Forest Management and Washington State's Forested Wetlands: Assessing Forest Harvest Patterns across Ownership Types in the Hoh Watershed

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Abstract

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Washington State's forested wetlands are essential sources of environmental provisioning, providing habitat support, water purification, and carbon sequestration. These ecosystems are managed under a combination of federal, state and tribal regulatory frameworks. However, the interaction between these wetlands and forest management policies remains a complex concern, as wetlands continue to experience uneven protection and their delineations are sometimes disputed among agencies. Historically, limitations in wetland mapping accuracy have constrained investigations into this relationship. This research leverages recent methodological advancements,

including the Landsat-based detection of Trends in Disturbance and Recovery (LandTrendr) algorithm and the Wetland Intrinsic Potential (WIP) tool, to quantify temporal anthropogenic disturbance patterns within forested wetlands from 1974 to 2022 and to explore whether these patterns can be meaningfully aligned with regulatory change over time.

The primary contribution of this research lies in the development and application of a spatially explicit disturbance analysis framework capable of quantifying long-term trends in forested wetlands. By contrast, the policy component remains preliminary and exploratory, serving as an initial attempt to assess whether regulatory change can be systematically examined alongside landscape-level disturbance dynamics. While causal attribution cannot be established, the analysis identifies consistent variation in disturbance patterns across ownership types, suggesting that ownership context warrants further investigation as a potentially influential factor. Translating ecological data into policy-relevant insights is inherently complex, especially when scientific evidence must be aligned with legislative and administrative frameworks. Future research may build upon this disturbance analysis framework to more rigorously evaluate policy influences across different regions and governance contexts.

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Land Acknowledgment

I acknowledge that this research engages with lands and waters that are the ancestral and contemporary homelands of the Hoh Tribe and the Quileute Tribe, whose cultural, spiritual, and ecological relationships with the Hoh River and surrounding forests continue today. I also recognize that the University of Washington is located on the traditional lands of the Coast Salish peoples, including the Duwamish Tribe and the Muckleshoot Indian Tribe.

I honor these communities as the original stewards of the lands and waters discussed in this research and acknowledge the enduring impacts of colonization and resource governance on Indigenous territories. I offer this acknowledgment in recognition of Indigenous sovereignty and in respect for the knowledge systems and stewardship practices that have shaped these landscapes for millennia.

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1. Introduction

Forested wetlands in Washington (WA) State are critical components of the state's ecological landscape, facilitating diverse benefits such as habitat provision, water purification, and carbon sequestration (Mitsch et al. 2015; Hough-Snee 2020). The interaction between these wetlands and forest management policies has become a topic of growing concern as land-use decisions and management practices can significantly impact wetland and forested wetland ecosystems (Turner et al. 2000; Hough-Snee 2020; Northwest Indian Fisheries Commission [NWIFC] 2026). Despite the evident importance of understanding these interactions, the lack of precise mapping often precluded thorough investigations into the influences of forest policy on forested wetlands (Mahdavi et al.2018). However, recent advancements in geospatial technology–including the LandTrendr algorithm (Kennedy et al. 2018), WIP tool (Halabisky et al. 2023; Stewart et al. 2024), and high-resolution mapped wetland data (Halabisky et al. 2016)–offer an opportunity to delve into this complex relationship. These tools have made it feasible to study temporal patterns of forest harvest within forested wetlands, shedding light on the impacts of forest policy over time.

Millions of hectares of wetlands worldwide, including those in Washington, face a range of threats that undermine their ecological health and functionality. The degradation of these wetland ecosystems compromises their ability to provide critical services such as water filtration, flood control, and carbon sequestration (Salimi et al. 2021; Bertassello et al. 2025; NWIFC 2026; Fennessy et al. 2017). Human-induced disturbances such as harvesting contribute to the decline in ecosystem functions and exacerbate the effects of climate change (Were et al. 2019). As part of the continuum of wetland landscapes, freshwater wetlands are of particular significance due to their remarkable carbon storage capacity. The “teal carbon” as coined by Nahlik and Fennessy (2016), represents the substantial organic carbon stock stored in these wetlands, contributing to global carbon sequestration efforts. However, the spatial distribution of this carbon storage, and how forest policies interact with ecological conditions, ownership patterns, and economic drivers to influence it, remain understudied.

Management of forested wetlands in Washington is governed by an interconnected set of federal and state policies, alongside tribal governance frameworks.

Federal statutes, including the Clean Water Act (CWA) of 1972 and the Endangered Species Act (ESA) of 1973, establish baseline protections for water quality and listed species that constrain land use near wetlands (33 U.S.C. §1251; 16 U.S.C. §1531). At the state level, regulations such as the Washington Forest Practices Rules (FPR; WAC 222) and the Forest Practices Habitat Conservation Plan (FPHCP) further guide timber harvest practices, buffer requirements, and habitat protection (Washington Department of Natural Resources 1997; WAC 222). Tribal governments maintain treaty-reserved rights and engage in resource stewardship across Washington landscapes (NWIFC 2026); however, the specific influence of tribal governance on forested wetland harvest patterns was not evaluated in this study. Collectively, these overlapping governance structures shape land-use contexts in and around forested wetlands.

The path from ecological research to practical, effective forest policies is challenging. The inherent complexities of environmental systems, the divergent interests of stakeholders, and the slow pace of policy adaptation to new scientific insights are significant obstacles in this process (Connelly et al. 2021; Jacob et al. 2025). Researchers must thoroughly understand the interdependencies within forested wetland ecosystems and clearly communicate them to policymakers (NWIFC 2026). Policymakers must then balance ecological sustainability with socioeconomic demands (Adams et al. 2021; NWIFC 2026). This complex process underscores the need for ongoing dialogue between researchers and policymakers. A robust framework for policy development and adaptive management practices could ensure that the latest scientific discoveries provide for the resilience and preservation of forested wetlands.

Thus, the purpose of this study is to describe anthropogenic disturbance trends such as forest harvest in wetland environments and explore the feasibility of tracking policy impacts on those trends. I conducted a literature review to determine which policies may have had an impact on forested wetlands. To examine whether these policies could be associated with observed forest harvest patterns, I developed and tested a flexible model incorporating multiple predictor variables of disturbance trends. Rather than confirming causal impacts, this approach evaluates whether such a framework can be used to investigate policy–disturbance relationships. Finally, I discuss how this exploratory framework could be adapted and applied to other landscapes and policy contexts.

1.1 Overview of Regional Biogeography and Ecology

Washington State is home to a significant number of forested wetlands that perform numerous essential ecological functions. Forested wetlands are crucial habitats for a wide array of endemic and endangered species. These wetlands provide a unique environment that combines terrestrial and aquatic ecosystems, resulting in high biodiversity (Hough-Snee 2020). Additionally, they play a pivotal role in water purification, acting as natural filters that remove pollutants and maintain water quality (Washington Department of Ecology 2024). Another critical function of these wetlands is carbon sequestration. They capture and store large amounts of carbon, thus playing a significant role in mitigating the impacts of climate change (Fennessy et al. 2018). The forested wetlands of Washington vary significantly across the state, from coastal regions to inland areas.

The area of interest for this study is the Hoh watershed, located in western Washington's Olympic Peninsula. This area is known for its dense, temperate rainforests, significant precipitation levels, and intricate hydrology. A hallmark of the Hoh watershed is its predominance of ecosystems fueled by the ample rainfall and snowmelt originating in the Olympic Mountains (NWIFC 2026). The region’s hydrology is primarily shaped by high annual precipitation, which can exceed 140 inches in some areas (National Park Service 2020). This substantial moisture input creates a variety of wetland types, crucial for supporting the area's rich biodiversity. These wetlands are perennial, maintained throughout the year by the steady rainfall and moderated evapotranspiration rates. Historical glacial activity significantly shaped the landscape and hydrological features of the Hoh watershed (NWIFC 2026). A significant portion of the watershed, including the Hoh Rain Forest, falls within the Olympic National Park, offering a layer of protection to its complex hydrological processes and the diverse ecosystems it supports.

1.2 Land-use history

The Washington State landscape has changed over time due to both natural processes and anthropogenic activity. Before European colonization, Indigenous communities actively managed forests and wetlands using practices such as controlled burning and selective harvesting to maintain ecological balance. Cultural burning was used to enhance food production, promote the growth of edible plants, and maintain open habitat mosaics that supported hunting and wildlife (Long et al. 2021). In addition to fire stewardship, Indigenous resource management emphasized careful, selective harvesting practices designed to sustain plant populations and ensure long-term regeneration (Turner 2020). These approaches reflect intentional landscape stewardship rather than passive resource use. Recent research indicates that Indigenous fire stewardship influenced forest structure in parts of the Pacific Northwest (Coughlan et al. 2024). However, this work does not document large-scale transformation of wetter forested systems, suggesting that any impacts on forested wetlands were likely localized, low in severity, or difficult to detect at broader spatial scales.

In contrast to the localized and adaptive stewardship practices that characterized pre-colonial land management, more intensive landscape transformation began in the early nineteenth century with Euro-American settlement and the expansion of commercial timber harvest (U.S. Forest Service 2014). Early logging activities primarily targeted upland forests before expanding more broadly across the regional landscape. Industrial timber harvest during the twentieth century substantially reduced late-successional and old-growth forest cover across the Pacific Northwest, particularly prior to the implementation of the Northwest Forest Plan in 1994 (Cooke Scientific Services 2005; Spies et al. 2018). Although federal lands subsequently experienced reduced harvest levels under ecosystem-based management frameworks, historical logging legacies continue to shape forest structure and landscape composition. Forested wetlands, embedded within this broader forest matrix, were likely affected by these regional harvest dynamics, although their extent and condition remain less well documented due to mapping limitations (Goldberg and Reiss 2016). Consequently, despite two centuries of timber harvest, it remains unclear how much forested wetland acreage has been lost, fragmented, or functionally altered in Washington State (Cooke Scientific Services 2005).

This uncertainty reflects broader limitations in documenting long-term wetland dynamics. While numerous studies have applied remote sensing and Geographic Information Systems (GIS) approaches to assess wetland extent and change at regional to global scales (Amani et al. 2025; Zhang et al. 2025), these analyses typically treat wetlands as a generalized freshwater class or prioritize classification accuracy over disturbance dynamics. Recent reviews emphasize rapid methodological advances in wetland mapping and multi-sensor integration (Yuan et al. 2025; Salas et al. 2024), yet they also identify persistent challenges, including uneven geographic coverage, spectral similarity among wetland classes, and limited standardization in data integration protocols. Consequently, forested wetlands remain underrepresented in landscape-scale assessments. Moreover, few studies integrate remote sensing-based forest harvest detection with land ownership patterns and regulatory or policy context, limiting the ability to evaluate how management practices and governance structures influence forested wetland outcomes across working forest landscapes.

1.3 Development of Forest Policies

Policymakers first introduced federal forest management legislation in the late nineteenth century, marking the beginning of formal conservation governance in the United States. The Forest Reserve Act of 1891 authorized the designation of federal forest reserves, and the Organic Administration Act of 1897 established their management purposes, including watershed protection and sustained timber supply (26 Stat. 1095; 30 Stat. 34). These early statutes reflected a conservation-oriented approach focused primarily on resource control and sustained yield. By the mid-twentieth century, however, the cumulative ecological impacts of widespread logging and land-use change had become increasingly visible across the Pacific Northwest. In response, forest governance began to expand beyond timber production to incorporate broader environmental protections. Federal legislation such as the Multiple-Use Sustained-Yield Act of 1960 (74 Stat. 215), the Wilderness Act of 1964 (78 Stat. 890), and the National Environmental Policy Act of 1969 (83 Stat. 852) formally integrated ecological considerations, public participation, and environmental review into forest policy (74 Stat. 215; 78 Stat. 890; 83 Stat. 852; Schultz et al. 2021).

Some federal laws, including the CWA and the ESA, have shaped forestry standards related to water quality and habitat protection (33 U.S.C. §1251; 16 U.S.C. §1531). The CWA establishes a federal regulatory framework for protecting water quality, including certain wetlands, by regulating discharges into waters defined as

“Waters of the United States” (WOTUS). However, the legal definition of WOTUS has evolved over time through rulemaking and judicial decisions, influencing the extent to which wetlands fall under federal jurisdiction (U.S. Environmental Protection Agency [U.S. EPA] 2023).

Under Section 401 of the CWA, states are authorized to review and certify that federally permitted activities comply with state water quality standards (33 U.S.C. §1341). In Washington, this authority is implemented through the Department of Ecology, which establishes water quality standards that include numeric criteria—measurable thresholds tied to designated uses such as aquatic habitat and recreation (Washington Administrative Code [WAC] 173-201A). Although point-source discharges may be limited in remote landscapes such as the Hoh watershed, state water quality standards still apply. For example, Washington has adopted numeric turbidity thresholds that help evaluate the impacts of activities such as road construction and timber harvest near wetlands (WAC 173-201A). The CWA has been instrumental in preserving wetland habitats from pollution and degradation by requiring states to set water quality standards and regulating discharges of pollutants into water bodies based on federal recommendations. It is critical to maintain the health and ecological functions of wetlands.

Federal agencies and states developed Habitat Conservation Plans (HCPs) under Section 10 of the ESA to balance development and land use with the protection of listed species and their habitats (16 U.S.C. §1539). HCPs provide a framework for mitigating the impacts of otherwise lawful activities on sensitive habitats, including wetlands.

At the state level, Washington adopted policies that further shaped environmental protections in forestry. The Washington Forest Practices Act (1974) and the associated FRP (WAC 222) were among the earliest state-level regulatory frameworks to incorporate environmental safeguards into logging practices, including requirements for riparian buffers and protections for aquatic resources (Revised Code of Washington 76.09; WAC 222). However, the ecological effectiveness of buffer widths and riparian prescriptions in conserving wetland and stream-adjacent habitats remains an area of ongoing scientific discussion (Washington Department of Natural Resources 1997). The Growth Management Act (GMA) of 1990 further expanded state oversight of land use by requiring counties and municipalities to designate and protect critical areas, including wetlands (Revised Code of Washington [RCW] 36.70A). By guiding zoning decisions and urban development patterns, the GMA sought to balance population growth with environmental protection. Nevertheless, development pressures and land-use decisions continue to pose challenges for wetland conservation, underscoring the importance of integrating wetland protections more effectively into planning frameworks.

Additional collaborative initiatives, such as Washington's Wetland Protection Program (WPP) (Washington Department of Ecology 2024) and the Salmon Recovery Act (1999) (RCW 77.85), aimed to strengthen habitat protection and watershed-scale management. While these policies and programs are designed to influence forestry and land-use practices that affect wetland health, their direct ecological impacts on forested wetlands require further evaluation.

Despite the extensive evolution of forest, water quality, and land-use policies at both the federal and state levels, substantial uncertainty remains regarding how these regulatory frameworks have translated into on-the-ground outcomes for forested wetlands (Washington Department of Natural Resources [DNR] 2025; Hough-Snee 2020). Federal monitoring programs developed under the Northwest Forest Plan (United States Department of Agriculture [USDA] and United States Department of the Interior [USDI] 1994) provide one of the most comprehensive long-term assessments of watershed condition in the region. Miller et al. (2017) evaluated 20 years of watershed monitoring data across federally managed lands and concluded that ecological condition trends reflect gradual and spatially variable responses to forest management. However, such assessments are typically conducted at broad watershed scales and do not explicitly isolate forested wetland disturbance dynamics or evaluate outcomes across mixed ownership contexts. This gap underscores the need for spatially explicit, ownership-sensitive analyses such as the one developed in this study. In particular, few studies have quantitatively evaluated whether policy implementation has altered forest harvest patterns, wetland extent, or condition within forested wetland systems over time. While recent remote-sensing studies have demonstrated the ability to detect wetland change, inundation dynamics, and habitat condition using time-series satellite data (Demarquet et al. 2023; Tough et al. 2025), these approaches are rarely applied in conjunction with land ownership patterns or regulatory and policy context. This gap is especially pronounced in landscapes dominated by working forests, where overlapping jurisdictions, mixed land ownership, and policy exemptions complicate assessments of regulatory effectiveness (Washington State Department of Ecology 2015).

1.4 Current State of Forested Wetlands: Conditions and Threats

The current condition of Washington's forested wetlands is a reflection of both historical land-use practices and the effectiveness of existing policies aimed at their conservation. Despite efforts to protect and manage these ecosystems, forested wetlands in Washington continue to face multiple challenges such as habitat degradation, pollution, agricultural runoff, invasive species, and climate change (Hough-Snee 2020). These pressures are consistent with global trends; a recent systematic review found that freshwater forested wetlands worldwide face compounding threats from land-use change, hydrological alteration, pollution, and climate variability (Yoezer et al. 2026).

Fragmentation and degradation are becoming defining features of the forested wetlands due to ongoing development and land-use changes. (Were et al. 2019). Landscape fragmentation has significant impacts on biodiversity and ecological function. Habitat loss and fragmentation reduce both wetland extent and the spatial connectivity required to sustain biodiversity (Keith et al. 2025; Davidson et al. 2019). Wetland-dependent fauna often decline in response to both habitat loss and the landscape context surrounding remaining wetlands. Across dozens of landscapes, Quesnelle et al. (2013) found that wetland bird occurrence was most strongly explained by the amount of wetland in the landscape. Freshwater turtles were strongly associated with the composition of the surrounding matrix, including forest cover as well as anthropogenic features such as cropland and roads. More recent work reinforces that intensive land uses around wetlands can amplify impacts on wildlife. In an urbanized region, Rahlin et al. (2022) showed that wetland bird occupancy varies with landscape conditions in the surrounding urban matrix, consistent with the idea that development and infrastructure influence wetlands beyond their boundaries. Roberts et al. (2023) found that wetland configuration can modulate relationships between land use and turtle relative abundance, indicating that patch arrangement and connectivity interact with surrounding land uses such as roads and agricultural cover. Further elucidating the importance of landscape structure, Dertien et al. (2020) found that mammal species richness across forested wetland landscapes was not only positively correlated with the total amount of wetland cover but also with the connectivity of those wetland patches. Landscapes with more extensive and connected wetland networks supported greater numbers of mammal species than landscapes with equivalent wetland area but greater fragmentation. These studies suggest that the fragmentation and reduction of wetland habitats can lead to a further decline in vertebrate biodiversity.

Besides biodiversity loss, fragmentation disrupts other essential ecological services of wetlands. Those include carbon sequestration, water filtration, nutrient retention, and flood mitigation (Dertien et al. 2020). Fragmentation significantly impairs carbon storage by reducing the total vegetation and soil area available for long-term carbon accumulation. Permanently flooded wetlands can sequester substantial quantities of carbon due to persistent anaerobic soil conditions that inhibit decomposition, often at rates that exceed those observed in many upland forest systems (Mitsch et al. 2015).

Landscape-scale fragmentation decreases wetlands' function as natural water filters. Fragmented wetland patches, especially those surrounded by agricultural or urban land, have diminished effectiveness in trapping sediments, intercepting nutrients, and breaking down pollutants. In the Lower Amazon floodplain forests, researchers found that fragmentation led to soil degradation, diminished pollination, and reduced water quality services (Renó et al. 2016). Moreover, nutrient retention suffers when wetland connectivity is lost. Bai et al. (2024) examined decadal trends in nutrient retention across forested landscapes in Kentucky, with particular attention to areas dominated by non-forest landowners. Their analysis found that increased forest fragmentation was associated with significant declines in water- and soil-related ecosystem service values. The authors further demonstrated that fragmentation disproportionately reduced nutrient cycling and purification functions, particularly within watershed contexts.

Fragmentation further weakens wetlands' capacity to buffer floods by disrupting hydrological connectivity and reducing landscape-scale water storage. Wetlands regulate flooding by temporarily storing surface water, slowing overland flow, and releasing water gradually back into connected streams and groundwater systems (Mitsch et al. 2015). When wetlands remain hydrologically connected, they function as integrated networks that dissipate flood energy and reduce peak discharge downstream. However, fragmentation isolates wetland patches, constrains lateral water movement, and limits their collective storage capacity. As Mitsch et al. (2015) note, drainage, channelization, and landscape alteration reduce the ability of wetlands to attenuate floodwaters, thereby increasing the magnitude and velocity of downstream flows. This hydrological disruption is closely linked to the broader ecosystem service declines associated with fragmentation. Just as disconnected wetlands exhibit reduced nutrient retention and purification functions (Bai et al. 2024), their diminished connectivity also compromises flood mitigation capacity. Dertien et al. (2020) emphasize that many wetland ecosystem services depend not only on local habitat conditions but also on spatial configuration and watershed context. Consequently, fragmentation affects wetlands not merely as isolated habitat patches but as components of larger hydrological systems.

Runoff from agricultural, industrial, and urban sources contributes to water quality degradation in forested wetland ecosystems. Wetlands, including forested systems, function as natural filters that remove sediments, nutrients, and contaminants from surface runoff through sedimentation, plant uptake, and microbial processes (Mitsch et al. 2015). However, when pollutant loads exceed ecological processing capacity, their ability to maintain water quality and ecosystem function declines. Runoff from agricultural fields and managed landscapes transports soluble nitrogen compounds into adjacent water bodies, fueling algal blooms that reduce dissolved oxygen and stress aquatic communities (Jani et al. 2020). Fertilizer applications also introduce phosphorus, potassium, and trace metals that increase nutrient loading when mobilized by stormwater, placing additional pressure on wetland nutrient cycling processes (Bai et al. 2024). Similarly, sediment runoff from roads represents a significant pollutant source. Road surface runoff carries heavy metals such as zinc, copper, lead, nickel, and cadmium, along with hydrocarbons and de-icing salts (Mahdavi et al. 2018). These contaminants often bind to fine sediments that accumulate in wetland soils, increasing turbidity and reducing light penetration, thereby impairing biological communities. As sediment and nutrient inputs intensify, wetlands can become overwhelmed, diminishing their capacity to filter pollutants and regulate water quality (Mitsch et al. 2015). In addition to chemical stressors, the introduction and spread of invasive plant and animal species disrupt ecological balance, frequently outcompeting native species and altering ecosystem processes (Mazurczyk & Brooks 2018). Collectively, nutrient loading, sediment deposition, contaminant accumulation, and biological invasion compromise the functional integrity of forested wetlands.

The ability of forested wetlands to capture and store atmospheric carbon is substantial but can be compromised by deforestation, land conversion, and urban development (Were et al. 2019). In addition to direct land-use change, Were et al. (2019) note that rising global temperatures intensify hydrological variability, increase evapotranspiration rates, and alter vegetation dynamics, thereby compounding stress on wetland carbon storage capacity. Non-anthropogenic climatic drivers further influence wetland structure and function. Changes in precipitation patterns, increased storm intensity, and rising temperatures are reshaping hydrological regimes and ecological processes within wetland systems (Salimi et al. 2021). Together, land-use change and climate variability act as interacting stressors that may reduce the resilience and long-term carbon sequestration potential of forested wetlands (Yoezer et al. 2026).

It would be an omission to consider wetland impacts solely through ecological or policy lenses without acknowledging the cultural dimensions of these landscapes. Local tribes continue to rely on wetlands for their provisioning or cultural services, but this has only had a minimal effect on wetland functionality. Historically, wetlands provided local tribes with materials for making tools, cultural artefacts, and served as food sources (Long et al. 2021). These practices highlight the strong cultural bonds between Indigenous people and the wetland ecosystems.

Landscape fragmentation and degradation reduce the delivery of key ecosystem services, including flood mitigation, sediment retention, and carbon sequestration (Mitsch et al. 2015; Were et al. 2019). Thus, the collective research on fragmentation and degradation of forested wetlands shows that these processes weaken hydrological connectivity, reduce vegetative cover, and wetland functionality in general. Understanding and preserving the carbon storage capability of these ecosystems, as well as their overall ecological functions, is vital in the broader context of global climate change strategies. To support the preservation of these ecosystems, a systematic framework is needed to evaluate the effects of policy interventions on forested wetland harvest, carbon storage, and overall ecological function.

Despite extensive documentation of the ecological consequences of fragmentation, pollution, and climate-driven stressors on forested wetlands, uncertainty remains regarding how forest, water quality, and land-use policies are reflected in spatial and temporal disturbance patterns within these systems (Goldberg and Reiss 2016). Although previous studies have established strong links between habitat fragmentation and declines in biodiversity and ecosystem services (Quesnelle et al. 2013; Roberts et al. 2023; Davidson et al. 2019; Kieth et al. 2025), relatively few assessments have examined forested wetland harvest dynamics over time while explicitly accounting for land ownership patterns and management context (Hough-Snee 2020; Zou et al. 2024). This limitation is particularly evident in working forest landscapes, where mixed ownership and overlapping governance structures complicate interpretation of cumulative impacts. Because policy effects ultimately manifest through changes in landscape forest harvest, understanding those patterns becomes central to evaluating policy effectiveness. Remote sensing provides a consistent, landscape-scale framework to detect and analyze these anthropogenic disturbances across heterogeneous and mixed-ownership landscapes, where direct attribution through field-based methods remains impractical.

Recent advances in remote sensing have significantly improved the ability to distinguish between different types of forest harvest using dense satellite time series and machine learning approaches. Contemporary studies show that Landsat-based frameworks can now detect disturbance occurrence, severity, and in some cases attribute causal agents such as harvest, fire, and flooding using spectral-temporal signatures combined with classification models. For example, recent work in the Great Lakes region demonstrated that Landsat time series can differentiate multiple disturbance classes—including harvest, fire, and land conversion—through trajectory-based modeling approaches (Fekety et al. 2025). Similarly, large-scale monitoring efforts such as the European Forest Disturbance Atlas provide annual, spatially explicit records of disturbance occurrence and severity across entire continents, highlighting the growing capability of remote sensing to capture disturbance dynamics consistently over time (Viana-Soto and Senf 2025).

At the same time, methodological comparisons emphasize that different disturbance detection algorithms vary in their sensitivity to disturbance type, intensity, and landscape context. A recent multi-algorithm evaluation using Landsat time series data showed that while disturbance detection is generally robust, classification accuracy differs across disturbance regimes and environmental conditions, particularly when separating subtle or low-severity disturbances (Liang et al. 2025). Emerging approaches that integrate machine learning and deep learning further improve attribution accuracy, but still face challenges due to overlapping spectral signals and mixed disturbance processes (Cué La Rosa et al. 2025).

Synthesis studies reinforce that, despite rapid methodological progress, reliably attributing disturbance agents at large spatial scales remains uncertain. Automated attribution frameworks can identify a range of disturbance types, yet accuracy declines when disturbances are temporally overlapping, spatially heterogeneous, or of low intensity (Stahl et al. 2023). Consequently, many contemporary landscape-scale analyses prioritize consistent detection of disturbance magnitude and timing rather than precise attribution, particularly when evaluating cumulative ecological impacts.

This study applies a landscape-scale, time-series remote sensing approach to quantify forest harvest dynamics in forested wetlands within the Hoh River watershed. Using Landsat-based disturbance detection, the analysis captures the timing, magnitude, and spatial distribution of disturbance across multiple decades, providing a consistent basis for comparison across ownership and management contexts. While remote sensing enables robust detection of disturbance events, limitations in spectral attribution make it difficult to distinguish all disturbance agents with high confidence, particularly for low-severity or overlapping disturbances. In addition, within the Hoh watershed, disturbance regimes are dominated by forest management activities, with relatively limited urban development, land conversion, or large-scale insect-driven mortality detectable at Landsat resolution. As a result, the disturbance signal identified by LandTrendr primarily reflects forest canopy removal associated with timber harvest and related management practices. Accordingly, this study interprets detected disturbance as a proxy for forest harvest intensity and extent, rather than attempting to attribute each event to a specific causal agent.

1.5 Forested Wetlands Recovery Trends

Forested wetlands provide invaluable services like carbon sequestration, water filtration, nutrient retention, habitat support, and flood control. Despite their importance, these ecosystems often go unrecognized in regulatory frameworks because they are not clearly mapped or connected to open surface waters (Demarquet et al. 2023). They are “cryptic” (i.e., buried beneath dense canopy) but can represent up to 86 % of all wetland carbon in areas like the Hoh River watershed. As a result, they serve as critical carbon hotspots yet current regulations routinely overlook (Stewart et al. 2024).

Unlike emergent wetlands, forested wetlands are often assumed to recover their structure and function relatively quickly after disturbance. However, empirical evidence and meta-analyses challenge this assumption. Global syntheses of wetland restoration outcomes show that even decades after restoration, many restored wetlands remain functionally distinct from reference conditions; structural attributes may recover faster while biogeochemical functions lag significantly, often remaining substantially below natural wetland levels more than 30 years post-restoration (Moreno-Mateos et al. 2012). A recent global meta-analysis by Schuster et al. (2024) further demonstrates that the timeframe required for restored freshwater wetlands to provide net climate benefits can exceed a century or more, with non-peat wetlands requiring approximately 141 years on average to transition from a net greenhouse gas source to a net sink and peatlands taking even longer (Schuster et al. 2024). These long recovery trajectories indicate that there is no predictable or linear timeframe for wetland recovery and that restoration outcomes are highly contingent on environmental setting, hydrology, and landscape context.

Moreover, restoration performance is highly variable across functions and settings, and many restoration projects do not fully replace the aggregate functions provided by undisturbed wetlands (Moreno-Mateos et al. 2012; Schuster et al. 2024). For example, structural ecosystem attributes such as vegetation composition may approach reference levels relatively quickly under favorable conditions, while biogeochemical processes like carbon and nutrient cycling lag far behind. This persistent functional lag highlights the importance of extended monitoring and adaptive management rather than assuming that a fixed permit timeframe (e.g., a decade) is sufficient to assess ecological success. Mitigation projects seldom fully replace the functions of the wetlands that planners or developers aim to offset (Morgan and Hough

2015; Cao et al. 2024). Thus, regulations should be grounded in current scientific understanding and focus on effective mitigation.

Cohen et al. (2010) and Kennedy et al. (2018) conducted insightful research that challenges the assumption that forested wetland ecosystems regain core ecological functions after 20 years. This research began with the observation that forested wetlands often receive less protection because policymakers assume they are low-risk and will recover on their own promptly. However, real-world recovery is more complex. Success depends on multiple factors such as clearly defined goals, understanding the timeframe correctly, as well as restored hydrology, soil composition, competition with invasive species, seed source availability, and overall landscape context. Remote sensing research using long-term Landsat satellite imagery has provided detailed insights into forest harvest and recovery patterns. By applying time-series tools such as LandTrendr, researchers can detect when forest harvests occur, measure their severity, and track how forests recover over time. Cohen et al. (2010) demonstrated that forested systems, including forested wetlands, follow disturbance–regrowth trajectories, but regrowth is neither guaranteed nor uniform. Their work showed that disturbances, including logging, land clearing, fire, and insect outbreaks, have varying impacts. After the harvest, spectral recovery indicating biomass gain can occur, yet this regrowth may stall or diverge depending on regional factors.

To assess whether a forested wetland has "recovered," Kennedy et al. (2018) utilized a remote-sensing methodology based on a repeatable monitoring framework. They segmented spectral trajectories annually with LandTrendr, and documented exactly when disturbance occurred, how biomass is trending over time, and whether the spectral signal was consistent with regrowth. Using sample plots and quantitative recovery thresholds, including attainment of 80 percent of pre-disturbance biomass within 20 years, the authors assessed whether sites were meeting the half-rotation recovery benchmark. Then, with the help of ground-truthing (i.e., measurement collected in the field), they validated whether soil carbon, hydrology, and biodiversity align with satellite-derived metrics.

In Washington's forested wetlands, therefore, assuming 20 years is sufficient for full recovery may be overly optimistic. Without proactive restoration such as reconnecting hydrology, reintroducing native tree species, and controlling invasives, these systems can take far longer to regain structural complexity, biomass, or ecological function. Further research, such as this thesis, is necessary to inform the optimal policies for the temporal recovery scale of these wetlands.

Despite growing recognition that forested wetlands recover more slowly and less predictably than assumed in many regulatory frameworks, there remains limited quantitative evidence evaluating recovery trajectories in relation to land management practices and policy assumptions. Much of the existing literature demonstrates that disturbance and regrowth dynamics in forested systems are highly variable and context dependent (Cohen et al. 2010; Kennedy et al. 2018), yet these insights have rarely been translated into evaluations of how mitigation timelines, recovery benchmarks, or protection standards perform in practice for forested wetlands.

Recent studies have applied remote sensing and land-use or land-cover change analyses to detect the harvest within wetlands, hydrologic change, and recovery dynamics across a range of ecosystems (Demarquet et al. 2023; Elyasi et al. 2025; Tough et al. 2025). Some efforts attempt to relate observed changes to management or planning scenarios through modeling approaches (Xu et al. 2025), while others emphasize condition assessment and conservation prioritization rather than regulatory evaluation (Krohmer et al. 2024; Yi et al. 2024). However, these analyses generally stop short of explicitly assessing how existing policy frameworks or regulatory assumptions influence observed forest harvest and recovery trajectories. Moreover, forested wetlands are rarely examined as distinct systems within this body of work, and such policy-relevant, time-series analyses have not yet been conducted within Washington State. Consequently, it remains unclear whether commonly assumed recovery periods, such as the half-rotation benchmark, align with observed disturbance and regrowth patterns in Washington's forested wetlands at landscape scales.

1.6 Research Objectives

This research aimed to investigate the relationship between forest policy and forested wetland forest harvest in Washington State. The primary objectives include the following:

Objective 1. Quantify Forest Harvest Trends: Analyze satellite imagery and detect temporal patterns of forest harvests within forested wetlands in the Hoh watershed.

Objective 2. Policy Analysis: Develop and explore a preliminary framework for analyzing state and federal policies to assess whether regulatory changes can be meaningfully aligned with forest harvest trends in forested wetlands, using the Hoh watershed as a test case.

Collectively, these objectives provide a structured approach for examining how regulatory change may correspond with landscape-level forest harvest patterns. This framework offers a replicable foundation for future research seeking to evaluate policy–ecology interactions across broader spatial and temporal scales.

1.7 Expected Results

The expected outcomes of this research include the development of a spatially explicit forest harvest analysis of forested wetlands within the Hoh watershed and the identification of variation in forest harvest patterns across ownership categories. While causal attribution between policy change and forest harvest cannot be presumed, the study aims to assess whether regulatory timelines can be systematically aligned with observed landscape dynamics. The anticipated contribution is therefore twofold: a robust quantification of forest harvest trends and an exploratory methodological pathway for examining potential policy-ecology linkages in future research. More broadly, the study is expected to provide a structured analytical framework that future research can refine to more rigorously evaluate the relationship between environmental governance and landscape-level ecological change.

The findings of this research have implications for a range of stakeholders involved in forest and wetland management, policy development, and conservation planning. By providing spatially explicit, time-series analysis of forest harvest dynamics in forested wetlands, this study contributes empirical evidence relevant to evaluating existing forest and wetland protection frameworks. Regulatory agencies and policymakers may use these results to assess whether current forest management and wetland protection policies align with observed forest harvest patterns and recovery trajectories. The analysis offers a basis for examining the adequacy of assumed recovery timelines and mitigation expectations embedded within existing regulatory frameworks. Forest managers and landowners may benefit from improved understanding of how forest harvest dynamics differ across ownership types and management regimes. Insights into the spatial distribution and timing of forest harvests may inform management practices that better account for forested wetland sensitivity. Tribal governments and natural resource managers may draw upon the findings to support habitat protection, restoration planning, and stewardship of culturally and ecologically significant wetland ecosystems. The study's emphasis on forested wetlands provides information relevant to the protection of aquatic habitats that support treaty-reserved resources. Conservation organizations and land-use planners may apply the analytical framework developed in this study to identify priority areas for forested wetland protection and restoration. More broadly, the results contribute to the scientific literature on forested wetland disturbance and recovery, supporting future research that integrates ecological analysis with policy and governance context.

1.8 Assumptions and Limitations

1) Recovery trajectories in this study are inferred primarily from spectral indicators of vegetation change derived from Landsat time series analysis. While these metrics serve as useful proxies for biomass loss and regrowth, they do not capture the full spectrum of wetland functions, including hydrologic connectivity, soil carbon accumulation, nutrient cycling, or biodiversity. Accordingly, observed regrowth patterns should be interpreted as indicators of vegetation recovery rather than comprehensive measures of functional wetland recovery.
2) Disturbance identified through the LandTrendr algorithm is assumed to represent anthropogenic disturbance, primarily logging activity. Although LandTrendr detects spectral change rather than land use directly, the dominant disturbance agent in the study region is timber harvest. For clarity and consistency, the terms disturbance and logging are therefore used interchangeably throughout this thesis, unless otherwise specified.

3) Land ownership is treated as static across the study period due to the availability of a single ownership dataset (1992). Temporal changes in ownership, including transitions from private or industrial ownership to conservation or public status, are not incorporated into the analysis. As a result, areas currently classified as conservation lands may reflect historical disturbances that occurred prior to ownership change, which may obscure differences in forest harvest patterns among ownership categories.
4) The policy review included in this thesis is selective rather than exhaustive. Only a subset of regulations relevant to forested wetlands was examined, based on their documented applicability to forest practices and wetland protection. The study does not include data on how these regulations were implemented, monitored, or enforced in practice. Evaluating enforcement mechanisms, compliance rates, and administrative capacity would substantially expand the scope of the research and fall beyond the boundaries of this thesis.
5) The analysis assumes that forest management and wetland protection policies exert cumulative effects over time rather than producing immediate or discrete shifts in logging patterns. Temporal alignment between policy enactment and forest harvest trends is therefore used to assess broad consistency rather than direct policy attribution. The statistical analyses are designed to identify trends and associations, not to establish causal relationships. Observed correspondence between policy periods and forest harvest dynamics should be interpreted as suggestive rather than definitive evidence of policy influence. Overlapping regulations, variable enforcement, fluctuating timber markets, and environmental variability further complicate causal inference.
6) Finally, this research is exploratory in nature, particularly with respect to policy analysis. Establishing causal links between regulatory frameworks and landscape-level logging patterns remains methodologically challenging. The approach presented here offers a structured framework for integrating remote sensing and policy timelines, which future research can refine through expanded datasets, comparative watersheds, and more advanced causal modeling techniques.
7) The Hoh River watershed serves as a case study of forested wetland anthropogenic disturbance within a working forest landscape. While it provides a meaningful and contextually relevant example, the findings may not be directly generalizable to regions

with different ecological conditions, ownership configurations, or regulatory environments.

2. Methodology

2.1 Study Area

To conduct this research, I selected the Hoh River watershed, located on the Olympic Peninsula on the west coast of Washington State (***Figure 1***). This watershed was selected because it is relatively undeveloped and I assumed it should be impacted by any policy changes. Small headwater watersheds within Olympic National Park exhibit strong hydrologic connectivity, shallow groundwater interactions, and complex vegetation–water feedbacks characteristic of temperate rainforest systems (Edmonds 1998). These ecological dynamics influence forested wetland function within the upper Hoh River watershed. It is also representative of the regional ecological configuration. The Hoh River originates from the Hoh Glacier on Mount Olympus within Olympic National Park, flowing approximately 56 miles westward through the Hoh Rain Forest before emptying into the Pacific Ocean near the Hoh Indian Reservation (Western Rivers Conservancy 2020). The watershed encompasses about 299 square miles, primarily within Jefferson County, with portions extending into Clallam County. This area is known for its temperate rainforest ecosystem characterized by high annual precipitation and a rich canopy (NWIFC 2026), exemplifying a type of forested wetland that poses challenges for traditional remote sensing methods of classification.

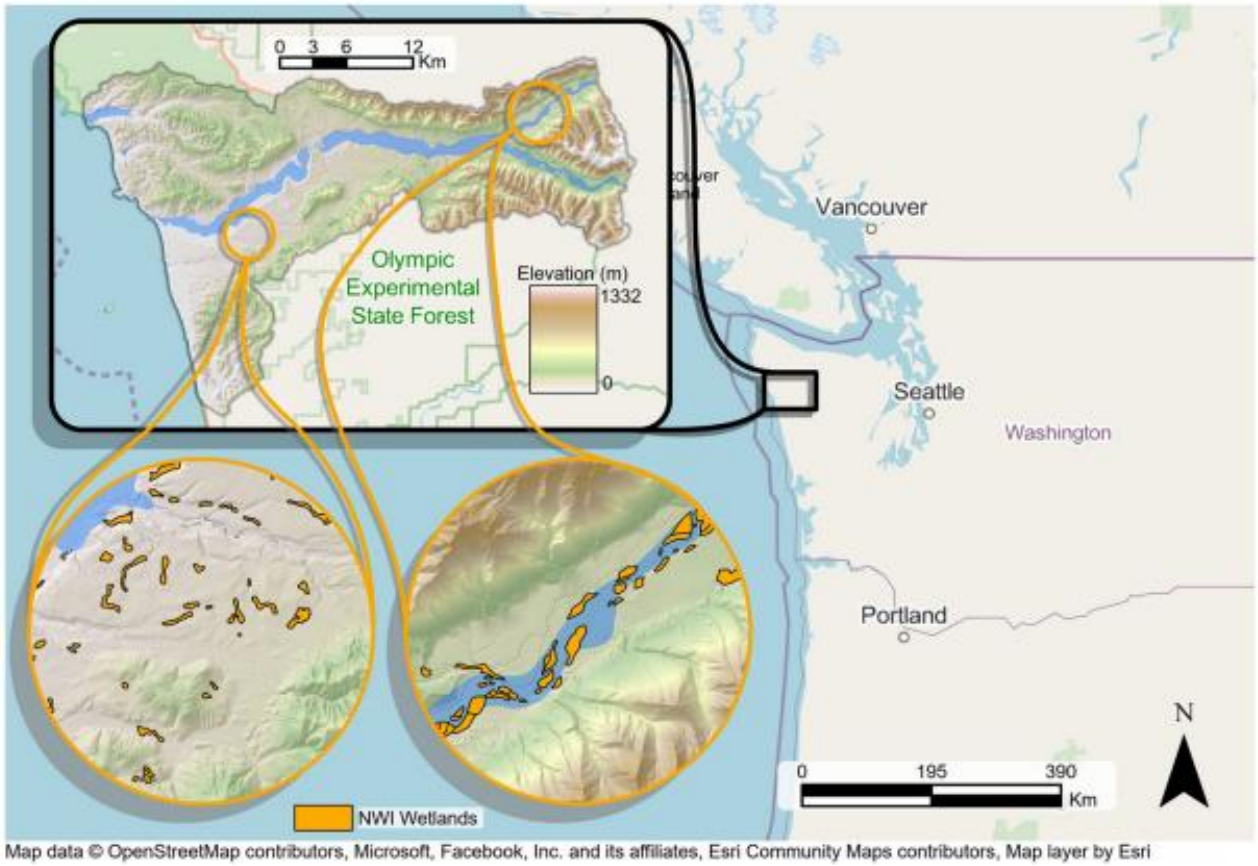


Figure 1 *The Hoh River watershed sits on the Pacific Northwest coast of Washington State. Inset maps illustrate the lower watershed's eastern and western reaches, with National Wetland Inventory wetlands highlighted in orange. The watershed boundaries are shaded light blue. Adapted from Stewart et al. (2024).*

Ownership of the lands within the Hoh River watershed is mixed, with federal, state, and tribal governments managing some areas and others managed by private landowners. The federal government owns and operates the Olympic National Park, protecting a large portion of the watershed, preserving its natural state, and minimizing human impact on the landscape (SEFS 2021). The federal government also owns the Olympic National Forest, which is managed by the U.S. Forest Service under a multiple-use framework that includes timber harvesting alongside recreation, watershed protection, and habitat conservation (U.S. Forest Service 1990; USDA and USDI 1994). This mosaic of ownership types plays a crucial role in the management and conservation efforts within the watershed, with each entity bringing different priorities and regulations to the table (NWIFC 2026). The protected status of much of this watershed ensures the conservation of its unique environmental attributes. State and private land managers balance conservation, recreation, and logging objectives, which contrasts with the stricter preservation policies on federally protected lands (Miller et al. 2017). This diverse ownership landscape underscores the importance of collaborative management strategies to maintain the ecological integrity of the Hoh watershed region.

2.2 Overview of Remote Sensing Framework

This research utilizes the LandTrendr algorithm within Google Earth Engine (GEE) to detect and quantify forest harvest patterns in Washington State's forested wetlands. LandTrendr was developed by Robert E. Kennedy and colleagues to analyze the annual Landsat time series for patterns of disturbance and recovery in vegetation cover. First described in Kennedy et al. (2010), the algorithm designed to analyze temporal patterns of land cover change using annual Landsat satellite imagery (***Figure 2***). It works by simplifying the spectral history of each pixel into a series of connected linear segments, making it possible to identify the timing, duration, and magnitude of forest harvest and recovery events across landscapes. The LandTrendr algorithm examines the changes in the color values (or spectral signatures) of each 30-meter pixel over time (spatial resolution) in satellite images. These changes are often related to vegetation health. The algorithm then simplifies each pixel's history into straight-line segments to highlight when and how big a disturbance or recovery event was (Kennedy et al. 2010). To do this, LandTrendr uses standard vegetation indices like the Normalized Burn Ratio (NBR) and Normalized Difference Vegetation Index (NDVI). These help the model detect disturbances such as tree removal or regrowth.

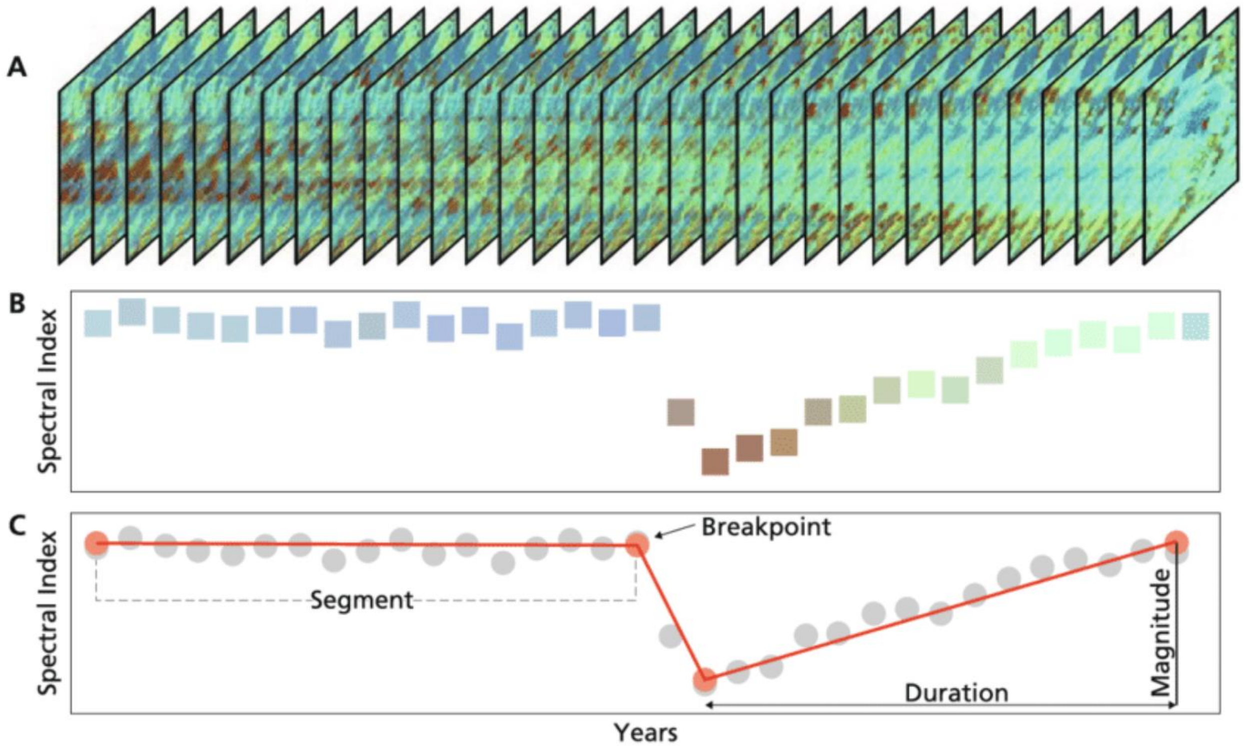


Figure 2 *Concept of the change detection algorithm of LandTrendr. Each pixel in the best available yearly composite depicted temporarily (a), contributes to a trajectory of a spectral index, i.e., NDVI (b). LandTrendr then detects magnitude, duration and timing of disturbance in the trajectory (c). Adapted from Kennedy and Braaten 2020; Kennedy et al. 2018.*

When logging activities remove vegetation from forested areas, the pixel values change sharply, and LandTrendr identifies these shifts as disturbances. When vegetation regrows over time, LandTrendr captures this gradual shift and marks it as a recovery.

In this research, LandTrendr was used to retrieve layers from 1974 to 2022, covering nearly 50 years of change. I used its built-in settings on GEE to run the analysis with parameters adjusted for forested wetlands, which can be challenging to assess due to water, mixed vegetation, and seasonal variation (Kennedy et al. 2018). The algorithm breaks down the time series into vertices that show where a significant change happened. It then links those points to understand when the change started, how long it lasted, and how severe it was. This method helps remove random noise from the data and focuses on meaningful changes.

The final result is a map that shows when and where vegetation loss occurred (***Figure 3***). I used this information to calculate my primary variable of interest: “Vegetation Loss.” “Vegetation Loss” is a continuous metric generated by the LandTrendr-based segmentation process. This metric represents the modeled probability that a given pixel has undergone forest disturbance in a specific year. While many detected disturbances in this region are associated with forest management activities such as clear cutting, thinning, and salvage logging, other factors including wildfire, insect outbreaks, disease, and localized development may also contribute to observed changes. Each pixel’s probability reflects the proportion of votes from a Random Forest model that classifies the pixel as disturbed. This probability-based output allows for more nuanced interpretation than binary classification, enabling correlation analysis with independent variables like land ownership class and forest policy implementation zones. Pixels with higher probability values indicate more substantial model confidence in vegetation loss events, providing spatial and temporal patterns of disturbance across the landscape.

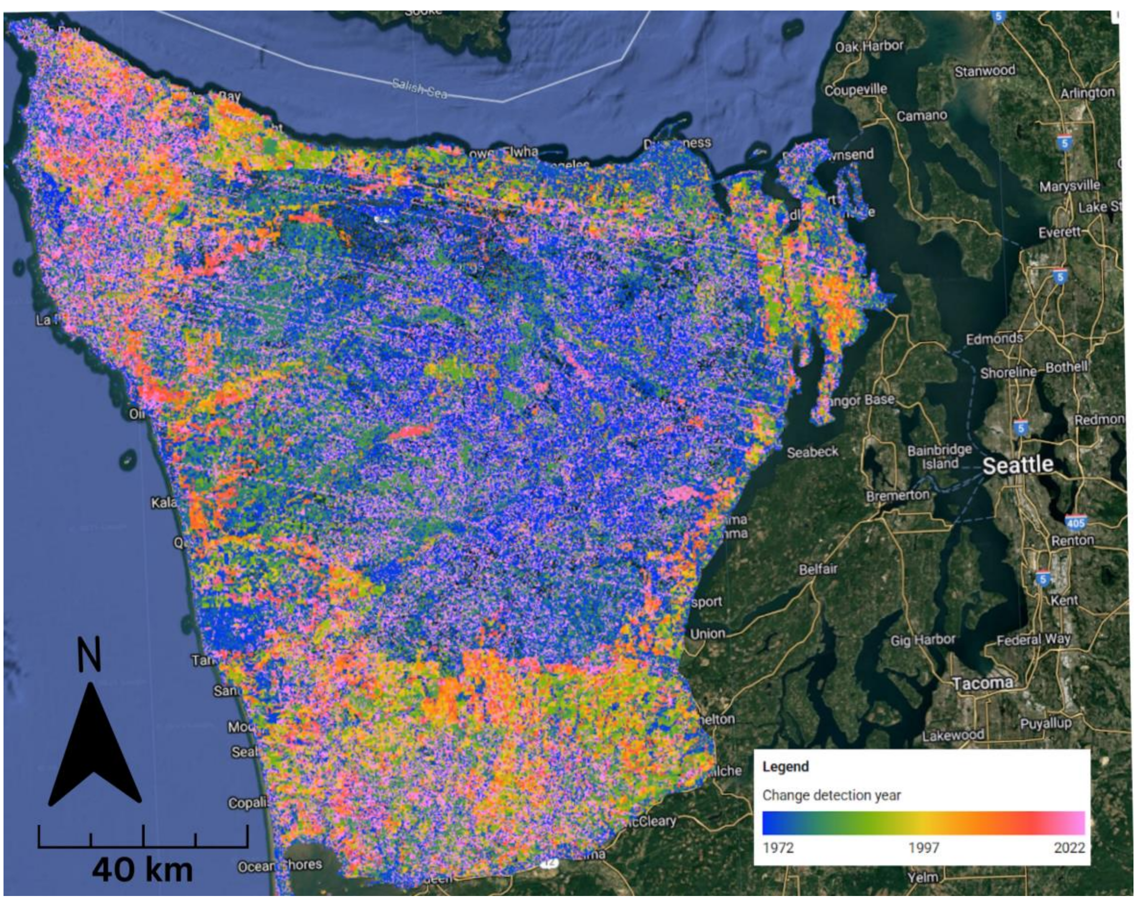


Figure 3 *Vegetation loss in Washington State's forested wetlands detected using the LandTrendr algorithm in GEE. The map displays false-color imagery showing the timing and magnitude of disturbance events from 1974 to 2022, with pixel values classified from "Loss" to "Greatest" based on spectral change magnitude.*

LandTrendr outputs were interpreted in the context of established validation approaches described in prior literature. The algorithm has been extensively evaluated using visual time-series interpretation tools such as TimeSync, as well as through comparison with independent disturbance datasets including fire perimeters, harvest records, and forest inventory data (Kennedy et al. 2010; Kennedy et al. 2018). Accuracy assessments typically report strong agreement for detecting stand-replacing disturbance events in forested systems. Nonetheless, because LandTrendr identifies spectral change rather than disturbance agent, disturbance signals in this study are interpreted as canopy change consistent with logging or other vegetation-altering events rather than definitive attribution to a specific cause.

To complement the forest harvest analysis, this research also used the WIP tool as described by Stewart et al. (2024). The WIP tool applies a machine learning model to estimate the likelihood that any given location within the landscape either functions as, or previously functioned as, a wetland. The model incorporates multiple spatial predictor layers, including lidar-derived topographic indices, vegetation characteristics, and soil properties, to generate a continuous probability surface at 4-meter spatial resolution. Each pixel is assigned a probability score representing the likelihood of wetland presence.

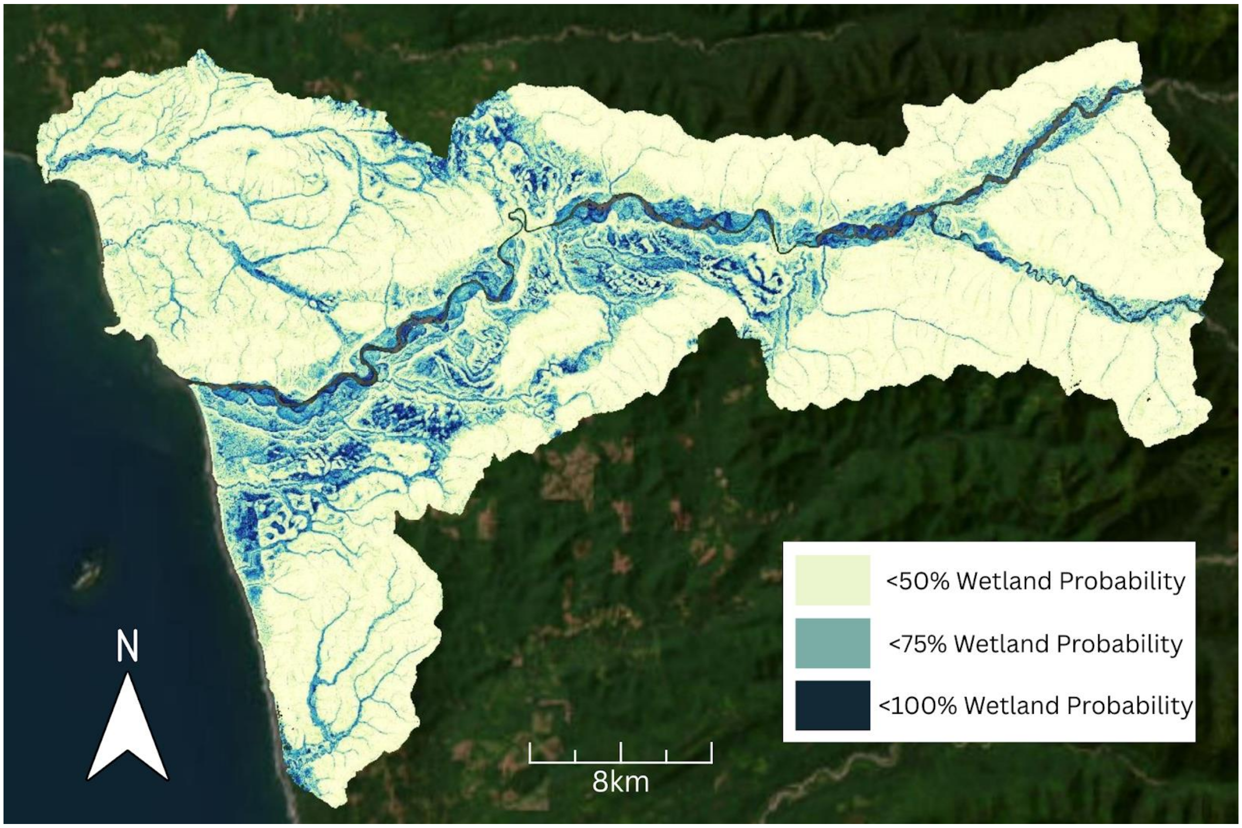


Figure 4 *Map of the Hoh River watershed showing forested wetland probability based on the WIP model. Areas with greater than 50% probability are included, with darker blue shades indicating a higher likelihood of wetland presence. The gradient reflects model-predicted probabilities derived from topography, vegetation, and soil data, highlighting both visible and cryptic wetlands across the landscape.*

In this thesis, the WIP probability surface was used to support spatial interpretation of wetland extent within the Hoh River watershed (***Figure 4***). Areas with predicted probabilities greater than 50% were classified as likely forested wetlands, allowing for inclusion of both mapped and previously undocumented "cryptic" wetlands. The resulting probability gradient highlights variation in wetland likelihood across the landscape, with darker blue tones indicating stronger model-predicted wetland potential. By incorporating this surface, the analysis captures wetland areas that may not be fully represented in conventional inventory datasets.

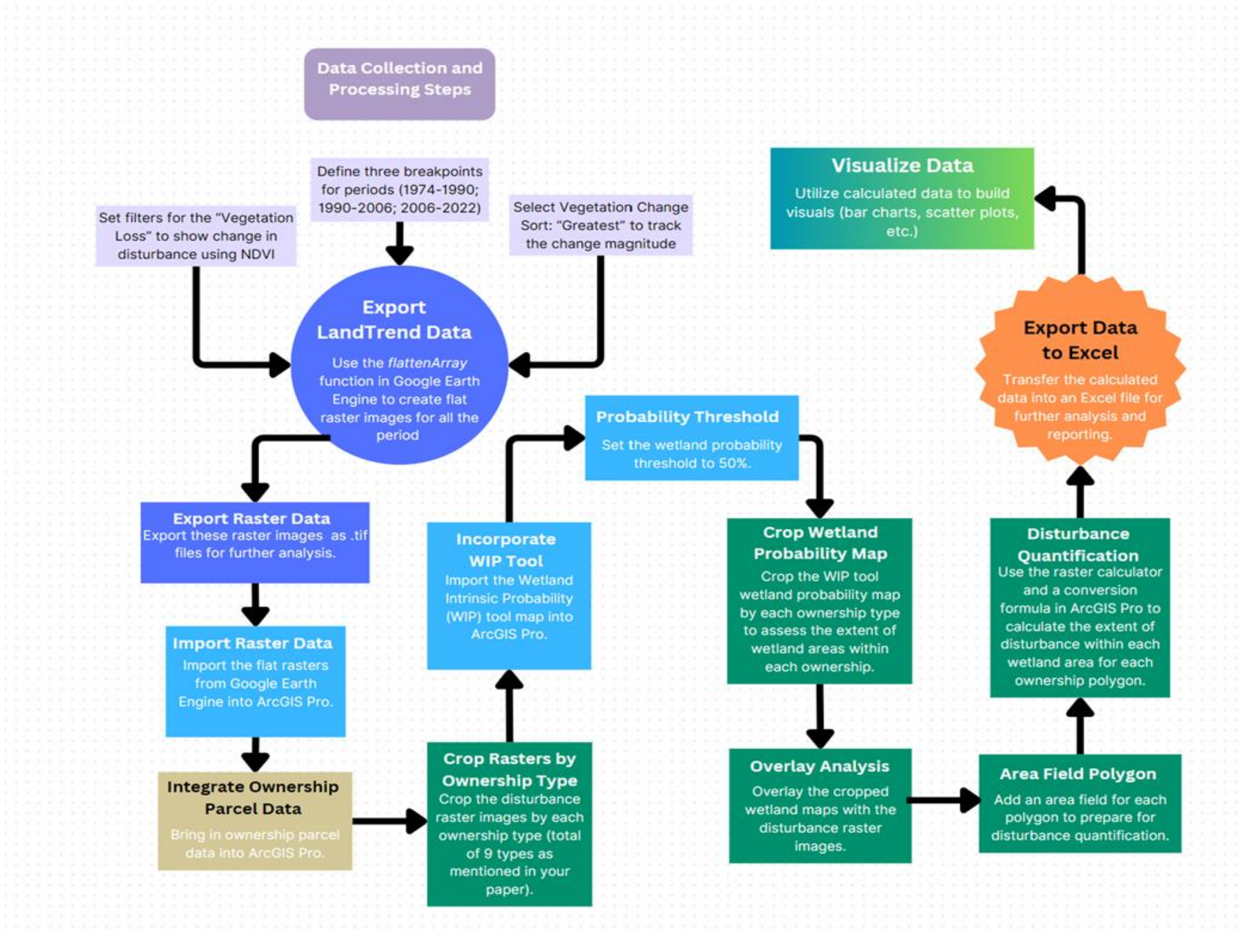


Figure 5 *Data collection and processing workflow for analyzing vegetation loss in forested wetlands*

The analytical workflow used to evaluate vegetation harvest in the Hoh River watershed is summarized in ***Figure 5***. LandTrendr outputs were first processed in GEE to extract annual vegetation change derived from Landsat time series. Within GEE, filters were set to "Vegetation Loss" to isolate logging signals using the NDVI, and the vegetation change parameter was set to "Greatest" to capture the most substantial spectral loss event for each pixel across the study period. The resulting forest harvest layers were exported as TIF files and imported into ArcGIS Pro (ESRI 2023), where they were spatially integrated with ownership parcel data. This overlay enabled quantification of vegetation loss across federal, state, tribal, and private ownership categories. The workflow includes the integration of WIP probability surfaces, allowing forest harvest patterns to be evaluated in relation to modeled wetland function and carbon storage potential. By linking LandTrendr-derived forest harvest metrics with ownership classification and WIP-based wetland probability layers, this structured processing sequence translates remote sensing outputs into policy-relevant spatial analysis. The workflow depicted in ***Figure 5*** demonstrates how vegetation change detection, ownership stratification, and wetland probability modeling were brought together to develop a spatial framework for analyzing forested wetland harvest.

2.3 Land Ownership Data

The Forestland Database integrates land ownership, usage, and valuation information with the physical attributes of the land to create a suite of metrics that reflect the economic, social, and environmental aspects of forest lands. This database was primarily constructed using county GIS and parcel data, tax information from assessors, and the National Land Cover Dataset (NLCD) to identify forested areas (SEFS 2021).

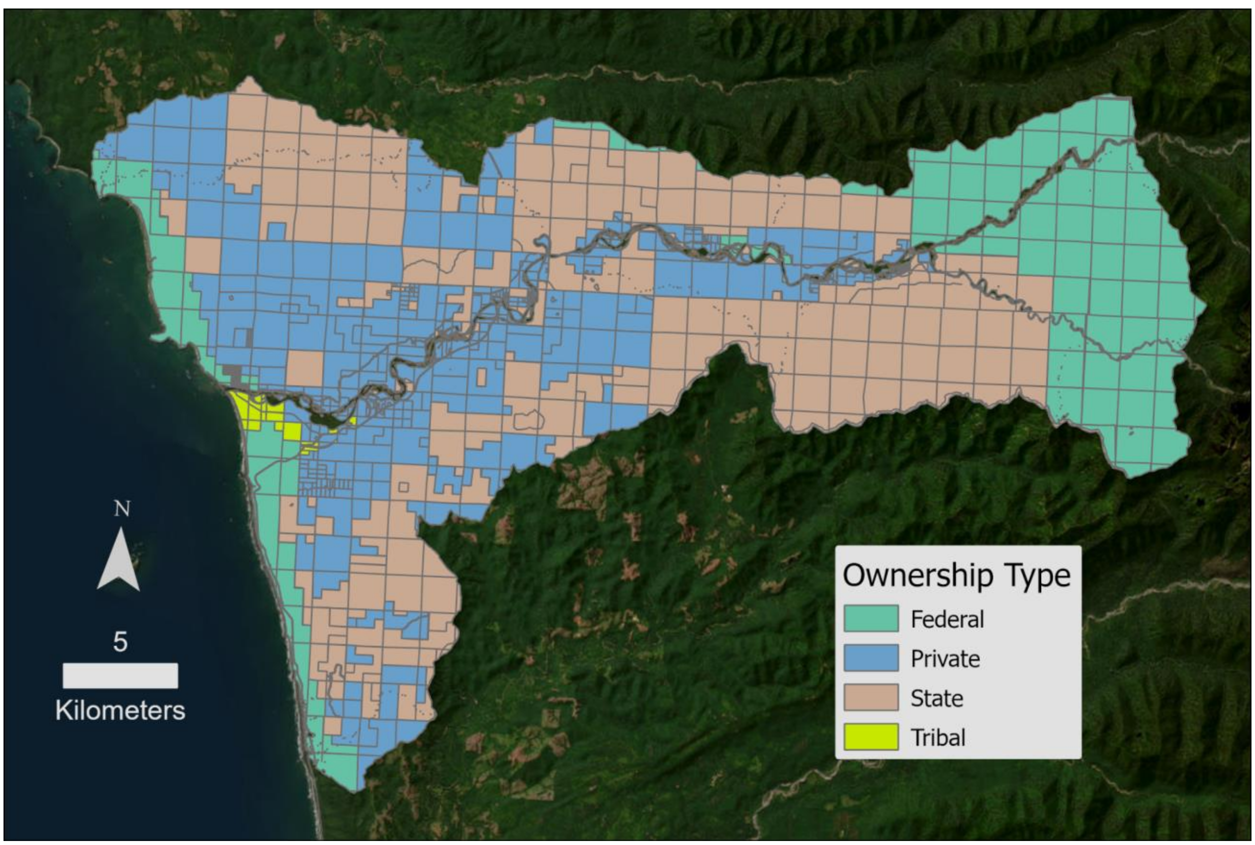


Figure 6 *Map displaying various ownership types of forestland in the Hoh River Valley, consolidated to four main categories.*

The ownership data were compiled in 2019 and include parcel GIS data and associated tax roll details from county assessors for all 39 counties in Washington. These data were standardized into a uniform format, culminating in the publication of the 2019 Washington State Parcel Database (SEFS 2021). For this study, parcel data were subset to the Hoh River watershed extent (***Figure 6***). LandTrendr disturbance outputs and WIP wetland probability layers were spatially intersected with ownership parcel boundaries in ArcGIS Pro. This overlay analysis enabled calculation of disturbed area (km^2) for each ownership category.

Table 1: Categorization of Forestland Parcels by Ownership Type*

Ownership Type	Type Description
Conservation	Forestland owned by a conservation entity
County Local	Forestland owned by the local county
Other	Forestland with other ownership not described
Other State	Other Washington State-owned forestland
Other Federal	Forestland owned and managed by federal agencies
Private Industrial Forestland	Forestland owned by large forest management companies
USFS	Forestland owned by the U.S. Forest Service
Washington Department of Natural Resources (DNR)	Forestland designated as Forest Trust and managed by the Washington State Department of Natural Resources

Table 1: Categorization of Forestland Parcels by Ownership Type*	
Ownership Type	**Type Description**
WA Small Forest Landowner	Privately owned forestland, either at least two contiguous acres in size with a minimum of 1 acre of forest cover, or that has a forest land use code. No more than 2500 acres west of the Cascade crest and 9990 acres east of the Cascade crest. No government, tribal, or corporate name.

**Adapted from SEFS 2021*

Forestland parcels were categorized according to ownership type using classifications developed by the Natural Resource Spatial Informatics Group (NRSIG), as summarized in ***Table 1***. These categories include conservation entities, county governments, state-managed forests, federal agencies, private industrial companies, small private forest landowners, and other ownership groups. Differentiating among these ownership types is essential because each operates under distinct regulatory mandates, economic incentives, and management objectives, all of which can influence forest harvest patterns and land-use decisions. The ownership framework provides more than a descriptive breakdown of parcel types; it establishes the structural basis for examining how governance context conditions landscape outcomes. I grouped parcels into analytically meaningful ownership categories, so that I could quantify forest harvest trends across institutional boundaries. Grouping parcels by ownership type allowed forest harvest patterns to be compared across different management contexts. This structure makes it possible to examine whether vegetation loss varies among federal, state, tribal, and private lands.

2.4 Policy selection

The policy landscape governing wetland protection in Washington State is structured around major statutory frameworks at both the federal and state levels, under which more specific regulatory instruments operate. For example, at the federal level, the CWA (33 U.S.C. §1251 et seq.) establishes the primary statutory authority affecting wetlands. Under this umbrella, Section 404 regulates the discharge of dredged and fill material into jurisdictional wetlands, the 404(b)(1) Guidelines (40 CFR Part 230) define environmental review standards for such permits, and the 2008 Federal Mitigation Rule (33 CFR Parts 325 and 332; 40 CFR Part 230) establishes requirements for compensatory mitigation. At the state level, the Forest Practices Act (RCW 76.09) serves as a central statutory framework for regulating forested wetlands on commercial forestland. Its implementing rules, codified in WAC Title 222, establish operational standards such as wetland typing (WAC 222-16-035), restrictions on road construction in wetlands (WAC 222-24-052), and limitations on ground-based logging in saturated soils (WAC 222-30-070). These regulations operationalize legislative intent by setting spatial boundaries, equipment limitations, and management requirements that influence forest harvest patterns in forested wetland systems.

Other statutory frameworks, including the Water Pollution Control Act (RCW 90.48), Shoreline Management Act (RCW 90.58), and Growth Management Act (RCW 36.70A), similarly translate broad environmental mandates into enforceable standards through implementing regulations and local ordinances. In addition, executive orders and agency guidance documents provide interpretive direction and promote consistent implementation, though they do not independently establish binding requirements. This layered structure—statute, regulation, and guidance—results in variation in how wetland protections are applied across jurisdictions and land-use contexts. While many of these frameworks reflect the overarching policy objective of "no net loss" of wetland functions (U.S. EPA 1990), the mechanisms through which that objective is pursued differ substantially between federal dredge-and-fill permitting, state forest practices regulation, and local land-use controls.

Tribal wetland and watershed protection policies in Washington operate under the sovereign authority of federally recognized tribes and are distinct from both federal and state statutory frameworks. Tribal governance is grounded in inherent sovereignty and treaty-reserved rights rather than delegated state authority (NWIFC 2026). As a result, tribal environmental policies function as independent regulatory systems within reservation boundaries and as co-management and advocacy frameworks in usual and accustomed areas beyond reservation lands. Many tribal environmental protections derive enforceability from federal recognition of treaty rights, including court decisions affirming tribal co-management authority over fisheries and aquatic resources. In addition, some tribes exercise regulatory authority through federally delegated programs, such as CWA water quality standards, and influence environmental decision-making through formal government-to-government consultation requirements and treaty-based legal obligations imposed on state and federal agencies.

The 2025 State of Our Watersheds report highlights several tribal initiatives aimed at protecting and restoring aquatic ecosystems that support treaty-protected resources, particularly salmon (NWIFC 2026). Initiatives such as the gwədzadad Habitat Strategy (NWIFC 2025) and the Treaty Rights at Risk initiative (NWIFC 2011) articulate strong protection frameworks rooted in cultural continuity, ecological resilience, and the preservation of treaty rights. However, these initiatives primarily function as strategic and planning instruments rather than binding regulatory mandates. Their effectiveness depends on intergovernmental coordination, federal trust responsibilities, and negotiated implementation rather than direct enforcement mechanisms comparable to state or federal permitting programs. Notably, the report emphasizes that while tribes retained treaty-reserved fishing rights when vast tracts of land were ceded, the continued degradation of fish-bearing streams and salmon populations undermines the practical value of those rights. In this sense, declining ecological conditions threaten not only environmental health but also the meaningful exercise of treaty-protected resources.

Although tribal governance plays an important role in shaping wetland and watershed outcomes in Washington, this thesis does not provide a comprehensive evaluation of tribal regulatory systems or enforcement mechanisms. The focus of this study remains on statutory and regulatory instruments within federal and state frameworks that provide clearly defined implementation dates and administrative structures for temporal analysis. A deeper examination of tribal environmental law, co-management authority, and treaty-based enforcement pathways would represent a valuable direction for future research, particularly in understanding how sovereign governance interacts with geospatial patterns of ecological change.

In addition to statutory and regulatory instruments, Washington’s wetland governance framework includes several guidance-based and programmatic documents that shape implementation but do not establish binding legal requirements. These include the Interagency Advance Mitigation Guidance (2012), which promotes coordinated mitigation planning prior to permitted impacts. They also include the Washington Wetland Program Plan (WPP), which outlines statewide strategic priorities for wetland protection, monitoring, and restoration. In addition, the 2019 Stormwater Management Manuals establish technical standards for managing runoff under the National Pollutant Discharge Elimination System (NPDES), the federal permitting program created under the CWA (33 U.S.C. § 1342) to regulate discharges of pollutants into waters of the United States. While these documents play an important role in promoting consistency, coordination, and best practices across agencies, they function as interpretive or technical guidance rather than enforceable regulatory mandates. Because the analysis centers on enforceable laws and regulations with identifiable implementation benchmarks, nonbinding guidance materials were not examined empirically.

Despite this framework, rules governing harvest within and around forested wetlands remain relatively limited. In some cases, forested wetlands classified under the FPR do not receive fixed-width buffers unless they intersect with Type S or F waters, meaning protections may depend on hydrologic classification rather than wetland status alone (NWIFC 2026). Additionally, conservation in Washington relies heavily on incentive programs since over 60% of the state's land base is privately owned.

The tables below (***Table 2*** and ***Table 3***) provide selected examples of policies relevant to forested wetlands in Washington. It is not intended as an exhaustive inventory of wetland-related regulations, which would extend well beyond the scope of this thesis. Rather, it highlights key statutory and regulatory instruments most pertinent to the analytical framework developed in this study.

Table 2: Federal Statutes and Implementing Regulations Governing Forested Wetlands						
Policy / Law / Guidance		**Implementation Date**	**Type**	**Description**	**Forested Wetland Relevance**	**Limitations**
Rivers and Harbors Act (33 USC §403)		1899	Law	Prohibits unauthorized obstruction/alteration of navigable waters (applicable to wetland fills)	Only if wetlands are connected to navigable waters	Applies only to navigable waters
	33 CFR Part 322	1986 as amended	Regulation	Establishes the regulatory framework for authorizing the construction of structures (such as piers, docks, bulkheads, and bridges) and other work in or affecting navigable waters.	Applies when wetland fill, dredging, or construction affects navigable waters	Only applies to navigable waters; does not regulate isolated wetlands
National Environmental Policy Act (NEPA)		1969	Law	Requires federal agencies to review environmental impacts of proposed actions	Indirect — applies when federal permits/actions affect wetlands	Only for federal actions or federally funded projects
	40 CFR Parts 1500–1508	1978 (rev.	Regulation	Requires federal agencies to analyze environmental impacts before	Triggers environmental review	Procedural only, does not mandate

Table 2: Federal Statutes and Implementing Regulations Governing Forested Wetlands					
	2020)		undertaking major federal actions significantly affecting the human environment	when federal permits (e.g., CWA Section 404), funding, or land management actions affect wetlands, including forested wetlands	environmental protection outcomes; applies only to federal actions or actions requiring federal approval
Northwest Forest Plan (NWFP)	1994	Policy (Federal Land Manageme nt Plan)	A regional forest management plan developed to protect late successional and old growth forests while allowing sustainable timber harvest on federal lands in the Pacific Northwest	A regional forest management plan developed to protect late successional and old growth forests while allowing sustainable timber harvest on federal lands in the Pacific Northwest	Applies only to federal lands; not designed specifically for wetlands; allows limited timber harvest under certain conditions
Clean Water Act (CWA)	1972	Law	Regulates discharges into WOTUS	If forested wetlands fall within federal	Jurisdiction limited to "WOTUS" (subject to

Table 2: Federal Statutes and Implementing Regulations Governing Forested Wetlands						
					jurisdiction (e.g., headwaters, floodplains)	shifting federal definitions)
	Section 404 (33 U.S.C. §1344)	1972	Regulation	Regulates discharge of dredge/fill material into WOTUS	Primary federal mechanism regulating wetland fill and conversion, including forested wetlands when jurisdictional	Applies only to jurisdictional wetlands; exemptions exist for certain normal silvicultural activities
	404(b)(1) Guidelines (40 CFR Part 230)	1980	Regulation	Establishes criteria to evaluate environmental acceptability of proposed discharges into wetlands	If forested wetlands fall within federal jurisdiction (e.g., headwaters, floodplains)	Applies only to Section 404-permitted actions
	EPA–Corps Memorandum of Agreement	1990	Regulation	Clarifies the mitigation sequence of avoidance, minimization, and compensatory mitigation	Applicable via federal permitting process for any wetland,	Superseded by later regulations, most notably the 2008

Table 2: Federal Statutes and Implementing Regulations Governing Forested Wetlands						
	(MOA) (Mitigation Sequencing)				including forested	Federal Mitigation Rule (FMR)
	Federal Mitigation Rule (FMR) (33 CFR 332; 40 CFR 230 Subpart J)	2008	Regulation	Standardizes compensatory mitigation requirements under CWA	Mitigation may involve reforestation or buffer creation in forested wetland types	Applies only to permitted federal impacts
Executive Order 11990 – Protection of Wetlands		1977	Executive Order	Directs federal agencies to avoid and minimize wetland impacts	May apply to federal land management near forested wetlands	Applies only to federal agencies
Executive Order 11988 – Floodplain Management		1977	Executive Order	Encourages avoidance/minimization of impacts to floodplains/wetlands	May apply in floodplain-associated forested wetlands	Federal actions only

Table 3: State-Level Statutes and Administrative Codes Governing Forested Wetlands in Washington					
Policy / Law / Guidance	**Implementation Date**	**Type**	**Description**	**Forested Wetland Relevance**	**Limitations**
Water Pollution Control Act (WPCA) (RCW 90.48)	1945	Law	State authority over water quality, includes wetland protections	Forested wetlands can be impaired by runoff, addressed through total maximum daily loads (TMDLs)	Applied via stormwater or NPDES permit conditions
WAC 173-201A	2003	Regulation	Water Quality Standards	Applies numeric and descriptive criteria to wetlands	Implemented via permits
WAC 173-220	1974	Regulation	NPDES (National Pollutant Discharge Elimination System) Permit Program	Regulates discharge affecting wetlands	Permit-based
WAC 173-226	1998	Regulation	Construction Stormwater Permit	Controls sediment runoff to wetlands	Applies to construction sites

	WAC 173-22-035	2011	Regulation	Defines technical delineation criteria	Used to define extent of forested wetlands in permitting	Does not regulate impacts by itself
Hydraulic Code (RCW 77.55)		1949	Law	Requires Hydraulic Project Approvals (HPAs) for in-water work	Only where hydrologic connections to forested wetlands exist	Protection is habitat-based and limited to projects affecting state waters; does not independently regulate isolated wetlands
	WAC 220-660	2001	Regulation	Hydraulic Project Approval (HPA) Rules	Governs permitting standards for in-water work, bank stabilization, culverts, and other activities that may affect wetland hydrology or fish habitat	Limited to projects affecting state waters; primarily habitat-focused rather than wetland-focused
State Environmental Policy Act (SEPA)(RCW		1971	Law; Regulation	Environmental review for state/local actions impacting wetlands	Only where forest conversion or development impacts wetlands	Applies only to permit-triggered actions

43.21C)						
	WAC 197-11	1984	Regulation	SEPA Rules (Environmental Review Procedures)	Establishes SEPA checklist, DNS, MDNS, and EIS processes used when wetlands may be impacted	Applies only when a government action or permit is required
	WAC 197-11-960	1984	Regulation	SEPA Environmental Checklist	Includes wetland impact questions (e.g., surface water, habitat, hydrology)	Informational tool; does not mandate protection
	WAC 197-11-444	1984	Regulation	Mitigated Determination of Non-Significance (MDNS)	Allows conditioning of projects to mitigate wetland impacts	Limited to impacts identified during SEPA review
Shoreline Management Act (RCW 90.58)		1971	Law	Local Shoreline Master Programs regulate shoreline wetlands	If forested wetland lies within shoreline jurisdiction	Only applies in shoreline jurisdiction
	WAC 173-26	2003	Regulation	Establishes Shoreline Master Program Guidelines	Includes wetland protection standards	Local implementation
	WAC 173-27	2003	Regulation	Outlines Shoreline Permit Procedures	Governs shoreline wetland permitting	Procedural

Forest Practices Act (FPA) (RCW 76.09)	1974	Law; Regulation	Regulates timber harvests, road building, and other activities in/near wetlands	Directly regulates *forested wetlands*, including water typing and wetland classification	Applies only to forestland regulated under FPA
WAC 222-16-035	2001	Regulation	Wetland typing (Type A and B forested wetlands)	Determines wetland classification and level of protection	Applies only within forest practices context
WAC 222-16-050	2001	Regulation	Water typing system (Type S, F, N waters)	Triggers riparian management zones that may overlap wetlands	Surface water-based system
WAC 222-24-035	2001	Regulation	Landing location and construction	Limits placement and size of landings in wet soils and near wetlands	Forest practice operations only
WAC 222-24-052	2001	Regulation	Road construction in wetlands	Establishes hydrologic protections when roads cross wetlands	Applies only to forest roads
WAC 222-24-020	2001	Regulation	Road construction and maintenance standards	Controls drainage, culverts, fill material impacting wetland hydrology	Road-related activities only
WAC 222-30-021	2001 amend	Regulation	Western WA Riparian Management Zones	Establishes buffers along Type S/F waters intersecting wetlands	Applies only where wetlands overlap

		(2013)				RMZs
	WAC 222-30-023	2001	Regulation	Riparian zones for exempt parcels	Modifies buffer standards for small forestland parcels	Small parcel exemptions
	WAC 222-30-070	2001	Regulation	Ground-based logging systems	Restricts equipment use in saturated soils to prevent compaction	Triggered by soil moisture conditions
	WAC 222-20-010 – 222-20-040	2001	Regulation	Timber harvest practices	Sets operational standards affecting canopy retention in wetland areas	Indirect wetland protection
	WAC 222-12-045	amend (2013)	Regulation	Policy and Adaptive Management	Seeks to avoid significant impairment of aquatic habitat capacity	Adaptive and monitoring-based
	WAC 222-12-090	2001	Regulation	Unstable slopes and sensitive sites	Includes protections for hydrologically sensitive areas	Applies only to defined unstable areas
Growth Management Act (GMA)		1990	Law	Requires local Critical Areas Ordinances (CAOs) to protect wetlands	Forested wetlands can be designated critical areas and regulated via buffers and	Applies only in GMA-adopted counties

				mitigation	
RCW 36.70A.172	1995	Law	Best Available Science requirement	Influences wetland buffer standards	Indirect impact; applies to local planning
Wetland Mitigation Banking Act (RCW 90.84)	2005	Law	Establishes legal framework for mitigation banks	Mitigation banks may include reforested wetland types	Doesn't regulate impacts directly
WAC 173-700	2008	Regulation	Mitigation Bank Standards	Governs approval of wetland mitigation banks	Mitigation only
Interagency Advance Mitigation Guidance (2012)	2012	Guidance	Guidance on implementing advanced mitigation	Applicable when mitigation involves forested wetland types	Not a regulatory rule
Washington Wetland Program Plan (WPP)	2015, 2023	Guidance; Update: 2023 (Strategic Plan)	Strategic coordination plan (monitoring, regulation, outreach)	Identifies forested wetlands as priority for inventory and restoration monitoring (WPP 2023)	Not a rule; nonbinding
Stormwater	2019	Guidance	Guidance on LID, runoff,	Not legally binding unless adopted	Addresses

Management Manuals (2019)			infiltration, wetland buffers	locally	stormwater inputs to forested wetlands

Throughout this study, I have focused on three policies that may have directly or indirectly influenced the conservation and logging of forested wetlands in Washington. While many statutes shape wetland outcomes, analyzing all of them is beyond the scope of this thesis. The purpose of this study was not to conduct an in-depth qualitative evaluation of each selected policy, but rather to use these policies as temporal reference points within statistical analyses. As acknowledged in the limitations section, the scope of this study does not extend to an assessment of policy enforcement mechanisms or the effectiveness of their implementation.

A brief overview establishes the relevance of each policy to forested wetland protection, without engaging in detailed legal, institutional, or implementation-level analysis. One of the primary objectives of this thesis was to investigate whether a replicable methodological approach could be developed to assess the relationship between policy interventions and forest harvest trends. This research did not seek to establish definitive causal effects, but rather to examine the extent to which geospatial harvest data can be systematically aligned with policy timelines. The resulting framework should therefore be understood as exploratory and preliminary, offering a basis for further methodological development.

I selected policies for the synthetic control statistical analysis based on how their timing aligned with the available forest harvest data. In this case, it began in 1974 using the LandTrendr dataset. Due to the need for a sufficient pre-policy observation window, earlier statutory enactments were not examined. The analysis therefore focuses on more recent regulations adopted under major laws. These regulations convert broader legislative goals into specific procedures and operational standards, providing clearer time-based and institutional reference points for examining potential alignment with geospatial forest harvest patterns.

WAC 173-226 (1998)

WAC 173-226 establishes Washington State's Construction Stormwater General Permit under the authority of the Water Pollution Control Act (RCW 90.48) and consistent with Section 402 of the CWA (33 U.S.C. § 1342). The rule implements the

National Pollutant Discharge Elimination System (NPDES) framework for construction activities that disturb soil and may discharge sediment-laden runoff to surface waters, including wetlands. The regulation requires permit coverage for projects exceeding specified logging thresholds and mandates preparation and implementation of a Stormwater Pollution Prevention Plan (SWPPP). Permit conditions include erosion and sediment control measures, site stabilization, runoff management practices, and inspection and monitoring requirements. In this way, WAC 173-226 translates statutory water quality objectives into enforceable, site-level construction standards.

Although the rule does not specifically target forested wetlands, it is relevant where land conversion, road construction, or development occurs within or near wetland areas. Construction-related sedimentation, altered runoff patterns, and increased peak flows may affect wetland hydrology and soil stability. The rule's influence on forested wetland forest harvest patterns is therefore indirect and dependent on whether activities meet construction permitting thresholds. It does not regulate timber harvest conducted under the Forest Practices Act unless associated activities independently trigger stormwater permit requirements. In this study, its relevance lies in its clear implementation date and enforceable structure, which provide a temporal reference point for evaluating potential alignment between regulatory adoption and observed forest harvest trends.

WAC 222-30-020 (2001)

WAC 222-30-020 (*Harvest Unit Planning and Design*) establishes design standards for harvest units within riparian management areas under the FRP. It is part of the broader FRP, which regulate private and state-managed forestlands to protect public resources. This specific rule requires foresters and landowners to design harvest areas in a way that reduces the risk of soil erosion, protects water quality, and preserves ecological functions. Planning must account for site-specific factors such as slope steepness, soil type, weather patterns, and proximity to streams or wetlands. It also includes provisions for maintaining stability on potentially unstable slopes and for avoiding damage to riparian buffers and other sensitive areas.

The regulation emphasizes that harvest unit boundaries should follow natural topographic breaks whenever possible and should avoid concentrating runoff or increasing the likelihood of slope failure. It encourages the use of retention patches, buffers, and road planning to reduce the cumulative impact of logging activities. When designing harvests near wetlands or headwater streams, additional precautions are required to maintain hydrologic connectivity and habitat integrity.

Federal Mitigation Rule (33 CFR 332; 40 CFR 230) (2008)

The Federal Mitigation Rule (FMR), finalized in 2008, established a standardized regulatory framework for compensatory mitigation under Section 404 of the CWA. The rule governs how unavoidable impacts to wetlands and other aquatic resources must be offset and prioritizes mitigation approaches that replace lost ecological functions. It formalized a preference hierarchy for mitigation options, favoring mitigation banks, followed by in-lieu fee programs, and lastly permittee-responsible mitigation, in order to improve ecological outcomes and long-term accountability.

A central objective of the rule is to support the federal goal of no net loss of aquatic resource functions by strengthening requirements for mitigation planning, performance standards, monitoring, and long-term management. The rule requires mitigation projects to include clear ecological objectives, success criteria, and enforceable assurances, such as financial guarantees and site protection mechanisms. By increasing consistency across jurisdictions, the regulation aims to reduce variability in mitigation quality and effectiveness that characterized earlier permitting practices. Although the rule applies broadly to federally regulated wetland impacts, its relevance to forested wetlands depends on federal jurisdiction. Forested wetlands subject to CWA permitting may be affected when forestry-related activities involve dredge or fill actions requiring Section 404 authorization. In these cases, mitigation may include wetland restoration, enhancement, or reforestation activities intended to replace lost hydrologic and ecological functions. However, because the rule operates through the federal permitting process, its influence is limited to activities that trigger federal review and does not directly regulate forest management practices outside of that context.

2.5 Statistical Analysis

The statistical approach for this study began with a descriptive analysis of logging trends in forested wetlands. Using Landsat-derived time-series data processed via the

LandTrendr algorithm, I extracted disturbance layers with the help of GEE. The analysis adopted a 20-year benchmark for recovery, based on the half-rotation assumption that forested wetlands can regain structural and ecological functionality two decades after logging. This benchmark, previously discussed in Kennedy et al. (2018), was used to identify wetland patches that had remained undisturbed since 2002 or earlier, suggesting potential recovery of ecological services.

The second component of the descriptive analysis involved a visual overlay of forest harvest trends by land ownership type (i.e., private, state, or federal) across the study period. I aligned these ownership-specific bar charts with the implementation dates of significant state policies to create the graphs for both uplands and wetlands. Although not designed to test causation, this temporal comparison provided initial insight into how policy timing may relate to forest harvest trends. Comparing wetlands and uplands added broader context, but as a primarily visual assessment, it did not allow for a clear or precise attribution of influence. I therefore included an additional graph comparing the percentage of disturbed or logged forest in wetlands and uplands to provide broader context.

To evaluate these relationships more rigorously, I then applied an experimental approach using the synthetic control method (SCM). The goal of SCM was to estimate what forest harvest patterns in the watershed's forested wetlands might have looked like in the absence of selected policy implementations. The synthetic control approach was introduced in the context of comparative case studies by Abadie and Gardeazabal (2003) and later formalized by Abadie, Diamond, and Hainmueller (2010), whose application to policy evaluation has since spread across economics and public policy literature. In this framework, a synthetic counterfactual is constructed as a weighted combination of control units that resembles the treated unit in the pre-policy period, enabling estimation of policy effects on post-policy outcomes. In my model I incorporated predictor variables including fires, timber harvest volumes, forest health indicators, and upland forest harvest trends. I applied the SCM using the R programming language (R Core Team 2024) and the 'causalimpact' package (Brodersen et al. 2015). Upland forest areas served as a primary predictor, assuming they experienced similar external pressures but were not directly affected by wetland-specific policies.

I trained this model using data from 1974 through the year of each policy's implementation, providing a robust pre-policy baseline. I applied the SCM approach to significant Washington State policies, including WAC-222-30-020 (1992), the Salmon Recovery Act (1999) to test whether each was statistically associated with altered forest harvest trajectories in forested wetlands. The SCM then projected post-policy wetland forest harvest patterns under a counterfactual scenario in which no intervention took place. By comparing the actual post-policy wetland disturbance to this modeled scenario, the analysis quantified the potential effect of the regulation. To determine if effects were disparate between land ownership types, I iterated this for the landscape as a whole and then for each ownership type: federal, state, municipal, private, conservation, and all other ownership types.

I calculated the estimated policy impact using the expression:

$$\mathbf{((Wetlands_{p}ost - Wetlands_{p}re) - (Uplands_{p}ost - Uplands_{p}re))}$$

which isolates the treatment effect by controlling for time-varying shocks common to both groups (Angrist and Pischke 2009). The synthetic control method extends this logic by constructing a weighted counterfactual that more closely matches pre-intervention trends (Abadie, Diamond, and Hainmueller 2010). Statistical significance was evaluated through p-values, indicating whether observed differences are likely due to the policy rather than random variation.

I defined "upland forest harvest" as events/areas identified by LandTrendr that also fell within the spatial extent of a WIP-identified upland area. Timber sales, fires, and forest health were collected from WA DNR annual reports (DNR 2023a; 2023b; 2023c). Timber harvest volumes from Jefferson and Clallam Counties data were obtained from the Washington Department of Revenue's open data portal (Washington Department of Revenue 2023a; 2023b) to serve as proxies for regional forestry activity and economic pressure on land use. Because timber harvesting is one of the most common drivers of forest disturbance in the region, incorporating this variable helped control for underlying trends unrelated to specific policy interventions. However, given that the Hoh watershed remains relatively undeveloped and largely protected, I did not include predictor variables commonly associated with urban or suburban development, such as housing density, road construction, or impervious surface expansion. That said, if this analytical framework were applied to more developed regions, development-related covariates could prove highly relevant and would likely improve the model's sensitivity to human-driven landscape changes.

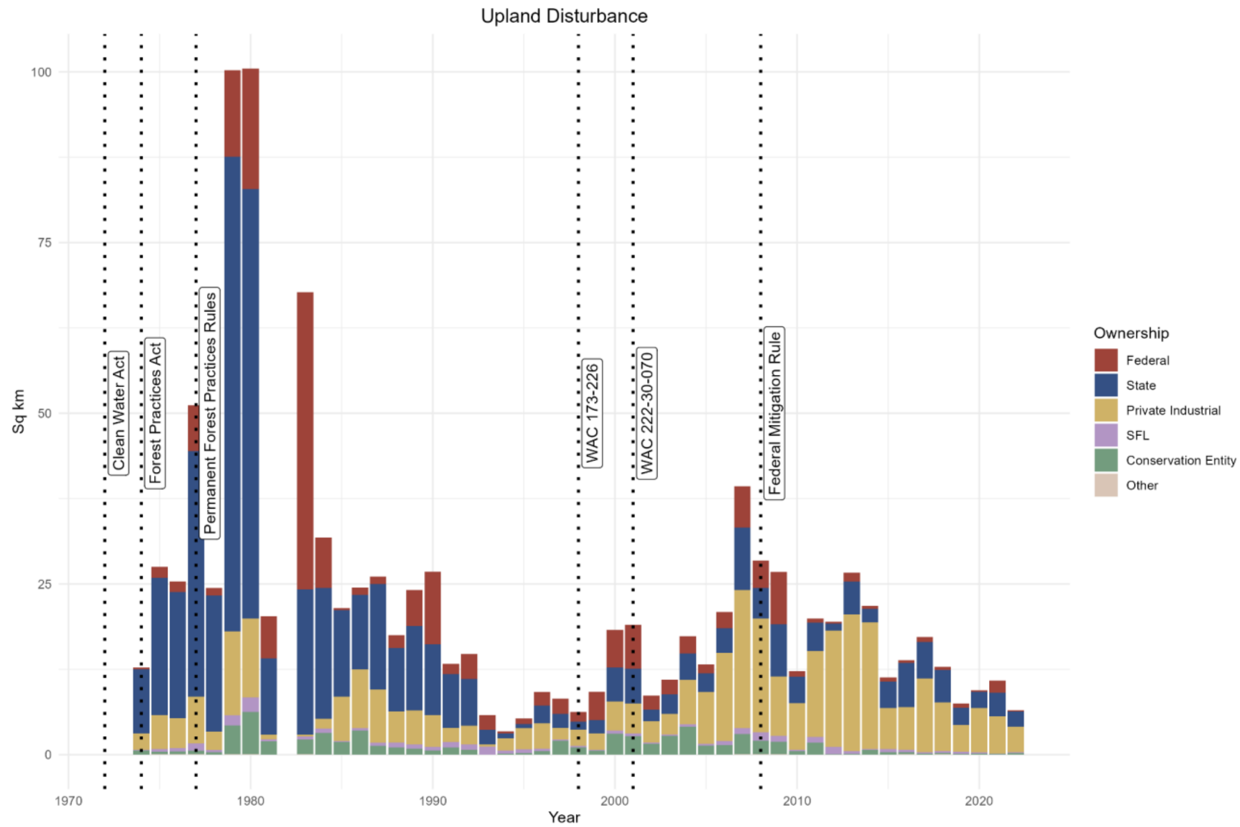
To strengthen future research within the Hoh watershed specifically, it would be beneficial to explore additional covariates beyond timber harvest data. These could include localized climate variables, precipitation trends, streamflow data, or more granular indicators of land-use practices. Including such variables may help reduce residual noise in the model and improve statistical significance, providing clearer insights into how different forces shape wetland disturbance patterns over time.

An SCM is a comparative case study approach that constructs a "synthetic" version of the treated unit. In this research, examined forested wetlands under a particular policy regime using a weighted combination of untreated units with similar pre-policy trends. This method enables the estimation of a counterfactual scenario: what forest harvest levels would likely have occurred in the absence of the policy, assuming that untreated comparison units reflect underlying trends and are not themselves affected by the policy. SCM is especially suitable for policy evaluations where randomized experiments are not possible.

3. Results

3.1 Temporal Analysis of Policy Implementation and Forest Harvest Trends

Instead of a spatial map, I developed a temporal visualization depicting the enactment of three selected regulations alongside preceding statutory frameworks.


Upland Disturbance
Sq km
100
75
50
25
0
1970
1980
1990
2000
2010
2020
Year
Clean Water Act
Forest Practices Act
Permanent Forest Practices Rules
WAC 173-226
WAC 222-30-070
Federal Mitigation Rule
Ownership
Federal
State
Private Industrial
SFL
Conservation Entity
Other

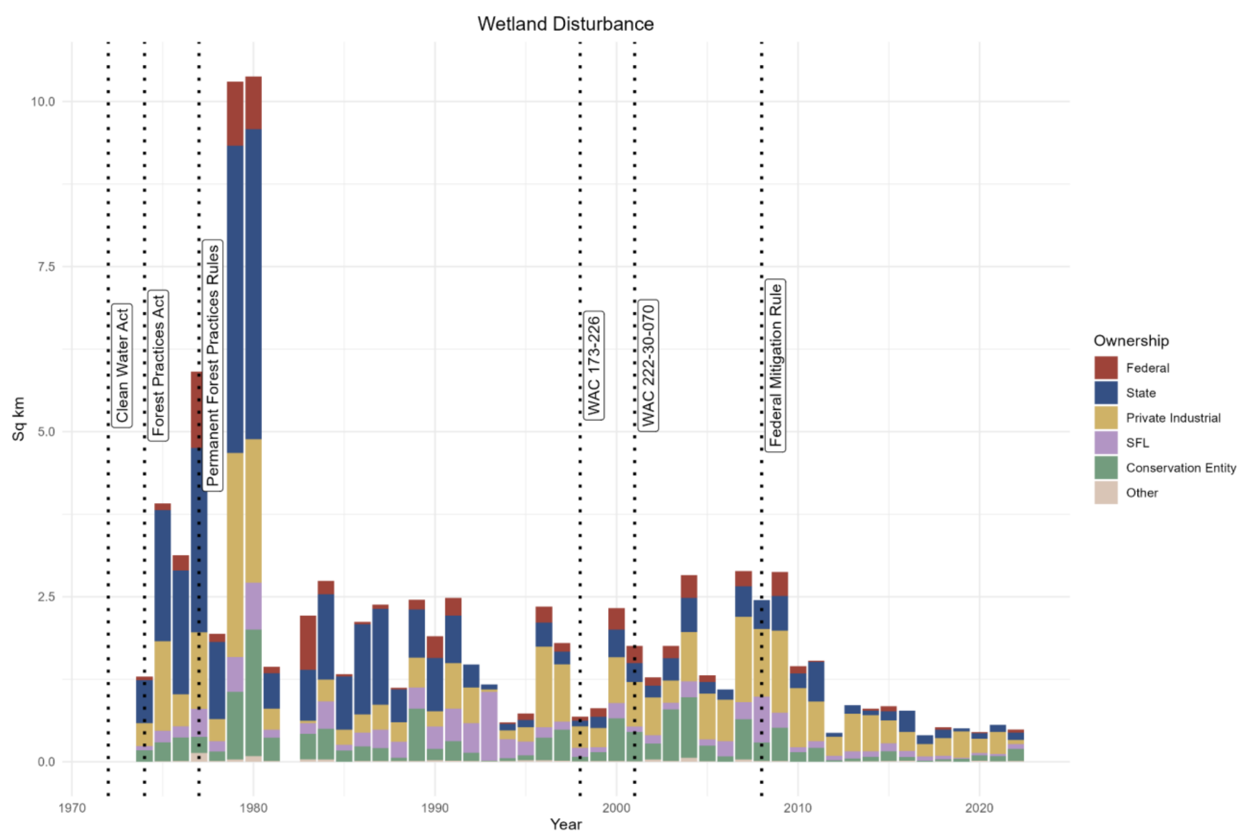

Wetland Disturbance
Sq km
10.0
7.5
5.0
2.5
0.0
1970
1980
1990
2000
2010
2020
Year
Clean Water Act
Forest Practices Act
Permanent Forest Practices Rules
WAC 173-226
WAC 222-30-070
Federal Mitigation Rule
Ownership
Federal
State
Private Industrial
SFL
Conservation Entity
Other

Figure 7a *and* ***Figure 7b*** *Temporal graph of policy implementation and forest harvest trends. The overlay of disturbance data (in km²), ownership classifications, and wetland probability to analyze forest harvest changes over time, providing context for management strategies in forested wetlands in Hoh watershed from 1974 to 2022.*

Figure 7a/b show when forest harvests occurred and which policies were in place at the time, helping to highlight what might have influenced those changes in wetlands and uplands of Hoh watershed. The bar charts break down forest harvest trends by land ownership and are aligned with the policy timeline, making it easier to compare how different ownership types may have been affected. While this is just one way to look at the data, the visual layout already points to patterns that suggest possible policy impacts. Visually, there appears to be a temporal correspondence between the enactment of major federal and state statutory frameworks—such as the CWA(1972), the ESA (1973), and Washington's FPA (1974)—and a subsequent decline in disturbed wetland areas. These statutes established broad regulatory authority and environmental mandates that reshaped forest and aquatic resource governance during that period. While this pattern does not establish causation, it suggests that the introduction of comprehensive environmental legislation may have contributed to shifts in logging dynamics within forested wetlands.

Further analysis using a three-year running average reveals notable differences between land ownership types for wetland areas. By plotting each combination of ownership type next to each other, I could compare how each changed differently following policy implementations. For example, state-owned lands show high logging levels in the 1970s and early 1980s, followed by a marked decline in activity (***Figure 7.1***). This is potentially reflecting internal policy reforms or conservation-oriented shifts in management. In contrast, private industrial lands exhibit more sustained harvest trends, peaking notably in the 1970s, then 1992-1996, and then finally beginning to decline after 2009.

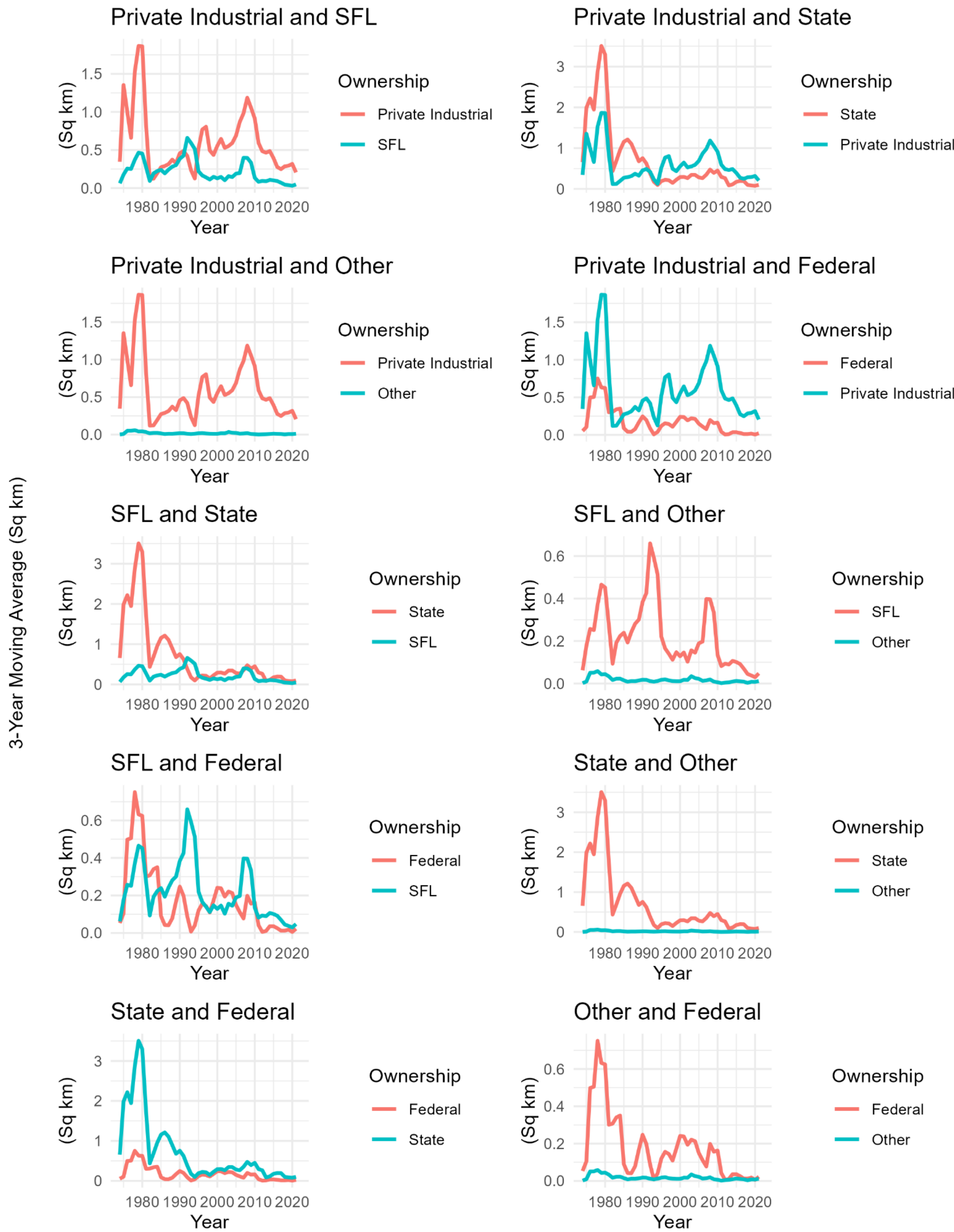


Figure 7.1 *Three-year moving average of logging (in square kilometers) across combinations of land ownership types in the Hoh River watershed from 1974 to 2022.*

Each panel compares two ownership categories to highlight contrasting forest harvest patterns over time.

To further contextualize forest harvest dynamics, I produced additional charts illustrating the proportion of total harvested area occurring within wetlands compared to uplands. Presenting forest harvest as a percentage of total harvest provides a relative metric that accounts for interannual variability in overall harvest intensity. This proportional comparison enables clearer evaluation of whether wetlands experienced disproportionate logging during particular policy periods. These supplementary figures are provided in Appendix [1].

3.2 Descriptive Statistics Results

In addition to examining the policy timeline, this research also looks at the data through the lens of recovery. As discussed earlier, 20 years is often used as a benchmark to evaluate whether a forested wetland has had sufficient time to regain its primary ecological functions. Forestry literature frequently references the concept of a "half-rotation" cycle as a basis for this assumption (Kennedy et al. 2018). Using this benchmark, I analyzed how much of the wetland area within the Hoh watershed remained undisturbed for at least 20 years before 2022. These areas qualify as "recovered" because they have not shown any detectable disturbance since 2002.

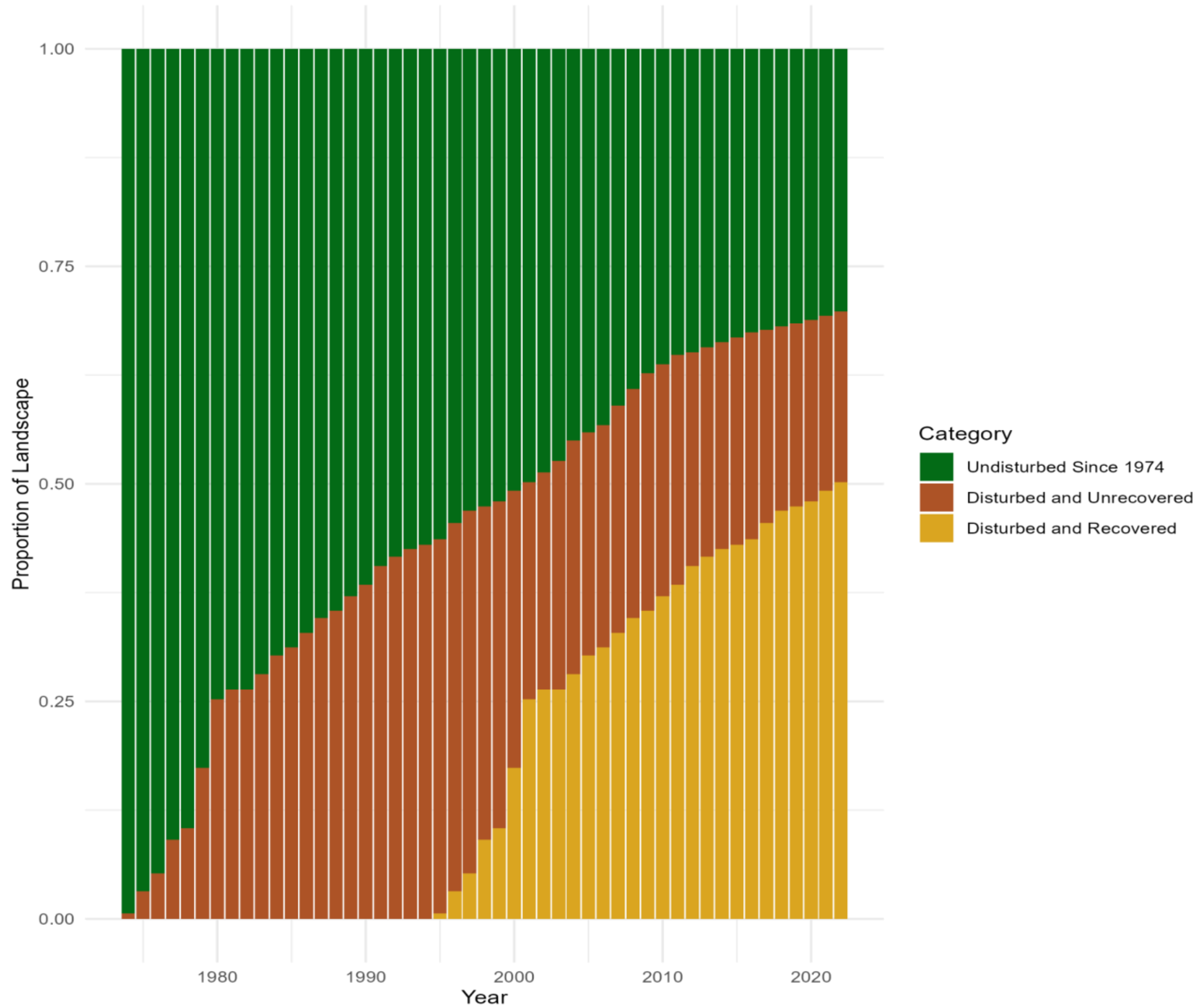


Figure 8a *Recovery timeline of forested wetlands in the Hoh River watershed from 1974 to 2022, based on a 20-year undisturbed benchmark. Green bars indicate wetlands with no detected disturbance since 1974, brown bars represent wetlands that experienced disturbance but have since recovered (20 years undisturbed), and yellow bars show recently disturbed wetlands.*

Figure 8a illustrates the outcome of this analysis, showing that approximately 50 percent of the wetlands had reached the recovery threshold by 2022. The share of recovered wetlands began increasing around 1995, possibly reflecting a period of reduced forest harvest or improved management practices.

At the same time, it is worth noting that 20 years is only an estimate. As was mentioned earlier, many studies suggest that wetlands often need more time to recover and may never fully regain all of their ecological functions. Allowing a more extended recovery period increases the chances that wetlands can rebuild their complexity and functionality. The graph also shows that the number of wetlands with no detectable disturbance since 1974 is declining. It is especially concerning given that the Hoh River watershed is relatively undeveloped and benefits from partial protection of Olympic National Park. Even in this setting, long-term undisturbed wetlands are becoming less common.

However, it is essential to acknowledge a limitation of this analysis. The available disturbance data begin in 1974, which means there is no record of what occurred before that year. Any wetland area that appears undisturbed between 1974 and 2022 may have experienced disturbance before 1974 (shown in green in ***Figure 8b)***. While they may be long undisturbed, I cannot validate that conclusion with the existing dataset. ***Figure 8b*** addresses the shortcomings of the previous analysis by removing the first 20 years of data, since any disturbances before 1974 are unknown and could affect the accuracy of recovery estimates. To provide a clearer view of more reliable trends, this figure begins in 1995. It consolidates the data into two categories: wetlands that are either undisturbed since 1974 or have recovered based on the 20-year benchmark, and wetlands that remain disturbed and unrecovered. This approach reduces uncertainty and highlights broader patterns of change. By 2020, the share of disturbed and unrecovered wetlands will decline to about 23 percent, suggesting a shift toward recovery across the watershed.

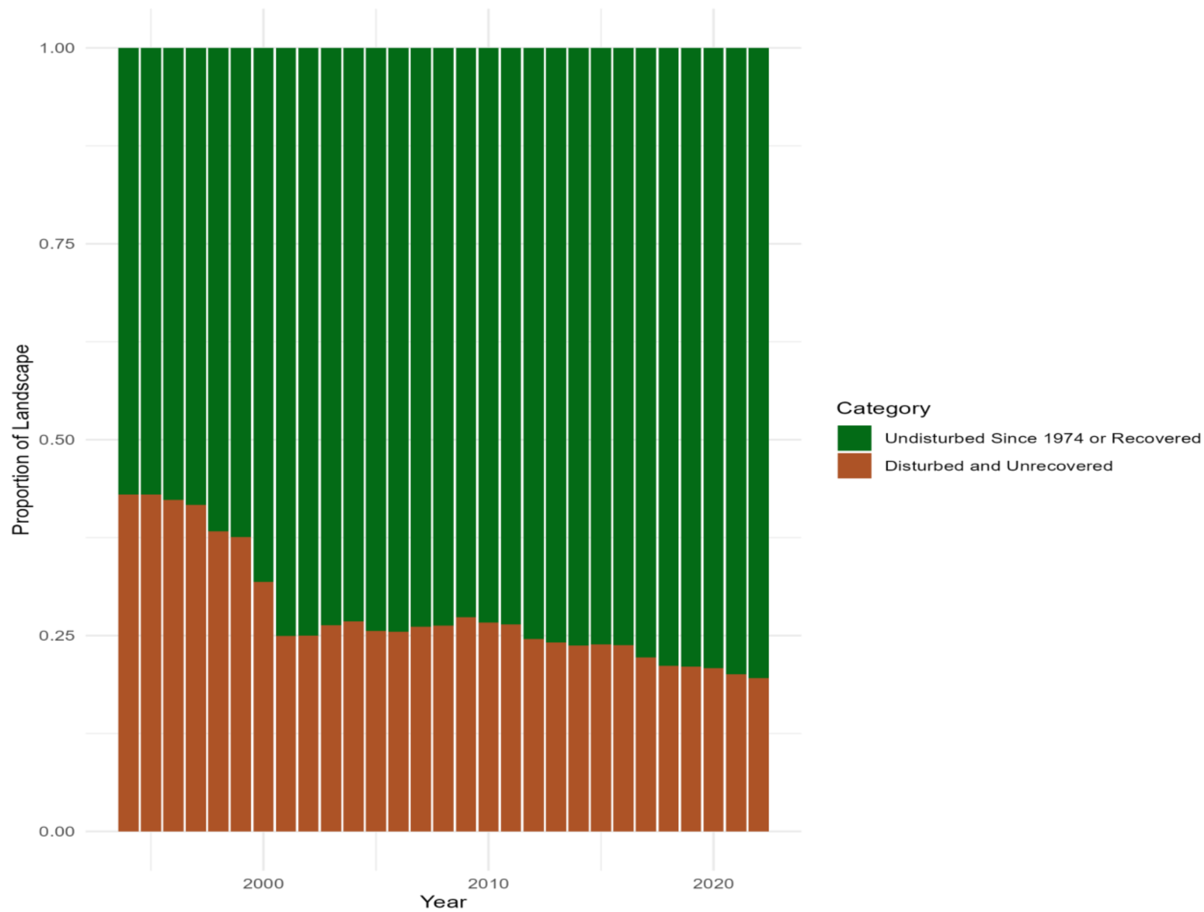


Figure 8b *Forested wetland recovery trends in the Hoh watershed beginning in 1995. This figure excludes the first 20 years of data to reduce uncertainty from unknown pre-1974 disturbances. It groups wetlands into two categories: those undisturbed since 1974 or recovered based on the 20-year threshold (green), and those that remain disturbed and unrecovered (brown).*

This recovery-based perspective complements the disturbance-focused analysis by offering a broader view of long-term trends. Although it does not provide direct evidence of ecological health or function, it helps set the foundation for deeper statistical evaluation of potential policy impacts.

To visualize where long-term undisturbed wetlands were located within the Hoh watershed and to understand how they correspond to different ownership categories, I developed a series of maps tied to various starting points in time. For example, ***Figure 9*** shows undisturbed wetlands as of 1992, which represents the midpoint of the disturbance dataset. I identified wetland areas that remained free of detectable disturbance from 1992 through 2022 and classified them by ownership type.

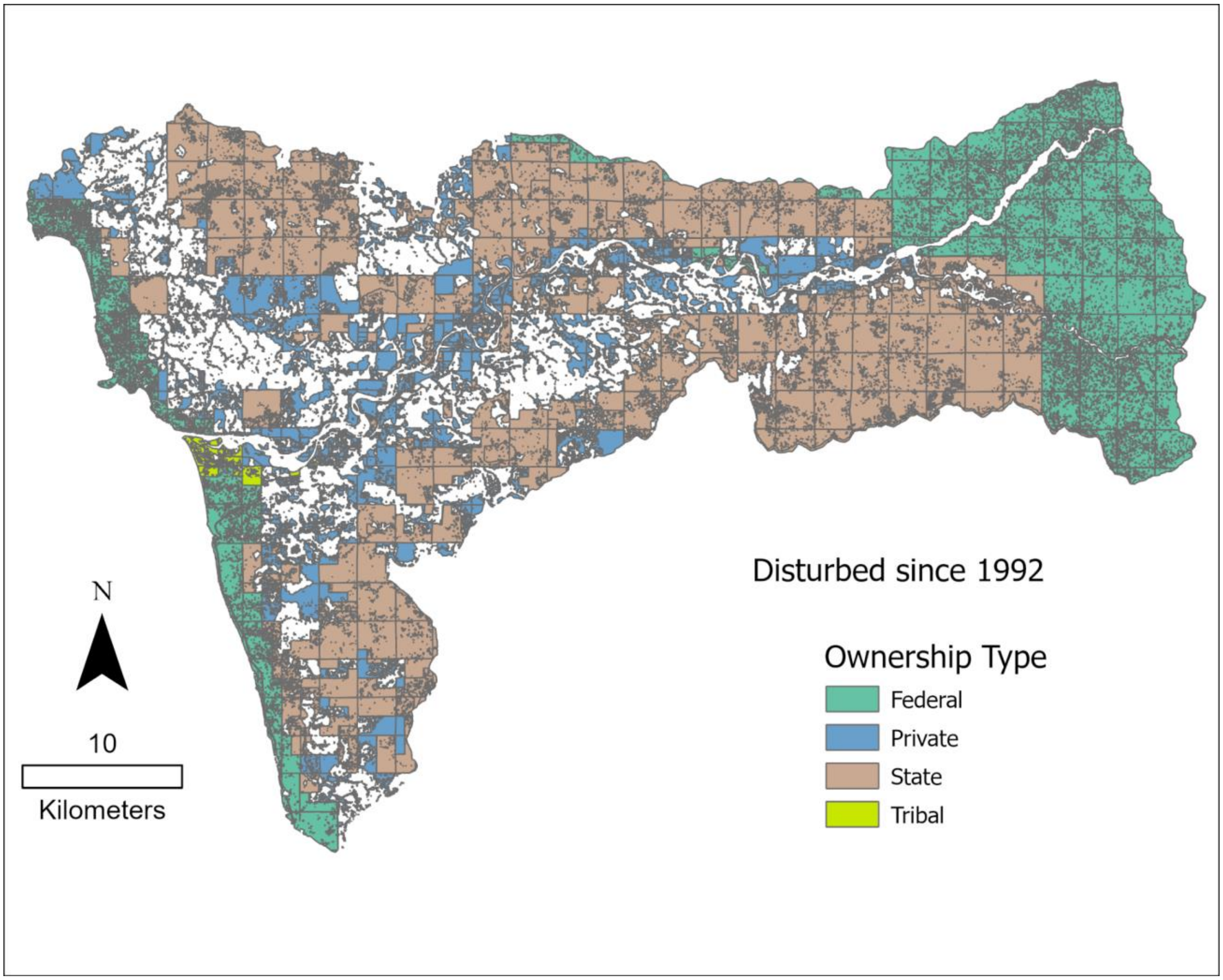


Figure 9 *Map of disturbed forested wetlands in the Hoh watershed as of 1992, defined as areas with a recorded disturbance from 1992 through 2022, were based on LandTrendr analysis. The map categorizes these wetlands by ownership class (federal, state, private, or other) and provides spatial context for understanding how ownership may influence forest harvest patterns. Basemap imagery and spatial layers were created in ArcGIS Pro.*

The spatial overview adds another layer of understanding by showing where undisturbed wetlands are across the Hoh watershed. It also helps reveal how different types of land ownership and management may play a role in whether wetlands stay undisturbed over time.

3.3 Synthetic Control Approach (Landscape Scale)

As described previously in ***Section 2.5***, SCMs estimate the difference between the treatment group pre-treatment and the treatment group post-treatment. I compare this to how the control group changed between the pre-policy and post-policy periods (***Figure 10***). Initially, I assumed that the difference between these two differences is likely due to the impact of the policy. However, when I ran the analysis, the results did not support that assumption, suggesting that the policy might not have had a measurable effect on wetland harvest by itself.

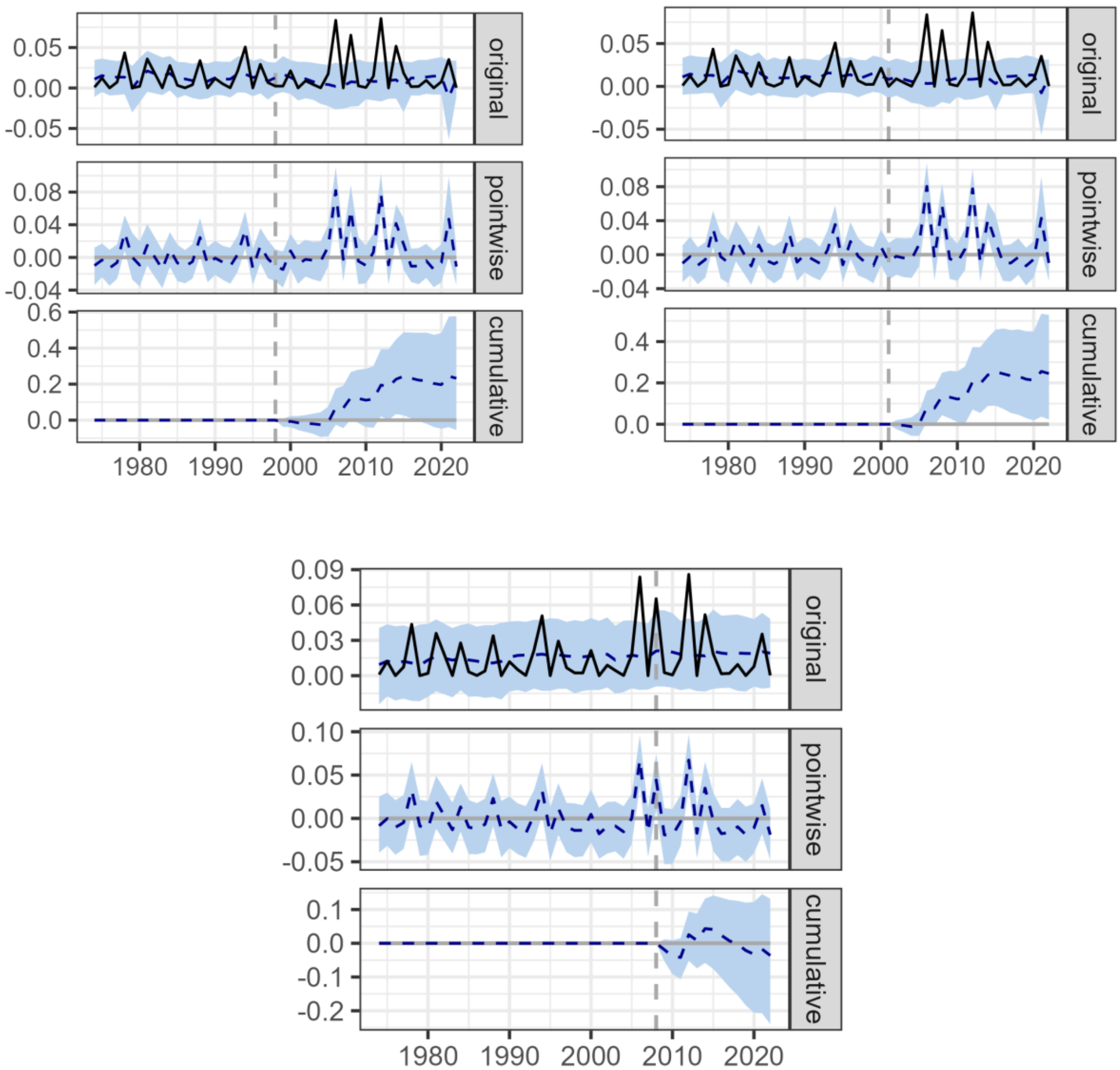


Figure 10 *Results of the synthetic control analysis evaluating three policy interventions (1998, 2001, and 2008) on forested wetland harvest in the Hoh watershed. Each row within the panels represents a different visualization of the assumed policy effect: the top row shows the actual and predicted forest harvest over time, the middle row shows the pointwise differences, and the bottom row displays the cumulative difference between observed and counterfactual outcomes. The shaded blue areas represent 95 percent confidence intervals.*

For the WAC 173-226 (1998) policy, the cumulative post-intervention forest harvest level was approximately 0.434 km². In contrast, the model predicted an cumulative amount of 0.202 if the policy had not been implemented. The estimated causal effect of the policy was 0.232, meaning an increase in logging, but the 95 percent confidence interval ranged from -0.053 to 0.580. Because this interval includes zero, the result is less conclusive and the p value of 0.06 indicates it is not statistically significant.

WAC 222-30-020 (2001) intervention observed a cumulative forest harvest post-intervention of 0.410, compared to a predicted 0.165 in the absence of the policy. The estimated causal effect was 0.245, with a confidence interval ranging from 0.031 to 0.526. While the p-value was 0.01, the fact that the SCM indicated an increase in harvest due to the law makes it difficult to interpret.

Finally, the 2008 FMR saw a cumulative impact of -0.03 , with a confidence interval ranging from -0.217 to 0.138 and a p value of 0.37. According to my analysis, none of the three policies significantly impacted forest harvest in wetlands. These outcomes underscore the importance of adding relevant covariates and refining model assumptions to increase the explanatory power of synthetic control methods. Expanding the analysis to include a broader set of policies may further strengthen inference; however, the overlapping and interacting nature of policy frameworks presents a methodological challenge for isolating individual policy effects.

3.4 Synthetic Control Approach (Controlled for Ownership)

Although no statistically significant effects were detected when forest harvest patterns were analyzed across all ownership categories collectively, stratifying the synthetic control analysis by ownership type revealed more nuanced responses. When ownership classes were evaluated independently, certain policy periods were associated with statistically detectable changes for specific ownership categories.

Table 4: Synthetic Control Treatment Effects by Ownership

	WAC 173-226 (1998)	**WAC 222-30-020 (2001)**	**Federal Mitigation Rule (2008)**

Table 4: Synthetic Control Treatment Effects by Ownership			
	Causal effect [confidence interval] (p-value)		
All Ownership	0.23 [-0.05, 0.58] (p=0.06)	**0.245 [0.02, 0.52] (p=0.02)**	-0.04 [-0.23, 0.13] (p=0.37)
Federal	-0.03 [-0.08, 0.01] (p=0.09)	**-0.036 [-0.075, 0.00] (p=0.03)**	**-0.022 [-0.05, 0.00] (p=0.04)**
State	**-0.17 [-0.33, 0.00] (p=0.04)**	-0.13 [-0.265, 0.05] (p=0.06)	-0.02 [-0.13, 0.08] (p= 0.35)
Municipal	0.00 [0.00,0.00] (p=0.16)	0.00 [0.00,0.00] (p=0.20)	0.00 [0.00,0.00] (p=0.40)
Private	-0.22 [-0.44, 0.06] (p=0.09)	-0.15 [-0.35, 0.05] (p=0.11)	**-0.11 [-0.19, -0.02] (p=0.01)**
Conservation	0.05 [-0.16, 0.29] (p=0.39)	-0.014 [-0.15, 0.19] (p=0.37)	**-0.07 [-0.14, 0.00] (p=0.02)**
Other	0.05 [-0.16, 0.28] p=(0.37)	0.00 [0.00, 0.00] (p=0.31)	0.00[0.00, 0.00] (p=0.10)

Based on reported p-values, two policy periods exhibited statistically significant responses on federal lands. Following the implementation of WAC 222-30-020 (2001), federal lands showed a negative treatment effect (p = 0.04), and a similar statistically significant response was observed following the FMR (2008) (p = 0.03). Within the synthetic control framework, federal lands experienced measurable deviations from their counterfactual trends during these periods. This suggests that harvest inf wetlands decreased after management changes in 2001 and 2008 by a small amount. Notably, the Northwest Forest Plan (1994) substantially reduced timber harvest on federal lands in the Pacific Northwest, meaning that the baseline level of forest harvest following its implementation was already low; as a result, the marginal effects of subsequent policies on logging were expected to be limited.

Similarly, WAC 173-226 (1998) was associated with a statistically significant negative effect on state-managed lands ($p = 0.04$), indicating that state lands exhibited a detectable departure from modeled baseline forest harvest trends following this regulatory period.

However, several other ownership categories exhibited relatively low p-values while their corresponding confidence intervals crossed zero (Conservation for 2008). In such cases, although the p-value approaches conventional significance thresholds, the crossing of zero within the confidence interval indicates statistical uncertainty regarding the direction and magnitude of the effect. These findings therefore cannot be interpreted as robust evidence of policy-associated change. "Municipal" and "other" ownership classes consistently showed no statistically significant effects, and conservation lands exhibited mixed results with wide confidence intervals.

The synthetic control analysis reveals statistically significant reductions in forested wetland harvest across multiple ownership categories following selected policy interventions (***Figure 11a–d***). The 1998 policy implementation on state-managed lands corresponds with the largest estimated reduction (−0.17 km^2), suggesting a measurable divergence from the counterfactual forest harvest trajectory. Similarly, the 2001 and 2008 interventions on federally managed lands are associated with smaller but statistically significant declines in logging (−0.036 km^2 and −0.022 km^2, respectively). Although the upper bounds of the confidence intervals for these federal estimates approach zero, the results remain significant at the 0.05 level, indicating consistent directional effects. Notably, the 2008 policy intervention on private lands demonstrates a comparatively larger and more robust reduction (−0.11 km^2), with a confidence interval fully below zero

(Figure 11d). This suggests that logging on private forestlands diverged more substantially from predicted trends following the policy's enactment. Across all ownership types examined, the negative treatment effects indicate lower observed forest harvest relative to modeled counterfactual trajectories, consistent with the hypothesis that these regulatory interventions may have contributed to reductions in forested wetland anthropogenic disturbance.

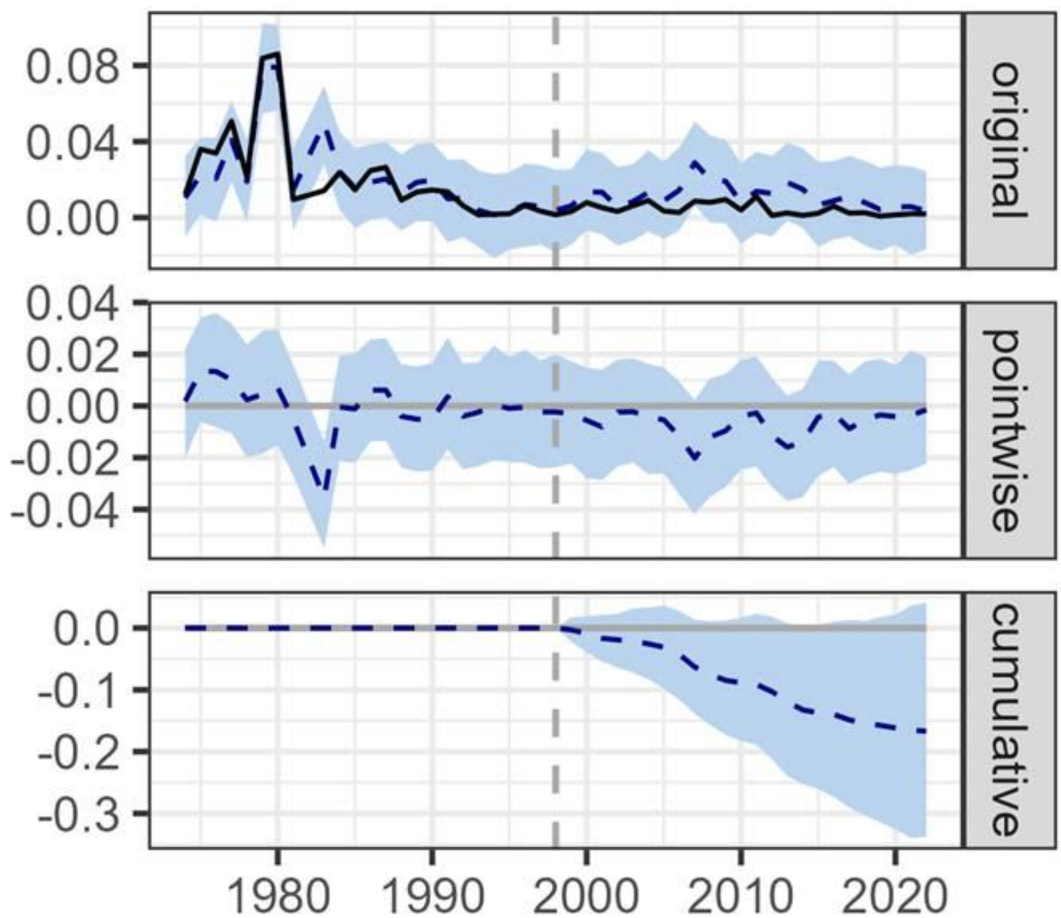


Figure 11a *Estimated effect of the 1998 policy intervention on state–owned forestlands in the Hoh watershed derived from the synthetic*

control analysis. The average post-policy treatment effect indicates a reduction in forested wetland anthropogenic disturbance of −0.17 km² (95% CI: −0.33 to 0.00; p = 0.04) relative to the counterfactual scenario. Negative values indicate lower observed forest harvest compared to the predicted no-policy trajectory.

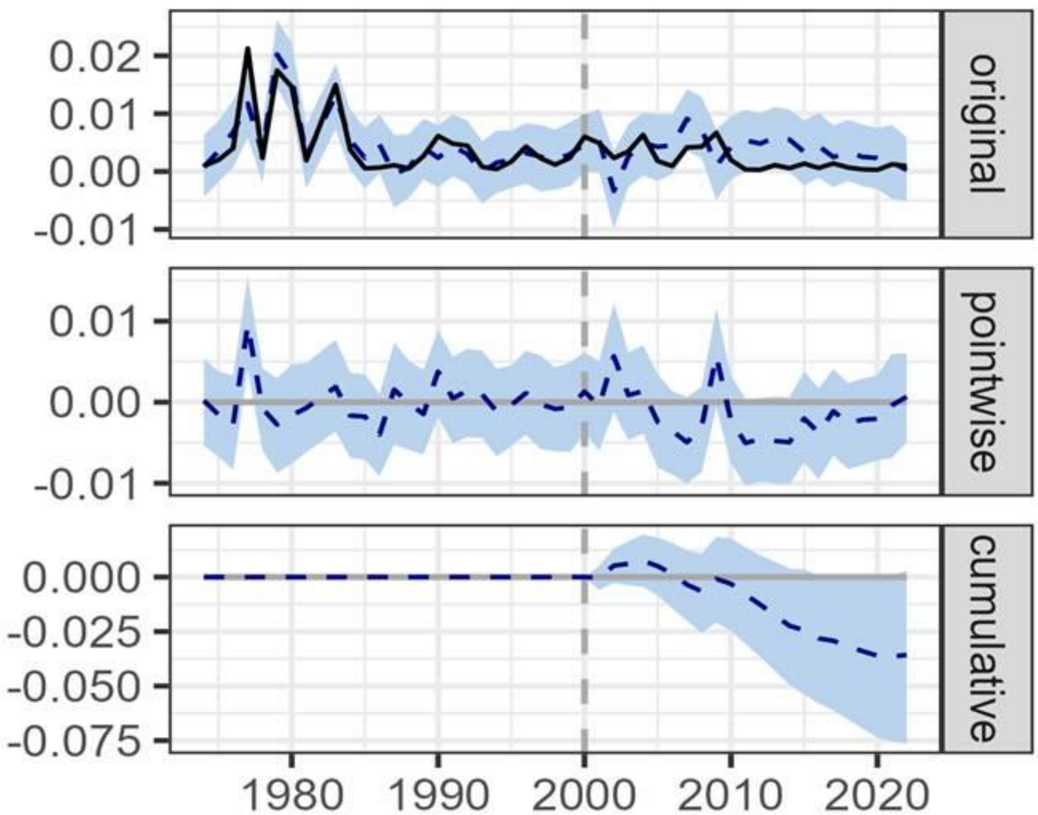


Figure 11b *Estimated effect of the 2001 policy intervention on federally managed forestlands in the Hoh watershed. The synthetic control model indicates a reduction in forested wetland anthropogenic disturbance of −0.036 km² (95% CI: −0.075 to 0.00; p = 0.03) relative to the counterfactual. The confidence interval approaches zero at the upper bound, but the effect remains statistically significant at the 0.05 level.*

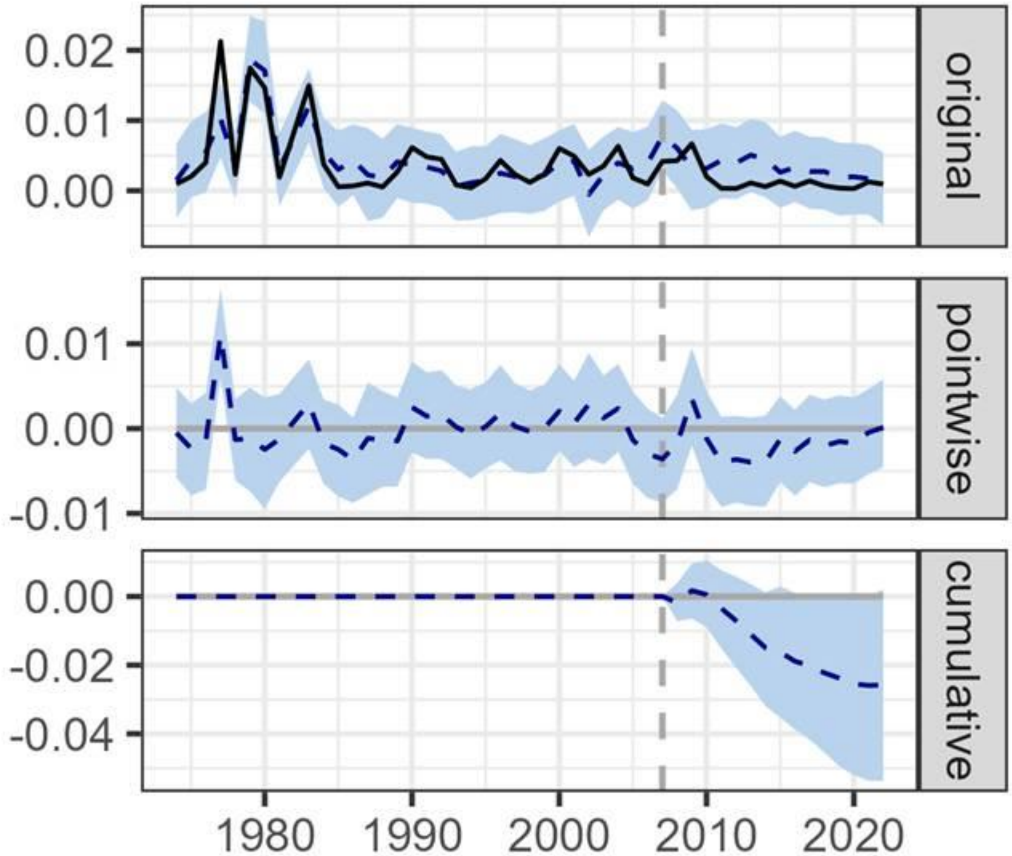


Figure 11c *Estimated effect of the 2008 policy intervention on federally managed forestlands. The analysis indicates a reduction in forested wetland anthropogenic disturbance of −0.022 km² (95% CI: −0.05 to 0.00; p = 0.04) relative to predicted forest harvest in the absence of the policy intervention.*

Taken together, these results suggest that aggregating forest harvest patterns across ownership types may obscure ownership-specific responses. At the same time, the statistical signals detected for certain ownership classes should be interpreted cautiously, as effect sizes were modest and confidence intervals frequently approached zero. These findings reinforce the importance of ownership context in mediating how regulatory changes may manifest across forested landscapes, while also highlighting the limitations of attributing forest harvest dynamics directly to specific policy interventions.

4. Discussion

4.1 Forest Harvest Dynamics in Forested Wetlands

The primary contribution of this research lies in the development and application of a spatially explicit framework to quantify long-term forest harvest dynamics in forested wetlands within the Hoh watershed. By leveraging LandTrender-derived disturbance detection and wetland probability mapping, this study provides one of the first temporally continuous assessments of anthropogenic disturbance in forested wetlands from 1974 to 2022. The results indicate clear temporal variability in forest harvest intensity over time and demonstrate meaningful differences across land ownership categories.

Although the watershed as a whole exhibits a general decline in logging following the high-activity decades of the 1970s and early 1980s, these aggregate trends mask substantial variation across ownership types. State-managed lands show pronounced reductions following earlier forest harvest peaks, while private industrial lands exhibit more sustained activity patterns with later declines. Municipal and conservation lands display consistently low forest harvest levels, reflecting either restrictive management regimes or limited harvestable area. These findings suggest that ownership structure is not merely a contextual variable but may represent an important mediating factor in landscape-level forest harvest dynamics.

The recovery-based analysis further complements this disturbance-focused perspective. Approximately half of forested wetlands met the 20-year undisturbed benchmark by 2022, suggesting that a substantial portion of the landscape has experienced prolonged periods without detectable forest harvest. However, the declining share of wetlands undisturbed since 1974 highlights the cumulative nature of disturbance over time. Even within a relatively protected watershed that includes significant federal holdings and adjacency to Olympic National Park, long-term undisturbed wetlands are becoming less common. This underscores the importance of examining both disturbance frequency and recovery intervals when evaluating wetland resilience.

4.2 Policy Signals and Statistical Interpretation

A central objective of this study was to explore whether regulatory timelines could be meaningfully examined alongside forest harvest trends using a synthetic control framework. At the landscape scale, none of the three selected regulatory interventions produced statistically significant reductions in forest harvest. Although effect estimates were consistently negative—suggesting potential reductions—the associated confidence intervals crossed zero and p-values exceeded conventional thresholds. These results indicate that, at an aggregated watershed level, detectable policy effects could not be statistically confirmed. However, stratifying the analysis by ownership revealed more nuanced responses. Certain policy periods were associated with statistically detectable deviations for specific ownership categories. In particular, WAC 222-30-020 (2001) and the FMR (2008) corresponded with statistically significant negative effects on federal lands, while WAC 173-226 (1998) was associated with a significant effect on state-managed lands. These signals suggest that regulatory changes may manifest differently depending on jurisdictional context and management structure.

At the same time, caution is warranted. Several ownership categories exhibited relatively low p-values while their confidence intervals included zero, indicating statistical uncertainty regarding the direction and magnitude of estimated effects. Effect sizes were modest, and overlapping regulatory regimes complicate attribution. The gradual and non-uniform forest harvest patterns observed in this analysis are consistent with broader findings from long-term federal monitoring under the Northwest Forest Plan. Miller et al. (2017), in their 20-year watershed condition assessment across federally managed lands in the Pacific Northwest, found that ecological condition trajectories rarely correspond to discrete regulatory implementation dates and instead reflect cumulative management histories, legacy logging effects, and spatial heterogeneity. Their analysis emphasizes that improvements in watershed condition unfold gradually and unevenly across landscapes, rather than as abrupt responses to singular policy enactments. Similarly, the forest harvest signals detected here do not indicate sharp inflection points following policy adoption but instead reveal incremental shifts embedded within broader landscape dynamics. Therefore, these findings should not be interpreted as definitive evidence of policy-driven reductions in forest harvest, but rather as exploratory signals that ownership context may condition how regulatory interventions translate into measurable landscape outcomes.

4.3 Ownership as a Mediating Factor

One of the most consistent findings of this study is the importance of land ownership in shaping forest harvest patterns. Differences in logging intensity and response to regulatory periods suggest that governance structure, management objectives, and economic incentives vary meaningfully across ownership categories.

Federal lands, often subject to additional environmental oversight and administrative review processes, exhibited statistically detectable responses in certain policy periods. State-managed lands demonstrated measurable shifts following specific regulatory interventions, potentially reflecting internal implementation dynamics or management reforms. In contrast, private lands displayed more sustained forest harvest activity over time, consistent with market-driven timber harvest cycles and economic pressures. Municipal and conservation lands, characterized by limited logging variability, may lack sufficient fluctuation to produce statistically detectable treatment effects.

These patterns reinforce the notion that policy does not operate uniformly across landscapes. Instead, regulatory instruments interact with preexisting governance structures, management cultures, and economic conditions. Aggregating forest harvest trends across ownership types may therefore obscure policy-relevant signals that become more visible when analyzed within institutional strata.

4.4 Methodological Reflections

The integration of geospatial forest harvest analysis with policy chronology presents several methodological challenges. First, environmental legislation often functions as a broad statutory framework implemented gradually through subsequent rulemaking, guidance, and enforcement. This temporal diffusion complicates attempts to isolate discrete “treatment” effects. Second, multiple overlapping policies operate concurrently, making it difficult to disentangle the influence of any single intervention.

Additionally, disturbance detection reflects observable canopy-level change rather than ecological function. Wetland recovery benchmarks based on disturbance absence provide useful proxies but cannot fully capture hydrologic or biogeochemical restoration processes. Furthermore, the relatively protected status of the Hoh watershed may limit detectable variability, reducing statistical power for policy evaluation.

The synthetic control method offers a structured approach for estimating counterfactual forest harvest trajectories, yet its sensitivity depends heavily on predictor variables and model specification. Although timber harvest volume was incorporated as a proxy for regional forestry activity, additional covariates—such as precipitation trends, streamflow variability, localized enforcement intensity, or finer-scale management indicators—may improve model performance in future applications.

4.5 Implications and Future Research

This research demonstrates that long-term forest harvest dynamics in forested wetlands can be quantified using remote sensing tools and that ownership stratification reveals meaningful variation in logging patterns. While definitive causal attribution to specific policies was not established, the exploratory alignment of regulatory timelines with forest harvest data suggests that further refinement of this approach may yield stronger analytical insights.

Future research could expand this framework to more intensively managed or rapidly developing watersheds, where greater disturbance variability may enhance statistical detectability. Incorporating additional socio-economic and climatic predictors, modeling lag effects more explicitly, and integrating enforcement or compliance data could strengthen causal inference. A deeper examination of tribal governance and co-management authority would also enrich understanding of how sovereign regulatory systems interact with landscape-level ecological change.

Ultimately, this study does not claim to establish causal impacts of environmental policy on forested wetland anthropogenic disturbance. Rather, it demonstrates that spatially explicit forest harvest analysis can serve as a foundational platform for more rigorous policy evaluation. By combining long-term ecological data with structured governance timelines, this research initiates a methodological pathway for future investigations seeking to better understand the relationship between environmental regulation and landscape transformation.

5. Key Findings

This study provides a comprehensive assessment of forest ahrvest dynamics in forested wetlands within the Hoh River watershed using Landsat time series analysis and ownership-based comparisons. Several key findings emerge from this analysis:

1) No distinct inflection points in forest harvest trends correspond to the implementation of major policies, indicating that policy effects are not immediately observable in landscape-scale disturbance patterns.
2) Forest harvest in Hoh Watershed is present across all ownership types, including protected areas, indicating that protection status does not eliminate forest harvest but alters its magnitude and likely its drivers.
3) Forest harvest occurs continuously throughout the study period rather than as isolated events, indicating sustained landscape-level pressure rather than episodic change.
4) Forest harvest is spatially heterogeneous across the watershed, reflecting the influence of localized management practices, accessibility, and ownership boundaries.
5) Time-series remote sensing provides a consistent and scalable means of detecting disturbance across complex landscapes, but it captures disturbance as an integrated signal rather than isolating individual causal mechanisms.
6) Although post-disturbance recovery is consistently observed in the spectral signal, many areas do not return to pre-disturbance conditions within the study period, indicating partial or prolonged recovery trajectories. Approximately only 50% of forested wetlands reached the defined recovery threshold by 2022.

7) The share of wetlands with no detectable disturbance since 1974 is steadily declining.
8) Recovery patterns are sensitive to methodological assumptions, particularly the use of a 20-year recovery threshold and the lack of pre-1974 disturbance data, which introduces uncertainty in identifying truly undisturbed wetlands.
9) Spatial analysis reveals that long-term undisturbed wetlands are unevenly distributed across the watershed, with patterns that correspond to ownership categories, suggesting that land management practices influence the likelihood of wetlands remaining undisturbed.

6. Conclusions

This thesis investigated long-term forest ahrvest dynamics in forested wetlands within the Hoh watershed and evaluated whether those dynamics can be examined in relation to environmental regulation. The results demonstrate clear temporal variation in logging intensity and, critically, reveal consistent differences across ownership categories for Hoh watershed wetland areas between 1974 to 2022.

Ownership emerged as a central organizing factor in understanding landscape change. Forest harvest trajectories differed between state, federal, private, and conservation lands, indicating that management regimes and institutional contexts shape how forested wetlands experience anthropogenic disturbance over time. These patterns were not evident when forest harvest was evaluated at the watershed scale alone, underscoring the importance of disaggregating ecological data by governance structure.

The attempt to evaluate policy interventions through a synthetic control framework did not produce statistically significant effects at the aggregate landscape level. However, ownership-stratified models identified measurable deviations in specific regulatory periods, particularly on federal and state lands. While these results do not establish definitive causal attribution, they demonstrate that policy signals are not uniformly distributed across ownership classes and may be detectable when institutional context is explicitly incorporated into analysis.

The principal achievement of this research lies in demonstrating that forest harvest trends in forested wetlands can be systematically quantified and meaningfully organized alongside governance timelines. Although the policy component remains exploratory, the analytical structure developed here provides a replicable foundation for more rigorous causal investigation.

Environmental legislation often aspires to influence landscape outcomes, yet empirical tools capable of testing those aspirations remain limited. This research contributes to that gap by establishing a structured pathway for assessing how regulatory systems and management regimes intersect with observable forest harvest dynamics. It offers a foundation for more targeted and adaptive wetland management in the Pacific Northwest and beyond. Future work should explore additional ecological indicators, refine recovery benchmarks, and examine how climate change and economic shifts may reshape wetland vulnerability in the coming decades.

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8. Appendix [1]

List of Acronyms and Abbreviations

Clean Water Act (1972)	CWA
Washington Department of Natural Resources	DNR
Determination of Non-Significance	DNS
Environmental Impact Statement	EIS
Endangered Species Act (1973)	ESA
Federal Mitigation Rule	FMR
Forest Practices Act (1974)	FPA
Forest Practices Habitat Conservation Plan	FPHCP
Forest Practices Rules	FPR
Google Earth Engine	GEE
Growth Management Act (1990)	GMA
Habitat Conservation Plans	HCP
Hydraulic Project Approval	HPA
kilometers	km
Low Impact Development	LID
Mitigated Determination of Non-Significance	MDNS
Memorandum of Agreement	MOA
Multiple-Use Sustained-Yield Act	MUSY
Normalized Burn Ratio	NBR
Normalized Difference Vegetation Index	NDVI
National Environmental Policy Act	NEPA
National Land Cover Dataset	NLCD
National Pollutant Discharge Elimination System	NPDES
Natural Resource Spatial Informatics Group	NRSIG
Northwest Indian Fisheries Commission	NWIFC
Revised Washington Code	RCW
synthetic control method	SCM
State Environmental Policy Act (1971)	SEPA

total maximum daily load	TMDL
United States Environmental Protection Agency	U.S. EPA
United States Department of Agriculture	USDA
United States Department of the Interior	USDI
United States Forest Service	USFS
Washington State	WA
Washington Administrative Code	WAC
Wetland Intrinsic Potential	WIP
Waters of the United States	WOTUS
Water Pollution and Control Act (1945)	WPCA
Washington Wetland Program Plan	WPP

Appendix [2]

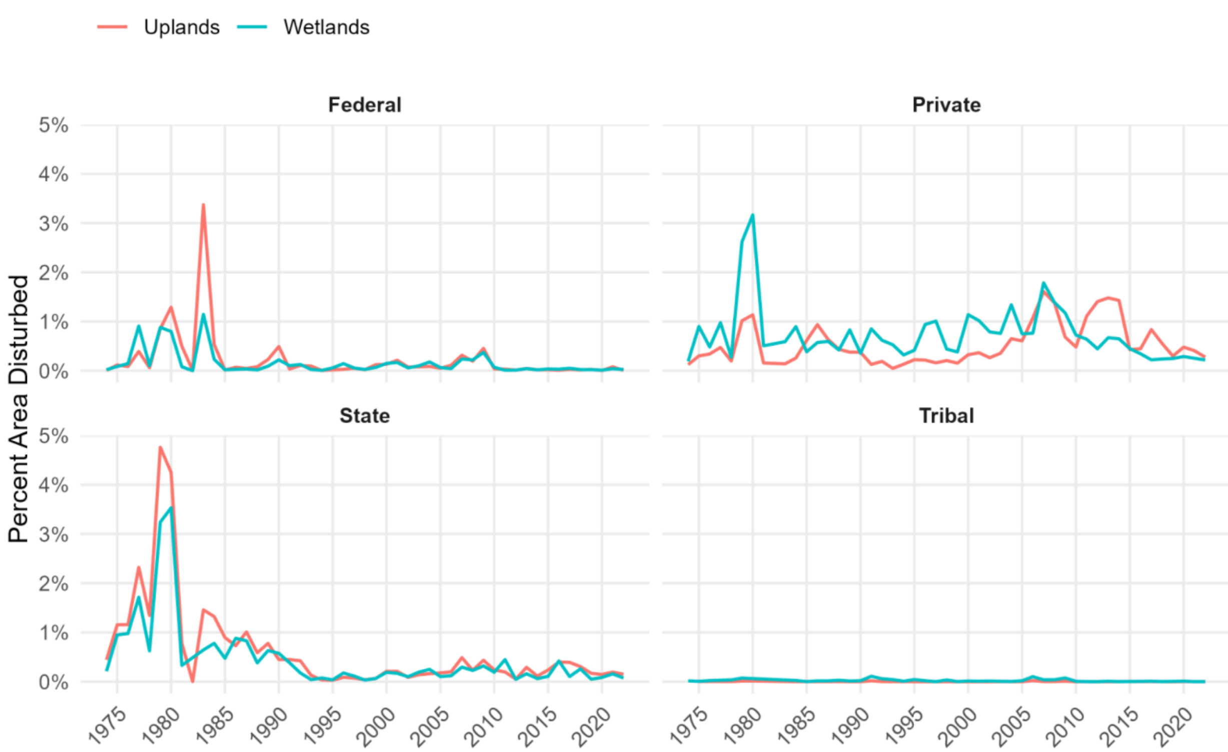

Figure 11 *Percentage of total harvested area occurring within wetlands and uplands in the Hoh River watershed from 1974 to 2022. Values are expressed as a proportion of total annual harvest area to illustrate relative forest harvest intensity between land cover types over time.*