Nitrogen Dynamics in a Harvested Rocky Mountain Catchment

by

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Author's Declaration

I hereby declare that I am the sole author of this thesis. This is a true copy of my thesis, including my final revisions, as accepted by my examiners.

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Abstract

While the impacts of forest harvesting on nitrogen (N) are largely well documented, changes to watershed N following harvesting are difficult to characterize within steep, mountainous terrain creating uncertainty for downstream ecosystem and public health. For drinking water supplies, increases in source water N can reduce disinfection efficiency and increase oxidant demand. In conjunction with increases in other nutrients, changes in source water N concentrations and species can affect the trophic status of drinking water supplies, potentially leading to further treatability challenges including cyanobacterial blooms that have the potential to lead to service disruptions. Thus, an understanding of changes in key nutrients like N is critical for source water protection and management in the drinking water industry, particularly as disturbances occur in key source watersheds. Mountainous terrain can create different hydro-climatic regions that govern watershed export of N after forest harvesting. Physiographic features such as hillslope positioning and aspect can not only create strong spatial variation in, but also be used to categorize radiation, temperature, and nutrient turnover therefore governing post-disturbance catchment exports of N.

The broad goal of this research was to explore the role of physiography (hillslope positioning and aspect), on regulating post-harvesting N production and transport into streams in the eastern slopes of the Rocky Mountains in Alberta, Canada. A combined approach employing the measurement of key soil N species (laboratory analysis), N

availability (ion exchange membranes), pore water N (suction lysimeters), and streamwater N species (historical data) allowed for a robust insight into how different fractions of N behave both spatially, and temporally.

Hillslope positioning (upper vs riparian) and aspect (north- and south-facing) were found to be important factors in N cycling. South-facing riparian zones showed greater potential nitrification, NH_4^+-N, NO_3^--N, available NH_4^+-N, available NO_3^--N, pH, TC, TN, and C/N ratios, and lower potential ammonification than any other locations investigated suggesting that these sites are more biogeochemically active and may contribute more to streamwater N than north-facing riparian zones. Compared to other types of forest disturbance (i.e. wildfire) that are common in nearby watersheds, clearcut harvesting did not produce a large impact on hillslope soil N availability or watershed scale production of N in 2016 (1st full growing season after harvesting). While a short transient pulse of streamwater NO_3^-, TDN, and TN was observed during a short series of rainstorms in the 3 to 4 spring months after harvesting, no harvest-associated effects on stream N export dynamics were detectable prior to, or 1.5 years afterwards. These findings support the notion of high potential watershed and ecosystem resistance to harvest impacts on N regimes in this region.

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Finally, I would like to thank my incredible fiancé Lisa. I could not have done this without her support.

Dedication

For my father, David Stewart, who continues to inspire and motivate me every day.

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Chapter 1: Introduction

Forested headwaters in the eastern slopes of the Rocky Mountains produce the majority of water supplies for Alberta's communities (Emelko et al., 2011). This region is also important to the province because beyond supporting public recreation, it supports many ecosystem services including non-renewable (mining, petrochemical) and renewable (forestry) resource development which help support Alberta's society, economy, and environment. Timber harvesting remains an extensive industry in this region, however, despite extensive research in many forested regions of North America, many knowledge gaps regarding the broader range of watershed impacts (i.e. changes in streamflow, water quality, etc.) resulting from forest harvesting still exist. For example, while harvesting effects on important nutrients such as nitrogen (N) have been studied extensively in many forest regions, it is difficult to generalize their magnitude and longevity. This is because physiographic and hydro-climatic factors such as topography, energy, and moisture regulate N production at the watershed scale. Their contributions to regulating post-harvesting N production and transport into streams are neither well-documented nor -understood. This information is needed for water treatment managers to understand their system and further recognize how different land disturbances may impact and potentially threaten downstream N treatment processes. Also, changes to streamwater can reduce disinfection efficiency and contribute to changes in the trophic status of drinking water supplies, potentially leading to further treatability challenges including cyanobacterial blooms that have the potential to lead to service disruptions.

Although substantial research has focused on harvesting effects on N, conflicting impacts have been reported; specifically, both increases and decreases in total soil N or soil NH_4^+-N have been demonstrated after harvesting (Jerabkova et al., Prescott et al., 2011). Similarly, it is difficult to draw generalizations about harvesting impacts on stream water N when there is high variability of results from study to study. While Palviainen et al. (2014) suggested that approximately 30% of watersheds by area may need to be harvested before detectable effects on N in headwater streams occur, such thresholds depend on a broad range of factors such as precipitation regime, topography, and vegetation type. For example, while harvesting often increases both watershed runoff and N exports, some studies have reported decreases in N after harvesting(Jerabkova et al., 2011). Differences in harvesting methods can also exert considerable influence on N cycling (Kreutzweiser et al., 2008). For example, disposal of logging slash (spreading or burning) governs the organic litter pool available for decomposition and mineralization. However, most studies on N turnover after harvesting have reported increases in nitrification and soil NO_3^--N concentrations; this is because, regardless of slash disposal practices, all harvesting practices leave behind some slash (Kreutzweiser et al., 2008). In general, harvesting can increase runoff creating a greater connectivity between the hillslopes and streams because of increased net precipitation, soil moisture storage, and increased surface/sub-surface hillslope runoff (Burton 1997; Jones et al. 2000; Troendle & King 1987). These changes can lead to increased NO_3^- transport within the soil and can cause water quality changes in connected surface waters (Schindler, 2012). In some cases, the increased NO_3^- in receiving streams may even adversely affect drinking water treatability downstream (Futter et al., 2010); particularly for subsurface supplies, requiring changes to existing infrastructure.

Generalizations regarding forest harvesting impacts on N exports across differing hydro-climatic regions are also limited because the impact due to physiography is not always considered in post-harvesting N studies. For example, the distribution of hillslope aspect within watersheds governs solar energy gain, soil temperature, and soil moisture storage (Fu & Rich, 2002), which all play key roles in regulating N cycling. South-facing hillslopes typically receive greater direct and diffuse solar radiation than north-facing slopes, and therefore tend to have lower soil moisture (Leij et al., 2004) and higher soil temperature (Fu & Rich, 2002). While variation in solar energy has been shown to drive N turnover (Gilliam et al., 2015; Hishi et al., 2014), no systematic studies reporting its effects on N cycling and transport to receiving streams after forest harvesting have been reported.

Key physiographic elements of forested mountain watersheds include hillslope, riparian, and stream (HRS) zones (Jencso et al., 2009), which govern the hydrologic and biogeochemical transport processes that influence nutrient (including N) export to receiving streams. While riparian zones may add nutrients through decay of vegetative matter, they are commonly referred to as buffer zones for their ability to remove nutrients, such as N through denitrification, microbial immobilization, or vegetative uptake (Dosskey et al., 2010; Rassam et al., 2006). While riparian zones generally comprise a small portion of total watershed area, they are directly connected to stream zones and therefore have a greater influence than hillslopes on the quality and quantity of matter that can be transported through surface waters out of the catchment (Pinay et al., 2015). Recent studies have shown that organic/mineral soil interface layers in riparian zones contain "hotspots" that control nutrient turnover (Burt et al., 2010; Darrouzet-Nardi & Bowman, 2011; McClain et al., 2003). These "hotspots" often occur at the intersection of critical hydrologic flow paths and microbiological processes that influence N cycling (Harms & Grimm, 2008; McClain et al., 2003). Notably, the role of these biogeochemical hotspots as important regulators of post-harvesting watershed N production has not been systematically studied.

While atmospheric inputs of N can be considerable, the majority of soil N in forests originates as organic N from trees and other vegetation (Kreutzweiser et al., 2008). The breakdown of dead vegetation by macrofauna helps to create soil organic matter (SOM) in the form of litter (Figure 1-1), which then undergoes mineralization by microbes, creating ammonia (NH_3) and later ammonium (NH_4^+) through ammonification. NH_4^+ then may return to the SOM pool through immobilization, adsorb onto clay particles, or transform into NO_3^- through nitrification. NO_3^- can be transformed by four biogeochemical processes, which therefore also determine the fate of mineral N; these are: assimilation, immobilization, denitrification, and leaching. Assimilation is uptake by vegetation reliant almost exclusively on inorganic N in the form of NO_3^- and NH_4^+ for growth (Porporato et al., 2003). One exception to this is in boreal forests where plants can also access organic sources of N (Näsholm et al., 1998). Removal of vegetation leads to a decrease in N demand by plants and microorganisms and thus, a decrease in losses of N from vegetative assimilation and immobilization until regrowth occurs, re-establishing these losses (Vitousek et al., 1979). Because NO_3^- is mobile in soil water and can be used as a terminal electron acceptor, NO_3^- can be lost by either leaching or denitrification (Bock et al., 1995). Leaching is of greater concern for NO_3^- because this can be an important source of N reaching streams in runoff. The supply of NO_3^- reaching streams is closely coupled with NH_4^+ availability and soil conditions (temperature, O_2, soil moisture) which would promote nitrification.

N cycling also varies considerably among broad forest vegetation types. For example, deciduous stands have a higher quality litter that promotes more rapid decomposition and turnover compared to coniferous litter (Futter et al., 2010; Scott & Binkley, 1997). Because coniferous litter takes longer to decompose, the potential impacts of land disturbance on N cycling and export may be longer lasting in conifer-dominated watersheds (Jerabkova et al., 2011), such as those that are typical of the Canadian Rocky Mountains.

Despite the extensive research on N in forests, effects of forest harvesting on soil and watershed N dynamics in high elevation Rocky Mountain catchments remain uncertain. Specifically, key knowledge gaps exist in understanding how these effects vary among landscape position within watersheds, and how variable hydrologic connectivity governs the magnitude of harvest impacts on hillslope soil and receiving stream N.

Accordingly, the broad goals of this research were to explore the role of higher order topographic and hillslope controls as key factors regulating post-harvesting N production and transport into streams. Chapter 2 describes a study investigating the effect of differences in 1) topographic controls on energy balance (north- and south-facing slopes) and 2) hillslope position (upper hillslope and riparian zones) affect N availability in soils after forest harvesting. Chapter 3 builds on the topographic framework presented in Chapter 2 to explore temporal dynamics of soil N production and transport to receiving streams. Lastly, in Chapter 4, the broader impacts of both Chapters 2 and 3 on improvements in scientific understanding of post-disturbance N dynamics are summarized. Recommendations for future research are also provided.

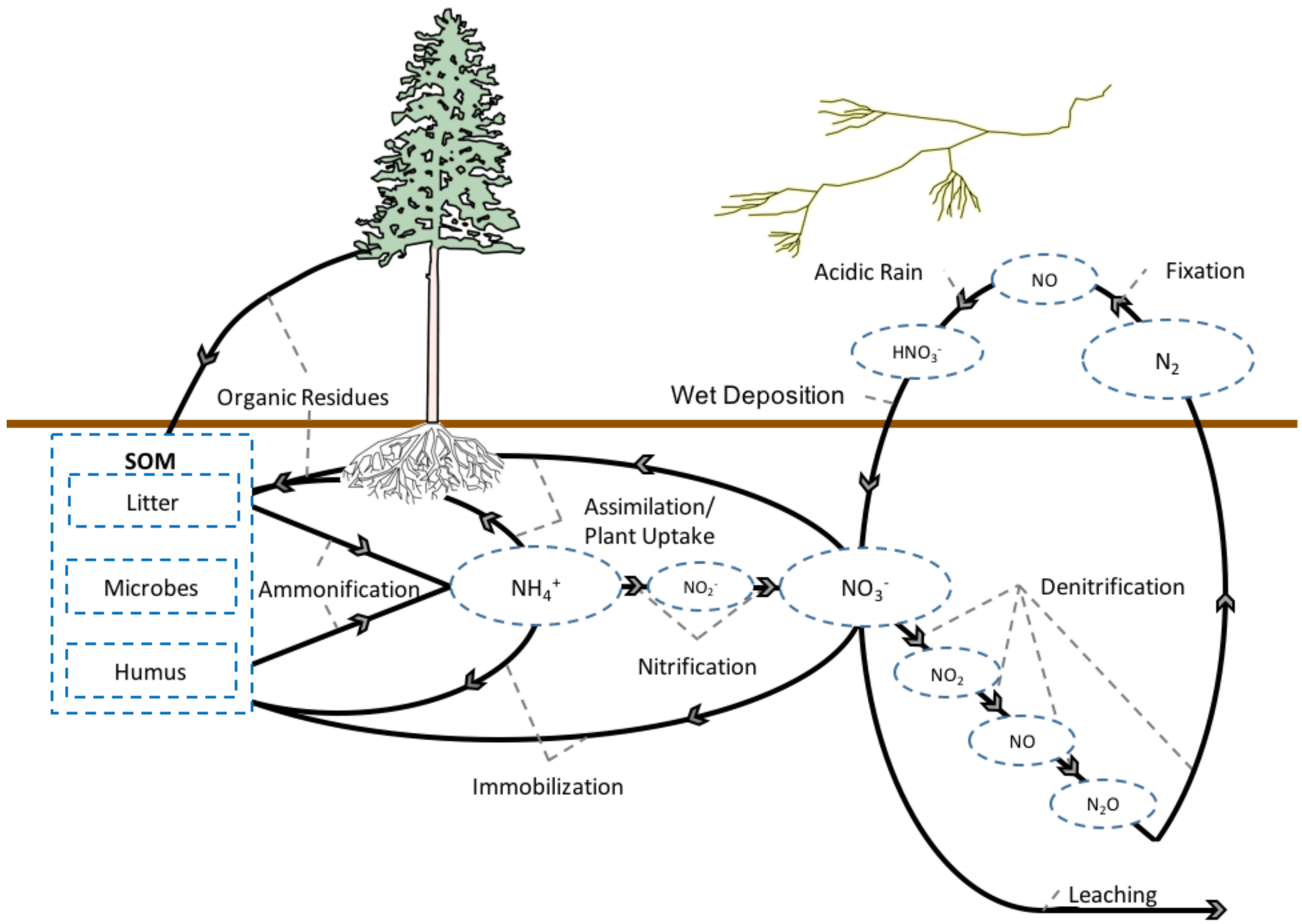

Figure 1-1 Nitrogen cycling in forests (after Ridolfi et al., 2003).

Chapter 2: Physiographic Controls of post-harvest soil N turnover and transport within a steep Rocky Mountain catchment

2.1 Introduction

Forested headwaters of the Rocky Mountains supply the majority of useable surface water for communities in Alberta, Canada (Emelko et al., 2011). In addition to the vast quantity of water originating from these headwaters, healthy forests also deliver high quality water by slowing runoff, stabilizing soils, filtering pollutants (Stein et al., 2005) and transforming nutrients (Sponseller et al., 2016). Land disturbance can affect water cycling in forests, thereby potentially affecting both regional water quality and quantity. One of the most extensive anthropogenic land disturbances that occur within Alberta's headwaters is timber harvesting. It can affect both physical (water, temperature, sediments, etc.) and chemical (nutrients, trace elements) water quality. Because N is the primary limiting nutrient regulating tree growth in many species, harvesting can cause complex changes to the ecosystem within watersheds (Jerabkova et al., 2011). Further, drinking water treatment managers must understand their system and how different disturbances can impact their source waters so that they can anticipate disinfection challenges and potential scenarios such as cyanobacterial blooms that may lead to service disruptions.

The impacts of forest harvesting on catchment hydrology (Burton, 1997; Jones et al., 2000; Troendle & King, 1987) and N turnover (Hope et al., 2003; Kreutzweiser, et al. 2008) have been studied extensively. While harvesting generally increases watershed runoff and exports of N, these effects vary substantially between forest types and hydroclimatic regions. Coniferous stands are more common at higher elevations, and respond differently than deciduous stands to land disturbance (Jerabkova et al., 2011). Impacts of harvesting on N turnover in coniferous stands are typically less pronounced compared to deciduous stands due to their poorer litter quality, which leads to lower N availability and less rapid N turnover by microbial populations (Futter et al., 2010; Scott & Binkley, 1997). Furthermore, different conifer species respond differently to land disturbance. For example, compared to White Spruce (*Picea glauca*), Lodgepole Pine (*Pinus contorta var. latifolia*) are able to maintain adequate foliar N nutrition and high tree productivity when organic material is reduced after forest harvesting (Kranabetter, et al., 2006). Part of the resilience of Lodgepole pine is attributed to ectomycorrhizal associations (Suillus species) that promote increased N uptake (Deckmyn et al., 2014). The effect of clear-cut harvesting on soil N in Lodgepole pine forests is reported to range from considerable to a low or no impact (Jerabkova et al., 2011). Overall clear-cut harvesting in coniferous stands has been shown to lead to minimal increases in NO_3^--N and NO_3^--N - as a proportion of soil inorganic N (SIN), and little to no impact on soil NH_4^+-N (Jerabkova et al., 2011). In addition, pH is an important factor in the response of these forests to harvesting;

soils with higher pH generally have greater NO_3^--N as a proportion of SIN, as well as greater nitrification rates (Jerabkova et al., 2011).

Many different hydro-climatic regions exist within steep mountainous terrain, and each of these regions has a chance of responding differently to land disturbance. Jencso et al. (2009) suggested breaking up physiographic elements within a watershed into hillslope, riparian, and stream (HRS) zones can provide important insights into watershed scale N cycling. Each of these zones is important from a N perspective. Upper hillslopes cover a large land area and are thought to drive the overall N supply, while riparian zones are often important for buffering inputs of water and nutrients to receiving streams (Dosskey et al., 2010; Rassam et al., 2006). When these three zones become hydrologically connected, that can transport matter (including nutrients), energy, and organisms between one another (Freeman, et al., 2007). Though they cover a smaller area, riparian zones can have a greater influence on the geochemistry of surface waters than hillslope regions (Pinay et al., 2015). However, water may also bypass riparian zones when connected through deep sub-surface pathways (Hinckley et al., 2012). Therefore, the impact of land disturbance on watershed geochemical exports can vary widely depending on the degree of land-stream coupling across different watersheds.

Many hydrological and biogeochemical processes that are controlled by hillslope position are also regulated by incoming solar radiation (insolation) (Fu and Rich, 2002). Insolation is controlled by topographical aspect, whereby south-facing hillslopes receive greater insolation (higher energy) than north-facing slopes. Variation in energy gain governs microclimatic and vegetative differences among contrasting slope aspects and have been found to significantly influence N turnover in mountainous hillslopes (Yimer, et al., 2006). For example, north-facing hillslopes tend to be cooler (Fu & Rich, 2002), with more dense vegetation comprised of fewer species (Gilliam, et al., 2014). The interaction of solar insolation with the physical soil conditions governing N turnover is not well understood, however.

Kusbach and Van Miegroet (2013) found that soil moisture had more of an impact on nutrient supply than soil temperature. Riparian soils are typically wetter than upper hillslope soils. However, soil moisture resulting from topographical aspect is more difficult to predict. Two studies exploring aspect controls on hillslope hydrology in Colorado found considerable differences in hillslope moisture storage between north and south-facing hillslopes (Ebel, et al., 2015; Hinckley et al., 2012). North-facing slopes generally have wetter soils with more connected flow through the soil matrix and south-facing slopes tend to have dryer soils with more rapid vertical transport (Hinckley et al., 2012).

While forest harvesting effects on watershed N export have been well researched, far less research has investigated physiographic controls such as topography, energy, and moisture governing variation in N turnover and transport after forest harvesting. Developing a better understanding of how variation in these landscape factors governs spatial variation in N turnover and the major forms of aqueous N after harvesting in topographically diverse watersheds is important because this knowledge can be directly used to design forest harvesting strategies to minimize impacts on N export.

The objective of this study was to explore the relative influence of 1) hillslope position (upper hillslopes vs riparian) and 2) radiation load among contrasting north and south-facing hillslope aspects (high and low solar energy gain) in regulating soil N turnover and mobile N (NO_3^-) one year after clearcut logging. It was hypothesized that south-facing hillslope aspects would receive greater solar insolation creating warmer soils with higher rates of N turnover, though dryer soils inhibit the transport of N. Conversely, cooler north-facing soils were hypothesized to have lower rates of N turnover with wetter soils that flush N more quickly from upper hillslopes to riparian areas. Riparian areas were expected to buffer N from entering the stream. To study these hypotheses, the influence of aspect as a driver of variation in soil conditions that govern N cycling (soil moisture and soil temperature) and their relationship with N availability was also explored one year after clearcut logging in the catchment.

2.2 Methods

2.2.1 Study Area

From January to October 2015, 167.9 ha of Star Creek watershed were harvested in the Crowsnest Pass of south-western Alberta (49°37′ N, 114°40′ W). Star Creek watershed is part of a larger monitoring network of the Southern Rockies Watershed

Project consisting of 34 hydro-climatic monitoring stations across 9 watersheds designed to study the consequences of large, landscape-scale disturbances after the 2003 Lost Creek Wildfire. These watersheds drain into the Crowsnest and Castle rivers to form the central headwaters of the Oldman River Basin, the highest water-yielding region of Alberta, Canada (Silins et al., 2014).

Three separate silvicultural treatments were applied across 3 sub-catchments within Star Creek watershed (Figure 2-1: clearcut (68.3 ha), strip-cut (43.9 ha), and partial cut harvesting (55.7 ha). Whole tree harvesting (WTH) was employed with all three treatments. Specifically, complete trees (bole, branches, and crowns) were skidded to landings using grapple skidders, where they were limbed and cut to length (stroke de-limber) for hauling to the mill. Excess slash was subsequently piled at landings and disposed of by burning the following winter.

Average annual precipitation for the region is 582.1 mm (1981-2010), with 30% falling as snow. June has the most (70.2 mm) precipitation and January has the least (34.8 mm). The mean annual air temperature is 3.6 ℃ with the highest average temperature occurring in July and August (14.3 ℃) and the lowest occurring in December (-7.4 ℃) (Environment Canada, 2016). In total, the Star Creek main study watershed drains 1035 ha and has elevation ranging from 1482 to 2631m.

The study is located within the montane cordillera ecozone with vegetation primarily dominated by lodgepole pine (*Pinus contorta* var. *latifolia*), with Douglas Fir (*Pseudotsuga menziesii* var. *glauca*) and Quaking Aspen (*Populus tremuloides*) interspersed. Stands with North-facing aspects typically have greater stand density with narrower individual crowns, while trees on south-facing slopes tend to be more widely spaced with larger individual crowns. Vegetation is rooted in well to imperfectly drained soils (Eutric or Dystric Brunisols) underlain by cretaceous shale and sandstone surficial geologic deposits (Bladon et al., 2008). South-aspect soils tend to have deeper rooting depths and thinner organic horizons.

2.2.2 Study Design

A factorial, post-hoc reference/impact study area design was used (Table 2-1). Study areas were selected by land condition (2 classes): undisturbed (reference), and clearcut harvest (impact). Four sites were located within each study area and included upper and lower (riparian) hillslope positions (2 hillslope positions) on both south- and north-facing aspects (2 aspect classes). The reference study area was selected downstream from the harvested sites in otherwise similar slope and aspect hillslope settings. Study plots were located within the 2x2x2 factorial design within generally similar hillslope settings. Slope angle was maintained visually, while slope aspect was kept within 15 degrees of North (0^o) and South (180^o) azimuth based on pre-layout preliminary plot location using a 20-m digital elevation model (1 m bare ground LIDAR re-sampled to 20 m) in ArcGIS 10.3. Distance from stream for upslope and riparian sites ranged from 400-450 m, and 5-25 m respectively. In each of the eight sites, five sampling plots (4 m^2) were established. Preliminary site and plot selection was completed using ArcGIS 10.3 followed by *in-situ* confirmation and final plot establishment. Ground surface micro-topography was gauged visually to constrain variability in N response by establishing plots on planer surfaces, avoiding concave/convex microsites (Figure 2-1).

2.2.3 Soil Nutrient Availability (Supply Rate) by PRS® Probes

The terms soil nutrient supply rate and availability are used interchangeably throughout this study. Soil nutrient availability was measured using Plant Root Simulator (PRS®) anion and cation probes which consist of exchange resin membranes mounted within plastic probes that were buried in the soil for a defined duration (Western Ag Innovations, Saskatoon, Canada). PRS® probe measurements reflect the relative supply rate of NH_4^+-N and NO_3^--N (μg) sequestered on each 10 cm^2 exchange window surface during the burial period (μg N 10 cm^{-2} duration of $burial^{-1}$, Figure 2-2). At each sample plot within the study area, three PRS® probe pairs (anion and cation) were buried vertically into both the organic-mineral layer interface and 20 cm into the underlying mineral layer for four consecutive 6-week burial periods beginning in early April 2016. Burial timing and duration were selected based on (i) timing of hydrological and biogeochemical processes (likelihood of runoff during the spring freshet and biogeochemical activity during the summer growing season), (ii) resin capacity (resins have a non-linear ion absorption rate), and (iii) field access logistics (access to sites during spring snowpack and soil frost preventing probe installation). Upon retrieval at the end of each burial period, probes were stored in sealed low-density polyethylene bags and new PRS® probes were placed in the same slots as the previous burial period to minimize sampling variation over subsequent measurement periods. Probes were thoroughly cleaned with a soft brush and Milli-Q® water (Millipore Corporation, Billerica, MA) within 48 hours to remove any residual soil. They were then shipped to Western Ag Innovations (Saskatoon, Canada) within 4 days of sampling. The PRS® probes in each sampling plot and depth were analyzed together by Western Ag Innovations (Saskatoon, Canada) as a composite sample (one value returned by the laboratory analysis) for a total of 80 samples per burial period. Samples were eluted with a 0.5 M HCl solution (Qian and Schoenau, 2002) and the extractions were analyzed colorimetrically for NH_4^+-N and NO_3^--N using a Technicon Autoanalyzer II (SEAL Analytical, Mequon, Wisconsin). Nutrient availability was expressed as the amount of nutrient adsorbed per surface area of the exchange resin over the time of burial (μg N 10 cm^{-2} burial $period^{-1}$, Qian and Schoenau 2002). While values less than 2 μg N 10 cm^{-2} duration of $burial^{-1}$ are considered below method detection limit, the large amount of replication in this study allow for meaningful results to be interpreted from these values.

2.2.4 Soil Characteristics and Geochemistry

Additional soil sampling was performed in August 2016 to provide information on soil attributes that may impact N cycling. For example, pH has been linked to increased nitrification rates (Shammas, 1986) and may indicate if mobile N is likely to form. C/N ratios act as indicators of substrate quality, and the degree to which a forested system is saturated or limited with respect to N (Currie, 1999; Hishi et al., 2014). NH_4^+-N and NO_3^--N enables comparing static soil N pools to time integrated availability measurements, and potentially mineralizable N indicates whether ammonification or nitrification is favoured in each study site. Integrated organic and mineral soil layers were sampled to a depth of 20 cm using a hand-held soil corer. Litter and duff layers of the forest floor were removed to expose mineral soil. Three sampling locations were randomly selected from the five sample plots within each site for a total of 24 soil samples. Samples were collected on August 13 and 14, 2016 and stored in sealed low-density polyethylene bags and transported to the laboratory for analyses within 3 days after collection. All soil analysis was carried out by the University of Alberta's Natural Resources Analytical Laboratory (NRAL). Soil samples were tested for pH (1:1 soil/water ratio), moisture content (oven dry method), and field capacity (0.01 MPa) determined from pressure plate soil water extraction. Total soil carbon (TC) and N (TN) concentrations were determined by dry combustion (Method 972.43) using a Costech EA 4010 Elemental Analyzer (AOAC, 2003). Soil NH_4^+-N and NO_3^--N were extracted using 2 M KCl before and after a 28-day aerobic incubation (Curtin and Campbell 2007, pp. 4-6) and analyzed colorimetrically on a SmartChem Discrete Wet Chemistry Analyzer. The difference in NH_4^+-N and NO_3^--N after and before incubation represent potential ammonification and potential nitrification, respectively. Mineralizable N is the sum of both potential ammonification and nitrification.

2.2.5 Soil Moisture and Temperature

Soil moisture and temperature were measured using combined dielectric volumetric water content and thermistor sensors (5TM, Decagon Devices, Pullman, WA) buried at both the organic-mineral layer interface and 20 cm into the mineral layer at each study site. Because of the similar geometry of 5TM sensors to PRS® probes (Figure 2-2), sensors (Em50, Decagon Devices, Pullman, WA) were buried at the same depth and angle as PRS® probes. Readings from the sensors were recorded every 20-minutes from May 1, 2016 through October 4, 2016. Disturbance by wildlife and equipment failures led to missing data at HNU (May 1 – 10, May 24 - 31, June 7 – 9, June 28 - July 6, August 11 – 23, September 1 – October 3), HSU (August 14 – September 21), and RSU (July 23 – October 3). Analysis was completed by removing data from all sites for durations of missing data, leaving 49 days across the duration of the field study.

2.2.6 Short-wave Radiation

Short-wave solar radiation (400 – 1100nm) was measured using four pyranometers (SP Lite 2, Kipp and Zonen, The Netherlands) mounted at 1.20 m off the ground at each upslope site (Figure 2-3). Three sensors were installed on May 31, 2016 at upslope reference sites (RSU, RNU) and at the north-facing upslope harvest site (HNU), and a fourth sensor was installed on August 24, 2016 at the south-facing upslope harvest site (HSU). Data for HSU prior to being installed was backfilled (estimated) using covariance with HNU.

2.2.7 Statistical Analysis

Soil nutrient availability was characterized by a strong right-skew and compared using the Kruskkal-Wallis median test, while soils data were compared using the two-sided student's t-test assuming unequal variance. Differences between potential ammonification and potential nitrification from the 28-day aerobic incubation were evaluated using a paired student's t-test. Soil temperature and water content, and short-wave radiation were analyzed over durations without missing data using a one-way ANOVA. Data analyses were performed using R statistical software (Version 3.4.1) and a significance threshold of $\alpha = 0.05$.

2.3 Results

2.3.1 Soil Nutrient Availability (Supply Rate) by PRS® Probes

Significant differences in NH_4^+-N supply rates were observed between reference and harvested sites (p<0.001, Table 2-2), with median supply rates of 6.51 and 4.44 μg N 10 cm^{-2} 177 days^{-1} (Table 2-2, Figure 2-4) respectively. While harvesting resulted in lower median NH_4^+-N supply rates in lower slope positions (p<0.001), statistically significant differences between harvested and reference sites in upper hillslope positions were not observed (p=0.756, Table 2-3, Figure 2-5). Slope aspect did not prove to be an influence on NH_4^+-N supply rates across harvested and reference sites (p=*0.808*, Table 2-4) in this study. Furthermore, NH_4^+-N supply rates did not show evidence of varying by aspect at either hillslope position for harvested or reference sites (p >0.096, Table 2-5, Figure 2-6) except for the upper hillslope positions in reference sites where NH_4^+-N supply rates were different among slope aspects

(p=0.019). Overall, NH_4^+-N supply rates were significantly different between depths (p=0.715, Table 2-6).

The more mobile NO_3^--N fraction of total N was similar among reference and harvested sites (p=0.825, Table 2-2) with median supply rates of 3.04 and 2.92 μg N 10 cm^{-2} 177 $days^{-1}$ (Table 2-2, Figure 2-4) respectively. Harvesting also did not prove to effect NO_3^--N in both upper (p=0.194) and lower (p=0.160) hillslope positions (Table 2-3, Figure 2-5). NO_3^+-N supply rates were 3.7x greater on south facing sites (7.01 μg N 10 cm^{-2} 177 $days^{-1}$) than north facing sites (1.88 μg N 10 cm^{-2} 177 $days^{-1}$) across both harvested/reference sites and slope positions (Table 2-4, Figure 2-6). However, while greater NO_3^--N on south facing slopes was strongly evident in lower slope positions on both harvested/reference sites ($p<0.004$), this same pattern was not observed in upper slope positions (Table 2-5) where NO_3^--N supply rates did not vary among slope aspect classes in the harvested sites (p=0.325) or were slightly greater on north-aspect slopes in reference sites (p=0.038). In contrast to NH_4^+-N, NO_3^--N supply rates were 87% greater in the deeper mineral layer (4.47 μg N 10 cm^{-2} 177 $days^{-1}$) than at the organic/mineral layer interface (2.39 μg N 10 cm^{-2} 177 $days^{-1}$, p=0.004, Table 2-6, Figure 2-7).

NH_4^+-N supply rates were generally greater than NO_3^--N supply rates (p<0.05) and comprised 60-68% of total available mineral N (NH_4^+ + NO_3^-) (Table 2-7).

2.3.2 Soil Characteristics and Geochemistry

Soil parameters were variable and did not differ across reference and harvested study areas, and instead varied among hillslope position and hillslope aspect with the lowest soil pH, TC, TN, and C/N ratios occurring on south-facing upper slope position soils, and the highest values for these same parameters occurring on south-facing riparian soils (Table 2-8).

However, NH_4^+-N, NO_3^--N, and potential nitrification were greater on harvested sites compared with reference sites, while potential ammonification was generally negative and significantly lower in harvested sites than in reference sites (Table 2-9). Differences in NO_3^--N, potential nitrification, and potential ammonification between harvest and reference sites were all significant ($p<0.05$, Table 2-10), while NH_4^+-N did not differ these sites ($p=0.288$, Table 2-10). Mean NH_4^+-N, NO_3^--N and showed trends among hillslope position and hillslope aspect with lowest values observed on soils with south-facing upslope locations, and highest values occurring on soils form south-facing riparian areas (Table 2-9. One exception to this is that the north-facing clearcut soils showed the greatest soil NH_4^+-N.

Compared with north-facing slopes, soils on south-facing slopes generally had greater potential nitrification and mineralizable N, and lower potential ammonification. Potential nitrification was higher in south-facing riparian soils compared with north-facing riparian soils (*$p<0.001$*, Table 2-11).

Overall, potential mineralization (potential ammonification + potential nitrification) tended to be positive, indicating the production of inorganic N in these soils. Potential ammonification tended to be negative (mean: -1.16 mg N / kg soil) compared with potential nitrification which was much larger, and always positive (mean:4.34 mg N / kg soil, $p<0.001$, Table 2-12). Because potential nitrification dominated potential ammonification, South-facing riparian soils had the largest potential mineralization because of high potential nitrification which was significantly higher than potential ammonification ($p<0.001$, Table 2-12).

2.3.3 Hydrometric (Soil Moisture and Temperature) and Short Wave Radiation

Clearcut harvesting increased soil temperature across both hillslope aspects (Table 2-13a) compared with reference soils, particularly in the south-facing clearcut where mean soil temperatures were 11.5 °C compared with 5.5 °C within south-facing upper hillslope reference soils (Table 2-13a). Because of high temporal and spatial variability, general patterns in both soil temperature and soil moisture content among harvesting, slope, and aspect classes were explored by categorizing mean seasonal soil temperature and moisture into 5 classes based on 95% confidence intervals from 1 (low) to 5 (high). While soil temperatures in south facing riparian sites were marginally greater than in north facing sites, variation of soil temperature among harvested and reference sites in lower slope positions varied less than those observed in upper slope positions. These small differences in soil temperature among riparian sites are reflected by overlapping 95% confidence intervals (group 3, Table 2-13a). Soils in upper north-facing clearcut sites became wetter, while soils in upper south-facing clearcut soils became dryer after harvesting. Consistent with variation in soil temperature, variation in soil moisture among lower slope riparian sites was less obvious than elsewhere, though south-facing riparian soils were slightly warmer and wetter than north-facing soils as shown by different 95% confidence interval grouping in Table 2-13b.

Except for north-facing clearcut soils, deeper mineral layers were consistently cooler than shallower soils by 1.04 °C within the riparian zone and 1.37 °C in upper hillslope positions. Riparian sites tended to have dryer soils (0.052 v/v dryer) while upper hillslopes had wetter soils (0.022 v/v wetter) compared with shallower soils (Table 2-13).

Mean daily short-wave radiation was 6.2 times greater within the clearcut with no tree cover than among forested reference areas. Between May 31 and October 3, 2016, mean solar insolation was 219.95 w/m^2 within the harvested area and 35.38 w/m^2 within upper reference stands. Slope-aspect had little effect on solar insolation throughout the study period.

2.4 Discussion

2.4.1 Soil Nutrient Availability (Supply Rate) by PRS® Probes

Mobile N supply rates from early spring to early fall were similar among harvested and reference study areas one year following clearcut harvesting in the Crowsnest Pass (Figure 2-4, Table 2-2). NH_4^+-N supply rates were greater within reference soils compared to harvested soils, however the difference was only due to riparian soils. NH_4^+-N showed no difference between the reference and harvest within upslope sites where clearcutting took place. These findings are consistent with other studies on N turnover after harvesting in coniferous stands (Jerabkova & Prescott, 2007), although both decreases and increases in soil NO_3^- have been previously observed post-harvest (Jerabkova et al., 2011). It is difficult to compare between studies; because of differences in landscape (topography, geology, vegetation, drainage form) and climate that can result in different nutrient responses to similar land disturbances. The implementation of different harvesting methods further complicates the establishment of causal explanations for changes to post-disturbance nutrient dynamics (Feller and Kimmins, 1984). Indeed, there have even been conflicting results when studying harvesting methods within the same watershed (Mann et al., 1988).

Results from this study suggest that competing sources and sinks of available N in the broader study area resulted in soil N availabilities that were relatively unimpacted by clearcut harvesting. Furthermore, changes in soil N were likely buffered by the more delayed (slow) decomposition of litter often observed within coniferous stands (Jerabkova et al., 2011) making the changes in soil N difficult to detect. The way harvesting was carried out probably impacted sources and sinks of N within the system, though these sources and sinks appear to have cancelled each other out from an available and soil N perspective. For example, whole-tree harvesting employed within the Star Creek watershed created a sink by removing organic matter (bole, branches, and crowns) while root systems were left in the ground and presented a potential N source. Burning of excess slash at landings represented additional, concentrated N sources because of both increased biomass inputs and localized effects of the slash burn on increased turnover of pre-existing soil organic material (Giardina, et al., 2000). Further, uptake of available mineral N as the dominant vegetation was converted from mature forest to rapidly growing post-harvest vegetation (grass, shrubs, seedlings) created rapidly changing N source-sink dynamics (Kreutzweiser et al., 2008). Strong vegetative regrowth just one year after harvesting within both north and south-facing stands was evident by thick fescue interspersed by small lodgepole saplings, suggesting that excess plant-available N likely was being used quickly, and efficiently.

It is generally believed that upper hillslopes drive the overall nutrient supply in mountainous terrain (Blackburn et al., 2017). These landscapes are hydrologically connected to biogeochemically active riparian areas, which principally remove (by denitrification) or retain (by uptake) the mineral N that they receive from upslope surface and sub-surface runoff. However, here, median supply rates of riparian soils were 2.2 times (NH_4^+-N) and 3.1 times for (NO_3^--N) greater than of upper hillslope soils, thereby suggesting that upper hillslopes in this system retained more N than the riparian areas. Thus, the substantially higher fluxes of available N within the riparian zone suggested these soils may be more responsible for nutrient supply than traditionally believed. Notably, this outcome also was recently observed in conifer dominated headwater catchments in Alberta's boreal forein sts (Blackburn et al., 2017).

NH_4^+-N and NO_3^--N were lowest in south-facing upslope soils and highest in south-facing riparian soils. This contrast by hillslope position in south-facing slopes suggests that south-facing upslope soils are highly retentive of inorganic N, while south-facing riparian soils may have stronger mineral N than paired north-facing slopes. The comparative contribution of soil N to streams is difficult to quantify, but the common opinion is that stream N primarily originates from north-facing slopes because they deliver proportionately more water than south-facing slopes. However, the present study suggests that a higher proportion of stream water N than was previously expected may originate from south-facing riparian soils. To better understand these processes, finer scale investigations of the hydrology and N turnover near the hyporheic zone would be required—these were beyond the scope of the present investigation.

NH_4^+-N supply rates were generally higher than NO_3^--N supply rates. The exception to this, though not significant, was within south-facing riparian soils. In soils with greater NH_4^+-N supply rates, more potential ammonification than nitrification would be expected, while the opposite would be expected for soils with higher NO_3^--N supply rates. Higher NH_4^+-N supply rate have been reported in other coniferous stands, likely because NO_3^--N can be more easily lost through denitrification, leaching, or uptake by vegetation (Kreutzweiser et al., 2008).

Mean NO_3^--N supply rates were significantly greater within the deeper mineral layers (Table 2-6, p = 0.004), while significant differences were not detected in NH_4^+-N supply rates at different depths (Table 2-6, p = 0.715). The maximum NO_3^--N supply rate among sites was 16.5 times higher in the deeper mineral layer compared with the organic mineral interface, providing evidence that not only is there greater available NO_3^--N at depth, but NO_3^--N hotspots occur in deeper soil layers. This deeper soil NO_3^--N suggests downward leaching and accumulation NO_3^+-N.

2.4.2 Soil Characteristics and Geochemistry

Few differences in soil parameters were evident between harvested and reference sites, likely due to high microsite variability (i.e., high variability at the micro-scale within the same site). Patterns were more consistent between the paired harvested and reference sites with similar hillslope aspect and positions. Mean soil NH_4^+-N, NO_3^--N, pH, TC, TN, and C/N ratios followed the same trend as NH_4^+-N and NO_3^--N supply rates and were lowest within south-facing upslope soils, and highest within south-facing riparian soils (Table 2-6). Potential nitrification was very high in these south-facing riparian soil, thereby suggesting the greatest potential mineralization (Table 2-11).

Soils have an equilibrium C/N ratio (dependent on soil type) whereby a lower C/N ratio indicates that the system is likely saturated with respect to N, and therefore likely contain higher quality substrates for microbe utilization. For forest soils, this equilibrium is typically around 20 (Gundersen et al., 1998). Therefore, soils with lower

C/N ratios, typically experience net mineralization; this leads to more inorganic N and therefore higher productivity (Manzoni et al., 2012); it also provides greater opportunity for N losses through leaching. Soils with high C/N ratios experience net immobilization and therefore N becomes locked up in organic forms unavailable for vegetative growth. Yet in this study, sites with higher C/N ratios also had more mineral N (south-facing riparian soils). The C/N ratio may not be the best metric for comparison, as these south-facing riparian zones had far greater TC and TN compared with other sites.

While, removal of vegetation decreases the pool of easily mineralizable N (Futter et al., 2010), clearcutting did not appear to impact the amount of mineralizable N in either north or south-facing clearcut soils compared to the reference. Hillslope aspect within the riparian zone was the only factor affecting mineralizable N, where south-facing riparian soils had greater mineralizable N, lower potential ammonification, and higher potential nitrification. Indeed, most sites followed this pattern where potential ammonification was negative, while potential nitrification was positive, suggesting that if soil conditions were similar to laboratory incubations (e.g. moisture, temperature, no vegetative uptake or leaching) NO_3^--N would be the dominant form of inorganic N in these soils. However, in the case of south-facing riparian sites where potential nitrification was quite large in comparison to other soils, greater soil NH_4^+-N than NO_3^--N was observed; however, no significant differences among NH_4^+-N and NO_3^--N supply rates were observed (with respect to hillslope position, Table 2-10). Thus, these data are consistent with other recent reports that south-facing riparian soils may be responsible for the production of NO_3^--N, and that this NO_3^--N is being somehow lost (e.g., denitrification, leaching, or plant root uptake). The observation that NO_3^--N supply rates increased with depth suggests that leaching is likely to be the dominant pathway for N mineralization in these areas. pH has been shown to be an important regulator of net nitrification, with higher pH leading to greater nitrification (Ste-marie and Pare, 1999). Indeed, soil samples from this study with greater pH also showed greater potential nitrification.

Mineralizable N can also be related to the hydrology of each site. For example, a higher proportion of mineralizable N will typically be from potential nitrification in well drained soils (through aerobic respiration) and from potential ammonification in poorly drained soils (Doran et al., 1996). It is possible to infer that because most of the potentially mineralizable N was from potential nitrification, that most soils likely are well drained.

2.4.3 Hydrometric (Soil Moisture and Temperature) and Short Wave Radiation

It was hypothesized that south-facing hillslope aspects would receive greater solar insolation. While the limited point-measurements were not sufficient to show this, south-facing hillslopes did have dryer, warmer soils. Higher soil temperatures within the clearcut (compared to reference soils) is consistent with other findings (Griffin et al., 2013). Higher soil temperatures have been typically linked with dryer soils, however, there are often higher water tables, greater soil moisture and temperatures after forest harvesting as a result of decreased evaporative losses due to forest canopy removal (Kreutzweiser et al., 2008). This trend of higher soil moisture was observed in the north-facing clearcut, but not the south-facing clearcut. The dryer soils found within south-facing clearcut hillslopes may have been a result of greater evaporative losses due to increases solar insolation. North-facing soils also could potentially have poorer drained soils. Hinckley et al. (2012) studied soil water movement by contrasting aspects in a similar Pinus Contorta dominated montane catchment and found south-facing soils drained quicker, and deeper while north-facing soils experienced shallower surface transport which aligns with our findings of soil moisture by aspect.

Because of the increase in soil temperature, greater availability of N might have been expected in the clearcut, especially if similar amounts of litter were available for decomposition; significant differences in available N were not observed, however (Table 2-3). Contrary to expectations, riparian soils were slightly dryer than upslope soils (Table 2-13b). South-facing riparian zones had warmer, wetter soils (Table 2-13a) that favour microbial activity and N turnover. These soils were likely warmer as vegetation is sparser within Star Creek's south-facing riparian zone. In north-facing riparian zones within Star Creek, there is a sharp slope declining toward the stream, whereas the south-facing riparian zones experience a much more gradual and flat slope into the stream which is likely why soils within the south-facing riparian zone were wetter.

Greater direct short-wave radiation reaching the forest floor within the clearcut compared to the reference is not surprising because reduced light interception after canopy removal. While greater radiation should be expected on south-facing slopes, two cases of marginally greater radiation reaching north-facing hillslopes were observed, one in each of the harvest and reference pyranometer locations. This difference by hillslope aspect is minimal compared to the differences seen in the harvest versus the reference, but likely reflects both micro-site scale variation in canopy cover and the topographical heterogeneity within steep mountainous terrain. Visual surveys of each site during early spring snowmelt revealed that north-facing slopes experienced a more delayed onset and prolonged snow melt than south-facing slopes, as expected. A greater density of pyranometers would have likely provided a better representation of north and south-facing hillslopes.

2.5 Conclusion

Clearcut harvesting in Star Creek watershed had little impact on N turnover and mobile N one year following harvest. While there was greater available NH_4^+-N in the reference compared to the harvest, the cause of this was only due to differences within the riparian zone. Sites with the same hillslope positioning and aspect from both the harvest and reference behaved similar with regards to both available NH_4^+-N and NO_3^--N. Direct harvest effects on soil moisture and temperature did not appear to drive harvest effects on soil N status in this study. While there was greater available soil NH_4^+-N than NO_3^--N, there was also less potential ammonification than nitrification, and greater NO_3^--N supply in deeper soils. This suggests that the soil and available mineral N loss at the study sites may be predominantly attributable to leaching. This study challenges the idea that upper hillslopes drive the overall N supply, with evidence of upper hillslopes being more retentive of N while riparian zones experienced greater N fluxes. Further, this study highlights the importance of hillslope aspect within riparian zones by demonstrating that south-facing soils experienced greater potential nitrification, NH_4^+-N, NO_3^--N, pH, TC, TN, and C/N ratios, and lower potential ammonification than any other locations. This suggests that south-facing riparian areas could be a major contributor to stream water N in the Star Creek watershed if the soils are hydrologically connected in areas of high NO_3^--N concentrations. Greater solar insolation within the clearcut appears to be the cause of greater soil temperatures, and while north-facing clearcut soils were wetter compared to reference soils, south-facing clearcut soils were dryer.

Table 2-1 Independent variables (factors) in the study design

Land condition	Dominant Land Classification	Hillslope Aspect	Hillslope Position
Harvested			
HNU	Harvested/Regrowth	North	Upper
HNL	Forested/Riparian	North	Lower
HSL	Forested/Riparian	South	Lower
HSU	Harvested/Regrowth	South	Upper
Reference			
RNU	Forested	North	Upper
RNL	Forested/Riparian	North	Lower
RSL	Forested/Riparian	South	Lower
RSU	Forested	South	Upper

Table 2-2 Soil NH_4^+ and NO_3^- supply rates [μg N 10 cm^{-2} 177 days^{-1}] within harvest and reference study areas over the entire study period (April 9 – October 3, 2016). Differences between groups were tested using the Kruskall-Wallis median test and underlined where significant (p<0.05).

	Harvest		Reference		
Species	Median	Range	Median	Range	*p*-value
NH_4^+	4.44	(2.18-26.22)	6.51	(3.98-18.02)	<ins><0.001</ins>
NO_3^+	2.92	(0.92-54.18)	3.04	(0.88-325.72)	0.825
Mineral N	8.06	(3.20-57.62)	10.85	(6.64-333.00)	<ins>0.029</ins>

Table 2-3 Soil NH_4^+ and NO_3^- supply rates [μg N 10 cm^{-2} 177 $days^{-1}$] within harvest and reference study areas separated by hillslope position over the entire study period (April 9 – October 3, 2016). Differences between groups were tested using the Kruskall-Wallis median test and underlined where significant (*p*<0.05).

	Lower Slope Position					Upper Slope Position				
	Harvest		Reference			Harvest		Reference		
Species	Median	Range	Median	Range	*p*-value	Median	Range	Median	Range	*p*-value
NH_4^+	3.00	(2.26-6.04)	7.19	(5.5-18.02)	<u><0.001</u>	6.44	(2.18-26.22)	5.96	(3.98-10.74)	0.756
NO_3^+	2.26	(0.92-20.42)	4.76	(1.3-181.56)	0.160	3.57	(1.1-54.18)	2.69	(0.88-325.72)	0.194
Mineral N	5.40	(3.2-23.78)	13.63	(7.28-189.94)	<u><0.001</u>	10.17	(3.74-57.62)	8.32	(6.64-333)	0.160

Table 2-4 Soil NH_4^+ and NO_3^- supply rates [µg N 10 cm^{-2} 177 $days^{-1}$] within north and south-facing lower hillslope positions (riparian zone) over the entire study period (April 9 – October 3, 2016). Differences between groups were tested using the Kruskall-Wallis median test and underlined where significant (p<0.05).

	Lower Slope Position				
	North-Facing		South-Facing		
Species	Median	Range	Median	Range	*p*-value
NH_4^+	5.63	(2.28-18.02)	5.37	(2.26-11.14)	0.808
NO_3^+	1.88	(0.92-6.68)	7.01	(1.72-181.56)	<ins><0.001</ins>
Mineral N	7.42	(3.2-20.78)	14.15	(4.36-189.94)	<ins>0.029</ins>

Table 2-5 Soil NH_4^+ and NO_3^- supply rates [μg N 10 cm^{-2} 177 $days^{-1}$] within north and south-facing upper (a) and lower (b) hillslope positions separated by land condition over the entire study period (April 9 – October 3, 2016). Differences between groups were tested using the Kruskall-Wallis median test and underlined where significant (p<0.05).

a) Upper Slope Position

	Harvest					**Reference**				
	North-Facing		**South-Facing**			**North-Facing**		**South-Facing**		
Species	Median	Range	Median	Range	*p*-value	Median	Range	Median	Range	*p*-value
NH_4^+	5.48	(2.18-11.58)	7.05	(4.16-26.22)	0.096	5.30	(3.98-9.72)	6.29	(5.68-10.74)	<u>0.019</u>
NO_3^+	4.94	(1.1-54.18)	3.00	(1.56-30.94)	0.325	3.57	(1.76-325.72)	1.96	(0.88-17.96)	<u>0.038</u>
Mineral N	10.17	(3.74-57.62)	11.11	(7.24-37.58)	0.880	9.90	(6.64-333)	7.76	(7.08-25.64)	0.364

b) Lower Slope Position

	Harvest					**Reference**				
	North-Facing		**South-Facing**			**North-Facing**		**South-Facing**		
Species	Median	Range	Median	Range	*p*-value	Median	Range	Median	Range	*p*-value
NH_4^+	3.18	(2.28-6.04)	2.80	(2.26-5.06)	0.384	6.76	(5.5-18.02)	8.12	(5.68-11.14)	0.096
NO_3^+	1.88	(0.92-3.42)	3.61	(1.98-20.42)	<u>0.002</u>	2.20	(1.3-6.68)	9.04	(1.72-181.56)	<u>0.004</u>
Mineral N	5.26	(3.2-9.1)	6.64	(4.36-23.78)	0.130	9.32	(7.28-20.78)	18.46	(7.4-189.94)	<u>0.011</u>

Table 2-6 Soil NH_4^+ and NO_3^- supply rates [μg N 10 cm^{-2} 177 $days^{-1}$] within the organic/mineral interface and 20cm deep into the mineral layer over the entire study period (April 9 – October 3, 2016). Differences between groups were tested using the Kruskall-Wallis median test and underlined where significant (p<0.05).

	Organic/Mineral Interface		**20cm Deep into Mineral**		
Species	Median	Range	Median	Range	*p*-value
NH_4^+	5.70	(2.28-26.22)	5.80	(2.18-11.82)	0.715
NO_3^+	2.39	(0.88-19.8)	4.47	(1.2-325.72)	<u>0.004</u>
Mineral N	7.88	(3.2-32.2)	10.57	(3.74-333)	<u>0.043</u>

Table 2-7 Soil NH_4^+ and NO_3^- supply rates [µg N 10 cm^{-2} 177 days^{-1}] among combined harvest, combined reference, and each individual site over the entire study period (April 9 – October 3, 2016). Differences between groups were tested using the Kruskall-Wallis median test and underlined where significant (*p*<0.05).

Land condition	Median NH_4^+	Range	Median NO_3^-	*Range*	*p*-value
HNU	5.48	(2.18-11.58)	4.94	(1.1-54.18)	0.940
HNL	3.18	(2.28-6.04)	1.88	(0.92-3.42)	0.001
HSL	2.80	(2.26-5.06)	3.61	(1.98-20.42)	0.427
HSU	7.05	(4.16-26.22)	3.00	(1.56-30.94)	0.008
Harvested	4.44	(2.18-26.22)	2.92	(0.92-54.18)	**0.**023
RNU	5.30	(3.98-9.72)	3.57	(1.76-325.72)	0.199
RNL	6.76	(5.5-18.02)	2.20	(1.3-6.68)	0.001
RSL	8.12	(5.68-11.14)	9.04	(1.72-181.56)	0.496
RSU	6.29	(5.68-10.74)	1.96	(0.88-17.96)	0.002
Reference	6.51	(3.98-18.02)	3.04	(0.88-325.72)	0.001

Table 2-8 Mean soil properties from August 13-14, 2016 soil samples of the eight study sites within the Star Creek Watershed.

Site	Field Capacity (%)	Water Content (%)	pH	TC (w/w%)	TN (w/w%)	C/N Ratio (-)
HNU	41.07	21.73	6.68	4.39	0.19	22.98
HNL	37.04	25.20	6.03	3.08	0.13	23.32
HSL	39.35	16.37	6.95	9.54	0.25	42.36
HSU	30.80	15.67	5.84	2.50	0.16	16.04
Harvested	37.06	19.74	6.37	4.88	0.18	26.18
RNU	46.96	25.84	6.75	7.00	0.19	38.37
RNL	45.65	24.37	5.99	4.81	0.19	25.38
RSL	38.05	14.25	7.33	8.67	0.20	48.95
RSU	27.67	10.53	5.14	1.68	0.08	20.88
Reference	39.58	18.75	6.31	5.54	0.17	33.39

Table 2-9 Mean soil NH_4^+-N and NO_3^--N from August 13-14, 2016 soil samples and results of 28-day aerobic incubation mineralization study of the eight study sites within the Star Creek Watershed.

Site	NH_4^+-N (mg/L)	NO_3^--N (mg/L)	Potential Ammonification (mg N/ kg OD soil)	Potential Nitrification (mg N/ kg OD soil)	Mineralizable N (mg N/ kg OD soil)
HNU	9.51	1.17	-2.40	3.19	0.79
HNL	5.12	0.95	-4.54	2.67	-1.87
HSL	6.89	2.72	-6.16	16.44	10.29
HSU	4.04	0.21	2.71	1.38	4.09
Harvest	6.39	1.26	-2.60	5.92	3.32
RNU	2.78	0.46	-1.55	2.53	0.98
RNL	1.52	0.68	1.71	0.99	2.70
RSL	3.65	2.75	-3.09	7.51	4.42
RSU	0.82	0.53	4.08	0.00	4.08
Reference	2.19	1.10	0.29	2.76	3.04

Table 2-10 Soil pH, field capacity (%), TC (w/w%), TN (w/w%), C/N (-), NH_4^+ (mg/L), NO_3^- (mg/L), potential ammonification (mg N/ kg OD soil), potential nitrification (mg N/ kg OD soil) and mineralizable N (mg N/ kg OD soil) within harvest and reference study areas by combined and separate slope positions from soil samples collected August 13 and 14, 2016. Differences between groups are tested using a student's t-test assuming unequal variance and underlined where significant (p<0.05).

	All Slope Positions			**Upper Slope Position**			**Lower Slope Position**		
	Harvest	**Reference**		**Harvest**	**Reference**		**Harvest**	**Reference**	
Parameter	Mean	Mean	*p*-value	Mean	Mean	*p*-value	Mean	Mean	*p*-value
pH	6.37	6.31	0.855	5.94	5.57	0.472	6.81	7.04	0.439
Field Capacity (%)	37.07	39.58	0.618	33.92	36.66	0.602	40.21	42.51	0.799
TC (w/w%)	4.88	5.54	0.763	2.79	3.24	0.486	6.97	7.84	0.857
TN (w/w%)	0.18	0.17	0.609	0.15	0.14	0.591	0.22	0.20	0.606
C/N (-)	26.18	33.40	0.594	19.68	23.13	0.842	32.67	43.66	0.571
NH_4^+-N (mg/L)	6.39	2.19	0.288	6.77	1.80	0.174	6.01	2.58	0.356
NO_3^--N (mg/L)	1.26	1.11	**0.026**	0.69	0.49	0.159	1.83	1.72	0.078
Potential Amm. (mg N/ kg OD soil)	2.60	0.29	**0.006**	0.016	1.26	0.456	-5.35	-0.69	**<0.001**
Potential Nit. (mg N/ kg OD soil)	5.92	2.76	**0.023**	2.38	2.63	0.232	9.56	4.25	**0.025**
Mineralizable N (mg N/ kg OD soil)	3.32	3.04	0.882	2.44	2.53	0.968	4.21	3.56	0.844

Table 2-11 Soil pH, field capacity (%), TC (w/w%), TN (w/w%), C/N (-), NH_4^+ (mg/L), NO_3^- (mg/L), potential ammonification (mg N/ kg OD soil), potential nitrification (mg N/ kg OD soil) and mineralizable N (mg N/ kg OD soil) within north and south-facing upper (a) and lower (b) hillslope positions separated by land condition from soil samples collected August 13 and 14, 2016. Differences between groups are tested using a student's t-test assuming unequal variance and underlined where significant (p<0.05).

a) Upper Slope Position

	Harvest			**Reference**		
	North-facing	**South-facing**		**North-facing**	**South-facing**	
Species	Mean	Mean	*p*-value	Mean	Mean	*p*-value
pH	6.03	5.84	0.847	5.99	5.14	0.205
Field Capacity (%)	37.04	30.80	0.186	45.65	27.67	0.059
TC (w/w%)	3.08	2.50	0.010	4.81	1.68	0.033
TN (w/w%)	0.13	0.16	0.379	0.19	0.08	0.037
C/N (-)	23.32	16.04	0.400	25.38	20.88	0.102
NH_4^+-N (mg/L)	9.51	4.03	0.018	2.78	0.83	0.153
NO_3^--N (mg/L)	1.16	0.21	0.444	0.46	0.53	0.408
Potential Amm. (mg N/ kg OD soil)	-2.40	2.71	0.014	-1.55	4.08	0.002
Potential Nit. (mg N/ kg OD soil)	3.19	1.38	0.122	2.53	0.002	0.053
Mineralizable N (mg N/ kg OD soil)	0.79	4.09	0.445	0.98	4.08	0.306

b) Lower Slope Position

	Harvest			**Reference**		
	North-facing	**South-facing**		**North-facing**	**South-facing**	
Species	Mean	Mean	*p*-value	Mean	Mean	*p*-value
pH	6.68	6.95	0.456	6.75	7.33	0.309
Field Capacity (%)	41.07	39.35	0.827	46.96	38.05	0.651
TC (w/w%)	4.39	9.54	0.084	7.00	8.67	0.350
TN (w/w%)	0.19	0.25	0.011	0.19	0.20	0.537
C/N (-)	22.98	42.36	0.412	38.37	48.95	0.916
NH_4^+-N (mg/L)	5.12	6.89	0.226	1.52	3.64	0.618
NO_3^--N (mg/L)	0.95	2.72	0.625	0.68	2.75	0.063
Potential Amm. (mg N/ kg OD soil)	-4.54	-6.16	0.352	1.71	-3.089	<0.001
Potential Nit. (mg N/ kg OD soil)	2.67	16.44	<0.001	0.99	7.51	<0.001
Mineralizable N (mg N/ kg OD soil)	-1.87	10.29	0.031	2.70	4.42	0.431

Table 2-12 Results from potential ammonification (mg N/ kg OD soil) and potential nitrification (mg N/ kg OD soil) in each of the eight study sites within the Star Creek Watershed. Potential ammonification represents the production of NH_4^+ and potential nitrification represents the production of NO_3^- (mg/L) during a 28-day anaerobic lab incubation. Differences between groups are tested using a paired student's t-test and underlined where significant (p<0.05).

	Potential Ammonification (mg N/ kg OD soil)	Potential Nitrification (mg N/ kg OD soil)	
Factor/site	Mean	Mean	*p*-value
HNU	-2.40	3.19	<u>0.024</u>
HNL	-4.54	2.67	<u>0.021</u>
HSL	-6.16	16.44	<u><0.001</u>
HSU	2.71	1.38	0.325
Harvest	-2.60	5.92	<u><0.001</u>
RNU	-1.55	2.53	0.057
RNL	1.71	0.99	0.350
RSL	-3.09	7.51	<u><0.001</u>
RSU	4.08	0.00	<u>0.018</u>
Reference	0.27	2.76	<u>0.036</u>
Overall	-1.16	4.34	<u><0.001</u>

Table 2-13 Daily soil temperature (a) and moisture (b) for days with complete data (n=49). Group numbers refer to categories of similar (overlapping 95% confidence intervals) temperature or moisture from low (1) to high (5).

a) Soil Temperature

	n	Mean	Standard Deviation	95% CI	Groups				
Harvested									
HNU	49	9.64	2.04	(9.10,10.17)				4	
HNL	49	7.09	2.08	(6.56,7.64)		2	3		
HSL	49	8.18	1.99	(7.64,8.71)		2	3		
HSU	49	11.51	2.19	(10.98,12.05)					5
Reference									
RNU	49	7.91	1.70	(7.38,8.45)		2	3		
RNL	49	7.48	2.12	(6.94,8.01)		2	3		
RSL	49	8.61	1.67	(8.07,9.14)			3	4	
RSU	49	5.45	1.26	(4.92,5.99)	1				

b) Soil Moisture

	n	Mean	Standard Deviation	95% CI	Groups				
Harvested									
HNU	49	0.332	0.026	(0.324,0.339)					5
HNL	49	0.109	0.023	(0.101,0.116)	1				
HSL	49	0.148	0.034	(0.140,0.155)		2			
HSU	49	0.146	0.031	(0.139,0.154)		2			
Reference									
RNU	49	0.191	0.017	(0.183,0.198)			3		
RNL	49	0.132	0.025	(0.124,0.139)		2			
RSL	49	0.182	0.027	(0.174,0.189)			3		
RSU	49	0.212	0.029	(0.205,0.220)				4	

Table 2-14 Daily soil moisture and temperature within the organic/mineral interface and 20cm deep into the mineral layer for days with complete data (n=49) in each of the eight study sites within the Star Creek Watershed. The depth with the larger temperature and moisture is in bold for each factor.

		Hillslope	Moisture (VWC)		Temperature (°C)	
Site	Hillslope Position	Aspect	Mineral Interface	20 cm Depth	Mineral Interface	20 cm Depth
HNU	Upper Hillslope	N	0.312	**0.350**	9.67	**10.17**
HNL	Riparian	N	**0.125**	0.091	**7.94**	6.80
HSL	Riparian	S	**0.188**	0.106	**9.08**	7.83
HSU	Upper Hillslope	S	0.134	**0.160**	**12.11**	11.59
Harvest			**0.190**	0.177	**9.70**	9.10
RNU	Upper Hillslope	N	0.179	**0.202**	**8.85**	7.47
RNL	Riparian	N	**0.148**	0.115	**8.09**	7.39
RSL	Riparian	S	**0.211**	0.150	**9.39**	8.30
RSU	Upper Hillslope	S	0.213	**0.214**	**8.36**	4.26
Reference			**0.188**	0.170	**8.67**	6.86

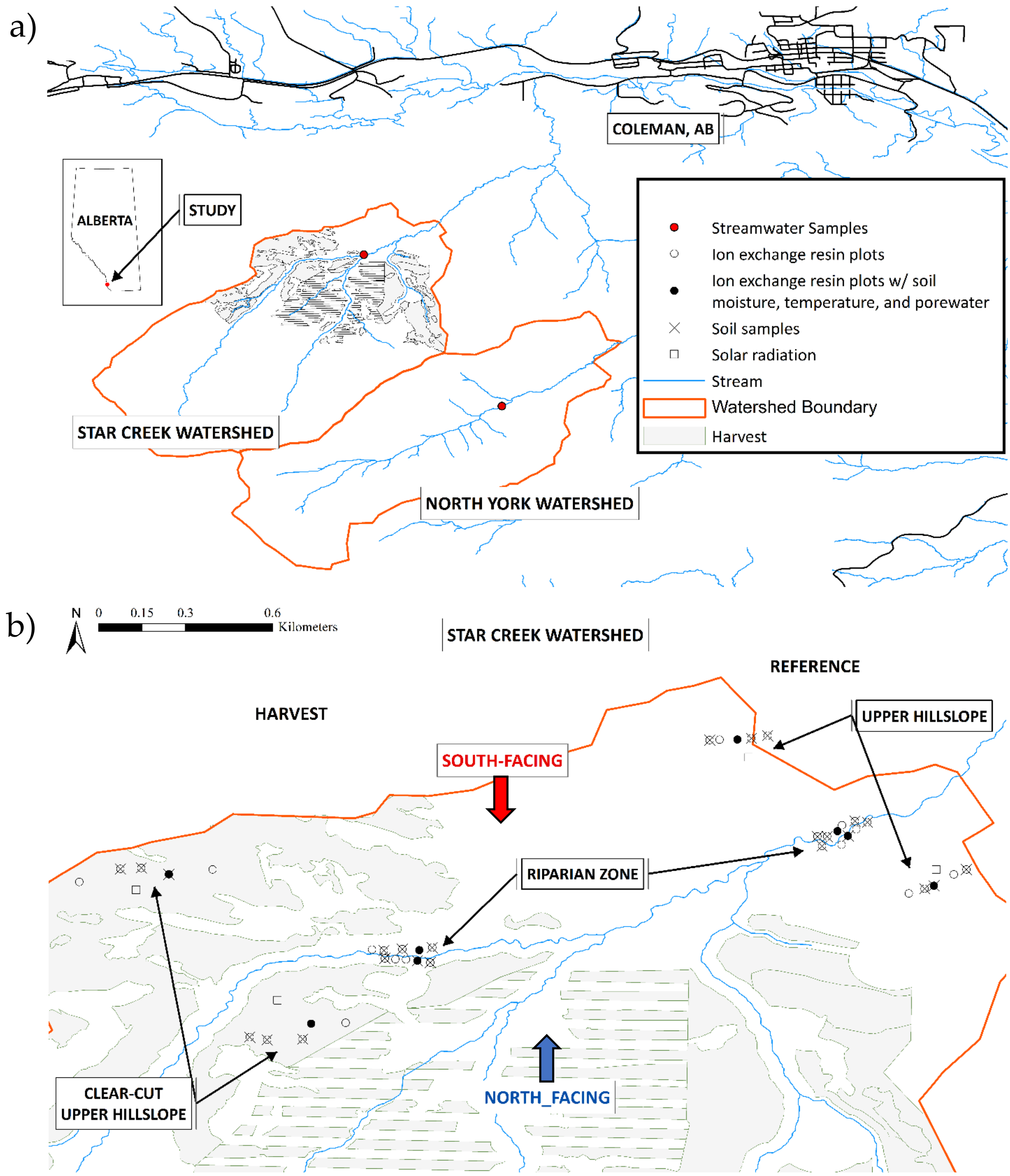

Figure 2-1 The top map (a) shows the location of the study area including watershed boundaries for both Chapter 2 (Star Creek) and Chapter 3 (Star Creek and North York) in relation to Alberta and Coleman, AB. The bottom map (b) shows harvest boundaries (shaded areas), and locations of sampling equipment for both Chapter 2 (excludes pore and stream water) and Chapter 3 (excludes soil samples).

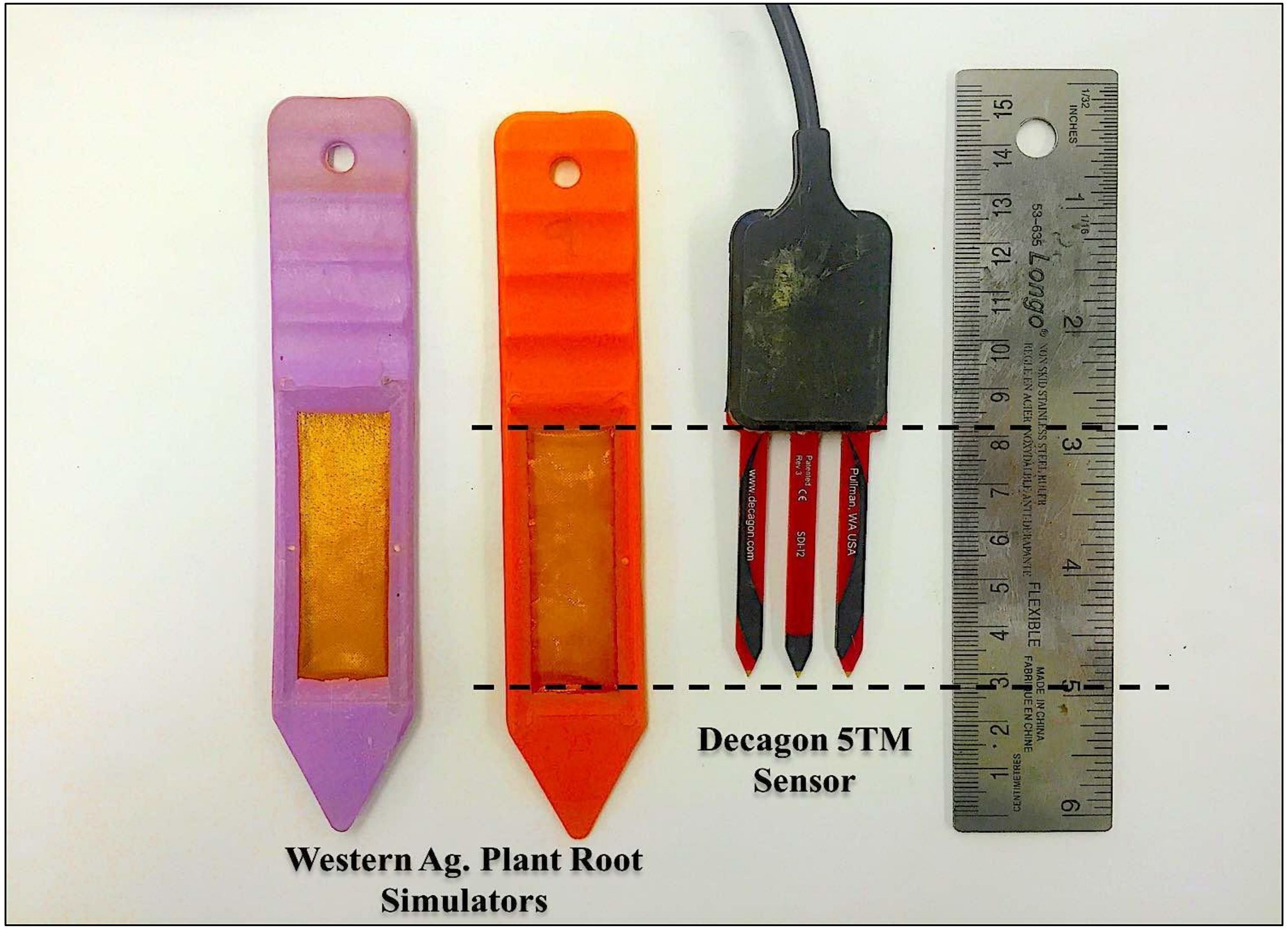

Figure 2-2 5TM Soil Moisture and Temperature Sensor and PRS® Ion Exchange Resin Probes Side by Side.

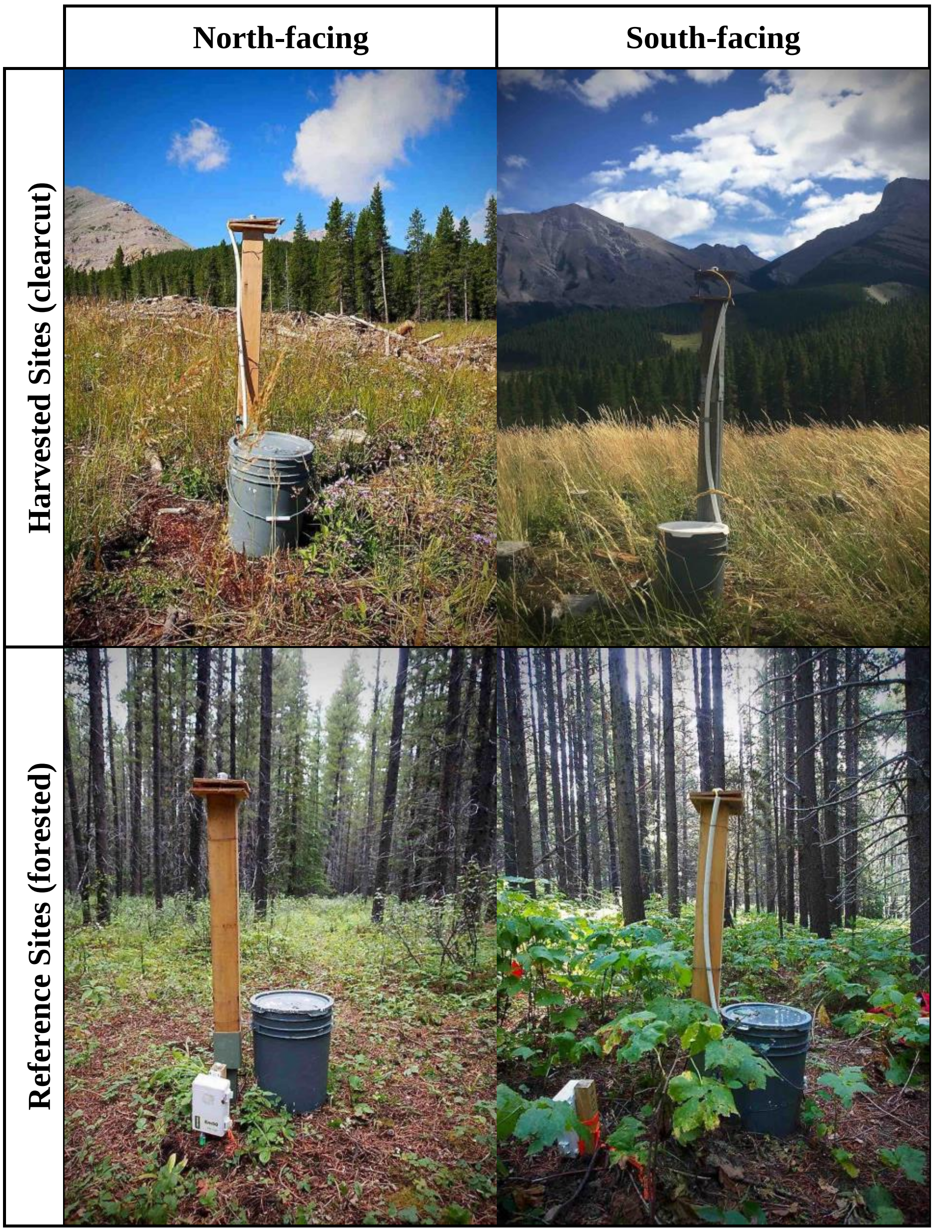

Figure 2-3 Pyranometers used to measure short-wave radiation installed at 1.20 m height (left to right: RNU, RSU, HNU, HSU).

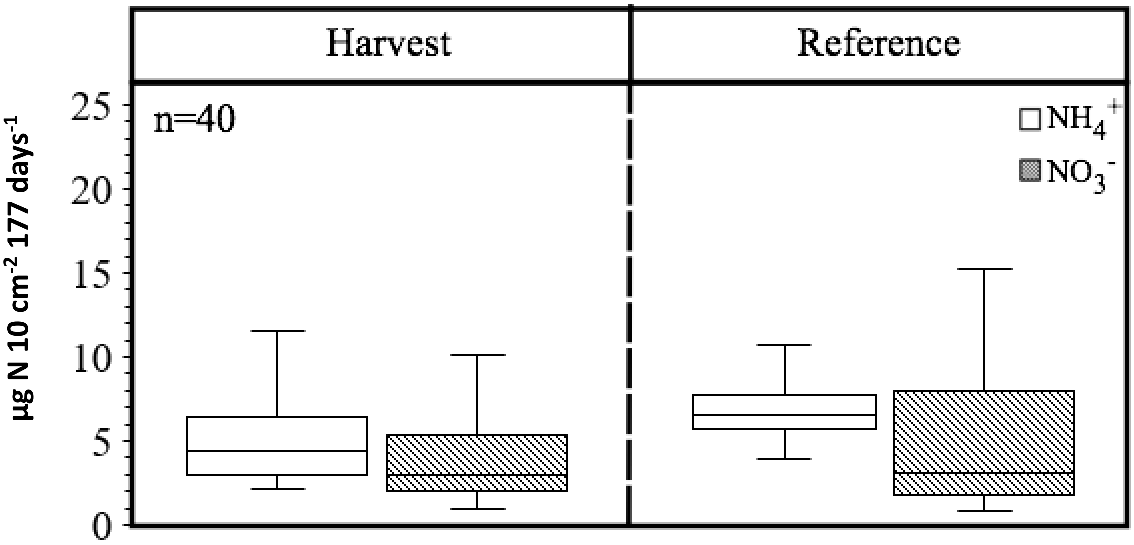

Figure 2-4 Distributions of soil NH_4^+ and NO_3^- supply rates within harvest and reference study areas over the entire study period (April 9 – October 3, 2016). Inner horizontal lines indicate median supply rates, lower and upper box positions represent 25th and 75th percentiles, and lower and upper whiskers represent 5th and 95th percentiles.

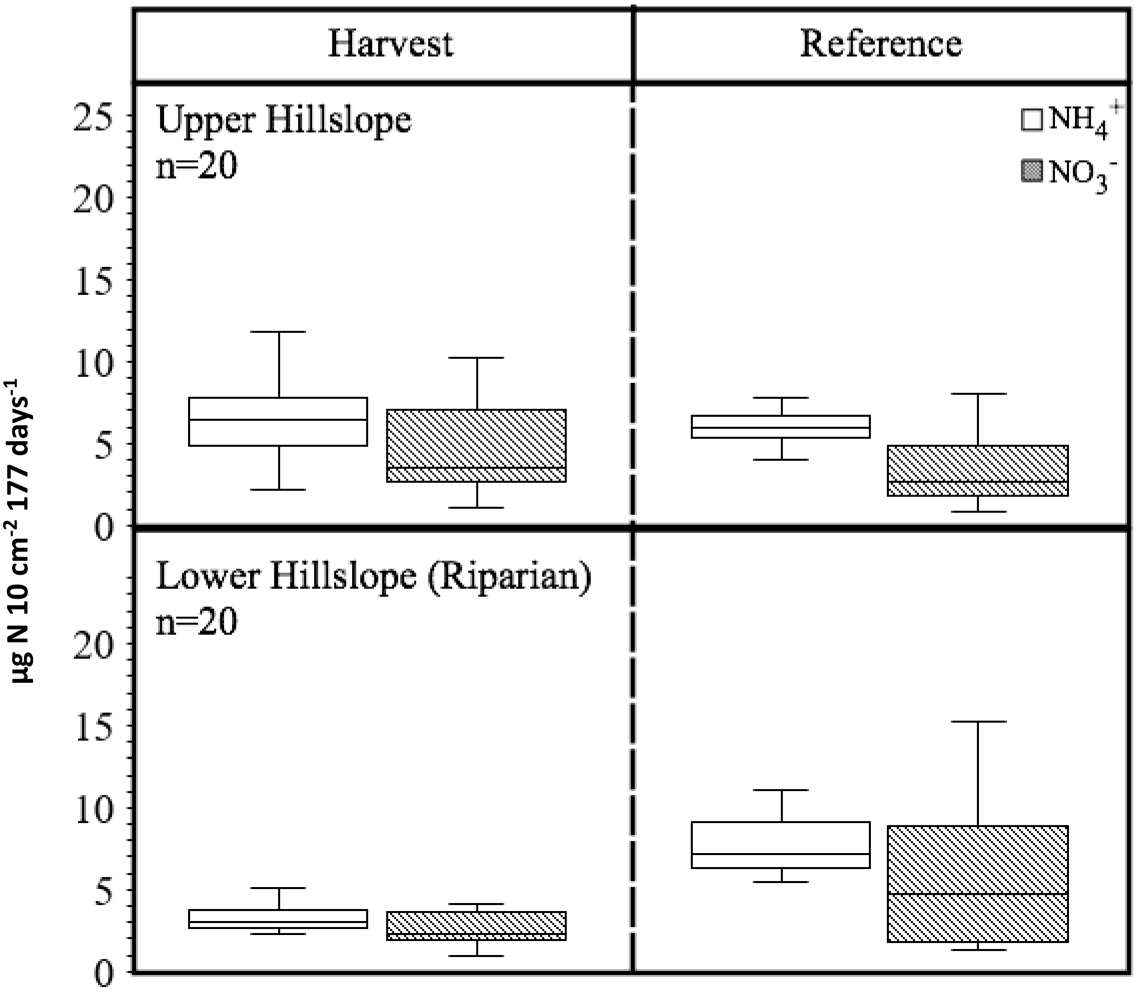

Figure 2-5 Distributions of soil NH_4^+ and NO_3^- supply rates within harvest and reference study areas separated by hillslope position over the entire study period (April 9 – October 3, 2016). Inner horizontal lines indicate median supply rates, lower and upper box positions represent 25th and 75th percentiles, and lower and upper whiskers represent 5th and 95th percentiles.

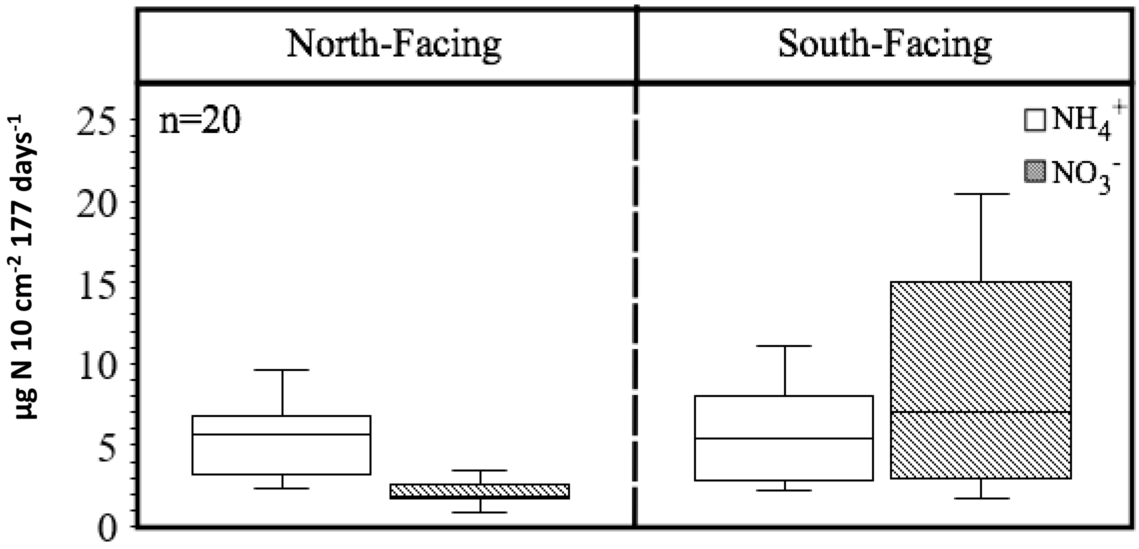

Figure 2-6 Distributions of soil NH_4^+ and NO_3^- supply rates within north and south-facing lower hillslope positions (riparian zone) over the entire study period (April 9 – October 3, 2016). Inner horizontal lines indicate median supply rates, lower and upper box positions represent 25th and 75th percentiles, and lower and upper whiskers represent 5th and 95th percentiles.

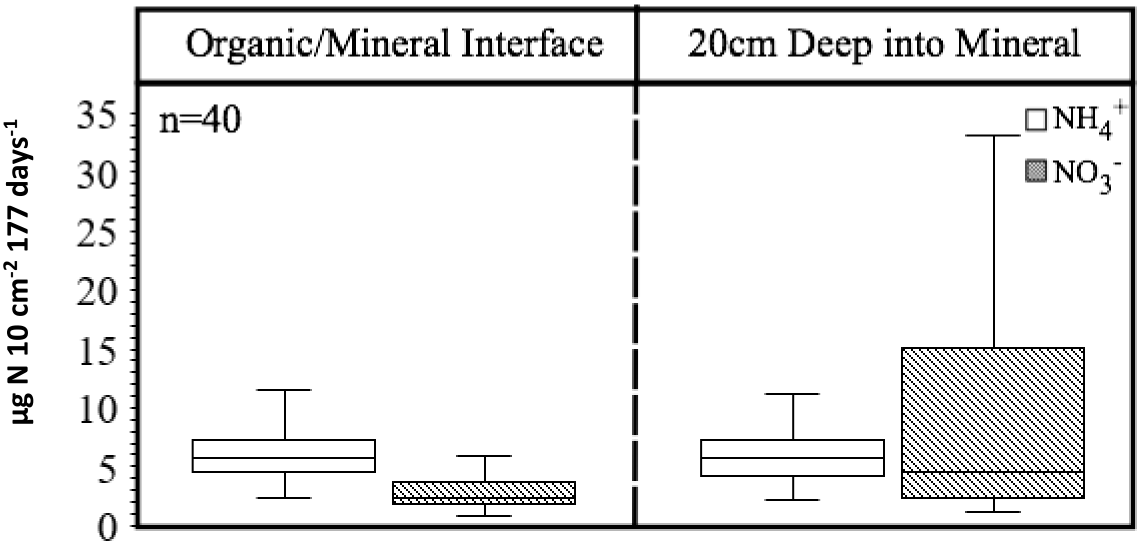

Figure 2-7 Distributions of soil NH_4^+ and NO_3^- supply rates within the organic/mineral interface and 20cm deep into the mineral layer over the entire study period (April 9 – October 3, 2016). Inner horizontal lines indicate median supply rates, lower and upper box positions represent 25th and 75th percentiles, and lower and upper whiskers represent 5th and 95th percentiles.

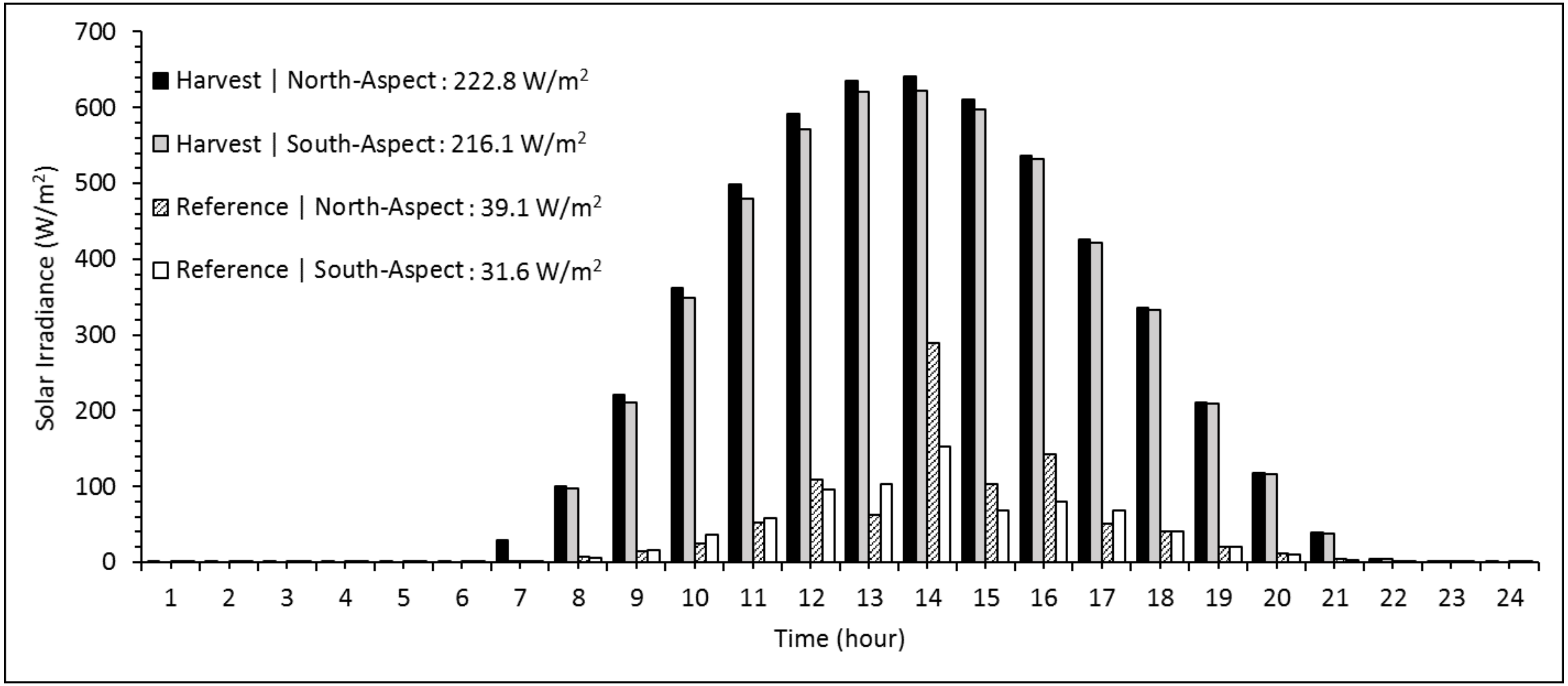

Figure 2-8 Mean hourly solar irradiance within the four-upper hillslope positioned sites over the entire period sensors were installed (May 31 – October 3, 2016). Data for the sensor placed within the harvest on the south-facing slope prior to the sensor being installed on August 24, 2016 was back-filled using data from the north-facing harvest sensor. Mean daily solar irradiance for each study site is noted in the legend.

Chapter 3: Temporal drivers of post-harvest soil nitrogen turnover and transport within a steep Rocky Mountain catchment

3.1 Introduction

Nitrogen (N) supply rates can vary greatly by season, particularly in forest soils (Huang and Schoenau, 1997) and because land disturbance from forest harvesting can both alter the timing of runoff from snow dominated forest landscapes (Winkler et al., 2017) and affect N cycling in forests (Hope et al., 2003; Kreutzweiser, et al. 2008), disturbances such as harvesting have significant potential to affect both the magnitude and timing of N export from forested landscapes. Furthermore, shifting climates and their effects, including earlier arrival of spring snowmelt, and potential changes to the proportion of rain and snow (Bavay et al., 2015; Emelko et al., 2011) could produce additive or synergistic effects on N export from forested watersheds.

Effects of forest harvesting on N export from watersheds result from the combined effects of changes in production of various N forms (NO_3^--N and NH_4^+-N) and their subsequent transport in surface/sub-surface runoff to stream networks. While numerous studies have shown that harvesting causes an increase in nitrification and NO_3^--N concentrations within forest soils, broad general conclusions regarding harvest effects on soil N after clearcut harvesting are uncertain because both increases and decreases in total soil N, or soil NH_4^+-N have been reported following clearcut harvesting (Jerabkova et al., 2011). Even within the same watershed, soil N has been shown to either increase and decrease depending on the harvesting method (Mann et al., 1988). Similarly, studies reporting on stream water chemistry and N export after clearcut harvesting also show a high degree of variability from study to study. Some of these variable findings reflects variation in the intensity (disturbance footprint) of harvesting among studies; Palviainen et al. (2014) suggests harvesting effects are not likely to be detectable where <30% of the watershed area has been harvested. Furthermore, N availability within hillslopes is strongly coupled with differing regional hydrological conditions (Schimel et al., 2004). Weather patterns before, during, and after a harvest, as well as the time of the year that the harvest takes place can vary the watershed's response to the disturbance (Kreutzweiser et al., 2008). For example, in snowpack dominated watersheds, harvest effects on N export may reflect changes in snow accumulation and snowmelt timing that may completely alter the timing of N turnover within a catchment. (Groffman et al., 2001; Brooks & Williams, 1999; Schimel et al., 2004; Bavay et al., 2009).

Transport of N from the landscape to surface waters is also highly variable among watersheds, in part because hydrological connectivity between hillslopes and receiving streams is governed by a broad range of factors including topography (Hinckley et al., 2012), geology, and disturbance factors (e.g. roads creating preferential pathways, soil compaction, etc., (Bachmair & Weiler, 2011). For example, research in the Colorado Rocky Mountains (Hinckley et al., 2014) showed differences in N transport to streams on contrasting north and south-facing hillslopes, reflecting the variable hydrologic connectivity driven by aspect, which influences antecedent moisture that plays an important role in hillslope runoff pathways. Indeed, the complex surficial geology reflecting glacial history of the Canadian Rocky Mountains is characterized by highly variable hydrologic coupling between hillslopes and surface waters (Stone et al., 2014), making it especially difficult to predict subsurface hydrological pathways and their associated temporal behaviour.

Vegetation dynamics and uptake of key limiting nutrients such as N during growth is a major factor governing for N availability and transport to streams (Jerabkova et al., 2006). The upper montane zone within the eastern slopes of the Canadian Rockies is dominated by Lodgepole Pine, which can tolerate nutrient-poor coarse textured soils (Chatterjee et al., 2008). Harvesting methods for Lodgepole also play a role in the timing and response of N within the soil (Kreutzweiser et al., 2008). For example, slash after logging will influence the size of the organic litter pool available for decomposition and mineralization. Thus, the pool of mineral N will reflect the balance of mineralization of organic N and uptake of mineral N by rapid growth of grasses, shrubs, and tree seedlings after harvest. In forest soils, N can be the primary nutrient limiting vegetation growth (Adair & Binkley, 2002) with the most rapid N uptake from soils in the spring and early summer and steady or slightly declining N uptake through mid- to latter summer. Soil N can also be immobilized by soil microbial communities. However, while the seasonal pattern of both N uptake by vegetation and immobilization by microbial communities are generally synchronous during the growing season, the comparative reduction in available soil N by these processes cannot be disentangled based on available soil solution N concentration alone. Thus, seasonal patterns of available or soil N reflect both uptake by vegetation and microbial immobilization processes.

Understanding N connectivity between hillslopes and streams is complex because of high spatial and temporal heterogeneity in processes regulating N availability and transport (Burt and Pinay, 2005; Darrouzet-Nardi and Bowman, 2011; Jencso et al., 2009). Recent research has focused on more specific locations within watersheds with disproportionately large reaction rates (hotspots) compared to average watershed conditions such as riparian zones where surface and groundwaters connect (Burt et al., 2010; McClain et al., 2003). When hotspots only exist for a relatively short amount of time, they are also know as "hot moments" (McClain et al., 2003). Hotspots and hot moments are often found where hydrologic flow paths converge combining reactants (McClain et al., 2003) and have been shown to be major contributors of resin available N at the landscape level (Darrouzet-Nardi & Bowman, 2011). However, a recent study by Morse et al. (2014) suggests that key watershed features governing N biogeochemistry can be overlooked by not considering mineral soil layers which may constitute hotspots and hot moments.

While many studies have investigated harvesting impacts on N turnover, comparatively limited knowledge exists on harvesting effects to N production and runoff in snow dominated, topographically complex regions such as the montane

Rocky Mountain in Canada. In particular, the seasonal timing of harvesting effects on N availability are not well documented but are likely important determinants of temporal patterns in N transport to streams which would regulate both the timing and magnitude of harvest impacts to stream N regimes. Thus, the overall objective of this study was to explore how biogeochemical N cycling within hillslopes was affected by clearcut harvesting, and determine association of these changes with watershed scale export of N. Within hillslopes, this research builds on the spatial structure investigated in Chapter 2 (hillslope position and aspect) to focus on temporal patterns in soil and pore water N and their relationship with watershed N yield during and the period previous to this study.

3.2 Methods

3.2.1 Study Area

Star Creek watershed is situated in the Rocky Mountains of south-western Alberta (49°37′ N, 114°40′ W). A detailed description of Star Creek watershed is reported in Chapter 2. Star Creek watershed is a third-order stream which drains into the Crowsnest River that forms the central headwaters of the Oldman River Basin, the highest water-yielding area in Alberta (Silins et al., 2014). Star Creek watershed was logged using three separate harvesting practices (clearcutting, strip-shelterwood, and partial-cut harvesting) during January to October of 2015 (Figure 3-1). Most of the harvesting took place within the upper montane ecozone which has vegetation primarily dominated by lodgepole pine (Pinus contorta var. latifolia). Prior to the commercial harvesting in 2015, Star Creek watershed was relatively undisturbed with historical disturbance only due to seismic exploration cut lines and ATV trails.

3.2.2 Study Design

The study employed a factorial (2^3), post-hoc reference/impact study area design (described in Chapter 2) focusing the Star Ck. West-fork where 55.7 ha. were clear-cut harvested (with patch retention) in 2015. This study was focused on evaluating the comparative seasonal N dynamics within harvested/reference forests (2 land disturbance classes) governed by slope aspect (2 aspect classes; north and south facing slopes) and slope position (2 slope position classes; upper hillslopes versus lower slope/riparian forests). Five plots were randomly established in harvested and reference sites each containing the 2 aspect and slope position classes above (Figure 2-1, Chapter 2).

3.2.3 Soil Nutrient Availability (Supply Rate) by PRS® Probes

Plant Root Simulator (PRS®) anion and cation exchange resins (Western Ag Innovations, Saskatoon, Canada) were used to measure soil nutrient supply rates from 5 replicate plots across all 8 study sites as described in Chapter 2. The nutrient supply rate was measured over four consecutive periods, across the spring through fall frost-free season in 2016 (1: April 9 - May 23, 2: May 23 - July 7, 3: July 7 - August 21, 4: August 21 - October 3) representing seasonal variation of soil N supply rate across the spring to late fall hydro-climate and growing season characteristic of this region.

3.2.4 Water Geochemistry (Pore and Stream)

To explore the relationship between temporal patterns in soil N supply rate with N concentration in hillslope pore water, pore water was sampled from one randomly selected plot within each of 8 treatment combinations described above. Hillslope pore water was sampled using suction lysimeters constructed from 1 m long 1.5″ PVC pipe-fitted to 0.05 MPa (1/2-bar) porous cups (Soil Moisture Equipment Corp., Goleta, CA) installed at each plot. Lysimeters were installed into augured holes (40-45 cm deep) in early May, 2016 and back-filled. Hillslope pore water was sampled with a hand pump 24-72 hours after applying a minimum of 50 kPa (½-bar) suction to sealed lysimeters by hand pumping. A minimum of 120 mL was required for 30 mL of final sample volume required for chemical analysis (needed for bottles to be triple rinsed). If fluid was present in a lysimeter, there was always at least 120 mL available for sampling. Pore water was sampled on five dates (May 5 and 11, June 8 and 22, August 10, 2016). Spatial and seasonal variation in soil moisture was too low in some plots to permit sampling pore water from all sites and dates. No pore water sampling was possible from any of the upper slope plots and only a variable number of lower slope / riparian plots resulting in a variable number of plots sampled during only 5 dates from early May-Aug (17 samples total). All samples were collected in acid-washed (10% HCl) and triple-rinsed high-density polyethylene bottles then placed in a cooler. Samples were subsequently refrigerated at 4 °C and transported to the laboratory for analyses within 3 days after collection.

Stream N concentration in Star Ck. West (clearcut harvested) and nearby North York Ck. (unharvested reference watershed) has been monitored throughout the years since 2009 as a part of the SRWP study (Silins et al., 2014). While this study is focused on post-harvesting N dynamics in 2016 (1st full growing season after the 2015 harvest), these data are included here because they provide direct insights on watershed scale N production during both the year of harvesting and 1st post-harvest year. Samples were collected every 10-14 days during the ice-fee season and every 30-40 days during overwinter baseflow periods (approx. 18-25 samples/yr.) Stream water samples were collected in acid-washed (10% HCl) triple-rinsed high-density polyethylene bottles and stored at 4°C before being transported to the laboratory for analyses within 4 days after collection. Streamflow (Q) was measured using standard area-velocity current metering techniques with a Swoffer velocity meter (Model 2100, Swoffer Instruments Incorporated, Seattle, WA, USA) or a Sontek acoustic doppler velocity meter (Flow Tracker ADV, Sontek/YSI, San Diego, CA, USA) on the West Fork of Star Ck. (above the confluence with Star Ck. East Fork) and upper North York Ck. (Figure 3-1) Measurements of Q occurred approximately every 14-days throughout the snow free period, with the frequency increased to every 7-days during peak snow melt. Stage readings were measured simultaneously from staff gauges to derive stage-discharge relationships for each stream. Continuous Q was then determined from continuous stage measurements recorded at 10-minute intervals using a gas bubbler (Waterlog Model H-350 Lite and H-355, Design Analysis Associates Inc., Logan, UT, USA) connected to a Campbell Scientific CR1000 datalogger (Logan, UT, USA).

Both pore and stream water samples were analyzed for NO_3^--N (NO_3^--N; 0.7 mm filter), TN (unfiltered), and TDN (0.45 mm filter) concentrations by automated cadmium reduction (Method 4500; NO_3^--N:F) using a Lachat QuikChem 8500 multichannel flow injection analyzer (Greenberg et al., 1999). NH_4^+-N concentrations were determined by the standard automated phenate method (Method 4500; NH_3:H; 0.7 mm filter) (Greenberg et al., 1999). Because NH_4^+-N was steadily below the method detection limits (2 μg L^{-1}) in streamwater, it was excluded from the results. All pore and streamwater analysis was carried out by the University of Alberta's Biogeochemical Analytical Service Laboratory (BASL).

3.2.5 Hydrometric (Soil Moisture and Temperature) and Short Wave Radiation

Soil nutrient availability data among each of the four burial periods showed a strong right-skew. Thus, soil N for each period were evaluated using the Kruskal-Wallis median test. Hotspots were defined as (greater than Q0.75 + 1.5 x IQR) and extreme (greater than Q0.75 + 3.0 x IQR) (Harms and Grimm, 2008) values across sampling locations (Pennock et al., 1992). Hotspots occurring for two or less consecutive burial periods are considered hot moments. Streamwater inorganic N was evaluated using a paired catchment regression approach (analysis of covariance; ANCOVA) to test for differences in relationships between flow-area weighted NO_3^--N, TDN, and TN yield (kg/ha/yr) in Star Ck. West Fork (clearcut harvested) and North York Ck. Upper (reference) for both the pre-harvest (2009-2014) and post-harvest (2015-2016) periods (Clausen and Spooner, 1993). Where differences in pre- and post-harvest regression relationships between harvested and reference watersheds were evident (α<0.05), differences in regression slopes and intercepts were tested. Statistical analyses were performed using R statistical software (Version 3.4.1).

3.3 Results

3.3.1 Temporal trends in soil N availability (supply rate)

In general, NH_4^+-N and NO_3^--N supply rates declined after the snowmelt freshet and continued to decline through the end of the active growing season followed by an increase during the late summer/fall (Table 3-1, Figure 3-4). Spatial trends (discussed in Chapter 2) such as south-facing riparian zones dominating the NO_3^--N supply compared to other locations or differences between harvested and reference sites were generally consistent across all four burial periods. However, the magnitude of spatial contributions varied among burial periods with greater mineral N availability in early spring and late summer/fall. NH_4^+-N showed greater median supply rates than NO_3^--N, but the stotal seasonal combined supply rate of NO_3^--N was greater (1076.24 μg 10 cm^{-2} 6 mo^{-1}) than NH_4^+-N (513.25 μg 10 cm^{-2} 6 mo^{-1}) because of high NO_3^--N found at hotspots.

The study period began during the later stages of the snowmelt freshet (April 9 - May 23, 2016), with a median supply rate of 1.10 μg N 10cm^{-2} 6 wk^{-1} for both NH_4^+-N and NO_3^--N (p=0.344, Table 3-1, Figure 3-5). Over this 6-wk period, air temperatures remained relatively steady with a mean temperature of 7.3℃, (Environment Canada, 2016). There were 12 hot moments during the April 9 - May 23, 2016 burial period, 10 of which were by NO_3^--N (Table 3-2a, 3-2b) representing only 15% of the hot moment occurrences, but these constituted 42% of the total season supply rate. By the end of the first burial, patches of snow had melted, and the mineral soil layer was well thawed. Vegetation began to grow by the second week of May (Figure 3-3). While median NH_4^+-N supply rates were significantly higher than NO_3^--N supply rates for both May 23 - July 7 and August 21 - October 3, 2016 burial periods (p=0.001, Table 3-1), median NO_3^- supply rates were significantly higher than NH_4^+-N supply rates during burial period 3 ($p<0.001$, Table 3-1). Through the end of May and into early July, the mean air temperature was 12.0°C, (Environment Canada, 2016), during which time considerable growth of grasses and small shrubs had occurred. During this period, median NH_4^+-N and NO_3^--N supply rates dropped to 1.06 and 0.00 μg N $10cm^{-2}$ 6 wk^{-1} respectively. There were only 6 instances of hotspots from both May 23 - July 7 and July 7 - August 21, 2016, all of which were for NO_3^--N (Table 3-2a, 3-2b). While these 6 measurements represented only 8% of the observations during these periods, they constituted 92 and 79% of the total NO_3^--N supply rates in burial periods 2 and 3 respectively.

By the end of July, median temperature had reached a study period high of 14.4°C (Environment Canada, 2016) and vegetation was dense and lush in all study areas. Median supply rates were 0.27 for NH_4^+-N and 1.00 μg N $10cm^{-1}$ 6 wk^{-1} for NO_3^--N. From August 21 - October 3, 2016 the mean air temperature dropped to 10.5°C (Environment Canada, 2016), and vegetation was progressively dying (in the case of annual grasses; Figure 3-3). August 21 - October 3, 2016 had the greatest combined supply rates comprising 48 and 51% of the total study NH_4^+-N and NO_3^--N respectively (Table 3-3a, 3-3b). Every study site except for the north-facing riparian site within the harvest had at least one occurrence of hotspots during this final burial, amounting to 21 hotspots (Table 3-2a, 3-2b). These 21 hotspots represented 26% of all observations during this period and constituted 86% of the total NO_3^--N supply rate.

The occurrences of N hot moments were strongly variable by soil depth. N supply measurements located below the organic layer at the organic/mineral layer interface produced 5 and 6 instances of NH_4^+-N and NO_3^--N hot moments (respectively) (Table 3-4). However, in the deeper mineral layer, while only 2 instances of NH_4^+-N were observed, 32 hot moments were evident NO_3^--N. Depth played a stronger role in overall NO_3^--N supply rates particularly due to the occurrence of deeper NO_3^--N hotspots. While the total NH_4^+-N supply rate from each layer did not vary by >12% (Table 3-3), the deeper mineral layer constituted substantially greater overall supply rates for NO_3^--N representing 65, 95, 90, and 88% of the total supply rate over the four burials respectively. While mean NO_3^--N was affected by soil depth due to the increased occurrence of hotspots, burial depth did not have a substantial impact on median supply rates in each individual burial period (Figure 3-4).

3.3.2 Seasonal variation in pore water N and harvest effects on stream N yield

Sampling of soil pore water was not possible in all lysimeters because of seasonal variation in soil moisture; only the north-facing riparian lysimeters within the harvest could be sampled over all 5 sampling dates (Tables 3-5a, 3-5b). Furthermore, because pore water could only be sampled at 2 lysimeters in harvested sites, and 3 in reference sites, no conclusions regarding harvesting effects on pore water N were possible. Although NO_3^--N is the more soluble inorganic form of N, the concentration of pore water NH_4^+-N was generally greater than NO_3^--N for lysimeters that enabled pore water sampling. The north-facing riparian lysimeter within the harvest was always nearly full of water compared to other sites and by June had NH_4^+-N concentrations more than 17 times greater than the second highest concentration observed in any other lysimeter. However, this was not true for the south-facing reference riparian site where NH_4^+-N was 1.6 times greater than NO_3^--N on May 11, but declined during the growing season when NO_3^--N was 1.6 and 8.2 times greater than NH_4^+-N on June 8 and 22 respectively.

Watershed area-flow weighted yield of NO_3^--N, TDN, and TN (streamwater, kg ha^{-1} yr^{-1}) were paired by date to explore linear relationships between the reference (Upper North York Ck.) and harvested (Star Ck. West Fork) watersheds during the pre-harvest (2009-2014) calibration period and the post-harvest period (2015-2016). However, preliminary analysis clearly illustrated that while the pre- and post-harvesting relationships for NO_3^--N, TDN, and TN appeared to be unaffected by harvesting, 3 individual observations during and after a large rainstorm (rain on snow) during the period May 25, 26, and June 2, 2015 showed strongly divergent relationships from the pre-harvest calibration period. Because the subsequent N yields showed no meaningful divergence from pre-harvest calibration relationships, separate linear relationships were developed for this storm and immediate post-storm period to avoid potential bias from this event in the interpretation of post-harvest relationships. Pre-harvest calibration relationships between reference and harvested watersheds were significant and reasonably precise ($p<0.001$; $R^2>=0.77$,) for NO_3^--N, TDN, and TN (Figures 3-6, 3-7, and 3-8). The post-harvest relationships for the late May storm event showed strongly elevated N production representing 554, 447, 449% increases in NO_3^--N, TDN, and TN yield, respectively, were produced by this single event ($p<0.001$, all caused by a change in slope, Table 3-6). However, there was no evidence that harvesting produced any detectable change in N production for any of the N species prior to, or after this individual event ($p>0.20$, Table 3-6).

3.3.3 Harvest effects and temporal patterns of soil moisture, temperature, and radiation.

In May 1, 2016 when sensors were installed, soils were moist, and temperatures were cool. Soil temperatures increased, and soil moisture decreased in the early part of the growing season until early Aug. followed by cooler wetter conditions through Sept. and Oct. (Figures 3-9, 3-10, 3-11, 3-11). As expected soil moisture is not as variable as soil temperature, likely due to comparatively few large precipitation events throughout the study. Soil temperature generally followed seasonal trends in air temperature and solar radiation (Figure 3-13). Generally, short wave radiation peaked around mid-June for all upper hillslope sites (Figure 3-13). From mid-June, short wave radiation steadily decreased through the end of the study. Peak short wave radiation was reached the first full day after sensors were installed (June 1, 2016). Peak daily short wave radiation was affected by both aspect and harvesting; 375.58 w/m^2 on June 15, 2016 in the north-facing clearcut, and 67.68 and 62.53 w/m^2 for sensors located in north (June 17, 2016) and south-facing (June 20, 2016) upslope reference sites respectively. The back-filled solar daily maximum insolation for the south-facing clearcut sensor was 359.85 w/m^2 on June 20, 2016. From June 1, insolation decreased as the growing season progressed reaching lowest recorded insolation values on their last full active day (Oct 3, 2016). Solar radiation was much greater within the clearcut sites as there was no canopy cover to block the sun.

Precipitation and stream discharge varied greatly from year to year with 2013 having the largest peak daily discharge, and 2016 having the lowest. The largest rainfalls in 2016 occurred in early June with rainfall reaching 11.3 mm/d in Stark Ck. and 7.5 mm/d in North York Main (Figure 3-14). Storms events during the two post-harvest years variable with 2015 having two large back to back storm events starting on May 26, and June 2 yielding 29.87 and 59.08 mm day^{-1}, respectively (Figure 3-14). While 2016 overall had lower maximum precipitation and stream discharge, higher discharges were sustained for a longer period of time, possibly due to a slower more sustained snowmelt period in 2016. Both harvest years had peak discharges that occurred between June 2 and June 3.

3.4 Discussion

3.4.1 Temporal trends in soil N availability (supply rate)

Temporal patterns in soil N supply rates varied inversely with observed patterns in vegetative growth one year following clearcut harvesting in the Crowsnest Pass. After early spring, N supply rates in both shallow and deeper soil layers declined coincident with higher soil temperatures near mid-late summer when vegetation growth peaked. As cooler, wetter fall conditions appeared, vegetation became dormant, and N supply rates increased to their highest values during the study. This is consistent with previous research showing seasonal variation in N uptake and low summer N supply rates during the growing season in other high elevation forests (Jaeger et al., 1999).

Median supply rates and ranges for NH_4^+-N and NO_3^--N were similar in late spring (end of spring freshet) when soils were still thawing and processes promoting N mineralization and mobilization were likely only beginning. The lack of vegetative N demand is likely why both species of inorganic N were similar during this period. However, by mid-summer (burial periods 2 and 3) NO_3^--N declined strongly especially within shallow soil layers. Given the low NO_3^--N supply rates, it is possible that there were either greater losses of NO_3^--N (e.g. denitrification, assimilation, leaching) or a decline in nitrification. However, a rise in maximum NO_3^--N supply rates in deeper soil layers suggests that N was still being mineralized and a combination of both vegetative/microbial uptake and perhaps some downward leaching of NO_3^- rather than a decline in nitrification was the likely cause of low NO_3^--N supply rates in surface soils. Similar decreases in available NO_3^--N because of uptake due to vegetative growth and microorganism competition during decomposition in the mineral layer have been suggested by other researchers (D. W. Johnson et al., 2009). Plants and soil microorganisms compete for mineral N (Jaeger et al., 1999; Kaye & Hart, 1997; Kuzyakov & Xu, 2013) and while microorganisms have been shown to take up most of the N after release from soil organic matter, in the long term plants tend to dominate N acquisition due to the unidirectional flow of soil nutrients to plant roots (Kuzyakov and Xu, 2013). This competition for mineral N between vegetation and microorganisms is thought to buffer losses due to leaching (Kuzyakov and Xu, 2013). However, leaching is still possible if hydrological connectivity is present, as higher amounts of mineral N were found in deeper mineral layers.

The presence of hotspots provided a differentiating feature among N species, study locations, and burial periods. Consistent with observations of NH_4^+-N and NO_3^--N hot moments below the shallow organic soil layer, other studies report similar hotspots just below the soil duff layer (Darrouzet-Nardi & Bowman, 2011; Johnson et al., 2010). However, both studies did not consider deeper soil layers (>10 cm depth). The most significant NO_3^--N hot moments were observed in deeper soil layers and accounted for the majority of Inorganic N (78%). These findings reinforce suggestions by Morse et al. (2014) that researchers may be underestimating important sources of watershed N when deeper mineral layers are ignored. Indeed, these deeper layers would be important pathways for sub-surface leaching and transport to stream networks.

NO_3^--N accounted for 2.10 times more than NH_4^+-N in the total available inorganic N primarily because of large flushes in hotspots within the deeper mineral layer of south-facing riparian soils This finding is consistnt with findings by others that N hotspots are often found at aquatic-terrestrial interfaces where hydrological flow paths converge creating meeting points for reactants (McClain et al., 2003). In the case of Star Creek, the south-facing riparian zone behaved very differently from the north-facing riparian zone. Vegetation on south-facing riparian zones in Star Creek was less dense than on north-facing slopes, thus it is possible that less vegetative N demand, and greater solar radiation reaching the ground surface may have promoted greater decomposition coupled with lower uptake by vegetation partially explaining the greater pulses of N observed within these areas.

Similar to findings by Darrouzet-Nardi and Bowman (2011), locations with hotspots were highly variable throughout the study period. In contrast to considering seasonal N turnover dynamics from the perspective of broader spatial/temporal averages, the notion of N hot moments becoming active at different times during the year can provide greater insight into important temporal and spatial elements that may drive larger watershed scale biochemical responses. For example, key N hot moments for NH_4^+-N and most NO_3^--N extreme values were observed in spring and late summer/fall (burial periods 1 and 4), with the largest occurrence in the fall (period 4), accounting for 21 of the 47 total extreme values. The notion of timing of biogeochemical hot moments in relation to periods promoting greater N availability during periods of lower microbial activity or vegetative uptake serves to highlight key periods when available N may correspond with greater soil moisture (spring or fall) that may promote greater hydrologic connectivity (Harms & Grimm, 2008). This may provide key insights into temporal patterns of hydrologic connectivity when N transport to streams is either less likely or more likely to occur.

3.4.2 *Seasonal variation in pore water N and harvest effects on stream N yield*

Available N found in pore water across study sites and periods did not align with results captured by PRS® ion exchange resins. While limitations to pore water sampling severely reduced the ability to sample across the harvesting and aspect units, some limited inferences are still supported by these results. In particular, NH_4^+-N in pore water was much greater than available NO_3^--N by an order of magnitude and this finding is consistent with observations in other studies in Lodgepole Pine forests (Asam et al., 2014). It should be noted that while pore water showed much greater levels of NH_4^+-N than NO_3^--N, and ion exchange resin samples showed more similar levels of NH_4^+-N and NO_3^--N, these two techniques measure different pools on N. Pore water is more of an indication of nutrient fluxes, while ion exchange membranes approximate plant root uptake (Dale W. Johnson et al., 2005), though the two may be used together to get a better idea of the entire system. Four soil pore water samples even had readings less than method detection limit for NO_3^--N, while NH_4^+-

N values in the same samples were 5 - 1180 μg N/L. These discrepancies between pore water and PRS® results could be a result of lysimeters sampling at a much greater depth, where anoxic conditions could halt nitrification, and promote denitrification. Further, these deeper layers could be beyond the major root systems such that pooled NO_3^--N has been taken up by growing vegetation (Johnson et al., 2009).

Stream N was affected (increased) by clearcut harvesting only during one series of heavy rains occurring immediately (3-4 months) after harvesting (May 25, 26, and June 2, 2015). While these rainfall events were not unusual, they were the largest rainfalls during the 1st two years after harvesting (2015 and 2016). It is possible that a pool of available mineral N was available during this 1st post harvest snowmelt freshet in combination with high antecedent soil moisture allowing a transient pulse of mineral N to be transported to Star Ck. However, it is important to note that except for this one event, no increase in stream N yield was evident in Star Ck. either before or after this event including the entire 2016 period. Thus, harvesting had little effect (other than the one series of spring storms) on stream N yield in 2015, and no effect on both available soil N and watershed scale production of N one full year after harvesting in 2016.

3.4.3 Harvest effects and temporal patterns of soil moisture, temperature, and radiation

Soil temperature was closely coupled with short wave radiation while soil moisture was more closely linked to precipitation (snowmelt or rain events) as expected (Figures 3-9 to 3-14). In general, as the growing season progressed, soils became warmer and dryer as radiation increased to mid-summer followed by decreased soil temperature/radiation and increased soil moisture in the late summer/fall. Geroy et al. (2011) found soils on north-facing hillslopes retained up to 25% more water than south-facing soils in the Colorado Rocky Mountains. These north-facing slopes store more water from wet winter months, which lasts longer into the dryer summer months and this pattern was also observed in reference stands of the present study. Compared to north-facing riparian soils after harvest, soils in reference stands were noticeably wetter during the early spring and continued to be wetter all season. Hinckley et al. (2012) suggests that north-facing slopes may remain more hydrologically connected through the soil matrix under slower, more sustained snowmelt typical of north facing slopes. Soil moisture in harvested north-facing riparian soils was similar to south-facing riparian sites which receive higher amounts of incoming solar radiation resulting in quick snowmelt with vertical transport of snowmelt (Hinckley et al., 2012).

Other than the May 2015 storm event, no effect of harvesting on stream N yield was evident for any of the N species. The generally lower precipitation and stream discharge observed in 2016 compared to all other years dating back to 2009 may have contributed to limited N mobility during the hillslope N investigation (April - October 2016).

3.5 Conclusion

Temporal patterns of inorganic soil N availability inversely paralleled the seasonal patterns of vegetative growth through the late spring, summer growing season, and onset of fall vegetation dormancy one year following clearcut harvest of Lodgepole Pine in Star Creek watershed. Inorganic N supply and soil moisture declined to seasonal minimum values during the peak of the summer growing season when soil temperatures, solar insolation, and vegetation were at their maximum values (June 15 - August 1, 2016). The largest release of available N throughout all sites occurred in the late summer / fall when both reduced uptake with vegetation dormancy and higher precipitation promoted greater hydrological connectivity. However, the strong presence of NH_4^+-N in deeper pore water provides evidence that anoxic conditions may be preventing nitrification, and promoting denitrification, thereby limiting the release of inorganic N to surface waters, even after a disturbance.

Clearcut harvesting produced no change in hillslope soil N availability or watershed scale production of N in 2016 (1^{st} full growing season after harvesting). While a short duration transient pulse of NO_3^-, TDN, and TN was observed during a short series of rainstorms in the spring 3-4 months after harvesting, no harvest associated effects on stream N regime were detectable prior to, or 1.5 years afterwards, this supports the notion of high potential watershed and ecosystem resistance to harvest impacts on N regimes in this region.

Table 3-1 Soil N supply rates [μg N 10cm^{-2} 6 wks^{-1}] of NH_4^+-N compared with NO_3^--N, and total Inorganic N over the four burial periods (April 9 – October 3, 2016). Differences between NH_4^+-N and NO_3^--N were tested using the Kruskall-Wallis median test and underlined where significant (p<0.05).

	NH_4^+-N		NO_3^--N		
Period	Median	Range	Median	Range	p-value
Apr. 9-May 23	1.10	(0.10,8.60)	1.10	(0.00,10.8)	0.344
May 23-July 7	1.06	(0.00,3.5)	0.00	(0.00,136.96)	0.001
July 7-Aug. 21	0.27	(0.00,4.04)	0.55	(0.00,71.32)	<0.001
Aug. 21-Oct. 3	2.97	(0.74,16.06)	1.00	(0.20,291.12)	0.001
	Inorganic N (NH_4^+-N + NO_3^--N)				
Apr. 9-May 23	2.70	(0.60,12.80)			
May 23-July 7	1.22	(0.00,140.02)			
July 7-Aug. 21	0.96	(0.04,71.54)			
Aug. 21-Oct. 3	4.10	(1.60,294.62)			

Table 3-2 Count of NH_4^+-N (a) and NO_3^--N (b) hot moments where supply rates [µg N $10cm^{-2}$ 6 wks^{-1}] reached moderately extreme (greater than $Q_{0.75}$ + 1.5 x IQR) and extreme (greater than $Q_{0.75}$ + 3.0 x IQR) values within each of the four burial periods (April 9 – October 3, 2016). Hotspots are identified by greater than two but less than four consecutive burial periods 'β' and all four burial periods ' ǂ '.

a) Count of NH_4^+-N Moderate and Extreme Hotspots and Moments
Total (Moderate, Extreme)

Site	Apr. 9-May 23	May 23-July 7	July 7-Aug. 21	Aug. 21-Oct. 3
HNU	-	-	-	-
HNL	-	-	-	-
HSL	-	-	-	-
HSU	1 (0,1)	-	-	2 (0,2)
RNU	1 (0,1)	-	-	-
RNL	-	-	-	1 (1,0)
RSL	-	-	-	-
RSU	-	-	-	2 (2,0)
Total	2 (0,2)	-	-	5 (3,2)

b) Count of NO_3^--N Moderate and Extreme Hotspots and Moments
Total (Moderate, Extreme)

Site	Apr. 9-May 23	May 23-July 7	July 7-Aug. 21	Aug. 21-Oct. 3
HNU β	1 (0,1)	2 (0,2)	-	4 (1,3)
HNL	-	-	-	-
HSL ǂ β	3 (0,3)	1 (0,1)	2 (1,1)	3 (1,2)
HSU	-	-	-	2 (1,1)
RNU	1 (0,1)	-	-	1 (1,0)
RNL β	-	-	1 (0,1)	3 (0,3)
RSL ǂ ǂ	5 (2,3)	3 (1,2)	3 (1,2)	2 (1,1)
RSU	-	-	-	1 (0,1)
Total	10 (2,8)	6 (1,5)	6 (2,4)	16 (5,11)
NH_4^+-N + NO_3^--N Total	12 (2,10)	6 (1,5)	6 (2,4)	21 (8,13)

Table 3-3 Sum of (a) NH_4^+-N and (b) NO_3^--N supply rates within the organic/mineral interface, 20cm deep into the mineral layer, both layers combined and only due to hotspots with percentages of supply rates within the organic/mineral interface, 20cm deep into the mineral layer, and due to hotspots in both layers, and percentage of measurements that are hot compared to total number of measurements within each of the four burial periods [μg N $10cm^{-2}$ 6 wks^{-1}]and throughout the entire study duration [μg N $10cm^{-2}$ 6 mo^{-1}] (April 9 – October 3, 2016). Moderately extreme and extreme values were combined as hotspots.

(a) NH_4^+-N

	Apr. 9-May 23	May 23-July 7	July 7-Aug. 21	Aug. 21-Oct. 3
Interface	73.5	49.43	19.62	136.7
Mineral	58.7	48.64	18.68	107.98
Total	132.2	98.07	38.3	244.68
Hotspots	14.4	0	0	49.26
% from Interface	56%	50%	51%	56%
% from Mineral	44%	50%	49%	44%
% from Hotspots	11%	0%	0%	20%
% Hot Measurements	3%	0%	0%	6%

(b) NO_3^--N

	Apr. 9-May 23	May 23-July 7	July 7-Aug. 21	Aug. 21-Oct. 3
Interface	45.6	15.36	20.64	66.52
Mineral	85.9	178.62	179.08	484.52
Total	131.5	193.98	199.72	551.04
Hotspots	55.4	178.46	157.66	486.7
% from Interface	35%	8%	10%	12%
% from Mineral	65%	92%	90%	88%
% from Hotspots	42%	92%	79%	88%
% Hot Measurements	15%	8%	8%	26%

Table 3-4 Count of NH_4^+-N and NO_3^--N hot moments where supply rates [μg N $10cm^{-2}$ 6 wks^{-1}] reaching moderately extreme (values greater than $Q_{0.75}$ + 1.5 x IQR) and extreme (values greater than $Q_{0.75}$ + 3.0 x IQR) values within the organic/mineral interface and 20cm deep into the mineral layer over the four burial periods (April 9 – October 3, 2016).

	Organic/Mineral Interface		20cm Deep into Mineral	
Site	NH_4^+-N *	NO_3^--N *	NH_4^+-N *	NO_3^--N *
HNU	-	2 (0,2)	-	5 (1,4)
HNL	-	-	-	-
HSL	-	-	-	9 (5,4)
HSU	3 (0,3)	1 (1,0)	-	1 (0,1)
RNU	1 (1,0)	1 (0,1)	-	3 (0,3)
RNL	1 (1,0)	-	-	2 (1,1)
RSL	-	2 (1,1)	-	11 (4,7)
RSU	-	-	2 (2,0)	1 (0,1)
Total	5 (2,3)	6 (2,4)	2 (2,0)	32 (11,21)

* Total Count (Moderate, Extreme)

Table 3-5 Pore water (lysimeters) measurements of (a) NH_4^+-N and NO_3^--N, and (b) TDN and TN [μg N/L] within each sampling location. '-' represent soil water could not be sampled (too dry). '<MDL' represent NO_3^- < 2 μg N/L. 'Err' represents samples which were not tested by the laboratory.

a) NH_4^+-N and NO_3^--N [μg N/L]

Sampling location	5May		11-May		8-Jun		22-Jun		10-Aug	
	NH_4^+	NO_3^-	NH_4^+	NO_3^-	NH_4^+	NO_3^-	NH_4^+	NO_3^-	NH_4^+	NO_3^-
HNU	-	-	-	-	-	-	-	-	-	-
HNL	411	98	629	58	1180	<MDL	1080	3	779	<MDL
HSL	-	-	24	8	9	<MDL	5	<MDL	-	-
HSU	-	-	-	-	-	-	-	-	-	-
RNU	-	-	59	15	29	3	32	4	25	3
RNL	-	-	-	-	33	5	-	-	-	-
RSL	-	-	427	266	67	110	33	269	-	-
RSU	-	-	-	-	-	-	-	-	18	3

b) TDN and TN [μg N/L]

Sampling location	5-May		11-May		8-Jun		22-Jun		10-Aug	
	TDN	TN	TDN	TN	TDN	TN	TDN	TN	TDN	TN
HNU	-	-	-	-	-	-	-	-	-	-
HNL	4960	6450	Err	Err	2950	3160	2180	2310	1750	1945
HSL	-	-	Err	Err	871	1090	883	878	-	-
HSU	-	-	-	-	-	-	-	-	-	-
RNU	-	-	Err	Err	366	414	430	425	482	611
RNL	-	-	-	-	833	1000	-	-	-	-
RSL	-	-	Err	Err	1180	1480	1240	1220	-	-
RSU	-	-	-	-	-	-	-	-	853	1000

Table 3-6 ANCOVA results of paired watershed Streamwater NO_3^-, TN, and TDN observations for North York Upper (Reference) and Star West Fork (Impact) during 'Pre Harvest' (2009-2014) vs. 'Post Harvest' (2015-2016, excluding the May 2015 storm event), and 'Pre Harvest' vs. 'Post Harvest May 25-June 6, 2015 storm event.

Species	Comparison	f/t value	critical F/t	df	p value	Adjusted Mean
NO_3^-	Pre Harvest v. Post Harvest	1.576	3.796	131	0.211	
NO_3^-	Pre Harvest v. Storm	94.387	3.836	97	<.001	7.525
	Slope	0.564	1.985	97	0.574	
	Intercept	61.185	1.985	97	<.001	
TDN	Pre Harvest v. Post Harvest	0.055	3.799	128	0.946	
TDN	Pre Harvest v. Storm	54.833	3.841	94	<.001	7.455
	Slope	0.186	1.986	94	0.853	
	Intercept	54.218	1.986	94	<.001	
TN	Pre Harvest v. Post Harvest	0.294	3.799	128	0.746	
TN	Pre Harvest v. Storm	35.925	3.839	95	<.001	8.178
	Slope	0.698	1.986	95	0.487	
	Intercept	83.761	1.986	95	<.001	

a)

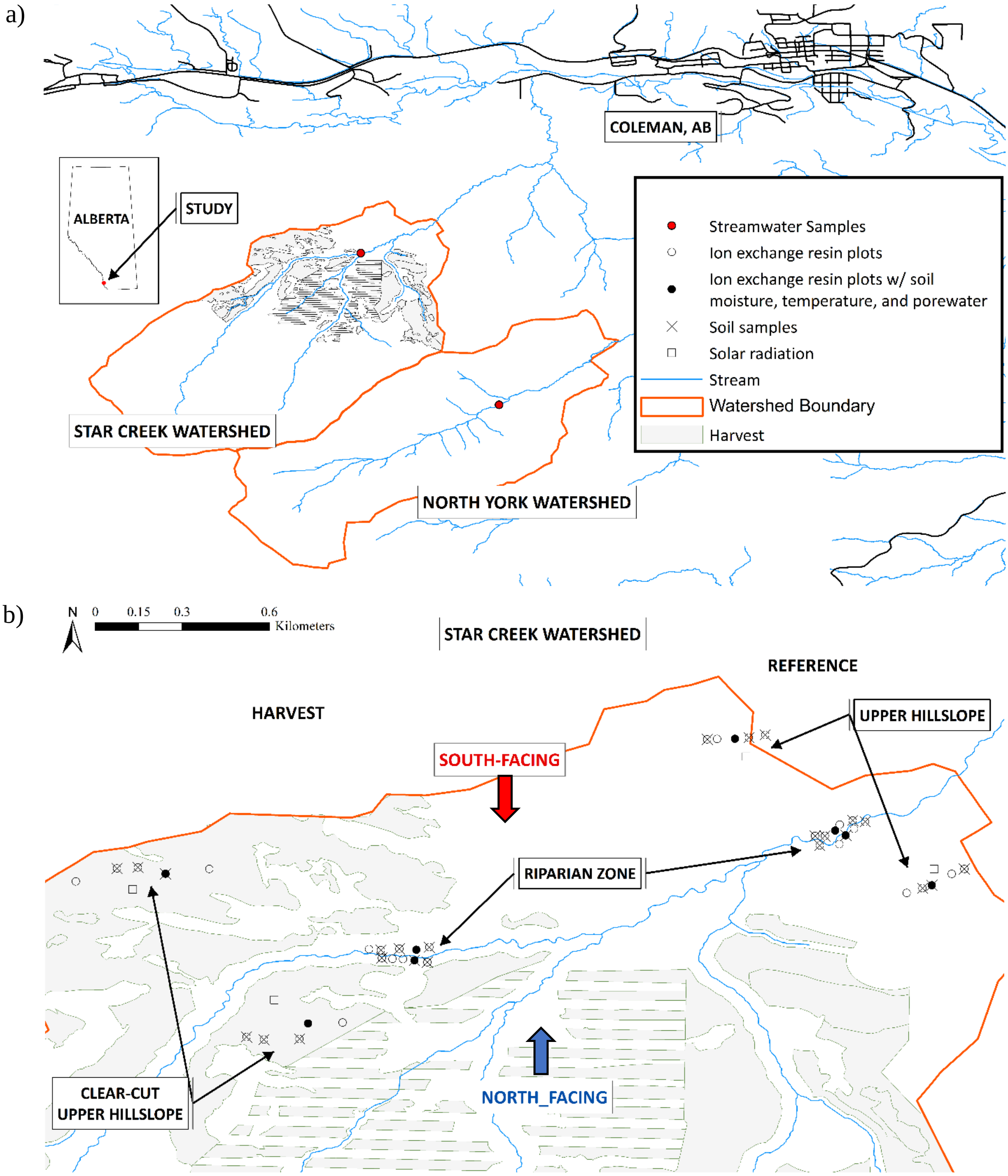

Figure 3-1 The top map (a) shows the location of the study area including watershed boundaries for both Chapter 2 (Star Creek) and Chapter 3 (Star Creek and North York) in relation to Alberta and Coleman, AB. The bottom map (b) shows harvest boundaries (shaded areas), and locations of sampling equipment for both Chapter 2 (excludes pore and stream water) and Chapter 3 (excludes soil samples).

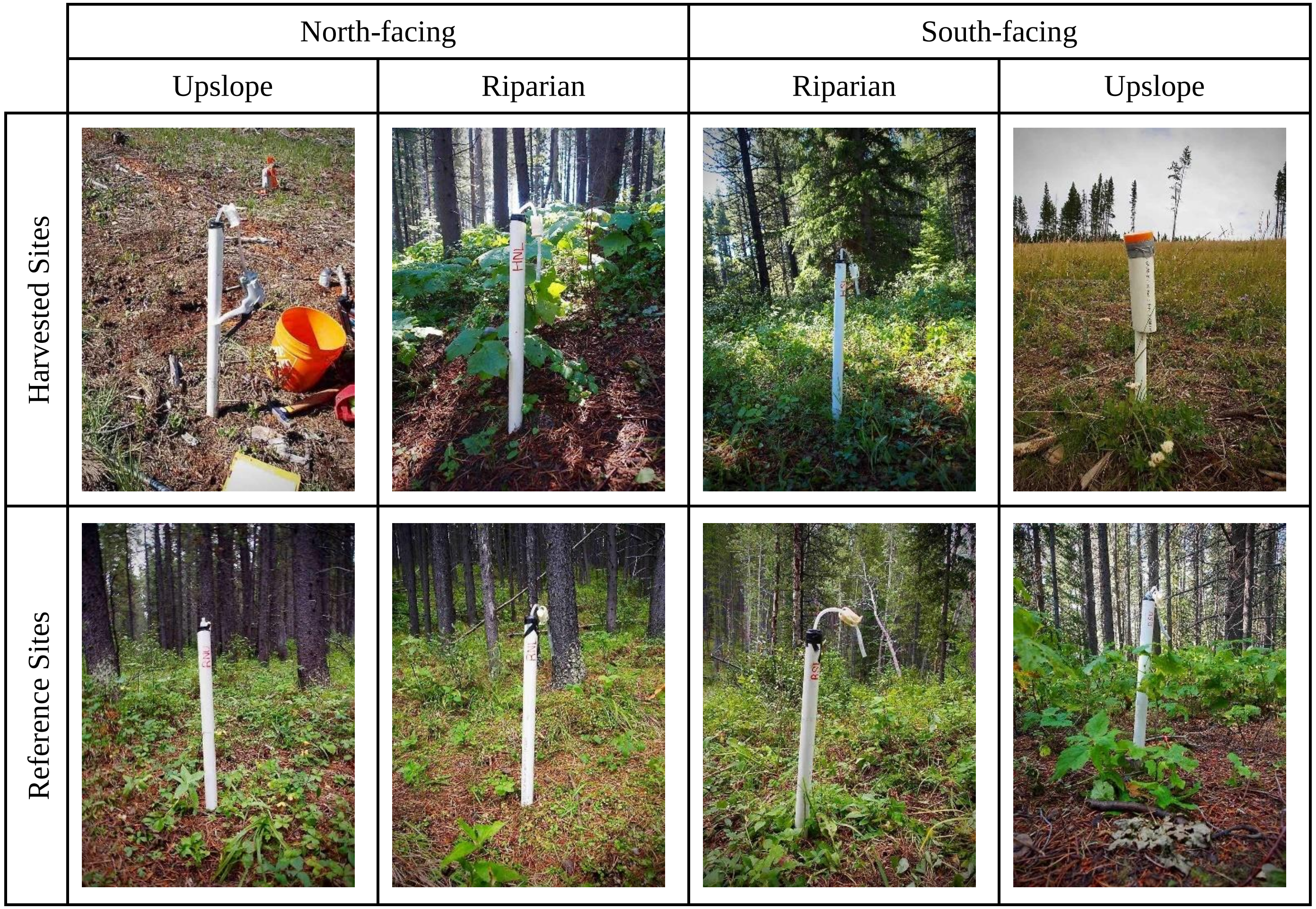

Figure 3-2 Porous suction cup lysimeters buried to a depth of 40 – 45 cm used to sample soil pore water at (top row, left to right: HNU, HNL, HSL, HSU; bottom row, left to right: RNU, RNL, RSL, RSU).

			
April 9, HNU, no vegetation within clearcut, patches of snow	April 9, HNL, minimal vegetation, patches of snow	April 29, HNL, light vegetation	April 30, RNL, very light vegetation
			
May 1, HNU, light vegetation within clearcut	May 31, RSU, thick vegetation	June 20, HNU, thick vegetation	June 20, RSU, thick vegetation
			
August 8, RNL, thick vegetation	August 8, HNU thick vegetation with flowers within clearcut	October 4, RNL, vegetation fading in riparian zone	October 4, HSU, vegetation fading in clearcut

Figure 3-3 Vegetative conditions at a range of locations and times throughout the study period

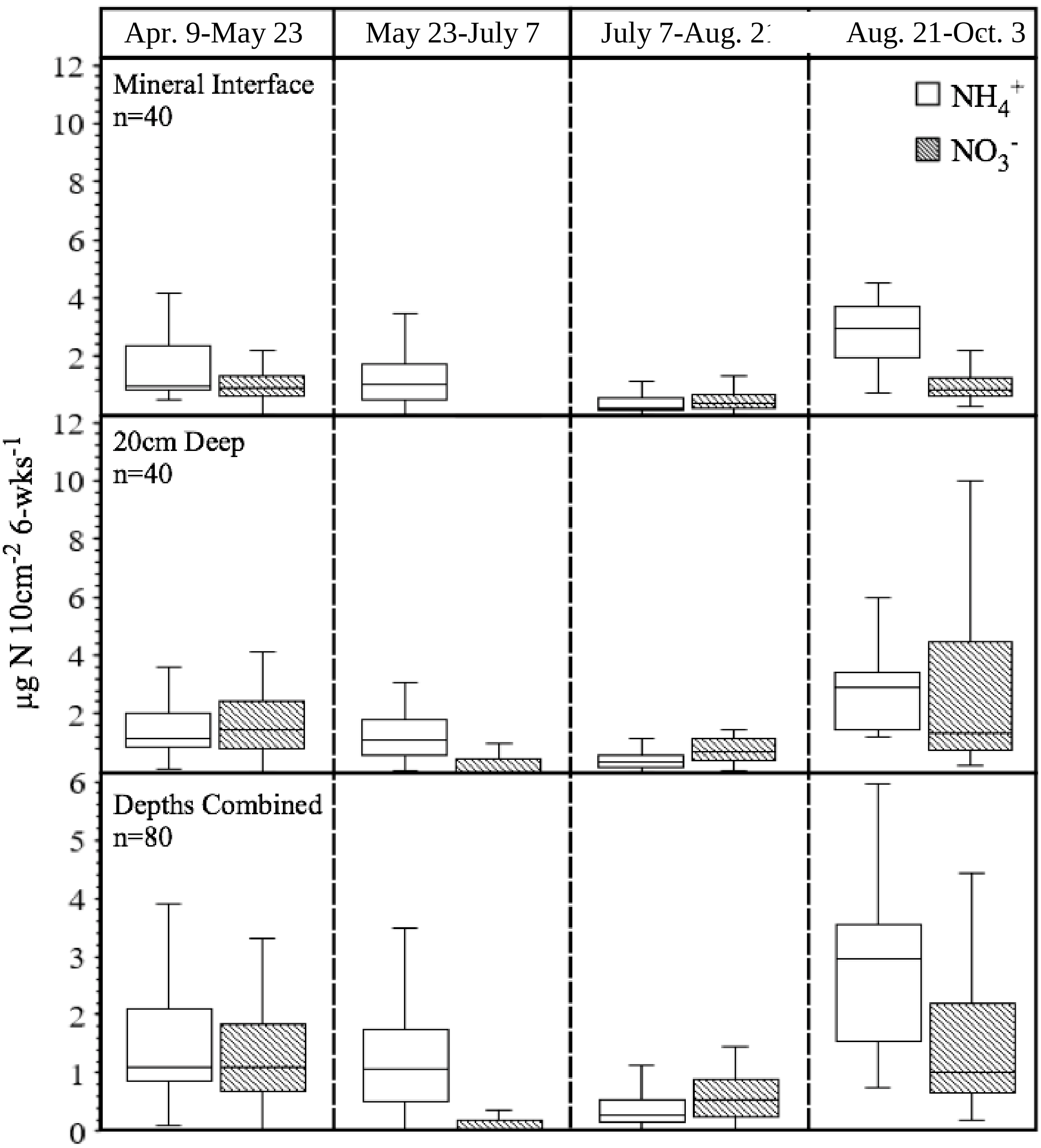

Figure 3-4 Distributions of soil NH_4^+-N and NO_3^--N supply rates within the entire study area over each consecutive 6-week burial period for the organic/ mineral layer interface, 20cm deep into the mineral layer and for both depth combined starting April 9, 2016. Inner horizontal lines indicate median supply rates, lower and upper box positions represent 25th and 75th percentiles, and lower and upper whiskers represent 5th and 95th percentiles. Note that depths combined has a different y-axis scale.

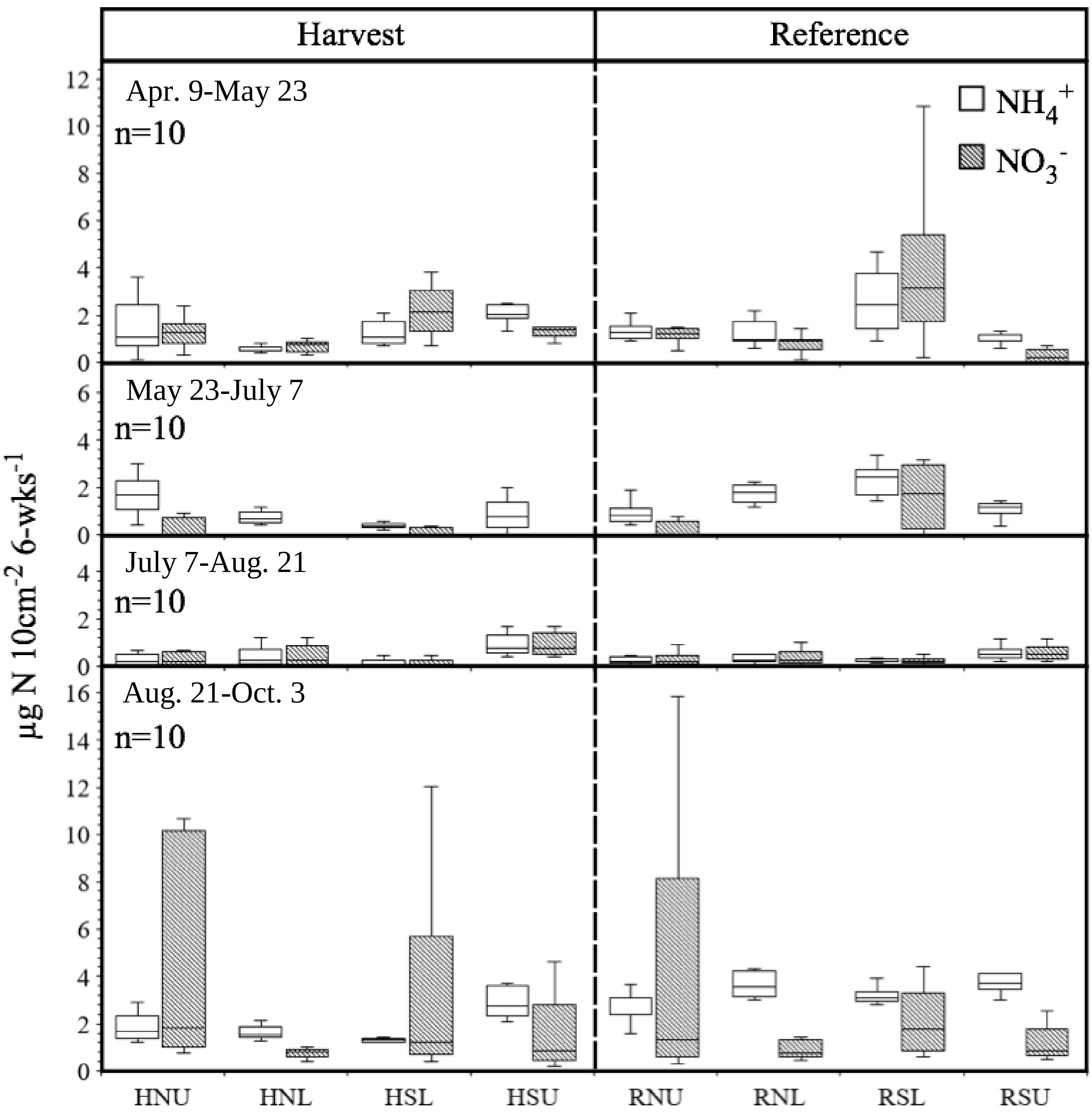

Figure 3-5 Distributions of soil NH_4^+-N and NO_3^--N supply rates within harvest and reference study areas over each consecutive 6-week burial period starting April 9, 2016. Inner horizontal lines indicate median supply rates, lower and upper box positions represent 25th and 75th percentiles, and lower and upper whiskers represent 5th and 95th percentiles.

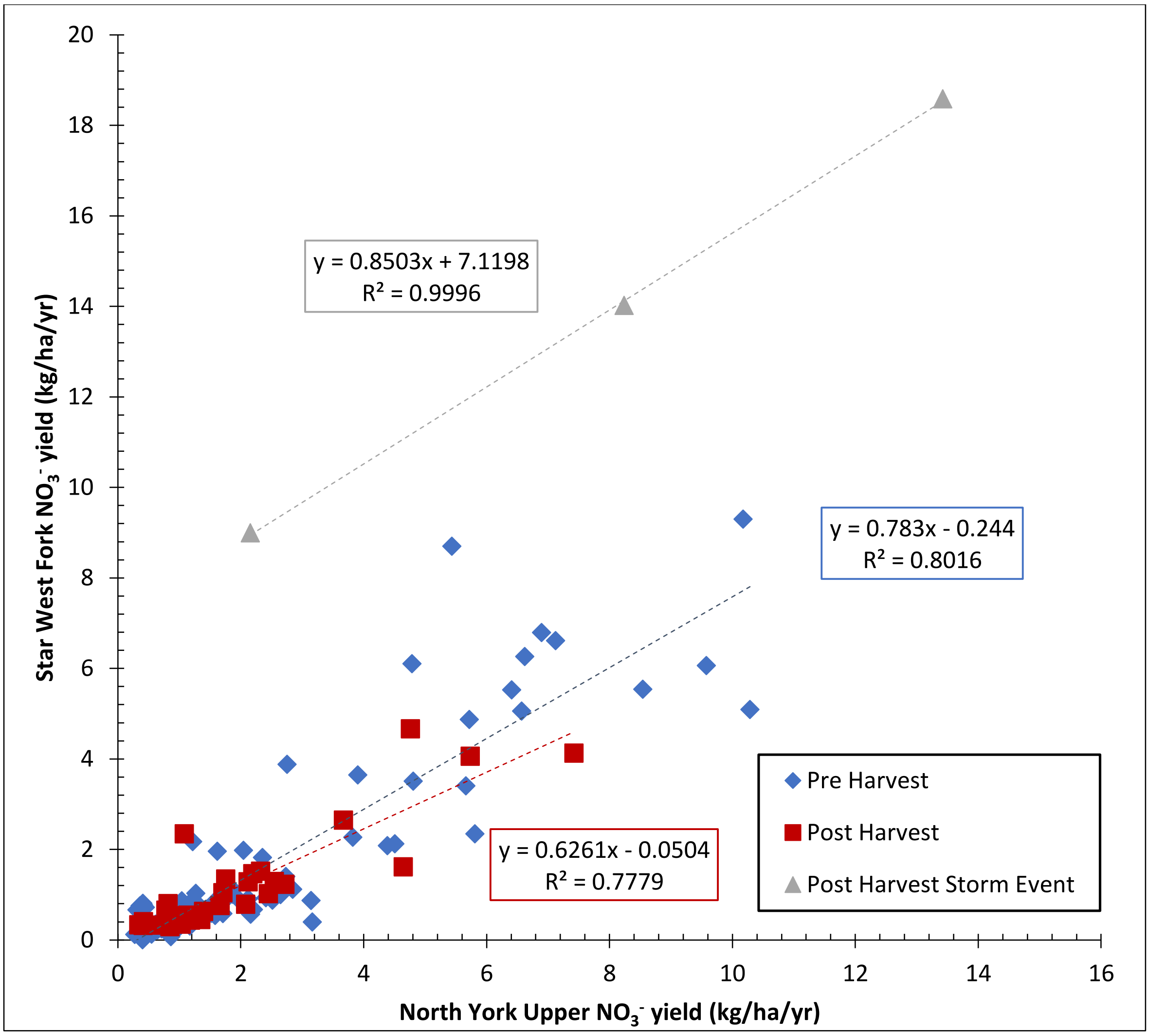

Figure 3-6 Paired watershed NO_3^- observations for North York Upper (Reference) and Star West Fork (Impact) during 'Pre Harvest' (2009-2014), 'Post Harvest' (2015-2016) excluding the May 2015 storm event), and 'Post Harvest May 25 - June 6, 2015 storm event' Linear regression equations of form y = mx + b and correlation coefficient (R^2) displayed for each grouping.

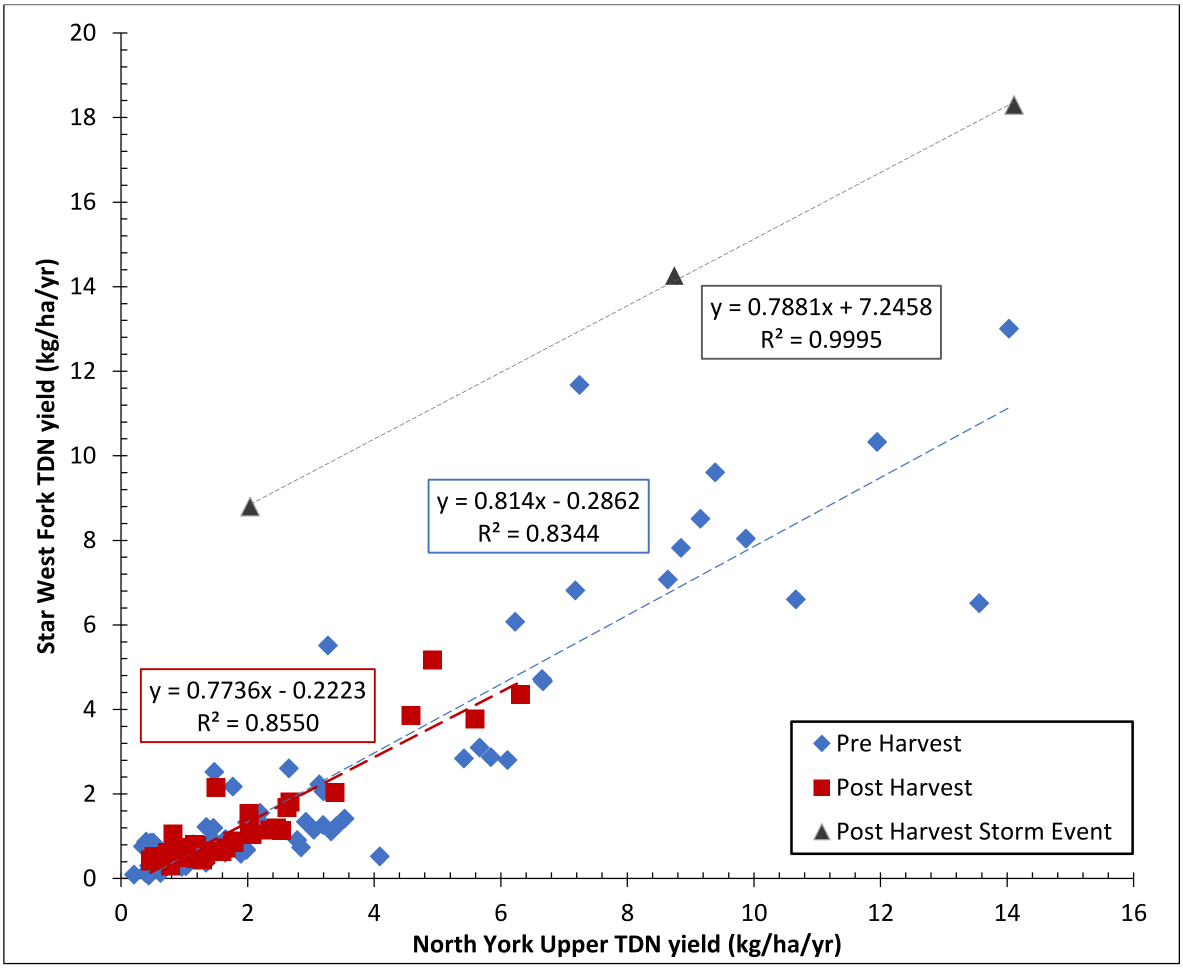

Figure 3-7 Paired watershed TDN observations for North York Upper (Reference) and Star West Fork (Impact) during 'Pre Harvest' (2009-2014), 'Post Harvest' (2015-2016) excluding the May 2015 storm event), and 'Post Harvest May 25 - June 6, 2015 storm event' Linear regression equations of form y = mx + b and correlation coefficient (R^2) displayed for each grouping.

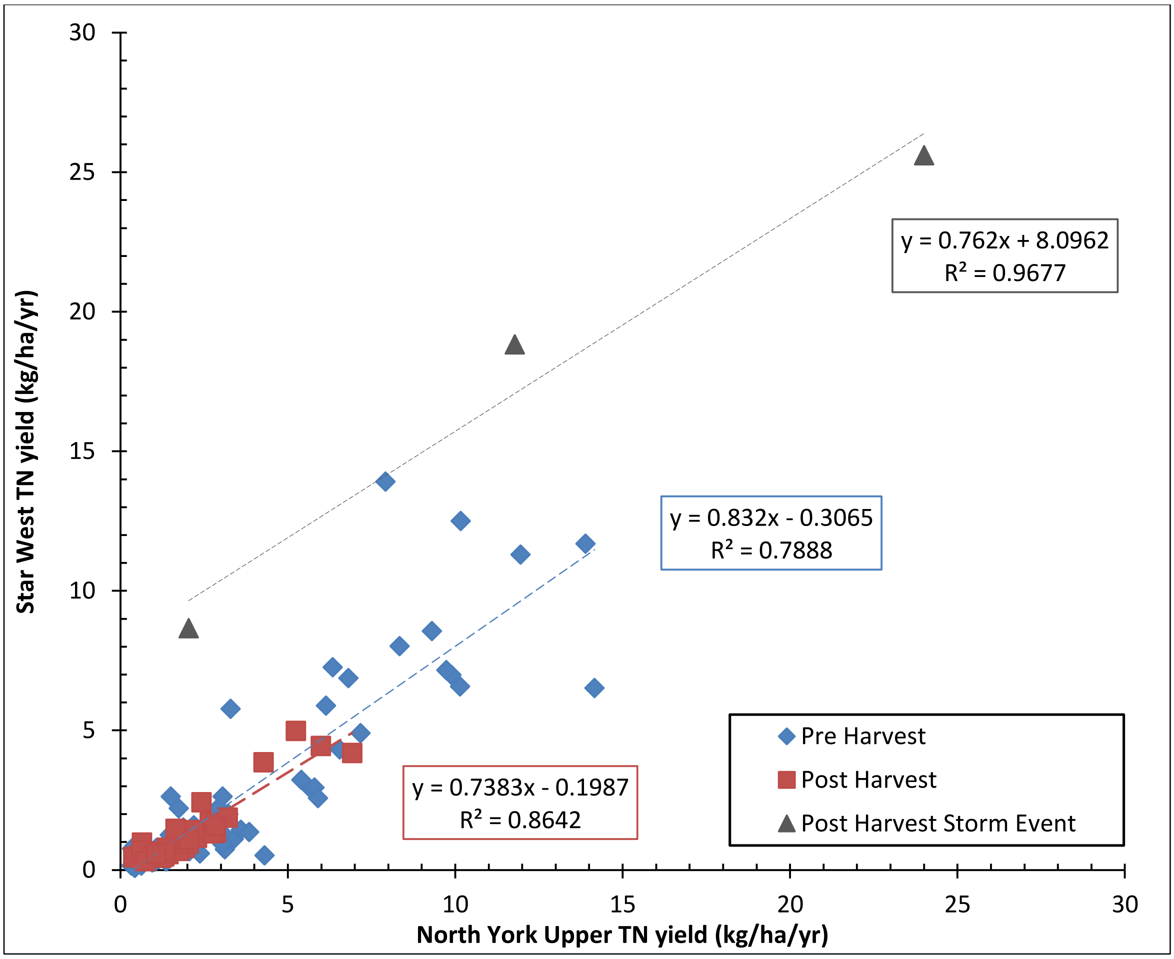

Figure 3-8 Paired watershed TN observations for North York Upper (Reference) and Star West Fork (Impact) during 'Pre Harvest' (2009-2014), 'Post Harvest' (2015-2016) excluding the May 2015 storm event), and 'Post Harvest May 25 - June 6, 2015 storm event' Linear regression equations of form y = mx + b and correlation coefficient (R^2) displayed for each grouping.

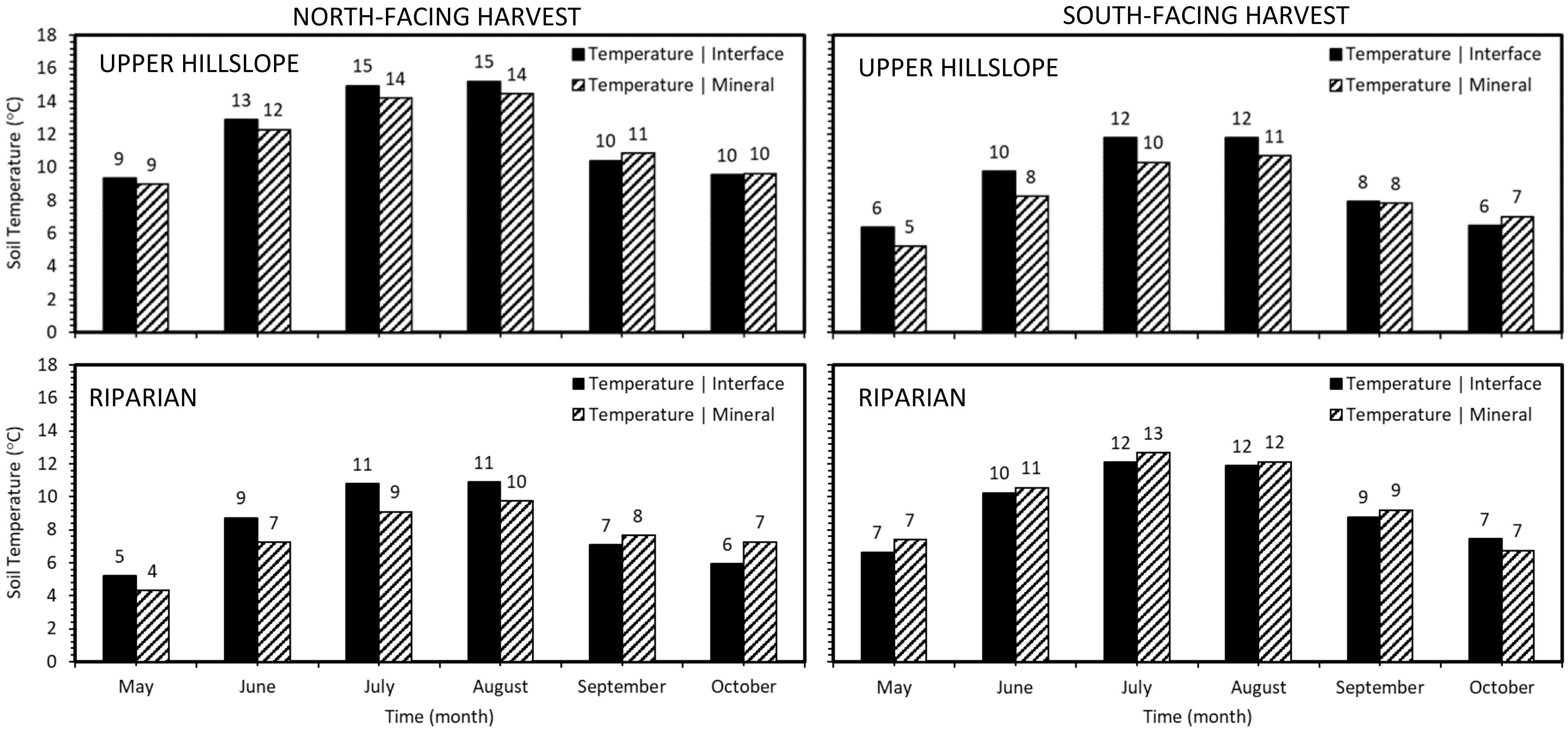

Figure 3-9 Mean monthly soil temperature within the four harvest sites among organic/mineral layer interface (black) and 20 cm deep into mineral layer (grey) over the entire period sensors were installed (May 1 – October 3, 2016). Numbers above each bar represent mean monthly soil temperature (°C). Data for sensors during error periods were excluded.

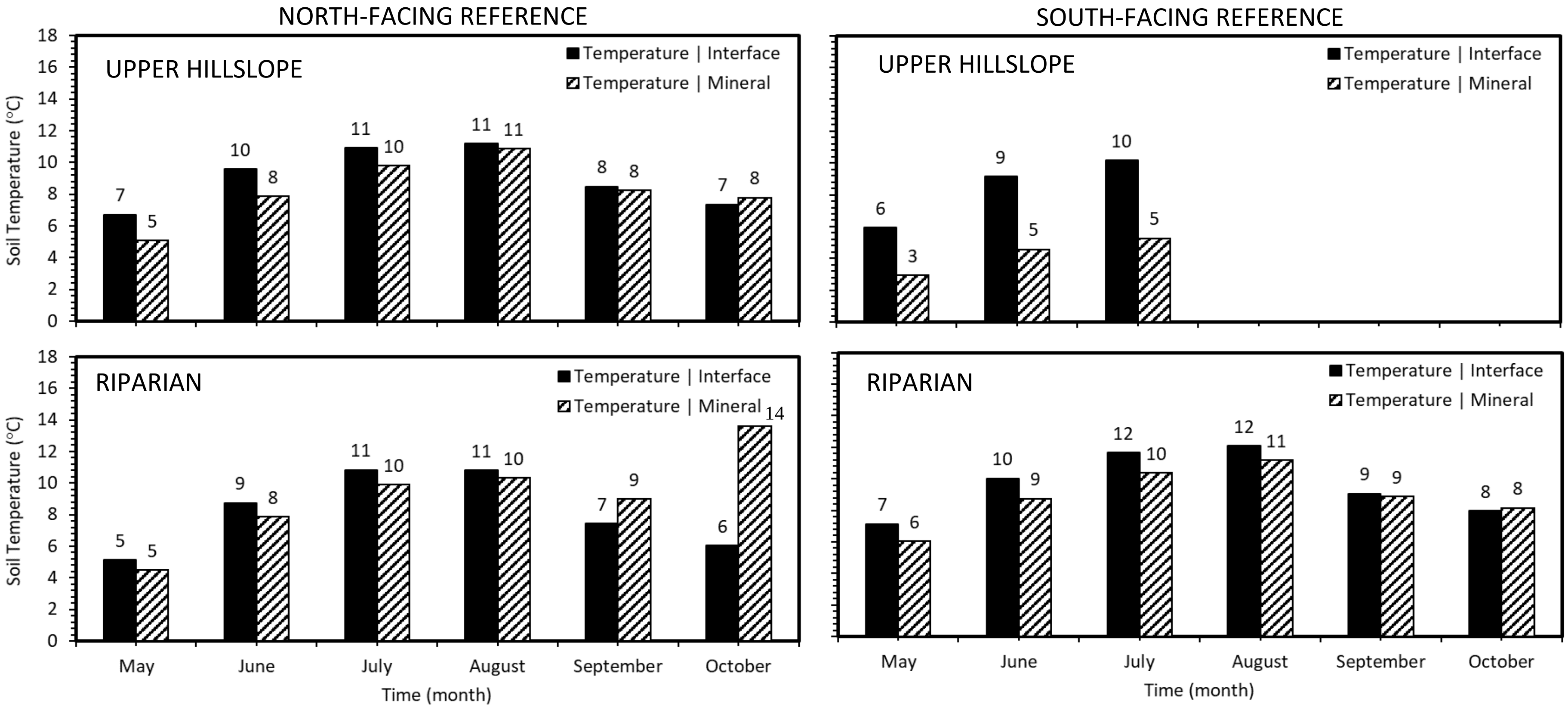

Figure 3-10 Mean monthly soil temperature within the four reference sites among organic/ mineral layer interface (black) and 20 cm deep into mineral layer (grey) over the entire period sensors were installed (May 1 – October 3, 2016). Numbers above each bar represent mean monthly soil temperature (°C). Data for sensors during error periods were excluded.

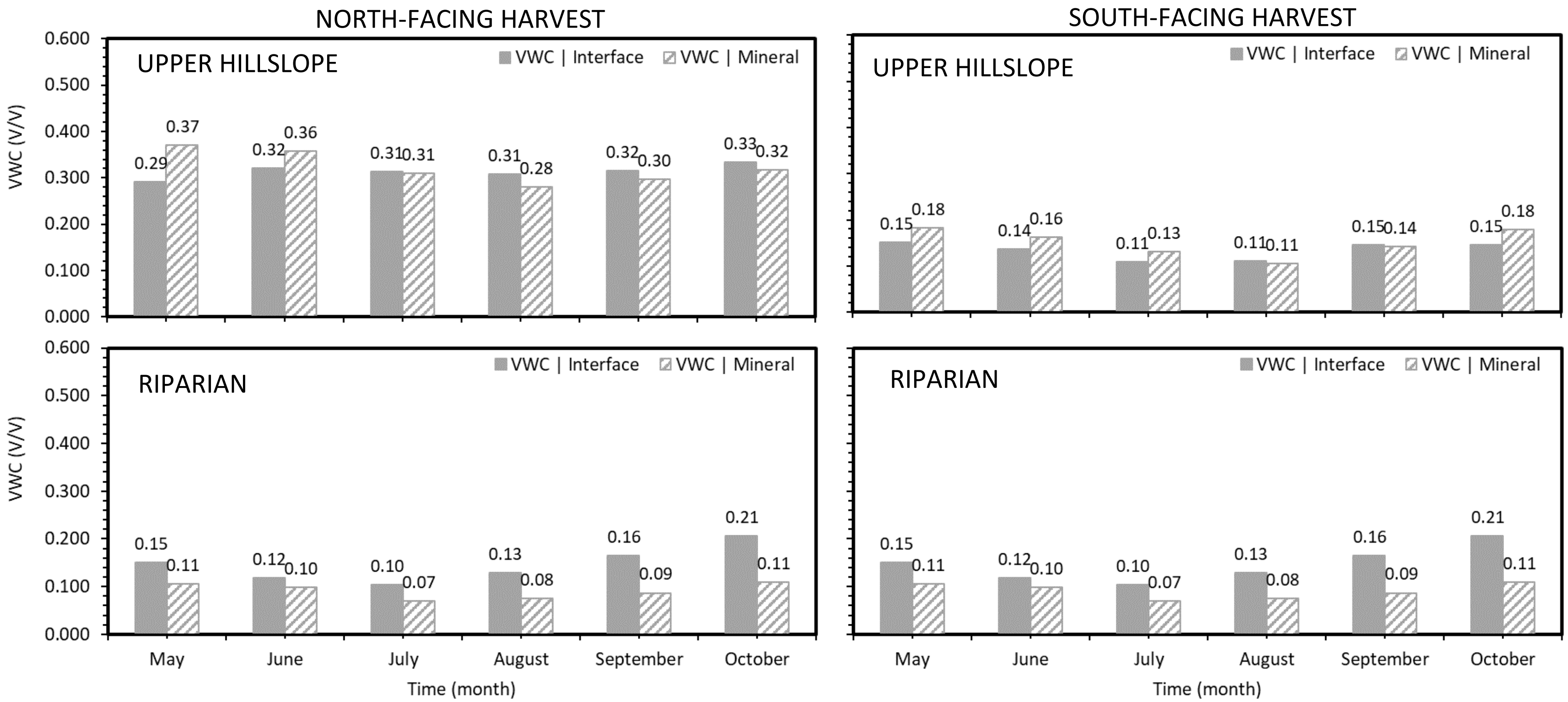

Figure 3-11 Mean monthly soil water content within the four harvest sites among organic/ mineral layer interface (black) and 20 cm deep into mineral layer (grey) over the entire period sensors were installed (May 1 – October 3, 2016). Numbers above each bar represent mean monthly VWC (V/V). Data for sensors during error periods were excluded.

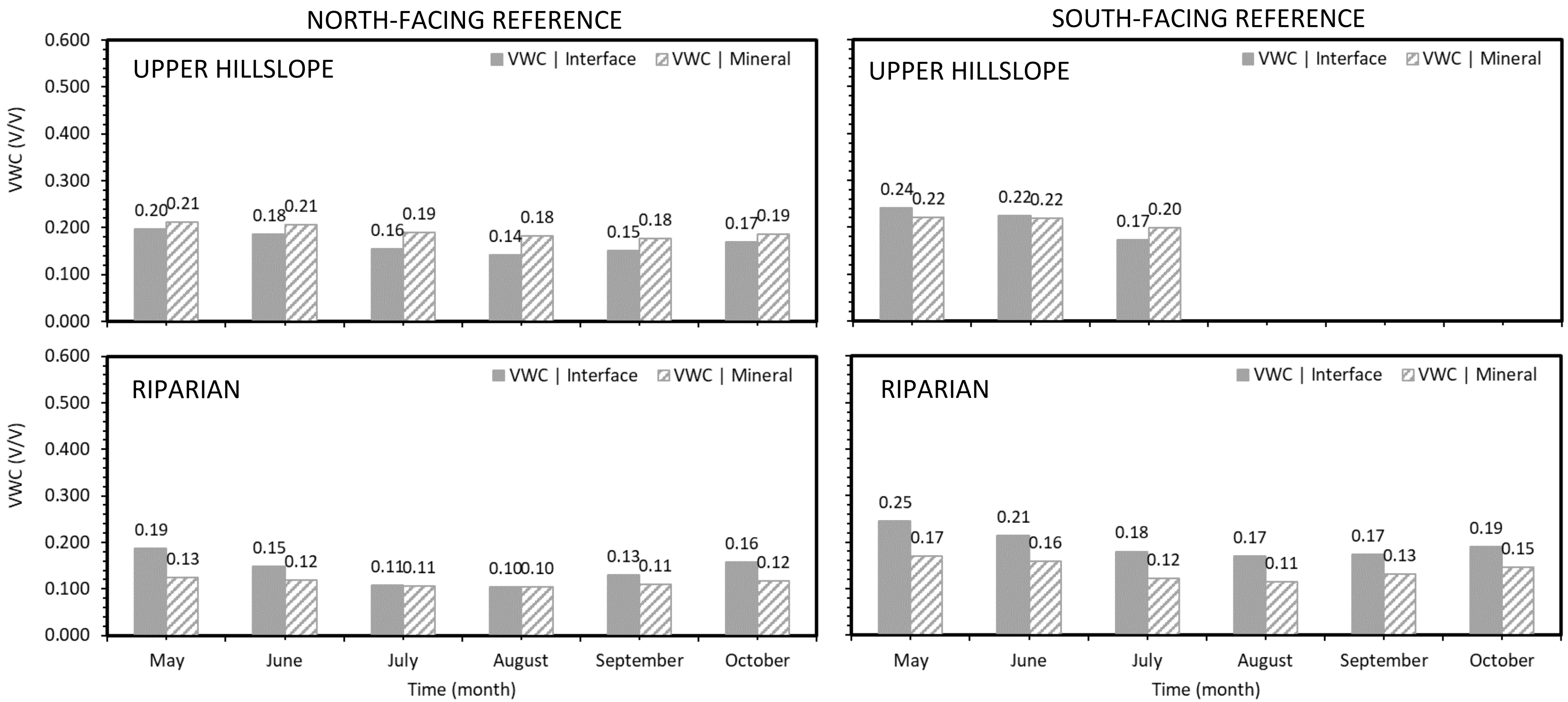

Figure 3-12 Mean monthly soil water content within the four reference sites among organic/ mineral layer interface (black) and 20 cm deep into mineral layer (grey) over the entire period sensors were installed (May 1 – October 3, 2016). Numbers above each bar represent mean monthly VWC (V/V). Data for sensors during error periods were excluded.

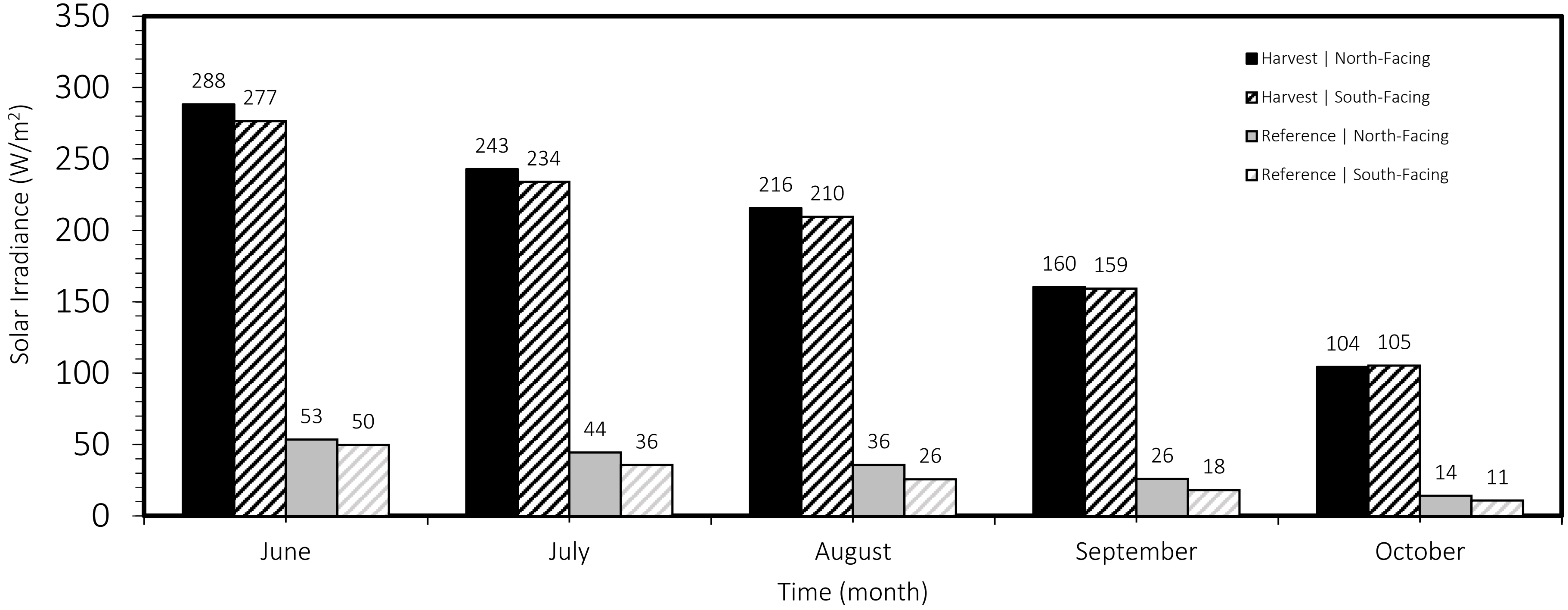

Figure 3-13 Mean daily solar irradiance within the four-upper hillslope positioned sites over the entire period sensors were installed (May 31 – October 3, 2016). Data for the sensor placed within the harvest on the south-facing slope prior to the sensor being installed on August 24, 2016 was back-filled using data from the north-facing harvest sensor. Numbers above each bar represent mean monthly mean solar irradiance (W/m^2).

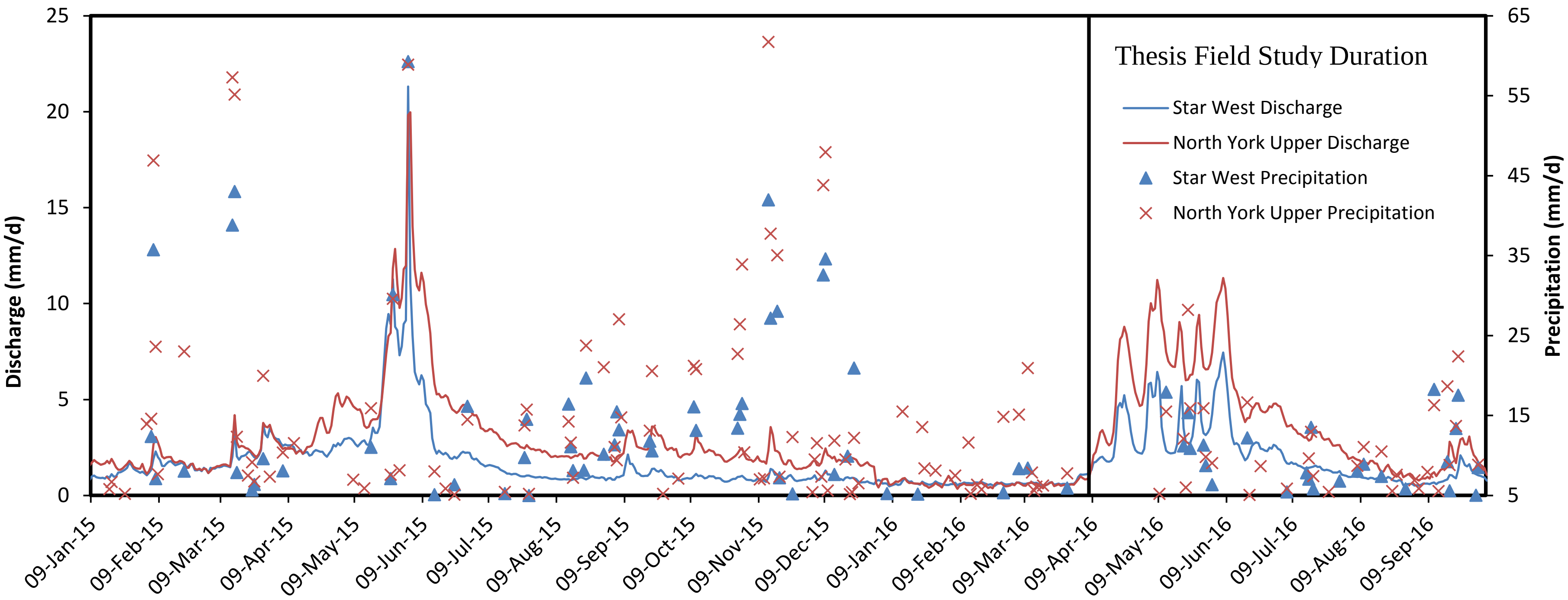

Figure 3-14 Mean daily discharge (solid line) and precipitation (markers) within Star Creek (Impact) and North York (Reference) during and after harvesting. The black vertical line represents the start of the hillslope field study.

Chapter 4: Synthesis

The broad goals of this study were to determine the magnitude of forest harvesting effects on a) N availability in soils and b) its subsequent impacts on both hillslope pore water and stream N yield within a steep Rocky Mountain headwater catchment, one year following harvesting.

The first data chapter (Chapter 2) focused on describing impacts of harvesting on resin-available soil N, static soil chemistry, and temporally integrated abiotic factors including soil moisture, soil temperature, and solar insolation within contrasting landscape positions. These landscape positions represented end-members of the topographically complex Star Creek West Fork watershed and included landscape disturbance (logged vs. reference), high and low energy gain (south vs. north-facing aspects), and hillslope positions (upslope vs. riparian). The results of Chapter 2 showed the clearcut harvesting in Star Creek watershed had little effect on static and resin-available N over the spring freshet and summer growing season one year following harvest (Figure 4-1). Clearcut harvesting increased solar insolation, and soil temperature within clearcut regions of the watershed. North-facing clearcut soils were wetter, while south-facing clearcut soils were dryer compared with matching reference stands. However, harvest effects on these abiotic factors did not correspond with any detectable effects of harvesting on N status in this soil. Leaching of NO_3^--N may have occurred on most sites as suggested by 1) greater median NH_4^+-N than NO_3^--N, 2) less potential ammonification than nitrification, and 3) greater NO_3^- supply in deeper mineral layers. Contrary to general expectations, upper hillslopes in Star Creek may have been more retentive of N compared to riparian zones as evidenced by observations of greater N fluxes in riparian soils. Additionally, hillslope aspect played an important role in these headwaters particularly within riparian zones where south-facing soils experienced greater potential nitrification, NH_4^+-N, NO_3^--N, pH, TC, TN, and C/N ratios, but lower potential ammonification than any other study site. These findings suggest that riparian areas could potentially control stream water N in Star Creek watershed during periods of riparian-stream hydrological connectivity.

The second data chapter (Chapter 3) built upon the objectives of Chapter 2 using the same spatial framework while primarily focusing on the temporal trends and extreme values (hot spot phenomena) evident in soil N supply rates, pore water, and watershed scale N yield comparisons between the Star Creek West Fork watershed and nearby North York Upper reference watershed. The results showed that resin-available N over the course of a spring freshet and summer growing season was inversely associated with seasonal changes in vegetation growth. The middle of the growing season (June 15 - August 1) when vegetation occupancy was greatest coincided with the highest soil temperatures, solar insolation and the lowest resin-available N and moisture. In contrast, when vegetation became dormant at the end of the growing season, the greatest resin-available N was observed at all sites. In combination with greater precipitation during this period, hydrological flow paths could become connected and transport of NO_3^--N to streams was most likely during this period.

When streamwater is investigated before and after the harvest, it appears that discharge is most closely linked to streamwater NO_3^-, TDN, and TN export. In 2016 discharges were low and export response to discharge within Star Creek (impact) and North York (reference) were also low, and similar. This was consistent with hillslope data suggesting low N turnover within surface and mineral soil layers.

Consistent with the observation that harvesting did not substantially impact available or soil N, no effect of harvesting on stream NO_3^-, TDN, and TN yield was observed in 2016. However, a transient, harvest-associated pulse of NO_3^-, TDN, and TN was observed during a short series in rain storms in late May 2015, 3 to 4 months after clearcut harvesting occurred in the West Fork of Star Ck. Harvesting had no effect (aside from this one series of spring storms) on stream N yield in 2015, and one full year after harvesting in 2016.

While Chapter 2 primarily focusses on spatial trends, and Chapter 3 focusses on temporal trends, these are separate dimensions of the same broader research questions. N cycling within forest floors can be highly variable both spatially, and temporally. While harvesting and reference stands showed similar N availability over the entire study period (6 months), available soil N varied inversely with vegetative growth through the spring, summer, and fall.

The results of both data chapters have important implications to our understanding of resistance of Lodgepole Pine dominated Rocky Mountain watersheds to forest harvesting effects on N. However, this apparent watershed resistance to harvesting impacts on N is in notable contrast to other important land disturbances. For example, previous SRWP research on a nearby wildfire (2003 Lost Creek wildfire) showed dramatic changes in stream water N one year following disturbance with increases in stream water NO_3^--N 6.5 times greater than reference watersheds (Bladon et al., 2008).

A pairwise reference approach accounting for major landscape units (hillslope position and aspect) is important within complex watersheds where ecosystem responses to interacting landscape factors is difficult to predict without real world, empirical measurements. Ion exchange resins combine information over time scales chosen by the user to provide useful information on temporal trends within steep mountainous catchments where the timing of intermittent pulses of activity (e.g. hotspots, hot moments) may not be captured by more static measurement techniques. Integrating this approach with other measurements including soil, pore water, and stream water allows for interpretation of spatially and temporally heterogeneous systems.

Recommendations for Future Research

Here, a novel approach was used to study the impact of forest harvesting on hillslope soil and receiving stream N dynamics and transport in the Star Creek

Watershed of the eastern slopes of the southern Rocky Mountains in Alberta, Canada. The study watershed includes a complex and heterogenous landscape, thereby precluding definitive, sole attribution of the observed outcomes to the specific factors investigated. Indeed, the work suggests that further lines of inquiry would be valuable. Nonetheless, the macro-scale processes presented in this research could serve as a basis for investigating other landscape disturbances within this steep mountainous terrain. Recommended follow up investigations are listed below.

1) **Determine the connectedness of riparian hotspot locations to adjacent streams.** The fate of large stores (hotspots) of inorganic N is uncertain within Star Creek watershed. Hotspots may be important contributors to overall watershed N export if they are hydrologically connected, and do not undergo significant losses (e.g. denitrification, uptake) between the hot spot and surface water. To determine if hotspots are indeed large contributors to streamwater N, an investigation into the micro-scale flowpaths within riparian zones, and the associated N transformations by microorganisms within them is recommended.
2) **Continue monitoring resin available N to capture legacy effects.** Coniferous stands have been shown to produce latent impacts following forest harvesting (Jerabkova et al., 2011). Continuing this study year round for 10+ years could bring to light spatial-temporal trends not evident in a short (<2 year) time frame.
3) **Continue monitoring stream water N to capture post-harvest storm behaviour.** A relatively dry 2016 season resulted in few storms to assist in interpreting storm

results from the 2015 post-harvest event. Continued monitoring of North York and Star Creek could shed more light on post-harvest NO_3^-, TDN, and TN export.

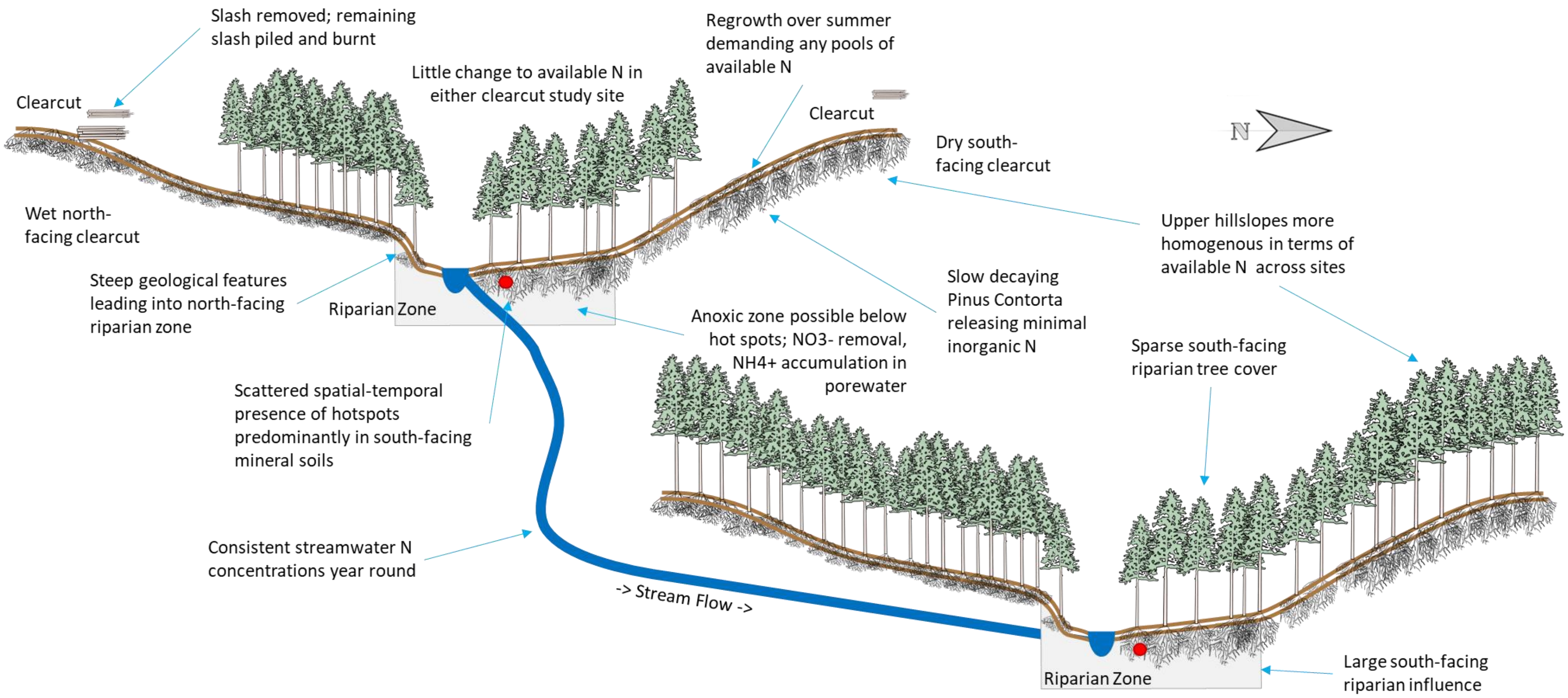

Figure 4-1 Conceptual diagram summarizing key study findings and observations within Star Creek Watershed. 2-dimensional representations of the harvest (top left) and reference (bottom right) are connected by Star Creek (in blue).

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