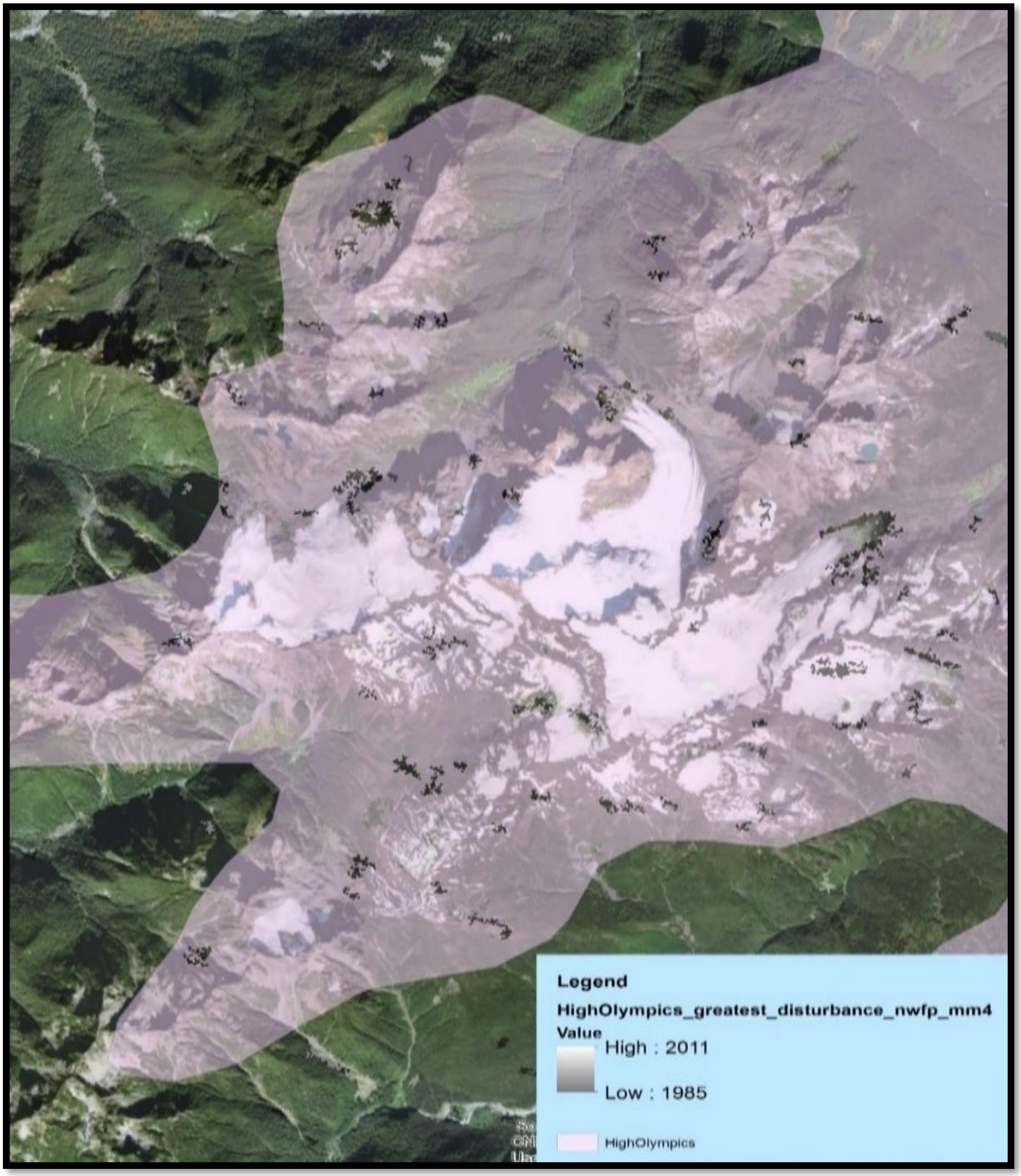

Figure A-13- Map of Disturbance in the High Olympics Ecoregion by YOD (Mount Olympus).

Appendix B- Line Graphs

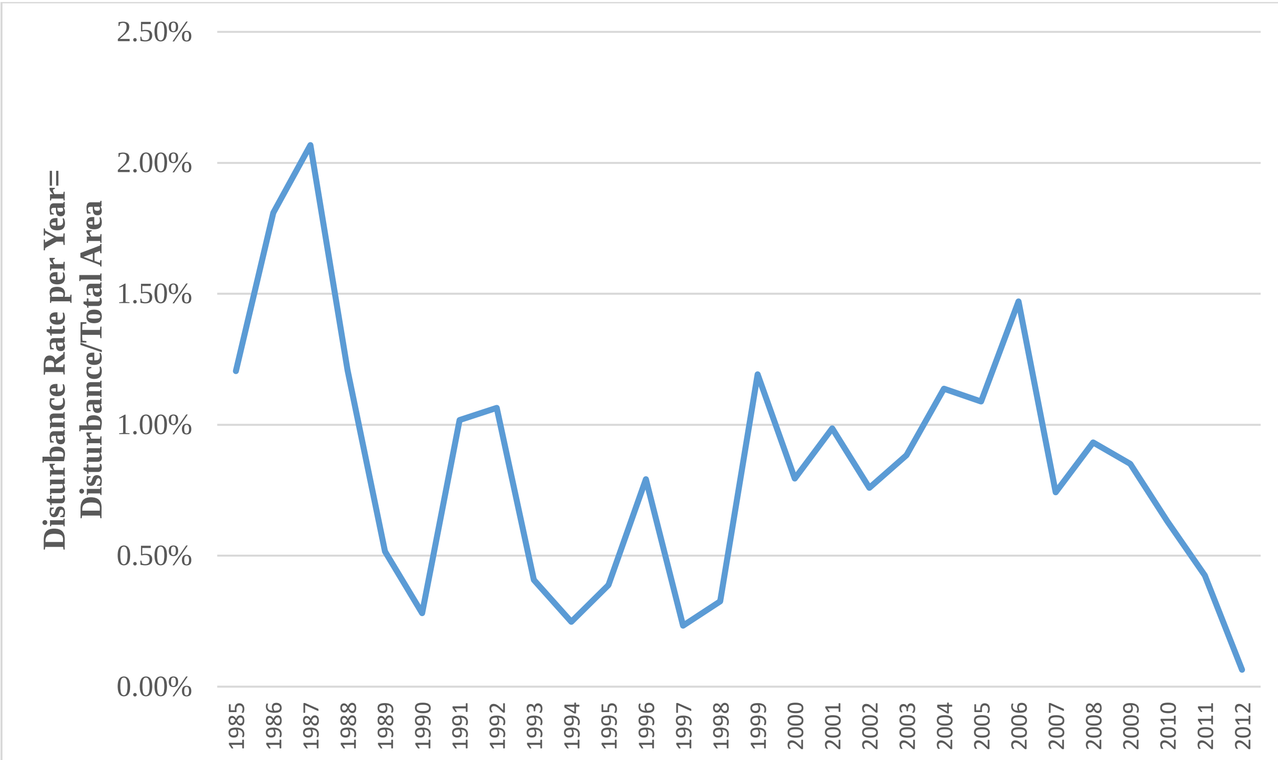

Figure B-1- Overall Annual Disturbance Rates in OESF

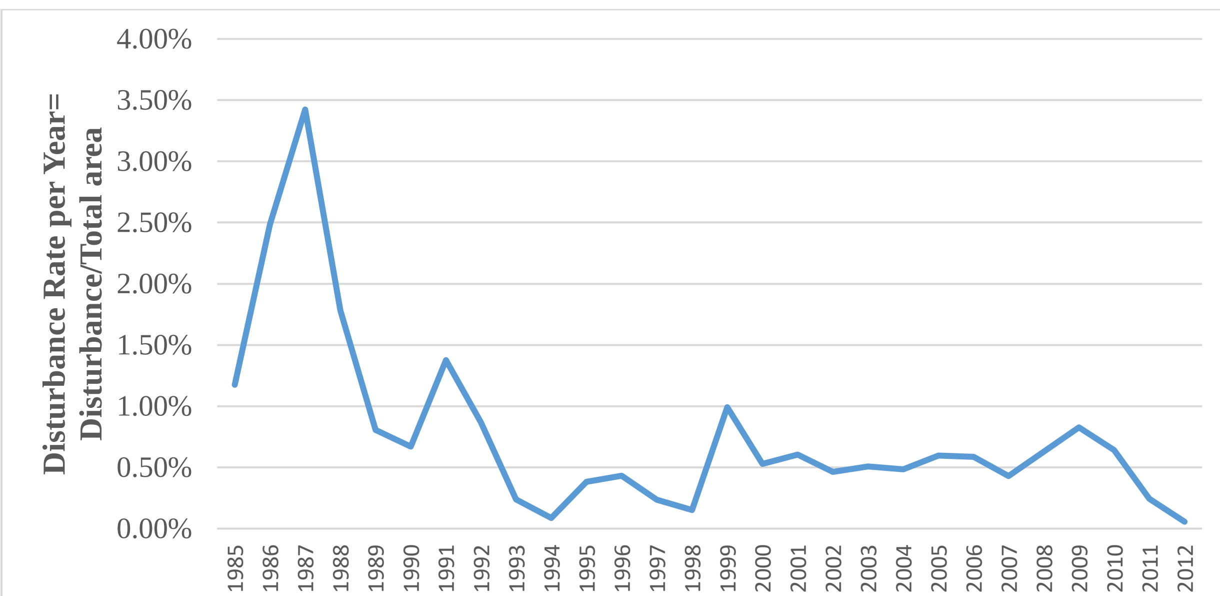

Figure B-2- DNR Annual Disturbance Rates in OESF

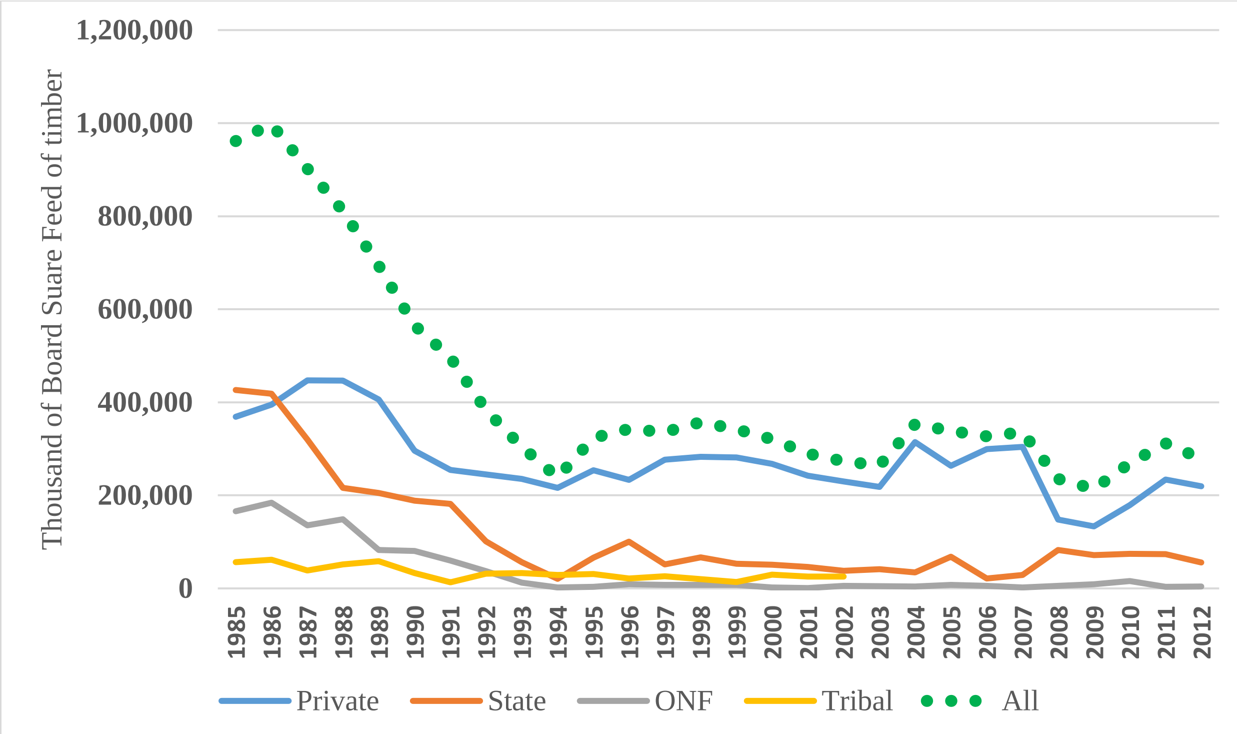

Figure B-3- Timber by Board Feet in Olympic Region by Landownership (Klallam County, Jefferson County, and Quinault Reservation, Washington) (Derived From WA DNR, 2018.)

*DNR stopped tracking data from Tribal lands in 2002

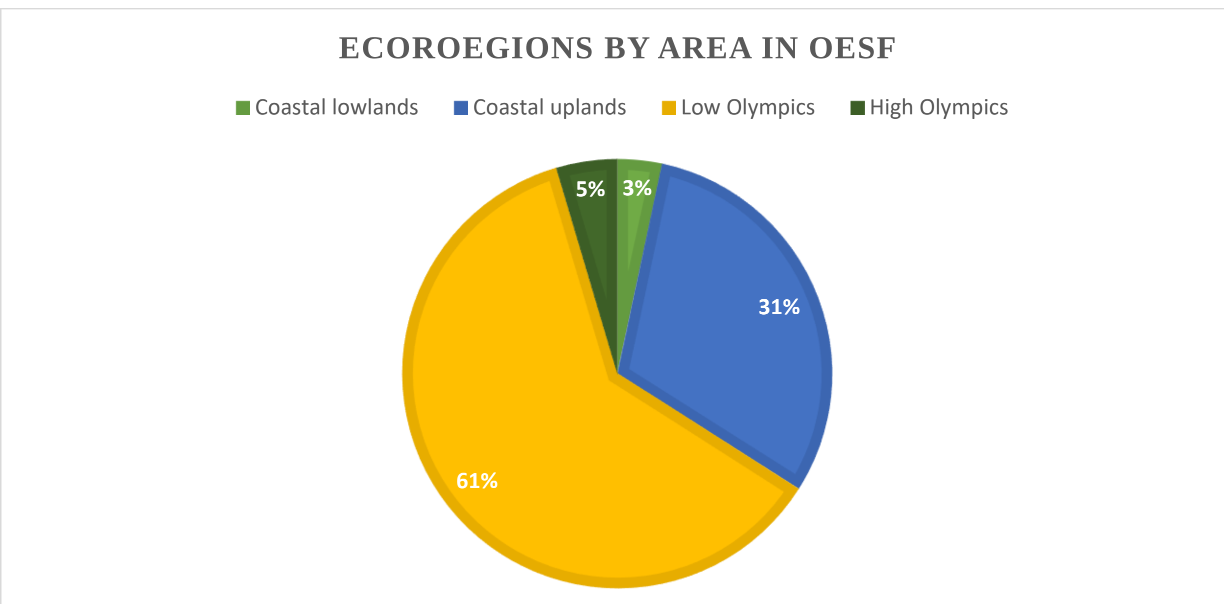

Figure B-4- Level IV Ecoregions in the OESF by Area

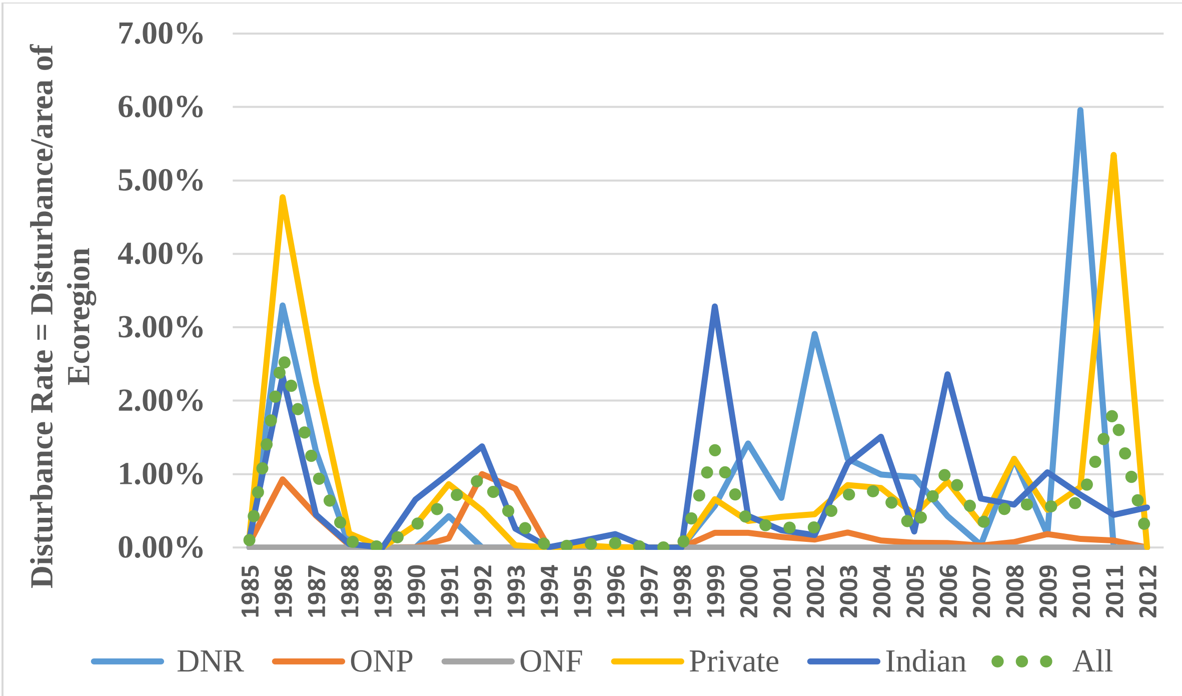

Figure B-5- Annual Disturbance Rate in Coastal Lowlands by Landownership

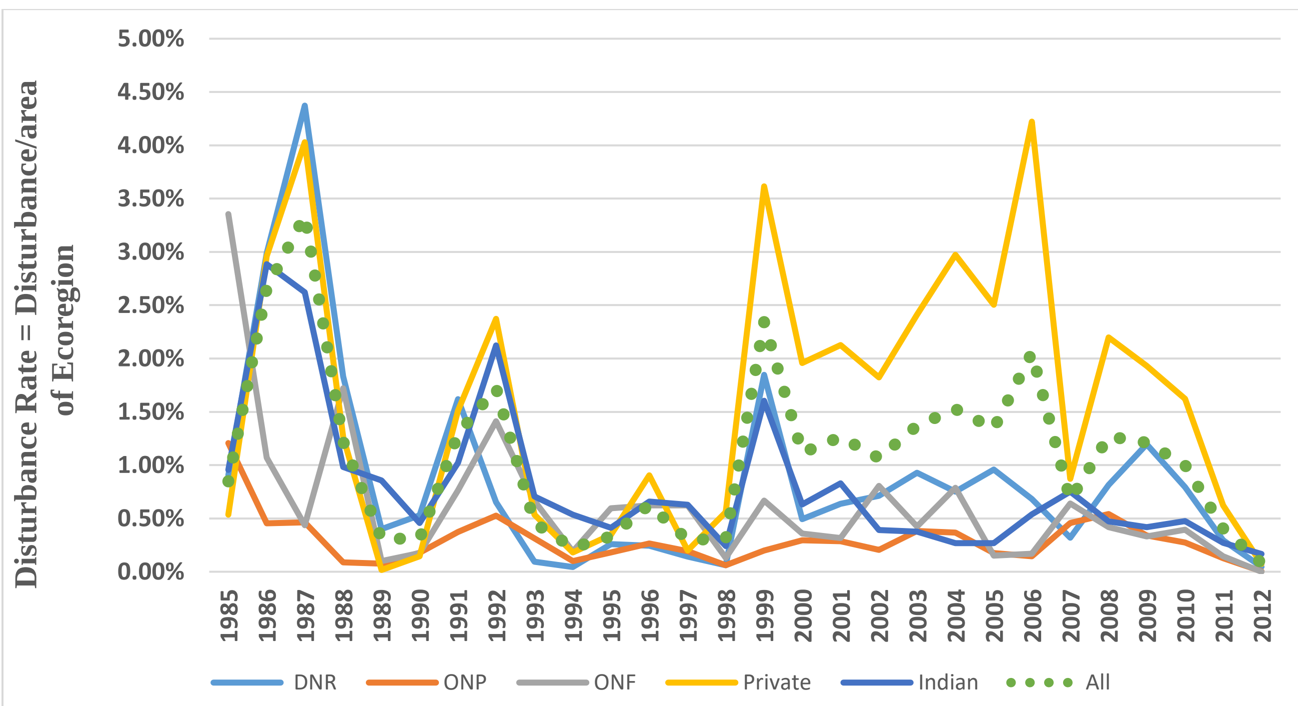

Figure B-6- Annual Disturbance Rate in Coastal Uplands Ecoregion by Landownership

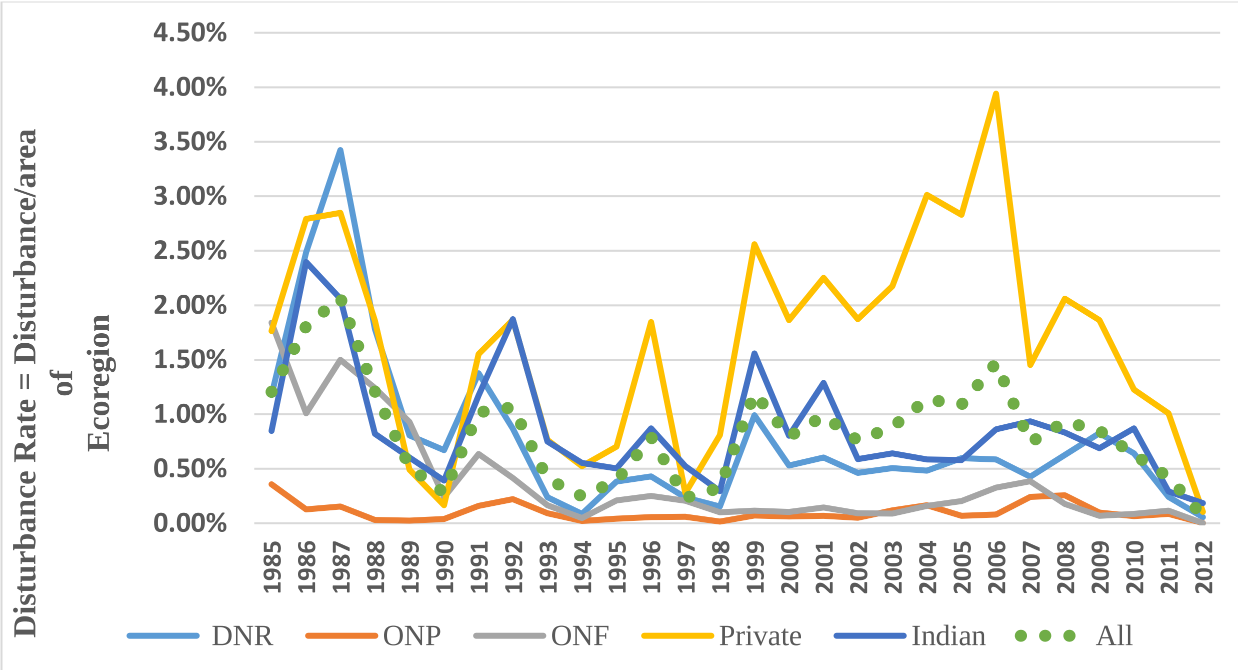

Figure B-7- Disturbance in Low Olympics Ecoregion by Landownership

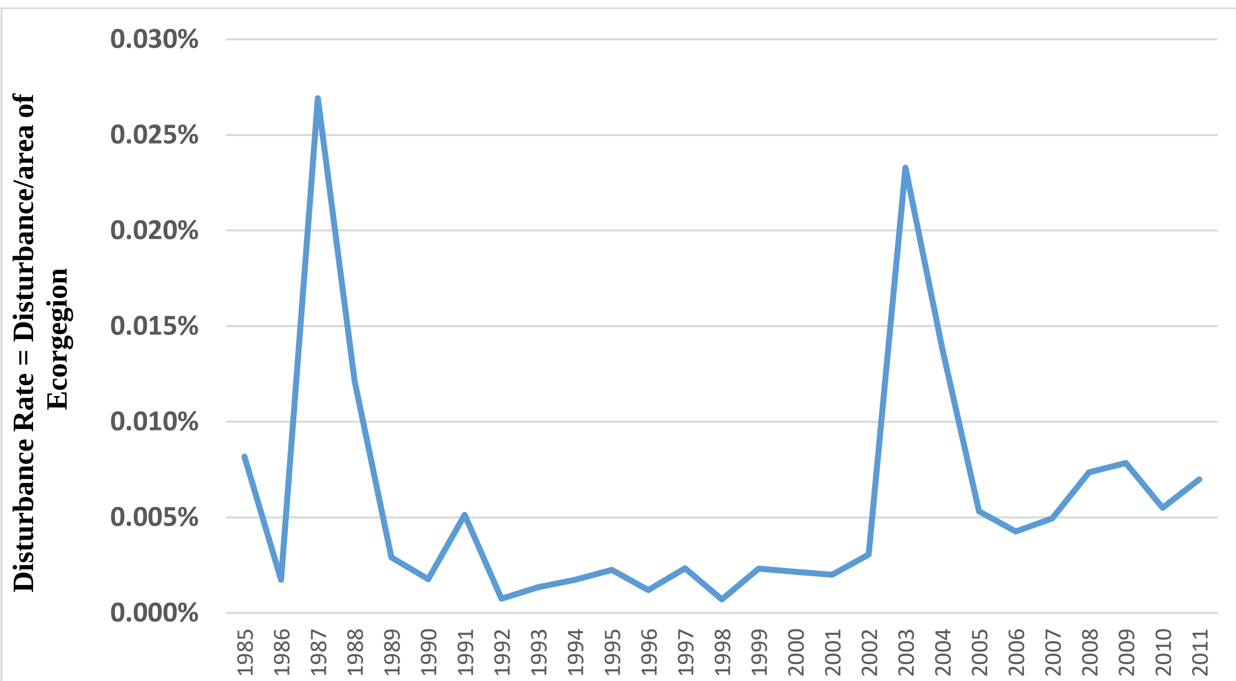

Figure B-8- Annual Disturbance Rate by High Olympic Ecoregion

(High Olympic Ecoregion only exists in the ONP).

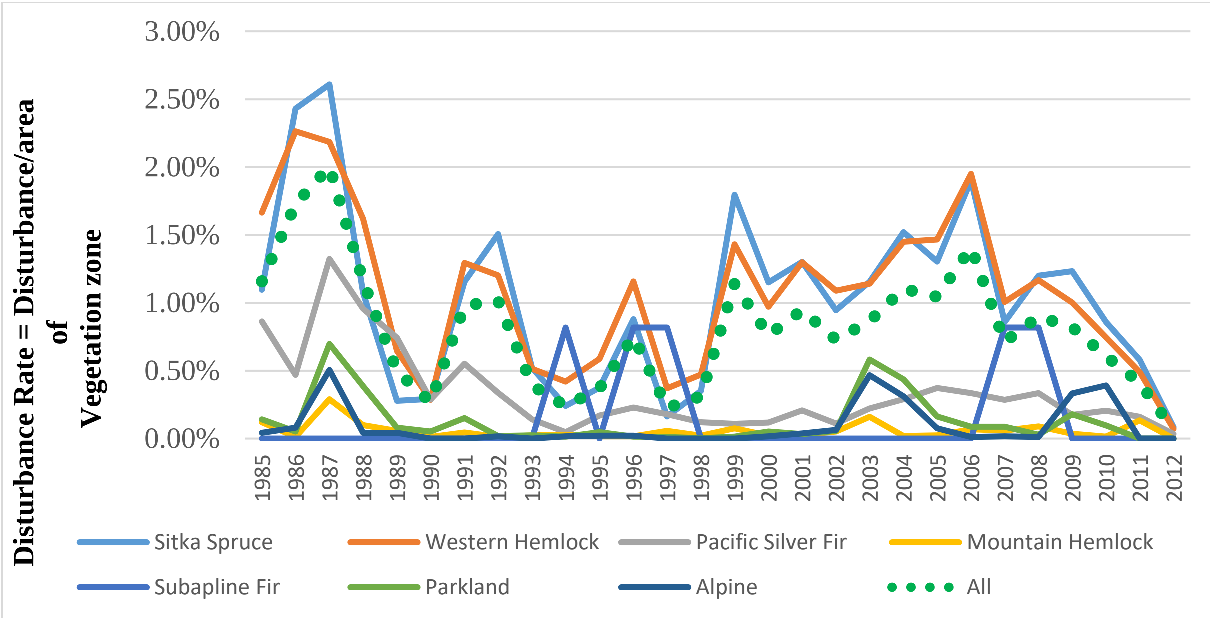

Figure B-9- Disturbance by Vegetation Zones in OESF

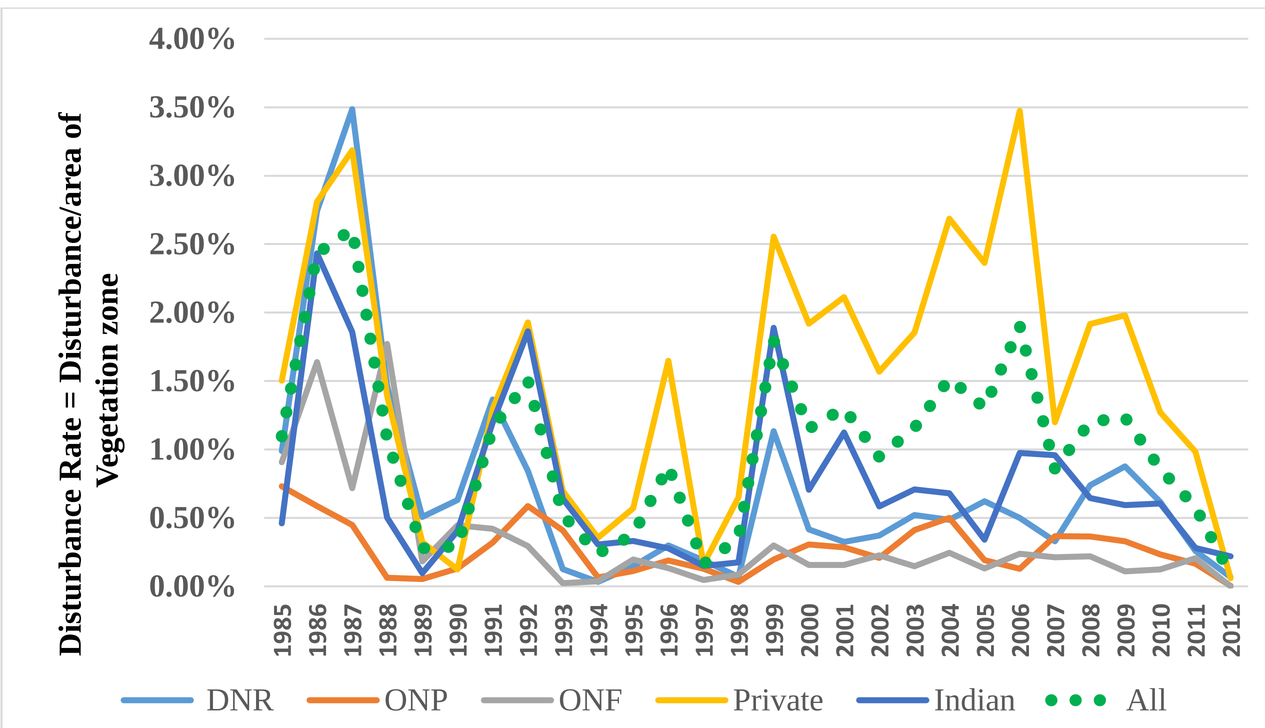

Figure B-10- Annual Disturbance Rate in Sitka Spruce Vegetation Zone by Landownership Type

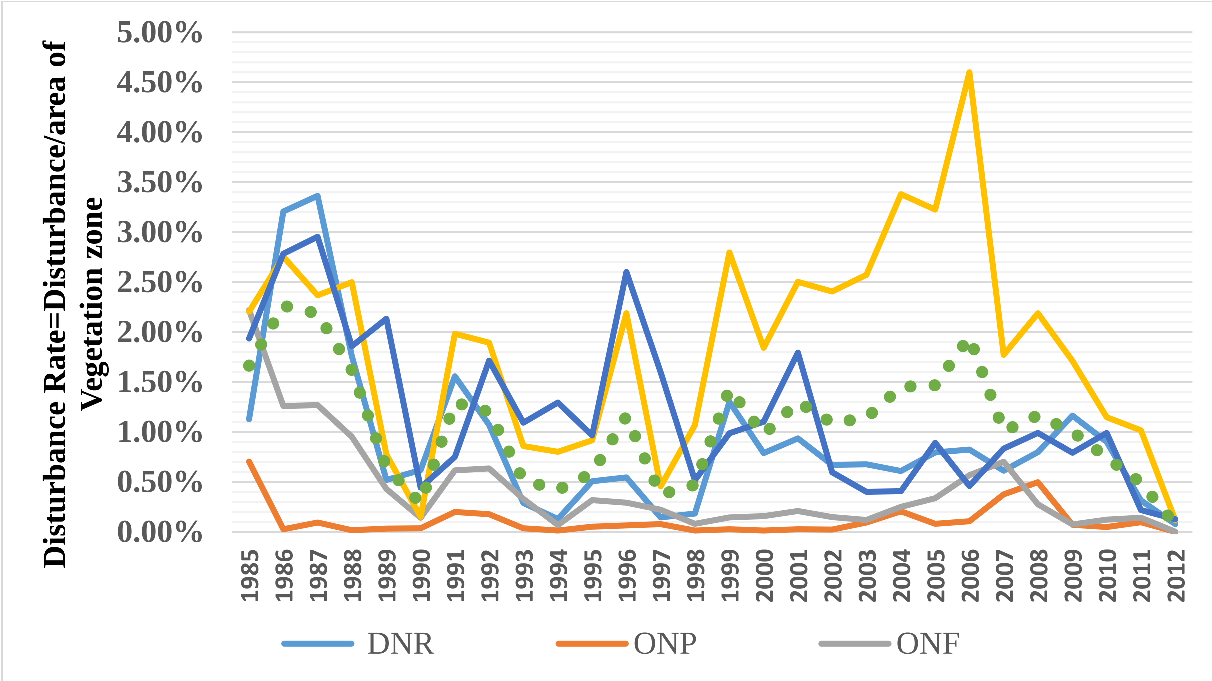

Figure B-11- Annual Disturbance in Western Hemlock Vegetation Zone by Landownership Type

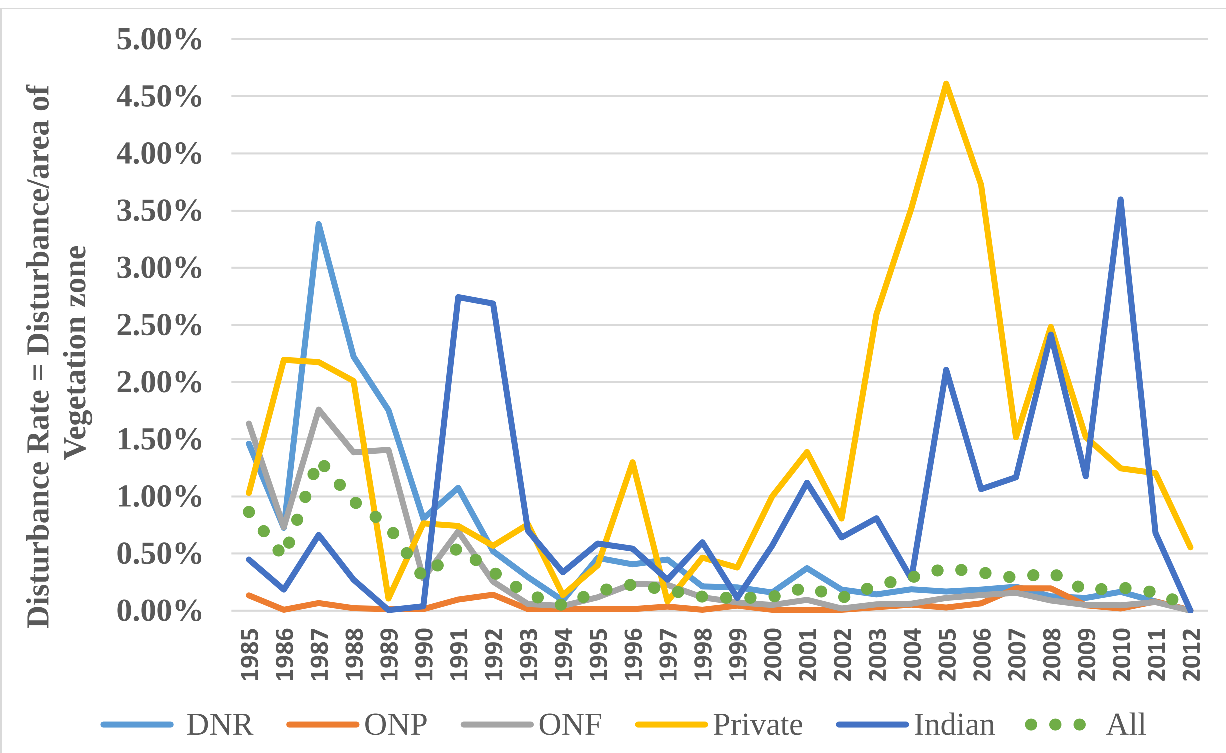

Figure B-12- Annual Disturbance in Silver Fir Vegetation Zone by Landownership Type

Appendix C- Disturbance Date with Predicted Piecewise Regresission Analysis Regression lines

Table C-1 Table Summary of Piecewise Regression Results for Each Landownership Type (Table 3-2 reproduced here as a reference for the Appendix C figures).

Model	Year[1] (SE)	Product[1] (SE)	Sum[2]	Adj. R^2	F-Ratio	P-Value
OESF (all ownership)	-1.08‡(.23)	0.74‡ (.17)	-0.34	.43	11.14	.0003
DNR	-1.62‡(.32)	0.91‡ (.24)	-1.05	.53	16.07	<.0001
ONP	-0.112*(.05)	0.08*(.03)	-0.03	.096	2.44	.1079
ONF	-1.04‡(.17)	0.52‡ (.13)	-0.52	.67	28.06	<.0001
Private	-1.52**(.53)	1.31**(.41)	-0.21	.24	5.27	.012
Tribal	-0.91**(.29)	0.51*(.22)	-0.40	.29	6.44	.0055

[1]coefficient values are shown x1000 for readability
[2]the sum of the 'year' and 'product' coefficients, which represents the slope of the linear function in the second time period (see Methods)
**p<0.05, ** P<0.01, ‡P<0.001*
This Table is in Chapter 3 and is placed here as a reference guide for the reader.

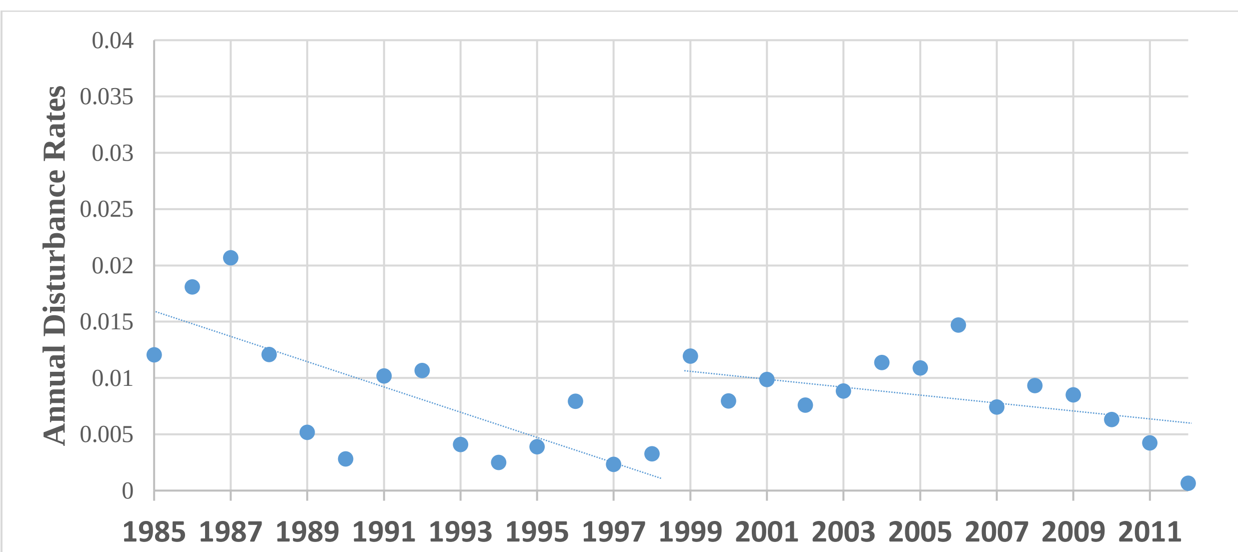

Figure C-2- Overall Annual Disturbance Rates in the OESF with Piecewise Regression Analysis Line

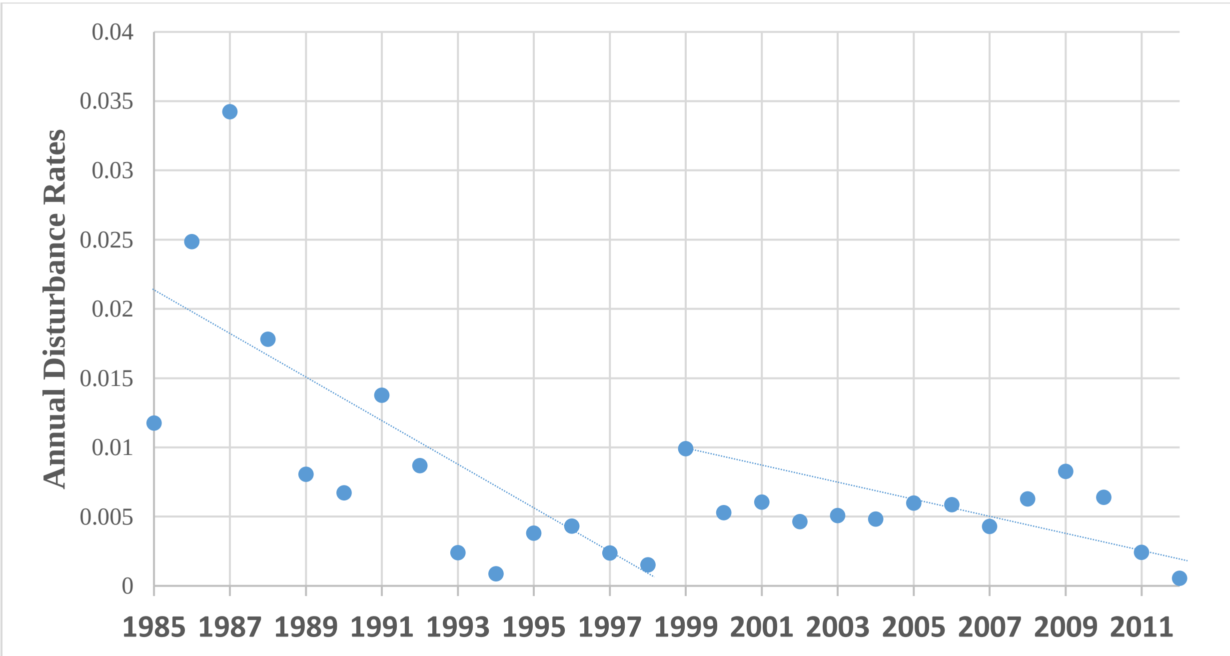

Figure C-3- DNR Annual Disturbance Rates in the OESF with Piecewise Regression Analysis Line

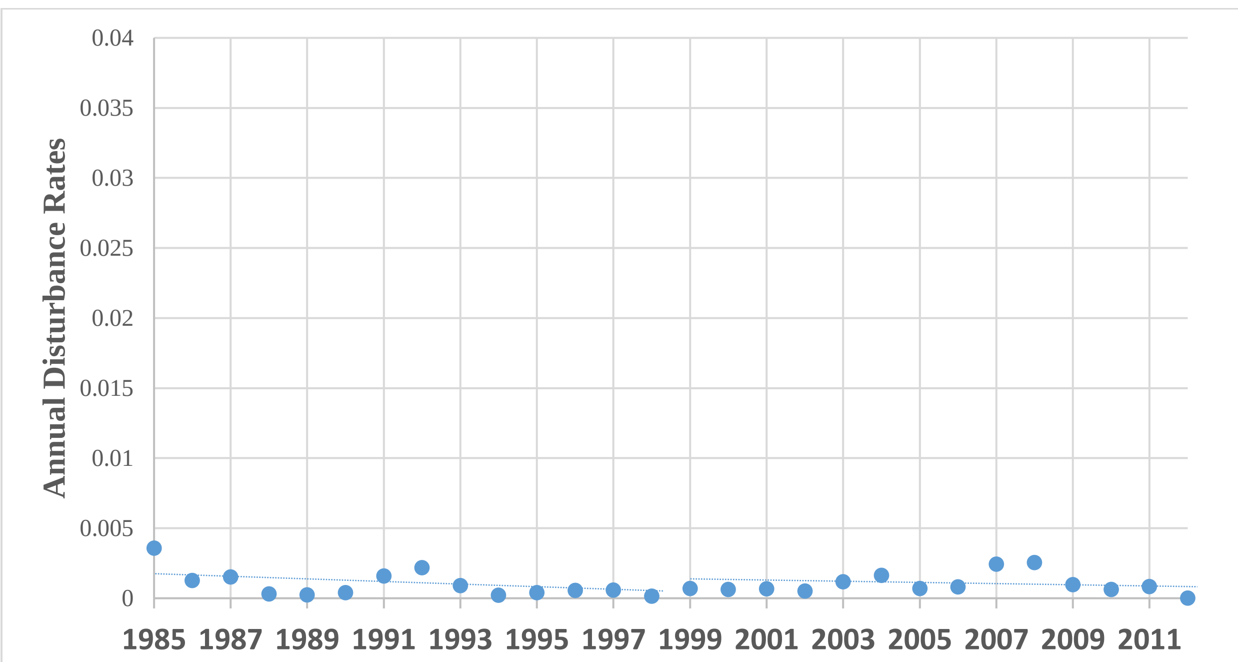

Figure C-4- ONP Annual Disturbances Rates in the OESF with Piecewise Regression Analysis Line

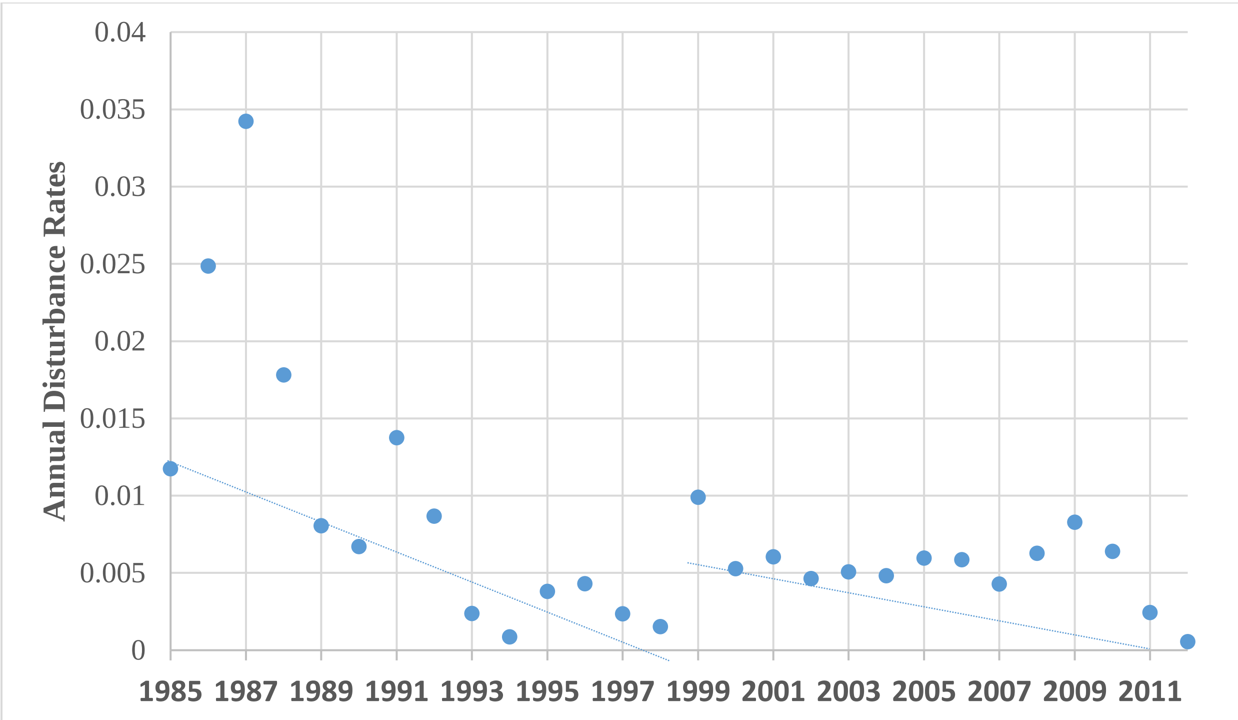

Figure C-5 ONF Annual Disturbance Rates in OESF with piecewise Regression Analysis Line

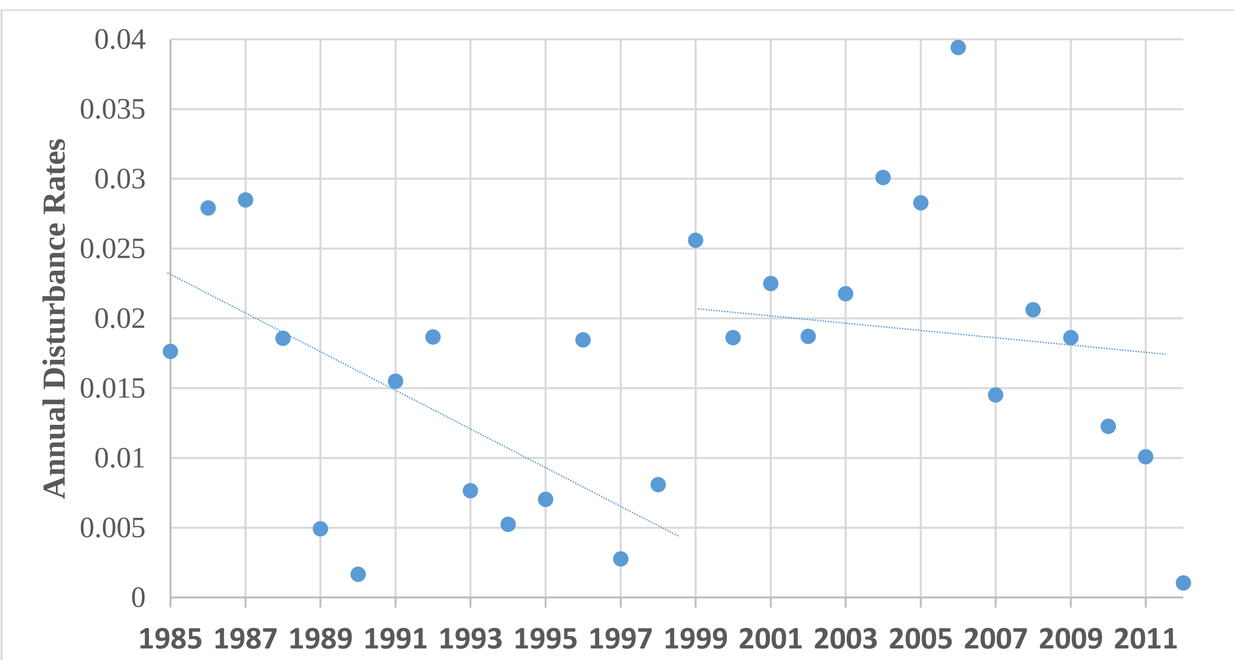

Figure C-6- Private Annual Disturbance Rates in the OESF with the Piecewise Regression Analysis Line

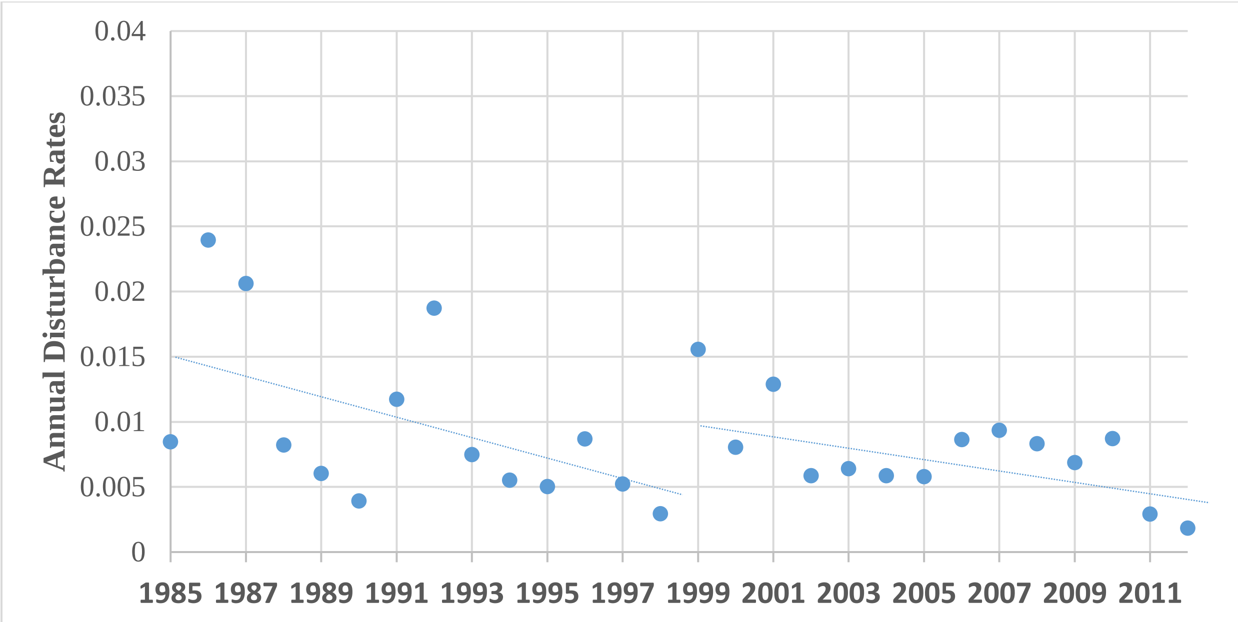

Figure C-7- Tribal Annual Disturbance Rates in the OESF with the Piecewise Regression Analysis Line

Appendix D- Tables

Table D-1- Yearly Disturbance Rate in Coastal Lowlands Ecoregion

	Disturbance Rate					
Year Group	**DNR**	**ONP**	**ONF**	**Private**	**Tribal**	**All**
85-98	0.36%	0.24%	0.00%	0.65%	0.47%	0.44%
99-12	1.18%	0.11%	0.00%	0.94%	0.95%	0.65%
Total	**0.77%**	**0.18%**	**0.00%**	**0.79%**	**0.71%**	**0.55%**

Table D-2- Yearly Disturbance Rate among Coastal Uplands

	Disturbance Rate					
Year Group	**DNR**	**ONP**	**ONF**	**Private**	**Tribal**	**All**
85-98	1.01%	0.32%	0.85%	1.11%	1.08%	1.00%
99-12	0.75%	0.27%	0.40%	2.07%	0.53%	1.19%
Total	**0.88%**	**0.30%**	**0.62%**	**1.59%**	**0.81%**	**1.10%**

Table D-3- Yearly Disturbance Rate among Low Olympic Ecoregion

	Disturbance Rate					
Year Group	**DNR**	**ONP**	**ONF**	**Private**	**Tribal**	**All**
85-98	1.01%	0.12%	0.61%	1.52%	0.88%	0.76%
99-12	0.44%	0.12%	0.13%	2.05%	1.51%	0.69%
Total	**0.72%**	**0.12%**	**0.37%**	**1.78%**	**1.19%**	**0.73%**

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