THESIS

STREAM NUTRIENT RESPONSE TO CONTEMPORARY TIMBER HARVEST PRACTICES IN WESTER OREGON

Submitted by

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In partial fulfillment of the requirements

For the Degree of Master of Science

Colorado State University

Fort Collins, Colorado

Spring 2017

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ABSTRACT

STREAM NUTRIENT RESPONSE TO CONTEMPORARY TIMBER HARVEST PRACTICES IN WESTERN OREGON

Timber harvesting has historically been shown to increase nutrient concentrations in stream waters by decreasing vegetative cover and nutrient uptake, allowing more nutrients to be leached into stream waters. Contemporary timber harvest practices, in which a streamside buffer is left in place, have not been studied. This study quantified the effects of contemporary timber harvesting practices, with a streamside buffer, in a Douglas-fir dominated watershed in the Oregon Coast Range, using a paired-watershed design. In the treatment (Needle Branch) and the control (Flynn Creek) watersheds, water quality samples collected from October 2006 through March 2016 were analyzed for nutrients. A clearcut harvest took place in the upper basin in 2009 (Phase 1), and in the lower basin in 2014 (Phase 2), and water samples were tested for nitrate (NO_3-N), total nitrogen (TN), ammonia (NH_3), orthophosphate (OP), and total phosphorus (TP).

Intra-watershed comparisons of nutrient concentrations were made using a Wilcoxon Rank Sum Test to determine statistical significance between sites and treatments. A Before-After Control-Impact (BACI) design was used to compare the treatment watershed to the control watershed across treatments. Results at Needle Branch showed statistically significant increases ($\alpha < 0.05$) in NO_3-N between pre-treatment (0.59 mg/L) and Phase 1 (0.97 mg/L), and between pre-treatment and Phase 2 (0.90 mg/L) at the outlet. TN also showed statistically significant increases between pre-treatment (0.87 mg/L), and Phase 1 (1.06 mg/L), and between pre-

treatment and Phase 2 (0.92 mg/L). NH_3 was also shown to be statistically significant between pre-treatment (0.011 mg/L) and Phase 1 (0.013 mg/L).

OP showed statistically significant increases between pre-treatment (0.018 mg/L) and Phase 1 (0.024 mg/L), and between pre-treatment and Phase 2 (0.022 mg/L), as did TP (0.018, 0.026, 0.020 mg/L during pre-treatment, Phase 1, and Phase 2, respectively).

Results in Flynn Creek showed statistically significant increases in NH_3 between pre-treatment (0.010 mg/L) and Phase 1 (0.013 mg/L). OP also showed statistically significant increases between pre-treatment (0.029 mg/L) and Phase 1 (0.034), and between pre-treatment and Phase 2 (0.032). TP also showed significantly significant increases between pre-treatment (0.028 mg/L) and Phase 1 (0.036 mg/L). Because similar results were observed in both the treatment and control watersheds, changes in these three constituents within the treatment watershed cannot be attributed to timber harvest. Neither NO_3-N nor TN showed any change between phases within Flynn Creek, therefore, changes in these constituents within Needle Branch can be attributed to timber harvest.

Contemporary timber harvest practices appear to have similar results as past harvesting practices, regarding nutrient concentrations in stream waters. With a streamside buffer, NO_3-N and TN concentrations were significantly increased following harvest. Contemporary timber harvest practices, however, did not affect NH_3, OP, and TP concentrations.

ACKNOWLEDGEMENTS

I would like to express my appreciation for my advisor, Dr. John Stednick, whose patience during my thesis writing process did not go unnoticed. I feel very fortunate to have studied under such an accomplished scientist, whose high standards pushed me to be a better student and scientist.

I would also like to acknowledge my committee members, Dr. Steven Fassnacht and Dr. William Sanford. Dr. Fassnacht has played an integral role in my graduate education. He has shaped my thought processes, my writing abilities, and he is also one of the first people to encourage me to pursue Watershed Science. For that I am grateful. Dr. Sanford is one of the first professors that I had at Colorado State University, and he taught the first hydrology-related course that I have taken, Hydrogeology. This is the course that began my journey into Watershed Science and I will forever associate Dr. Sanford with that positive experience.

I would like to thank my mom, without whose endless love and support I never would have been able to continue my education, and who has given unwavering encouragement every step of the way; and Kellie and Peter, who have made me a part of their family and have enthusiastically joined me on this journey.

Finally, I would like to thank Ryan, who has stood by me throughout the ups and downs of my graduate career. His love, patience, and endless encouragement have kept me afloat during the last two years; I don’t know where I would be without him, and I am forever grateful for his support.

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CHAPTER 1 - INTRODUCTION

1.1 Background

Timber harvest activities have been occurring in Oregon since the early 1800s. Demand for the resulting products have varied throughout the decades, depending upon economic vitality, environmental legislation, and other factors, and today the forest sector economy still accounts for up to 30% of the economic base in some Oregon counties (OFRI, 2016). Oregon forest managers are tasked with balancing the demand for timber with environmental needs, such as protecting forest ecosystems, water resources, and aquatic life. Past harvesting practices, which included extracting timber throughout the riparian zone, have been shown to increase nutrient concentrations in stream waters, and efforts have been taken in the past few decades to mitigate this result. These efforts include the implementation of Best Management Practices (BMPs), which differentiate past harvesting practices from contemporary harvesting practices. Contemporary timber harvest practices involve the use of streamside management zones (SMZ) as a BMP, which are vegetated riparian buffer strips that are left in place during timber harvest to protect water quality, and preserve habitat for fish and other wildlife.

Awareness of the effects of timber harvest on stream nutrients began with the often-cited Hubbard Brook Experimental Forest study. In this study, which took place in the White Mountains of New Hampshire, all vegetation in a treatment watershed was clearcut in the winter of 1965, and vegetation regrowth was suppressed for the subsequent two years with the use of herbicides. Concentrations of nitrate increased from a volume-weighted average concentration of 0.9 mg/L prior to the clearcut, to 53 mg/L two years after the clearcut. During the same period, nitrate concentrations in the control watershed exhibited similar seasonal patterns before and after the clearcut, averaging <0.1 mg/L in the summer and reaching values as high as 2 mg/L in the spring. Deforestation and herbicide application had altered the nitrogen cycle, increasing nitrification, which resulted in a greatly increased export of nitrate. As a result of this treatment, nitrate concentrations in the stream water had almost continuously exceeded drinking water standards, and did not return to pretreatment levels until 3 to 5 years after herbicide treatments had stopped (de la Creataz and Barten, 2007). Additionally, a dense bloom of algae appeared each summer in the stream from the treatment watershed up until the time this study was published (Likens et al., 1970).

During the same period as the Hubbard Brook Study, a similar study was being conducted in the Alsea Watershed, located in the Oregon Coast Range. This study used a paired-watershed design using three watersheds. One watershed was clearcut (Needle Branch), while another was patch cut with streamside vegetation left in place (Deer Creek). A third catchment served as a control and remained untreated (Flynn Creek). In 1966, timber was harvested using a cable yarding system with no streamside buffers, and logging slash was subsequently burned. Nutrient measurements began in January of 1964 and continued through June 1969. The results showed that, while phosphorus concentrations remained unchanged in all three catchments, maximum nitrate-N concentrations increased from 0.70 to 2.10 mg/L in Needle Branch, while nitrate-N export increased from 4.94 to 15.66 kg/ha/yr the first year after treatment. Concentrations were estimated to return to prelogging levels six years after treatment. Concentrations and flux of nitrate-N in Flynn Creek and Deer Creek did not increase significantly after the treatment period (Brown et al., 1973).

An additional study, which took place in the Coyote Creek Experimental Watershed, located on the west slope of the Oregon Cascades, also used a paired-watershed design. One watershed was completely clearcut, the second was patchcut, and the third was shelterwood cut.

Timber harvest took place betweeen May and October of 1971. Slash was burned in the fall of 1973. The treatments led to increased nitrate concentrations on both the patchcut and the clearcut watersheds, peaking at 0.51 mg/L the year following the clearcut. Additionally, yields of nitrate peaked in the clearcut watershed during the same year as treatement at 2.9 kg/ha/yr. Nitrate and total dissolved nitrogen losses from the clearcut watershed took approximately 5-6 years to return to control levels. Yields of orthophosphate and total dissolved phosphorus were reported to be higher in the clearcut catchment than the other treated watersheds, although no values were reported (Adams and Stack, 1989).

Following the results of these studies, Oregon established the Oregon Forest Practices Act (ODOF, 2014), which represented the first set of comprehensive laws in the nation to govern forest practices (Adams and Storm, 2011). While the act was first published in 1971, the rules have been evolving ever since. The act established standards for all commercial activities involving the harvest and management of trees on Oregon forestlands, and established BMPs for the protection of water resources, which included restricting timber harvest near waterways, as well as requiring trees and vegetation to be left in place along streams in which fish live (ODOF, 2014). These BMPs were meant to ensure, in part, that nutrient concentrations in stream waters, following timber harvest, would not increase; and the enactment of these BMPs are what differentiate contemporary timber harvesting practices from older harvesting practices.

When a forested ecosystem has been harvested, the nutrient cycles within that ecosystem are altered (Binkley, 1986). The loss of vegetation prevents nutrient uptake, and the exposed soil is more susceptible to erosion (Rankinen, 2004). In undisturbed forests, erosion rates are generally negligible; but these rates can increase after timber harvest, as can the loss of nutrients via soil erosion (Binkley, 1986). This was demonstrated in a comparative analysis of natural and disturbed streams in the Pacific Northwest following timber harvest and slash burning, which found that more than half of the nitrogen that entered the stream had combined with or adsorbed to sediment (Fredriksen, 1971). Nitrogen transported via erosional processes are a major source of nitrogen that eventually degrades surface water, particularly that which is transported in soil organic matter, which is more susceptible to erosion because it is concentrated near the soil surface (Follett, 2001).

Nutrients that are not lost during sediment transport may be removed by leaching. Because the soil is often exposed following timber harvest, soil temperature and soil moisture are elevated, increasing rates of decomposition, mineralization, and nitrification (Gundersen et al., 2006). This leads to an increase of nitrate in the soil, which is compounded by a lack of vegetative uptake. Because nitrate is completely water soluble and mobile, and because of the low capacity of soils to retain this anion (Pierzynski and Sims, 2005), it moves with the water, over and through the land surface and sub-surface, respectively, until it re-enters the available soil pool, is utilized by microbes or plants, becomes denitrified, or enters surface waters (Follett, 2001).

Phosphorus may also be lost from soils via surface processes and pathways such as erosion and overland flow; in most soils, however, the susceptibility of dissolved phosphorus to transport is small due to the low solubility of phosphorus (Pierzynski and Sims, 2005). Additionally, phosphorus is generally in such high demand in forest ecosystems, even disturbed ecosystems, that leaching is unlikely, as the nutrient is quickly uptaken or immobilized (Lukac and Godbold, 2011).

1.2 Nitrogen

In the Pacific Northwest, nitrogen is the major growth-limiting nutrient for coniferous forests (Edmonds et al., 1989). Nitrogen, essential for all living organisms, controls important biogeochemical processes, such as decomposition, nutrient cycling, and atmospheric chemisty (Werner, 2005). The most common form of nitrogen, dinitrogen gas (N_2), is unavailable to plants, with the exception of those few that are capable of biological N fixation (Binkley, 1986). Nitrogen inputs into forest ecosystems primarily come fom N_2 deposition from the atmosphere, as well as from biological nitrogen fixation, which is the enzymatic reduction of inert N_2 gas to ammonium (NH_4^+) (Nadelhoffer, 2001). Additionally, inputs are also available in the form of nitrogen oxides (NO_x), which are created during the combustion of fossil fuels, as well as from lightning emmisions (Vitousek et al., 1997). To become biologically available, nitrogen goes through the process of fixation, where atmospheric nitrogen is converted to ammonia (NH_3), which, in soils, is primarily bound to clay particles in the form of ammonium (NH_4^+) (Werner, 2005). Ammonium is biologically available for uptake by vegetation; however, it may also undergo the process of nitrification, in which bacteria of the genus *Nitrosomonas* oxidize the ammonium to nitrite, and then bacteria of the genus *Nitrobacter* further oxidize the nitrite to nitrate. Nitrite produced in the first reaction is quickly converted to nitrate and the nitrite seldom accumulates within the ecosystem (Boyd, 2000). Rapid conversion of nitrite to nitrate is important because of the toxicity of nitrite to plants and animals, even at low concentrations (Pierzynski and Sims, 2005). Nitrate is the most plant available form of nitrogen, while also being the most mobile; any nitrate in excess of plant and microbial uptake requirements can leach through the soil profile and make its way to stream waters (Gundersen et al., 2006).

Once within the stream, nitrogen can take several paths. It can denitrify, which is the only process that completely removes ammonium and nitrate from aquatic systems (Thomas, 2009). More commonly, however, ammonium that makes its way to stream waters can either be converted to nitrate by nitrifying microorganisms, or, as with nitrate that makes its way to stream waters, it can be taken up by aquatic primary producers, such as algae, or by bacteria and fungal communities on woody debris (Ashkenas et al., 2004). That which is not removed from the stream by aquatic biota may be removed by riparian vegetation, which generally accounts for a small amount of nitrogen removal (Thomas, 2009). When stream waters experience excess nitrogen inputs, aquatic microbes and plants will increase production to take advantage of the surplus nutrient; but as nitrogen levels increase, production becomes less efficient, resulting in excess nitrogen transported downstream (Thomas, 2009).

Excess nitrogen in stream waters can have various environmental and health consequences including eutrophication and methemoglobinemia, or blue baby syndrome. Methemoglobinemia is caused by consuming excess nitrate (Follett and Follett, 2001), and can affect fish, as well as people, limiting the oxygen-carrying capacity of the blood, and potentially causing anoxia (Stednick and Kern, 1994). Arguably the greatest concern of excess nitrate in stream waters, however, is eutrophication, which can be caused by much lower concentrations of nitrogen than those required to contaminate drinking water (Pierzynski and Sims, 2005). Eutrophication causes an acceleration of growth of algae and other aquatic plants (Pierzynski and Sims, 2005), which eventually depletes the waters of dissolved oxygen, and therefore threatens the livelihoods of other aquatic species. In addition, with respect to drinking water, excess algal growth has the potential to increase water treatment costs by clogging screens and requiring more chemicals, and it can cause serious taste and odor problems (Follett, 2001).

1.3 Phosphorus

Phosphorus is primarily associated with energy processes within organisms (Orlov, 1992). The common form of phosphorus in forested ecosystems is orthophosphate (PO_4^{3-}) (Binkley, 1986), which is the only inorganic form in which phosphorus occurs in sizable amounts, and which is plant available (McClain et al., 1998). Phosphorus is unique in that its reactions do not involve a change in oxidation state (McClain et al., 1998). The primary source of phosphorus in natural ecosystems is via the chemical and physical processes of weathering of soil minerals and other geological materials (Pierzynski and Sims, 2005), which is caused by water and dilute acids in the soil solution (Lukac and Godbold, 2011). This weathering inputs inorganic phosphorus (PO_4^{3-}) into the ecosystem (EPA, 2015). PO_4^{3-} is plant available, and has one of four possible fates: uptake by plants or microbes; precipitation with calcium, iron, or aluminum; adsorption by anion exchange sites or sesquioxides; or leaching from the rooting zone of the forest (Binkley, 1986). In the case of uptake, the phosphorus is returned to the soil via decomposition, and the cycle continues (US EPA, 2015). In natural ecosystems, where there is little to no human intervention, most of the phosphorus accumulated is eventually cycled back into the soil as plants die (Pierzynski and Sims, 2005).

It takes hundreds of years for phosphorus to accumulate to the extent that is generally found in forest ecosystems. The demand for phosphorus in these ecosystems is generally so high when compared to the phosphorus pool, that even if plant demand for phosphorus is removed, i.e. via harvesting, there is little leaching loss of phosphorus from the ecosystem (Lukac and Godbold, 2011). When vegetation is removed from a forest ecosystem, geochemical and biological processes are adequate enough to retain phosphorus and prevent leaching and subsequent increases in streamwater concentrations (Binkley, 1986), allowing uptake by roots and microbes in the upper soil profile to retain phosphorus in the ecosystem (Binkley, 1986).

Phosphorus has no known direct toxic effects to humans or animals (Pierzynski and Sims, 2005); however, just as with nitrogen, there are environmental concerns associated with phosphorus in surface waters. These concerns center on increases of biological activity in aquatic ecosystems. In most freshwater ecosystems, the growth of algae and aquatic plants is limited by phosphorus. When phosphorus levels increase in these ecosystems, growth of aquatic organisms is stimulated to ecologically undesirable levels (Pierzynski and Sims, 2005). The increased growth of aquatic organisms can lead to eutrophication, which is defined as "*an increase in the fertility status of natural waters that causes accelerated growth of algae or water plants*" (Pierzynski and Sims, 2005, p. 186). The accelerated growth of algal plants increases the biological oxygen demand (BOD) of the ecosystem, which in turn decreases the concentrations of dissolved oxygen (DO) in the water. It the worst case scenario, the decreased dissolved oxygen can lead to fish kills and hypereutrophication, limiting the biodiversity of the ecosystem.

1.4 Effects of Contemporary Timber Harvest Practices on Nutrients in Stream Water

Since the adoption of the Oregon Forest Practices Act in 1971, states across the country have adopted similar standards. Since these practices, which include BMPs such as SMZs and vegetated riparian buffers, have become the norm, several studies have been performed to determine the impact of contemporary timber harvest practices on stream nutrients.

In the Mica Creek Experimental Watershed in northern Idaho, water samples were collected during three treatment intervals: pre-treatment (1992-1997), post-road construction (1997-2001), and post-harvest (2001-2006). All timber harvesting activities were conducted in compliance with the Idaho Forest Practices Act, and every treatment site showed statistically significant increases in NO_3+NO_2 concentrations following both clearcut and partial cut harvest practices. Increases at the clearcut treatment sites were greatest, where mean monthly concentrations increased from 0.06 mg/L N during the calibration and post-road periods to 0.35 during the post-harvest period. No change was observed in concentrations of total Kjeldahl nitrogen, nor for total phosphorus. The only site to show statistically significant changes in orthophosphate concentrations following timber harvest was the downstream cumulative site, where concentration doubled, from 0.01 to 0.02 mg/L (Gravelle et al., 2009).

In the Hinkle Creek Watershed, located in the Cascade Mountains of Oregon, water quality measurements occurred from October 2002 to September 2011, and timber harvest took place between August 2005 and May 2006 in non-fish-bearing headwater basins, and without fixed width stream buffers. Additional clearcuts occurred between August 2008 and January 2009 in fish-bearing streams with fixed width stream buffers. All treatment watersheds showed a statistically significant increase in nitrate (NO_3+NO_2) concentrations after clearcutting, the most notable of which went from 0.015 mg/L to 0.248 mg/L in a 75% clearcut catchment. Changes in orthophosphate were insignificant (Meininger, 2011).

In the Dry Creek Watershed of Southwest Georgia, water quality monitoring took place for two years before timber harvest, which began in 2001, and one year after timber harvest, ending in 2004. Additionally, there were two more years of monitoring after site preparation and planting. This study showed a high level of variability in concentrations within years, between years, and between watersheds. The only constituents that showed a statistically significant increase in the treatment watershed were nitrate/nitrate (NO_x), which increased from 0.5724 mg/L to 0.8389 mg/L, and total nitrogen, which increased from 1.0192 mg/L to 1.3111 mg/L.

The elevated levels of both of these constituents did not occur until the two-year monitoring period after site preparation (Marchman et al., 2015).

Finally, at the Hill Demonstration Forest and Umstead Research Farm in North Carolina, water quality monitoring took place from 2007 through 2013, on two paired watersheds, with two treatment watersheds and two reference watersheds. Logging took place in the first treatment watershed between July and September of 2010, and in the second treatment watershed between November 2010 and January 2011. This study was focused on trying to model nutrient concentrations after timber harvest, and therefore did not present statistical significance of measured concentrations before and after timber harvest. However, measured values of nitrate-N (NO_3-N) increased from 0.03 mg/L to 0.45 mg/L in a treatment watershed where 48% of the riparian buffer was selectively harvested, and from 0.01 mg/L to 0.13 mg/L in a treatment watershed where 27% of the riparian buffer was selectively harvested. Additionally, NO_3-N flux increased from 0.03 kg/ha/yr to 1.14 kg/ha/yr and from 0.003 kg/ha/yr to 0.68 kg/ha/yr (Boggs et al., 2015).

These represent some of the few studies in the current literature that attempt to quantify the effects of contemporary timber harvest practices (Table 1.1). These studies all used paired-watershed designs, and all found significant increases in nitrate following treatment. Between these studies, however, there is much variability in the magnitude of the results, which is likely attributable to differing vegetation, geology, and climate among these locations. This variability suggests that, because no study has been performed in the Oregon Coast Range since the original Alsea Watershed Study, further examination is warranted to assess the effects of contemporary timber harvest practices in that region.

Table 1.1: Summary of results from studies assessing the effects of contemporary timber harvest practices on nutrient concentrations in surface waters.

Watershed	Location	Pretreatment Monitoring	Posttreatment Monitoring	Harvested Area (%)	Mean Pretreatment NO_2+NO_3 (mg/L)	Mean Posttreatment NO_2+NO_3 (mg/L)	Mean Pretreatment PO_4^{3-} (mg/L)	Mean Posttreatment PO_4^{3-} (mg/L)	Citation
Mica Creek	Northern Idaho	1992-1997	2001-2006	50	0.06	0.35	0.01	0.02	Gravelle et al., 2009
Hinkle Creek	Oregon Cascade Range	2002-2005	2006-2011	75	0.015	0.248	0.032	0.027	Meininger, 2011
Dry Creek	Southwest Georgia	2001-2003	2003-2004	54	0.5724	0.8389	0.0044	0.0054	Marchman et al., 2015
Hill Demonstration Forest & Umstead Research Farm	North Carolina	2007-2010	2011-2013	48	0.03 (NO_3-N)	0.45 (NO_3-N)	0.07 (TP)	0.08 (TP)	Boggs et al., 2015

1.5 Nutrient Criteria

Aside from sedimentation, the United States Environmental Protection Agency (EPA) has found that nutrients are the second leading cause of water quality impairment in rivers (EPA, 2000). According to the Clean Water Act (CWA), water quality standards must be maintained for the protection and propagation of fish, shellfish, and wildlife in and on the water (Killam, 2005). In addition, it also calls for the protection of the physical, chemical, and biological integrity of those waters. Given the potential environmental risks associated with elevated nitrogen and phosphorus concentrations in stream waters, the EPA has recommended numeric criteria to states to determine whether waters have exceeded acceptable levels of these nutrients. These recommendations differ depending upon the ecoregion in question, which are regions of similar biota, as well as abiotic, aquatic and terrestrial components. There are fourteen ecoregions across the United States. Ecoregion II is characterized as western forested mountains, dominated by conifer; and within this ecoregion there are Level III Ecoregions, which are subecoregions, one of which is the Oregon Coast Range (Figure 1.1). The Oregon Coast Range Level III Ecoregion, which encompasses the Alsea Watershed, is characterized as being "*highly productive, rain-drenched coniferous forests*" (EPA, 2000, p. 8).

Within the aggregate Ecoregion II, Level III subecoregion, the EPA has compiled data to determine recommendations for reference conditions (Table 1.2) which represent "*the natural, least impacted conditions or what is considered to be the most attainable conditions*" regarding nutrient concentrations in streams (EPA, 2000, p. 34). The EPA determined that the lower 25th percentile concentrations of all streams within the region and subecoregion would approximate nutrient levels that protect against cultural overenrichment. The 25th percentile of nutrient concentrations was determined, for all seasons, by taking the median value, over a decade, of the

25th percentiles for each of the four seasons. If a season was missing, the median was calculated with three seasons of data. The calculated value of total nitrogen is based on the sum of total Kjeldahl nitrogen (TKN) and NO_3-N (EPA, 2000).

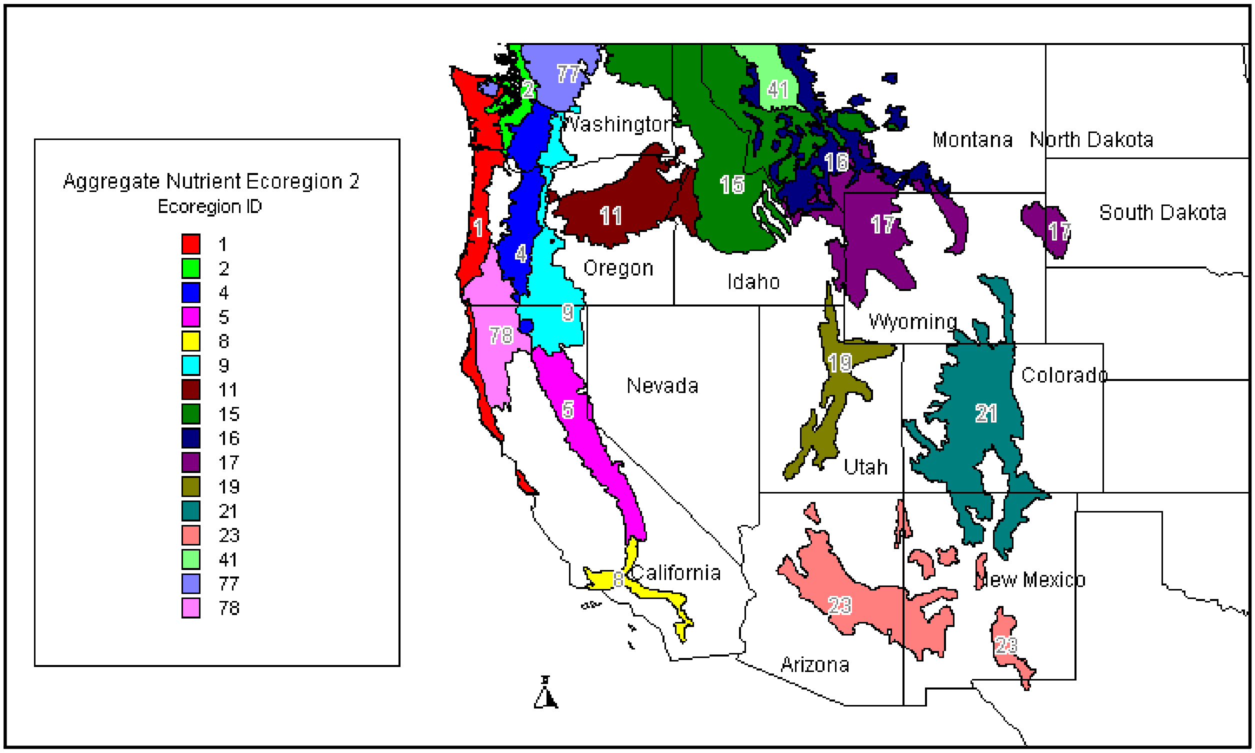

Figure 1.1: Level III Ecoregions within Aggregate Ecoregion II (EPA, 2000).
*The Alsea Watershed is within the area labeled '1,' in red

Table 1.2: EPA recommended nutrient reference conditions for nutrients in Level III Ecoregion II streams (EPA, 2000).

	# of Streams	Reported Values		EPA Recommened Nutrient Criteria
		Min	Max	
TKN (mg/L)	15	0.05	0.83	0.08
NO_3-N (mg/L)	129	0.01	3.70	0.26
TN (mg/L) - calculated	NA	0.06	4.53	0.34
TN (mg/L) - reported	37	0.08	2.62	0.24
TP (µg/L)	133	2.50	330	19.5

1.6 Hypothesis and Study Objectives

Hypothesis:

Although contemporary timber harvest practices have been assessed in a variety of watersheds and locales across the nation, they have not been analyzed in the Pacific Northwest, specifically the Oregon Coast Range. Given that previous studies have found elevated nutrient concentrations following these practices, the study hypothesis is that contemporary timber harvest practices in the Oregon Coast Range will not increase nutrient concentrations in stream waters.

Study Objectives:

1. Determine data stationarity of stream nutrient concentrations from a control watershed by comparing concentrations over multiple time periods, to ensure that the watershed can serve as a control.
2. Assess intra-watershed variability of stream nutrient concentrations within the treatment watershed by comparing concentrations before and after timber harvest, and at multiple locations.
3. Assess inter-watershed variability of stream nutrient concentrations by comparing concentrations in the treatment watershed to those in the control watershed before and after timber harvest.
4. Determine if nutrient concentrations in the treatment and the control watershed exceed recommended criteria by comparing concentrations, before and after timber harvest, to EPA recommended nutrient criteria.

CHAPTER 2 - METHODS

2.1 Study Site

The Alsea watershed is located approximately 21 kilometers southwest of Corvallis, Oregon and 29 kilometers northwest of Eugene, Oregon (Figure 2.1), in the Siuslaw National Forest in the Oregon Coast Range. The climate in the Alsea watershed is maritime and annual precipitation is approximately 250 centimeters, most of which is rain. Air temperatures generally range from -7 to 32º C (Hall and Stednick, 2008).

This study used a paired-watershed design using two small catchments. For a paired watershed study to be successful, the control watershed needs to be situated near enough to the treatment watershed to be subject to similar natural phenomena, such as precipitation patterns, that might affect long-term nutrient cycles and biological populations, while also being far enough from the treatment watershed to be beyond the influence of the treatment (Stewart-Oaten et al., 1986). The control watershed also needs to demonstrate consistency in nutrient concentrations during all periods of treatment, known as data stationarity. Data stationarity is the idea that, while natural systems do fluctuate within a given time period, these fluctuations will be similar from year to year (Milly et al., 2008). Stationarity of the control watershed is important because it supports the assertion that there are minimal outside forces, beyond treatment, that may have affected nutrient dynamics in the region. If stationarity exists within the control watershed, then any changes that occur in the treatment watershed can be attributed to the treatment.

The control watershed in this study was Flynn Creek, which is approximately 219 ha with a mean slope of 27.9%, a mean elevation of 280 m, and drainage density of 0.47 km km^{-2}

(Bladon et al., 2016). The dominant vegetation in Flynn Creek is mixed hardwood and conifer stands. The hardwood is primarily red alder (*Alnus rubra)* and accounts for approximately 64% of the cover; and conifer is primarily Douglas-fir (*Pseudotsuga menziesii)* and accounts for 36% of the vegetation cover. Understory in Flynn Creek consists of sword fern (*Polystichummunitum)*, vine maple (*Acer Circinatum)*, salmonberry (*Rubus spectabilis)*, and salal *(Gaultheria shallon)* (Table 2.1). This catchment has remained undisturbed since the great Alsea fire of about 1850 (Hall and Stednick, 2008), and was designated as a Research Natural Area in 1975 by the USDA Forest Service (Bladon et al., 2016).

Needle Branch, which served as the treatment watershed, is 94 ha with a mean slope of 37%, a mean elevation of 220 m, and a drainage density of 1.01 km km^{-2}. The dominant vegetation in Needle Branch is conifer, primarily Douglas-fir, which accounts for 80% of vegetation cover. Mixed hardwoods account for the remaining 20% of vegetation cover. Understory vegetation in Needle Branch is primarily vine maple and sword fern. Also present are salal, bracken fern (*Pteridium aquilinum)*, salmonberry, thimbleberry (*Rubus parviflorus)*, and dewberry (*R. vitifolius)* (Table 2.1). Needle Branch was originally harvested in 1966, during the original Alsea Watershed Study, and was last commercially thinned in 1998 (Hall and Stednick, 2008).

Within the Alsea watershed, approximately 71% of the soil is of the Bohannon-Slickrock association (Corliss, 1973). These include gravelly loam soils approximately 51 to 102 centimeters deep, and gravelly clay loam soils more than 122 centimeters deep. Both are formed from material weathered from sandstone of the Tyee sandstone formation. Also included within the watershed are soils of the Honeygrove-Digger-Hatchery association, Kilckitat association, Skinner-Astoria-Fendall association, and Knappa-Nehalem association (Corliss, 1973).

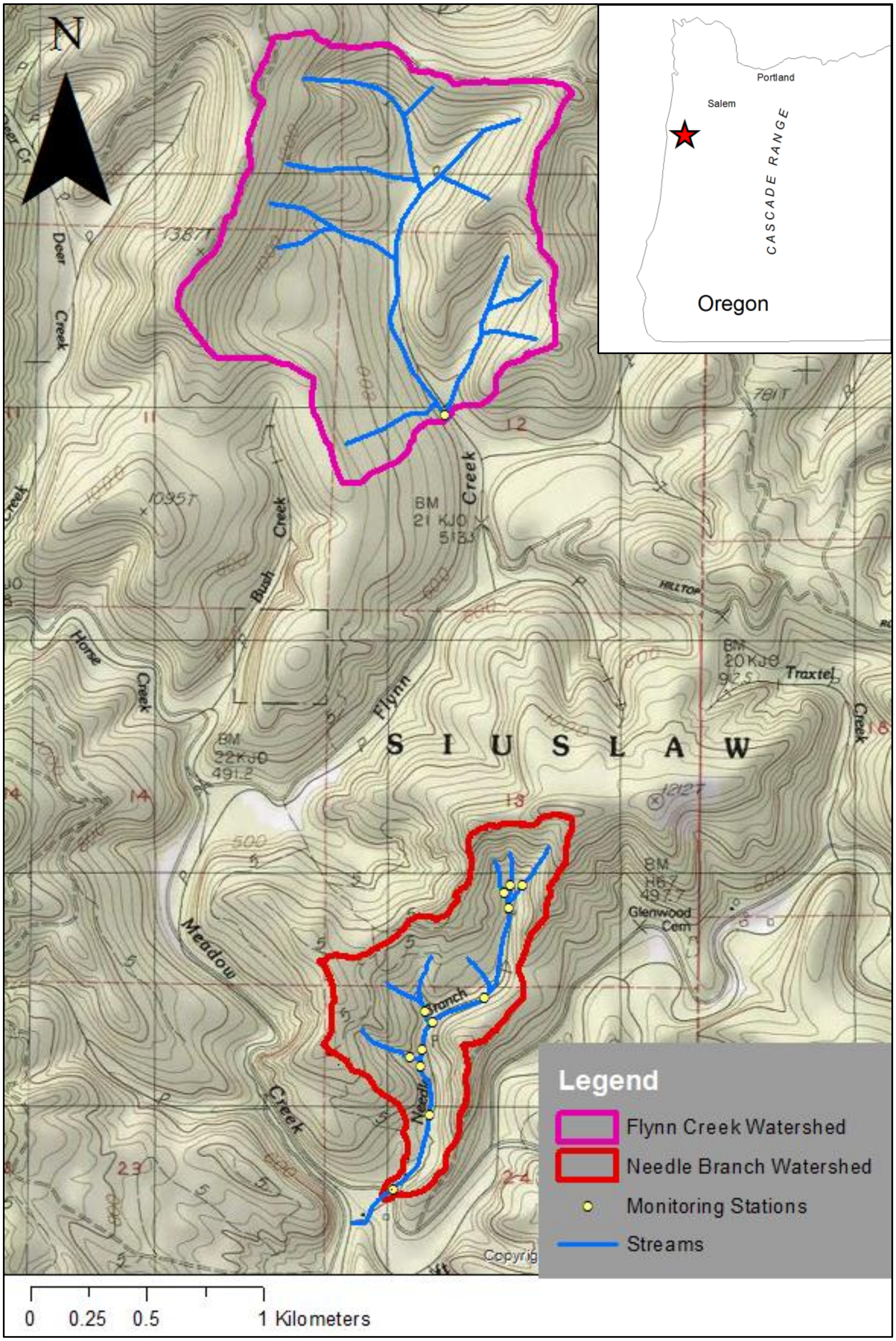

Figure 2.1: Location of the Alsea Watershed.

Table 2.1: Alsea Watershed characteristics.

	Flynn Creek	**Needle Branch**
	Control	Treatment
Area (ha)	219	94
Mean Slope (%)	27.9	37
Mean Elevation (m)	280	220
Drainage Density (km km^{-2})	0.47	1.01
Hardwood Cover (%)	64	20
Conifer Cover (%)	36	80
Understory	Sword fern Vine maple Salmonberry Salal	Sword fern Vine maple Salmonberry Salal Bracken fern Thimbleberry Dewberry
Harvested Area (ha) Phase 1 (2009) Phase 2 (2014)	 -- --	 37.2 39.7

The New Alsea Watershed Study, which is a follow up to the original Alsea Watershed Study, began in 2006 to determine how contemporary timber harvest practices affect water and salmonid resources, including nutrient concentrations in surface water (Hall and Stednick, 2008). This study included two phases, and monitoring of nutrients in streams began in October 2005 and continued to March 2016. The Phase 1 timber harvest took place in upper Needle Branch between June and September of 2009, and was part of a 37.2-hectare clear cut by Plum Creek Timber Company (PCTC), which, at the time, owned and managed the upper two-thirds of the watershed (Figure 2.1). Both cable logging and ground-based logging were used in Phase 1, and a 15 m vegetated streamside buffer was left in place on both sides of Needle Branch (Bladon et al., 2016). Slash piles following the Phase 1 clearcut were burned in November 2009. The south slopes of the upper watershed were broadcast burned in December 2010, and the site was replanted in early 2011, with 1,025 trees per hectare (J. Light, personal communication, 2016).

The Phase 2 timber harvest of the New Alsea Watershed Study took place in lower Needle Branch between September and November 2014, and was part of a 39.7-hectare clear cut (Figure 2.1). Phase 2 also included cutting a 2.4-hectare patch west of Needle Branch between July and August 2015. Phase 2 used the same methods of harvest as Phase 1. Slash piles were burned in November 2015, and no broadcast burning occurred. Replanting took place in February 2016, with 808 trees per hectare (J. Light, personal communication, 2016).

2.2 Data Collection

This study used a paired watershed design, with Flynn Creek serving as the control watershed (Figure 2.1). Nutrient concentrations, including nitrite + nitrate-N (NO_3-N), total nitrogen (TN), ammonia (NH_3), total phosphorus (TP), and orthophosphate (OP) were measured in Needle Branch and Flynn Creek, monthly, from October 2005 to March 2016. Stream gauges

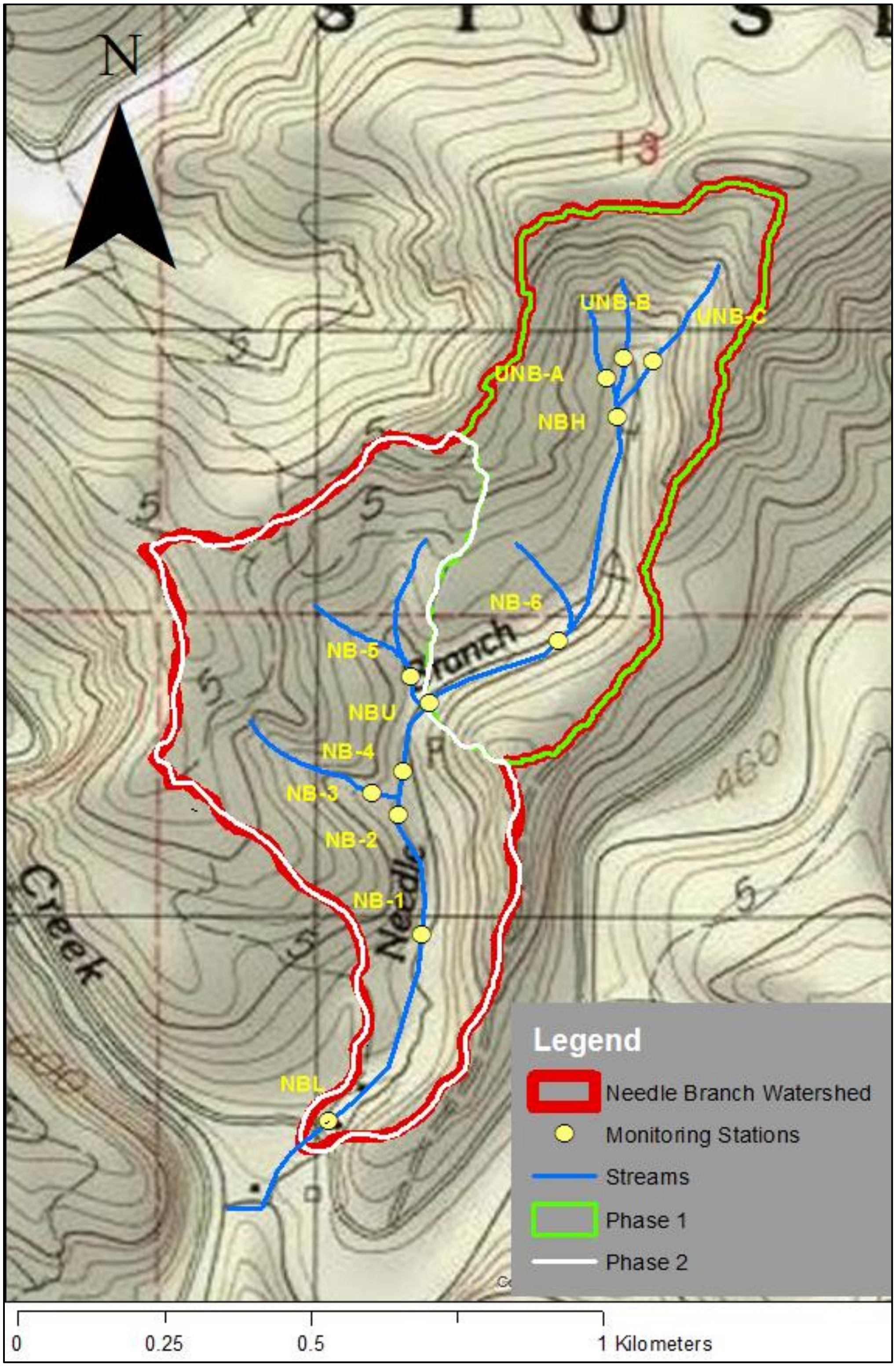

Figure 2.2: Monitoring station locations within the Needle Branch Watershed.

in Flynn Creek and Needle Branch were located at the outlets of each watershed, while additional gauges in Needle Branch were located throughout the watershed (Figure 2.2). These sites were selected to be the same as, or similar to, the original data collection sites on Flynn Creek and Needle Branch from the original Alsea Watershed Study (NCASI, 2006).

Nutrients were collected, transported, stored, and analyzed using methods outlined in the National Council for Air and Stream Improvement, Inc. (NCASI) standard operating procedures, which are comparable to methods approved by the EPA under the Clean Water Act. Samples were collected monthly, from mid-depth in the channel thalweg, using 125 to 500 mL polyethylene containers. Samples were iced to less than 6.0ºC during transport and storage, and were delivered to the laboratory within 24 hours of collection, where they were analyzed for NO_3-N, TN, NH_3, TP and OP (NCASI, 2006). Samples were collected at the outlet of the control watershed (Figure 2.1), as well as at the outlet of the treatment watershed, and at various locations along the main stem and at three tributaries within the treatment watershed (Figure 2.2).

2.2.1 Lab Analysis

All nutrient samples were analyzed by NCASI, in Corvallis, Oregon. Samples were originally analyzed using an ALPKEM 3000 flow injection analyzer. In June 2007, however, the ALPKEM flow analyzer was replaced with a Bran and Luebbe flow analyzer. All samples were analyzed according the NCASI standard operating procedures (NCASI, 2014).

Between October 2005 and April 2010, total nitrogen was measured using a Kjeldahl digestion procedure (TKN). At the beginning of the study, TKN measurements were performed using a copper sulfate digestion solution. Beginning in June 2007, the reagent was changed to mercuric sulfate, which was used to achieve lower and more consistent method blank levels compared with the copper sulfate method blanks. Regardless of the reagent used, however, the majority of sample measurements were at or near the levels in the method blanks, raising QA/QC concerns. In April 2010, TKN methods were discontinued, and in January 2010 total nitrogen analysis methods changed to an alkaline persulfate procedure (TPN), providing four months of overlapping data (NCASI, 2014). To allow for consistent data analysis, the samples that were analyzed using the TKN method were adjusted to better approximate TPN by adding the measurements of NO_3-N for each given month to the TKN measurement for that month.

Between October 2005 and June 2006, total phosphorus measurements were conducted using a copper sulfate Kjeldahl digestion procedure (TKP). This method was changed to an acidic persulfate procedure (TPP) in June 2006 because of high blank values and high variability associated with the TKP procedure (NCASI, 2014).

2.2.2 Quality Assurance/Quality Control

Quality assurance/quality control (QA/QC) checks were conducted on 5-10% of the samples and ensured that each sample complied with specific data quality criteria. QA/QC included duplicates, matrix spikes, method blanks, validation checks, and calibration checks. Grab samples for nutrient analyses were of sufficient volume to include QA/QC laboratory measurements, and an additional grab sample was collected quarterly to assess field precision. Sample QA/QC analyses were conducted with each analytical batch of 20 or fewer samples, and data that failed to meet QA/QC requirements were flagged in laboratory reports (NCASI, 2006).

2.3 Statistical Analysis

Nutrient analysis began with time series plots of each constituent at each site to determine if visible patterns existed. Where applicable, concentration data were plotted with discharge data to show the relationship between the two. This was followed by a determination of sample size, mean, and standard deviation of each constituent, at each site, for pre-treatment, Phase 1, and Phase 2.

Statistical analyses in R were used to determine if the data were normally distributed. To determine normality, normal quantile plots were created for each constituent at each site (Ott and Longnecker, 2010). Where the normal quantile plot follows a straight line, the data are assumed to be normal; where the normal quantile plot shows deviations from a straight line, however, the data cannot be assumed to be normal and non-parametric alternatives should be used in analyzing the data. All constituents, at all sites, were found to have deviations in the normal quantile plots and, therefore, non-parametric alternatives were used, such as a Wilcoxon Rank Sum Test (Ott and Longnecker, 2010) and a two-way ANOVA on ranks (Ofungwu, 2014).

2.3.1 Study Objective 1: Stationarity of Control Site

Data normality at Flynn Creek was determined using normal quantile plots for each constituent, and stationarity was determined using a non-parametric alternative to a two-sample t-test, a Wilcoxon Rank Sum Test (Ott and Longnecker, 2010), to determine if monthly median concentrations before treatment were comparable to monthly median concentrations after Phase 1 and after Phase 2, respectively. If values before and after each treatment are comparable, then Flynn Creek exhibits data stationarity and can be used as the control watershed. Changes in nutrient concentrations were tested for statistical significance at the $\alpha \leq 0.05$ level. Boxplots were created to represent the distributions of each constituent.

2.3.2 Study Objective 2: Intra-Watershed Nutrient Response

Normality of concentration data in the treatment watershed was also determined using normal quantile plots for each constituent at each location. Variation in monthly median concentrations, at each site, were determined using a Wilcoxon Rank Sum Test (Ott and

Longnecker, 2010), which determined whether monthly median concentrations after Phase 1, and after Phase 2, were statistically different from those before treatment at each site within the treatment watershed. Changes in nutrient concentrations were tested for statistical significance at the $\alpha \leq 0.05$ level. Boxplots were created to represent the distributions of each concentration, and pairwise comparisons were used to understand the variation of concentrations of each constituent throughout the treatment watershed for each phase of treatment.

2.3.3 Study Objective 3: Inter-Watershed Nutrient Response

Concentrations at sites within Needle Branch were compared to Flynn Creek using a Before-After Control-Impact (BACI) design (Smith, 2002). A non-parametric alternative to a two-way ANOVA (Ofungwu, 2014) was performed on concentrations from Flynn Creek and all sites within Needle Branch. The BACI effect from these analyses refer to the interaction between 'Period' and 'SiteClass.' 'Period' refers to time, which is either pre-treatment, Phase 1, or Phase 2; and 'SiteClass,' refers to Flynn Creek, which was classified as the control, or any of the sites within Needle Branch, which were classified as treatment. If the BACI effect is significant, then that indicates that the effect of the period on concentration depends upon the whether the site was a control or a treatment site, and variation in concentration can be attributed to treatment.

A Wilcoxon Rank Sum Test was also used to evaluate the differences in concentration between the control site and each treatment site, before treatment and after Phase 1 and Phase 2 of treatment (Stewart-Oaten et al., 1986). Data from Flynn Creek were paired with those at each site within Needle Branch, according to month, and differences were determined (Control minus Treatment) for each data pair. Where both watersheds did not have a sample in a given month, then that month was not used in the analysis. Pre-treatment differences were compared to Phase 1 differences, as well as to Phase 2 differences.

2.3.4 Study Objective 4: Comparison to EPA Nutrient Criteria

Where applicable, EPA recommended nutrient criteria were plotted with the nutrient time series to determine if and how often concentrations exceeded the criteria for the Level III subecoregion (EPA, 2000). These plots were made for both Needle Branch and Flynn Creek, and included the pre-treatment time period, as well as the Phase 1 and Phase 2 periods.

CHAPTER 3 - RESULTS

3.1 Overview

Stream nutrient concentrations were measured before and after two timber harvest entries (Phase 1 and Phase 2) in Needle Branch, as well as during the same time periods in Flynn Creek. All data were compiled and found to be non-normally distributed; therefore, non-parametric statistics were used.

3.2 Study Objective 1: Stationarity of Control Site

In Flynn Creek, concentrations of NO_3-N followed similar seasonal patterns before and after timber harvest (Figure 3.1), increasing during the winter (up to 2.11 mg/L), being flushed out with the fall rain, and decreasing during summer. Concentrations of TN followed similar seasonal patterns. NH_3, OP and TP concentrations did not appear to be seasonal (Figure 3.1).

Flynn Creek NO_3-N distributions before and after both timber harvests, as well as distributions of concentrations of TN did not change (Figure 3.2). Distributions of NH_3, however, show statistical differences between pre-treatment and Phase 1 ($p = 1.74E-02$), as do OP ($p = 3.07E-03$) and TP ($p = 1.39E-02$) concentrations. (Figure 3.2). Phase 2 OP and TP concentrations, however, are not statistically different from neither pre-treatment concentrations nor Phase 1 concentrations.

3.3 Study Objective 2: Intra-Watershed Nutrient Response

Nutrient concentrations were measured at multiple locations within Needle Branch, during three time periods: pre-treatment, Phase 1, and Phase 2. Concentrations during these three phases were compared to one another to determine the timber harvest effect on nutrient concentrations. To make this determination, nutrient concentrations from water years 2006 to

2009 (pre-treatment) were compared to those following the Phase 1 harvest (2009) and those following the Phase 2 harvest (2014).

Variations in NO_3-N concentration along the main stem of Needle Branch increased after timber harvest; NO_3-N had higher concentration after treatment than before, and the highest peaks occurred at the upstream sites (Figure 3.3). The same is true of TN concentration within the treatment watershed (Figure 3.4), but not of NH_3 concentration (Figure 3.5). Additionally, intra-watershed patterns in OP and TP showed little seasonal variation (Figure 3.6 and Figure 3.7, respectively), with higher concentrations existing upstream.

NO_3-N concentrations statistically increased after Phase 1 of timber harvest compared to pre-treatment concentrations at all locations within Needle Branch. Phase 2 NO_3-N concentrations statistically increased from pre-treatment concentrations at NBL and NBU, but not at NBH; and Phase 2 concentrations significantly increased from Phase 1 concentrations at NBH, but not at NBL nor at NBU (Table 3.1). Additionally, NO_3-N concentrations, for all periods of treatment, appear to decrease downstream (Figure 3.8). The three upstream tributaries (UNB-A, UNB-B, and UNB-C) of NBH had the highest concentrations before and after each treatment (Figure 3.9).

Comparison of TN concentrations, before and after timber harvest, show that Phase 1 TN concentrations are significantly higher ($p \leq 0.05$) than pre-treatment concentrations at all treatment sites, but Phase 2 concentrations are only statistically higher than pre-treatment values at NBL ($p = 0.0449$) (Table 3.2). Comparison of NH_3 concentrations, before and after timber harvest, show that Phase 1 NH_3 concentrations are not significantly different ($p \leq 0.05$) than pre-treatment concentrations at any site within Needle Branch, with the exception of NBL (Table 3.3). Concentrations of OP (Table 3.4) and TP (Table 3.5) show that pre-treatment concentrations are statistically lower than Phase 1 concentrations at all sites within Needle Branch. Phase 2 concentrations, however, are not statistically different from pre-treatment concentrations, or Phase 1 concentrations, at any location.

3.4 Study Objective 3: Inter-Watershed Nutrient Response

Nutrient concentrations in Needle Branch were compared to nutrient concentrations in Flynn Creek using a Before-After Control-Impact (BACI) design (Smith, 2002). The first of two BACI analyses used a non-parametric alternative to a two-way ANOVA (Ofungwu, 2014), which showed significant interaction of NO_3-N concentration between 'Period' (pre-treatment, Phase 1, or Phase 2) and 'SiteClass' (control or treatment) (Table 3.1). This interaction indicates that the effect of pre-treatment, Phase 1, or Phase 2 on NO_3-N concentration on contemporary timber harvest practices do affect NO_3-N concentration. TN also showed significant interaction between 'Period' and 'SiteClass,' although the interaction was only significant between pre-treatment and Phase 1 periods. OP, TP and NH_3 did not show a significant interaction between any periods of treatment.

The second BACI analysis was performed by pairing concentrations, according to date, from the control site with concentrations from each treatment site, finding the difference of each pair, and comparing those differences across phases (Stewart-Oaten et al, 1986) using a Wilcoxon Rank Sum Test (Ott and Longnecker, 2010). This assessment relies on the fact that concentrations in the control watershed are stationary; and therefore, if differences vary among phases, then that variance can be attributed to the treatment. The Wilcoxon Rank Sum Test showed that NO_3-N concentrations, during Phase 1, increased at each treatment site; and NO_3-N concentrations during Phase 2 increased at NBL and NBU, but not at NBH, compared to pre-treatment values. NO_3-N concentrations during Phase 2 at NBL and NBU, although higher than pre-treatment values, did not differ statistically from concentrations of Phase 1, (Table 3.6).

Similar results are shown for TN; and the Wilcoxon Rank Sum Test showed that NH_3, OP, and TP (Table 3.6) exhibited no BACI interaction at any site during any time period. For these constituents, therefore, the effects of each period (pre-treatment, Phase 1, or Phase 2) on NH_3, OP and TP concentrations are not dependent upon whether the site in question is a control site or a treatment site, so changes in concentrations cannot be attributed to timber harvest.

The original Alsea Watershed Study had similar results to this study: following treatment, NO_3-N concentrations within Needle Branch increased, while NO_3-N concentrations within Flynn Creek stayed the same (Brown et al., 1973). When comparing time series from the original study with time series from the current study, it appears that NO_3-N concentrations increase following timber harvest when a streamside buffer exists, and when a streamside buffer is absent (Figure 3.10). The Flynn Creek time series from the original study and from this study shows a similar range of NO_3-N concentrations throughout time (Figure 3.11).

A Mann-Kendall Test and Sen's Slope Estimate for the Trend of Annual Data (MAKESENS) (Salmi et al., 2002) was performed on the NO_3-N data to determine when concentrations would return to pre-treatment levels. The MAKESENS test uses two types of statistical analyses, the first of which is the nonparametric Mann-Kendall test, which determines trend, and the second of which is the nonparametric Sen's method, which determines the magnitude of trend. The test results in an equation for each watershed, giving a negative slope and a y-intercept. These, when combined with the year that data collection began and mean pre-treatment concentration, yield an estimate of the year in which concentrations will return to pre-treatment levels. If the resulting slope, however, is positive, then it indicates that the concentrations may continue to increase and there is no estimate of when concentrations will return to pre-treatment levels. The results indicate that mean NO_3-N concentrations will return to pre-treatment levels in approximately 2020, which is six years after the Phase 2 treatment (Table 3.7). These results are similar to those determined in the original Alsea Watershed Study, which determined that concentrations would return to pre-treatment levels within six years (Brown et al., 1973), although the methods used to make that determination are unclear.

3.5 Study Objective 4: Comparison to EPA Nutrient Criteria

Comparison of nutrient concentrations within Needle Branch to the EPA recommended nutrient criteria show that, during low flows, concentrations are typically within the recommended criteria. During high flows, however, values are consistently higher than the EPA recommended nutrient criteria for NO_3-N (Figure 3.3), TN (Figure 3.4), and TP (Figure 3.7), during all periods of treatment. The same, however, is true of concentrations in Flynn Creek for all three constituents (Figure 3.1), which indicates that the exceedances are not the result of timber harvest, but rather are intrinsic to the larger region. OP and NH_3 concentrations were not evaluated because the EPA has not established recommended nutrient criteria for these constituents in Level III Ecoregion II streams.

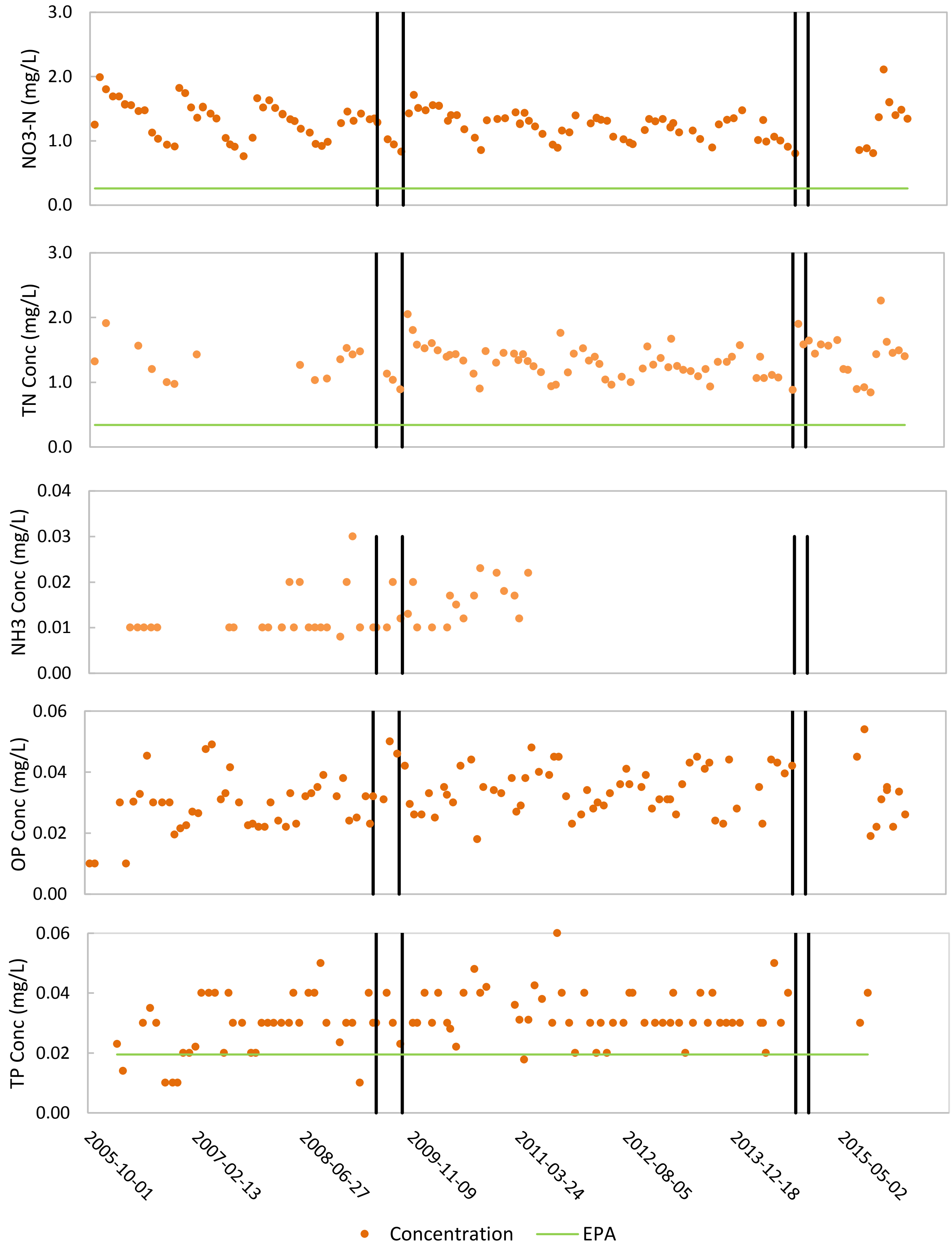

Figure 3.1: NO_3-N, TN, NH_3, OP, and TP concentrations at Flynn Creek (Control), and the EPA recommended nutrient criteria. Black, vertical lines indicate periods of treatment.

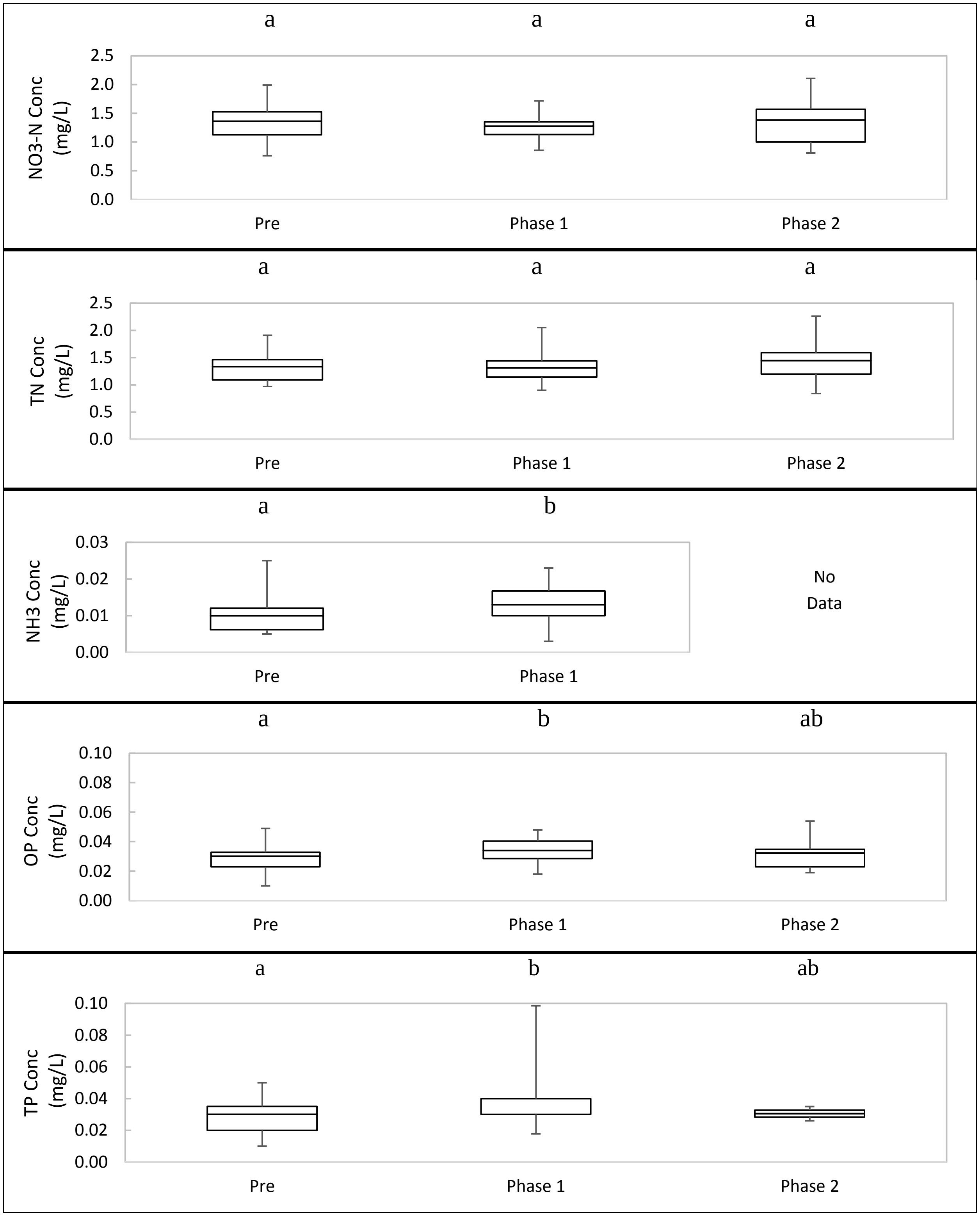

Figure 3.2: Distributions of NO_3-N, TN, NH_3, OP, and TP concentrations, at Flynn Creek (control), for each phase of treatment. Constituent distributions that do not share a letter are significantly different, in accordance with the Wilcoxon Rank Sum Test.

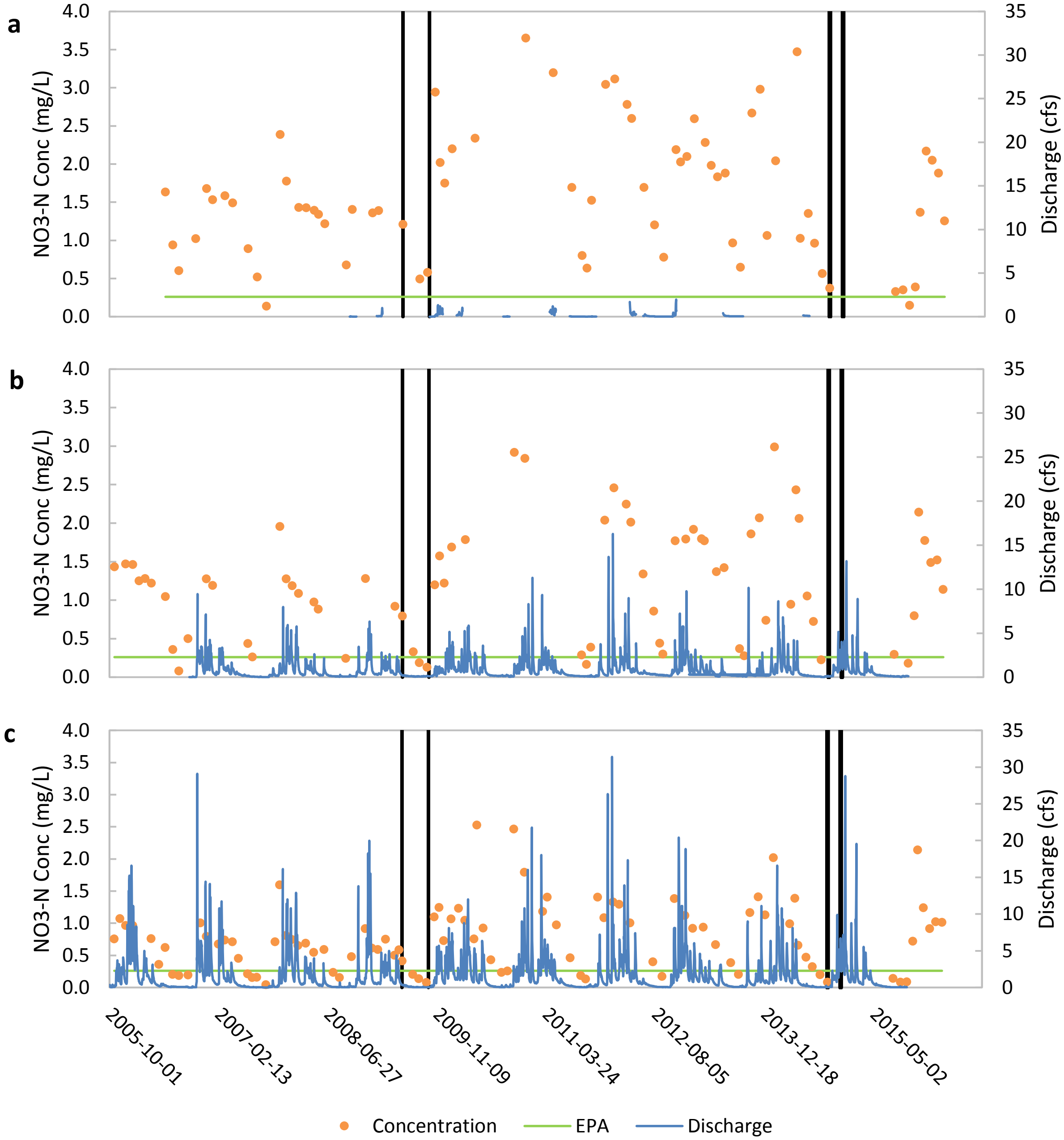

Figure 3.3: NO_3-N concentrations and discharge at (a) NBH, (b) NBU, and (c) NBL, and EPA recommended nutrient criteria. Black, vertical lines indicate periods of treatment.

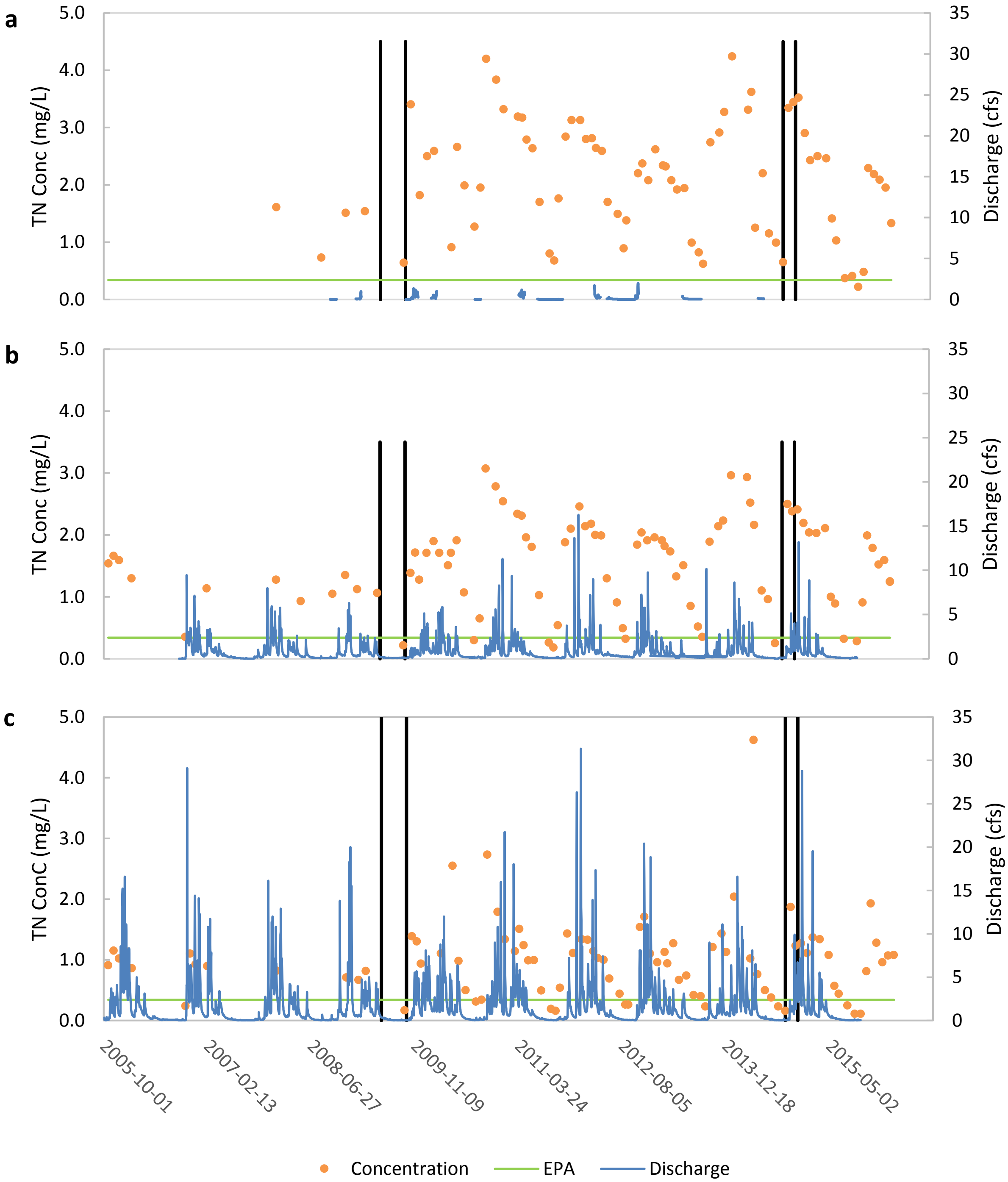

Figure 3.4: TN concentrations and discharge at (a) NBH, (b) NBU, and (c) NBL, and EPA recommended nutrient criteria. Black, vertical lines indicate periods of treatment.

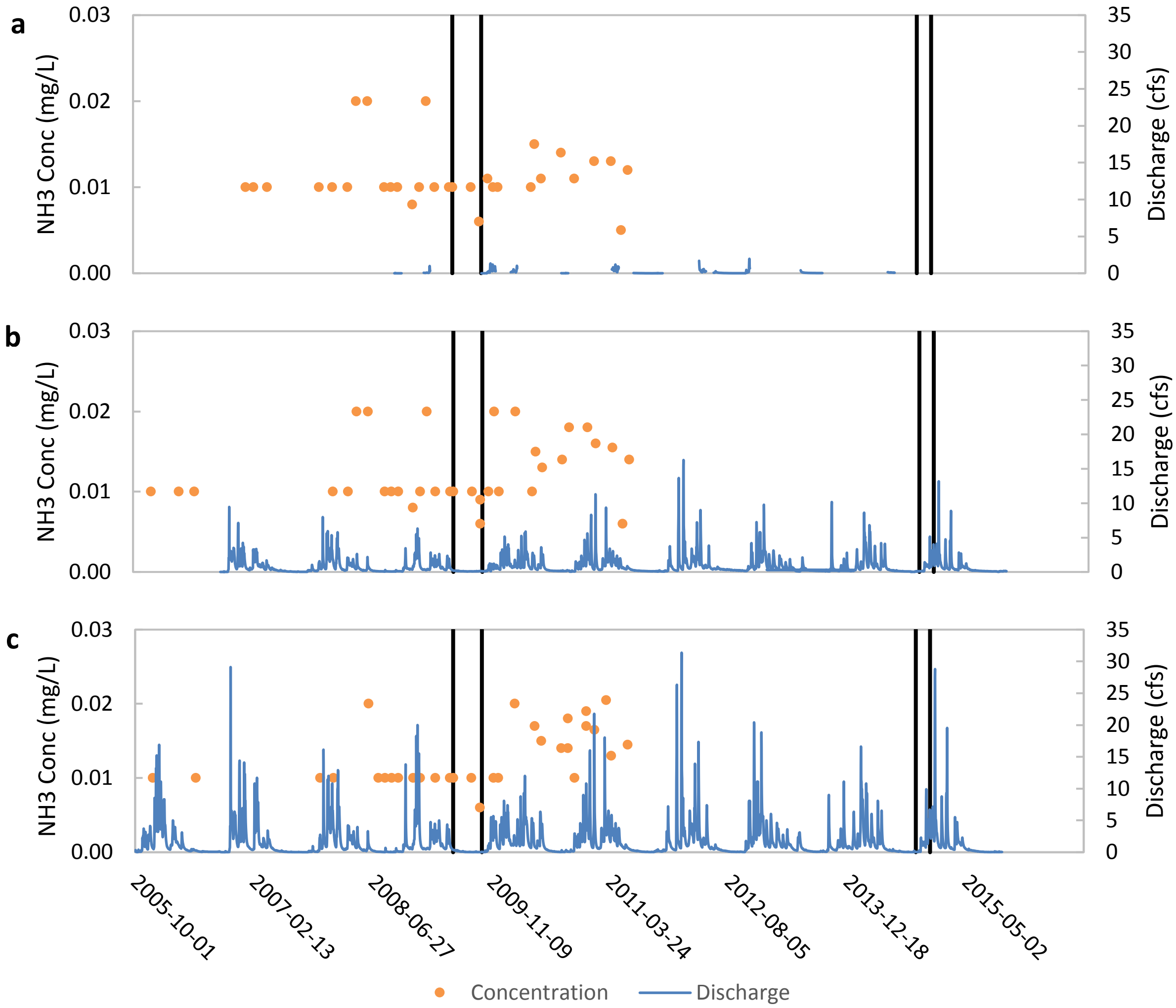

Figure 3.5: NH_3 concentrations and discharge at (a) NBH, (b) NBU, and (c) NBL. Black, vertical lines indicate periods of treatment.

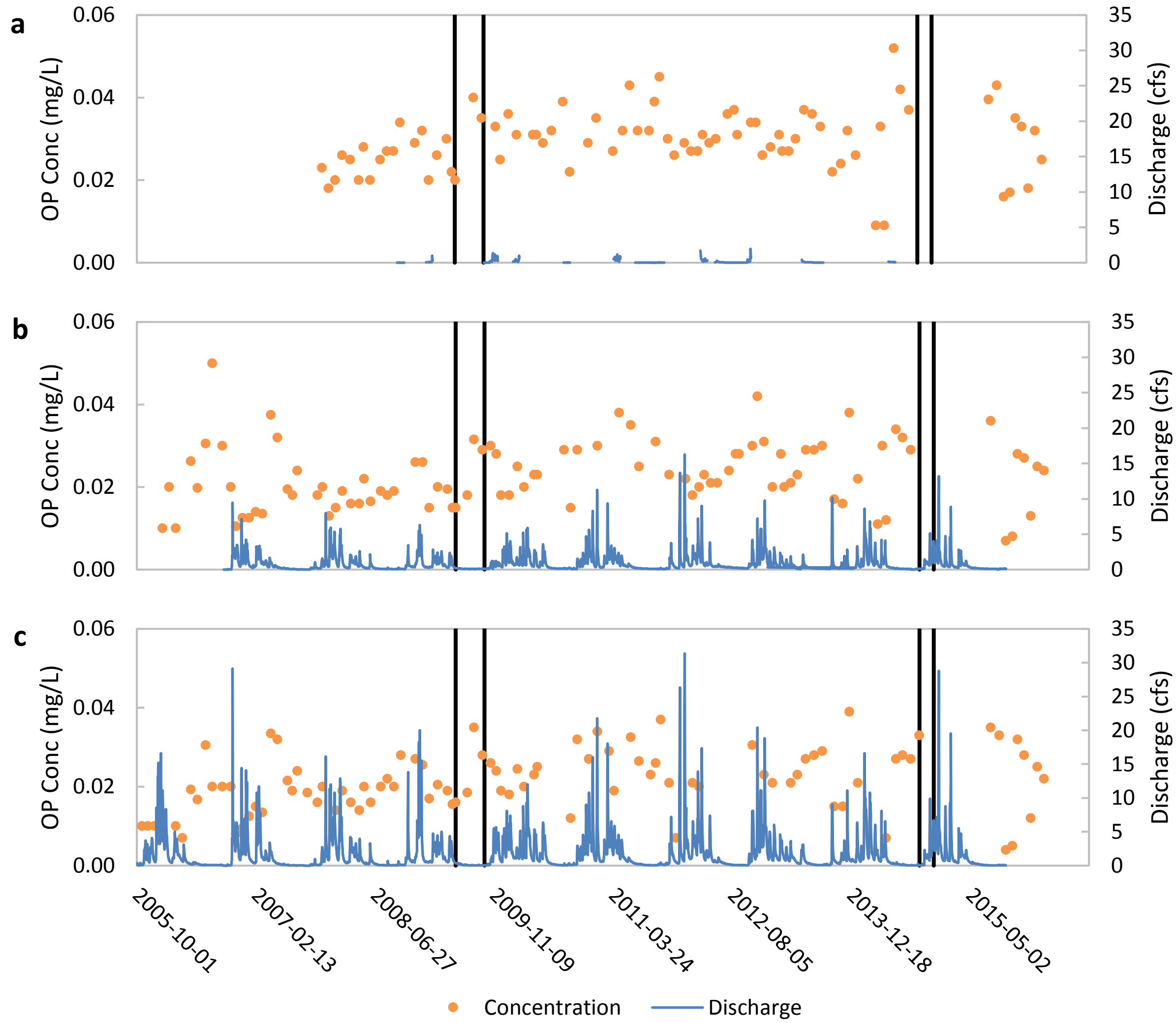

Figure 3.6: OP concentrations and discharge at (a) NBH, (b) NBU, and (c) NBL. Black, vertical lines indicate periods of treatment.

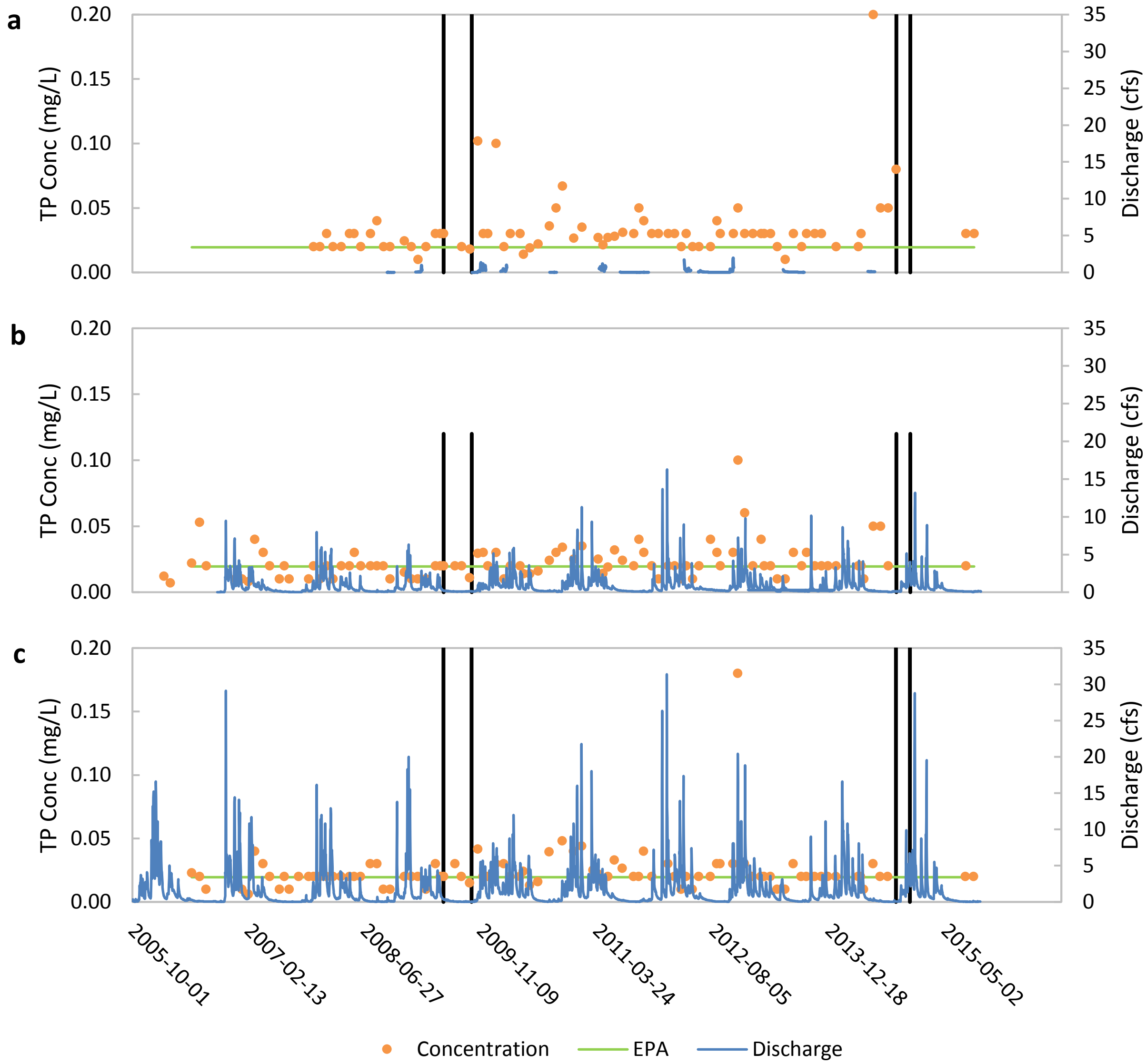

Figure 3.7: TP concentrations and discharge at (a) NBH, (b) NBU, and (c) NBL, and EPA recommended nutrient criteria. Black, vertical lines indicate periods of treatment.

Table 3.1: Summary statistics of NO3-N concentrations (mg/L), and p-values based on the results of a Wilcoxon Rank Sum Test.

Site	Pre			Phase 1			Phase 2			Pre v Phase 1	Pre v Phase 2	Phase 1 v Phase 2
	n	mean (sd)	median	n	mean (sd)	median	n	mean (sd)	median	p-value	p-value	p-value
UNBA	19	1.73 (0.51)	1.70	43	2.60 (0.80)	2.65*	---	---	---	1.08E-04	---	---
UNBB	8	1.17 (0.28)	1.27	37	1.66 (0.94)	1.82*	---	---	---	7.75E-04	---	---
UNBC	12	1.34 (0.35)	1.24	32	2.36 (0.74)	2.20*	---	---	---	6.18E-05	---	---
NBH	23	1.26 (0.48)	1.39	36	2.00 (0.84)	2.02*	9	1.10 (0.82)	1.25	7.24E-04	5.86E-01	1.53E-02
NB6	40	0.95 (0.44)	1.06	25	1.46 (0.63)	1.60*	---	---	---	8.05E-04	---	---
NBU	24	0.99 (0.47)	1.14	36	1.47 (0.80)	1.63*	8	1.17 (0.70)	1.31	1.30E-02	2.29E-02	3.08E-01
NB4	24	0.64 (0.37)	0.68	22	0.91 (0.44)	0.95*	---	---	---	2.94E-02	---	---
NB2	20	0.64 (0.35)	0.72	18	0.98 (0.44)	1.13*	---	---	---	1.29E-02	---	---
NB1	41	0.60 (0.32)	0.64	29	0.89 (0.44)	0.98*	---	---	---	1.93E-03	---	---
NBL	38	0.59 (0.32)	0.61	43	0.97 (0.57)	1.00*	9	0.81 (0.67)	0.91	6.79E-04	3.45E-02	2.66E-01
FC	47	1.35 (0.28)	1.36	58	1.25 (0.19)	1.28	10	1.34 (0.40)	1.38	2.20E-16*	3.58E-03*	3.86E-03*

*Period:SiteClass interaction from two-way ANOVA results of Flynn Creek compared to Needle Branch, for a model that also includes Period, Month, Site, and SiteClass.

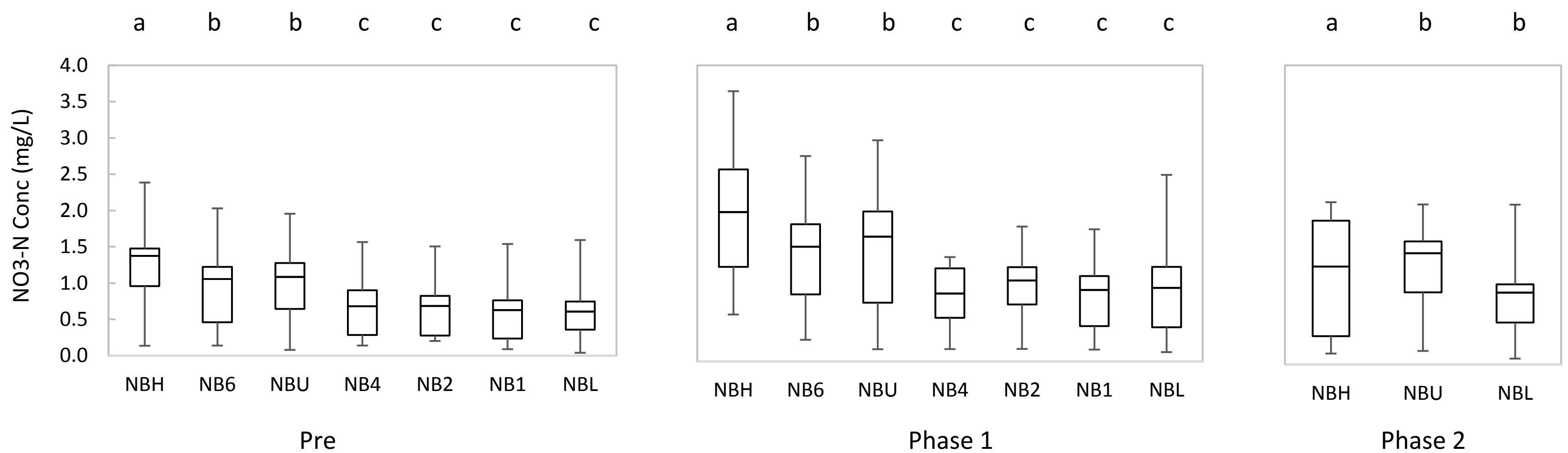

Figure 3.8: NO_3-N concentrations, along the main stem of Needle Branch, for each phase of treatment. Distributions that do not share a letter are significantly different at $\alpha = 0.05$.

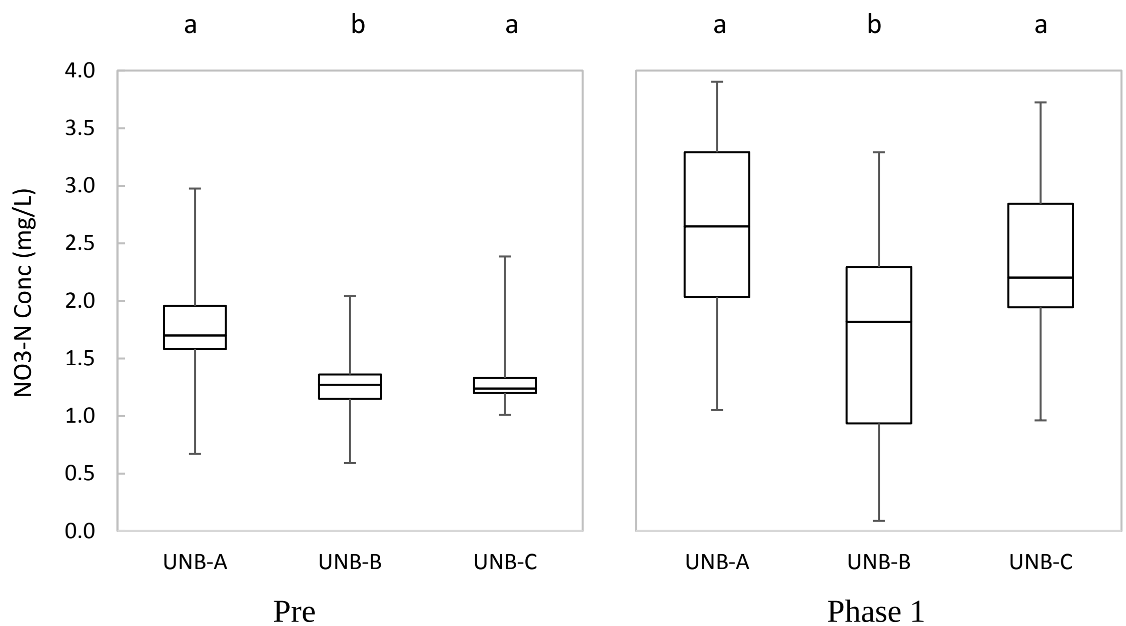

Figure 3.9: NO_3-N concentrations on the three upstream tributaries of Needle Branch, for each phase of treatment (Phase 2 was not measured at these locations). All three sites are tributaries to NBH. Distributions that do not share a letter are significantly different at $\alpha = 0.05$.

Table 3.2: Summary statistics of TN concentrations (mg/L), and p-values based on the results of a Wilcoxon Rank Sum Test.

Site	Pre			Phase 1			Phase 2			Pre v Phase 1	Pre v Phase 2	Phase 1 v Phase 2
	n	mean (sd)	median	n	mean (sd)	median	n	mean (sd)	median	p-value	p-value	p-value
NBH	4	1.35 (0.41)	1.53	53	2.27 (0.93)	2.34	16	1.72 (1.00)	2.02	3.14E-02	5.59E-01	4.13E-03
NBU	12	1.20 (0.35)	1.21	56	1.61 (0.76)	1.81	16	1.47 (0.66)	1.56	2.23E-02	2.04E-01	6.36E-02
NBL	13	0.87 (0.24)	0.90	54	1.06 (0.75)	1.01	16	0.92 (0.51)	1.08	1.43E-02	4.49E-02	9.35E-02
FC	14	1.32 (0.26)	1.34	55	1.31 (0.24)	1.31	16	1.41 (0.35)	1.45	1.09E-03*	8.35E-02*	8.94E-03*

*Period:SiteClass interaction from two-way ANOVA results of Flynn Creek compared to Needle Branch, for a model that also includes Period, Month, Site, and SiteClass.

Table 3.3: Summary statistics of NH_3 concentrations (mg/L), and p-values based on the results of a Wilcoxon Rank Sum Test.

	Pre			Phase 1			Phase 2			Pre v Phase 1
	n	mean (sd)	median	n	mean (sd)	median	n	mean (sd)	median	p-value
UNBA	11	0.013 (0.00)	0.012	8	0.014 (0.00)	0.015	No Data			8.93E-01
UNBB	9	0.013 (0.01)	0.011	6	0.015 (0.00)	0.016				4.63E-01
UNBC	4	0.013 (0.01)	0.012	4	0.014 (0.01)	0.013				8.54E-01
NBH	16	0.010 (0.01)	0.007	12	0.012 (0.01)	0.011				1.05E-01
NB6	16	0.012 (0.01)	0.010	10	0.015 (0.00)	0.015				5.11E-01
NBU	15	0.010 (0.01)	0.010	14	0.012 (0.00)	0.012				4.22E-01
NB4	12	0.011 (0.01)	0.009	10	0.013 (0.00)	0.012				3.09E-01
NB2	14	0.011 (0.01)	0.010	5	0.013 (0.00)	0.013				1.09E-01
NB1	23	0.012 (0.01)	0.010	10	0.015 (0.00)	0.016				5.62E-01
NBL	13	0.011 (0.01)	0.010	13	0.013 (0.00)	0.013				3.28E-02
FC	22	0.010 (0.01)	0.010	15	0.013 (0.01)	0.013				5.67E-01*

*Period:SiteClass interaction from two-way ANOVA results of Flynn Creek compared to Needle Branch, for a model that also includes Period, Month, Site, and SiteClass.

Table 3.4: Summary statistics of OP concentrations (mg/L), and p-values based on the results of a Wilcoxon Rank Sum Test.

Site	Pre			Phase 1			Phase 2			Pre v Phase 1	Pre v Phase 2	Phase 1 v Phase 2
	n	mean (sd)	median	n	mean (sd)	median	n	mean (sd)	median	p-value	p-value	p-value
NBH	19	0.025 (0.00)	0.025	52	0.033 (0.01)	0.031	9	0.029 (0.01)	0.032	4.42E-04	3.83E-01	6.64E-01
NBU	38	0.020 (0.01)	0.019	46	0.025 (0.01)	0.025	8	0.021 (0.01)	0.025	3.01E-03	7.23E-01	2.31E-01
NBL	42	0.018 (0.01)	0.019	39	0.024 (0.01)	0.024	9	0.022 (0.01)	0.025	1.42E-03	1.37E-01	9.46E-01
FC	41	0.029 (0.01)	0.030	55	0.034 (0.01)	0.034	10	0.032 (0.01)	0.032	5.83E-01*	9.61E-01*	9.12E-01*

*Period:SiteClass interaction from two-way ANOVA results of Flynn Creek compared to Needle Branch, for a model that also includes Period, Month, Site, and SiteClass.

Table 3.5: Summary statistics of TP concentrations (mg/L), and p-values based on the results of a Wilcoxon Rank Sum Test.

Site	Pre			Phase 1			Phase 2			Pre v Phase 1	Pre v Phase 2	Phase 1 v Phase 2
	n	mean (sd)	median	n	mean (sd)	median	n	mean (sd)	median	p-value	p-value	p-value
NBH	18	0.025 (0.01)	0.024	45	0.036 (0.03)	0.028	2	0.030 (0.01)	0.030	7.86E-03	1.84E-01	9.41E-01
NBU	10	0.017 (0.01)	0.016	24	0.023 (0.01)	0.020	1	0.018 (---)	0.018	1.89E-03	6.28E-01	7.50E-01
NBL	32	0.018 (0.01)	0.019	14	0.026 (0.01)	0.025	2	0.020 (0.00)	0.020	3.04E-02	8.99E-01	5.57E-01
FC	37	0.028 (0.01)	0.027	59	0.036 (0.01)	0.030	2	0.031 (0.01)	0.031	8.96E-01*	8.55E-01*	9.93E-01*

*Period:SiteClass interaction from two-way ANOVA results of Flynn Creek compared to Needle Branch, for a model that also includes Period, Month, Site, and SiteClass.

Table 3.6: P-values resulting from BACI analysis using a Wilcoxon Rank Sum Test on the differences between the control site and each treatment site, comparing each phase of treatment.

	NO3-N			TN			NH3			OP			TP		
	Pre v Phase 1	Pre v Phase 2	Phase 1 v Phase 2	Pre v Phase 1	Pre v Phase 2	Phase 1 v Phase 2	Pre v Phase 1	Pre v Phase 2	Phase 1 v Phase 2	Pre v Phase 1	Pre v Phase 2	Phase 1 v Phase 2	Pre v Phase 1	Pre v Phase 2	Phase 1 v Phase 2
UNBA	2.58E-06	---	---	---	---	---	8.93E-01	---	---	---	---	---	---	---	---
UNBB	8.06E-05	---	---	---	---	---	4.63E-01	---	---	---	---	---	---	---	---
UNBC	9.14E-08	---	---	---	---	---	8.54E-01	---	---	---	---	---	---	---	---
NBH	4.97E-08	4.53E-01	5.94E-03	3.14E-02	5.59E-01	4.13E-03	1.05E-01	---	---	6.35E-01	7.91E-01	9.88E-01	1.47E-01	7.33E-01	8.52E-01
NB6	5.45E-08	---	---	---	---	---	5.11E-01	---	---	---	---	---	---	---	---
NBU	2.07E-08	9.69E-04	1.11E-01	2.23E-02	2.04E-01	6.36E-02	4.22E-01	---	---	4.92E-01	6.61E-01	3.07E-01	3.65E-01	7.49E-01	9.21E-01
NB4	7.01E-07	---	---	---	---	---	3.09E-01	---	---	---	---	---	---	---	---
NB2	2.35E-07	---	---	---	---	---	1.09E-01	---	---	---	---	---	---	---	---
NB1	3.85E-07	---	---	---	---	---	5.62E-01	---	---	---	---	---	---	---	---
NBL	1.74E-10	1.91E-05	2.01E-01	1.43E-02	4.49E-02	9.35E-02	6.16E-01	---	---	5.79E-01	9.29E-01	8.03E-01	6.92E-01	4.38E-01	3.61E-01

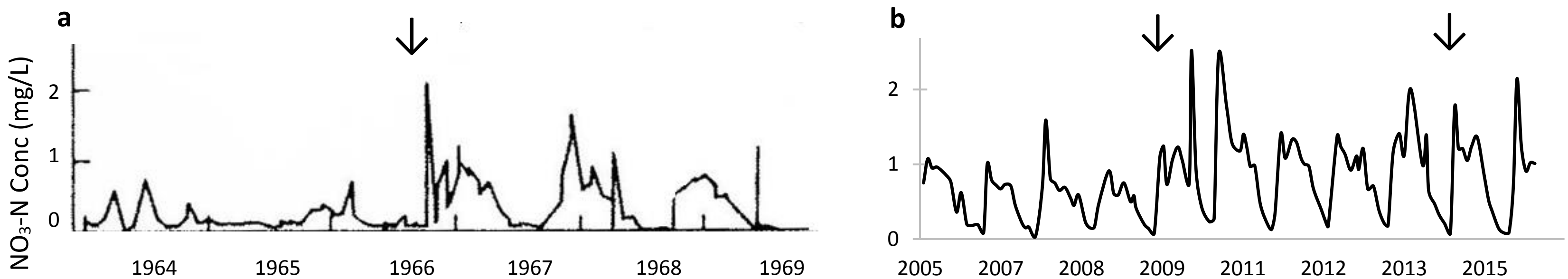

Figure 3.10: NO_3-N concentrations in Needle Branch (NBL) from the Original Alsea Watershed Study (a) and from the current Alsea study (b). Arrows indication timber harvest.

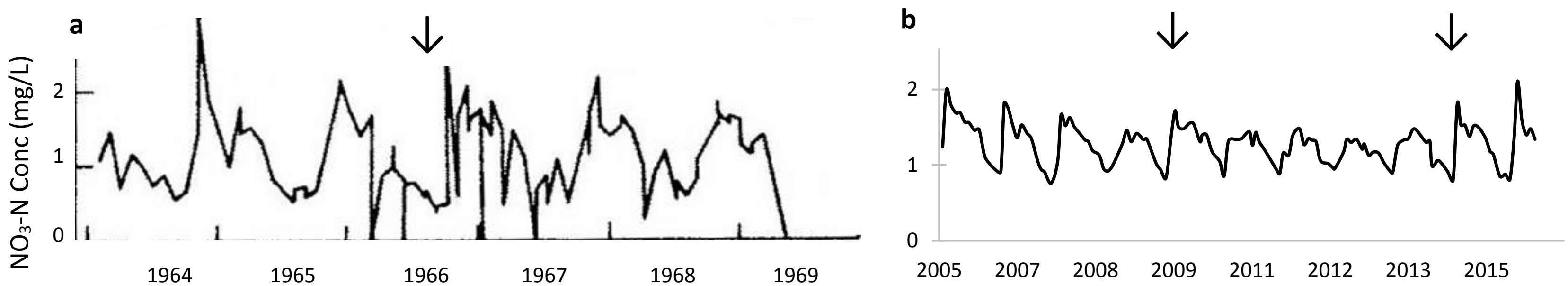

Figure 3.11: NO_3-N concentrations in Flynn Creek from the Original Alsea Watershed Study (a) and from the current Alsea study (b). Arrows indicate timber harvest.

Table 3.7: Mann-Kendall test for trend and Sen's slope estimates for NO_3-N concentrations, determining when mean NO_3-N concentrations will return to pre-treatment levels in Needle Branch.

	Slope	y-intercept	Mean pre-treatment Value	Year to return
NBL	-0.0384	1.11	0.58 mg/L	2020
NBU	0.0202	1.37	0.98 mg/L	--
NBH	-0.1060	2.75	1.28 mg/L	2020

CHAPTER 4 - DISCUSSION

A control watershed (Flynn Creek) and a treatment watershed (Needle Branch) were monitored for three years prior to timber harvesting with contemporary forest practices, for four years after Phase 1 of treatment (2009), and for one and a half years after Phase 2 (a second harvest) (2014). Previous studies have completed similar investigations (Adams and Stack, 1989; Boggs et al., 2015; Brown et al., 1973; Gravelle et al., 2009; Likens et al., 1970; Marchman et al., 2015; Meininger, 2011), albeit in differing landscapes and climates. This study is unique, analyzing contemporary timber harvest practices, those in which a streamside management zone is left in place, within the Oregon Coast Range, and including sub-watershed water quality sampling.

Data stationarity in Flynn Creek was determined by comparing pre-treatment nutrient concentrations to Phase 1 and Phase 2 nutrient concentrations using a Wilcoxon Rank Sum Test. This watershed was found to have stationarity of data for NO_3-N and TN, rendering Flynn Creek an appropriate control watershed. Data stationarity could not be established for NH_3, OP, or TP; but, given the ability of forest ecosystems to retain phosphorus (Binkley, 1986), and the lack of treatment within these watersheds, the lack of stationarity of OP and TP may be attributable to a statistical artifact of the low concentrations. A recent study found that TP concentrations are increasing, on a large scale, in lakes and streams throughout the conterminous U.S., and that the most alarming increases have been occurring in relatively undisturbed catchments (Stoddard et al., 2016). Causes of increased TP may be related to increased atmospheric deposition, which may be related to climate change, increased atmospheric dust, and bio-mass burning emissions, e.g. forest fires. Regardless of the mechanism of increased OP and TP in Flynn Creek, it is possible that the same mechanism increased TP and OP within Needle Branch, which would undermine assertions that increases within the treatment watershed were attributable to contemporary timber harvest practices.

In contrast to Flynn Creek, the Wilcoxon Rank Sum Test performed within Needle Branch showed all sites to have Phase 1 NO_3-N concentrations that were statistically higher than the pre-treatment concentrations; and two out of three sites showed Phase 2 to have statistically higher NO_3-N concentrations compared to the pre-treatment period. During Phase 2 of treatment, the only site at which NO_3-N concentrations were not significantly different than pre-treatment concentrations was NBH, which is situated upstream of the clearcut that comprised Phase 2, and therefore no change in NO_3-N concentrations was to be expected at that location. Furthermore, at this location (NBH), Phase 2 and Phase 1 concentrations were statistically different from each other because NBH was only subject to one of the treatment periods (Phase 1). At NBL and NBU there was no statistical difference in NO_3-N concentrations between Phase 1 and Phase 2, which was to be expected at NBL since it is downstream of treatment during both phases of treatment.

The increases in NO_3-N concentration in stream waters within Needle Branch were caused by the removal of vegetation via timber harvest. The removal of vegetation decreased shade cover and caused an increase in exposure of the soil to radiation, thus increasing soil temperature. Additionally, less vegetative cover also decreased interception, allowing more precipitation to reach the soil and increasing soil moisture. The increase in temperature and moisture of the soil increased the rate of decomposition, mineralization, and nitrification, leading to excess nitrate in the soil (Gundersen et al., 2006). Also, because NO_3-N is extremely mobile, excess NO_3-N leached through the soil, making its way to stream waters (Binkley, 1986), elevating concentrations.

Within the treatment watershed, the highest NO_3-N concentrations occurred at the furthest upstream locations; and concentrations were lower as they traveled downstream. Nutrient losses are of greater importance on steeper slopes (Fredriksen et al., 1975), where less vegetation is available for nutrient uptake, which may explain why the three uppermost locations (UNB-A, UNB-B, and UNB-C) have the highest concentrations of NO_3-N. As the slope of the watershed decreases from upstream to downstream, concentrations tend to decrease and attenuate, partially from the decrease in slope, and also from increased discharge, which dilutes the nutrients as they move downstream. Additionally, the vegetated buffer strip that was left along the riparian zone during treatment facilitated NO_3-N uptake as water travelled downstream, as did in-channel organisms, such as algae and bacteria, further decreasing concentrations.

To support the results of these comparisons of concentration, concentration data could have been combined with discharge data to evaluate whether nutrient loads are affected by contemporary timber harvest practices. In general, nutrient concentration increases when discharge increases. With higher discharge, there is shorter residence time of nutrients as they are quickly flushed downstream, which limits uptake of vegetation and organisms, increasing nutrient concentration, and nutrient export. Unfortunately, adequate discharge data were not available for these watersheds. Had discharge data been available, however, similar methods of comparison could have been employed as those that were used to compare concentrations. Additionally, a double mass curve of loads could have been created to determine if nutrient loads increased after timber harvest. Based on the results of concentration comparisons, annual export would likely have been greater in Needle Branch after timber harvest, while remaining unchanged in Flynn Creek. Results such as these would be consistent with results from the original Alsea Watershed Study, where nitrate exports increased from 4.94 to 15.66 kg/ha the first year after treatment (Brown et al., 1973).

In addition to discharge data, precipitation data within the watershed could have been used to help assess nutrient changes in the treatment watershed. Where precipitation events occur, it would be expected that nutrient concentrations in stream waters would increase due to increased overland flow, as well as throughflow, carrying nutrients over and through the soil, respectively, and into the stream. Additionally, precipitation data could be used to determine the nutrient budget of the watershed, establishing whether nutrient exports are greater than imports from precipitation. Unfortunately, precipitation data within Needle Branch is limited and does not include chemistry analysis to determine nutrient concentrations within the precipitation.

Relying on nutrient concentration data, without precipitation or discharge data, confirms that contemporary timber harvest practices yield similar results to practices used in the original Alsea Watershed Study, which did not include streamside management zones. Concentrations in the current study, however, were higher than in previous Alsea studies, both before and after treatment, which may be attributed to differences in vegetation and climate. At the outlet of Needle Branch (NBL), the peak concentration of NO_3-N reached 2.52 mg/L, which is higher than values observed in previous Alsea Watershed studies. In the original Alsea Watershed Study, NO_3-N concentrations peaked at 2.10 mg/L after treatment (Brown et al., 1973). Consider also that in the current study the pre-treatment mean NO_3-N concentration at NBL was 0.59 mg/L. In the original Alsea Watershed Study, the pre-treatment mean NO_3-N concentration at NBL was 0.16 mg/L, and the post-treatment mean NO_3-N concentration was only 0.44 mg/L, illustrating that concentrations within Needle Branch have been elevated since the original treatment in 1966. In general, nitrate losses from forest ecosystems are greatest where the nitrogen capital of the ecosystem is high prior to disturbance (Binkley and Brown, 1993), and the nitrogen capital of Needle Branch may have increased since the timber harvest of the original Alsea Watershed Study due to a change of biomass species.

Red alder (*Alnus rubra)*, which is a pioneer species that invades recently disturbed conifer forests and is associated with riparian areas (Sigleo et al., 2010), is a N-fixing species that has the ability to add an estimated 50-100 kg N/ha/yr to a mixed conifer-alder ecosystem. Increasing the nitrogen capital leads to high rates of accumulated and leaked nitrogen out of alder stands (Greathouse et al., 2014). Given the nature of red alder and its prevalence in the Oregon Coast Range, it is reasonable to assume that the percent cover of this species is greater now than it was during the original Alsea Watershed study, and thus the nitrogen capital of Needle Branch would have been greater during the pre-treatment period than in the past. The increase in the nitrogen capital gives the potential to leach more nitrate, which would explain the higher values of NO_3-N concentrations in stream waters in this study as compared to the original Alsea Watershed Study.

Phase 1 values of NH_3 were found to be statistically different from pre-treatment concentrations at NBL. No other site within Needle Branch showed statistically different concentrations before and after timber harvest. Since NH_3 concentrations were also significantly different between the pre-treatment and Phase 1 periods in Flynn Creek, changes at NBL cannot be attributed to the treatment. Additionally, Phase 1 values of both OP and TP were found to be statistically different from pre-treatment concentrations at all sites within Needle Branch. Since the same is true of these constituents in Flynn Creek, the causes of these changing values are not related to timber harvest.

In addition to analyzing nutrient concentrations within the treatment watershed, concentrations were compared to the control watershed. To determine if changes in nutrient concentrations in Needle Branch could be attributed to contemporary timber harvest practices, concentrations in Needle Branch were compared to those from Flynn Creek using a Before-After Control-Impact (BACI) design (Smith, 2002), with both a two-way ANOVA (Ofungwu, 2014), and Wilcoxon Rank Sum Tests on the differences between the control site and each treatment site (Stewart-Oaten et al, 1986). Both of these tests revealed that contemporary timber harvest practices affected NO_3-N and TN concentrations in Needle Branch, but not NH_3, OP, or TP concentrations. Over the three different time periods, Needle Branch showed changes in nutrient concentration while Flynn Creek did not, despite Flynn Creek having consistently higher concentrations of NO_3-N and TN, which is likely caused by Flynn Creek's higher percentage of red alder cover (Stednick, 2008). The changes in NO_3-N and TN concentrations in stream waters within Needle Branch were caused by decreased vegetation, causing higher soil temperature, higher soil moisture, and decreased vegetative uptake, causing more soil nitrogen, and greater concentrations of nitrate leaching through the soil.

Comparing current results to results from the original Alsea Watershed Study further supports the assertion that contemporary timber harvest practices cause elevated NO_3-N concentrations, and yield similar results to the harvesting practices used in the original Alsea Watershed Study. NO_3-N concentrations within Flynn Creek have remained relatively constant over time, from 1964 to 2016 (Figure 3.11). Needle Branch, however, shows elevated NO_3-N concentrations compared to the original study, as well as elevated NO_3-N concentrations compared to the pre-treatment period (Figure 3.10).

A trend analysis performed in the original Alsea Watershed Study estimated NO_3-N concentrations to return to pre-treatment levels within six years following timber harvest. A MAKSENS trend analysis in this study came to the same conclusion: that NO_3-N concentrations would return to pretreatment levels by 2020, which is six years following the Phase 2 timber harvest. NO_3-N concentrations, however, do not appear to have returned to the original study's pre-treatment levels, which had an annual average of 0.16 mg/L (Brown et al., 1973). Instead, pre-treatment concentrations from this current study averaged 0.59 mg/L, suggesting that the effects of timber harvest will last much longer than six years. The discrepancy in these mean values may be the result of increased red alder cover within Needle Branch since the 1966 timber harvest of the original Alsea Watershed Study. Since red alder is nitrogen-fixing species, it has the effect of increasing the nitrogen capital of a watershed, which, in turn, increases the available nitrogen to be leached.

The availability of nitrogen in Needle Branch helps to explain why, regardless of the period of treatment, all measured NO_3-N and TN concentrations, during high flow, exceeded the EPA recommended nutrient criteria (EPA, 2000) for the Oregon Coast Range. Measured NO_3-N and TN concentrations also exceed the EPA recommended nutrient criteria within Flynn Creek, which had higher percentages of red alder cover than Needle Branch in the original Alsea Watershed Study, as well as in the current study. Given that NO_3-N and TN concentrations exceed EPA recommended nutrient criteria throughout the Alsea Watershed, even in subbasins that have been untreated for more than a century, signifies that nitrogen is naturally present in higher concentrations in this region, and that the EPA recommendations may need to be revised to better represent the natural regime. Rather than sampling all streams within a region, treated and untreated, to determine where the criteria should stand, the EPA could only sample untreated watersheds within a region, and use the mean high flow concentration to determine the reference condition. This would ensure that reference conditions are representative of the natural state, and that regions with organically high nutrient concentrations are not in exceedance of an artificially low criterion.

CHAPTER 5 - CONCLUSIONS

Contemporary timber harvest practices are those in which a streamside management zone is left in place for streamside protection. This differs from timber practices of the past, where there was no streamside protection, and which was shown to increase nutrient concentrations in stream waters, particularly NO_3-N and TN. The objective of this study was to determine if the presence of streamside protection mitigated the impacts to water quality following timber harvest, which it did not; as well as to determine if nutrient concentrations within the watershed were within the EPA recommended nutrient criteria, which they were not.

Results from this study mirror those from the original Alsea Watershed Study, indicating that contemporary timber harvest practices have similar effects on water quality as previous harvesting practices, where no streamside protection existed. In both studies, a paired-watershed design was used to determine the effect of contemporary timber harvest practices on nutrient concentrations in stream waters. In this study, concentrations within the treatment watershed were compared to one another to determine intra-watershed variability of nutrient concentrations, and they were also compared to concentrations within a control watershed to determine inter-watershed variability.

Water quality monitoring indicated that contemporary timber harvest practices significantly increased concentrations of NO_3-N (from a pre-treatment mean of 0.59 mg/L to a Phase 1 mean of 0.97 mg/L, and a Phase 2 mean of 0.81 mg/L) and TN (0.87, 1.07, and 0.92 mg/L, respectively), but not concentrations of NH_3, OP, or TP. While concentrations of NH_3, OP, and TP did increase in the treatment watershed following Phase 1 of treatment (0.011 to 0.013 mg/L, 0.018 to 0.024 mg/L, and 0.018 to 0.026, respectively), the same was true in the control watershed, and therefore the changes in concentration cannot be attributed to timber harvest. NO_3-N and TN, in contrast, showed significant increases in the treatment watershed, but not in the control watershed, indicating that the changes in these concentrations can be attributed to timber harvest.

Intra-watershed analysis within the treatment watershed shows that concentrations tend to decrease, particularly NO_3-N and TN, as they travel downstream. This is the result of in-channel processes, such as immobilization by algae, bacteria, and/or fungal communities, as well as dilution caused by increased discharge. Mean concentrations at the steep upstream tributaries to Needle Branch (UNB-A, UNB-B, and UNB-C) were two to three times higher than concentrations at the watershed outlet (NBL).

Inter-watershed analysis between Needle Branch (treatment) and Flynn Creek (control) reveal that, while NO_3-N and TN concentrations remained unchanged in Flynn Creek throughout the monitoring period, concentrations increased in Needle Branch following both phases of treatment, indicating that contemporary timber harvest practices caused the increase in concentration. This analysis also indicated that concentrations of NH_3, OP, or TP increased in both the treatment and control watersheds throughout the monitoring period. Since the increase occurred in both watersheds, it cannot be attributed to contemporary timber harvest practices.

NO_3-N, TN, and TP concentrations exceeded EPA recommended nutrient criteria in almost every instance, with a few exceptions at low flows. These exceedances occurred before and after timber harvest, in both the treatment and control watersheds. Since the exceedances were not caused by timber harvest, and since they occur in the control watershed, which has been free from anthropogenic changes for more than a century, the recommended nutrient criteria do not appear to represent natural conditions for this region. These nutrients have naturally higher concentrations in these two watersheds than the EPA recommended nutrient criteria, which is likely the result of local vegetation and geology.

Although NO_3-N and TN concentrations appear to naturally be relatively high in the Alsea Watershed, contemporary timber harvest practices do significantly increase these concentrations further. The inclusion of streamside protection in timber harvesting practices was meant, in part, to mitigate the effects of timber harvest on water quality. The findings from this study, however, indicate that these practices have similar impacts on water quality as previous timber harvest practices.

CHAPTER 6 - RECOMMENDATIONS

Further study in the Alsea Watershed, and throughout the Oregon Coast Range, would improve our understanding of the role of contemporary timber harvest practices, and streamside protection zones, on nutrient dynamics.

Recommendations for future studies include:

1. An examination of nutrient loads to quantify nutrient exports from each watershed to gain an understanding of how these actually change with contemporary timber harvest practices within the Alsea Watershed. A double mass analysis of loads would help us understand if contemporary timber harvest results in increased loads from the treatment watershed.
2. A thorough comparison of current data to the original Alsea Watershed Study data, if it can be obtained, to determine long-term effects of the original Alsea Watershed Study timber harvests, as well as cumulative effects of contemporary timber harvest practices.
3. The National Land Cover Database could be used to analyze how the dominant vegetative cover has changed over time within the treatment watershed. Analyzing these changes, along with concentration data, would give a better understanding of the role of changing vegetation on nutrient dynamics. It could be determined if Red Alder density has increased in Needle Branch over time, and whether this has impacted long-term nutrient concentrations and fluxes.

4. An examination of the effects of different sizes of streamside management zones, which would determine if expanding the riparian buffer zone would better help to mitigate the effects of timber harvest on water quality.
5. An investigation into groundwater and surface water interactions to quantify the contribution of stream water nutrients that are originating from, or being lost to, groundwater.
6. Usage of the Seasonal Kendall Trend Analysis, which would give more accurate estimates of nutrient trends than the MAKESENS test, better accounting for seasonality.
7. Comparison of nutrient concentrations at treatment sites within Needle Branch to concentrations at NB-3 and NB-5, both of which are also within Needle Branch, and neither of which were subject to the Phase 1 timber harvest. These two locations share similar vegetative cover and underlying geology as the treatment sites, and may serve as better controls than Flynn Creek for that reason.

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APPENDICES

APPENDIX A: Sampling Dates

Table A.1: Parameters and dates of sampling at each gauge for the data analyzed

Gauge Site	Parameters Sampled	Dates of Sampling
FC	NO_3-N TN NH_3 OP TP	October 2005 – March 2016 October 2005 – March 2016 April 2006 – August 2014 October 2005 – March 2016 October 2005 – August 2014
NBL	NO_3-N TN NH_3 OP TP	October 2005 – March 2016 October 2005 – March 2016 December 2005 – August 2014 October 2005 – March 2016 October 2005 – August 2014
NBU	NO_3-N TN NH_3 OP TP	October 2005 – March 2016 October 2005 – March 2016 December 2005 – August 2014 October 2005 – March 2016 October 2005 – August 2014
NBH	NO_3-N TN NH_3 OP TP	May 2006 – March 2016 November 2007 – March 2016 August 2006 – August 2014 November 2007 – March 2016 November 2007 – August 2014
NB-1	NO_3-N NH_3	November 2005 – June 2014 December 2005 – December 2010
NB-2	NO_3-N NH_3	November 2005 – June 2014 December 2005 – September 2010
NB-4	NO_3-N NH_3	November 2005 – June 2014 July 2006 – September 2010
NB-6	NO_3-N NH_3	November 2005 – June 2014 June 2006 – December 2010
UNB-A	NO_3-N NH_3	October 2007 – August 2014 March 2008 – December 2010
UNB-B	NO_3-N NH_3	November 2007 – August 2014 January 2008 – December 2010
UNB-C	NO_3-N NH_3	November 2007 – August 2014 November 2007 – December 2010

APPENDIX B: Time Series of Nutrient Response

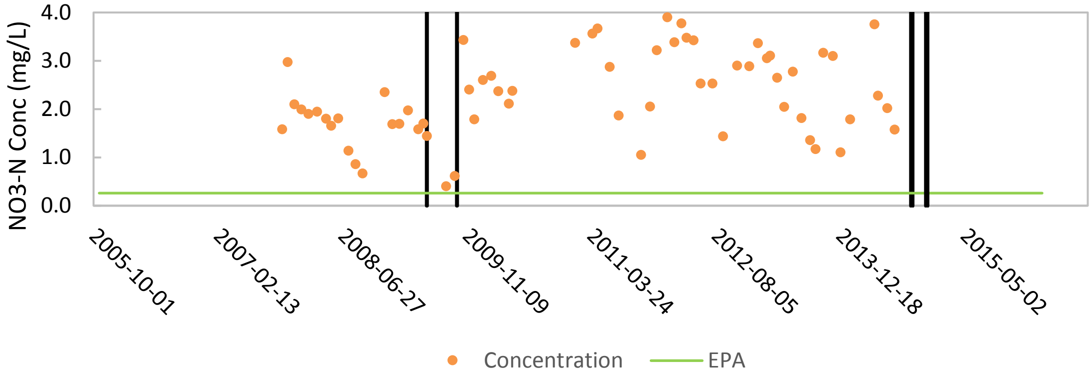

Figure B.1: Time series of NO_3-N concentrations at UNB-A. Black, vertical lines indicate the period of treatment.

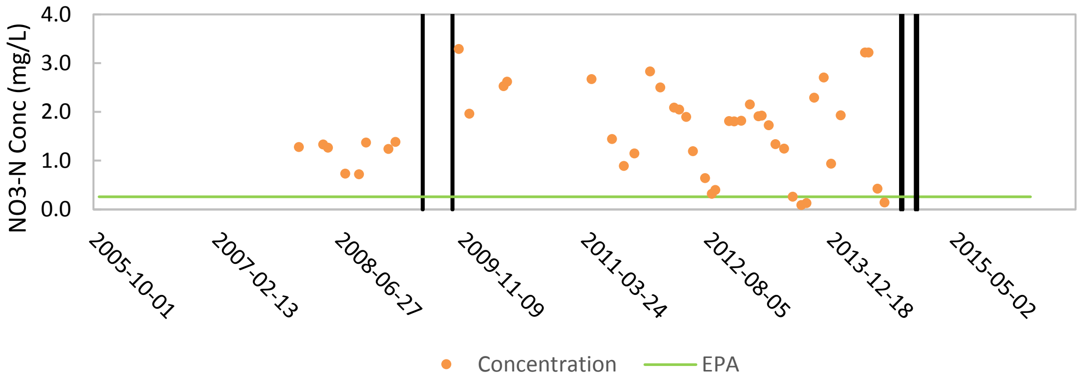

Figure B.2: Time series of NO_3-N concentrations at UNB-B. Black, vertical lines indicate the period of treatment.

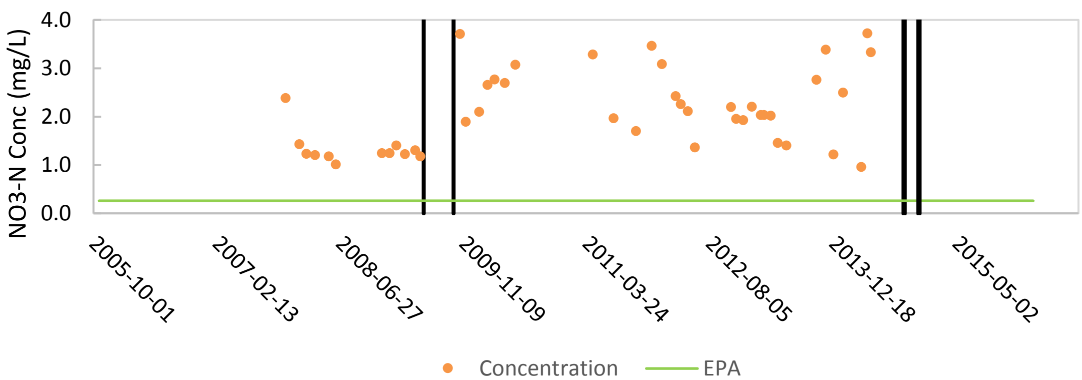

Figure B.3: Time series of NO_3-N concentrations at UNB-C. Black, vertical lines indicate the period of treatment.

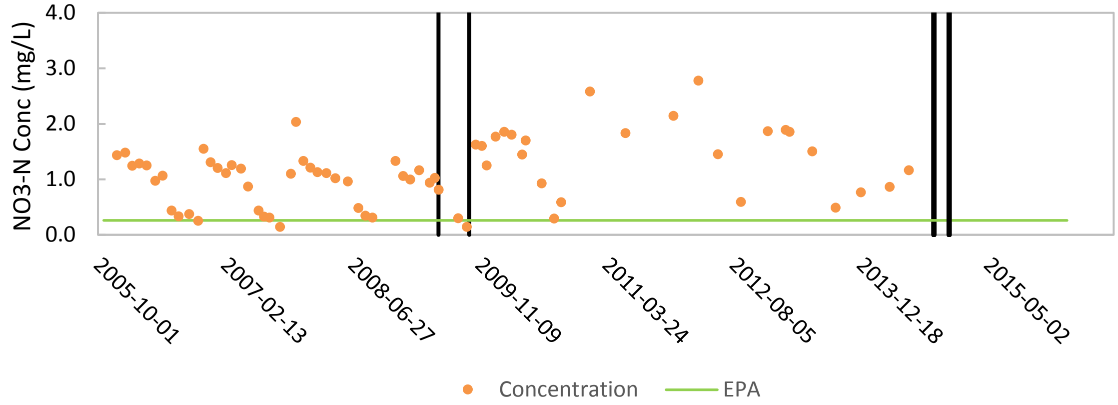

Figure B.4: Time series of NO_3-N concentrations at NB-6. Black, vertical lines indicate the period of treatment.

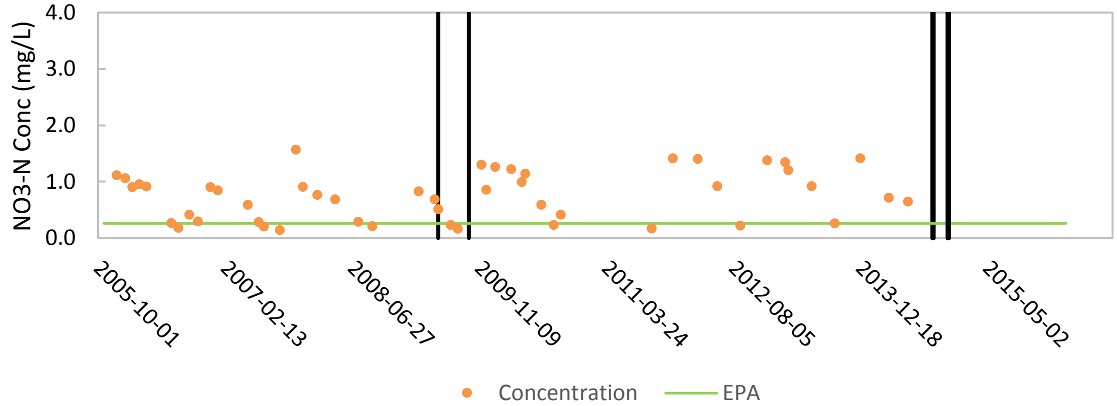

Figure B.5: Time series of NO_3-N concentrations at NB-4. Black, vertical lines indicate the period of treatment.

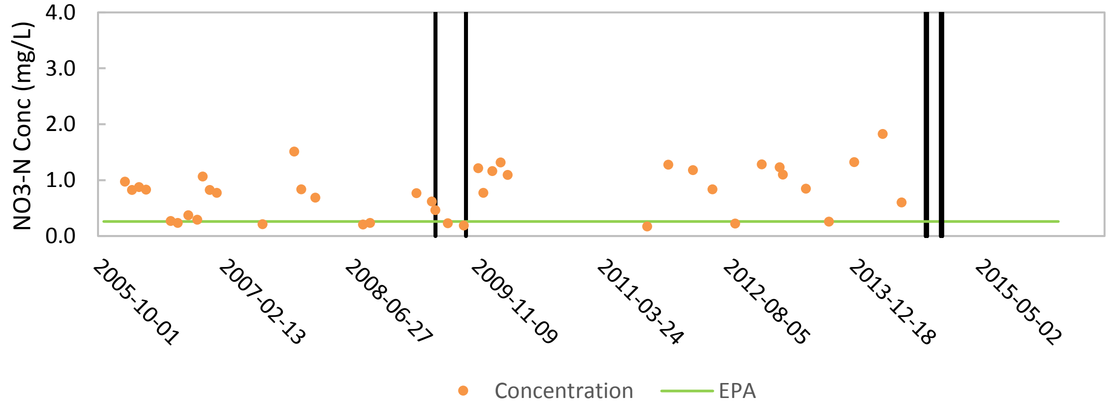

Figure B.6: Time series of NO_3-N concentrations at NB-2. Black, vertical lines indicate the period of treatment.

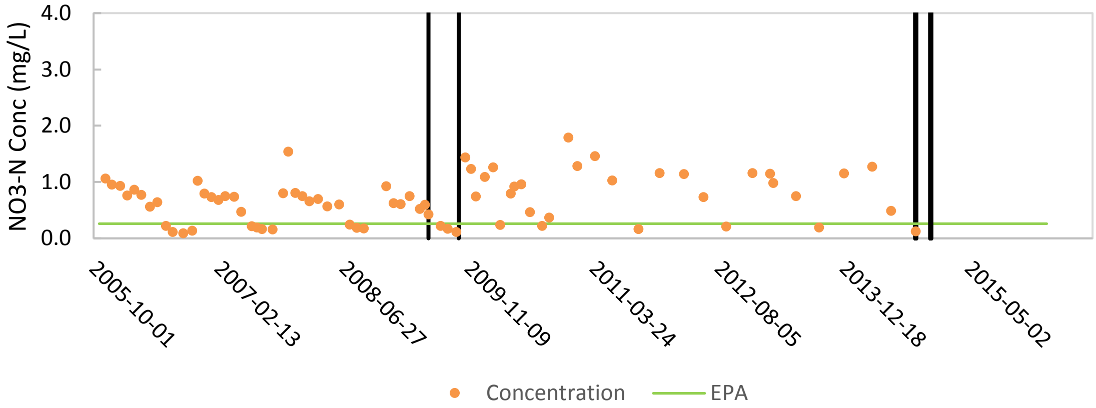

Figure B.7: Time series of NO_3-N concentrations at NB-1. Black, vertical lines indicate the period of treatment.

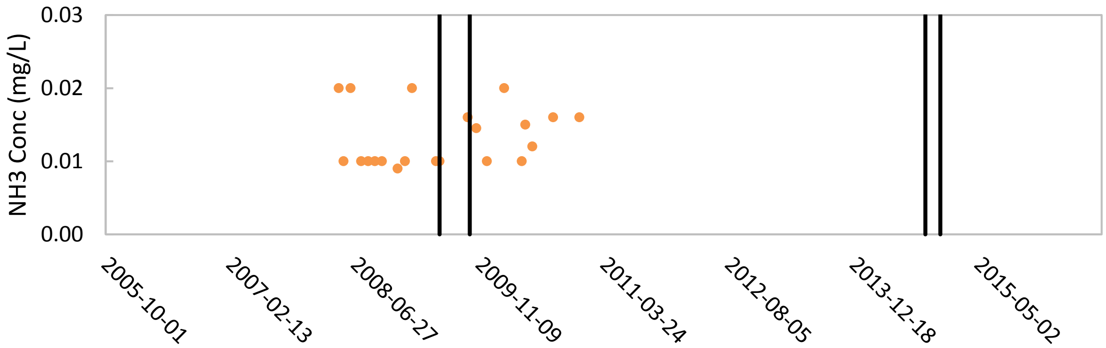

Figure B.8: Time series of NH_3 concentrations and discharge at UNB-A. Black, vertical lines indicate the period of treatment.

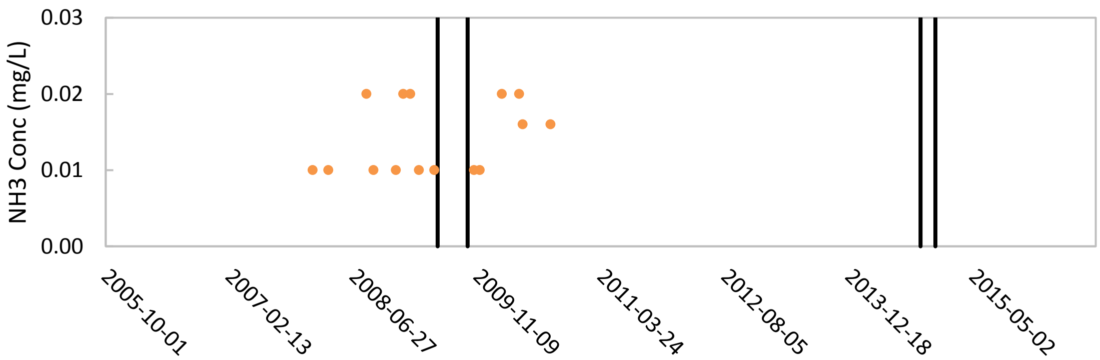

Figure B.9: Time series of NH_3 concentrations and discharge at UNB-B. Black, vertical lines indicate the period of treatment.

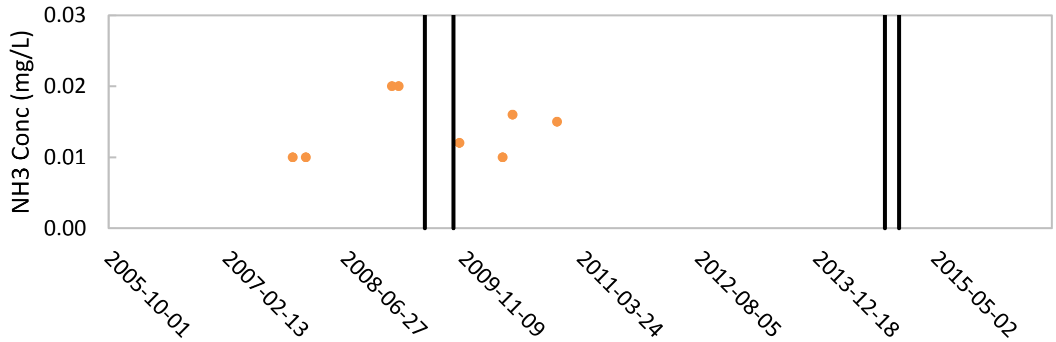

Figure B.10: Time series of NH_3 concentrations and discharge at UNB-C. Black, vertical lines indicate the period of treatment.

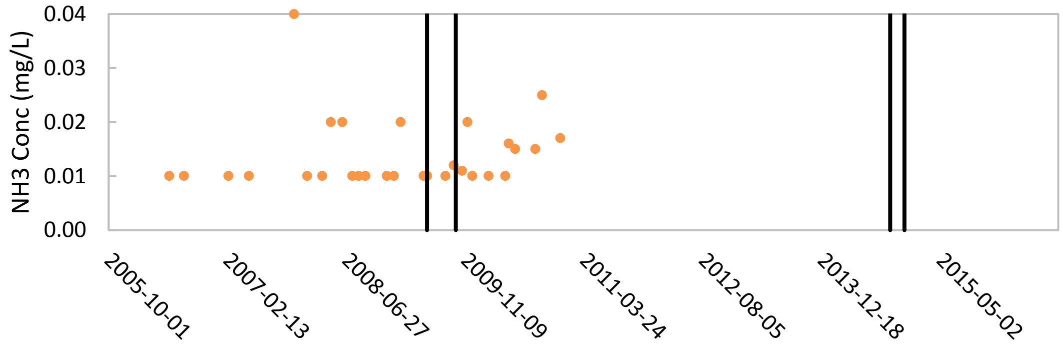

Figure B.11: Time series of NH_3 concentrations and discharge at NB-6. Black, vertical lines indicate the period of treatment.

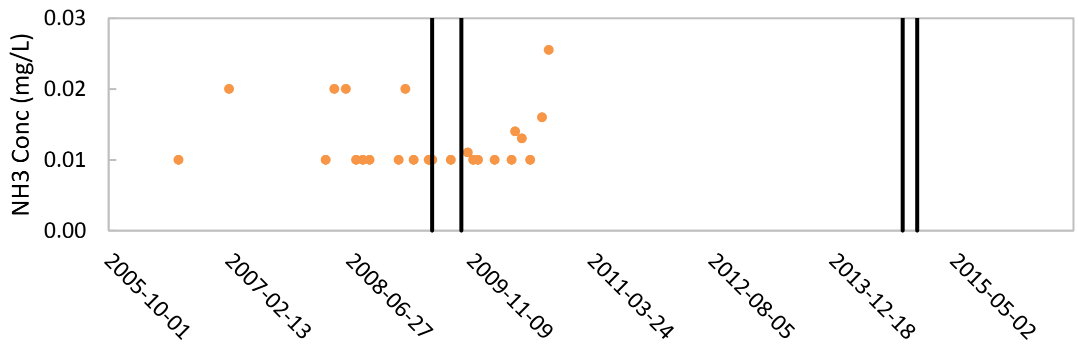

Figure B.12: Time series of NH_3 concentrations and discharge at NB-4. Black, vertical lines indicate the period of treatment.

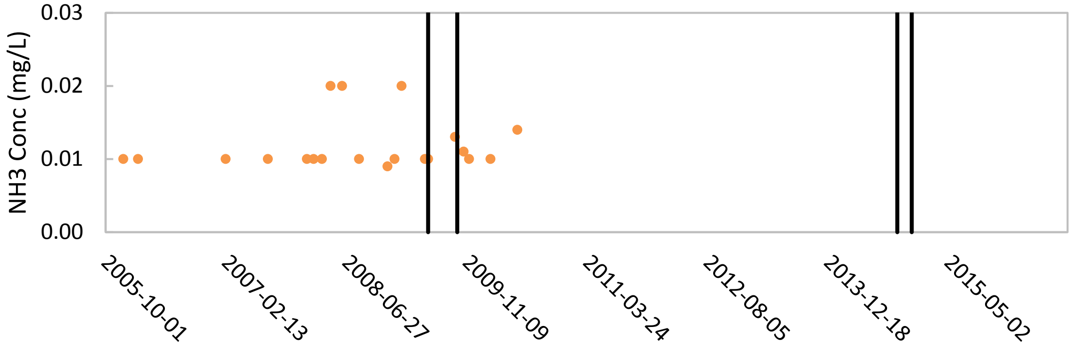

Figure B.13: Time series of NH_3 concentrations and discharge at NB-2. Black, vertical lines indicate the period of treatment.

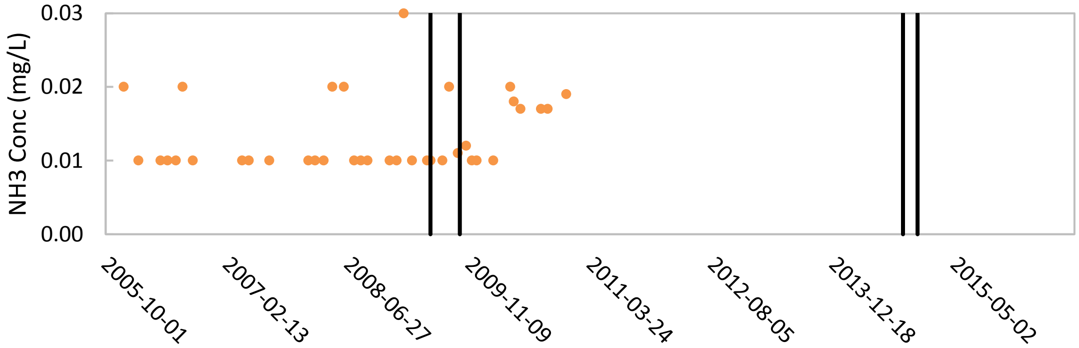

Figure B.14: Time series of NH_3 concentrations and discharge at NB-1. Black, vertical lines indicate the period of treatment.

APPENDIX C: Box Plots of Nutrient Concentration Response

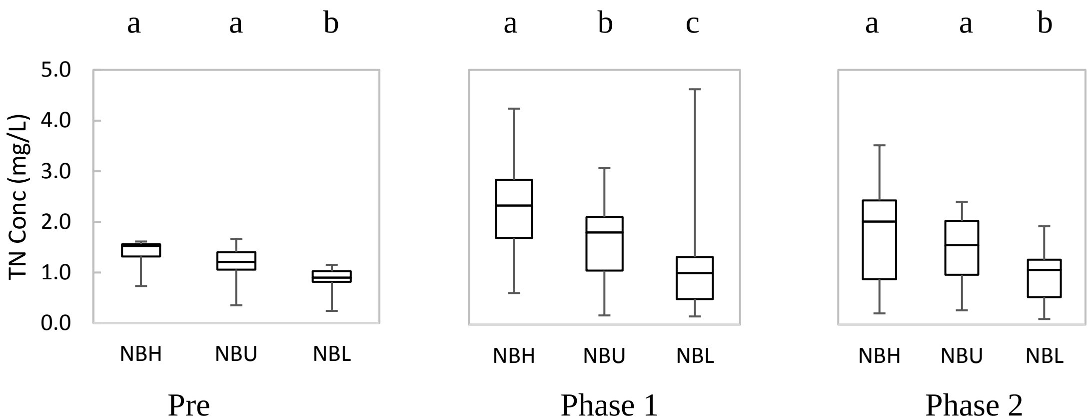

Figure C.1: Boxplots of TN concentrations at each location, for each period of treatment. Distributions that do not share a letter are significantly different.

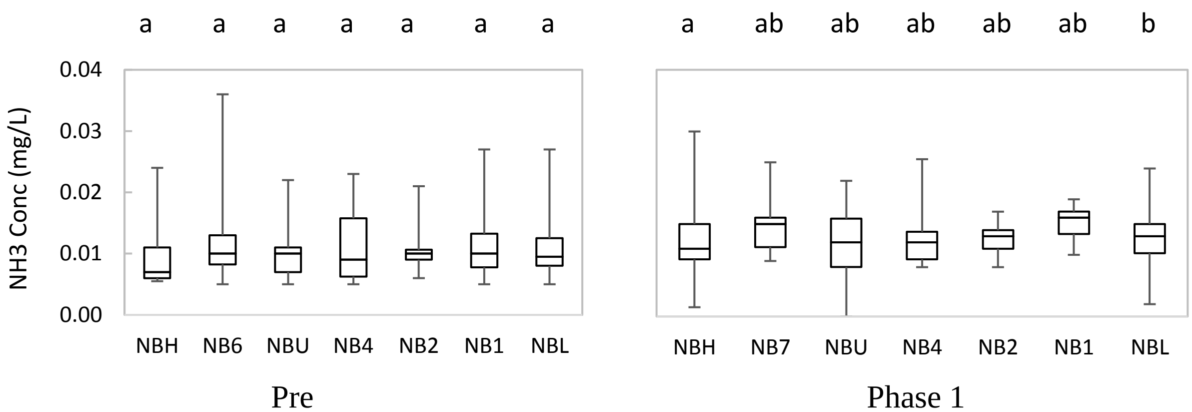

Figure C.2: Boxplots of NH_3 concentrations along the main stem of Needle Branch, for each period of treatment. Distributions that do not share a letter are significantly different

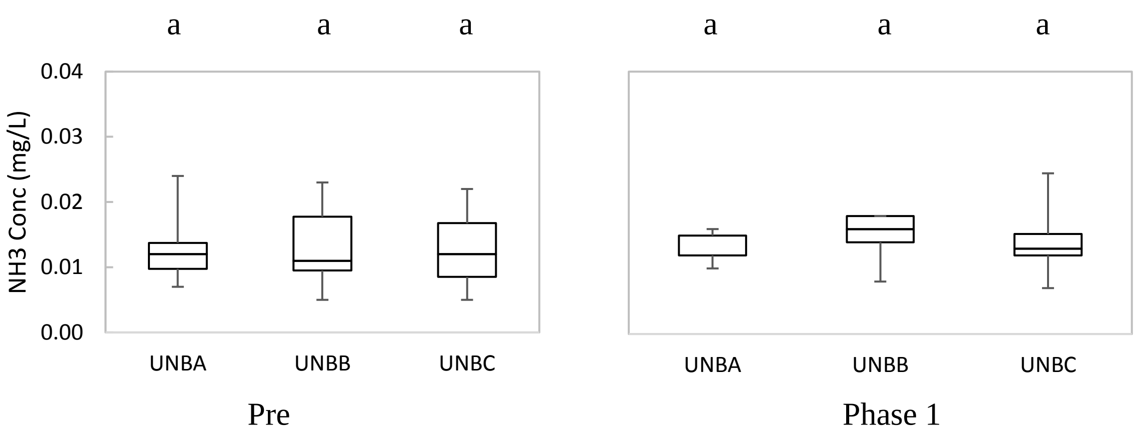

Figure C.3: Boxplots of NH_3 concentrations at three upstream tributaries in Needle Branch, for each period of treatment. Distributions that do not share a letter are significantly different.

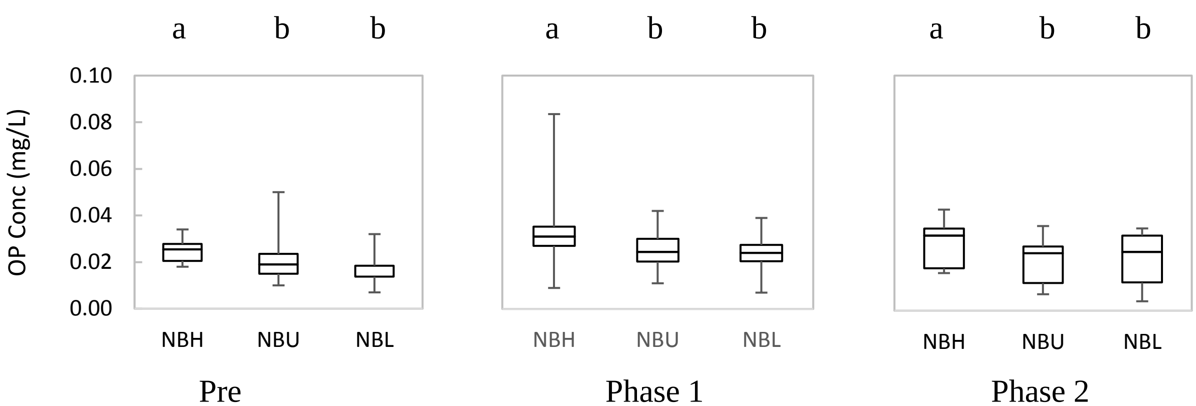

Figure C.4: Boxplots of OP concentrations at each Needle Branch location, for each period of time. Distributions that do not share a letter are significantly different.

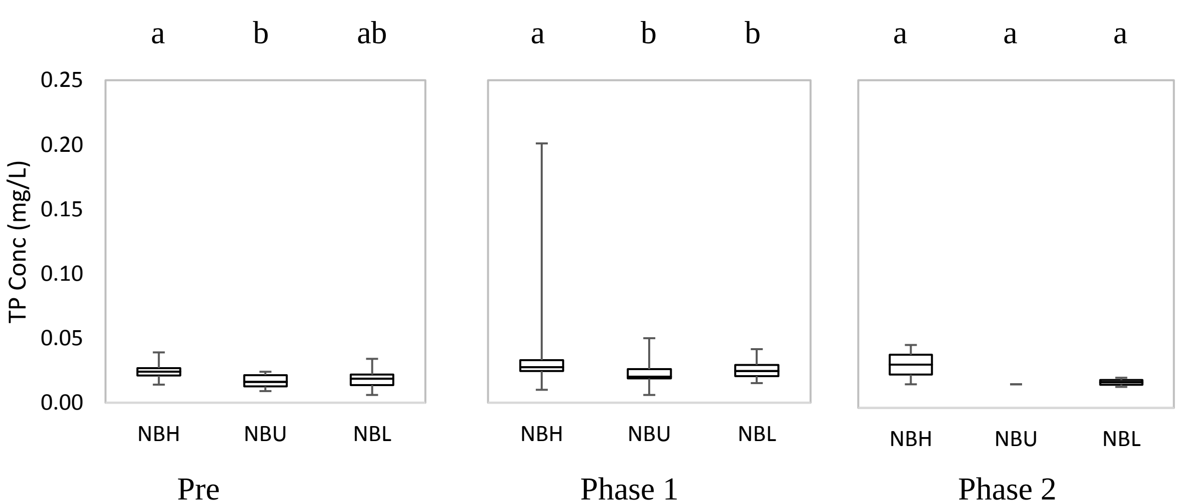

Figure C.5: Boxplots of TP concentrations at each Needle Branch location, for each period of time. Distributions that do not share a letter are significantly different.