Growing Short Rotation Hybrid Poplar in the Pacific Northwest for Bioenergy: Effects on Nutrient Leaching

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Authorization to Submit Thesis

This thesis of Bhanu Bhattarai, submitted for the degree of Master of Science with a Major in Natural Resources and titled "GROWING SHORT ROTATION HYBRID POPLAR IN THE PACIFIC NORTHWEST FOR BIOENERGY: EFFECTS ON NUTRIENT LEACHING," has been reviewed in final form. Permission, as indicated by the signatures and dates below, is now granted to submit final copies to the College of Graduate Studies for approval.

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Abstract

Increasing bioenergy crop production may negatively affect soil and water quality through leaching of excess nutrients. We studied the effects of growing hybrid poplar in the Pacific Northwest on nutrient leaching of ammonium (NH_4^+), nitrate (NO_3^-) and orthophosphate (PO_4^{3-}). This research will help to predict soil and water quality for the full scale planting from the regional agricultural land use shifts. Nutrient leaching was estimated as a product of soil water drainage using the water balance method and nutrient concentration in the soil leaching solution collected using suction lysimeters installed at 50 cm depth. Depending on site environmental condition, impact on nutrient leaching from hybrid poplar was either low or high compared to the agricultural system. Jefferson, OR agriculture had highest NO_3^- leaching (2.5 kg ha^{-1}) compared to all sites and management. Among poplar plantation sites, NO_3^- leaching was highest in Jefferson poplar (1 kg ha^{-1}). Ammonium and PO_4^{3-} were less than 0.005 kg ha^{-1} across all sites and management. It is expected that nutrient leaching in hybrid poplar will eventually drop down as root system gets well established compare to the agricultural system.

Key words: renewable resources, water balance method, soil water drainage, suction lysimeters, ammonium, nitrate and orthophosphate.

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Dedication

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Chapter1 Literature Review

1.1 LANDSCAPES OF ENERGY RESOURCES

There is a trend away from the predominant use of fossil fuels to more diverse sources of energy. Fossil fuel is expected to be a dominant source of energy and will remain so for at least some years in the future, whereas renewable resources are steadily becoming a larger part of the global energy mix. In the global energy market, the share of fossil fuel is expected to decrease from, 82% to 76% and that of renewable energy to increase from, 11% to 16% from 2011 to 2020 (Mondial et al., 2013). Under current policies in the world, the demand for renewable energy will increase to 60% by 2035 and the global demand of bioenergy including both traditional and modern biomass uses is expected to grow to 13% by 2020 (International Energy Agency, 2013). Bioenergy from biomass is considered as a potential substitute of fossil fuel in the future because of its renewability, sustainability and environmental benefits (Mann & Tolbert, 2000 and Demirbas, 2009). In the United States, energy resources are also expected to follow the global pattern. It is predicted that fossil fuel will decline from 82% to 80% from 2012 to 2040 while renewable energy is expected to increase from 9% to 12% during same time range (US EIA, 2015). Recent legislation mandates biofuel ethanol production of 36 billion gallons by 2022 (U.S. Department of Energy, 2011 and US EIA, 2014), this would demand more lands under bioenergy crops in the future to meet the goals. According to Qin et al. (2014) it needs about 280 million tons of cellulosic biomass under current technologies to meet the goal set-up by EIS Act of 2007. In US about 370 million oven dry tons of woody biomass can be sustainably produced annually (US Department of Energy, 2011). The use of woody biomass as bioenergy resources at this scale will stimulate increased plantations of bioenergy crops in the future.

1.2 HYBRID POPLAR

Hybrid poplar is a common term that refers to crosses of *Populus* species in the family Salicaceae. As a short rotation woody crop (SWRC), hybrid poplar is an important feedstock to produce biomass for energy and other traditional products including timber, pulp and paper. Several features of poplar species make it desirable for timber and energy production in the United States and the world: high productivity, vegetative propagation from unrooted cuttings, coppicing ability and flexibility to clonal breeding that maintains genetic gains (Heilman, 1999; Stanton et al., 2002 and Alig, et al., 2000). Poplar has high productivity, 8 to 12 dry Mg ha^{-1} $year^{-1}$ in USA (Sannigrahi, 2010) and has high net energy ratio, output energy to input energy of about 10-20 (Yuan et al., 2008) compared to other energy crops. About 50,000 acres of lands were under hybrid poplar plantation in the Pacific Northwest in 2002 (Stanton et al., 2002) whereas suitable crop land for planting hybrid poplar is about 1,274,000 acres within the region (Alig et al., 2000). This could potentially serve as important renewable feedstock to produce a sustainable bioenergy resource in the Pacific Northwest.

1.3 WOODY BIOMASS AS BIOENERGY RESOURCES

In addition to hybrid poplar, multiple choices of biomass energy resources are available for energy production. Bioenergy compromises any source of energy produced from biological materials, including a wide variety of agricultural crops, woody plants and animal sources. Energy crops include woody or herbaceous perennial grasses as an important feedstock for cellulosic ethanol production. The choice of feedstock is determined by its ability to meet the needs of present generation without affecting future generation needs (World Commission on Environment and Development, 1987). Other physical and chemical properties like productivity, moisture, ash, cellulose contents etc. have an important role in selecting the bioenergy crops (McKendry, 2002). Use of bioenergy crops is growing because of increased energy costs, energy dependency, desire to reduce the greenhouse gas emissions responsible for climate change as mandated by national and international laws and policies (IPCC, 2011). Expansion of biofuel production on existing productive lands like agricultural and forested lands trigger food versus fuel debate, increase in GHG emissions and other ecological and environmental problems like soil and water quality (Whitacre, 2011 and Elbehri et al., 2013). Cultivating bioenergy plants on existing agricultural soil will put pressure on food demand, food security, and forest land to expand for agriculture to incorporate increasing demand of food and bioenergy in the future. However, growing bioenergy on marginal lands will reduce pressure on existing agricultural and forest lands and help to solve issues of food price and food security. In addition, low nutrient requirements and high water use efficiency of bioenergy crops will help reduce leaching and conserve soil and water quality if bioenergy crops were planted in fertile agricultural and forested lands (Johnson et al., 2007; Searchinger et al., 2008 and Popp et al., 2014).

1.4 SOIL AND WATER QUALITY

There are contrasting opinions about the impacts of growing bioenergy crops. According to Kort, et al. (1998), Thornton, et al. (1998), and Johnson et al. (2007), plantations of herbaceous energy crops and SWRC provide substantial protection to soil and ground water and reduce erosion and runoff, energy crops are efficient in nutrient use and bind soils more strongly through dense root system minimizing soil loss and nutrient. The production of forest biomass as a renewable energy also help in maintaining forest biodiversity from diverse structure within landscape that allows for nesting, foraging habitat for birds and mammals and often protects from predator by providing cover (Tolbert, 1998 and Tolbert & Wright, 1998) in addition to fuel and energy sources. However, most of the positive effects of bioenergy production are generalized in comparison with conventional crop systems and are based on small scale farm research. Searchinger et al. (2008) using worldwide agricultural model found increase in emissions of GHG by 50% by the conversion of corn lands to switchgrass in US. The production of biomass on large scale may deplete the soil nutrient stocks which eventually might increase the GHG emission and make biomass production neither sustainable nor carbon neutral (Schulze et al., 2012). Although opportunity exists, justifiable concerns regarding the long-term environmental impacts of using forest-based energy feedstock have emerged. There are increasing concerns about possible negative environmental impacts associated with bioenergy production at large scale (Rowe et al., 2009).

Soil and water quality may be highly influenced when expanding SWRC biomass production. Impacts on soil and water quality can occur at different phases of biomass planting; management and harvesting that include site preparation, use of fertilizers, herbicides, pesticides, silivicultural activities and harvesting. Like conventional agricultural systems, growing SWRC can affect soil and water quality during the lifecycle of bioenergy crops. Soil organic matter content, flux of nutrients, erosion and compaction can cause soil and water degradation by changing carbon dynamics, and water pollution as well as emission or consumption of traces gases affecting plant productivity and soil quality (Lal et al., 1999; Lal, 2001; Lattimore et al., 2009; and Berhongaray & Ceulemans, 2015). Heilman & Norby (1998) pointed out the importance of matching woody crop nutrients requirements with soil characteristics to minimize the impacts on soil and water quality from biomass production. Most of the studies have shown significant loss of nutrients and sediment to water bodies at initial stage of bioenergy plantation causing pollution at different rate of fertilization (Mann & Tolbert, 2000 and Thornton et al., 1998). Excessive amounts of nutrients like nitrogen and phosphorous speed up addition of nutrients to aquatic ecosystem known as eutrophication process (Gentle et.al., 2010) and have adverse effects on water quality (Schlesinger & Bernhardt, 2013). However, planting SWRC also offer many benefits. The construction of buffer strips of bioenergy crops help retain the nutrients and slow down the eutrophication process improving soil and water quality (Haycock & Pinay, 1993; Coleman & Stanturf, 2006; Dale et al., 2011 and Neary & Koestner, 2012). Dipesh, et al., (2014) have shown that, SWRC are capable of extracting high amount of nutrients from nutrient rich animal waste lagoon (699 kg nitrogen and 9 kg phosphorous per hectar). Similarly, the use of energy crops and SWRC plantations for phytoremediation in contaminated soil help to improve the quality of both soil and water (Stanton et al., 2002; Volk et al., 2004; Coleman & Stanturf, 2006; Johnson et al., 2007) by accumulating, degrading and rendering harmless substances back in soils and water. Water leaching from the soil surface to the subsurface can move substantial amount of nutrients and other chemical elements to the subsurface and ground water (Holder et.al, 1991). Understanding nutrient flux is not only helpful from an environmental perspective to determine the impact on water quality, but also equally important from an economic perspective for efficient nutrient management.

1.4.1 NUTRIENT LEACHING

There are several methods to calculate water flux and collection of leachate for nutrient analysis to estimate nutrient leaching. Gaskin et al. (1989) used Darcy's law to calculate water flux and multiplied that by the leachate nutrient concentration collected from suction lysimeters to calculate nutrient flux. Calculation of water flux using Darcy's law require potential gradient between two points and average hydraulic conductivity. Qualls et.al., (1999) studied nutrient flux in clear-cut and mature deciduous forest using short term nutrient flux and long term nutrient flux at uncut plot. Water balance method and stream water flow were used to calculate short term and long term water flux. Water balance method is used to calculate flow of water using several hydrological parameters like precipitation, runoff and evapotranspiration. A comparative study of different techniques for measuring nitrate leaching was done by Pampolino et al. (2000). Different techniques used to calculate nutrient leaching was done using resin capsules, suction lysimeters, subsurface drainage and pan lysimeters in the clayey agro ecosystem. They found that resin capsules are more efficient in capturing the NO_3^- transport where macropore flow is dominant. Similar comparative study was done for lysimeters and porous ceramic cups in different soil types for nitrate leaching by Wang et al. (2012). They found that suction lysimeters are inappropriate in determining the cumulative leaching in silt loam and stony silt loam because of preferential flow, but were useful in sandy loam soil where they observed uniform soil flow. Nikièma et al. (2012) studied the effect of converting pastureland to energy crops plantation on nitrogen leaching using water balance model to calculate water flow and suction lysimeter to collect the leachate for nutrient analysis. Ceramic suction lysimeter are easy to install, allow continual measurement of leached water from the exact same point and considered as suitable technique to collect nutrient leaching (Webster et al., 1993) compare to other lysimeters that require considerable soil disturbance. However, calculations of nutrient flux from this method require weather data and soil physical parameters to calculate water flux either using water balance method or water flow models. Water balance method is considered suitable method when all the required meteorological data are available. In absence of site specific meteorological observation and water flow models; direct observation of water potential gradient along with other soil physical properties are considered as a good measurement of water flow. Although direct calculation of water flow can be used from the volume collected in the suction lysimeters they are more prone to error (Qualls et al., 1991). According to Qualls et al. (1999) , calculation of water flow from Darcy's law using potential gradient give higher water flux by 140% than water balance method. Hence, the water balance method is considered an appropriate method to calculate water flux when all the required meteorological data are available.

Computer simulation models based on numerical equations are also widely used in studying nutrient leaching. An overview of different models used in the study of nutrient leaching are briefly explained by Cichota & Snow (2009). Jemison et al. (1994) evaluated the LEACHM model for nitrate leaching in non-manure and manure corn field. Lee & Jose (2005) studied the nitrate leaching in cottonwood and pine using the tension lysimeters and LEACH model. A two dimensional HYDRUS-2D was used by Ajdary et al. (2007) to study nitrogen leaching in agricultural system under different fertigation rates. A similar approach was used by Palmer et al. (2014) using Hydrus-1D to calculate water flow to study the effect of conversion of open lands to SWRC in US Northern Lake States. In the case of SRWC grown in soils found in the Pacific Northwest, the most appropriate method is the use of the water balance method to calculate water drainage and collection of leachate using suction lysimeters. Identifying sites that are vulnerable to leaching is necessary to monitor regularly and design effective management plan to reduce the impacts. Vulnerable sites can be found based on site environmental conditions and nutrient status discussed in the following section.

SRWC for bioenergy is more like agriculture than conventional forestry with an aim of high productivity within a short rotation cycle. The excessive use of chemicals to boost production may impair waterways and groundwater affecting aquatic ecosystem (Simpson et al., 2009 and Liu et al., 2012). Therefore, soil and water quality is a major environmental concern of biomass production (Heilman & Norby, 1998 and Neary & Koestner, 2012). Most of the research on nutrient leaching are concentrated on the effects of fertilization. However, very little is known about the leaching in absence of fertilization. Further, there is a lack of extensive and regional level study to fully understand the effects on soil and water quality at landscape level (Mann & Tolbert, 2000). Growing plants decrease nutrient stock and require fertilization, pesticides and herbicides in a long term to obtain the desirable production of biomass in the future. Understanding the spatial and temporal dynamics of nutrient flux is important both from environmental and economic perspective to provide best management practices for sustainable production of bioenergy in the future.

1.4.2 FACTORS AFFECTING NUTRIENT LEACHING

Nutrient leaching largely depends on species, soil types, management practices and climate. Nutrient leaching is affected by species type and whether it is a monoculture or a mix of multiple species (Tilman et al., 1996). Some plant species are better than others in nutrient retention. For instance, Lee & Jose (2005) found low leaching in poplar by 3% compared to pine. Similarly, polycrops plantion are more efficient in nutrient use than monocrop plantation because of high root dispersion at different depths. Multiple cropping system reduces leaching by 4 kg N ha^{-1} $year^{-1}$ than single cropping system (Ewel & Bigelow, 2011).

Plant species adaptation and site quality have important control over nutrient cycling. Plants growing on nutrient rich soil grow rapidly and are inefficient in nutrient use whereas plants growing on nutrient deficient soil grow slowly and are more efficient in nutrient use (Hobbie, 1992). In nutrient deficient soil, plants have low productivity, but long lived tissues help to increase total photosynthesis per nitrogen use than plants grown in nutrient rich soil (Chapin, 2011).

Other factors like soil types and soil size also affect leaching. Different soils have different nutrient retention capacity and have significant effects on leaching. Coarse sand has high NO_3^- leaching than loamy sand by 40 kg N ha^{-1} because of low nutrient retention capacity of loamy sand (Mortensen, et al., 1998). However, in soil with high preferential flow, clayey soils have high nitrogen leaching than sandy soil by 2 kg N ha^{-1} (Aronsson & Bergström, 2001).

Management practices like fertilization, land conversion, harvesting and irrigation also influence leaching. Fertilization rate above 56 kg N ha^{-1} increased NO_3^- leaching to more than 10 mg L^{-1}, the maximum allowable concentration set by Environment Protection Agency (EPA) U.S. (Lee & Jose, 2005). Land conversion from pasture to SWRC showed higher leaching of NO_3^- during initial period by 51 kg ha^{-1} (Nikièma et al., 2012). Similar results were found in agricultural land conversion to SWRC by Joslin & Schoenholtz, (1997), Thornton, et al. (1998) and Palmer et al. (2014). Qualls et.al. (1999) found 51% increase in dissolved organic nitrogen following harvesting of a mature forest in organic horizon of soil.

Climatic conditions and irrigation is one of the most influential factors of nutrient leaching. Nutrient leaching generally increases when water input either precipitation or irrigation is more than evapotranspiration (Di & Cameron, 2002). However, summer weather conditions may guide the nutrient leaching of following seasons, fall and winter (Scholefield et al., 1993). In plants, during dry summer nutrient leaching increases by low nutrient uptake and in moist conditions nutrient uptake by plants increases therby reducing nutrient leaching (Di et al., 1999). There is no simple answer to the factors affecting the nutrient leaching, but it always varies by plant species, environmental conditions and management practices.

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Chapter 2 Growing Short Rotation Hybrid Poplar for Bioenergy in the Pacific Northwest: Effects on Nutrient Leaching

Abstract

Biomass as a renewable energy resource is increasing as a solution to mitigate climate change and advance energy independence. However, increasing bioenergy crop production may negatively affect soil and water quality through leaching of excessive nutrients. We studied the effects of growing hybrid poplar in the Pacific Northwest on nutrient leaching of ammonium (NH_4^+), nitrate (NO_3^-) and orthophosphate (PO_4^{3-}) to see if regional agricultural lands shifts to hybrid plantation affect soil and water quality. Nutrient leaching was estimated as a product of soil water drainage using the water balance method and nutrient concentration in the effluent collected from suction lysimeters installed to sample at 50 cm below the soil surface. We found that during hybrid poplar plantation establishment, the impact on nutrient leaching was either lower or higher than adjacent reference agricultural systems depending on site environmental conditions. The Jefferson, OR agriculture had highest NO_3^- leaching (2.5 kg ha^{-1}) compared to all sites and management. However, NH_4^+ and PO_4^{3-} were less than 0.005 kg ha^{-1} in all sites and management. It is expected that nutrient leaching will eventually drop down in hybrid poplar compare to the agricultural system as tree root systems become established. This research will help to predict soil and water quality as regional agricultural land use shifts to include hybrid poplar bioenergy crops in the Pacific Northwest.

Key words: renewable resources, water balance method, soil water drainage, suction lysimeters, ammonium, nitrate and orthophosphate.

2.1 INTRODUCTION

Hybrid poplar is an important feedstock to produce biomass for energy and other diverse products that include timber, pulp and paper. Because of these features and several other features: high productivity, vegetative propagation from unrooted cuttings, coppicing ability, and flexibility to clonal breeding that maintains genetic gains (Heilman, 1999; Stanton et al., 2002 and Alig, et al., 2000), hybrid poplar is desirable for timber and energy production in the United States and the world. Poplar has high productivity, 8 to 12 dry Mg ha^{-1} $year^{-1}$ in USA (Sannigrahi, 2010) and has high net energy ratio, that is to say the output energy to input energy of about 10-20 compared to other energy crops with energy ratios below 10 (Yuan et.al., 2008). About 50,000 acres of lands were under hybrid poplar plantation in Pacific Northwest in 2002 (Stanton et al., 2002) whereas suitable crop land for planting hybrid poplar is about 1,274,000 acres within the region (Alig et al., 2000). This could potentially serve as important renewable feedstock to produce a sustainable bioenergy resource in the Pacific Northwest. However, open questions remain on environmental aspects of bioenergy production from SWRC at a large scale. In particular,impacts on soil and water quality such as soil nutrient stocks, eutrophication and pollution of water bodies are areas of significant knowledge gaps (Tuskan, 1998; Tolbert & Wright, 1998; Lattimore et al., 2009; Dale et al., 2011 and Elbehri et al., 2013).

SWRC can affect soil and water quality by changing organic matter content (Lal et al., 1999; Mann & Tolbert, 2000), nutrient leaching, erosion and compaction (Lal et al., 1999; Lal, 2001; Mann & Tolbert, 2000; Lattimore et al., 2009; and Berhongaray & Ceulemans, 2015). SWRC for bioenergy is more like commercial farming with an aim of high productivity within a short rotation cycle. Such high management intensity will decrease the nutrient stocks and require more frequent fertilization, pesticide and herbicide application which will encourage the excessive use of the chemicals and fertilizers (Shepard, 2006). These products may find their way to surface and groundwater with potential effects on aquatic ecosystems and health (Simpson et al., 2009 and Liu et al., 2012). Hence, water quality is a major concern of environmental sustainability of biomass production (Heilman & Norby, 1998 and Neary & Koestner, 2012).

Nutrient leaching is the loss of water soluble nutrient from soil during off-site water movement. Nutrient leaching is an important indicator of soil quality. High leaching causes negative effects on both nutrient stocks of soil and downstream water quality (Adegbidi et al., 2001; Schlesinger & Bernhardt, 2013). If high nutrient leaching causes excessive amount of nutrients like nitrogen and phosphorous in surface waters it may speed up the eutrophication process (Gentle et al., 2010).

Best management practices of SWRC plantations also offer many benefits like reduction of nutrient leaching and improvement of water quality compared to conventional agriculture system (Kort et al., 1998, Johnson et al., 2007, and Thornton et al., 1998). For example, construction of buffer strips of bioenergy plants help retain the nutrients and slow down the eutrophication process improving soil and water quality (Haycock & Pinay, 1993; Coleman & Stanturf, 2006; Dale et al., 2011 and Neary & Koestner, 2012). Dipesh, et al. (2014) have shown that, SWRC are capable of extracting high amount of nutrients from nutrient rich animal waste lagoon (699 kg nitrogen and 9 kg phosphorous per hectar) thereby reducing the nutrient leaching. Similarly, the use SWRC plantations help phytoremediation in contaminated soil to improve the quality of both soil and surface water (Stanton et al., 2002; Volk et al., 2004; Coleman & Stanturf, 2006; Johnson et al., 2007) by accumulating, degrading and rendering harmless substances in soils and water. However, other studies have shown high leaching during the initial stage of SRWC establishment (Thornton et al., 1998 Joslin & Schoenholtz, 1997 Nikièma et al., 2012) that becomes significantly lower at the later stages of bioenergy plantations (Aronsson & Bergström, 2001) compared with crop lands.

Most studies are based on a single growing season at different fertilization rates. However, there is a lack of extensive and long term studies from biomass crops production in the absence of fertilization. Therefore, it is important to understand the behavior of nutrients in the soils to maximize productivity and prevent off site nutrient movements to minimize the impacts on soil and water quality. Monitoring of nutrient leaching at different regions of the Pacific Northwest is important to predict soil and water quality for the full scale planting from the regional agricultural land use shifts because of diverse regional environmental conditions and management practices.

In this study, we focus on nutrient leaching to test if it hybrid poplar bioenergy plantations will have a negative impact on water quality compared to agricultural land at large scale planting. We hypothesized that the magnitude of nutrient leachate concentration depends on site and management types (poplar and agriculture). To test this we compared poplar plantations with adjacent agricultural fields at three locations in the Pacific Northwest. The overall objective of this research was to calculate nutrient leaching and compare between management types. Specific objectives of the research were to:

I. Compare seasonal and annual soil water drainage below 50 cm by site and management.
II. Measure seasonal and annual variation by site and management type of leachate ammonium (NH_4^+), nitrate (NO_3^-) and orthophosphate (PO_4^{3-}) concentration .
III. Estimate seasonal and annual nutrient leaching of NH_4^+, NO_3^- and PO_4^{3-} by site and management.

2.2 MATERIALS AND METHODS

2.2.1 SITE DESCRIPTIONS

The study was conducted in three poplar demonstration sites established by GreenWood Resources. The poplar demonstration sites were established at Hayden, ID, Stanwood, WA (Pilchuck), and Jefferson, OR (Figure 2.2.1). In addition to the poplar sites adjacent agricultural lands at Pilchuck and Jefferson were chosen for comparison. Brief physiographic information on the study sites are shown in the Table 2.2.1.

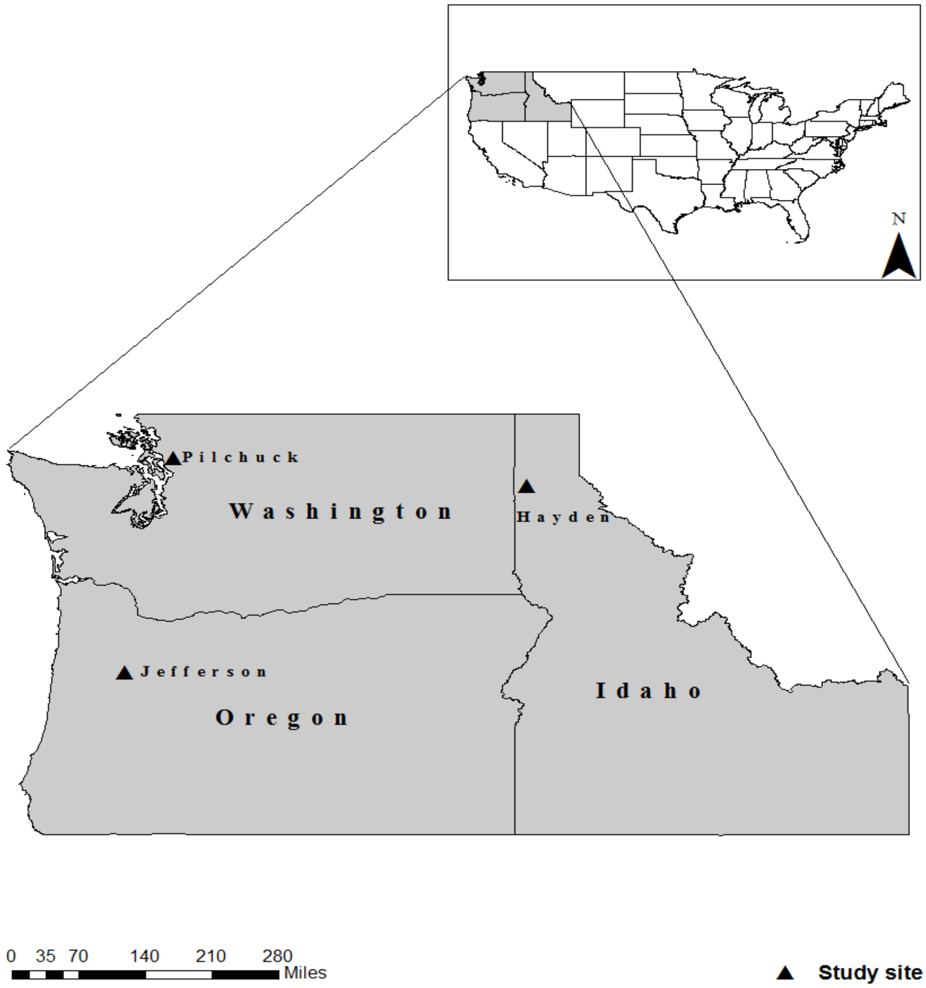

Figure 2.2.1 Study sites in Idaho, Washington and Oregon.

Table 2.2.1. Physiographic information about study site.

Site	Parental material	Soil type	Mean annual precipitation (mm)
Hayden	Volcanic ash and loess over outwash	Avonville fine gravelly silt loam	560-660
Pilchuck	Glacial drift derived from sandstone and siltstone with an admixture of volcanic ash	Cathcart loam	760-1520
Jefferson	Silty alluvium	Amity silt loam	1020-1270

Source: Soil Survey Staff 2015

2.2.2 EXPERIMENTAL SETTING

Poplar was planted in spring 2012 in Hayden and Jefferson, and in spring 2013 in Pilchuck. Eight random points were identified in each poplar site; and 2 to 4 points were identified in each agricultural site to install suction lysimeters (Soil Moisture Equipment Corp., Santa Barbara, CA) and soil moisture sensors. Suction lysimeters were installed to extract soil water at 50 cm from the soil surface according to manufacturer's recommendations . Installation included augering to 50 cm, adding a slurry of silica flour, inserting the pressure tested lysimeter, backfilling with screened soil and capping with a bentonite plug. The depth was selected to be at or below 80% of poplar fine roots. We used Gale & Grigal's (1987) asymptotic nonlinear function and the mean root distribution coefficient, (β=0.967) (Jackson et al., 1997) to calculate a depth of 50 cm above which 80% of poplar roots would occur. We assumed that water at this depth was likely to drain to ground water under wet conditions.

We used volumetric moisture and matric potential sensors to measure soil water equivalent depth. Soil moisture sensors (5TM, Decagon Devices Inc., Pullman, WA) were installed horizontally at 15 cm and 30 cm below the soil surface to record soil moisture in 4 random lysimeters installation points on the poplar site and 2 random lysimeters installation points in the agricultural site. Similarly, soil matric potential sensors (MPS-2, Decagon Devices Inc., Pullman, WA) were installed at 50 cm in 4 random lysimeters installation points in the poplar site and 2 random lysimeters installation points in the agricultural site. Matric potential readings were later converted to volumetric moisture using van Genuchten model (van Genuchten, 1980). A data logger (Em 50, Decagon Devices Inc., Pullman, WA) recorded hourly readings from these sensors.

2.2.3 SAMPLE COLLECTION AND ANALYSIS

We collected soil water samples seasonally (summer, fall, winter and spring) from summer 2013 to summer 2014. Suction lysimeters were placed under tension at 70 kPa for 24 hours. Up to 125 ml of water was collected from each lysimeter and transported on ice to the laboratory where they were frozen to -5^{0}C within 24 hours. Frozen samples were then sent to the Logan Forestry Sciences Laboratory, (Logan, Utah) to determine NH_4^+, NO_3^- and PO_4^{3-} concentration colorimetrically using a Lachat instrument (QuickChem 8500 Series 2 Flow injection Analysis System, Loveland, CO).

Four soil samples from each poplar site and three from each agricultural site was collected for particle size analysis (PSA) and pH measurement. Soil samples were collected from three depths; 0-10 cm, 20-30 cm and 40-50 cm to represent a soil column in the poplar and agricultural sites. PSA was performed using hydrometer methods described by Bouyoucos (1962), Gee and Bauder (1986), and ASTM (2000). We assumed a negligible amount of $CaCO_3$ and/or soluble salts present in our soil samples. The percent of clay, silt, and sand was calculated using the graph of log particle diameter size and cumulative percent of fine particles from GetData Graph Digitizer version 2.26.0.20 (Fedorov, 2013). The percent of particle size was averaged by depth and those values were used to predict the van Genuchten soil parameters (van Genuchten, 1980) and saturated hydraulic conductivities using Rosetta program in HYDRUS-1D version 4.16.0090 (Schaap et al., 2001). Rosetta output supplied residual soil water content (θ_r), saturated soil water content (θ_s), the α parameter in the soil retention function, the exponent in the soil retention function (n) and saturated hydraulic conductivity (K_s). The van Genuchten model uses the parameters to calculate the volumetric moisture content from matric potential readings. The volumetric water content was used to calculate the equivalent depth of water stored in the soil profile from 0 cm to 50 cm. The change in soil water storage was calculated for each depth increment, 0-20 cm, 20-40 cm and 40-50 cm by subtracting final volumetric water content from initial volumetric water content. The total sum of the change in soil water storage over the entire monitoring depth gave the change in equivalent depth of water stored in the soil profile from 0-50 cm.

The soil pH was measured using 1:1 H_2O pH (Soil Survey Laboratory Staff, 2004). The 1:1 H_2O pH was performed using 10 grams of soil weighed into plastic cup and adding with 10 ml of triple distilled water. Finally, the pH probe was inserted after stirring for 30 seconds and reading was noted immediately after another 30 seconds.

2.2.4 ESTIMATION OF WATER DRAINAGE AND NUTRIENT FLUX

Soil water drainage below 50 cm of soil surface was calculated using the water balance method as shown in equation 1.

$$\mathbf{DR} = \boldsymbol{P} + \boldsymbol{I} - \boldsymbol{ET} + \boldsymbol{\Delta W} \tag{1}$$

Where DR is soil water drainage below 50 cm from soil surface, P is the precipitation, I is irrigation, ET is evapotranspiration and ΔW is the change in the equivalent depth of water stored in soil profile; 0 -50 cm. We assumed there was no or negligible water runoff in our sites. The weather data were obtained from the nearest meteorological station. The nearest meteorological site used for Hayden, was Green Bluff, Spokane county (Lat: 47.81469, Lng: -117.29939), for Jefferson it was Corvallis, East (Lat: 44.5696, Lng: -123.23812) and Pilchuck it was WSU Mt. Vernon (Lat: 48.43849 and Lng: 122.38566). For each site we first calculated reference evapotranspiration using FAO Penman-Monteith equation from net radiation, soil heat flux, mean daily air temperature, wind speed, saturation vapour pressure deficit, slope vapour pressure curve and pyscrometric constant based on weather data (Allen et al., 1998). We used average monthly crop coefficient of hybrid poplar as calculated in Gochis & Cuenca (2000) assuming hybrid poplar were not under water stress at all time. However, during dormant seasons from November to March assuming 0% growth stage we used 0.15 crop coefficient for hybrid poplar (AgriMet, 2015). At Pilchuck and Jefferson agriculture sites we used crop coefficient of hay grass and winter wheat as given in Allen et al. (1998). Finally, the drainage below 50 cm was calculated using the average precipitation, evapotranspiration and change in soil water storage value for each site and management. Hayden was the only site with an irrigation applied during dry summer until early fall.

The Nutrient leaching below 50 cm was a product of nutrient concentration of soil water at 50 cm and water drainage (DR) below 50 cm as shown in the Equation 2.

$$\boldsymbol{Nutrient\ leaching = Nutrient\ Concentration \times DR} \qquad (2)$$

The nutrient concentration used in Equation 2 was the average concentration of all water samples obtained during the seasonal sampling. The average seasonal and annual, soil water drainage and nutrient concentration were used to calculate average seasonal and annual nutrient leaching in all sites and management. We used solstice and equinox dates to define the season. Therefore, each management type had single soil water drainage and nutrient leaching measurements of NH_4^+, NO_3^- and PO_4^{3-} for each season.

2.2.5 DATA ANALYSIS

The effects of independent variables; site, management and time (seasonal and annual) for nutrient concentration were studied using unbalanced factorial design. The unbalanced design included three sites with poplar in Hayden, Pilchuck and Jefferson and two sites with agricultural management in Pilchuck and Jefferson. The statistical analysis was performed using the car package (Fox & Weisberg, 2011) for ANOVA. Differences within site, management and time were analyzed using the lsmeans package at 0.05 significance level (Lenth & HervÃ, 2015). However, for soil water drainage and nutrient leaching single average seasonal and annual value was used for each management for comparision. All analyses and graphing were performed using R studio version 0.98.1103 (R Core Team, 2014).

2.3 RESULTS

2.3.1 SOIL CHARACTERISTICS

Soil physical and chemical parameters varied by site, management and depth. The average PSA showed that the Hayden site has silt loam, Pilchuck sites have loam and sandy loam in poplar and agriculture and Jefferson sites have silt loam in both poplar and agriculture management (Table 2.3.1). The average hydraulic conductivity was found to be highest at Pilchuck agriculture sites, (0.55 m day^{-1}) and lowest at Jefferson poplar sites, (0.14 m day^{-1}). The pH measurement showed all the sites were slightly acidic ranging between 4.98 and 6.75 (Table 2.3.1).

Table 2.3.1. Soil physical and chemical properties.

Site and Management	Depth (cm)	Soil properties†								
		Sand (%)	Silt (%)	Clay (%)	θ_r (m^3m^{-3})	θ_s (m^3m^{-3})	α (m^{-1})	n	K_s (m day^{-1})	pH
Hayden Poplar	0-15	28.68 (4.72)	59.3 (5.41)	12.02 (0.80)	0.05	0.42	0.45	1.68	0.31	5.20 (0.57)
	20-35	31.80 (4.90)	57.61 (4.14)	10.59 (1.71)	0.05	0.42	0.47	1.67	0.38	5.18 (0.35)
	40-50	31.7 (4.88)	58.98 (4.17)	9.32 (1.76)	0.05	0.42	0.47	1.68	0.44	5.45 (0.42)
Pilchuck Poplar	0-15	45.82 (6.41)	44.15 (4.61)	10.03 (1.94)	0.04	0.40	0.97	1.52	0.26	5.0(0.24)
	20-35	48.143 (2.85)	44.33 (3.22)	7.52 (0.71)	0.04	0.40	1.10	1.50	0.35	5.36 (0.12)
	40-50	44.91 (12.85)	46.79 (12.76)	8.3 (1.05)	0.04	0.40	0.88	1.54	0.33	5.52 (0.25)
Pilchuck Agriculture	0-15	62.9 (3.39)	28.59 (2.28)	8.51 (1.45)	0.04	0.39	2.83	1.41	0.43	5.41 (0.08)
	20-35	66.1 (5.84)	29.18 (6.57)	4.72 (0.73)	0.03	0.39	3.44	1.42	0.62	5.60 (0.52)
	40-50	67.84 (4.90)	27.17 (5.76)	5.0 (1.03)	0.03	0.39	3.65	1.43	0.61	5.60 (0.23)
Jefferson Poplar	0-15	15.81 (4.92)	62.84 (4.30)	21.36 (2.71)	0.07	0.44	0.52	1.63	0.14	6.09 (0.82)
	20-35	16.43 (2.90)	63.55 (2.67)	20.03 (0.64)	0.07	0.44	0.50	1.64	0.15	4.98 (0.37)
	40-50	18.86 (5.85)	61.92 (5.27)	19.21 (0.86)	0.07	0.43	0.48	1.65	0.16	5.51 (0.26)
Jefferson Agriculture	0-15	18.92 (3.93)	59.75 (3.77)	21.33 (0.96)	0.07	0.44	0.51	1.63	0.14	6.75 (0.48)
	20-35	20.06 (0.64)	59.74 (2.12)	20.2 (2.75)	0.07	0.43	0.50	1.64	0.15	5.52 (0.52)
	40-50	14.71 (2.49)	58.35 (1.57)	26.95 (3.41)	0.08	0.45	0.64	1.57	0.12	5.62 (0.14)

† Number in the parentheses represents the standard deviation and θ_r= residual soil water content θ_s= saturated soil water content **α**= parameter in soil retention function **n** =exponent in the soil retention function and K_s =saturated hydraulic conductivity.

2.3.2 SOIL WATER DRAINAGE

Soil water drainage followed the pattern of precipitation distribution. The total precipitation received during the study period from summer 2013 to summer 2014 at Hayden, Jefferson and Pilchuck were 416 mm, 696 mm and 901 mm (Ag WeatherNet, 2015). Seasonal soil water drainage also followed the seasonal precipitation distribution pattern. Seasonal precipitation during the study period was higher in winter followed by fall, spring and summer in all sites. The average annual soil water drainage showed Pilchuck poplar had the highest drainage and Hayden poplar had the lowest drainage below 50 cm from the soil surface (Figure 2.3.1). However, differences between management types was observed in Jefferson and Pilchuck. Water drainage below 50 cm in agricultural management was lower than poplar at Jefferson and Pilchuck. In general, average seasonal water drainage were higher in winter and fall. The exception to this pattern was observed in spring in Hayden and Pilchuck poplar.The average spring and summer drainage in Jefferson and Pilchuck agriculture were negative. Similarly, average summer drainage at Jefferson poplar was negative. Negative drainage represents no water drainage below 50 cm during seasons mentioned and was indicated as zero drainage (Table 2.3.2).

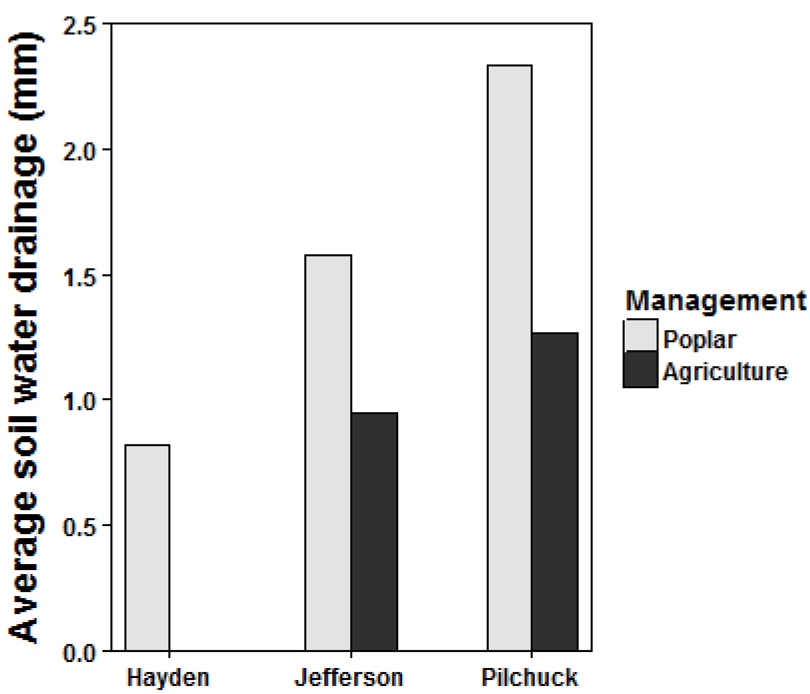

Figure 2.3.1. Annual average soil water drainage below 50 cm by site and management.

Table2.3.2 Average seasonal soil water drainge below 50 cm by site and management.

Site	Management	Season	Drainage (mm)
Hayden	Poplar	Winter	1.392
		Spring	1.274
		Summer	0.294
		Fall	0.294
Jefferson	Poplar	Winter	3.242
		Spring	1.402
		Summer	0.000
		Fall	1.668
Jefferson	Agriculture	Winter	2.481
		Spring	0.000
		Summer	0.000
		Fall	1.319
Pilchuck	Poplar	Winter	3.760
		Spring	2.390
		Summer	0.976
		Fall	2.190
Pilchuck	Agriculture	Winter	3.247
		Spring	0.000
		Summer	0.000
		Fall	1.821

2.3.3 NUTRIENT CONCENTRATION

Nutrient concentration showed high deviation. Ammonium and PO_4^{3-} concentrations were substantially lower than NO_3^- concentration. Both annual and seasonal mean concentrations of NH_4^+ and PO_4^{3-} were less than 0.4 mg L^{-1}, but the mean NO_3^- concentration showed greatest variation ranging from 0.01 to 98 mg L^{-1}. Mean annual concentrations of NH_4^+, NO_3^- and PO_4^{3-} showed two way interaction between site and management (Table 2.3.3). Mean annual NH_4^+ concentration in the Jefferson agriculture was 0.06 mg L^{-1} higher than the Jefferson poplar site. Mean annual NO_3^- concentration at the Jefferson agriculture site was 65 mg L^{-1} higher than the Jefferson poplar site, and 79.01 mg L^{-1} higher than the Pilchuck agriculture site (Figure 2.3.2). Similarly, mean annual PO_4^{3-} concentration at the Jefferson agriculture site was 0.063 mg L^{-1} higher than the Jefferson poplar site and 0.081 mg L^{-1} higher than the Pilchuck agriculture site.

Table 2.3.3. Analysis of Variance results for annual concentration of ammonium (NH_4^+), nitrate (NO_3^-) and orthophosphate (PO_4^{3-}). Effects evaluated include site and management. P-values less than 0.05 represent significant effects.

Effect	NH_4^+		NO_3^-		PO_4^{3-}	
	F	P	F	P	F	P
Site	0.69	0.5	97.08	<0.01	5.95	<0.01
Management	8.53	<0.01	189.69	<0.01	8.64	<0.01
Site x Management	6.96	0.01	119.85	<0.01	4.83	0.03

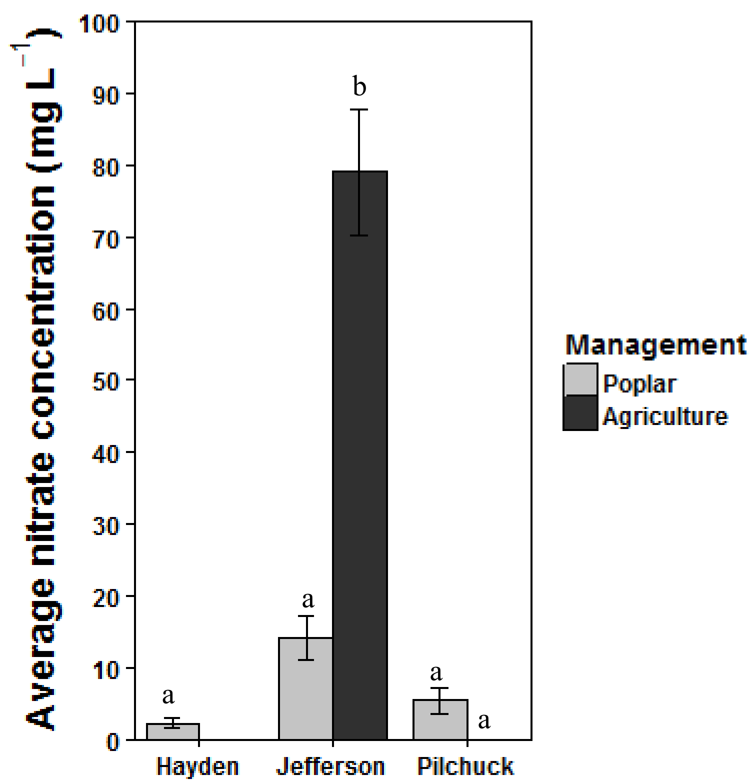

Figure 2.3.2. Average annual nitrate concentration. Different letters indicate significant ($p<0.05$) differences between site and management. Bars represent standard error of the mean. The average concentration of Pilchuck agriculture was 0.01 mg L^{-1} and Hayden had no agricultural site.

Average seasonal concentrations of NH_4^+ and PO_4^{3-} showed significant three way interactions between site, management and season. NO_3^- showed several significant two way interactions between site and season, site and management, and management and season (Table 2.3.4). The average seasonal NH_4^+ and PO_4^{3-} concentration by site and management are shown in the Figure 2.3.3 and Figure 2.3.4. Seasonal average winter and fall NO_3^- concentration was higher at Jefferson (Figure 2.3.5). Mean winter NO_3^- concentration was higher in agriculture (Figure 2.3.6). Similarly, mean seasonal NO_3^- concentration was higher at Jefferson agriculture. Jefferson agriculture exhibited highest average NO_3^- concentration across all seasons at 20 mg L^{-1} whereas average fall and winter NO_3^- concentration at Jefferson poplar were greater than 10 mg L^{-1}. Lysimeters did not always yield samples, especially when soil moisture was low. Due to difficulties obtaining water samples from each lysimeter, we averaged concentrations of all water samples obtained during seasonal sampling at each poplar and agricultural sites.

Table 2.3.4. Analysis of Variance results for seasonal concentration of ammonium (NH_4^+), nitrate (NO_3^-) and orthophosphate (PO_4^{3-}). Effects evaluated include site, management and season. Absence of interactions indicates they were insignificant and removed from the model. P-values less than 0.05 represent significant effect.

Effect	**NH_4^+**		**NO_3^-**		**PO_4^{3-}**	
	F	**P**	**F**	**P**	**F**	**P**
Site	0.43	0.64	97.82	<0.01	82.91	<0.01
Season	4.70	<0.01	5.43	<0.01	77.62	<0.01
Management	8.03	<0.01	246.97	<0.01	96.44	<0.01
Site x Season	3.96	<0.01	5.46	<0.01	31.92	<0.01
Site x Management	0.01	0.93	109.09	<0.01	122.03	<0.01
Management x Season	5.58	<0.01	2.99	0.04	48.30	<0.01
Site x Management x Season	3.57	0.04			40.53	<0.01

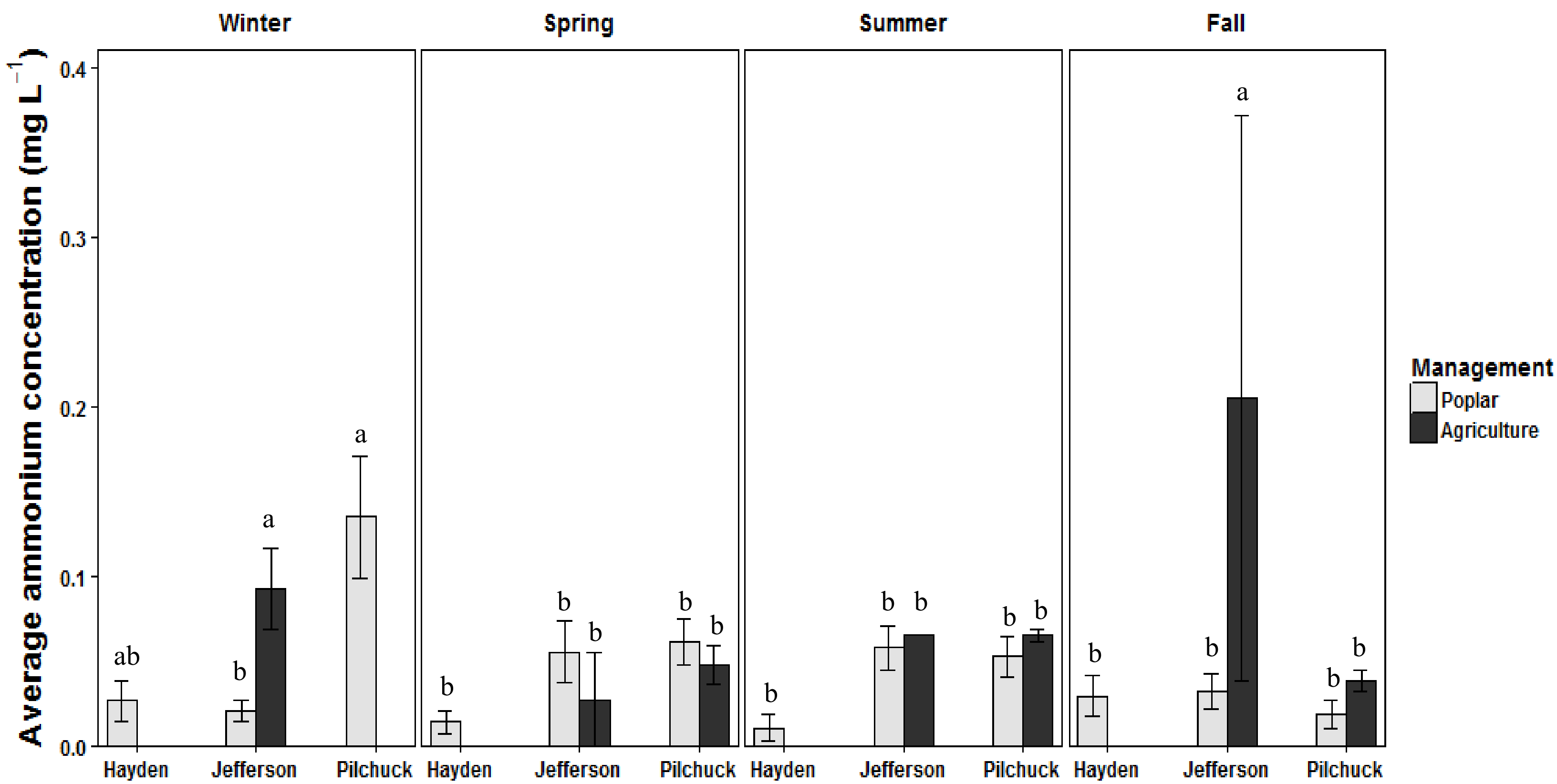

Figure 2.3.3. Average seasonal ammonium concentration for the two management types at each of the locations. Different letters indicate significant ($p<0.05$) differences between site and management within season. Bars represent standard error of the mean. Lysimeters did not yield water samples in winter at Pilchuck agriculture site and Hayden did not have an agriculture site. In summer, sample size (n=1) at the Jefferson agriculture sites.

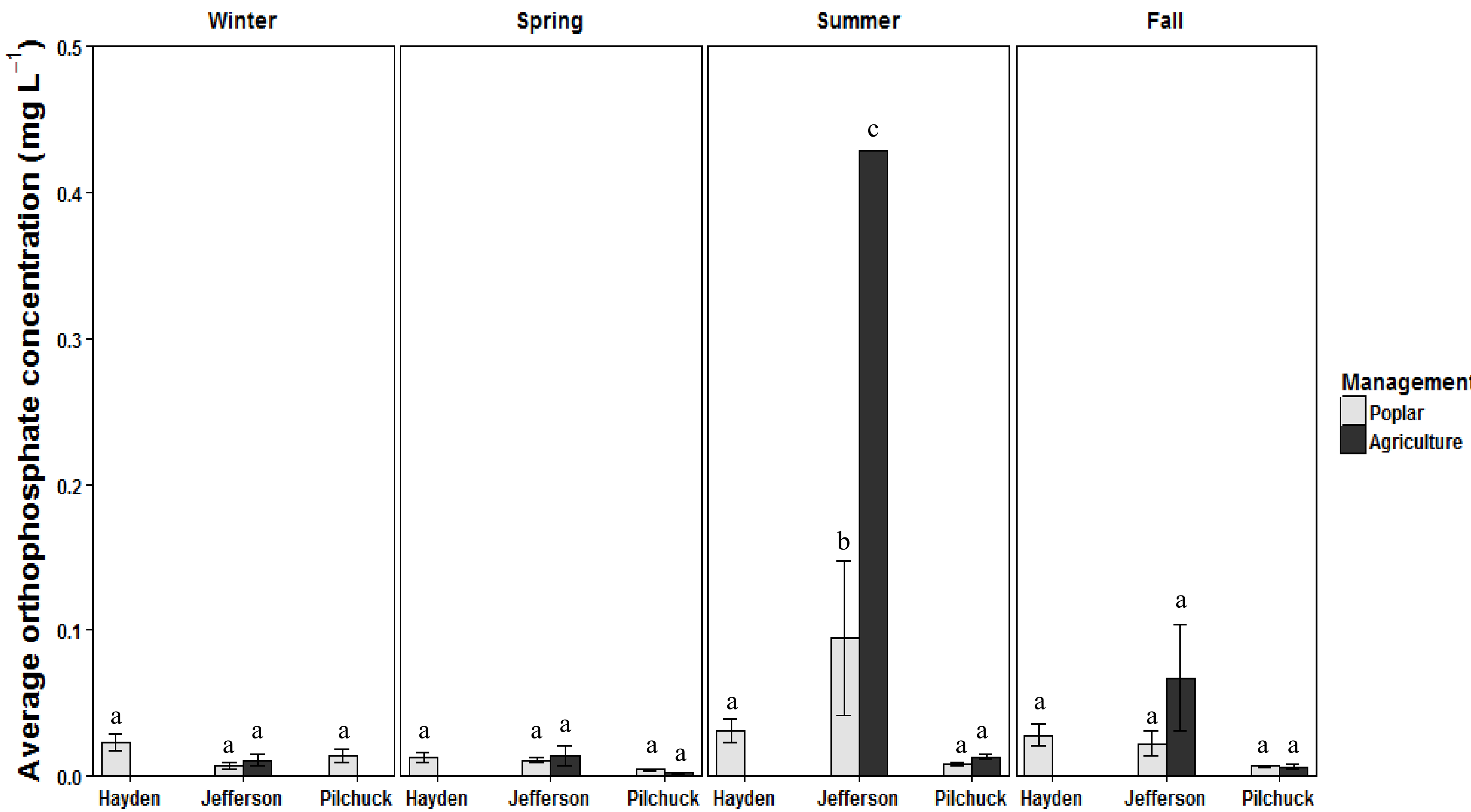

Figure 2.3.4. Average orthophosphate concentration in milligrams per liter. Different letters indicate the significant ($p<0.05$) differences between site and management within season. Bars represent standard error of the mean. Water samples were not obtained from the Pilchuck agriculture site and Hayden did not have an agriculture site. In summer, sample size (n=1) at Jefferson agriculture site.

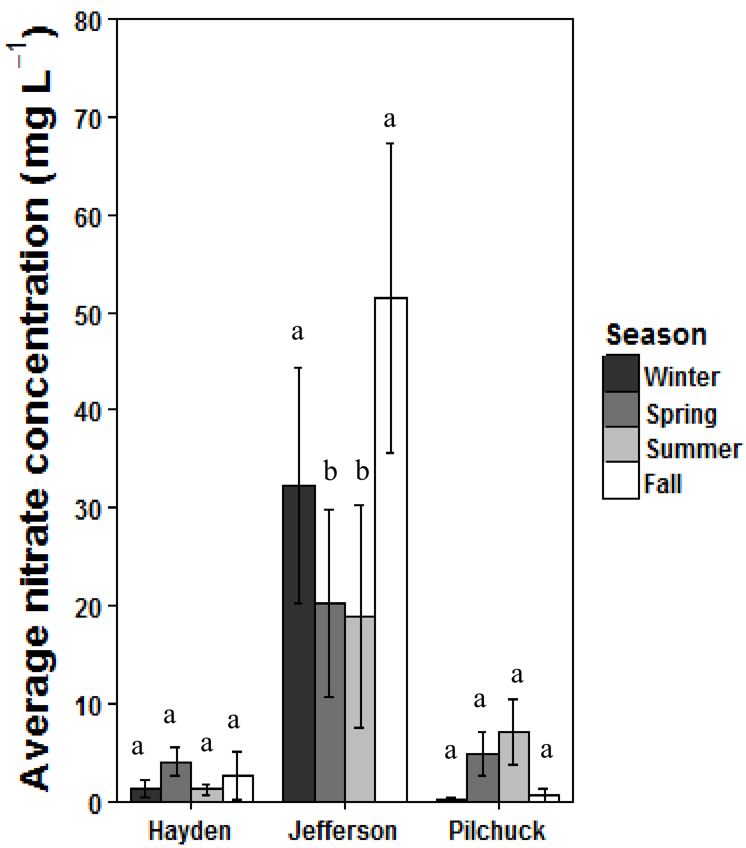

Figure 2.3.5. Average seasonal nitrate concentration for each site. Different letters indicate the significant ($p<0.05$) differences between seasons within each site. Bars represent standard error of the mean.

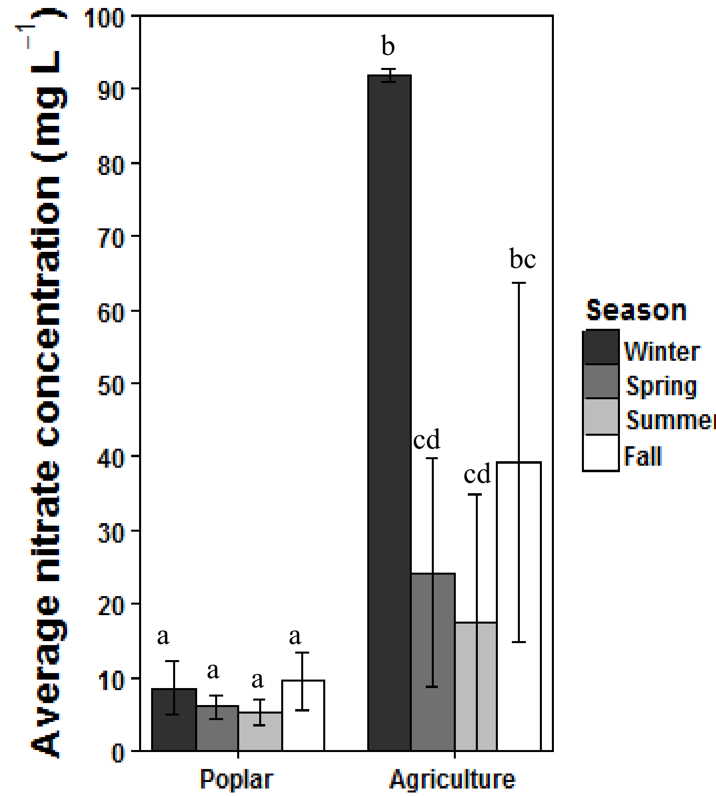

Figure 2.3.6. Average seasonal nitrate concentration of poplar and agriculture management. Different letters indicate a significant ($p<0.05$) differences. Bars represent standard error of the mean.

2.3.4 NUTRIENT LEACHING

Nutrient leaching varied by management and site type. At Jefferson, agriculture nutrient leaching was higher than poplar whereas at Pilchuck, agriculture was lower than poplar. However, for poplar management, nutrient leaching differed by site. NO_3^- leaching was highest at Jefferson poplar, but NH_4^+ and PO_4^3 leaching were highest at Pilchuck poplar. The average annual nutrient leaching was comparatively higher for NO_3^- than NH_4^+ and PO_4^{3-}. The annual mean nitrate leaching ranged from 0.121 NO_3^- g ha^{-1} to 892.980 NO_3^- g ha^{-1} (Figure 2.3.7). Jefferson agriculture had the highest NO_3^- leaching whereas Pilchuck poplar had the lowest. The mean annual NH_4^+ (Figure 2.3.8) and PO_4^{3-} (Figure 2.3.9) were less than 2 g ha^{-1}.

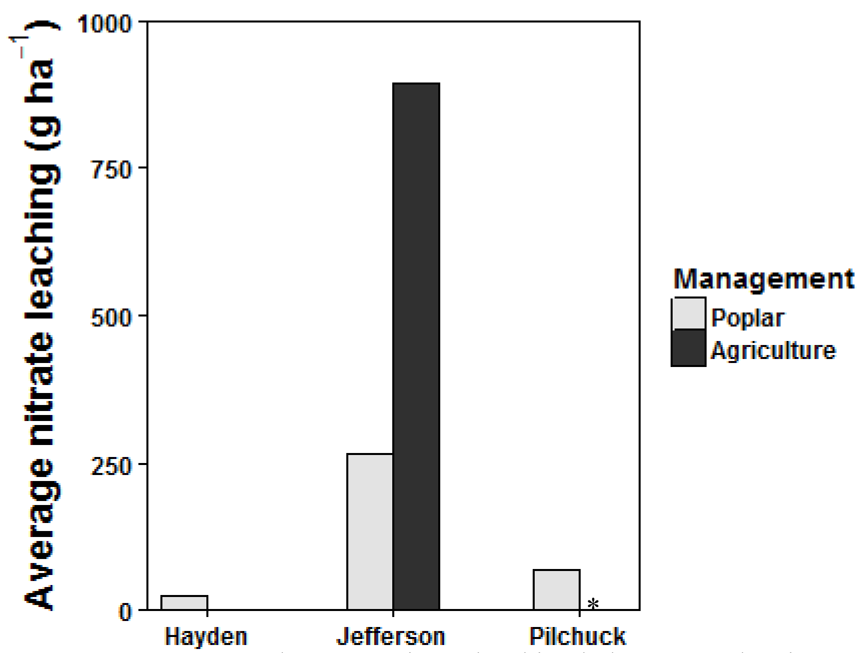

Figure 2.3.7. Annual average nitrate leaching below 50 cm by sites and management types. *Pilchuck agriculture had 0.121 NO_3^- g ha^{-1} leaching.

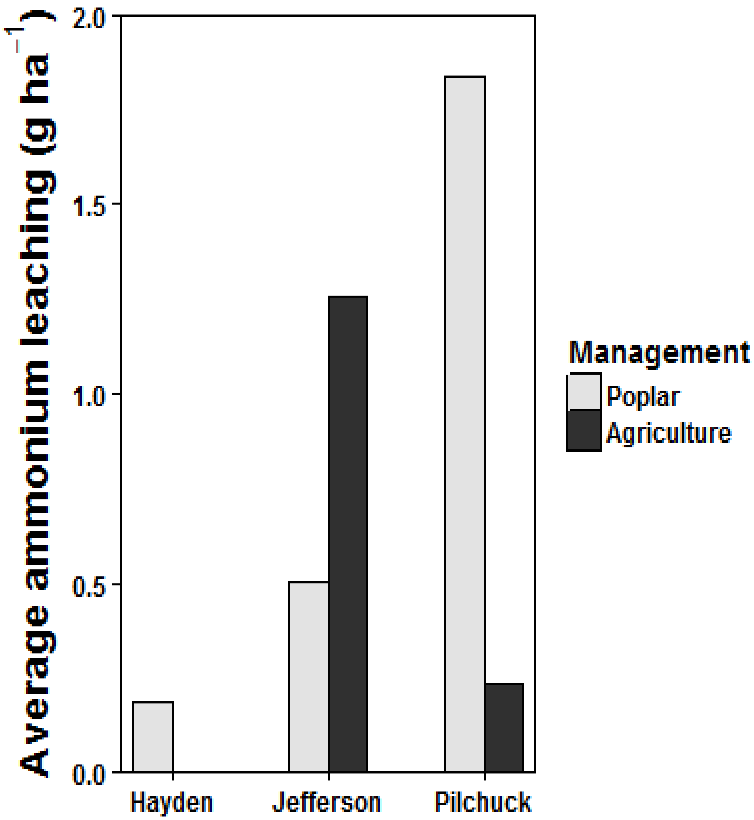

Figure 2.3.8. Annual average ammonium leaching below 50 cm by sites and management types .

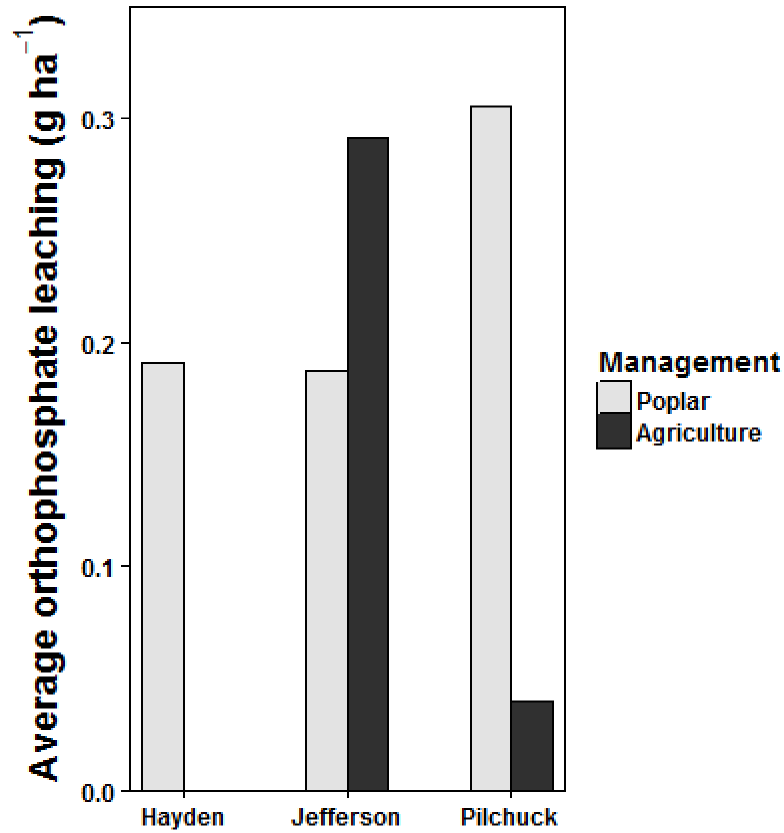

Figure 2..3.9. Annual average orthophosphate leaching below 50 cm by sites and management types.

Seasonal nutrient leaching was found highest when sufficient water was available for drainage. In general, winter and fall exhibited higher nutrient leaching except for NO_3^- and PO_4^{3-} in Pilchuck poplar and NO_3^- in Hayden poplar (Table 2.3.5). The mean summer nutrient leaching at Jefferson poplar and mean summer and spring nutrient leaching at Jefferson and Pilchuck agriculture were zero because there was no drainage water available for leaching. Seasonal mean NO_3^- leaching was higher than NH_4^+ and PO_4^{3-}, similar to mean annual nutrient leaching. The highest seasonal mean NO_3^- leaching was observed in winter at Jefferson agriculture, whereas the lowest mean NO_3^- leaching was in the fall at Pilchuck agriculture. But seasonal NH_4^+ and PO_4^3 leaching were less than 6 g ha^{-1} in all sites and managements. Seasonal average winter NH_4^+ leaching was highest at Pilchuck poplar (5 g ha-1) and average fall PO_4^{3-} leaching was highest at Jefferson agriculture (0.891 g ha-1).

Table 2.3.5 Average seasonal nutrient leaching of ammonium (NH_4^+), nitrate (NO_3^-) and orthophosphate (PO_4^{3-}) by site and management

Site	**Management**	**Season**	**Nutrient flux (g ha^{-1})**		
			NH_4^+	**NO_3^-**	**PO_4^{3-}**
Hayden	Poplar	Winter	0.376	18.994	0.323
		Spring	0.185	52.899	0.166
		Summer	0.093	17.692	0.181
		Fall	0.097	8.773	0.092
Jefferson	Poplar	Winter	0.690	495.271	0.217
		Spring	0.778	97.963	0.153
		Summer	0.000	0.000	0.000
		Fall	0.538	471.516	0.378
Jefferson	Agriculture	Winter	2.307	2279.703	0.272
		Spring	0.000	0.000	0.000
		Summer	0.000	0.000	0.000
		Fall	2.711	1292.215	0.891
Pilchuck	Poplar	Winter	5.085	9.964	0.522
		Spring	1.472	166.310	0.105
		Summer	0.377	73.240	0.441
		Fall	0.411	26.609	0.152
Pilchuck	Agriculture	Winter	NA	NA	NA
		Spring	0.000	0.000	0.000
		Summer	0.000	0.000	0.000
		Fall	0.698	0.364	0.120

2.4 DISCUSSIONS AND CONCLUSIONS

2.4.1 DISCUSSIONS

2.4.1.1 Soil water drainage

The drainage of soil water was influenced by precipitation amount and management type. The low drainage water in agriculture management in Jefferson and Pilchuck was caused by the high crop coefficient of agricultural crops compare to hybrid poplar. The high crop coefficient increases the crop water demand (evapotranspiration) thereby decreasing the amount of water for drainage. Similarly, seasonal drainage was affected by seasonal precipitation distribution pattern and crop growth stage. Null water drainage at Jefferson and Pilchuck in spring and summer is due to longer growing seasons that increases the evapotranspiration and cause water deficit mostly when precipitation is low and crops are unable to meet the crop water demand. In addition, low seasonal soil water drainage at Pilchuck agriculture site is due to thick root network developed by perennial hay grass compared to shallow root found in Pilchuck poplar. The deep rooted dense networks of roots have high water use efficiency thus reducing the water drainage (Davis and Pase, 1977). Despite low precipitation, Hayden had consistently positive leaching water available. Hayden received irrigation at 2 mm day^{-1} for 3 days a week during the growing period from summer to early fall. In addition, Hayden had precipitation in the form of snow from late fall to early spring. Snow melt increases infiltration in excess of 100 mm in a snow melting period (Iwata, et al., 2010) and excess of water from irrigation adds high amount of water for infiltration. The constant supply of water could be the reason of consistent soil water drainage annually and throughout all seasons at Hayden.

A water balance method was chosen as the primary method over Darcy's law to calculate soil water drainage. Our calculation of water flux using potential gradient were much higher, greater than 100% of precipitation on each site. We concluded, that potential gradients measured using electronic tensiometer were inconsistent and gave much higher gradient value. This ultimately gave us very high water flux. Further, the accuracy of the electronic tensiometer is ± 25% within the range of -9 kPa to

-100 kPa and increases as potential reading increases (Decagon Devices, 2014). Qualls, et al. (1999) also found higher water flux by 140% using Darcy's law from observed soil matric potential than water balance method. Hence, we concluded that the calculation of water flux using potential gradient using electronic water potential gives unrealistic readings.

2.4.1.2 Nutrient concentration

Large management effects on mean annual NH_4^+, NO_3^- and PO_4^{3-} concentration occurred due to high nutrient concentrations observed in the Jefferson agriculture field compared with poplar. Similarly, large management effect was observed for seasonal mean NH_4^+ concentration at Jefferson in winter and fall. Like wise, seasonal mean PO_4^{3-} concentration was significant due to of large management effects observed at Jefferson poplar and Jefferson agriculture in summer. Although summer mean concentration of PO_4^{3-} at the Jefferson agriculture site was significantly higher, only one sample was collected there during summer and a single water sample would not be sufficient to draw a statistical inference due to 0 degree of freedom. In summer when soils is dry it is difficult to get sufficient samples. However, at the Jefferson poplar site we theorize that during summer when plant growth starts to retard and the soil is dry, accumulations of phosphorous increases in soil. Saunders & Metson (1971) found higher concentration of phosphorous in summer due to slow growth of grasses and clovers and low moisture content in the soil. However, significant seasonal mean NO_3^- concentration occurred due to the large site effect observed at Jefferson in winter and fall, and management effect in agriculture in winter. Similarly, seasonal NO_3^- concentration between site and management was significant due to large magement effects observed at the Jefferson agriculture.

We hypothesize that average soil temperature, above 5 C during fall and winter at Jefferson and Pilchuck favored nutrient mineralization. However, the average seasonal winter and fall temperature at Hayden was lower than Jefferson and Pilchuck and the mean soil temperature was below 0.6 C in winter at 20 cm below the surface. The effect of temperature on nitrogen mineralization increases with warmer temperature (Chapin, et al., 2011). We speculate that higher nitrate leaching at Jefferson resulted from the high pH (Table 2.3.1) that favors nitrification (Haynes & Swift, 1986). The high mobility of the NO_3^- anion shows low interaction with the negatively charged soil matrix and hence has high mobility in the soil unlike NH_4^+, but PO_4^{3-} is highly reactive and less prone to leaching (Lehmann & Schroth, 2003). This also explains why NO_3^- concentration is higher than other nutrients and PO_4^{3-} concentration is almost constant in soil water through out sites and management.

Soil types and agricultural systems likely caused differences in nutrient concentrations between study locations. The soil at Jefferson is derived from a nutrient rich alluvium that contains organic matter deep in the soil profiles (Heilman & Norby, 1998 and Soil Survey Staff, 2015). The low nutrient concentration at Pilchuck was due to poor nutrient soil that was derived from sandstone and siltstone with an admixture of volcanic ash (Soil Survey Staff, 2015). In addition to the native fertility derived from site and parent material, Jefferson and Hayden plantations were established in a past agriculture land where residual fertilizer effects can be expected.

Different agriculture system at Jefferson and Pilchuck also explain management effects on soil water nutrient concentrations. At the Jefferson agriculture field, seasonal wheat was planted with fertilization whereas the Pilchuck agriculture had perineal hay grass without fertilization. The high past and current input of fertilizer to rich soil explains high nutrient concentrations at the Jefferson agriculture field. Excessive amounts of nutrient in leaching water can cause surface and ground water pollution (Schlesinger & Bernhardt, 2013) and speed up eutrophication of surface water (Carpenter et al., 1998). Energy crop systems must repair and not increase such water pollution in order to be considered sustainable.

Most previous studies show high NO_3^- concentration in leachate and runoff during establishment of SWRC when grown with different rates of fertilization (Mann & Tolbert, 2000 and Thornton et al., 1998). SWRC without fertilizer initially have high NO_3^- concentrations and subsequently decrease during plantation development (Goodlass et al., 2007and Schmidt-Walter & Lamersdorf, 2012). McLaughlin et al. (1985) studied the effect of ground cover on nitrate leaching in hybrid poplar and report above 150 mg NO_3^- L^{-1} in bare soils during initial growing seasons. Schmidt-Walter & Lamersdorf (2012) observed soil water concentrations of 17 mg NO_3^- L^{-1}. However, it is common to observe high NO_3^- concentration in a high nutrient input system (P Heilman & Norby, 1998) like Jefferson agriculture. Zhu et al. (2000) observed upto 75 mg NO_3^- L^{-1} concentration from winter wheat at 60 cm below the soil surface in nutrient input agriculture system.

2.4.1.3 Nutrient leaching

Nutrient flux is guided by both biological and mechanical properties of soil. Both water drainage and nutrient concentration were major driving forces of nutrient leaching. The high annual average NH_4^+ leaching at Pilchuck poplar suggest high mineralization of organic matter. The low annual average NO_3^- leaching at Pilchuck poplar suggest either nitrification is low or if nitrification is occurring then it is being lost through relatively high denitrification. We speculate that in fall and winter when soil moisture increases it creates conducive environment to mineralize the organic nitrogen. However, due to the coarse textured soils found at Pilchuck, it exhibits low nitrifaication rate. Zak et al. (1998) found net low nitrification in coarse textured soils in an oak ecosystem. In addition, in a nitrogen limited site, nitrification is restricted to preserve nitrogen (Miegroet & Cole., 1985). The other factors that could favor high NH_4^+ leaching could be high mobilization of NH_4^+ at Pilchuck poplar site due to larger particle size of soils (Table 2.3.1). Smaller particle size retains the nutrient tighter than larger soil particle size (Chapin et al., 2011). Comparatively nutrients leaching was higher at Jefferson on both agriculture and poplar sites. The high nutrient leaching at Jefferson sites could be due to the combination of nutrient rich sites and high soil water drainage. The low nutrient leaching at the Pilchuck agriculture site could be due to well-developed root systems of hay grass that are efficient at nutrient acquisition (Beale & Long, 1997). Seasonal nutrient leaching was more pronounced by the combination of high drainage volume and high nutrient concentration in all sites and management.

Our finding of nutrient leaching were considerably lower than other studies (Thornton et al., 1998 and Nikièma et al., 2012) . A study by Thornton et al. (1998) found up to 35 kg NO_3^- ha^{-1} loss as leaching whereas Nikièma et al. (2012) found annual leaching loss of 54 kg NO_3^- ha^{-1} from hybrid poplar. The highest leaching loss of NO_3^- at Jefferson was less than 1 kg NO_3^- ha^{-1} in poplar and in agriculture it was less than 2.5 kg NO_3^- ha^{-1} . The high NO_3^- leaching by Thornton et al. (1998) was due to the effect of fertilization whereas the high NO_3^- leaching by Nikièma et al. (2012) at poplar was due to high nitrification and intense application of cow manure. In a nutrient input system like in Jefferson agriculture, the high leaching is obvious to expect. Francis et al. (1995) found the higher NO_3^- leaching from winter wheat agriculture system in similar soil type. The measured NO_3^- leaching varied from 14-102 kg NO_3^- ha^{-1} $year^{-1}$ (Francis et al., 1995).

Long term monitoring throughout the complete lifecycle of SWRC is important to understand the trend and factors affecting nutrient leaching. This will help us understand the dynamics of nutrient leaching depending upon the site types and guide appropriate timing for soil amendments. Long term monitoring will also help to minimize water pollution and efficient use of fertilizer to reduce economic loss. Ultimately, it will help to establish hybrid poplar as a viable alternative energy resource in the Pacific Northwest.

2.4.2 CONCLUSIONS

Nutrient leaching varied by site nutrient status, management and available drainage water. Depending on site environmental condition, impact on nutrient leaching from hybrid poplar is either low or high compare to the agricultural system during the initial period of the plantation. In a nutrient rich site, an agriculture system is expected to have high nutrient leaching whereas in nutrient limited site, lower nutrient leaching is expected in agriculture compared to poplar. The high nutrient leaching at the nutrient rich agriculture site was due to conventional tillage farming practices in addition to fertilization effect. However, at nutrient limited agriculture site the low nutrient leaching was due to well developed root of perinnial hay grass compare to less established roots of poplar. Likewise, irrigation increases nutrient leaching. Sites with a constant water supply via irrigation increases drainage water thereby increasing nutrient leaching. We concluded, that well developed root retains nutrients and increase water use efficiency thereby decreasing nutrient leaching.

Protecting soil and water quality is an important sustainable criteria that will help to establish hybrid poplar as a major bioenergy resource. The variation of nutrient leaching by site and management found in the Pacific Northwest will help to identify vulnerable sites that are prone to leaching and guide necessary management guidelines that will ensure growing hybrid poplar does not degrade soil and water quality. It is expected that in longer period during the complete life cycle of hybrid poplar nutrient leaching will eventually drop down as root systems get well established.

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