Forested Wetlands Effectiveness Project

Chronosequence Study Design

Nate Hough-Snee, Paul Adamus, Leah Beckett, Kevin Bladon, Howard Haemmerle, Dan Moore, Dan Sobota, John Van Sickle

Cooperative Monitoring
Evaluation & Research

CMER
2019.December.17

This Page intentionally left blank

Washington State
Cooperative Monitoring, Evaluation, and Research Committee (CMER) Document

Forested Wetlands Effectiveness Project Chronosequence Study Design

Prepared by
Nate Hough-Snee, Paul Adamus, Leah Beckett, Kevin Bladon, Howard Haemmerle, Dan Moore, Dan Sobota, John Van Sickle

Prepared for the
Wetlands Science Advisory Group
of the
Cooperative Monitoring, Evaluation, and Research Committee (CMER)
of the

Washington State Forest Practices Board
Adaptive Management Program
Washington State Department of Natural Resources
Olympia, Washington

CMER 2019.December.17

Washington State Forest Practices Adaptive Management Program

The Washington Forest Practices Board (FPB) has adopted an adaptive management program in concurrence with the Forests and Fish Report (FFR) and subsequent legislation. The purpose of this program is to:

> Provide science-based recommendations and technical information to assist the board in determining if and when it is necessary or advisable to adjust rules and guidance for aquatic resources to achieve resource goals and objectives. (Forest Practices Rules, WAC 222-12-045)

To provide the science needed to support adaptive management, the FPB made the Cooperative Monitoring, Evaluation and Research Committee (CMER) a participant in the program. The FPB empowered CMER to conduct research, effectiveness monitoring, and validation monitoring in accordance with guidelines recommended in the FFR.

Document Type and Disclaimer

This Study Design was prepared for the Cooperative Monitoring, Evaluation and Research Committee (CMER) to support design and implementation of Forest and Fish Adaptive Management research and monitoring studies. The project is part of the Forested Wetland Program Program and was conducted under the oversight of the Wetlands Science Advisory Group.

This Study Design was reviewed and approved by CMER and was reviewed and approved through the Adaptive Management Program's independent scientific peer review process (ISPR)[1]. As a CMER document, CMER is in consensus on the scientific merit, conclusions, and interpretations of the document. Recommendations contained within this document are those of the authors and may not reflect the views of any or all CMER members.

The Forest Practices Board, CMER, and all the participants in the Forest Practices Adaptive Management Program hereby expressly disclaim all warranties of accuracy or fitness for any use of this document other than for the Adaptive Management Program. Reliance on the contents of this document by any persons or entities outside of the Adaptive Management Program established by WAC 222-12-045 is solely at the risk of the user.

Proprietary Statement

This work was developed with public funding, as such it is within the public use domain. However, the concept of this work originated with the Washington State Forest Practices Adaptive Management Program and the authors. As a public resource document, this work should be given proper attribution and be properly cited.

---

[1] a process used to "determine if the scientific studies that address program issues are scientifically sound and technically reliable; and provide advice on the scientific basis or reliability of CMER's reports" (Board Manual Section 22.4.1).

Full Reference

Hough-Snee, Nate. Paul Adamus, Leah Beckett, Kevin Bladon, Howard Haemmerle, Dan Moore, Dan Sobota, John Van Sickle. 2019. Forested Wetlands Effectiveness Project: Chronosequence Study Design. Cooperative Monitoring Evaluation and Research. 12-17-2019. Washington Department of Natural Resources, Olympia, WA.

Author Contact Information

Nate Hough-Snee
Meadow Run Environmental
nate@meadowrunenv.com

Forested Wetlands Effectiveness Project
Chronosequence Study Design

Forested Wetland Effectiveness Project Technical Writing and Implementation Group:
Nate Hough-Snee, Paul Adamus, Leah Beckett, Kevin Bladon, Howard Haemmerle, Dan Moore,
Dan Sobota, John Van Sickle

Cooperative Monitoring, Evaluation, and Research Committee
Washington State Department of Natural Resources
Adaptive Management Program

December 2019

TABLE OF CONTENTS

Common abbreviations and acronyms within the study design document.

Abbreviation	**Term**
AMP	Washington State Department of Natural Resources Adaptive Management Program
cfs	cubic feet per second
CMER	Cooperative Monitoring, Evaluation, and Research Committee
DNR	Washington State Department of Natural Resources
FPA	Forest Practices Application
FPHCP	Forest Practices Habitat Conservation Plan
FWEP	Forested Wetlands Effectiveness Project
MBACI; BACI	Multiple Before-After-Control-Impact Study Design
Policy	Timber/Fish/Wildlife (TFW) policy committee
QA/QC	Quality assurance – quality control
RCBD	Randomized-Complete-Block Study Design
Title 222 WAC	Washington State Forest Practices Act
TMDL	Total Maximum Daily Load
TWIG	Technical Writing and Implementation Group
WAC	Washington Administrative Code
WetSAG	Wetlands Scientific Advisory Group
WFPB; the Board	Washington State Forest Practices Board

FOREWORD

Policy Context and the History of the Forested Wetland Effectiveness Project

Washington State Forest Practices are regulated through the Forest Practices Act (Washington State Forest Practices Board 1975; Title 222 WAC) and forest practices rules adopted by the Washington Forest Practices Board (herein *the Board*). The Board is charged with administering a formal, science-based Adaptive Management Program (AMP) to provide technical information and science-based recommendations that assist the Board in determining if and when it is advisable to adjust rules and guidance to achieve the resource objectives and performance targets outlined in the Washington Forest Practices Habitat Conservation Plan (FPHCP; WA DNR 2005). The FPHCP's overall performance goals were designed to ensure that forest practices will not significantly impair aquatic habitats' capacity to:

a) Support harvestable levels of salmonids;
b) Support the long-term viability of other covered species; or
c) Meet or exceed water quality standards, including protection of beneficial uses, narrative and quantitative criteria, and anti-degradation (WAC 222-12-045).

The FPHCP's specific wetland-related resource objectives and performance targets are outlined in Appendix N of Schedule L-1 of the FPHCP and address a suite of interrelated hydrologic, geomorphic, and ecological aquatic habitat parameters. In support of the FPHCP's performance goals, these targets aspire to "no net loss" in the hydrologic and water quality functions of wetlands in and around working forest lands.

The Cooperative Monitoring, Evaluation, and Research Committee (CMER), which is assigned members and administered by the Board, is responsible for developing and executing studies that answer questions on whether resource objectives and performance targets are being met. Rule specific projects are listed and described in the CMER workplan (Cooperative Monitoring, Evaluation, and Research Committee 2017, 2019), which is updated every two years. Additionally, CMER relies on scientific advisory groups (SAGs) that, based on topical rule groups and programs, draft and update sections of the workplan and develop projects. Projects are prioritized by CMER based on the quality and quantity of available science underlying related forest practices rules and the potential risks that management under current rules may pose to aquatic resources (CMER 2017). The Wetlands Scientific Advisory Group (WetSAG) updates, revises, and recommends priorities for projects in the CMER work plan that pertain to the Wetlands Rule Group (WAC 222-30).

WetSAG, CMER, and Policy reprioritized the Forested Wetlands Effectiveness Project (FWEP) in 2014 after a proposed wetland road mitigation project was determined to be infeasible. This prioritization was based on several significant knowledge gaps in forest practice effects on wetlands, as well as the potential impacts that forest practices may have on wetlands' ecological, hydrological, and geomorphic functions. WetSAG requested and received funding for the Forested Wetlands Effectiveness Project from the Timber/Fish/Wildlife Policy Committee (herein Policy). The Board determined that the Forested Wetlands Effectiveness Project would follow a LEAN pilot process in which initial project development and experimental design would be conducted by a technical writing and implementation group (TWIG) comprised of experts in wetland ecology, hydrology, biogeochemistry, and forestry. The TWIG (Appendix 1;

Table A.1) was formed in late 2014 and began with the task of revising critical questions from the CMER workplan and writing broader study objectives. The critical questions and objectives that the FWEP TWIG identified were approved by Policy in January 2016. The TWIG met twice in the spring of 2016 to discuss study design alternatives in the context of the best available science on this topic. The best available science was initially compiled for WetSAG (Adamus 2014a) and then later approved by Policy (Beckett et al. 2016) to guide the development of the FWEP and subsequent wetland studies.

The Forested Wetlands Effectiveness Project's Best Available Science and Study Design Alternative Document (Beckett et al. 2016) outlines five potential study designs to answer the CMER-approved critical questions surrounding forested wetlands. In September 2017, the TWIG decided to prioritize two study designs, one of which is an observational, space-for-time chronosequence study, and the other a before-after-control-impact study (BACI). Both studies are designed to answer the critical questions identified in Adamus (2014b) and Beckett et al. (2016) and address key resource objectives and performance targets. The chronosequence is designed to precede and inform the design of the later BACI study and will go through CMER committee approval and begin implementation before the BACI study design is finalized and approved by CMER. The chronosequence was reviewed by WetSAG, CMER, and the Independent Scientific Peer Review panel (ISPR) in 2018, and revised in 2019 following ISPR's 2018 request for changes. Revisions were undertaken by the FWEP in spring of 2019 and reviewed by the ISPR editor in the summer/fall of 2019 before being revised and presented to CMER. The document that follows is the most up-to-date version of the chronosequence study (December 2019).

1. INTRODUCTION

1.1 Forested wetlands and Washington State Forest Practices Rules

Forested wetlands provide unique ecological and hydrological functions that support numerous and distinct aquatic and terrestrial biota (Richardson 1994, Sun et al. 2002). In Washington State, wetlands – "areas that are saturated or covered with water long enough and often enough that their soils and plants differ from those in nearby uplands (WAC 222-16-035)," are common across many ecoregions. Accordingly, Washington State Department of Natural Resources (DNR) forest practices rules (Title 222 WAC) categorize wetlands for management based on their hydrology and vegetation: forested wetlands, type A wetlands, and type B wetlands (Table 1.1). Current forest practices rules define forested wetlands ***as wetlands with at least 30% canopy cover of merchantable tree species*** (WAC 222-16-035). Within Washington State, forested wetlands often occur in and around actively managed commercial forest lands (Figure 1.1; Figure 1.2), and in many regions, forested wetlands also make up a majority of the wetlands that occur along and within the areas for which forest practices applications (FPAs) are submitted.

To better understand how forest practices impact forested wetlands, the DNR has commissioned the Forested Wetlands Effectiveness Project (FWEP), a team of scientists tasked with synthesizing the state of the science around forested wetlands and designing studies that quantify how forest practices impact wetland resources. Specifically, the FWEP will investigate if forest practices rules, as they apply to forested wetlands, are effective at:

1. Maintaining and/or restoring key wetland ecosystem functions; and
2. Meeting resource objectives and performance targets laid out in the Forest Practices Habitat Conservation Plan (FHCP) within one half of a timber rotation cycle (20-years, at minimum).

Forest Practices Rules Addressed by the Forested Wetland Effectiveness Program

There are several forest practices rules pertaining to forested wetlands and timber harvest, and a primary goal is "no net loss" of the spatial extent and function of wetlands on the landscape. Mirroring the federal Clean Water Act, in 1989, Booth Gardiner, Washington State's then governor, adopted a statewide policy of no net loss of area and function of wetlands, and this included forest practices[i]. Forest practices rules were subsequently developed to meet this statewide mandate (Title 222 WAC; Table 1.2).

---

[i] "It is the interim goal...to achieve no overall net loss in acreage and function of Washington's remaining wetlands base. It is further the long-term goal to increase the quantity and quality of Washington's wetlands resource base." (E.O. 89-10)

Table 1.1. Wetland typing system definitions used in DNR forest practices rules as defined in Washington Administrative Code (WAC-222-16-035).

Wetland Type	Description (Directly from WAC-222-16-035)	Notes
Forested wetlands	Any wetland or portion thereof that has, or if the trees were mature would have, a crown closure of 30 percent or more.	Any wetland
Type A wetlands	(i) Are greater than 0.5 acres in size, including any acreage of open water where the water is entirely surrounded by the wetland; and (ii) Are associated with at least 0.5 acres of ponded or standing open water. The open water must be present on the site for at least 7 consecutive days between April 1 and October 1 to be considered for these rules.	All forested and non-forested bogs greater than 0.25 acres shall be considered Type A wetlands.
Type B wetlands	Applied to all other non-forested wetlands greater than 0.25 acre.	Examples include scrub-shrub and meadow systems without ponded water

Table 1.2. Washington State Administrative Code (Title 222 and Title 220 WAC) forest practices rules that consider forested wetlands. These protections are not as comprehensive as those for non-forested wetlands (Type A and Type B wetlands).

Washington Administrative Code	Rule description as applied to forested wetlands
WAC 220-30-010	Wetland areas serve several significant functions in addition to timber production: Providing fish and wildlife habitat, protecting water quality, moderating, and preserving water quantity. Wetlands may also contain unique or rare ecological systems. The wetland management zone and wetland requirements specified in this chapter are designed to protect these wetland functions when measured over the length of a harvest rotation, although some functions may be reduced until the midpoint of the timber rotation cycle. Landowners are encouraged to voluntarily increase wetland acreage and functions over the long-term.
WAC 220-30-020 (6):	Forested wetlands. Within the wetland, unless otherwise approved in writing by the department, harvest methods shall be limited to low impact harvest or cable systems. Where feasible, at least one end of the log shall be suspended during yarding. Landowners are encouraged to retain leave-trees in forested wetlands. If the RMZ or WMZ lies within a forested wetland, leave tree requirements for those areas may be counted toward percentages of this subsection. Approximate determination of the boundaries and mapping of forested wetlands greater than 3 acres shall be required. The department shall consult with the Department of Fish and Wildlife and affected Indian tribes about site-specific impacts of forest practices on wetland-sensitive species in forested wetlands.
WAC 222-24-035	Minimize the placement and size of landings within forested wetlands.
WAC 222-30-070	Where harvest in wetlands is permitted, ground-based logging systems shall be limited to low impact harvest systems. Ground-based logging systems operating in wetlands shall only be allowed during a period of low soil moisture or frozen soil conditions.
WAC 222-12-045 (Forest Practices Rules):	Adaptive Management Program, Program Elements, Key questions, and resource objectives: Resource objectives are intended to ensure that forest practices, either singularly or cumulatively, will not significantly impair the capacity of aquatic habitat to: a) support harvestable levels of salmonids b) support the long-term viability of other covered species; or c) meet or exceed water quality standards (protection of beneficial uses, narrative and numeric criteria, and anti-degradation).

1.2 Problem Statement

Forested wetlands do not frequently occur on the harvest sites for which most forest practice applications (FPAs) are submitted (Figure 1.1). However, where wetlands do occur at FPA locations, forested wetlands are the most frequently occurring wetland type (Figure 1.2).

Although their habitat value, hydrological and ecological processes, and distributions on the landscape are not well understood (Adamus 2014a, Beckett et al. 2016), forested wetlands receive the least protection among wetland types defined within current Washington State forest practices rules (*Forest Practices Habitat Conservation Plan* 2005). Low-impact timber harvest is permitted in forested wetlands where there is a live-crown canopy closure of at least 30% of merchantable species, or where there would be such canopy if trees were mature (Table 1.2; WAC-222-16-035).

While Washington State's forest practices rules include wetland buffer protections and harvest restrictions in and around non-forested wetlands, forested wetlands do not currently receive these protections. Because fish-bearing streams (Type F streams), like Type A and Type B wetlands, have existing buffer rules to govern harvest, wetlands that are adjacent or connected to non-fish-bearing (Type N streams), are effectively those with the least protection under current forest practices rules (Beckett et al. 2016). Under current rules, forested wetlands may be harvested without buffering even though the effects of timber harvest and other forest practices on forested wetland structure and function have not been extensively studied. This poses a challenge to the adaptive management program because the impacts of timber harvest in and around forested wetlands on these ecosystems' hydrological, ecological, and habitat functions are not well understood (Beckett et al. 2016). Given the full range of forested wetland and forest types that occur within Washington State and are impacted by harvest, this knowledge gap is compounded when applying or revising relevant forest practices rules.

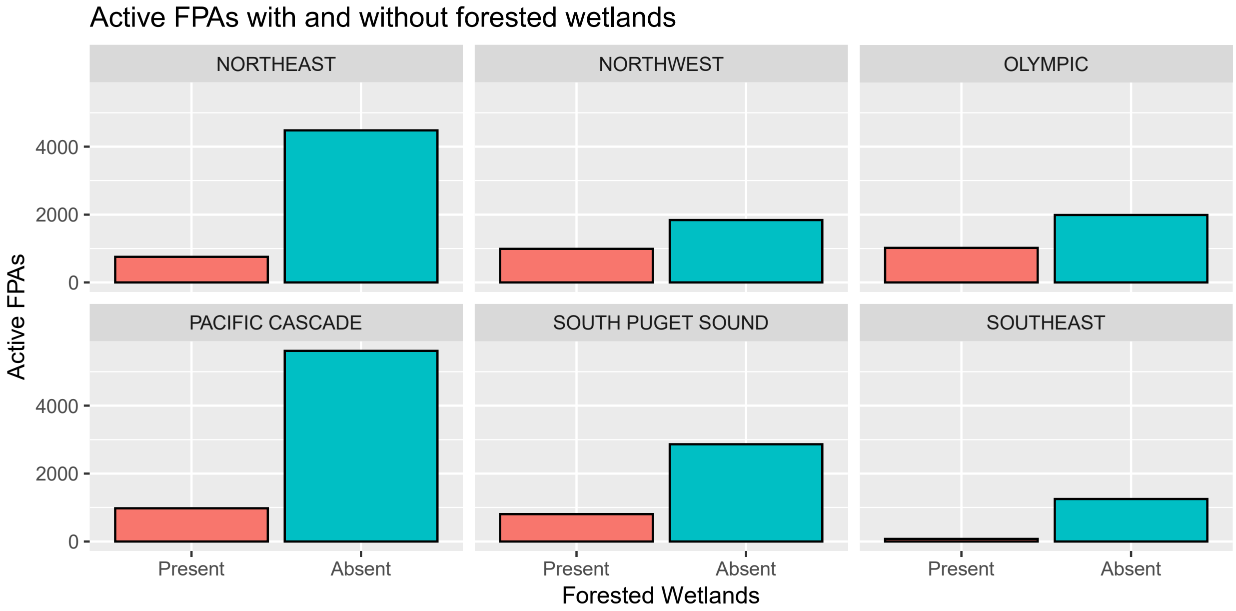

Figure 1.1. Active forest practice applications without (Absent) and with forested wetlands (Present) by Washington State DNR regions. In general, most FPAs are not submitted where forested wetlands occur, regardless of region.

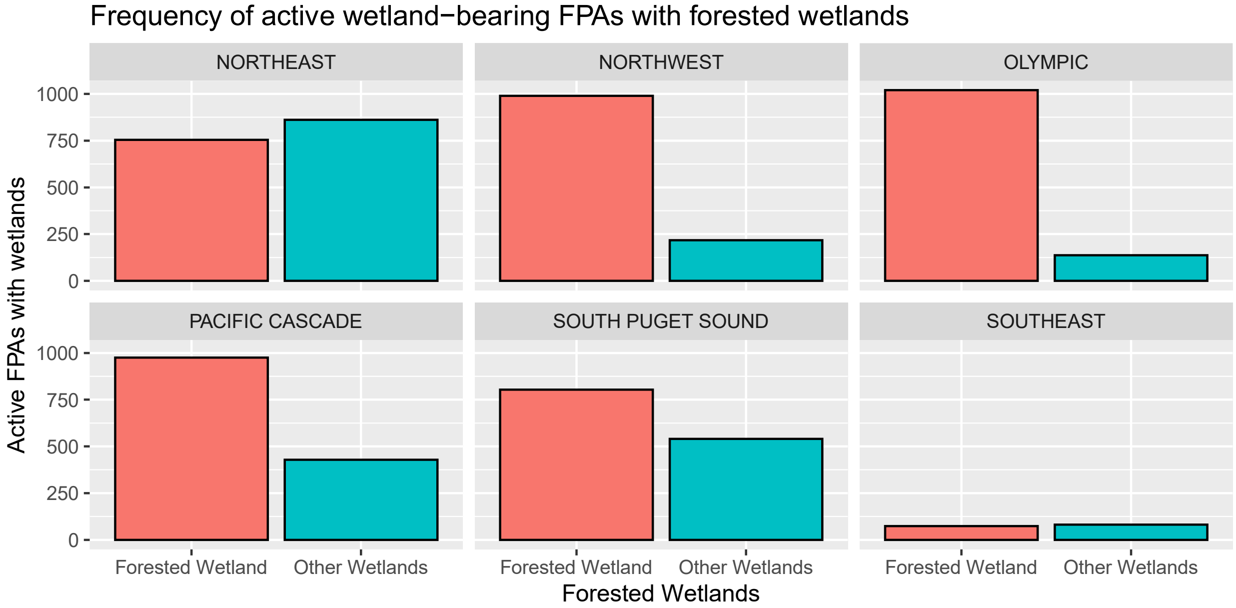

Figure 1.2. Wetland-bearing active forest practice applications (FPAs with wetlands of any type) show that in many Washington State DNR regions, such as the Olympic and Pacific Cascade regions, forested wetlands are the majority wetland type on which FPAs are submitted. The "Other Wetlands" column in this figure corresponds to the absence of forested wetlands and the presence of Type A, Type B, or Type A and Type B wetlands at a given FPA.

1.3 Project Purpose, Study Objectives, and Critical Questions

Research Objectives

The FWEP has two objectives:

1. To examine how well current forest practices rules meet the performance target of a no net loss of wetland functions by half of a timber rotation cycle (≥ 20-years), and Washington State Department of Ecology water quality standards.

2. To develop study designs that, when implemented, will yield information on the changes in wetland functions and associated aquatic resources due to the implementation of forest practices under existing forest practices rules.

Critical Questions

To meet these objectives, the FWEP has several related questions that guide the research:

1. What are the effects of forest practices on hydrologic regimes, water quality, and terrestrial and aquatic plant and animal habitats in forested wetlands and their connected downstream waters linked by surface or subsurface flow? What are the magnitude and duration of these effects?

    i. How does timber harvest in and around forested wetlands alter processes that influence hydrologic regimes in those wetlands, in downstream waters and the connectivity between them?

    ii. How does timber harvest in and around forested wetlands alter processes that influence water quality in those wetlands and downgradient waters?

    iii. How does timber harvest in and around forested wetlands alter processes that influence plant and animal habitat functions in wetlands, in connected waters, and surrounding uplands?

2. How well do current forest practices rules in forested wetlands meet FPHCP (Schedule L-1, Appendix N) aquatic resource objectives and performance targets, and the goal of no net loss of functions of those wetlands by half of a timber rotation cycle while meeting water quality standards?

1.4 Literature Summary

The FWEP's research objectives and critical questions are based upon the existing body of scientific knowledge surrounding forest practice effects on wetlands, forested or otherwise, primarily in the Pacific Northwest and secondarily, elsewhere in climatically and ecologically similar regions of North America (*sensu* Adamus 2014a). However, no studies in the Pacific Northwest have focused on the ecological and hydrological effects of forest harvesting on forested wetlands (Adamus 2014a). Indeed, the functions of forested wetlands in the Pacific

Northwest have rarely been measured (e.g., Janisch et al. 2011). Many of the probable effects of forest practices on forested wetland resources remain regionally understudied, and no forest practice effects on forested wetlands have been longitudinally documented within Washington State (Adamus 2014a). Here we briefly review how forest practices are likely to impact forested wetland hydrology and ecology, water quality, and habitat quality within Washington State's forested wetlands (*sensu* Adamus 2014a, and Beckett et al. 2016).

Hydrology and Ecology

Harvesting within forested wetlands and their surrounding upslope forests often results in hydrological changes to forested wetlands. For example, in other regions of North America, research has shown that harvesting timber in and around forested wetlands results in wetter conditions at least temporarily, including higher water tables and increased surface water yields within the wetland immediately following harvest (Burton 1997, Sun et al. 2000, 2001, Boggs et al. 2016). This "watering-up" can be at least partially attributed to a loss of tree canopy-mediated rainfall interception and evapotranspiration (Jones et al. 2000) that reduces flood retention times and increases runoff rates (Devito et al. 2005). The rate of hydrologic recovery following forest harvest is driven by the rate at which forest vegetation reestablishes and matures (Dubé et al. 1995, Roy et al. 2000). Because hydrological and ecological change in forested wetlands are inextricably linked, vegetation dynamics influence hydrology just as hydrologic dynamism influences vegetation (Brown et al. 2005, Manners et al. 2015).

Accordingly, post-harvest increases in the frequency, duration, and depth of standing water and elevated water tables often result in changes to forested wetland structure and composition. These changes can include lower tree seedling recruitment and growth rates (Roy et al. 2000), reduced site productivity due to a reduction in the aerated zone necessary for root growth (Conner 1994, Aust and Blinn 2004), and, in some cases, conversion of conifer stands to novel or early-successional types that do not reflect forested wetlands elsewhere on the landscape (Jones et al. 1994, Sharitz and Lee 1998, Roy et al. 2000). In research outside the Pacific Northwest, formerly merchantable, coniferous forested wetlands may regenerate as hydrophytic graminoids, and in some cases, open water (Shaffer et al. 2009). In the Pacific Northwest, formerly coniferous forested wetlands may transition to deciduous forests dominated by nitrogen-fixing red alder. How wetlands change in response to watering up in Washington is hard to predict as the elevations at which individual species occur within forested wetlands relative to flooding and saturated soil have rarely been studied (Hough-Snee - In Revision; *PeerJ*). For many dominant Pacific Northwest wetland plant species, there is either no information or only *ex situ* greenhouse studies on how these species respond to flood stress (Ewing 1996) or biomass-removing disturbance, making it hard to understand how common forested wetland types are structured under different hydrologic conditions.

Without basic information on forested wetland hydrology and ecology, the spatial and temporal dynamics across which forested wetlands might change following forest harvest cannot be predicted or quantified. Transitions between forested wetland to upland forest stands and from closed canopy forested wetlands to open water, emergent, or scrub-shrub systems may have been historically common at decadal to centennial scales, aligning with natural climate variability (Banner et al. 1983) and disturbance from wildfire, insect outbreaks, and windthrow events. However, watershed-scale industrial timber harvest may have increased the frequency with which forested wetlands transition to other wetland types due to hydrology-mediated vegetation change (Asada et al. 2004). The stability of forested wetlands as component ecosystems within forested landscapes remains unquantified, both in the context of natural climatic variability and from widespread forest management. How these systems change in response to nearby biomass-removing disturbance must be extrapolated from comparable systems in similar ecoregions (Adamus 2014a)

Water Quality and Temperature

Identifying timber harvest and associated hydrologic changes as the causal mechanism behind changes in wetland functions like water quality, remains challenging given the lack of studies on how nutrients, temperature, and primary productivity change in forested wetlands following harvest and post-harvest succession. Nutrient dynamics vary naturally over space and time within wetlands (Cui et al. 2005), which complicates anticipating how forested wetland ecosystems might change at a given location. Following harvest, greater amounts of carbon may be stored in soils due to increased soil saturation that reduces decomposition rates (Miao et al. 2017). However, soil disturbance and increased soil temperature from canopy loss may increase soil respiration and soil organic carbon decomposition (Clark et al. 2004, D'Angelo et al. 2005). Wetland and watershed nitrogen and phosphorus dynamics may also change as biological temperatures increase (Neill et al. 2001).

Forest practices can modify some of the primary ecosystem services conferred by forested wetlands as evidenced by changes in the parameters that represent them: temperature, dissolved oxygen, pH, and total suspended solids (Shepard 1994, Boggs et al. 2016). The timing, frequency, and magnitude of nutrient inputs into wetlands from across their watersheds can be disturbed by vegetation removal, hydrologic alteration, and changes to transpiration and evaporation at the stand to catchment scales (Bannister et al. 2015). Soil fertility could decline if more soil nitrogen is exported due to increased denitrification rates from newly unshaded, warmed soil, and more reduced (anoxic) conditions associated with watering-up (Melillo et al. 2011). Similarly, phosphorus could be redistributed based on changes to hydrology and related soil inundation and redox potential. Nitrogen-fixing species (e.g. *Alnus spp.*) may also replace pre-disturbance vegetation, importing additional nitrogen into the system (Kaelke and Dawson 2003, Nakagawa et al. 2012). When this nitrogen is exported during high flow events, forested wetlands may serve as a source of nitrogen elsewhere in the watershed (Laurén et al. 2005, Schelker et al. 2016). Similarly, forested wetlands may export greater amounts of dissolved organic carbon post-harvest, which could stimulate primary production in connected streams and water bodies (Kreutzweiser et al. 2008), though this effect could be short term (1-3 years; Shepard 1994).

Surface water temperature increases from timber harvest will depend partly on water table depth, and wetlands with deeper water tables may be less likely to experience measurable post-harvest temperature increases in surface waters than surface waters originating from wetlands with shallow water tables (Moore and Wondzell 2005). Post-harvest changes in wetland-adjacent stream temperatures will also depend on streamflow magnitude, duration, and timing, and on the duration of stream connection to the wetland (Bladon et al. 2016), the proportion of the wetland discharge which is subsurface as opposed to surface, and the distance and time it takes for water to reach a stream (Anderson et al. 1976). Similarly, stand structure, understory vegetation cover, and large wood that alter stream and floodplain roughness impact how water flows through forested wetlands both before and after harvest. Changes to these vegetative roughness elements may impact site hydrology in some wetlands post-harvest, shifting nutrient cycling and transport from historic regimes and loads following logging (Trieste and Jarrett 1987).

Sediment inputs associated with timber harvest will vary based on the type of equipment used during harvest (Brown 2010), extent and proximity of the harvest, and the level of soil compaction and harvest effects on magnitude of overland flow. Post-disturbance changes in sediment loads at harvested sites are usually short term (1-3 years; Shepard 1994). Wetland capacity to retain additional incoming sediment depends partly on whether the wetland is already at full storage capacity, as affected by time elapsed since last precipitation as well as long-term antecedent precipitation. As precipitation increases within a basin or wetland, surface flow and associated sediment transport increase, reducing sediment settlement and retention within the wetland (Phillips 1989). Wetlands with drawn down or naturally low water tables may be able to store more runoff and sediment than wetlands of a similar size and landscape position that are already at or near full capacity due to recent timber harvest.

Forested Wetland Habitat Responses to Forest Practices

Many fishes, amphibians, reptiles, birds, and other terrestrial and semi-aquatic vertebrates use off-channel, depressional, and riverine forested wetlands within larger forested landscapes as habitat during portions of their life cycles (Wigley and Roberts 1994a, 1994b). It is beyond the scope of this document to review the specific habitat requirements of this fauna, however, we note that any changes to hydrology, sediment transport, nutrient cycling, and biological temperature are likely to impact both state and federally-mandated Total Maximum Daily Loads (TMDLs) either locally, or in connected downstream waters. By improving the fundamental understanding of the timing and magnitude of material fluxes and vegetation succession in wetlands, new field studies will provide much-needed data that builds and validates conceptual models of forested wetland development and change. Forested wetland ecosystem development and change can be linked to specific biota in subsequent studies after the critical questions posed here have been thoroughly addressed (section 1.3).

Data Limitations and Knowledge Gaps

Based on the brief literature review here and the reviews of Adamus (2014a) and Beckett et al. (2016), it is clear that forested wetlands are poorly understood and have only been studied in a limited capacity across Washington State and the larger Pacific Northwest. It should be emphasized that the rationale for conducting FWEP studies is to build a body of knowledge about how forested wetlands function ecologically and hydrologically, and how these functions respond to forest practices across space and time. This information is not presently available from studies within the Pacific Northwest or across Washington State's many diverse ecoregions. Accordingly, many of the possible responses to forest harvest in Washington State's diverse forests have, out of necessity, been predicated on assumptions applied to systems elsewhere in the U.S and southern Canada (Adamus 2014a, Beckett et al. 2016).

1.5 Research and monitoring approach

To address the research objectives and answer the above critical questions, two separate, tiered field studies will be conducted that reduce the critical questions to sets of specific, testable hypotheses. The two studies to take place in managed forestlands across Washington State are:

1. An observational space-for-time (chronosequence) study that will investigate stream-adjacent forested wetland hydrology and ecology at multiple time-steps post-harvest.
2. An experimental Multiple Before-After-Control-Impact (BACI) design investigating the effects of forest and wetland harvest on stream-adjacent wetland and downstream hydrological and ecological functions.

Within the context of previous CMER and FWEP TWIG activities, the chronosequence study presented here will inform the BACI study design, while providing fundamental research that improves CMER's understanding of how stream-adjacent forested wetlands change following forest practices (Figure 1.3). Here we describe the chronosequence study while the BACI study will be described in a subsequent proposal to CMER with additional context and background information based on the chronosequence study.

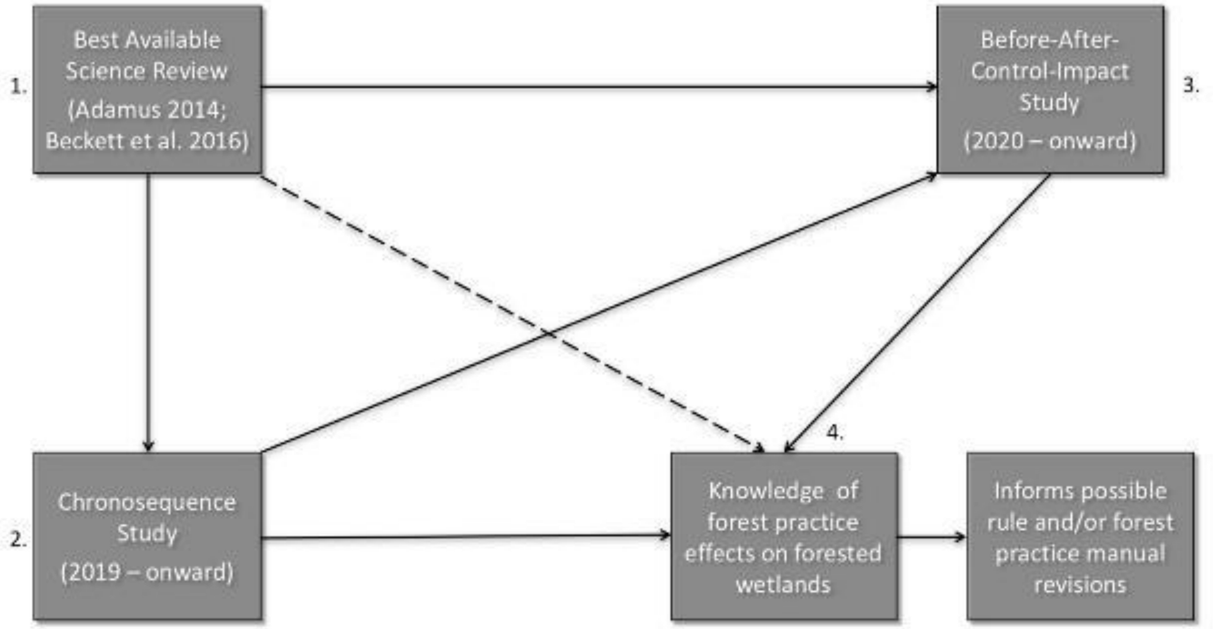

Figure 1.3: Conceptual map of how recent FWEP TWIG efforts, including recent literature review and best available science documents (1; Adamus 2014, Beckett et al. 2016), inform CMER mandates by increasing the body of information on forested wetland function (4) and how the proposed chronosequence study (2) serves as a pilot that informs the proposed before-after-control-impact study (3).

2. CHRONOSEQUENCE STUDY

2.1 Introduction to the Chronosequence

The fundamental goal of the Adaptive Management Program's Forested Wetlands Effectiveness Project is to understand how forested wetlands change in response to forest practices, and the duration and magnitude of these changes over time. However, studying post-harvest changes in forested wetlands over time is challenging due to the practical underpinnings of forest and forested wetland management:

1. Significant time must pass following harvest to understand how forest practices affect ecosystem structure and function beyond immediate, post-harvest stages.
2. Forest and forested wetland harvest occur based on landowners' economic and resource goals and timeframes rather than within randomized, controlled experimental settings over discrete timeframes.

These practical considerations mean that forest harvest in and around forested wetlands is not randomly distributed across the landscape and does not usually allow for consistent pre- and post-harvest monitoring of harvest impacts on forested wetlands. Given this, observational studies are useful for understanding typical post-harvest ecological and hydrological variability in forested wetlands recovering from forest harvest. The design and implementation of longitudinal studies of how forest practices affect forested wetlands over time can be greatly informed by these observational approaches. To this end, the FWEP will implement an observational chronosequence study that examines post-harvest forested wetland ecosystem development *before* implementing a long-term before-after-control-impact (BACI) study that answers related questions over shorter timeframes. Identifying patterns and variability in forested wetland development within the observational chronosequence will directly inform the design and implementation of the subsequent forested wetland harvest BACI study.

The BACI will be presented as a stand-alone design following the implementation of the chronosequence study. Both research designs are warranted (Beckett et al. 2016) as they will provide complementary information on trends in forested wetland hydrologic and ecological recovery from timber harvest. Elsewhere in the world, chronosequence designs have been used to construct ecological forecasting models in wetlands (Banet and Trexler 2013). In another study, harvest effects on forest biodiversity were detected using a BACI design but not in a paired chronosequence design intended to capture the same patterns (França et al. 2016). Chronosequence analyses can be informative, especially as pilot studies, and have been discussed in the regional context of watershed restoration and effectiveness monitoring (Roni 2013).

Chronosequence studies have been successfully implemented to assess how created estuarine wetlands and restored bottomland hardwood wetlands develop (Zedler and Callaway 1999, Stanturf et al. 2001), how soil organic matter forms over time in floodplain forests (Wigginton et al. 2000), and how hydrology and biogeochemical cycling change over time in restored wetlands (Berkowitz and White 2013). Chronosequence approaches are also common in upland forest harvest and floodplain forest development studies (Archer 2003, Merritt and Shafroth 2012), where recovery from disturbance over time is the response of interest. However, this approach has not been applied to quantify forest harvest impacts on forested wetland hydrology, ecology, and associated biogeochemical processes in the Pacific Northwest (Beckett et al. 2016).

The chronosequence study strives to answer two sets of actionable questions derived from the CMER work plan's critical questions:

1. How does forested wetland hydrology change over time following post-harvest forest stand development? Specifically:
    a. How does the hydrology of recently harvested forested wetlands compare to the hydrology of recently undisturbed second-growth forested wetlands?
    b. How does the timing, duration, and magnitude of flow and material transport differ between recently harvested and recently undisturbed second-growth forested wetlands?
2. How do forested wetland vegetation and canopy-mediated habitat conditions change over time following post-harvest forest stand development? Specifically:
    a. How does recently harvested forested wetland vegetation composition compare to recently undisturbed second-growth forested wetland vegetation over time?
    b. Do canopy and vegetation-mediated habitat attributes (e.g., inundation duration, soil, and wetland temperature, etc.) converge between recent post-harvest forested wetlands and recently undisturbed second-growth forested wetlands over time?

2.2 Chronosequence Study Design

In addressing these questions, the chronosequence study will identify post-harvest patterns in forested wetland ecology and hydrology within and around baseline forested wetlands (recently unharvested, second growth, "control" wetlands) and forested wetlands of different ages since forest harvest. By comparing ecological and hydrological conditions in groups of forested wetlands that were harvested at different times in the past (e.g., two, 10, 20 years), the development of wetland functions can be estimated over half of a timber rotation cycle (at minimum, 20-years). This observational study design, also known as space-for-time substitution, will identify common developmental trajectories within forested wetlands following disturbances associated with forest practices.

Space-for-time designs are used to look at long-term development in ecosystems that may eventually converge in their structure, function, and composition over time (Wigginton et al. 2000, Berkowitz and White 2013). When examining forested wetlands at different post-harvest developmental stages, individual forested wetlands can be treated as if they are different age classes of the same forested wetland. This substitution of *space* for *time* is possible only if sample sites are homogeneous in their natural variability that may also affect forested wetland responses to harvest.

The approach for the chronosequence is to identify six forested wetlands from each post-harvest age class (e.g., two, 10, 20 years), as well as six unharvested, “baseline” forested wetland. All wetlands will be based within the same hydrologic landscape class (Leibowitz et al. 2016) and ecoregion (Omernik 1995) to ensure all wetlands have similar landscape-scale characteristics, including regional hydroclimatic regime. This strategy should help reduce natural and spatial variability inherent in chronosequence data (Kappes et al. 2010). Because site-scale hydrological and ecological attributes among the wetlands will be sampled within comparable locations, observed site-scale differences should be more attributable to wetlands’ differing ages since harvest, rather than differing landscape characteristics (See *Site Selection* below).

A key management question is whether wetlands in the 20-year age class, the half a timber rotation cycle recovery goal, have “recovered” from the harvest event. That is, are the ecological and hydrological functions and conditions of the 20-year post-harvest wetlands comparable to those of wetlands that have not been recently harvested? This question can be addressed by comparing the recently undisturbed baseline and 20-year wetlands from each group. Sampling wetlands of intermediate age classes (2 and 10 years, post-harvest) provides additional information:

1) If harvested wetlands do indeed recover completely after half a timber rotation cycle, then observation of the 20-year age class alone offers no information at all about *how* forested wetlands recover from harvest impacts. By sampling additional, younger post-harvest age classes, short and intermediate-term harvest impacts on forested wetlands can be quantified.

2) The sampling of younger age classes would hopefully identify temporal trajectories of post-harvest wetland recovery. Such observations would help support conclusions about how wetlands change as they recover over 20 years.

Study Population

The study population for the chronosequence design is forested wetlands that occur within timber harvest units on state and private timberlands in Washington State (Table 1.1; 2.1; WAC 222-16-035). For this study, only forested wetlands that occurred under the Forest Practices Habitat Conservation Plan (FPHCP) and harvested under forest practices rules will be considered (Figure 2.1; Figure 2.2). The FPHCP covers roughly 9.3 million acres of private and state timberlands across Washington State. Federal and tribal lands are harvested under different guidance and are not considered for this study.

As of June 2019, 4,616 of 22,649 active FPAs (20%) and 33,031of all 228,367 FPAs (13%) provide the population from which chronosequence treatment (2-, 10-, and 20- years post-harvest) sites will be selected (Table 2.1). Recently unharvested baseline sites will be selected from forested wetlands on forest land managed under the State Trust Lands Habitat Conservation Plan (STHCP). Treatment and baseline sites will be selected from a pool of candidate sites with the same landscape attributes.

Baseline stands will be 40 to 50-year old second-growth forest that have not undergone recent natural disturbance, commercial harvest, or silvicultural management prescriptions (e.g., thinning). If this is unfeasible, additional unharvested baseline forested wetlands that occur on federal, tribal, NGO (e.g. The Nature Conservancy) or private timberland will be considered.

When comparing forested wetlands' responses to disturbance, it is not reasonable to compare harvested sites to old-growth forested wetlands (Painter 2009) or other, less common managed stand types regulated under forest practices rules. Old-growth forests are likely to exhibit different vegetation than managed forests leading to different hydrology, light and gap dynamics, large wood volume and types, and the size and persistence of hummocks and swales.

Table 2.1. Summary of active forest practice applications as of May 2019 with on-site forested wetlands.

FPA pool	Washington State DNR Region	FPAs with forested wetlands	
		Count	Percent
Active FPAs (N = 22,649)	Northeast	754	16.3
	Northwest	990	21.4
	Olympic	1020	22.1
	Pacific Cascade	975	21.1
	South Puget Sound	803	17.4
	Southeast	74	1.6
	All Regions	**4616**	**20.3% of total active FPAs**
All FPAs (N = 241,084)	Northeast	4257	12.9
	Northwest	6475	19.6
	Olympic	7623	23.1
	Pacific Cascade	6851	20.7
	South Puget Sound	7055	21.4
	Southeast	770	2.3
	All Regions	**33031**	**13.7% of total FPAs**

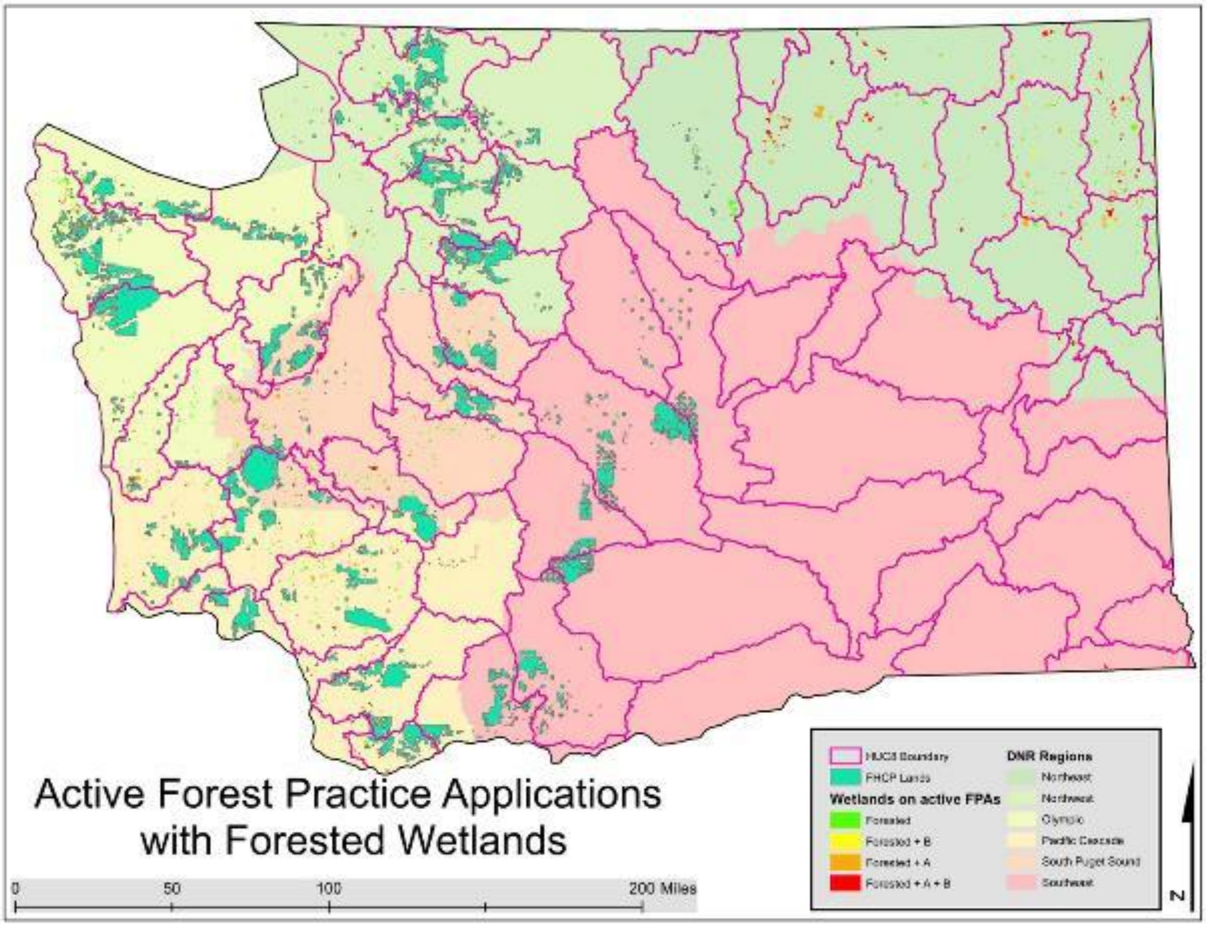

Figure 2.1. All active Washington State forest practice applications with a combination of forested wetlands, forested and type B wetlands, forested and type A wetlands, and forested and types A and B wetlands. FPAs are overlain on DNR lands managed under the State Trust Lands Habitat Conservation Plan (STHCP) from which baseline forested wetlands may be selected. Harvested forested wetland samples will be drawn from FPAs with forested wetlands that occur on Forest Practices Habitat Conservation Plan (FPHCP) lands within the Olympic, Pacific Cascade, and South Puget Sound DNR regions.

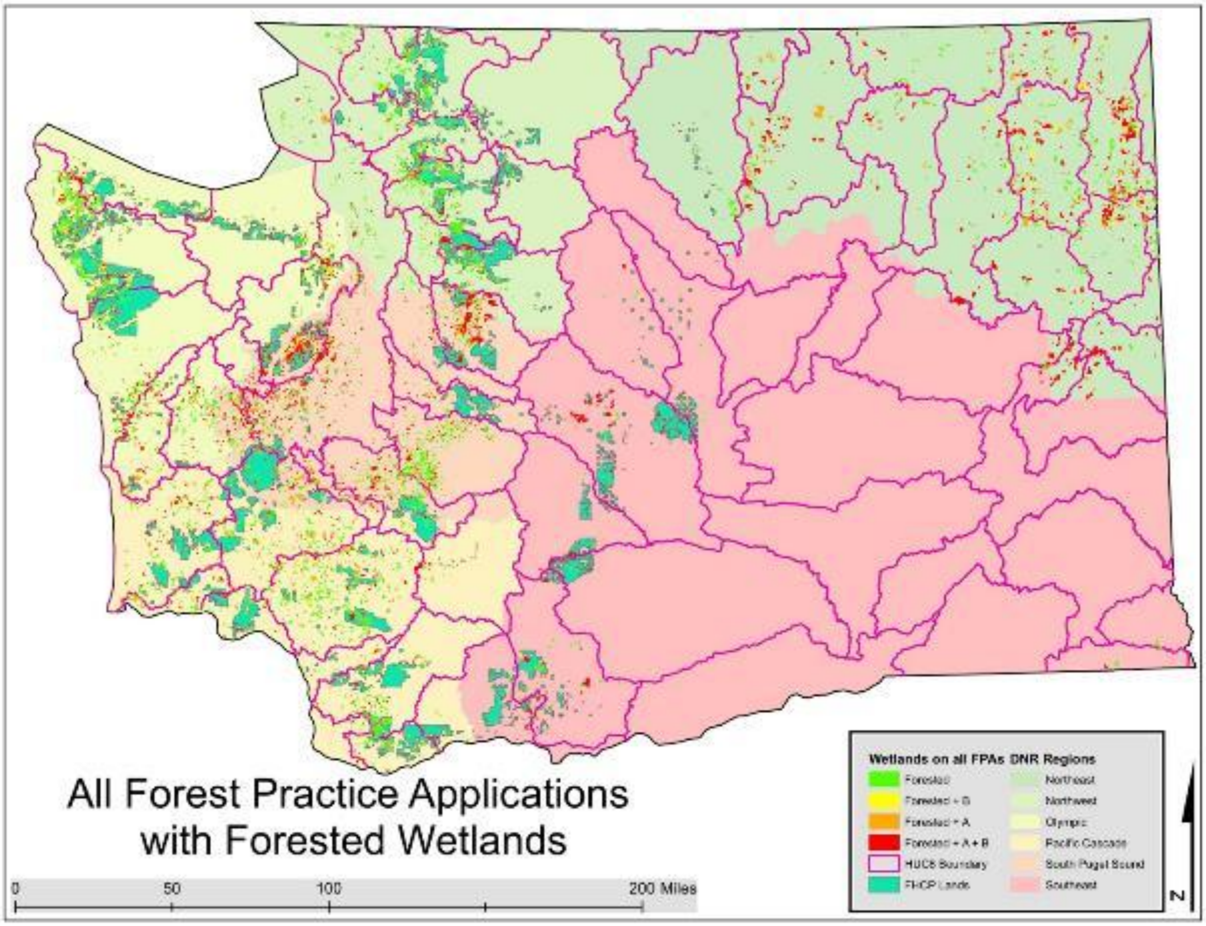

Figure 2.2. All Washington State forest practice applications with a combination of forested wetlands, forested and type B wetlands, forested and type A wetlands, and forested and types A and B wetlands. FPAs are overlain on DNR lands managed under the State Trust Lands Habitat Conservation Plan (STHCP) from which baseline forested wetlands may be selected. Harvested forested wetland samples will be drawn from FPAs with forested wetlands that occur on Forest Practices Habitat Conservation Plan (FPHCP) lands within the Olympic, Pacific Cascade, and South Puget Sound DNR regions.

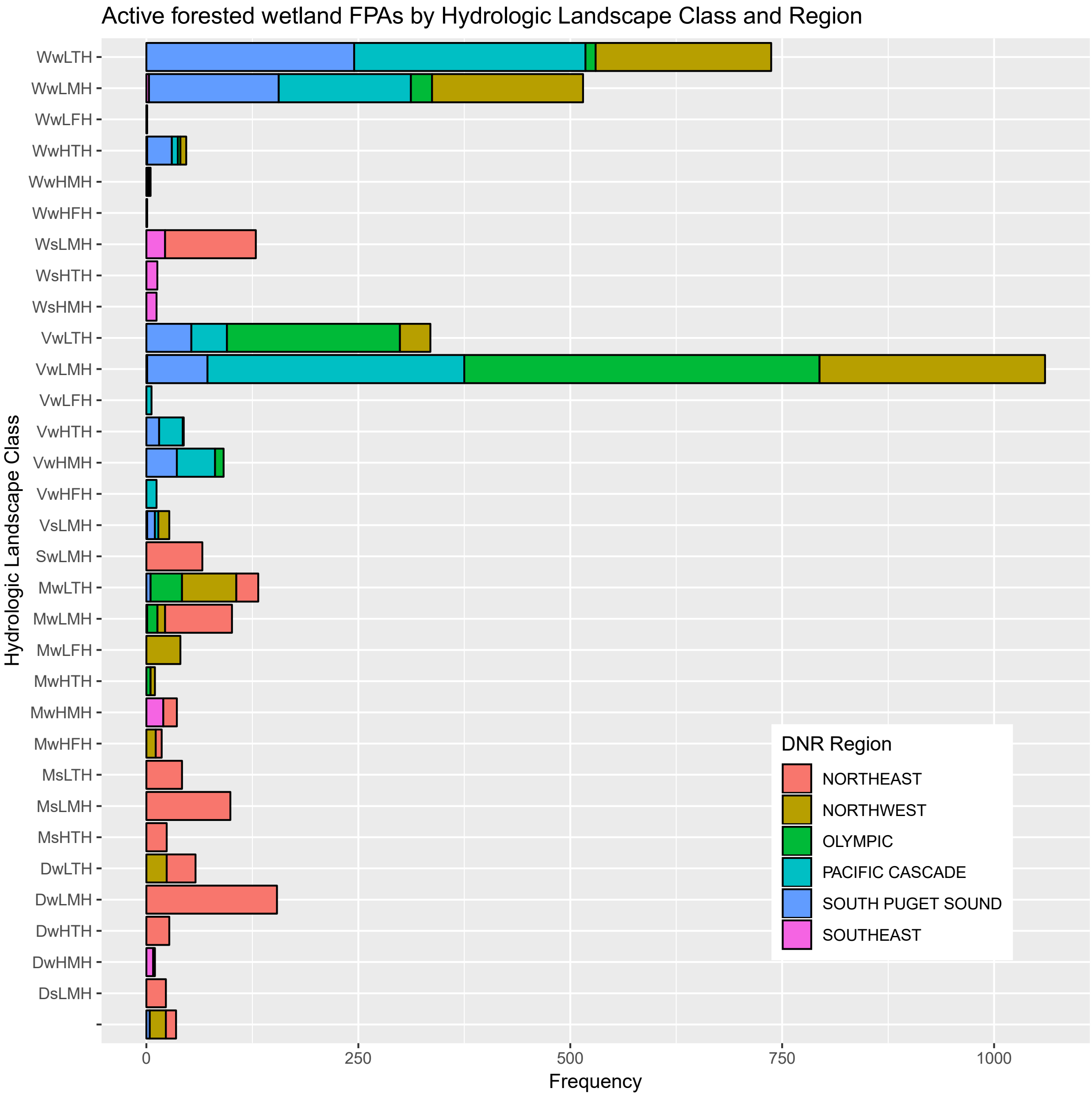

Figure 2.3. Frequency of active forest practice applications by hydrologic landscape class. The most abundant hydrologic landscape class on which FPAs occur is the VwLMH (Very wet climate, winter seasonality, low aquifer permeability, mountainous terrain, high soil permeability) class, which is common to the Northwest, Olympic, Pacific Cascade, and South Puget Sound regions (Leibowitz et al. 2016). This VwLMH HLC is the one from which sample sites will be selected.

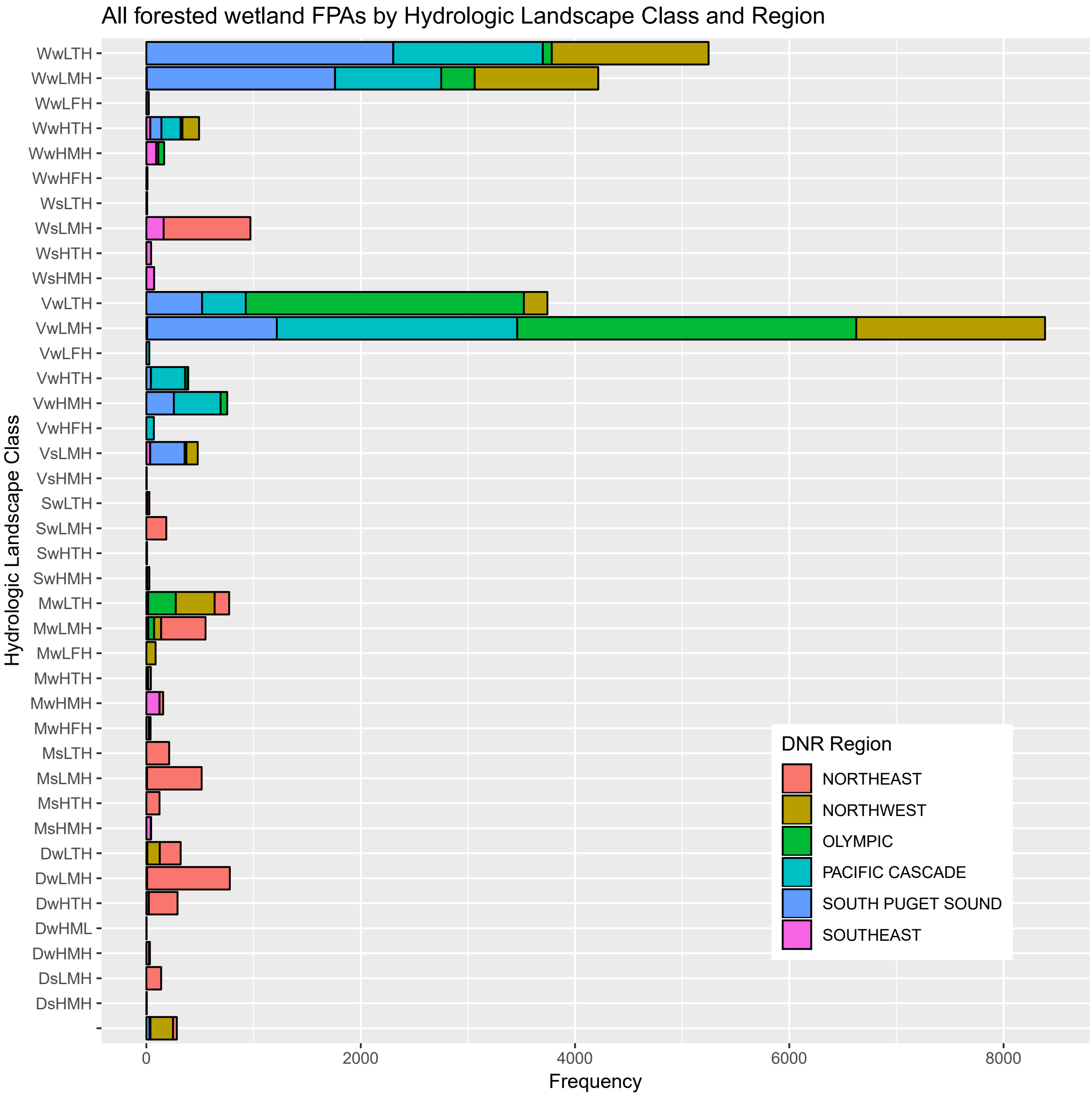

Figure 2.4. Frequency of all forest practice applications by hydrologic landscape class. Note that like the active FPAs, the most abundant hydrologic landscape class on which FPAs occur is the VwLMH (Very wet climate, winter seasonality, low aquifer permeability, mountainous terrain, high soil permeability) class, which is common to the Northwest, Olympic, Pacific Cascade, and South Puget Sound regions (Leibowitz et al. 2016).

Site Selection

Site selection will be based on a landscape analysis of FPAs to ensure that observational units (forested wetlands) and the watersheds within which they occur are similar in their natural hydrologic and ecological variability. This systematic approach to site selection will consolidate sample sites within similar ecological and hydrological landscape domains, minimizing the natural spatial variability inherent to chronosequence studies.

The steps in site selection will be to:

1. Identify candidate harvest units with similar climate and hydrology based on hydrologic landscape classes.

Hydrologic landscape classes (HLCs; Winter 2001)), are an index that accounts for climate, climate seasonality, aquifer permeability, terrain class, and soil permeability (Leibowitz et al. 2016) with 80 km^2 watershed units (similar to HUC12 watersheds). The most abundant hydrologic landscape class into which forested wetland-bearing FPAs fall is the VwLMH class (Very wet climate, winter seasonality, low aquifer permeability, mountainous terrain, high soil permeability; Figure 2.3; Figure 2.4). We will identify candidate forested wetland sites within this common hydrologic landscape class.

2. Identify sites within the VwLMH hydrologic landscape class and Olympic, Pacific Cascade, and South Puget Sound DNR Regions that occur within the Coast Range Level III ecoregion.

The Coast Range Level III EPA EcoRegion runs north to south through western Washington along the Pacific Ocean and through the Pacific Cascade, South Puget Sound, and Olympic DNR Regions in which forested wetland-bearing FPAs are most common (See Figure 1.2). By limiting site selection efforts to within the VwLMH class and Coast Range ecoregion, the study will be representative of the areas with the most FPAs that affect forested wetlands and minimize natural spatial variability between sites. DNR regions are an administrative unit, not an environmental gradient, and will not be specifically addressed within the study design or analysis.

3. Identify a pool of candidate harvest units with similar originating forest stands and harvest practices.

We will identify roughly 45-acre harvest units that originated as mature second or third-growth forest and that contain forested wetlands where both the surrounding harvest unit *and* forested wetland were harvested within the study treatment timeframes (2-, 10-, 20-years since harvest and recently undisturbed baseline sites) and have not undergone any additional management (vegetation control or silvicultural treatments) since harvest.

4. Identify sites with appropriate age classes within the pool of candidate harvest units.

Sites that meet the appropriate HLC, ecoregion, and DNR regions will be binned into age classes based on the number of years that have passed since harvest: 2-, 10-, or 20-years (Table 2.2).

5. Additional landscape covariate analyses to ensure appropriate site similarity.

The geomorphic setting of each wetland will be characterized based on the bedrock composition and depth of bedrock and organic soils to ensure that wetlands are of similar hydrologic and geomorphic context beyond the broader HLC analysis. This is discussed in *Observational Unit* below. The framework of (Montgomery and Buffington 1997) provides an easy to identify classification for streams and valley bottoms. Additionally, valley geometry metrics can be compared using GIS methods. For example, confinement, valley width (Carlson 2009, Nagel et al. 2014, Gilbert et al. 2016), sinuosity, the proportion of valley with wetland soil, etc. could be compared using both GIS methods and field reconnaissance. USGS StreamStats (U.S. Geological Survey 2016) will be used to characterize peak and low flow recurrence based on USGS regression equations for the study region (Mastin et al. 2016).

Additional factors beyond wetland and stream valley setting will be analyzed to ensure sites match in their physical attributes. These factors will include the sizes of each forested wetland, harvest unit and watershed, slope and stream gradient, aspect, and soil type, among others (Table 2.3). Each site's landscape characteristics (Table 2.3) will be summarized in GIS, further guiding site selection by identifying site-level covariates. GIS analyses will be field validated with initial site surveys and summary statistical analyses.

6. *Over select sites and choose random sampling sites within each age class for field validation.*

As many candidate sites as possible will be identified during site selection to allow for random selection of sites that can be vetted during field reconnaissance. We anticipate that some sites that are identified will be found to be unsuitable during reconnaissance, and so backup sites will be identified within each age class within the VwLMH class. From the pool of candidate and backup sites within each age class, study sites will be selected at random to reduce underlying bias in site selection.

7. Disqualify any randomly selected sites with exceptional land management during or following timber harvest.

Sites with similar environmental covariates, but whose post-harvest management likely impacted vegetation succession or hydrology at the site will be disqualified from consideration within each age group. A late summer 2018 WetSAG field trip identified additional harvest-related considerations for site selection, including temporary and permanent road placement, culvert installation, slash piles, planting techniques, and herbicide application. Windthrow events and insect outbreaks are other examples of possible disqualifying disturbances.

Preliminary site selection from GIS following the above workflow took place in 2017 and 2019, but due to study approval delays, the same evaluation of FPAs and their surrounding watersheds will occur in the fall before study implementation with DNR's updated Forest practice Application database. The resulting pool of sites will be analyzed as in steps one through six before initial site reconnaissance in step seven.

Table 2.2. Age classes of forested wetlands to be sampled within the Chronosequence study. Baseline consists of recently undisturbed second-growth forested wetlands, while 2-, 10-, and 20-year age classes are years post-harvest and reflect immediately to mid-term response intervals.

Age class	Description	Rationale
Baseline	Recently unharvested second-growth wetlands (baseline)	Captures recently undisturbed second-growth forested wetland ecological and hydrological patterns.
2-years	Wetlands and surrounding harvest unit harvested two years before sampling	Shows early post-harvest forested wetland succession and hydrologic response to stand development.
10-years	Wetlands and surrounding harvest unit harvested 10- years prior to sampling	Shows continued stand development and hydrologic responses to forest development.
20-years	Wetlands and surrounding harvest unit harvested 20-years prior to sampling	Shows forested wetland succession, including canopy closure and stem exclusion and hydrologic recovery.

Observational Unit

The observational unit within this study will be each individual stream-adjacent forested wetland. These stream-adjacent wetlands are at least seasonally connected to perennial, non-fish bearing streams (Np streams) via overland flow. Uncertainty surrounding forest practice rule effectiveness relative to Np and fish-bearing streams is discussed at length in Beckett et al. (2016). Ideally, these will be small streams that are not fish-bearing due to their size and not their position on the landscape (e.g. above a topographic break like a gorge or waterfall). For example, many steep streams like cascades or waterfalls will neither support fish nor will they have the topography and soils to build and maintain stream adjacent forested wetlands (Buffington and Montgomery 2013).

Four- to six-acre forested wetlands will be selected within four treatment age classes (Table 2.2; Figure 2.5): baseline (recently undisturbed, mature second growth or third growth that have not been harvested in the last forty years), 2 years (harvested 2-years prior), 10 years (harvested 10-years prior), and 20 years (harvested 20-years prior). Twenty years was selected as the maximum age class because of limited digital availability of forest practices applications that provide older harvest records and because 20 years is the low-end range of half a commercial timber rotation cycle prioritized by schedule L-1 of the Forests and Fish Report (Washington State Department of Natural Resources 1999).

Selected forested wetlands will be roughly four to six acres in size for two main reasons. Based on a field survey with field-mapped forested wetlands (Beckett et al. 2016), as well as a desktop survey of 200 Forest Practices Applications, wetlands within this size range occurred more frequently in harvest units than larger forested wetlands (Beckett et al. 2016). The mean size of a harvested forested wetland was 3.9 acres at the state level (± std. dev of 5.8 acres) and within the DNR's Olympic Region more than 60% of forested wetlands were between three and five acres (Beckett et al. 2016) Though forest practices affect many smaller forested wetlands and larger wetland complexes, these wetlands may be difficult to identify and sample. We will preferentially locate a single, hydrologically continuous wetland at each location rather than wetland complexes consisting of many small wetlands. A hydrologically continuous wetland is one in which surface water connectivity is continuous with the adjacent stream during at least some portion of the wet season, as indicated by the ordinary high-water mark. A wetland complex includes many hydrologically disjunct wetlands separated by natural (shallow bedrock or impervious substrate) or anthropogenic (roadbeds) breaks in topography.

Small forested wetlands less than three acres in size, are not reported on forest practices applications and may be difficult to locate during site selection. In many cases, coniferous forest vegetation encroaches on these small wetlands, making them less detectable with remote sensing based on canopy spectral signature or satellite images classified as forest composition (e.g., LANDFIRE). Small wetland responses to harvest may also be challenging to measure with consistent protocols because many of these wetlands are hillslope wetlands and/or are only connected to streams by groundwater. "Geographically isolated wetlands" or slope wetlands that are perennially isolated from surface flows that connect to larger water bodies, are *not* a part of this study, even though their hydrology influences streamflow (Tiner 2003, Mushet et al. 2015) and connectivity between wetland sediment, nutrient, and other material fluxes (Calhoun et al. 2017).

We will select candidate sites with harvest units that are roughly the same size. Common harvest trends show that this size is roughly 40-50 acres (Hough-Snee 2019, unpublished, analyzed forest practice application data). We will attempt to select candidate sites with similar contributing catchment areas and similar vegetation age, size, and composition. We will summarize the landscape setting of forested wetlands within each harvest unit by attributing it with a categorical attribute of “edge,” “center,” or “partly outside harvest unit” based on harvest unit maps. Depending on the distribution of sites that occupy the edge or center within a given harvest unit, this attribute may be used to bin sites. We will exclude sites with larger forested wetlands that are only partly impacted by harvest because the wetland spans multiple, discrete harvest units.

For each forested wetland, the proportion of the catchment harvested, including units outside the harvest unit of interest, will be considered as well as the resulting vegetation structure and composition when selecting sites. Highly harvested watersheds, watersheds where multiple harvest units route water through the same wetland and/or stream will be excluded from the list of candidate sites. Anomalous natural disturbances that disproportionately impacts the candidate site or watershed, including wildfire, landslide, road washout, etc., may also disqualify sites that meet all other criteria.

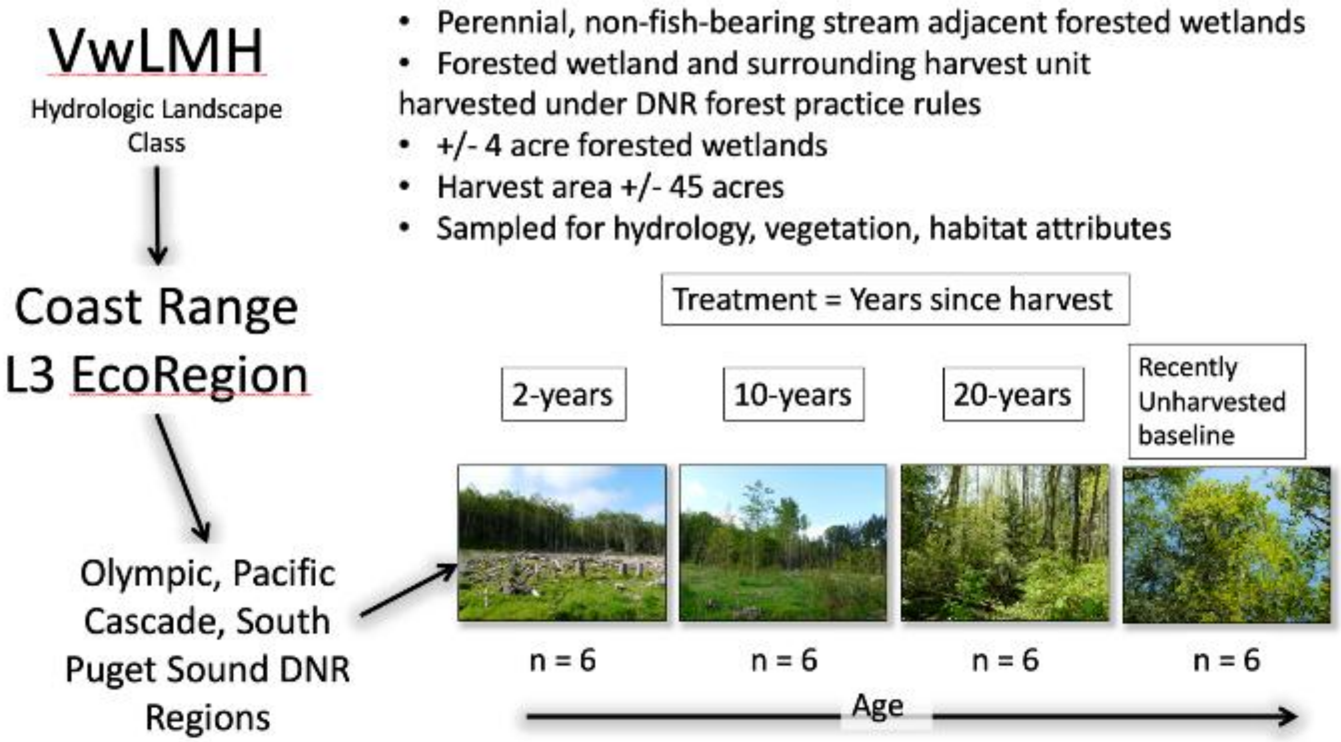

Figure 2.5. Schematic of the chronosequence site selection workflow by hydrologic landscape class, EPA EcoRegion DNR regions, and treatment levels and minimum sample sizes.

Sample Size

We propose a *minimum* sample size of 24 forested wetlands (Figure 2.5; N = 24)) with six wetlands in each age class (n = 6). If additional resources are allocated to the project, or a subset of response variables are measured instead of the full panel outlined in Table 2.4, then the sample size should increase to 28 (n = 7 per treatment) or 32 (n = 8 per treatment) sites. Because the number of sites may increase and it is advantageous to randomly select sample sites from within a pool of candidate sites, it is paramount that GIS-based site selection identifies as many sites within each age class as possible.

Sampling Scheme

Each sample forested wetland site will include the (1) forested wetland, (2) adjacent non-fish bearing stream segment (Np), and (3) the surrounding harvest unit. Each stream will be a low-order perennial, non-fish-bearing (Np) stream under forest practices rules to maintain consistent buffer treatments. Each site will be visited at minimum five times: once to evaluate site access and field reconnaissance (recon visit), once to take point measurements and install probes, data loggers, and gauges (initial visit), once each year to collect growing-season point measurements and download data from loggers (measurement visit), and once to collect gauges and data loggers, and take additional point measurements as necessary (final visit).

Recon visits will take place in the winter and spring before initiating monitoring. This visit will confirm that sites are appropriate, map the site for instrumentation, and identify likely access and safety issues. Initial visits will occur after leaf-out and will include point measurements for forest basal area, leaf area index, and stand age. Species lists will be produced for each site during this visit. Measurement visits will occur mid-summer each year, and during this visit, gauges and data loggers will be installed (year one), and the full panel of growing season vegetation and habitat measurements will be taken (years one and two). The data loggers will be maintained and monitored, at minimum, for two water years beginning October of site instrumentation. Final visits to collect probes and gauges will occur after roughly 28 months of data logger monitoring. Additional equipment maintenance and data download visits will occur as necessary. Vegetation measurements will occur in both growing seasons of the study year.

Because western Washington's streams generally peak in the winter and fall during rain events, monitoring equipment will be installed two months before the water year and will remain in place two months after the second water year to ensure that at least two years of complete, synchronous data are collected for all sites. All sites will be instrumented and measured in the same starting year to help reduce interannual variation between sites caused by regional climate patterns. Hydrologic, vegetation, and habitat variables will be instrumented and sampled as listed in the data parameters section.

Data Parameters

Each forested wetland site will have several field-measured response variables (Table 2.4). These variables were selected based on their anticipated long-term response to forest harvest and fall into three broad categories: hydrology, vegetation, and forested wetland habitat.

Table 2.3. Independent variables considered for site selection. Hydrologic Landscape Class (Leibowitz et al. 2016) is the primary selection criteria from which sites will be selected as it encompasses multiple hydrologic, climatic, and soil attributes. Variables' priority and order are outlined in Beckett et al. (2016).

Independent Variable Category	Variable	Methods	Data Source
	Hydrologic Landscape Class	**GIS – Primary stratifying variable**	**EPA – Hydrologic Landscape Classes**
Watershed	Catchment drainage area, slope, elevation, aspect	USGS Stream Stats; GIS	USGS National Elevation Dataset;
	Slope of harvest unit	GIS - during site selection	USGS National Elevation Dataset
	Aspect of harvest unit	GIS - during site selection	USGS National Elevation Dataset
	Harvest unit area	GIS - during site selection	WA DNR - Forest practices applications
	Peak and minimum discharges	USGS StreamStats	USGS StreamStats
Forest vegetation	Conifer vs deciduous forest cover	GIS - during site selection; Field validated	Remote sensing (Classified NAIP imagery)
	Stand-level dominant species in the surrounding watershed	GIS - during site selection	USGS Pacific Northwest SPARROW model inputs; LANDFIRE existing vegetation type
	Standage prior to and following harvest; Watershed stand average age	GIS - during site selection	WA DNR - Forest practices applications and landowner data; LANDFIRE existing vegetation height (EVH)
	Existing wetland vegetation	GIS - during site selection	LANDFIRE existing vegetation type
Site biophysical setting	Site productivity (site class)	GIS - during site selection	WA DNR
	Soil types	GIS - during site selection	USDA STATSGO; WA DNR soils
	Wetland type - Cowardin or HGM class	Estimated in GIS and field validated following GIS analyses	National wetland inventory, Landfire map, ground sample

Table 2.4. Response variables to be measured in the chronosequence study. Priority variables from Beckett et al. (2016) are in **bold**, and secondary variables are in plain text.

Variable group	Response Variable	Methods under consideration	Sampling interval	Within-site measurements per observational unit
Hydrology	Streamflow	Stage-discharge relationships	Daily/hourly	2 - upstream-downstream
	Wetland water table depth	Groundwater wells	Daily/hourly	3
	Wetland surface water occurrence (hydroperiod)	Time-lapse camera paired with groundwater wells and pressure transducers	Daily	1
	Stream-wetland surface connectivity		Daily	1
Vegetation	Tree basal area, stem density, and height by species	Modified forest inventory plots	Point; Annual measurement visit	3
	Dominant understory shrub and herb composition	Relevé samples (Mueller-Dombois and Ellenberg 2002)	Point; Annual measurement visit	3
	Stand age structure	Tree age derived from cores	Point; Annual measurement visit	5
	Leaf area index	Hemispherical photography	Point; Annual measurement visit	3
Habitat	**Sediment concentration and turbidity**	Turbidity meter	Point; Seasonal measurements	
	Nitrogen, phosphorus, dissolved organic carbon,	Hemispherical photography and/or solar pathfinder.	Point; Annual measurement visit	3
	Wetland canopy and effective shade	Hemispherical photography and/or solar pathfinder.	Point; Annual measurement visit	3
	Soil temperature and moisture	Soil temperature and moisture probe and data logger	Daily/hourly	3
	Stream temperature	Temperature probe and data logger	Daily/hourly	2 - upstream-downstream of wetland

	Physical attributes to characterize stream	Bankfull width, surface water gradient, sinuosity, and sediment size distribution	Point; Modified from USFS PIBO protocols.	One reach per wetland site will be measured.

Hydrology is the most complex forested wetland attribute to measure, and the chronosequence study will coarsely assess several response hydrologic parameters: streamflow, water table depth, wetland surface water occurrence, and wetland-stream connectivity. Sites will be instrumented to evaluate how water moves through each stream and its adjacent wetland. To measure streamflow, water table depth pressure transducers with data loggers will be installed at the upstream and downstream end of the adjacent stream segment. For the forested wetland, groundwater wells will be instrumented with pressure transducers to detect water table depth laterally from the stream to the wetland center and upslope. Because groundwater wells have a slotted profile, they capture the maximum height of free water over the intake depth rather than the mere presence or absence of water as a piezometer does. We will use transducers that have automatic barometric pressure correction to avoid the need for a separate barometric pressure sensor from which to calibrate pressure readings in each well.

Surface water connectivity between the stream and wetland will be documented with a time-lapse camera that takes daily images of the wetland. From these images, the duration of time that the wetland and stream are connected, as well as the specific windows in time, will be calculated. The number of days in which surface water occurs in the wetland will also be captured.

Soil moisture and temperature will be measured with temperature probes and data loggers across each forested wetland in three distinct zones: the wetland buffer, wetland edge, and the wetland center. This is to account for gradients from the upland toward the stream, including the center of the forested wetland. These point measurements are not intended to continuously capture conditions across hydrological or environmental gradients, but to provide a site-level estimate of soil habitat variables within each portion of the wetland.

Forest vegetation both affects how water moves through a forested wetland and responds to wetland hydrology, making it a key parameter in the chronosequence study. Each wetland will be typed under the Cowardin and hydrogeomorphic (HGM) frameworks during recon and initial site visits (Cowardin et al. 1979, Brinson 1993). Modified circular forest inventory and analysis (Bechtold et al. 2005) plots will be installed around each wetland groundwater well. These plots will be 18-m radius plots within which, trees will be identified to species and standing live and dead tree diameter at breast height (DBH) will be measured. A subsample of tree cores will be taken to estimate standing forest age class by species. Tree cores will be taken from five trees of median size class within the forested wetland stand. Stand basal area, stem frequency, and size class frequency will be calculated by species at each forested wetland from forest plot data. Seven-meter radius shrub and understory herbaceous vegetation relevé plots will be assessed at each overstory forest inventory plot to characterize the understory vegetation (Mueller-Dombois and Ellenberg 2002). This approach is rapid and can categorize a larger area than smaller quadrat-based measurements or line-point intercept methods.

Additional response habitat variables include leaf area index, and canopy and effective shade. Field collected vegetation composition and forest structure data (i.e., assemblages or communities) will account for the dominance of conifer vs. broadleaf tree communities that may affect hydrologic response variables. For example, a forested wetland dominated by nitrogen-fixing red alder may have different groundwater regimes, soil moisture, and soil nutrient levels than a site dominated by western hemlock (Compton et al. 2003). Seasonal differences in evapotranspiration between broadleaf trees and conifers may account for some of these differences in wetland function. However, groundwater regimes directly affect which species can establish, survive, and reproduce following harvest within a given wetland. Because of this bi-directional relationship between hydrology and vegetation, it is important to understand both vegetation structure and hydrology at each sample location.

Data Collection Procedures

Independent variables that sites will be selected from will rely on landscape-level GIS data, as well as past harvest information. Landscape-level data will include hydrologic landscape classes, catchment size, slope of unit and wetland, vegetation assemblage, and soil type (Table 2.3). Past harvest information will rely on Forest Practices Applications, reconnaissance site visits, and additional internal records, maps, etc. from landowners.

Response variables will be measured *in situ*. Some variables will be collected over time for the duration of the study (two years), such as soil moisture and soil and surface water temperatures. These variables will be collected using data loggers, which automatically record data at set time intervals. Variables that are not interpretable from one-time measurements will be collected with data loggers over both years plus the buffer two months on each end of the study. For example, a single soil moisture measurement may reflect seasonal measurement timing, a recent precipitation event, or broader hydrologic trends. Those factors may have a larger effect on the point measurement than past harvest activities. However, a years-worth of soil moisture data can provide insight into patterns that transcend season or individual precipitation events, and comparing those annual trends across site may provide information on the effects of harvest on soil moisture.

Statistical Analysis Procedures

Because the chronosequence is a pilot study that informs the subsequent BACI study, analysis is based on three related goals to:

1. Observe the range (mean, variance) of conditions for response hydrological and ecological variables within forested wetlands of different age classes.

Under the assumptions of the chronosequence, data from the six sites within each age class can be interpreted as describing the temporal successional trajectory of change within the sample population. Thus, data for each response variable and each group will be plotted as a time series, to show the estimated change in the variable over time at two-, ten-, and 20-years post-harvest, as well as the unharvested baseline. These observational trends will show how ecological and hydrological parameters change over time.

2. Quantify differences in the means between forested wetland age classes using hypothesis testing (Table 2.5; ANOVA, PERMANOVA), identifying covarying environmental differences that may confound hypothesis testing as appropriate.

The six forested wetlands within each age class can be treated as statistically independent observational units for hypothesis testing. Thus, we will use a one-way analysis of variance (ANOVA) to test a response variable for different means among the four age classes. For ANOVA tests with significant test results (alpha of $P < 0.05$(Anderson 2001)) subsequent multiple comparisons of the different means will test for pairwise differences between age class pairs (Zar 2010). Tukey's Honest Significant Difference (HSD) is a conservative approach that reduces the likelihood of type one error in which a true null hypothesis is rejected.

These multiple comparison methods also yield estimated mean differences and their confidence intervals. Such results characterize the average condition of each age class and the differences between them within the study area. Because this is a pilot study, trends in data between age classes will be informative to the BACI study, even if traditional hypothesis testing does not yield quantifiable differences between age groups.

We can apply the same one-way analysis strategy, via multivariate ANOVA (MANOVA), to multiple response variables, such as the hydrology variables in Table 2.4, that are conceptually linked and likely correlated (Johnson and Wichern 1988). Conventional MANOVA employs Euclidean distances between multivariate observations. Thus, it is not suitable for vegetation species assemblages (Table 2.4), which typically have sparse matrices of site-by-species data (McCune and Grace 2002). However, the PERMANOVA method (Anderson 2001, Anderson and Ter Braak 2003) can perform permutation-based ANOVA tests on multiple distance measures, such as Bray-Curtis dissimilarity, that are better suited to species assemblage data.

While the proposed ANOVA-based analytical framework is our first choice, we realize that we may need to modify such an approach due to the nature of the study and our limited sample size. Due to the limited proposed sample size (N = 24 at minimum; N = 32 if possible), it is unlikely that any covariates, in addition to the landscape groups, could be included in ANOVA models of a response variable. Additionally, there is concern that the family-wise error rate, the probability of coming to at least one false conclusion when making multiple hypothesis tests, may be high with 13 different tests at the alpha $P < 0.05$ level (family-wise error rate = $1-(1-0.05)^{13} = 0.487$). Based on this concern, will use Bonferroni correction for any P-values (Significance declared at $P < (0.05/13) = 0.004$). An alternative approach would be to use ANOVA to test only the point-measured priority hydrologic variables and a few vegetation variables, reducing the likelihood of falsely rejecting a null hypothesis (family-wise error rate = $1-(1-0.05)^5 = 0.223$; $P < (0.05/5) = 0.01$). We may use non-parametric methods to generate P values such as permutation tests (e.g. univariate PERMANOVA) that do not have the same assumptions about the distribution of the data.

If the ANOVA framework is untenable, we may explore regression models that seek to predict a selected response variable from age class as a continuous predictor. If this is done, then model selection may also involve landscape covariates. Models would be compared using maximum likelihood methods and Akaike's information criterion (AIC). This continuous response would show trends from 2 years to the recently undisturbed second-growth forest (40-50 years) as a continuous variable. While our design is explicitly created to compare means, the utility of keeping a regression approach as an alternative analytical framework is well-founded in the ecological literature (Raikow 2010).

Additionally, within Washington State and Oregon, there are established total maximum daily loads (TMDL), threshold values that 'healthy' streams should not exceed on a daily basis, for temperature and total suspended solids. Ideally, these values can be tested against observed means in an equivalence testing framework. While limited power may preclude identifying statistically significant differences at the prescribed alpha, growing season means for water quality parameters will be compared graphically for each age treatment to the TMDL values to assess if and when the means exceed state prescribed thresholds (McBride 2005).

Table 2.5 Description of proposed hypothesis to be tested on response variables in the analytical framework.

Hypothesis	Description	Ecological Description
Null	Mean parameter values do not differ between treatment (age) classes. That is, the mean of the most recently harvested age class matches the baseline age class	Measurable degraded functions from harvest in the 2-, 10-, and 20-year age classes from the baseline (control) have not been detected.
Alternative	Mean parameter values differ between treatment (age) classes; $\mu_{two} \neq \mu_{ten} \neq \mu_{twenty} \neq \mu_{baseline}$ Note: Largest anticipated difference in means between 2-year and baseline classes.	Forest harvest activities have caused degradation that has not recovered within half of a timber rotation timeframe. This is expressed by differences in the means of different response variables by age class.

3. Observe patterns in hydrologic and vegetation data using multivariate techniques (ordination, clustering, etc.) that visualize and characterize differences between sites' hydrologic and ecological parameters.

Time series data (data collected continuously using loggers) will be plotted for individual sites and as summary statistics for each site. Group means of summary statistics. Multivariate comparisons of sites' response variables at many different points in time are possible using the non-parametric PERMANOVA method above will rely on the summarization of data into only ecologically meaningful flow statistic summaries (Olden and Poff 2003, Harvey et al. 2008) rather than the full series. By using permuted data to identify a pseudo-F value for hypothesis tests, the temporal autocorrelation inherent to the series is destroyed (Anderson 2001), so we must rely on comparing streamflow summaries rather than the series themselves.

Forested wetland sites' vegetation composition will be plotted in unconstrained ordination using non-metric multidimensional scaling (NMDS). The use of NMDS ordination will allow the visualization of the multivariate vegetation composition data on which hypothesis testing will occur using PERMANOVA. Individual hydrologic variables will then be regressed against the final ordination solution axes. This ordination exercise is intended to capture the holistic site-level similarity between forested wetland vegetation and further identify how site-level vegetation and measured hydrology variables relate to one another in an exploratory way.

Interpretation of Results

The results of the chronosequence observational study will provide summaries of conditions in forested wetlands of differing ages post-harvest within a half of a timber rotation cycle. Age-related trends in hydrological and ecological conditions across forested wetlands at each time interval will be used to represent the trajectory of forested wetlands over half a timber rotation cycle. In other words, conclusions can be drawn regarding the recovery of harvested forested wetlands over two decades. There are caveats given the influence of inter-site variability, but this space-for-time study will allow us to compare the hydrological and ecological variables across forested wetlands of multiple age classes.

A primary goal of the chronosequence study is to inform subsequent studies in forested wetland ecosystems, including the BACI study design. By characterizing forested wetland sites of different ages, future study field methods can be tweaked, important response and independent variables identified, and analytical techniques adapted as necessary. Additionally, if significant differences between response variables are found, then rates of change for key ecological and hydrological variables can be estimated within representative forested wetlands of the Olympic and Pacific Cascade DNR regions.

Quality Assurance and Quality Control

Quality assurance and control (QA/QC) will be built into the study at multiple levels, from design to implementation. Throughout the preliminary design of this study, site selection and the response variables of interest have been considered in numerous ways. The primary QA/QC responsibility lies in making sure that a defensible study design has been laid out and the sites selected from within the pool of candidate sites are randomly selected. If possible, the number of measured variables may be reduced only to a few key variables for the chronosequence (pilot) study (See Table 2.4) so that more sites can be measured, increasing statistical power. Additionally, site selection has been reduced from a statewide study with significant logistical constraints and higher natural spatial variability to a study that examines forested wetlands in a key portion of Washington State. With this reduced spatial coverage, there is likely to be less variance in ecological and hydrological data, which will give more power to tests between age class comparisons.

Data collection is a common pitfall in which field studies can lose valuable data, so field personnel will be thoroughly trained. Crews will be trained by project leads to ensure consistency in protocols and to minimize data collection error. A field manager or senior technician was recommended as essential personnel (Hough-Snee 2019 project budget). This senior staff would ideally have experience working with wetland hydrology, vegetation, data loggers, and managing junior staff.

Data stewardship is of the utmost importance in QA/QC. While field data collection methods such as paper vs. digital handheld device applications have not been finalized, data will be backed up frequently and saved to multiple devices and/or cloud-based servers. Field recorded data will be backed up at the end of each day prior to electronic entry: field crews will photograph daily field notes and paper-form data. Data back-ups will be held at the host organization's offices in hard-copy and digital forms. Data will be entered between field hitches and flags made in SQL databases to identify entry errors and/or potential anomalous entries. Any flagged data entries will be rectified with paper forms or original logger entries.

Measurement equipment will be lab calibrated per manufacturer's guidelines and again in the field prior to deployment as necessary. Multiple pre-deployment times series field measurements will be taken with each sensor and data logger to identify any drift in data that is detected in pre/post calibrations. These measurements will be for multiple days and cross-calibrated with known environmental conditions. Steps will be taken to ensure the protection of loggers and probes during field deployment to prevent interference or malfunctioning as necessary. At present, it has been proposed that data pressure transducers and other loggers upload to cloud storage in real-time via cellular phone service. If data is collected to local, offline loggers, then loggers will be downloaded at quarterly intervals.

Project Caveats and Risks Discussion

Because chronosequence designs are observational rather than experimental, specific conclusions cannot be drawn about the causal effects of forest practices on forested wetland hydrology and ecology. For example, inter- and intra-annual rates of change in forest composition, hydrologic variables, and related habitat attributes cannot be inferred under this study design. While the chronosequence study will describe patterns in forested wetland succession along a post-harvest time sequence, we will not be able to attribute differences in variables among age groups to forest harvest alone.

Site variability in a landscape setting, pre-harvest vegetation, and natural hydrology, as well as variation in harvest techniques and intensities may cloud the detection of post-harvest differences in response variables between age classes. Selecting sample locations on independent attributes that are likely to affect forested wetland hydrology and ecology will reduce unexplained environmental and spatial variability. Increased replication will also improve detection of post-harvest trends that vary with forested wetland age, although financial and temporal limitations may preclude using a larger sample size than proposed. Finding sufficient site replicates within each treatment and selecting additional site-level covariates beyond hydrologic landscape classes are vital tasks to make the study as useful as possible.

Aside from the observational nature of the chronosequence study precluding definitive conclusions from being drawn on the specific causal effects of forest practices on forested wetlands, there is risk associated with any study that relies primarily on remotely-monitored data collected with loggers, probes, or time-lapse cameras. Because the sampling apparatus will be left unattended at each site for a majority of the year, missing data can arise if electronic equipment fails, is stolen, or destroyed. If missing data occurs for long enough, for any reason, then a given site's time series attributes may be lost.

Another area of risk is intra-annual, seasonal variation in sampling. If site visits are spaced too loosely across a seasonal gradient, rather than occurring relatively simultaneously in one season, then comparisons among season-dependent response variables may be skewed by time effects. For example, should one site be sampled for vegetation in early spring and another mid-summer, then the composition of those samples may reflect the timing of vegetation emergence rather than between-site differences in vegetation. Variables such as soil and water temperature, tree canopy, and other habitat variables such as shade and soil moisture are susceptible to seasonal effects and will require well-coordinated sampling.

Similarly, annual and multiyear variability in precipitation and temperature could produce results that do not reflect those that might occur under other multi-year to multi-decadal scale climate cycles (e.g., ENSO and PDO; Rasmusson and Wallace 1983, Mantua and Hare 2002). While no field study is guaranteed to occur during "average" conditions or conditions that are informative of future climate, the conclusions should be contextually interpreted based on climate during the study. If the timeframe in which sampling occurred was anomalous, then inter- or intra-annual variability may explain unanticipated similarity between age classes.

One of the largest risks in a preliminary study is the overinterpretation of results from a relatively small sample size. Here, our study uses an ANOVA framework with a limited sample size and power, with a backup analysis structure based on the sites that are used in the study (regression and multivariate exploratory approaches). Additionally, because sample sites will be distributed across the DNR regions in which forest practice applications with forested wetlands are most common, a relatively small spatial extent that excludes a majority of the state, application of these results to ecologically and hydrologically different regions elsewhere in Washington should proceed with caution.

3. REFERENCES

Adamus, P. 2014a. Effects of Forest Roads and Tree Removal in or Near Wetlands of the Pacific Northwest: A Literature Synthesis. Washington State Department of Natural Resources, Olympia, WA.

Adamus, P. 2014b. Wetland Research and Monitoring Strategy: Forest Practices and Wetlands. Washington State Department of Natural Resources, Olympia, WA.

Anderson, H. W., M. D. Hoover, and K. G. Reinhart. 1976. Forests and water: effects of forest management on floods, sedimentation, and water supply. U.S. Department of Agriculture, Forest Service, Pacific Southwest Forest and Range Experiment Station., Berkeley, CA.

Anderson, M. J. 2001. A new method for non-parametric multivariate analysis of variance. Austral Ecology 26:32–46.

Anderson, M., and C. Ter Braak. 2003. Permutation tests for multi-factorial analysis of variance. Journal of Statistical Computation and Simulation 73:85–113.

Archer, J. K. 2003. Understory vegetation and soil response to silvicultural activity in a Southeastern mixed pine forest: A chronosequence study. etd.fcla.edu.

Asada, T., B. G. Warner, and A. Banner. 2004. Sphagnum invasion after clear-cutting and excavator mounding in a hypermaritime forest of British Columbia. Canadian Journal of Forest Research 34:1730–1746.

Aust, W. M., and C. R. Blinn. 2004. Forestry best management practices for timber harvesting and site preparation in the eastern United States: An overview of water quality and productivity research during the past 20 years (1982–2002). Water, Air and Soil Pollution: Focus 4:5–36.

Banet, A. I., and J. C. Trexler. 2013. Space-for-Time Substitution Works in Everglades Ecological Forecasting Models. PLoS ONE 8:e81025.

Banner, A., J. Pojar, and G. E. Rouse. 1983. Postglacial paleoecology and successional relationships of a bog woodland near Prince Rupert, British Columbia. Canadian Journal of Forest Research 13:938–947.

Bannister, J. M., E. R. Herbert, and C. B. Craft. 2015. Spatial Variability in Sedimentation, Carbon Sequestration, and Nutrient Accumulation in an Alluvial Floodplain Forest. Pages 41–55 *in* J. Vymazal, editor. The Role of Natural and Constructed Wetlands in Nutrient Cycling and Retention on the Landscape. Springer International Publishing, Cham.

Bechtold, W. A., P. L. Patterson, and others. 2005. The enhanced forest inventory and analysis program: national sampling design and estimation procedures. US Department of Agriculture Forest Service, Southern Research Station Asheville, North Carolina.

Beckett, L., P. Adamus, D. Moore, D. Sobota, and H. Haemmerle. 2016. Forested Wetlands Effectiveness Project Best Available Science and Study Design Alternatives Document. Washington State Department of Natural Resources, Olympia, WA.

Berkowitz, J. F., and J. R. White. 2013. Linking Wetland Functional Rapid Assessment Models with Quantitative Hydrological and Biogeochemical Measurements across a Restoration Chronosequence. Soil Science Society of America Journal 77:1442.

Bladon, K. D., N. A. Cook, J. T. Light, and C. Segura. 2016. A catchment-scale assessment of stream temperature response to contemporary forest harvesting in the Oregon Coast Range. Forest Ecology and Management 379:153–164.

Boggs, J., G. Sun, and S. McNulty. 2016. Effects of Timber Harvest on Water Quantity and Quality in Small Watersheds in the Piedmont of North Carolina. Journal of Forestry 114:27–40.

Brinson, M. M. 1993. A hydrogeomorphic classification for wetlands. U.S. Army Engineer Waterways Experiment Station, Vicksburg, MS.

Brown, A. E., L. Zhang, T. A. McMahon, A. W. Western, and R. A. Vertessy. 2005. A review of paired catchment studies for determining changes in water yield resulting from alterations in vegetation. Journal of Hydrology 310:28–61.

Brown, K. 2010. Effectiveness of forestry best management practices in minimizing harvesting impacts on streamflow and sediment loading in low-gradient headwaters of the gulf …. digitalcommons.lsu.edu.

Buffington, J. M., and D. R. Montgomery. 2013. 9.36 Geomorphic Classification of Rivers. Pages 730–767 Treatise on Geomorphology. Elsevier.

Burton, T. A. 1997. Effects of basin-scale timber harvest on water yield and peak streamflow. Journal of the American Water Resources Association 33:1187–1196.

Calhoun, A. J. K., D. M. Mushet, L. C. Alexander, E. S. DeKeyser, L. Fowler, C. R. Lane, M. W. Lang, M. C. Rains, S. C. Richter, and S. C. Walls. 2017. The Significant Surface-Water Connectivity of "Geographically Isolated Wetlands." Wetlands 37:801–806.

Carlson, E. A. 2009. Fluvial riparian classification for national forests in the western United States. Thesis, Colorado State University, Fort Collins, CO.

Clark, K. L., H. L. Gholz, and M. S. Castro. 2004. Carbon dynamics along a chronosequence of slash pine plantations in north Florida. Ecological Applications.

Compton, J. E., M. R. Church, S. T. Larned, and W. E. Hogsett. 2003. Nitrogen export from forested watersheds in the Oregon Coast Range: The role of N-2-fixing red alder. Ecosystems 6:773–785.

Conner, W. H. 1994. Effect of forest management practices on southern forested wetland productivity. Wetlands 14:27–40.

Cooperative Monitoring, Evaluation, and Research Committee. 2017. 2017–2019 Biennium CMER Work Plan. Washington State Department of Natural Resources, Olympia, WA.

Cooperative Monitoring, Evaluation, and Research Committee. 2019. 2019-2021 Biennium CMER Work Plan. Page 69. Washington State Department of Natural Resources, Olympia, WA.

Cowardin, L. M., V. Carter, F. C. Golet, and E. T. LaRoe. 1979. Classification of wetlands and deepwater habitats of the United States. Fish and Wildlife Service, US Department of the Interior Washington, DC, USA.

Cui, J., C. Li, and C. Trettin. 2005. Analyzing the ecosystem carbon and hydrologic characteristics of forested wetland using a biogeochemical process model. Global Change Biology.

D’Angelo, E. M., A. D. Karathanasis, E. J. Sparks, S. A. Ritchey, and S. A. Wehr-McChesney. 2005. Soil carbon and microbial communities at mitigated and late successional bottomland forest wetlands. Wetlands 25:162–175.

Devito, K. J., I. F. Creed, and C. J. D. Fraser. 2005. Controls on runoff from a partially harvested aspen-forested headwater catchment, Boreal Plain, Canada. Hydrological Processes 19:3–25.

Dubé, S., A. P. Plamondon, and R. L. Rothwell. 1995. Watering up After Clear-Cutting on Forested Wetlands of the St. Lawrence Lowland. Water Resources Research 31:1741–1750.

Ewing, K. 1996. Tolerance of four wetland plant species to flooding and sediment deposition. Environmental and Experimental Botany 36:131–146.

Forest Practices Habitat Conservation Plan. 2005. . Washington State Department of Natural Resources, Olympia, WA.

França, F., J. Louzada, V. Korasaki, H. Griffiths, J. M. Silveira, and J. Barlow. 2016. Do space-for-time assessments underestimate the impacts of logging on tropical biodiversity? An Amazonian case study using dung beetles. Journal of Applied Ecology 53:1098–1105.

Gilbert, J. T., W. W. Macfarlane, and J. M. Wheaton. 2016. The Valley Bottom Extraction Tool (V-BET): A GIS tool for delineating valley bottoms across entire drainage networks. Computers & Geosciences 97:1–14.

Harvey, G. L., N. J. Clifford, and A. M. Gurnell. 2008. Towards an ecologically meaningful classification of the flow biotope for river inventory, rehabilitation, design and appraisal purposes. Journal of Environmental Management 88:638–650.

Janisch, J. E., A. D. Foster, and W. J. Ehinger. 2011. Characteristics of small headwater wetlands in second-growth forests of Washington, USA. Forest Ecology and Management 261:1265–1274.

Jones, J. A., F. J. Swanson, B. C. Wemple, and K. U. Snyder. 2000. Effects of Roads on Hydrology, Geomorphology, and Disturbance Patches in Stream Networks. Conservation Biology 14:76–85.

Jones, R. H., R. R. Sharitz, P. M. Dixon, D. S. Segal, and R. L. Schneider. 1994. Woody plant-regeneration on 4 floodplain forests. Ecological Monographs 64:345–367.

Kaelke, C. M., and J. O. Dawson. 2003. Seasonal flooding regimes influence survival, nitrogen fixation, and the partitioning of nitrogen and biomass in Alnus incana ssp. rugosa. Plant and Soil 254:167–177.

Kappes, H., A. Sundermann, and P. Haase. 2010. High spatial variability biases the space-for-time approach in environmental monitoring. Ecological Indicators 10:1202–1205.

Kreutzweiser, D. P., P. W. Hazlett, and J. M. Gunn. 2008. Logging impacts on the biogeochemistry of boreal forest soils and nutrient export to aquatic systems: A review. Environmental Reviews 16:157–179.

Laurén, A., L. Finér, H. Koivusalo, and ... 2005. Water and nitrogen processes along a typical water flowpath and streamwater exports from a forested catchment and changes after clear-cutting: a modelling study. Hydrology and ….

Leibowitz, S. G., R. L. Comeleo, P. J. Wigington, M. H. Weber, E. A. Sproles, and K. A. Sawicz. 2016. Hydrologic Landscape Characterization for the Pacific Northwest, USA. JAWRA Journal of the American Water Resources Association 52:473–493.

Manners, R. B., A. C. Wilcox, L. Kui, A. F. Lightbody, J. C. Stella, and L. S. Sklar. 2015. When do plants modify fluvial processes? Plant-hydraulic interactions under variable flow and sediment supply rates: Plant-hydraulic interactions. Journal of Geophysical Research: Earth Surface 120:325–345.

Mantua, N. J., and S. R. Hare. 2002. The Pacific Decadal Oscillation. Journal of Oceanography 58:35–44.

Mastin, M. C., C. P. Konrad, A. G. Veilleux, and A. E. Tecca. 2016. Magnitude, frequency, and trends of floods at gaged and ungaged sites in Washington, based on data through water year 2014. US Geological Survey.

McBride, G. B. 2005. Using statistical methods for water quality management: issues, problems and solutions. John Wiley & Sons.

McCune, B., and J. B. Grace. 2002. Analysis of ecological communities. MGM SSoftware Design, Gleneden Beach, OR.

Melillo, J. M., S. Butler, J. Johnson, J. Mohan, P. Steudler, H. Lux, E. Burrows, F. Bowles, R. Smith, L. Scott, C. Vario, T. Hill, A. Burton, Y.-M. Zhou, and J. Tang. 2011. Soil warming, carbon-nitrogen interactions, and forest carbon budgets. Proceedings of the National Academy of Sciences 108:9508–9512.

Merritt, D. M., and P. B. Shafroth. 2012. Edaphic, salinity, and stand structural trends in chronosequences of native and non-native dominated riparian forests along the Colorado River, USA. Biological Invasions 14:2665–2685.

Miao, G., A. Noormets, J.-C. Domec, M. Fuentes, C. C. Trettin, G. Sun, S. G. McNulty, and J. S. King. 2017. Hydrology and microtopography control carbon dynamics in wetlands: Implications in partitioning ecosystem respiration in a coastal plain forested wetland. Agricultural and Forest Meteorology 247:343–355.

Montgomery, D. R., and J. M. Buffington. 1997. Channel-reach morphology in mountain drainage basins. Geological Society of America Bulletin 109:596–611.

Moore, R. D., and S. M. Wondzell. 2005. Physical hydrology and the effects of forest harvesting in the Pacific Northwest: a review. Journal of the American Water Resources Association 41:763–784.

Mueller-Dombois, D., and H. Ellenberg. 2002. Aims and Methods of Vegetation Ecology. The Blackburn Press, Caldwell, NJ.

Mushet, D. M., A. J. K. Calhoun, L. C. Alexander, M. J. Cohen, E. S. DeKeyser, L. Fowler, C. R. Lane, M. W. Lang, M. C. Rains, and S. C. Walls. 2015. Geographically Isolated Wetlands: Rethinking a Misnomer. Wetlands 35:423–431.

Nagel, D. E., J. M. Buffington, S. L. Parkes, S. Wenger, and J. R. Goode. 2014. A landscape scale valley confinement algorithm: delineating unconfined valley bottoms for geomorphic, aquatic, and riparian applications. U.S. Department of Agriculture, Forest Service, Rocky Mountain Research Station, Fort Collins, CO.

Nakagawa, Y., T. Nakamura, H. Yamada, and F. Nakamura. 2012. Changes in nitrogen and base cation concentrations in soil water due to the tree cutting in a wetland alder forest in the Kushiro Wetland, northern Japan. Limnology.

Neill, C., L. A. Deegan, S. M. Thomas, and C. C. Cerri. 2001. Deforestation for pasture alters nitrogen and phosphorus in small Amazonian streams. Ecological Applications 11:1817–1828.

Olden, J. D., and N. L. Poff. 2003. Redundancy and the choice of hydrologic indices for characterizing streamflow regimes. River Research and Applications 19:101–121.

Omernik, J. M. 1995. Ecoregions: A Framework for Managing Ecosystems. The George Wright Forum 12:35–50.

Painter, L. 2009. Redefining Old-Growth in Forested Wetlands of Western Washington. Environmental Practice 11:68–83.

Phillips, J. D. 1989. Fluvial Sediment Storage in Wetlands. Journal of the American Water Resources Association 25:867–873.

Raikow, D. F. 2010. Dose-response versus ANOVA. Frontiers in Ecology and the Environment 8:121–122.

Rasmusson, E. M., and J. M. Wallace. 1983. Meteorological Aspects of the El Nino/Southern Oscillation. Science 222:1195–1202.

Richardson, C. J. 1994. Ecological functions and human values in wetlands: A framework for assessing forestry impacts. Wetlands 14:1–9.

Roni, P. 2013. Stream and watershed restoration: a guide to restoring riverine processes and habitats. Wiley-Blackwell, Chichester.

Roy, V., J.-C. Ruel, and A. P. Plamondon. 2000. Establishment, growth and survival of natural regeneration after clearcutting and drainage on forested wetlands. Forest Ecology and Management 129:253–267.

Schelker, J., R. Sponseller, E. Ring, L. Högbom, S. Löfgren, and H. Laudon. 2016. Nitrogen export from a boreal stream network following forest harvesting: seasonal nitrate removal and conservative export of organic forms. Biogeosciences 13:1–12.

Shaffer, G. P., W. B. Wood, S. S. Hoeppner, T. E. Perkins, J. Zoller, and D. Kandalepas. 2009. Degradation of Baldcypress–Water Tupelo Swamp to Marsh and Open Water in Southeastern Louisiana, U.S.A.: An Irreversible Trajectory? Journal of Coastal Research 10054:152–165.

Sharitz, R. R., and L. C. Lee. 1998. Limits on Regeneration Processes in Southeastern Riverine Wetlands. Paper presented at North American riparian conference:139–143.

Shepard, J. P. 1994. Effects of forest management on surface water quality in wetland forests. Wetlands 14:18–26.

Stanturf, J. A., S. H. Schoenholtz, C. J. Schweitzer, and J. P. Shepard. 2001. Achieving Restoration Success: Myths in Bottomland Hardwood Forests. Restoration Ecology 9:189–200.

Sun, G., S. G. McNulty, D. M. Amatya, R. W. Skaggs, L. W. Swift, J. P. Shepard, and H. Riekerk. 2002. A comparison of the watershed hydrology of coastal forested wetlands and the mountainous uplands in the Southern US. Journal of Hydrology 263:92–104.

Sun, G., S. G. McNulty, J. P. Shepard, D. M. Amatya, H. Riekerk, N. B. Comerford, W. Skaggs, and L. Swift. 2001. Effects of timber management on the hydrology of wetland forests in the southern United States. Forest Ecology and Management 143:227–236.

Sun, G., H. Riekerk, and L. V. Kornhak. 2000. Ground-water-table rise after forest harvesting on cypress-pine flatwoods in Florida. Wetlands 20:101–112.

Tiner, R. W. 2003. Geographically isolated wetlands of the United States. Wetlands 23:494–516.

Trieste, D. J., and R. D. Jarrett. 1987. Roughness coefficients of large floods. Pages 32–40 *in* L. G. James and M. J. English, editors. American Society of Civil Engineers, New York.

U.S. Geological Survey. 2016. The StreamStats program. http://streamstats.usgs.gov,.

Washington State Department of Natural Resources. 1999. Forests and Fish Report. Washington State Department of Natural Resources, Olympia, WA.

Washington State Forest Practices Board. 1975. Washington State Forest Practices Act. Page RCW 76.09.

Wigginton, J. D., B. G. Lockaby, and C. C. Trettin. 2000. Soil organic matter formation and sequestration across a forested floodplain chronosequence. Ecological Engineering 15:S141–S155.

Wigley, T. B., and T. H. Roberts. 1994a. A review of wildlife changes in southern bottomland hardwoods due to forest management practices. Wetlands.

Wigley, T. B., and T. H. Roberts. 1994b. Forest management and wildlife in forested wetlands of the southern Appalachians. Water, Air, & Soil Pollution 77:445–456.

Winter, T. C. 2001. The concept of hydrologic landscapes. Journal of the American Water Resources Association 37:335–349.

Zar, J. H. 2010. Biostatistical analysis. 5th ed. Prentice-Hall/Pearson, Upper Saddle River, N.J.

Zedler, J. B., and J. C. Callaway. 1999. Tracking Wetland Restoration: Do Mitigation Sites Follow Desired Trajectories? Restoration Ecology 7:69–73.

APPENDIX 1

Table A.1: Current and recent personnel comprising the Forested Wetlands Effectiveness Project (FWEP) TWIG through the summer of 2018.

Name	Affiliation	Expertise
Angela Johnson - Project Manager (Left DNR June 2018)	Washington Department of Natural Resources	Water quality; DNR Adaptive Management Program
Paul Adamus (*consulting member – retired July 2019*)	Adamus Resource Assessment, Inc. Oregon State University	Wetlands, hydrology, forest practice effects on aquatic ecosystems
Kevin Bladon	Oregon State University	Watershed and forest hydrology
R. Dan Moore (*consulting member)*	University of British Columbia	Forest practice effects on aquatic ecosystems; floodplain ecology
Dan Sobota (*Withdrawn May 2019*)	Oregon Department of Environmental Quality	Biogeochemistry, water quality, wetlands
John Van Sickle (*consulting statistician - retired July 2019*)	Oregon State University	Statistics; Statistical applications to natural resources
Nate Hough-Snee	Meadow Run Environmental, LLC; Currently Four Peaks Environmental	Wetland, riparian, and forest ecology
Howard Haemmerle – project manager (2017; rejoined July 2018; *retired* July 2019)	Washington Department of Natural Resources	Adaptive Management Program; Botany; Project management
Leah Beckett - former CMER Staff (Departed NWIFC 2017)	Northwest Indian Fisheries Commission	Wetland ecology