EVALUATING THE POTENTIAL FOR INCREASED FORAGE PRODUCTIVITY AND SOIL CARBON SEQUESTRATION IN STRIP-THINNED SILVOPASTURES.

By

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ABSTRACT

Forested ecosystems are essential in supporting the majority of terrestrial species on Earth. Forest products contribute significantly to the global economy as well as contributing in sequestering carbon as part of climate change mitigation. In British Columbia, conventional forest and range management has historically considered multiple-use landscape resources independently. We explored an opportunity to integrate the forest and ranching industries, in order to enhance both forestry and grazing practices, so that forest production and understory forage productivity can be fully realized. Silvopasture, which is the complementary use of land for forestry and range productivity for livestock, is a practice that integrates these two sectors. Previous research has shown that a successful integration of forage, cattle and timber management can provide significant economic, social and environmental benefits such as increasing forage yield and quality, tree growth, enhancing soil carbon storage, and increasing soil water availability.

Our objective was to test the integration of forage and timber management to improve forage quantity, quality and to enhance soil carbon sequestration. Specifically, we tested two hypotheses: (H1) 20 m width strip–thinning will maximize forage yield and quality and (H2) 20 m width thinning will sequester more soil carbon than uncut control or 10 m and 15 m thinning. In British Columbia, Canada, a mid-rotation forest of planted 45-year old lodgepole pine was harvested July 2018 at 10 m, 15 m and 20 m width strips in three adjacent forest sites at an elevation range between 1340 – 1400 m. Baseline data including tree stand density, understory plant species composition, and soil carbon and nitrogen were collected pre-harvest, June 2018. An agronomic seed mix was broadcast at 12 kg/ha: 30% *Dactylis glomerata*, 30% *Bromus riparius*, 30% *Thinopyrum intermedium*, and 10% *Trifolium repens* was seeded in October 2018. Field experiments, laboratory analysis and remote sensing were used in the second and third phase of this research to monitor forage quality and quantity, soil total carbon, nitrogen and organic carbon as well as soil carbon sequestration. We found that all strip widths enhanced forage quality, but the 20 m strips produced more yield than other treatment units. We found higher soil compaction and increased pH level in 20 m strips than other treatment units. However, a higher soil carbon and nitrogen was found in 15 m and 10 m strips than in 20 m. Our results provide evidence for optimizing land use in silvopasture.

Keywords: forested ecosystem, forest and range productivity, climate change, carbon sequestration, silvopasture, multiple use, ecosystem goods and services.

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ANPP: Aboveground Net Primary Production
AGL: Above Ground level
ADF: Acid Detergent Fiber
BC: British Columbia
BNPP: Belowground Net Primary Production
CP: Crude Protein
DOC: Dissolved Organic Carbon
DLS: Downwelling Light Sensor
DSM: Digital Surface Model
GDP: Gross Domestic Product
Gt: gigatonne
GPS: Global Positioning System
GSD: Ground Sample Distance
GNSS: Global Navigation Satellite System
LWIR: Long-Wave Infrared
Mt: megatonnes
NCE: Net Carbon Exchange
NIR: Near- Infrared
NDVI: Normalized Difference Vegetation Index
NDRE: Normalized Difference RedEgde
NDF: Neutral detergent Fiber
PCoA: Principal Coordinates Analysis
PERMANOVA: Permutational multivariate analysis of variance
%TN: Percentage Total Carbon
%TN: Percentage Total Nitrogen
RPAS: Remotely Piloted Aircraft system
RTK: Real-Time Kinematic
SON: Soil Organic Nitrogen
SOM: Soil Organic Matter
SOC: Soil Organic Carbon
TDN: Total Digestible Nutrients
UAVs: Unmanned Aerial Vehicles
USDA: United States Department of Agriculture
UTM: Universal Transverse Mercator
VOC: Volatile Organic Carbon
WGS: World Geodetic System

CHAPTER 1- GENERAL INTRODUCTION

A significant rise in the human population and high demand in livestock products have led to a rapid increase in the livestock sector (Onteru et al. 2010). Approximately 30 percent of the earth surface is occupied by livestock production which generates more than $1.4 trillion of the global asset (Thornton 2010). The livestock sector has contributed significantly to humanities economic development in employing over 1.3 billion people globally and impacting the GDP (Gross Domestic Product) by 33 percent in developing countries (Thornton 2010).

In Canada, this sector has been an important socio-economic driver as it employs around 228,811 people across the country and contributes approximately $13.2 billion to the national GDP (Kulshreshtha et al. 2012). As a resource-driven economy, it is important to keep developing more effective techniques to improve and maintain livestock productivity in ways that the sector will continue to be sustainable socially and economically and keep fostering the integrity of the ecosystem.

Forest and ranching industries in North America are long-standing practices. However, research and application of both practices on the same land base is not well understood (Fike et al. 2004). An intentional management system such as agroforestry has a long history and is recognized as a sustainable and efficient land-use strategy across the world, in integrating both ranching and forest industries. The combination of ranching or agriculture with forestry can be beneficial to farmers in a short and long period of time with the intention of providing significant economic benefits such as timber, crops, fruits, forage, livestock, and biomass while minimizing nutrient runoff and soil erosion (Wilson and Lovell 2016).

Over the years, various forms of agroforestry management systems including silvopasture, alley-cropping, shelterbelts, and buffer strips have been practiced (Wilson and Lovell 2016); but the silvopasture system has been more often used in many regions, specifically intended and intensively managed for the production of trees, forage, and livestock (Klopfenstein et al. 1997). The silvopasture system, an intentional combination of trees along with vegetation and livestock on the same land base, has historically been recognized as a successful practice with an overall goal of increasing the total production and benefits of farmers (Verma et al., 2017). Implementing silvopasture systems may be more beneficial than a single conventional forestry system and a monoculture forage based grazing system (Frey et al. 2012). Despite the management complexity, silvopasture systems can offer various social, economic and environmental benefits (Jose 2009) including soil erosion prevention, soil fertility improvement by fixing nitrogen through trees and forage species, water quality improvement, improved wildlife habitat and biodiversity conservation (Shrestha et al. 2004; Baah-Acheamfour et al. 2015). In addition, silvopasture management contributes to carbon sequestration and return on investment by creating a stable source of cash flow before and after timber harvest (Klopfenstein et al. 1997; Husak and Grado 2002).

The adoption of silvopasture has been highly recommended by several researchers and extension agents as it can be used on both small and large scales (Frey et al. 2012) in meeting high global demand in forage productivity for not only livestock, but also food for human consumption as well as wildlife, with a significant contribution toward environmental accountability. However, all these benefits will depend on different factors including the management approaches of both integrated systems (Jose and Dollinger 2019).

Grazing Management

Grazing management is one of the factors that can be used to influence productivity and sustainability of a silvopasture system. Effective livestock management and understanding animal-pasture relationships (stocking rate, stock density, timing and uniformity of use) (Krzic et al. 2004) by adopting various strategies such as rotational grazing, can be an essential tool that can help in improving forage productivity, facilitating better plant regrowth after a grazing period as well as improve soil organic carbon (Sanderman et al. 2015). Rotational grazing is an organized strategy of moving livestock through different areas to allow forage to restore its reserved energy and encourage better recovery without diminishing animal performance (Hao et al. 2013; Wang et al. 2020). Rotational grazing is a very important strategy as forage productivity tends to decline with intensive uncontrolled livestock grazing or severity of weed spread (De Bruijn and Bork 2006; Hao et al. 2013). In addition, livestock behaviour, timing and grazing duration are important strategies to consider in enhancing forage productivity and ensuring a sustainable silvopasture system (Delcurto et al. 2005; Zampaligré and Schlecht 2018) as livestock tend to select more palatable young forage species than other species; which tends to increase the vigour of unpalatable species and decrease the growth of palatable forage (Willms et al. 1980).

Forage production in a silvopasture system is not only impacted by improper grazing management but also the amount of tree canopy closure, variation in soil moisture and solar radiation intercepted and used by the understory forage species in complex biochemical pathways (Lin et al. 1999). The effect of solar radiation on forage productivity might depend on the types of understory vegetation species such as cool-season grasses, which tend to be more shade tolerant, and warm-season grasses, which are considered as low shade tolerant due to different photosynthetic rates (Lin et al. 1999). In addition, the variation in soil moisture competition between trees and underlying vegetation (shrubs, forbs and grass) might depend on different soil depth as moisture variation is often seen above 30 cm soil depth (Jose et al. 2000).

According to Lindgren & Sullivan (2014), thinning is one of the silviculture methods used to improve forage productivity by increasing soil moisture, and reduce soil nutrients competition, improving solar radiation and humidity while achieving the ecological goal of promoting biodiversity. This integration of forage, timber, and livestock on the same land base through forest thinning can also be economically attractive to farmers and landowners, and is successfully practiced in different regions around the world (Karki et al. 2009). However, there is still a gap in scientific studies on how different methods of forest thinning may affect forage quality and quantity, as well as the quality of the soil. A variation of commercial thinning is strip thinning, where harvest is concentrated in strips of variable widths. An assessment of strip thinning in enhancing forage and timber productivity in mid-rotation lodgepole pine using various strip widths is the primary focus of this study. In addition, this research project also explored the effect of introducing silvopasture through strip thinning on soil carbon and nitrogen storage.

Ecological restoration and carbon sequestration through silvopastoralism

Ecosystems have been altered due to various causes including human activities with a significant impact on animal habitats, plant diversity and the introduction of invasive species (Norris 2012). Ecological restoration is the process of conserving or supporting ecosystem biodiversity that has been disturbed or damaged, such that a self-sustaining ecosystem is returned to its natural state in providing ecosystem services (Harris et al. 2006). This concept is considered one of the effective solutions for habitat recovery, mitigating threatened or endangered species, as well as a tool to mitigate the effect of climate change (Harris et al. 2006).

The adoption of reforestation or the use of forest management systems in supporting ecological restoration has contributed positively to the global economy, sequestration of carbon as part of climate change mitigation and the provision of vital services to the majority of terrestrial species

(Seely et al. 2002; Hogarth et al. 2013); including food and shelter for various animals, fuel and nutrient cycling, timber production and recreation activities (Hall et al. 2019).

Between 1990- 2007, The world's forests sequestered more than 30% of the total annual green house gas emissions including atmospheric carbon (Hoberg et al. 2016). An estimated 500 Gt to 800 Gt of carbon sequestered by forest ecosystem was aboveground (Nilsson and Schopfhauser 1995), while most carbon sequestered by grassland ecosystems is found belowground (Soussana et al. 2004). It is well known that the largest terrestrial carbon sink occurs in a forested ecosystem, but managed forests through a proper planned agroforestry system has the potential to sequester more carbon both above and belowground and improve carbon dynamics (Nair et al. 2009).

Previous research has demonstrated that agroforestry system using a silvopasture approach, can also be implemented to provide similar benefits than just a pasture system (Howlett, Mosquera-Losada, et al. 2011). In addition, silvopasture has the potential of improving biodiversity, forage productivity (quantity and quality) for animals (Jose and Dollinger 2019). Silvopasture is also considered as one of the effective strategies to reduce atmospheric CO_2 by storing carbon above and mostly below-ground, and accumulating high net carbon from the atmosphere via photosynthesis beneficial to the environment (4.38tC ha^{-1} yr^{-1}) (Nair et al. 2009; Feliciano et al. 2018). Overall, more than two-thirds of carbon sequestered from the atmosphere is stored in the soil and approximately 2100 Gt of carbon can be found in the terrestrial ecosystem. Vegetation and tree growth play a meaningful role in facilitating the exchange of carbon between the atmosphere and the soil through photosynthesis (De Deyn et al. 2008) (Figure 1.1). Some aspects, such as plant respiration and biodegradation, enable the transfer of carbon back to the atmosphere. However, the amount of carbon sequestered through photosynthesis and decomposition is relatively larger; and can be a significant addition to the soil carbon pool (Bhattarai et al. 2017).

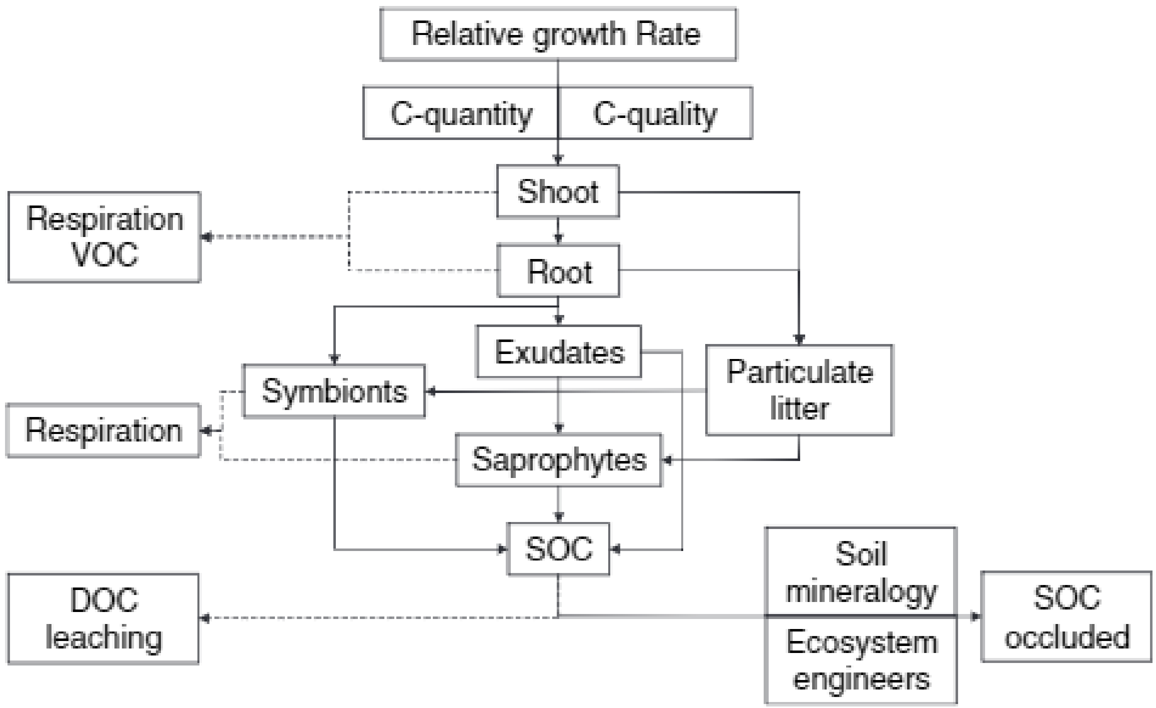

Figure 1.1 *"Soil carbon in and output by plants and associated soil heterotrophs. Solid lines indicate carbon incorporation and dotted lines are soil carbon loss; SOC: soil organic carbon, VOC: volatile organic carbon, DOC: dissolved organic carbon"* *(De Deyn et al. 2008).*

Remote sensing technology in silvopasture systems

As explained above, silvopastoral practices are normally applied to increase livestock productivity by enhancing the quality and quantity of forage throughout the growing season (Jose and Dollinger 2019); and to keep providing environmental services including sequestrating atmospheric carbon above and below ground (Andrade et al. 2008). Physical on-the-ground field-based methods are successful techniques that have long been used to monitor silvopasture systems. However, there is an opportunity to develop aerial remote sensing methods for a more improved, flexible and fast quantitative method to complement physical measurement in monitoring livestock forage production and ecosystem services (Viljanen et al. 2018). Several studies have documented the use of remote sensing methods as alternatives to monitor forest products (Larrinaga and Brotons 2019) and forage in grazing lands (Michez et al. 2019).

Remote sensing methods (including photogrammetry, multispectral and hyperspectral imaging) are all processes of measuring or obtaining information of an object or an area non-invasively by utilizing a specialized recording device without coming in direct contact with the object or area of interest (Sugiura et al. 2005; Viljanen et al. 2018). Spectral remote sensing technology, imaging spectroscopy specifically (measuring the intensity of electromagnetic radiation between a radiation source, typically the sun and the object) has been widely applied in the biological world since the late 1980s after launching airborne sensors and later in the 1990s with the addition of spaceborne sensors (Pu 2017).

This spectral method has been successfully integrated recently with advanced technology such as UAVs (Unmanned Aerial Vehicles) also known as RPAS (Remotely Piloted Aircraft system). These tools have become more accessible to rangeland managers to efficiently monitor forage productivity and quality for grazing animals (Michez et al. 2019). They are used also to quantify forest aboveground biomass; by providing relevant 3-dimensional information over a larger scale created by spectral information (Michez et al. 2019). The spectral information most commonly used for forest and silvopasture management is provided by a combination of multiple spectral bands in the electromagnetic spectrum including: Red, NIR (Near Infrared) and RedEdge; and used to produce vegetation indices algorithms such as NDVI (Normalized Difference Vegetation Index) and NDRE (Normalized Difference RedEgde) defined as:

NDVI = (NIR - Red) / (NIR + Red)

NDRE = (NIR - RedEdge) / (NIR + RedEdge)

Both indices are normally used as an indication of plant productivity including: yield assessment (Zhang et al. 2019) as well as vegetation stress detection, plant vigor, nitrogen uptake, fertilizer demand and leaf chlorophyll and nutrient content (Kanke et al. 2016). NDVI is derived from a normalized transformation of the near-infrared (NIR) band to Red in the visual spectrum resulting in a reflectance ratio. The index defines values from -1 to +1, where negative values mean the absence of vegetation (Pettorelli et al. 2005). NDRE index is similar to NDVI but uses the ratio of near-infrared and red-edge. The red band is replaced by red-edge band which sits between both Red and Near Infrared (Figure 1.2), which has shown to have a lot of utility when used in remote sensing studies with plants (Fitzgerald et al. 2006).

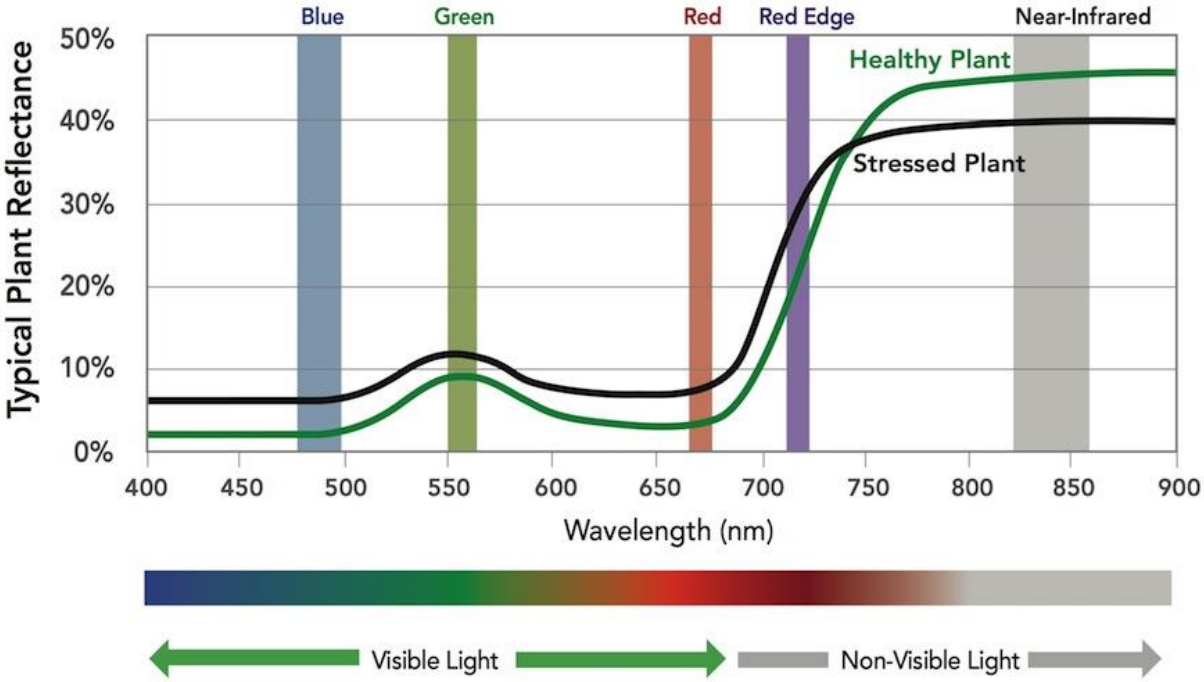

Figure 1.2: *An example of a typical plant reflectance curve detailing the wavelengths and position of visible and non-visible light (Micasense Inc.)* (Parker 2019).

Research objectives

This study explored an opportunity of integrating the forest and ranching industries, to enhance both forestry and grazing practices, so that forest production and understory forage productivity can be fully realized. The major outcome of this research is development of improved grazing and range management strategies through a silvopasture system by optimizing forage production where grazing potential has been lost due to tree-canopy closure, while maintaining the environmental sustainability. The above outcome was achieved by conducting two seasons of field experiments and laboratory data analysis.

This thesis is separated into two data chapters focussed on the following specific objectives:

- ✓ Chapter 2. Test the effect of integrating forage and timber management through strip thinning on forage productivity and plant community composition following agronomic seed addition. Statistical comparisons of understorey vegetation were evaluated to determine which strip thinning width has the largest influence on forage quality and quantity, plant richness and diversity.

- ✓ Chapter 3. Assess the impact of strip-thinned areas and the addition of agronomic plant species on soil carbon sequestration as part of climate change mitigation. The impact of thinning on soil pH, bulk density, soil organic matter, total carbon, total nitrogen and net carbon exchange between the soil and the atmosphere at 10 m, 15 m and 20 m widths was evaluated statistically and compared to un-thinned control treatments.

Furthermore, remote sensing technology using a high-resolution multispectral sensor was an additional component in the second chapter; and used as a comparative model on forage productivity between the strip thinned areas. The results of this thesis will assist foresters and ranchers to continue to work together to optimize their operations on a shared land base and keep fostering ecosystem integrity including greenhouse gases reduction.

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CHAPTER 2 – UNDERSTORY PLANT COMMUNITY ESTABLISHMENT WITHIN A LODGEPOLE PINE SILVOPASTURE SYSTEM

INTRODUCTION

British Columbia (BC) and elsewhere around the world have been investing in forest management and conservation practices for biodiversity (Sullivan et al. 2001) including lodgepole pine (*Pinus contorta*) species (Woods 2003). *Pinus contorta* is among the dominant coniferous tree species in BC, representing 41% of total tree seedlings planted, with high growth success in a wide range of forest site conditions (Woods et al. 2000). This species occupies 14.9 million hectares of BC forestland. Although Lodgepole pine is described as a low shade tolerance species (Axelson et al. 2009), once fully established can affect the growth of understory plant species. Modern forest management is increasingly considering forest biodiversity in planning, including plant community growth which is considered a major food source for wildlife and livestock (Thomas et al. 1999). Therefore, the density of tree crown closure is an important consideration in managing forests (Zaborske et al. 2002) since understory vegetation depends highly on the amount of sunlight, nutrients and soil moisture content (Lindgren and Sullivan 2014). Dense crown closure and soil nutrients are major factors that affect the timber and forage supply in BC, as well as ecological disturbances such as forest fire and mountain pine beetle (*Dendroctonus ponderosae Hopkins)* (Axelson et al. 2009). The mountain pine beetle is a North American native forest insect that attacks and kills forest tree species. Lodgepole pine stands have suffered the greatest beetle outbreak, causing mortality in up to 20 million ha of pine forests in Canada and the United states (Alfaro et al. 2015).

Silvopasture practice such as thinning can be an effective approach to diversify forest services including understory diversity and composition (Thomas et al. 1999). Forest thinning, a silvicultural practice that selectively removes trees to facilitate healthy growth of remaining trees and understory vegetation (Verschuyl et al. 2011), has many benefits on forage production in a forested area; such as: increasing forest floor light by reducing canopy closure, reducing soil nutrients competition, and improving soil moisture availability (Pang et al. 2013). McConnell and Smith (1970) studied the response of understory vegetation to thinning versus un-thinned areas, and found that thinned area increased grasses by 51%, forbs by 37% and shrubs by 12% with a significant increase in timber production. In addition, thinning can also be useful to reduce wildfire severity (Verkaik and Espelta 2006) and increase soil temperature due to increased solar insolation on the ground surface, which can have a positive effect on the performance of soil microbial activities; and facilitates the conversion of organic N to a plant available form (Pang et al. 2013).

In general, forage productivity depends heavily on a healthy soil and the capacity of microbial activity in the soil. Temperature plays a significant role in influencing soil microorganisms' activities including organic matter decomposition and recycling plant material (Pietikäinen et al. 2005). Some soil microorganisms (bacteria and fungi) associate symbiotically with plant roots; for instance, white clover (*Trifolium repens L.)* for the fixing of nitrogen, which is an essential element for plant growth (Caradus et al. 1996). Lindgren and Sullivan (2014) examined the potential influence of thinning on understory vegetation quality and quantity in young forests; and found that thinning influences vegetation growth by improving the amount, distribution and timing of forage use. However, little is known on the appropriate thinning distance and target canopy density for enhancing forage yield and quality, particularly with respect to the many different tree species used in silvicultural practices.

This chapter aims to test various widths of strip thinning, a form of forest stand thinning, in a lodgepole pine forest for improving forage yield and the factors that might influence nutritional value and digestibility of forage for livestock feed such as Crude Protein (CP), soluble carbohydrate, fat, lignin, Total Digestible Nutrients (TDN), Acid Detergent Fiber (ADF) and Neutral detergent Fiber (NDF) as a response to strip thinning. A balance of nutrients and digestible fiber is highly recommended in order to maintain animal health as the quality depends on the ratio of positive nutrients (CP, carbohydrates, fat, and minerals) and negative nutrients (NDF, ADF, and lignin) which are the most used parameters to determine forage nutritional value (Uniyal et al. 2005; Zeng and Chen 2018). The addition of high quality and leafy, palatable forage species can be a good complement to native species in increasing nutritional value in a grazing area while maintaining a diverse, sustainable ecosystem (Svejcar and Vavra 1985).

Schweitzer et al (1993) showed that over-seeding nutritious agronomic forage species (non-native species) can be a beneficial addition to native species in optimizing beef production, and enhancing wildlife habitat while maintaining timber yields. However, some non-native species, once fully established in an area, can pose a significant threat to native ecosystems. Non-native species have the ability to dominate and alter native ecosystems. Some of the non-native plant species categorized as invasive species can eliminate less competitive neighbouring plants by releasing compounds that may modify soil chemistry (Weidenhamer and Callaway 2010).

However, there are some species which are socially, economically and environmentally beneficial to the ecosystem by providing desirable ecosystem functions (Schlaepfer et al. 2011) such as orchardgrass (*Dactylis glomerate*), white clover (*Trifolium repens)* (Orefice et al. 2019) and intermediate wheatgrass (*Thinopyrum intermedium*) (Wills et al. 1998).

The increase of capability in scientific research has led to a success in developing more advanced methods to manage ecosystem resources including: in depth assessment of forage yield and nutritional value (Insua et al. 2019); as well as mapping, and modeling the distribution, and effect of invasive species on native plant species (Joshi et al. 2004). Satellite based remote sensing technology is one of the methods currently adopted in this research project to monitor understory vegetation growth and health through photosynthetic activities (Michez et al. 2019). Despite the recent high popularity of remote sensing in assisting natural resource managers and foresters, the use of remote sensing technology has been recommended for almost four decades (Tueller 1989) in estimating: above ground vegetative biomass; forage quality such as crude protein, different detergent fibers and soluble carbohydrate in the field (Zeng and Chen 2018), and also measuring and monitoring soil carbon sequestration (Goetz and Dubayah 2011). Multispectral remote sensing application has greatly attracted the attention of several scientists worldwide in extracting plant phenotypic information including monitoring plant growth and development (Deng et al. 2018). The NDVI (Normalized Difference Vegetation Index), derived from spectral remote sensing applications, is among several indices commonly used in ecological studies as predictors for forage productivity parameters such as: net primary production, active radiation for plant photosynthetic rate, leaf area index, evapotranspiration and plant biomass (Borowik et al. 2013).

This chapter summarizes the results from the field experiment conducted before and after strip thinning lodgepole pine forests in the southern interior of British Columbia, Canada. Data were collected using physical ground data collection and remote sensing data collection using a multispectral sensor onboard a RPAs with the objectives of: 1) evaluating plant community growth, species richness and diversity of both native plant species and agronomic species (seeded) as a response to strip- thinning; 2) assessing the effect of strip- thinning on palatable forage quality, health, and utilization; and, 3) use of NDVI and NDRE index products derived from remote sensing to assess forage growth and availability.

The overall goal of this study was to integrate ranching and forest industries by increasing the productivity of feed in terms of volume and quality on the same land-base. This approach will contribute in optimizing land use through a silvopasture model created by strip thinning.

MATERIALS & METHODS

Site Description

To evaluate the integration of forest and grazing management approaches, as well as continuous monitoring of soil carbon sequestration, an operational-scale pilot was established in a mid-rotation forest stands of 45-year old lodgepole pine. The stands were harvested at the end of July 2018 at 10 m, 15 m and 20 m width strips across 101.4 hectares of the three adjacent forest sites, situated in Goudie, Kelowna, British Columbia at an elevation range between 1340 – 1400 m. The 10 m width strips were separated by 20 m timber buffers, and 15 m and 20 m width strips were separated by 30 m and 40 m timber buffers respectively (Appendix-A.15). The location of the first block (32.8 ha) was at 49°55'24"N latitude and 119°14'37"W longitude with a minimum elevation of 1340 m and a maximum elevation of 1380 m. The second block (42.2 ha) was located at 49°56'9"N latitude and 119°14'25"W longitude with a minimum elevation of 1380 and maximum elevation of 1400 m and the third (26.4 ha) at 49°56'30"N latitude and 119° 14'50"W longitude with a minimum elevation of 1380 m and 1400 m and a general average slope of 11.3% (Arithmetic slope). Strip thinning harvest method was implemented following a randomized complete block design with four treatments per block (Figure 2.1). On average, nine strips were designed in 10 m width treatments (average length of 297 m), seven strips in 15 m width treatments (average length of 256 m) and five strips in 20 m width treatments (average length of 241 m) in each of the three adjacent blocks (Figure 2.1).

For data collection purposes, two strips were selected in 10 m, 15 m, and 20 m strips including two plots in the uncut control areas and sample data were collected from the center areas of the strip toward north for strips facing north and east for strips facing east.

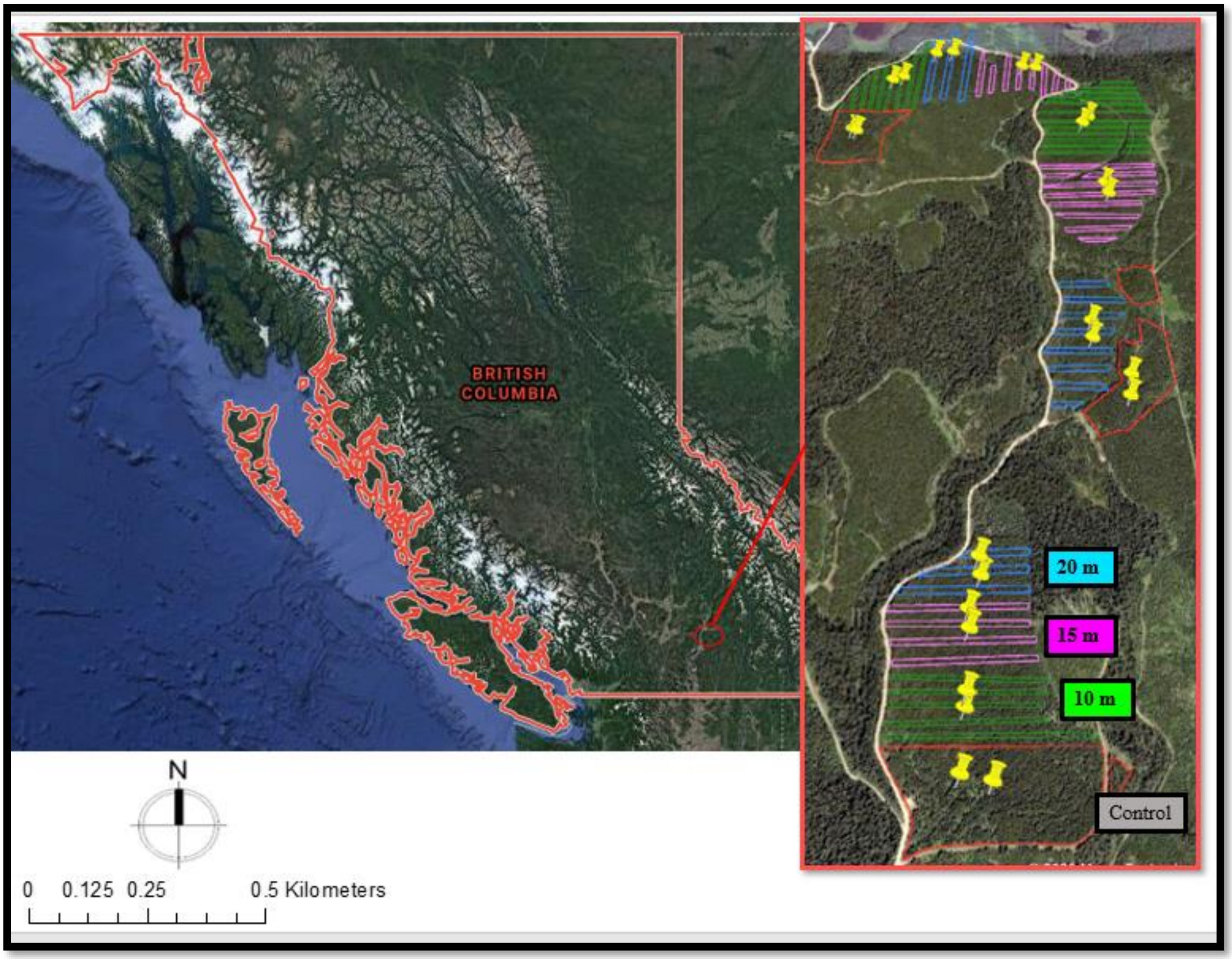


Figure 2.1: *An operational- scale pilot map initiated at a 101.4 ha area in the Okanagan region, Goudie, Kelowna, BC. The experiment was conducted on three blocks with four treatments. The red marked areas are control treatments. The green strips are 10 m wide, purple strips are 15 m wide and blue strips 20 m width. The yellow pins indicate the sampling points.*

Research Design

Four highly palatable agronomic seed mix species were selected and seeded at 12 kg/ha in October 2018 after timber harvesting (Table 2.1). Species selected were based on the fact that they are preferred by livestock and wild animals, and suitable to intensive rotational grazing systems (USDA- United States Department of Agriculture 2019).

Table 2.1. Highly palatable agronomic plant species used for improving the quantity and quality of animal forage

October, 2018		Additional seed mix		Ratio (%)
	1	*Dactylis glomerata*	Orchard grass	30%
	2	*Bromus riparius*	Meadow brome	30%
	3	*Thinopyrum intermedium*	Intermediate wheatgrass	30%
	4	*Trifolium repens*	White clover	10%

These four forage species are highly palatable to all classes of livestock and wildlife and are one of the earliest species to initiate growth in the spring with highly significant growth during cool conditions (USDA- United States Department of Agriculture 2019). They are very resistant to winter conditions but less productive under extreme hot conditions, saline soils and wet or poorly drained areas (USDA- United States Department of Agriculture 2019).

Pre-harvest field data collection

Baseline data including a percent cover understory vegetation survey were collected before strip thinning activities in June 2018. A 50 m transect was established in the middle of four designated treatment plans. Five sampling points per selected strip were established at 10 m intervals along the 50 m transect. At each sampling interval, a 0.5 m by 0.5 m quadrat was placed, and percent cover data by species were recorded in order to estimate plant species composition, richness and diversity (Figure 2.2) (Daubenmire 1984).

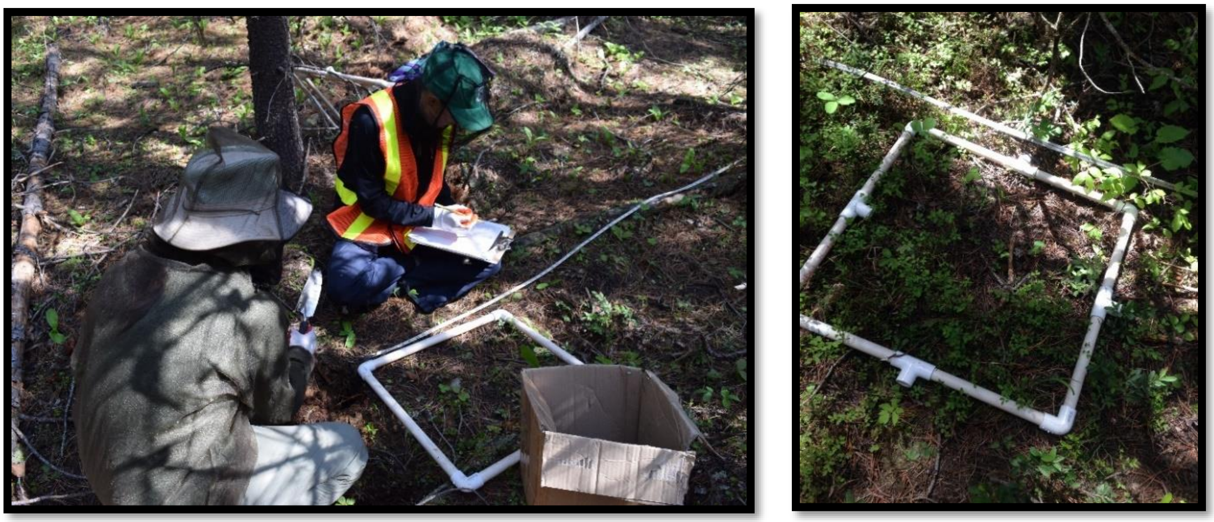


Figure 2.2. *An extended Daubenmire method of a 0.25 sq. m quadrat used to collect % cover data per species within three adjacent forest sites located in Goudie, Kelowna, British Columbia before strip harvesting activities.*

Post-harvest field data collection.

Post-harvest data collection was carried out in summer 2019 and 2020 after timber harvesting and seeding in the designed blocks/areas. The strip thinning harvest method provided an opportunity for additional forage by reducing forest canopy cover, nutrients competition while retaining the same percentage of timber as a conventional thinning approach. Field data collection and remote sensing were used in the designated treatments to explore the effects of strip harvesting on plant productivity, plant community composition, richness, and diversity as well as evaluate the long-term suitability of using additional agronomic plant species known to increase Animal Unit Months within the widths of the designed strips.

The Daubenmire cover class method was carried out in July, August 2019 and July 2020 to visually assess percent cover by species and productivity within quadrats (Bonham et al. 2004). A 50 m transect was established from the designated sampling points parallel to the thinned strips (Figure 2.1). A total of 10 sampling points (using 0.5 m by 0.5 m quadrats) were recorded in each treatment unit (5 sampling points per strip) to provide the estimates of plant species composition, species richness and diversity post timber harvest. Biomass was clipped within each quadrat at ground level without considering the previous year’s litter. Samples were separated into seeded species, unseeded-native palatable and unseeded non-palatable species (Appendix. A.16) (USDA-United States Department of Agriculture 2019). All clipped samples were dried at 70^{o}C for 48h in a forced convection constant temperature drying oven, DKN 812 series of Yamato scientific Co., Ltd, then weighed on an analytical scale to calculate biomass yield in gram per m^2 (Pavlů et al. 2006). Seeded and unseeded-native palatable species were ground to pass a 1 mm screen and analyzed using a FOSS high-performance InfraXact™ based NIR and transflectance analyzer with a scanning range of 570 - 1850 nm (FOSS Analytical 2010) in order to determine the essential parameters usually used to assess energy and digestibility level in forage such as CP (Crude Protein), S.Carb (Soluble Carbohydrates), Fat, Lignin, ADF (Acid Detergent Fiber), NDF (Neutral Detergent Fiber) and TDN (Total Digestible Nutrients) (Zeng and Chen 2018). NIR spectrum used by FOSS InfraXact is above the visible and Middle InfraRed (MIR) region of the electromagnetic spectrum.

Remote sensing data collection

An improved DJI Matrice 210 RTK V2 quadcopter was equipped with a Micasense Altum camera (Figure 2.3) for monthly aerial flights over the study area during the 2019 and 2020 growing seasons. The DJI Matrice 210 RTK (Real-Time Kinematic) Version 2 is an improved high precision quadcopter equipped with an upgraded positioning system mobile ground station consisting of a high precision GNSS (Global Navigation Satellite System) receiver (Figure 2.4). The Micasense Altum camera is a multispectral camera with five separate high-resolution bands including: Blue, Green, Red, RedEdge, and NIR with an addition of a radiometric thermal camera and a sun irradiance sensor (DLS 2 contains an integrated GPS) (Figure 2.3) to measure specific incoming solar irradiance for radiometric correction. The Altum sensor resolution has a GSD (Ground Sample Distance) of 5.2 cm per pixel at 120 m AGL (Above Ground level) and 81cm per pixel for thermal camera at 120 m.

The canopy reflectance data were collected on a clear-sky day twice during vegetation peak productivity from late July 2019 to August 2019 and repeated in July 2020. The drone was deployed perpendicular to the designed thinned strips at a flying height of 70 m AGL (Above Ground Level) and a flying speed of 3 ms^{-2} in order to cover the entire area of 101.4 ha (Fig. 2.1) and targeted vegetation growth in the open strips as suggested by Micasense, Inc. Prior to spectral reflectance measurement over the study area, the DLS 2 was mounted on the drone and images of a calibrated white reflectance panel (Figure 2.4) were recorded before and after each flight to calibrate raw pixel to absolute reflectance images in order to provide more accurate and reliable data. The flight missions followed the same flight plan with a front overlap and side overlap of

75% as recommended by Micasense, Inc. To ensure accuracy of Altum images geo-records, the RTK mobile ground station was paired to the drone RTK receivers, and we ensured a maximum connection was provided throughout the entire flight missions.

Figure 2.3. *Drone (UAV currently known as RPA) equipped with a high resolution multispectral camera with a blue (475 nm center, 20 nm bandwidth), green (560 nm center, 20 nm bandwidth), red (668 nm center, 10 nm bandwidth), red edge (717 nm center, 10 nm bandwidth), near-IR (840 nm center, 40 nm bandwidth) narrow bands and thermal sensor (LWIR: 8- 14μm).*

Figure 2.4. *D-RTK 2 mobile station (left), a high-precision global navigation satellite system receiver compatible with a new aircraft version, it uses navigational satellites from other networks in providing Aircraft accuracy. Multispectral sensor calibrated reflectance panel (right).*

Remote sensing data processing

Professional photogrammetry software (PiX4D Mapper Pro- Educational version 3.1.23) was used for processing multispectral images using a standard AfM (Structure from Motion) (Barbasiewicz et al. 2018). Calibration images recorded prior to each mission deployment were automatically added to the software processing memory. The software assessed each image geolocation, computed manual tie point positions, and image overlap in the first step of data processing. The second step consisted of constructing a point cloud and mesh and, the final step of the process consisted of building a DSM (Digital Surface Model), Orthomosaic and Index products including the normalized difference vegetation index (NDVI) and normalized difference red edge (NDRE) used to assess forage availability and productivity (Zhang et al. 2019). As detailed in Chapter 1, both index products were built from red, NIR and red_edge bands processed in the final step of software data processing.

The mean NDVI and NDRE values were retrieved using an advanced ArcGIS Desktop version 10.7.0.10450 and the images in TIFF format from the processed index products layers were uploaded into ArcMap workflow. The GPS information recorded during field data collection, which consists of strip location, sampling point locations, and distance from the sampling plots to the buffer zone, were used to mark the sampling points. Five-polygon shapefiles (approx. 0.5 m by 0.5 m quadrats) were created at each 10 m along the 50 m line (transect) drew from the pinned points following the WGS 1984 UTM Zone 11N coordinate system. The polygonal shapefile of each plot was used to extract digital values from NDVI and NDRE layers; and the mean values for each sampling point were calculated by Zonal statistic in ArcGIS.

STATISTICAL ANALYSIS

Data analysis and graphical outputs were completed using R version 3.6.2 (The R Foundation for Statistical Computing). Vegetation weight per treatment, species richness, diversity as well as forage nutrient parameters, and remote sensing data were tested for normality using the shapiro test (Jensen 2009; Mohd Razali and Bee Wah 2011). Variances within groups were tested for homogeneity using the Fligner-Killeen test (Conover et al. 1981) and when necessary, data were transformed using a natural logarithm or a square root function (sqrt). Shannon Wiener Diversity Index (H’) was used to assess understory species diversity and count species richness of each quadrat in the four treatments.

The designed experiment allowed a comparison of means among the four treatments in the three adjacent blocks design using an analysis of variance test for forage productivity as well as NDVI and NDRE analysis. Analysis of variance test was followed by the Tukey post-hoc test to find treatments that were significantly different from each other at a 5% probability level. Kruskal Wallis tests followed by Dunn's post-hoc test, using the Benjamini-Hochberg procedure to control for multiple comparisons were applied to the data that did not follow a normal distribution and equal variance assumptions. Analysis of covariance (ANCOVA) was employed to control for a priori effect pre-timber harvest 2018.

A Principal Coordinates Analysis (PCoA) using Bray Curtis distance matrix was a good ordination method applied to visualize and compare understory species community composition in each treatment unit for data collected pre-harvest 2018. A Jaccard distance matrix was applied to data collected post-harvest 2019 and 2020. PCoA and Jaccard similarity index were able to converge, capture and explain more variance in our post-harvest 2019 and 2020 dataset; and Bray Curtis captured more variance explained in species surveyed in July 2018. PCoA is theoretically an extension of Principal Component Analysis (PCA), and widely applied in ecology and used with any dissimilarity matrix (Paliy and Shankar 2016).

Permutational multivariate analysis of variance (PERMANOVA) was performed on the same PCoA matrix (Number of permutations = 999) and tested if understorey species communities were similar among the different treatment units (Control, 10m, 15m, 20m strip). PERMANOVA is a semiparametric method, and appropriate for community composition partitioning, and a powerful tool for the analysis of similarity or variation in plant species community composition (Anderson 2017).

RESULTS

Forage productivity

Yield

After vegetation survey, biomass was harvested in July 2019, August 2019 and July 2020 in order to estimate biomass production between treatment units. Due to a high rainy season and the late germination of the agronomic seed mix, our analysis did not consider the data collected in July 2019 (Canada Government 2019). August 2019 biomass yield was higher in 20 m thinned treatments, but a statistical analysis did not show any significant difference between the treatment units (p >0.05). However, biomass harvested in July 2020 showed a significant effect of strip thinning on vegetation growth, with a higher forage yield in 20 m and 15 m thinned treatments compared to 10 m thinned treatments, and very low yield in the uncut control ($p < 0.05$). The uncut control treatment was different from all the thinned treatments. The 15 m and 20 m thinned treatments did not show any difference (Figure 2.5).

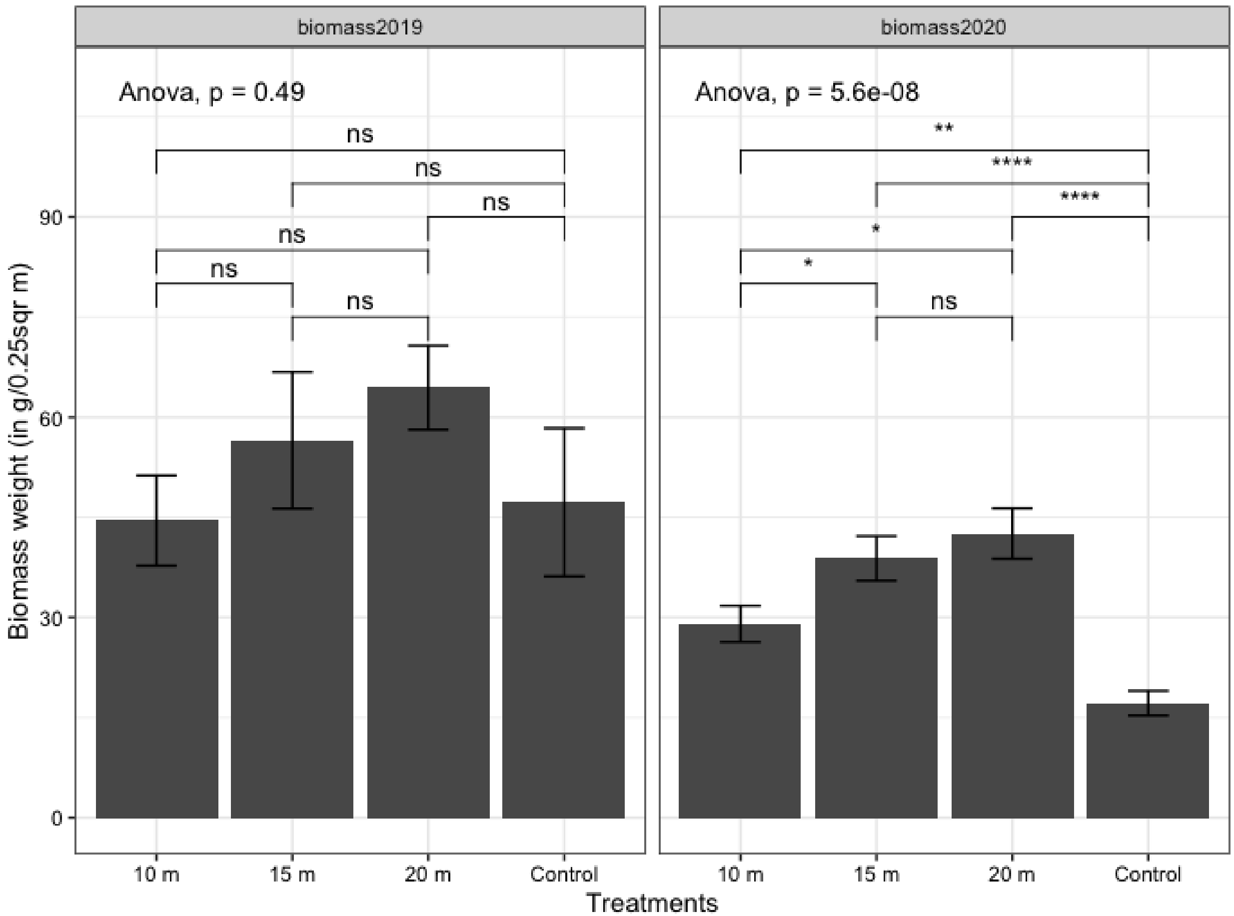


Figure 2.5 *Mean total biomass weight in gram per 0.25 sq.m for understory vegetation harvested in each treatment in August 2019 and July 2020. Error bars represent standard error of the mean (n= 6 for each group in 2019 and 30 for each group in 2020). (NS= non-significant; * = p≤ 0.05; ** = p≤ 0.01; *** = p≤ 0.001; **** = p≤ 0.0001).*

Quality

Both seeded agronomic species and unseeded-native species were harvested and analyzed separately in August 2019 and July 2020, for determining the amount of forage quality content in control, 10, 15 and 20 m thinned treatments. The quality analysis of agronomic species added post timber harvesting excluded the uncut control treatment because they were not part of the seeded treatment units. Seven major parameters were selected to determine forage quality content in each treatment unit: CP (Crude Protein), Soluble Carbohydrate, fat, lignin, NDF (Neutral Detergent Fiber), ADF (Acid Detergent Fiber) and TDN (Total Digestible Nutrients) (Asekova et al. 2016).

All the seven nutrients parameters assessed post-harvest 2019 and 2020 (Table 2.2 & table 2.3) were compared between 10 m, 15 m and 20 m thinned treatments including uncut control treatment for native palatable species and without uncut control treatment for seeded agronomics (Appendix. A.16). No influence of any strip thinning on forage quality was observed at any thinning width including the uncut controls, both in agronomic seed mix added (Table 2.2), and unseeded native palatable species (Table 2.3) ($p > 0.05$).

Table 2.2: Post timber harvest 2019 and 2020 mean understory seeded agronomic vegetation harvested in the opening strips.

August 2019 seeded agronomic species				
	10 m	**15 m**	**20 m**	**P-Value**
TDN	59.62 ± 3.52	59.66 ± 0.49	59.66 ± 5.42	1
CP	7.98 ± 1.03	8.56 ± 0.26	6.66 ± 0.94	0.37
NDF	52.42 ± 2.88	54.27 ± 1.35	50.73 ± 4.18	0.76
Lignin	8.01 ± 0.98	9.37 ± 1.68	7.18 ± 0.90	0.56
FAT	2.39 ± 0.14	2.95 ± 0.70	2.26 ± 0.16	0.49
ADF	38.35 ± 3.16	38.3 ± 0.44	38.32 ± 4.87	1
Sol_Carbos	9.18 ± 0.67	9.72 ± 0.71	9.45 ± 0.71	0.9
July 2020 seeded agronomic species				
TDN	53.49 ± 3.03	54.27 ± 3.22	56.78 ± 2.55	0.58
CP	9.92 ± 1.24	9.40 ± 1.49	10.25 ± 0.83	0.82
NDF	55.07 ± 1.45	54.90 ± 0.80	53.44 ± 1.25	0.59
Lignin	6.74 ± 0.21	6.31 ± 0.19	6.41 ± 0.29	0.36
FAT	4.19 ± 1.14	4.10 ± 1.35	2.94 ± 0.53	0.37
ADF	43.86 ± 2.72	43.16 ± 2.89	40.91 ± 2.29	0.58
Sol_Carbos	11.72 ± 1.82	15.84 ± 1.62	13.63 ± 1.15	0.11

Values are means ± standard error in august 2019 (n= 3) and July 2020 (n= 6). TDN= Total Digestible Nutrients. CP= Crude Protein. NDF= Neutral Detergent Fiber. ADF= Acid Detergent Fiber. Treatments means were compared using ANOVA test (significant level p= 0.05).

Table 2.3: Post timber harvest 2019 and 2020 mean understory native vegetation harvested in all treatment units.

August 2019 Unseeded native palatable species					
	10 m	15 m	20 m	Uncut control	P-value
TDN	58.79 ± 2.82	62.94 ± 1.69	59.58 ± 3.56	56.94 ± 0.73	0.51
CP	8.81 ± 0.77	11.07 ± 1.10	7.15 ± 1.07	8.68 ± 0.25	0.071
NDF	62.93 ± 4.07	53.60 ± 4.34	61.52 ± 6.17	63.34 ± 2.87	0.4
Lignin	7.17 ± 0.85	7.15 ± 0.07	6.21 ± 0.47	7.27 ± 0.10	0.55
FAT	2.84 ± 0.62	2.48 ± 0.61	2.87 ± 0.35	2.16 ± 0.46	0.77
ADF	39.1 ± 2.54	35.38 ± 1.52	38.39 ± 3.20	40.77 ± 0.66	0.51
Sol_Carbos	8.92 ± 1.33	9.11 ± 0.50	8.53 ± 1.12	6.54 ± 0.25	0.36

July 2020 Unseeded native palatable species					
	10 m	15 m	20 m	Uncut control	P-value
TDN	53.58 ± 0.96	53.50 ± 1.04	52.94 ± 2.57	51.80 ± 3.80	0.95
CP	9.58 ± 0.88	9.23 ± 0.92	11.01 ± 1.41	12.55 ± 1.21	0.19
NDF	61.70 ± 4.41	60.87 ± 3.22	58.05 ± 2.20	57.30 ± 1.95	0.67
Lignin	7.26 ± 0.44	6.83 ± 0.13	6.52 ± 0.20	6.94 ± 0.19	0.22
FAT	3.46 ± 0.78	3.39 ± 0.54	4.74 ± 0.95	5.40 ± 1.33	0.38
ADF	43.78 ± 0.86	43.85 ± 0.93	44.36 ± 2.31	45.38 ± 3.42	0.95
Sol_Carbos	7.95 ± 1.52	9.73 ± 1.01	13.21 ± 0.91	10.8 ± 1.80	0.09

Values are means ± standard error in august 2019 (n= 3) and July 2020 (n= 6). TDN= Total Digestible Nutrients. CP= Crude Protein. NDF= Neutral Detergent Fiber. ADF= Acid Detergent Fiber. Treatments means were compared using ANOVA test (significant level p= 0.05).

Species richness, and diversity

Percent cover per species identified and collected in June 2018, August 2019 and July 2020 were used to determine species richness and diversity. Understory plant species richness and diversity pre-harvest June 2018 was significantly different between 15 m and 10 m thinned treatments as well as uncut control treatments ($p < 0.05$). A high species richness was found in the areas assigned to the 15 m treatments, and low in the areas assigned to the uncut control, and 10 m treatments (Figure 2.6). Species diversity was higher in the areas assigned to the 15 and 20 m strip treatments, and lower in the areas assigned to the 10 m strip treatments ($p< 0.05$) (Figure 2.7).

Understory species richness and diversity assessed post-harvest August 2019 were not affected by any strip-thinned width. In addition, we did not observe any effect in uncut control treatment as well ($p > 0.05$) (Figure 2.6& 2.7). However, Post harvest July 2020 found a significant difference in species richness (Figure 2.6) and diversity (Figure 2.7) between 15 m, 20 m thinned treatments and uncut control treatment ($p < 0.05$), with a higher species richness and diversity in the 15 m and 20 m thinned strips and very low species richness and diversity in the uncut control treatment units (Figure 2.6 & 2.7).

The analysis of covariance (ANCOVA) was applied to test the interaction effects between pre-harvest 2018 and post-harvest 2019 and 2020. The results obtained found a significant difference ($p < 0.05$), with a high species richness and diversity in 20 m and 15 m thinned treatments and low in uncut control. 15 m was also significantly higher than 10 m thinned treatments (Table 2.4).

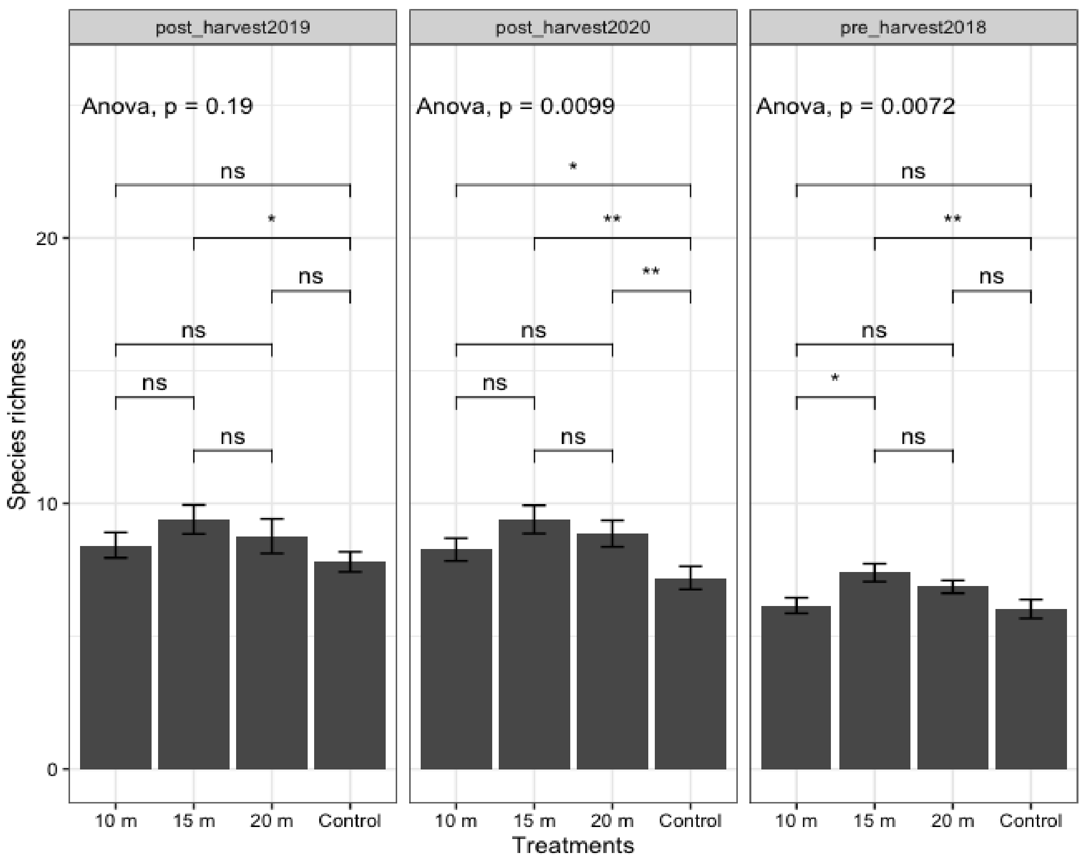


Figure 2.6 *Mean species richness for understory vegetation harvested in each treatment unit pre-harvest 2018, post-harvest 2019 and 2020. Error bars represent standard error of the mean (n= 30 for each group). (NS= non-significant; * = p≤ 0.05; ** = p≤ 0.01; *** = p≤ 0.001; **** = p≤ 0.0001).*

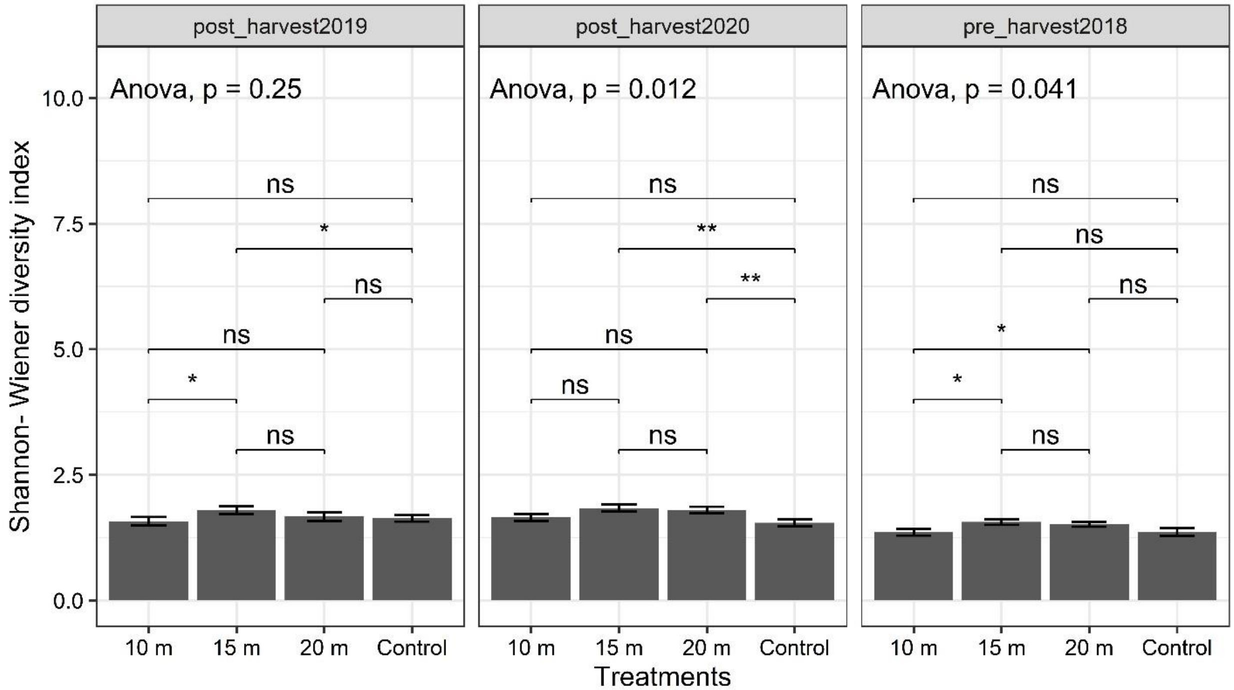


Figure 2.7 *Shannon-Wiener (H) mean species diversity for understory vegetation harvested in each treatment unit pre-harvest 2018, post-harvest 2019 and post-harvest 2020. Error bars represent standard error of the mean (n= 30 for each group). (NS= non-significant; * = p≤ 0.05; ** = p≤ 0.01; *** = p≤ 0.001; **** = p≤ 0.0001).*

Table 2.4: ANCOVA and post-hoc test results for understory species richness and diversity pre-harvest 2018 and post-harvest 2019-2020.

Species Richness				
	Estimate	Std. Error	t value	Pr(>|t|)
15 m - 10 m	1.1111	0.3612	3.077	0.01191 *
20 m - 10 m	0.5444	0.3612	1.508	0.43406
Control - 10 m	-0.6111	0.3612	-1.692	0.32939
20 m - 15 m	-0.5667	0.3612	-1.569	0.3977
Control - 15 m	-1.7222	0.3612	-4.769	< 0.001 ***
Control - 20 m	-1.1556	0.3612	-3.2	0.00803 **
Species diversity				
	Estimate	Std. Error	t value	Pr(>|t|)
15 m - 10 m	0.20227	0.05702	3.547	0.00274 **
20 m - 10 m	0.13221	0.05702	2.319	0.09552.
Control - 10 m	-0.01734	0.05702	-0.304	0.99022
20 m - 15 m	-0.07006	0.05702	-1.229	0.60902
Control - 15 m	-0.21961	0.05702	-3.851	< 0.001 ***
Control - 20 m	-0.14955	0.05702	-2.623	0.04482 *

Understory community composition

Understory species community composition was identified individually in each treatment unit within each of the three blocks. In June 2018, thirty-eight species were identified but only five species were reasonably palatable to livestock with an extremely low percent cover (Table 2.5). Pine grass (*Calamagrostis rubescens*) was a dominant grass species and covered 5% of the entire area but was less dominant than some shrubs species such as grouseberry (*Vaccinium scoparium*) (8% cover of the entire area).

Table 2.5. Estimate percent cover of six native grazed plant species on three experimental design blocks pre-harvest 2018 in Goudie, Kelowna B.C

Scientific name	Common name	% cover
Calamagrostis rubescens	Pinegrass	5
Carex spp.	Sedges	0.3
Osmorhiza berteroi	Mountain sweet cicely	1.1
Chamerion angustifolium, also recognised as Epilobium angustifolium	Fireweed	0.2
Taraxacum erythrospermum	Dandelion	0.1

PERMANOVA and PCoA were used to compare and plot treatment units for the year 2018. Variation in species community composition was seen across the treatment units at a $p < 0.01$ (Figure 2.8). By comparing each treatment individually, PERMANOVA showed a significant variation between uncut control and the areas designated to be thinned at 15 m width ($p < 0.05$) (Figure 2.10). The relationship between the understory species composition of the uncut control community and the areas designated to be thinned at 10 m and 20 m width was not significant ($p > 0.05$) (Figure 2.9 & 2.11). Bray-Curtis distance matrix measured treatment units' species community composition, and the first PCoA explained 15.85 percent of the total variance, while the second PCoA explained 14.14 percent of the variation in community composition between uncut control and the areas assigned to be 10 m, 15 m, and 20 m treatments. PCoA with Bray Curtis distance matrix between control and areas assigned for the 10 m treatments explained 19.74 percent and 12.35 percent of the total variances. Uncut Control and areas assigned for 15 m treatment were measured with the same distance matrix and PCoA explained 15.9 percent and 14.8 percent of the total variances. The final comparison between control and areas assigned for 20 m treatments was explained by 18.04 percent and 13.17 percent of total variances.

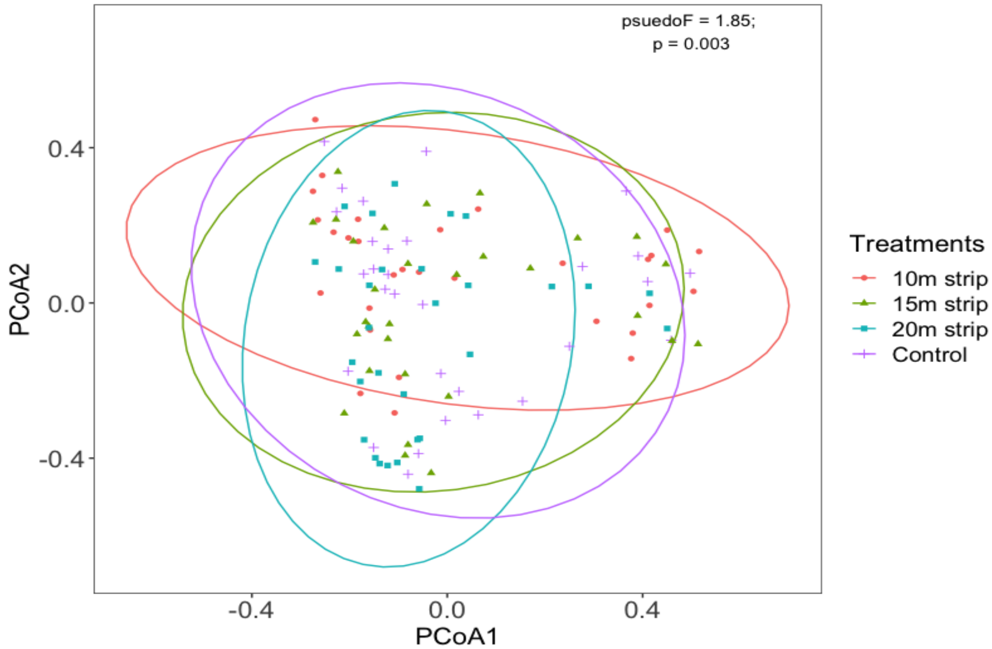


Figure 2.8 *PCoA (Principal Coordinates Analysis) ordination method for year 2018 pre-harvest species community composition of four treatment units in the three adjacent forest areas.*

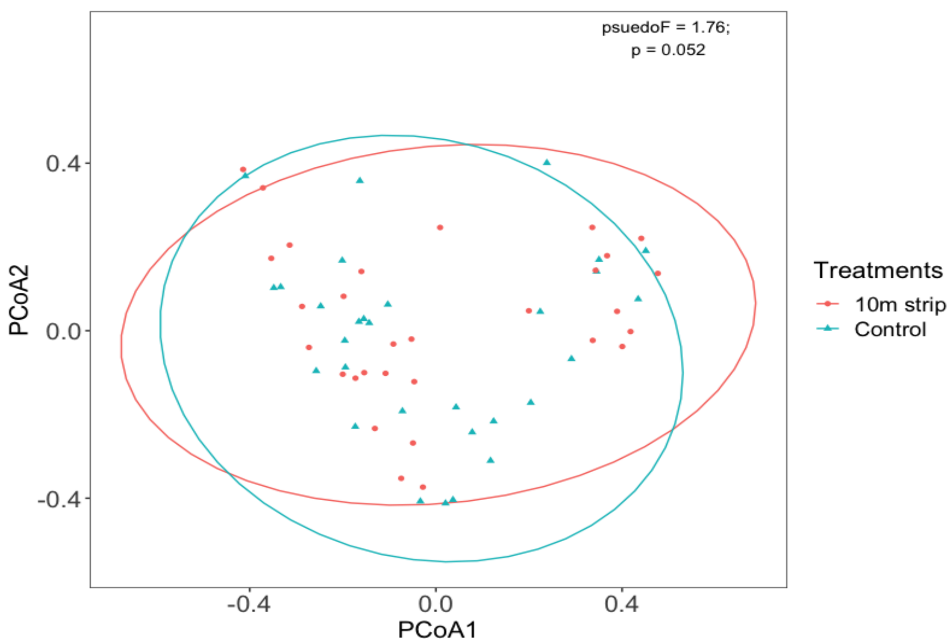


Figure 2.9 *PCoA for year 2018 pre-harvest species community composition comparing uncut control and 10 m width treatments in the three adjacent forest blocks.*

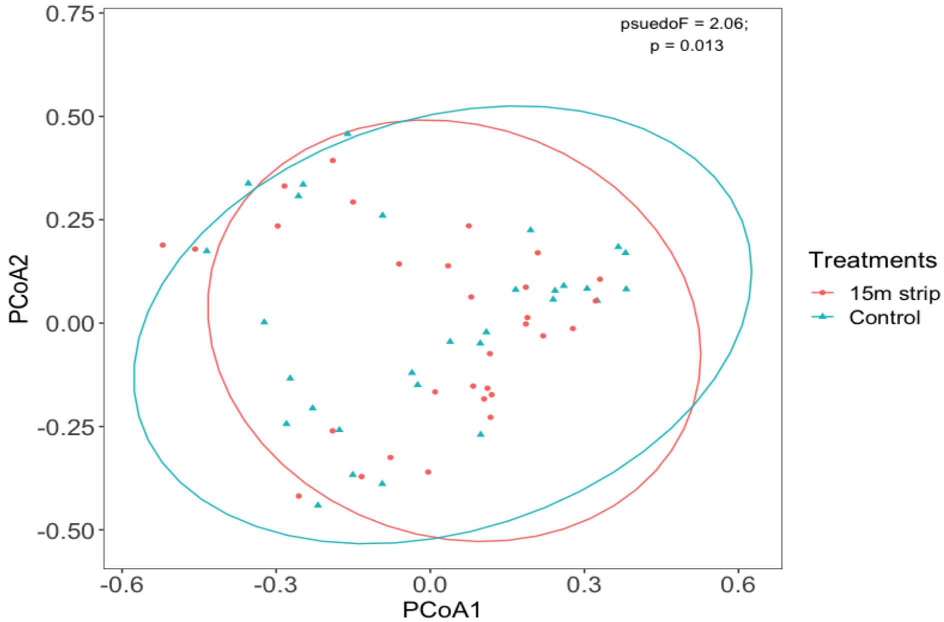


Figure 2.10 *PCoA comparison between uncut control and 15 m width treatments in the three adjacent forest blocks pre-harvest June 2018.*

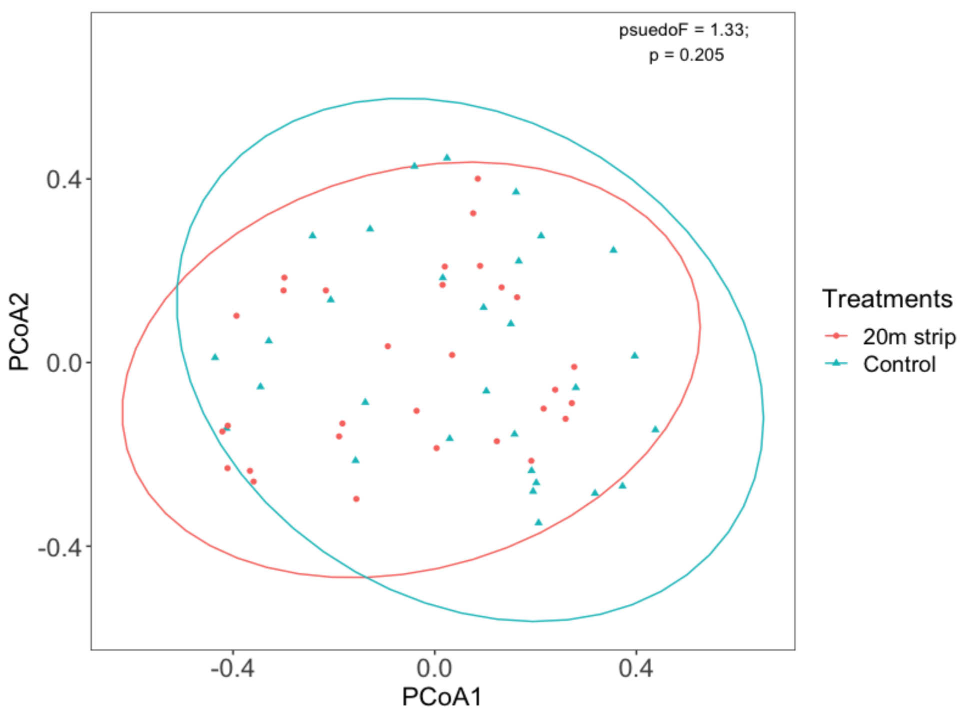


Figure 2.11 *PCoA comparison between uncut control and 20 m width treatments in the three adjacent forest blocks pre-harvest June 2018.*

In August 2019, a total of fifty understory plant species were observed. Thirteen high to moderately palatable species were identified during species survey including the seeded agronomic species (Table 2.6). Orchardgrass (*Dactylis glomerata L.*) was a dominant species covering 8.6% of the entire area.

Table 2.6. Estimate percent cover of thirteen grazed plant species on three experimental design blocks post-harvest 2019 in Goudie, Kelowna B.C

Scientific name	Common name	% cover
	Agronomic seeded species	
Dactylis glomerata L.	Orchard grass	8.6
Trifolium repens	White clover	3.5
Thinopyrum intermedium	Intermediate wheatgrass	0.9
Bromus riparius	Meadow brome	2.1
	Native palatable species	
Puccinellia spp.	Alkali grass	0.5
Calamagrostis rubescens	Pinegrass	2.5
Calamagrostis canadensis	Canada Blue joint	2.3
Poa pratensis L.	Kentucky Bluegrass	0.3
Carex spp.	Sedges	1
Festuca idahoensis Elmer	Idaho fescue	1.6
Osmorhiza berteroi	Mountain sweet cicely	0.4
Taraxacum erythrospermum	Dandelion	0.2
Chamerion angustifolium	Fireweed	0.3

Plant community composition was significantly different across all treatment units (Control, 10 m, 15 m, and 20 m strips) ($p < 0.001$). Variation in community composition between 10 m, 15 m, 20 m strip thinned treatments and uncut control was represented by the first PCoA; and explained by 16.54 percent of the total variance, while the second PCoA explained 10.87 percent (Figure 2.12). The first PCoA between the uncut control and the 10 m thinned treatments explained 13.08 percent and the second explained 7.99 percent of the total variance. The uncut control was compared again with 15 m thinned treatments and the first PCoA explained 13.23 percent of the total variance while the second explained 8.36 percent. Uncut control treatment was finally compared with 20 m thinned treatments and the analysis explained 10.31 percent and 7.93 percent of the total variance (Figure 2.13).

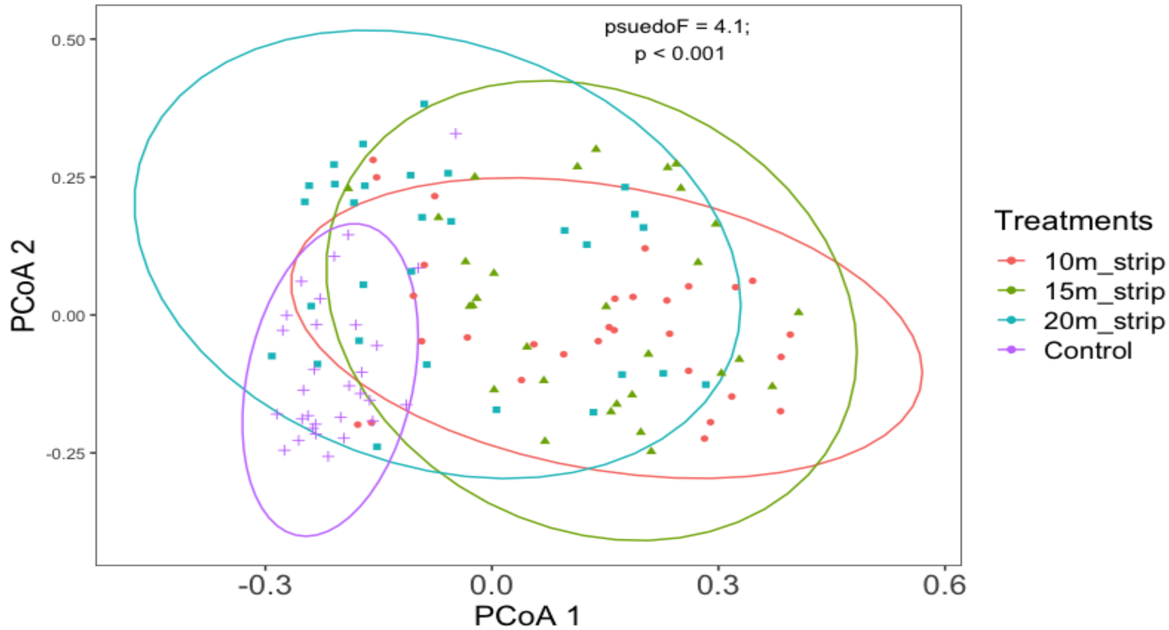
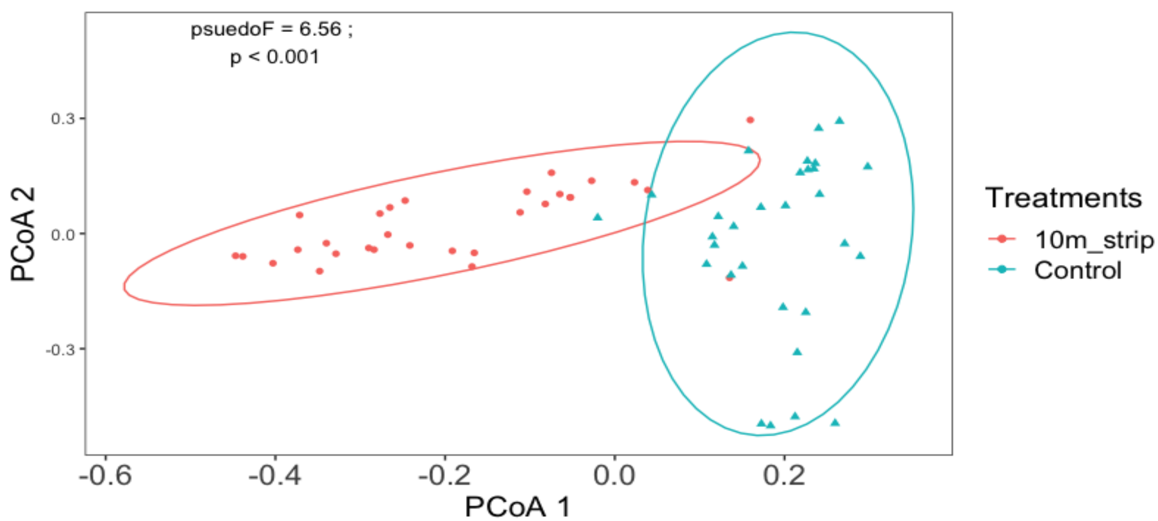


Figure 2.12 *PCoA comparing understory species community composition between Uncut control treatment, 10 m, 15 m and 20 m strip thinned treatments one year post timber harvest (August 2019).*



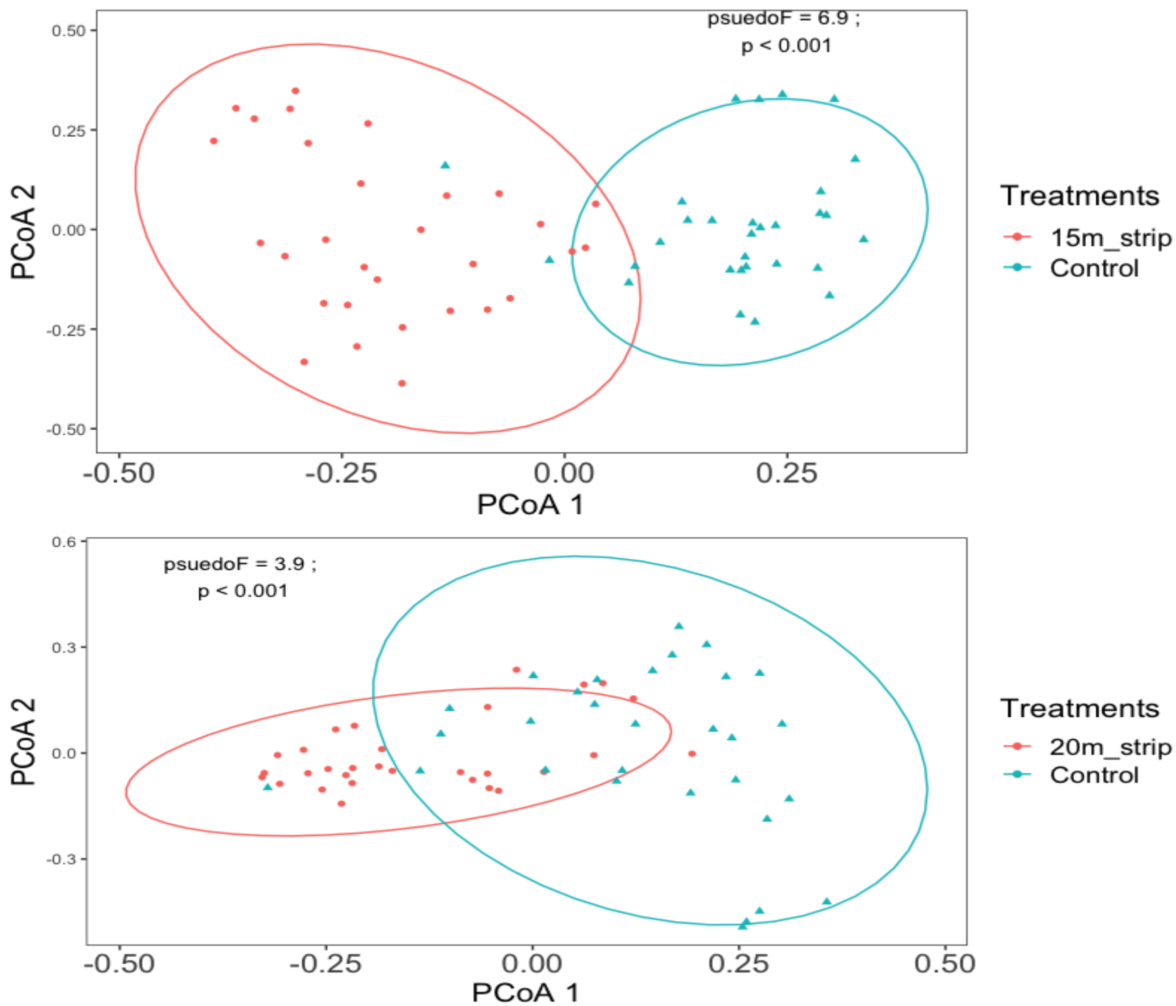


Figure 2.13 PCoA analysis comparing uncut control treatment to 10 m, 15 m and 20 m thinned treatments individually after one-year post harvest (August 2019).

In July 2020, a total of fifty-nine understory plant species were observed. Fifteen high to moderately palatable species were identified during species survey including the seeded agronomic species (Table 2.7). Alkali grass (*Puccinellia spp.)* was a dominant species which covered 24.1% of the entire area.

Table 2.7. Estimate percent cover of fifteen grazed plant species on three experimental design blocks post-harvest 2020 in Goudie, Kelowna B.C

Scientific name	Common name	% cover
	Agronomic seeded species	
Dactylis glomerata L.	Orchard grass	22.3
Trifolium repens	White clover	14.1
Thinopyrum intermedium	Intermediate wheatgrass	11
Bromus riparius	Meadow brome	8
	Native palatable species	
Puccinellia spp.	Alkali grass	24.1
Calamagrostis rubescens	Pinegrass	23.5
Festuca occidentalis	Western fescue	20.7
Calamagrostis canadensis	Canada Blue joint	11.6
Bromus inermis	Smooth brome	11.7
Koeleria macrantha	Prairie junegrass	11.7
Carex spp.	Sedges	9.5
Festuca idahoensis Elmer	Idaho fescue	7.4
Osmorhiza berteroi	Mountain sweet cicely	6.6
Taraxacum erythrospermum	Dandelion	5.6
Chamerion angustifolium	Fireweed	5

Plant community composition was significantly different across all the treatments (Control, 10 m, 15 m, and 20 m strips) ($p < 0.001$). Community composition of all treatment units was represented by PCoA method; and explained by 9.8% of the total variance, while the second PCoA explained 17% (Figure 2.14). A significant variation in species community composition was found between uncut control and 10 m thinned treatment units and PCoA explained 13% and 22% of the total variance ($p < 0.001$) (Figure 2.15). The comparison between uncut control and 15 m thinned treatment units was also significantly different in species community composition ($p < 0.001$), and PCoA explained 11% and 20% of the total variance (Figure 2.16). Uncut control was finally paired with 20 m thinned treatments and both treatment units were different in species community composition ($p< 0.001$), and the analysis explained 10% and 18% of the total variance (Figure 2.17). Variation across strip thinned widths was also noticed after comparing 10 m, 15 m and 20 m strip widths ($p< 0.01$) (Appendix A7, A8 & A9).

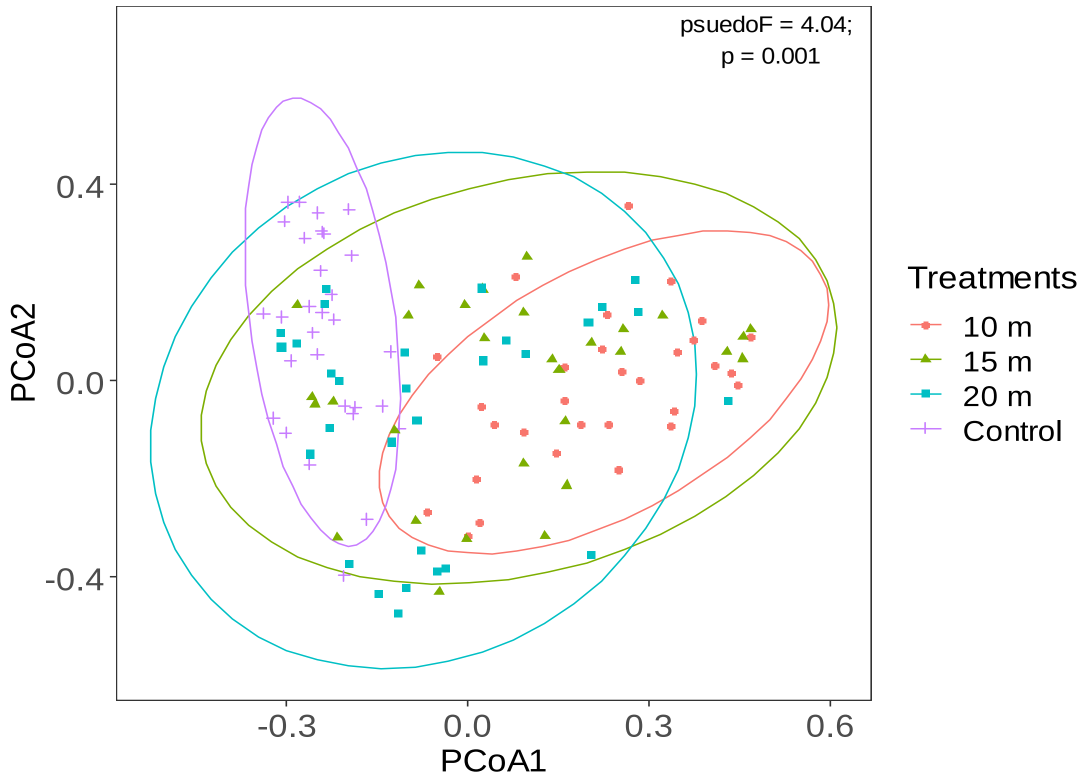


Figure 2.14 *PCoA comparing understory species community composition across all treatment units two year post timber harvest (July 2020).*

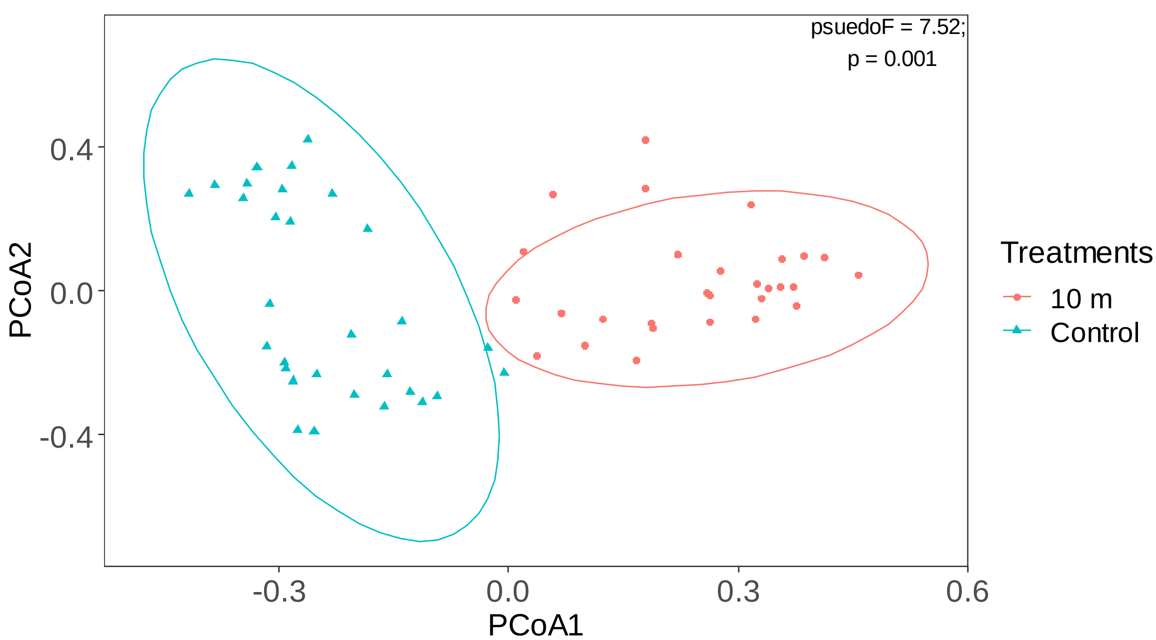


Figure 2.15 *PCoA comparing understory species community composition between uncut control and 10 m thinned treatments two year post timber harvest (July 2020).*

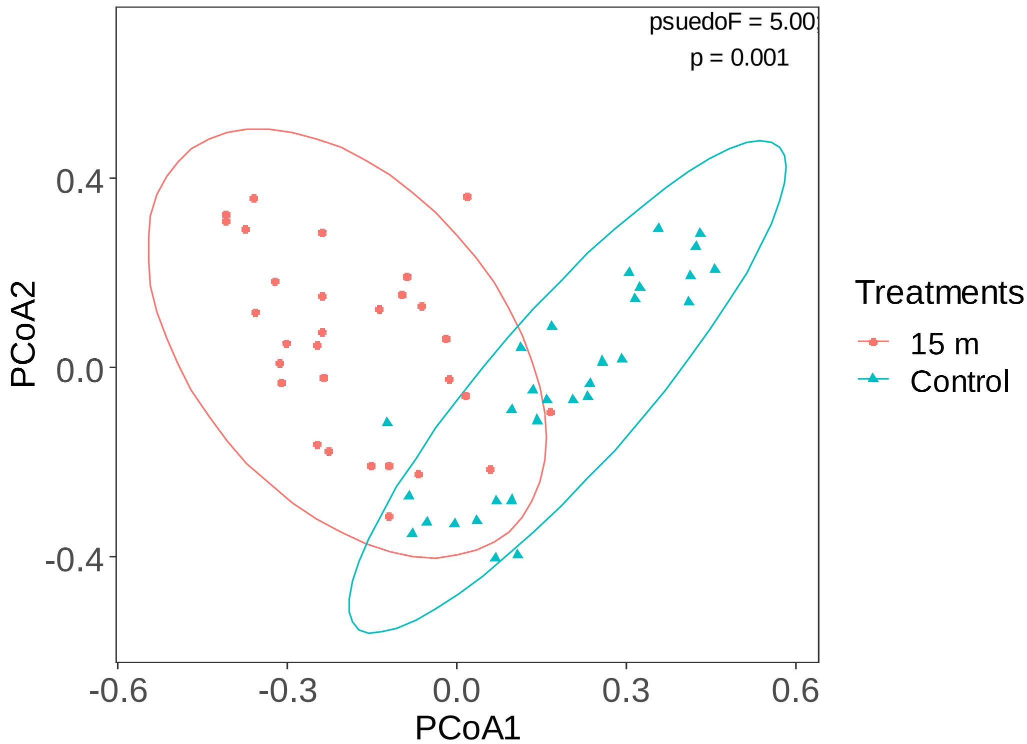


Figure 2.16 *PCoA comparing understory species community composition between uncut control and 15 m thinned treatments two year post timber harvest (July 2020).*

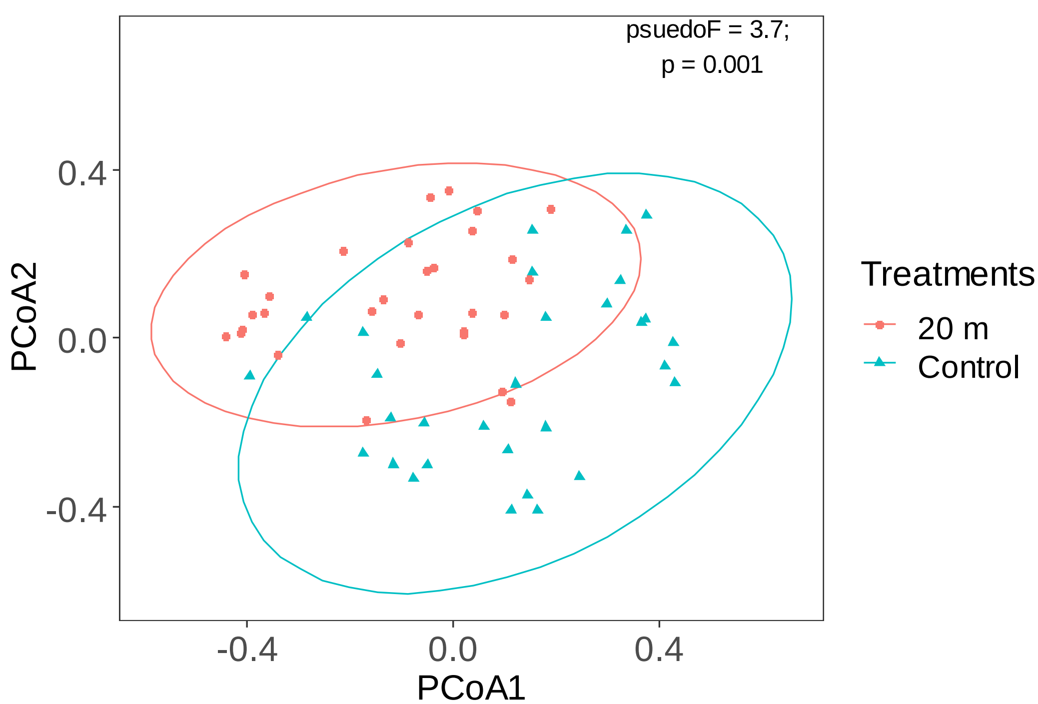


Figure 2.17 *PCoA comparing understory species community composition between uncut control and 20 m thinned treatments two year post timber harvest (July 2020).*

Strip thinned NDVI and NDRE index products derived from multispectral remote sensing

Additional to ground sampling, forage productivity in the thinned strips of the three adjacent blocks were monitored using NDVI and NDRE index products post-harvest 2019 and 2020 (Borowik et al. 2013; Kanke et al. 2016) (Figure 2.18). The statistical analysis did not find any significant different in all thinned strips both post harvest 2019 and 2020 (p>0.05) (Table 2.8). Though, NDRE analysis conducted in July 2019 did find a difference with a high index product in 15 m and low in 10 m thinned treatments (p<0.05) (Table 2.8).

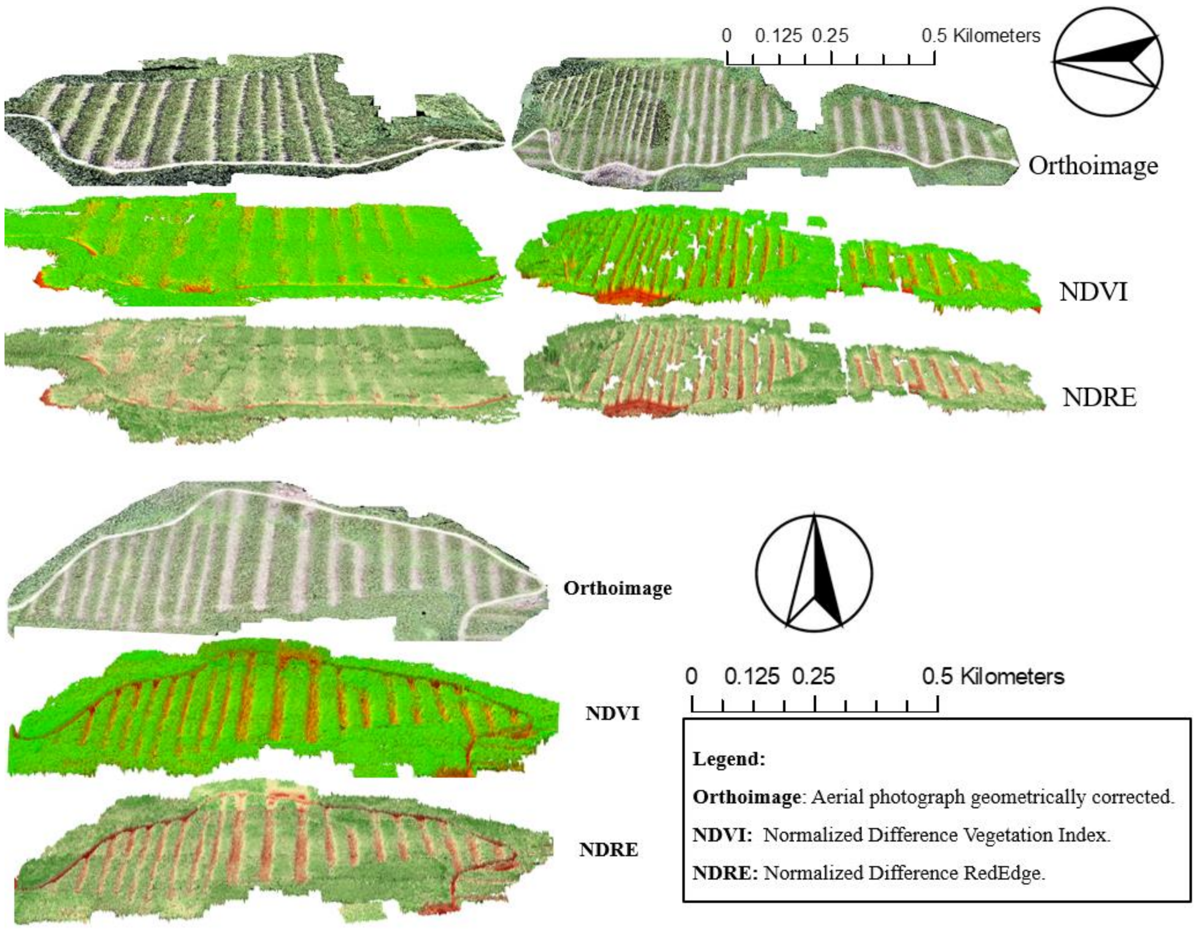


***Figure 2.18** Orthomosaic images with corresponding NDVI and NDRE indexes of the three adjacent forest sites located in Goudie, East Kelowna, British Columbia. Orthoimages and multispectral sensor images were taken post timber harvest.*

Table 2.8: Mean values comparison of understory vegetation greenness and availability measured by NDVI and NDRE index products derived from a multispectral sensor between strip-thinned treatments

July 2019	10 m	15 m	20 m	p-Value
NDVI	0.35 ± 0.014	0.41 ± 0.025	0.4 ± 0.022	0.5
NDRE	0.14 ± 0.008	0.18 ± 0.011	0.16 ± 0.012	0.01

August 2019	10 m	15 m	20 m	p-Value
NDVI	0.53 ± 0.018	0.56 ± 0.022	0.54 ± 0.025	0.6
NDRE	0.24 ± 0.006	0.28 ± 0.016	0.26 ± 0.0167	0.15

July 2020	10 m	15 m	20 m	p-Value
NDVI	0.74 ± 0.015	0.72 ± 0.023	0.73 ± 0.021	0.8
NDRE	0.17 ± 0.006	0.17 ± 0.007	0.18 ± 0.009	0.6

Values are means ± standard error (n= 30 for each group). NDVI= Normalized Difference Vegetation index. NDRE= Normalized Difference Red Edge Index. Treatments means were compared using ANOVA test (significant level p= 0.05).

DISCUSSION

Forage yield and quality

Variation in forage productivity is often observed with the level of thinning. For example, the productivity is high after timber harvesting and drops dramatically over time depending on the level of thinning and canopy closure (Thomas et al. 1999; Krzic et al. 2004). However, forage productivity does not increase immediately due to thinning. Significant growth and development of forage in open thinned areas can be observed within 10 years (Alaback and Herman 1988). Forage quantity assessment conducted two years post timber harvesting in our study area found a high variation in yield between the wider (15 m and 20 m strip widths) and the thinner treatments (10 m width) as well as the uncut control. A higher biomass was found in the wider areas (15 m and 20 m strips) and lower biomass found in the thinner areas (10 m strips) as well as in un-thinned areas (uncut control). This was most likely due to light limitations restricting growth because of high tree density, the degree of open canopy and the overall basal area along with perhaps soil moisture in the first meters of the standing forest which all influence understory species development (McConnell and Smith 1965; Peitz et al. 2001). Levels of temperature and sunlight absorbed by forage in wider thinned areas stimulate a rapid synthesis of plant cells and accelerate plant development (Lindgren and Sullivan 2014). However, the effect of thinning across the strip widths, including un-thinned controls on harvested biomass quality was not significant both post-harvest 2019 and 2020. It is possible that the reason for non-differences in CP, soluble carbohydrate, fat, lignin, TDN, ADF and NDF in all treatment units could be due to the fact that seeded and native palatable species are not fully established and the fact that unpalatable species were excluded in our analysis process.

Ishii, Maleque, & Taniguchi, (2008) showed that strip thinned stands have greater influence on both forage and timber production such as increasing tree DBH (Diameter at Breast Height) than un-thinned stands. Thinned stands increase the amount of incident light that reaches the forest floor and reduces nutrients and moisture competition resulting in higher understory forage growth and development as well as increasing tree stem growth, crown size and timber value, which might explain some of the outcome obtained.

Understory species richness and diversity

Timber harvesting through strip thinning influenced understory species richness and diversity. As expected, changes in species richness and diversity were observed after two years post-harvest in July 2020 with high species richness and diversity in 15 m and 20 m thinned treatments. A study of biodiversity response to intensive biomass production from forest thinning in North American forests conducted by Verschuyl et al., (2011) found that understory species richness and diversity frequently respond positively to forest thinning. When we compared the thinned strips and the uncut control areas one year post timber harvest, the assessment showed a similar plant species richness and diversity; and greater richness and diversity in the thinned stands than uncut control stands two years post-harvest, which is consistent with other studies (Ares et al. 2010; Verschuyl et al. 2011). However, it is possible that both overstory and understory species community composition pre-harvest 2018 may have influenced the outcome observed post-timber harvest, especially in the 15 m treatments, as the baseline survey conducted pre-harvest 2018 found a significant difference between the treatment units with a high species richness and diversity in the areas assigned to be harvest at 15 m width and low in the areas allocated to 10 m width and uncut control treatment. A similar trend was also seen post-harvest 2019 and 2020. The analysis of covariance which assessed the interaction effect between pre-harvest 2018 and post-harvest 2019-2020 found that both 20 m and 15 m produced high species richness and diversity than uncut control and 10 m thinned treatments.

Understory species community composition

In addition to the difference in species richness and diversity pre-harvest 2018, species community composition was different as well among treatment units, both before and after timber harvesting. Variations in species community composition observed pre-harvest 2018 between the areas allocated to 15 m strip widths and uncut control treatments were probably due to the difference in forest density, canopy openings or crown size (Lochhead and Comeau 2012).

According to Halpern & Spies (1995), plant species richness and diversity has long been used to describe plant species community composition; and thinning significantly influences understory vegetation community both in the short and long term. A two-year assessment of the effect of strip thinning on understory plant community showed a significant variation across all treatment units. Late establishment of plant species across the thinned strips and delay in germination of some agronomic seed mix added in October 2018 might have played a role in the variation seen both post-harvest 2019 and 2020 assessment. Several mechanisms and factors can influence understory plant community response post timber harvesting including survival and dispersal rate, succession and competition for a long-term effects (Gilliam and Roberts 2003).

NDVI and NDRE vegetation index products

Previous studies have shown that NDVI and NDRE index products are commonly used to predict vegetation growth and availability (Liu et al. 2019; Zhang et al. 2019). In our study, Both index products were generated from data collected by an Altum multispectral camera, which has shown to produce highly accurate direct geo-referencing data for plant phenotyping analysis (Hutton et al. 2020). The results obtained post-harvest 2019 and 2020 did not find any significant difference between thinned strips at any width. However, the NDRE index product of July 2019 detected a significant change with a higher vegetation growth in the 15 m strip widths and lowest growth in the 10 m widths. The presence of bare ground and the height difference of understory vegetation in the open strips might have significantly affected our result as NDVI and NDRE are both sensitive to soil conditions such as soil moisture, soil structure and topographic features (Camps et al. 2016; Chen et al. 2019; Ihuoma and Madramootoo 2019).

H. Q. Liu & Huete (1995) mentioned that signal contribution from non-vegetation components can reduce the accuracy in determining the relationships between individual reflectance bands and plant parameters, especially during early plant development stages as the stability of these indices depends on vegetation maturity and coverage.

CONCLUSION

Biodiversity conservation in BC's managed forests has emphasized how species diversity and ecological functions can be maintained, while simultaneously improving timber productivity (He and Barclay 2000). Forest management through an integration of forage, livestock and timber management approach appears both viable and valuable to promote biodiversity and enhance overstory and understory vegetation (Udawatta et al. 2019). Our research suggests that the above integrated management approach can be successfully accomplished through a silvopasture system.

Our study tested the influence of strip thinning at 10 m, 15 m and 20 m widths on forage productivity. Our hypothesis predicted that the widest strip, thinned at 20 m widths, would maximize forage productivity better than thinner strips such as the 15 m and 10 m widths used in this study, as well as the un-thinned control areas. In order to determine forage productivity, our investigation focused on assessing differences in forage growth and development in terms of yield and quality, species richness, diversity and community composition produced by each strip width as well as un-thinned control areas. Although the parameters used to determine nutritional value and digestibility of forage for livestock feed such as CP, soluble carbohydrate, fat, lignin, TDN, ADF and NDF across all designed treatment units was not influenced by thinning, the yield obtained provided evidence on the benefit of using strip thinned methods in enhancing forage for livestock and wildlife. Based on two years assessment, strip thinning contributed to understory vegetation growth and diversity (Ares et al. 2010).

Forage productivity results obtained post-harvest in 2019 and 2020 partially supported our hypothesis. In addition to high biomass yields obtained in the widest strips, our results showed that thinning in general adds to the abundance, richness and diversity of forage. However, our hypothesis was not fully supported because the 15 m strip widths was seen to produce more species richness and diversity than the 20 m strip widths. Despite a high species richness and diversity observed in the 20 m and 15 m thinned strips, continued study is important in order to explore in depth how thinning affects biodiversity; and how disturbance might influence species diversity overall in open strips (Verschuyl et al. 2011). And while not significantly different in this particular study, the use of aerial remote sensing by UAVs showed promise in measuring forage productivity; and should continue to be explored as a research tool in the future for these types of silvopasture applications in which data collection using traditional methods is logistically difficult.

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CHAPTER 3 – EFFECT OF SILVOPASTURE SYSTEMS ESTABLISHED THROUGH FOREST THINNING ON SOIL CARBON AND NITROGEN STOCKS.

INTRODUCTION

Soil plays a pivotal role in delivering a wide range of ecosystem services including the support of agriculture and silvopastoral production (Lavelle et al. 2006). Maintaining soil properties is critical for achieving additional ecosystem social, economic and environmental needs such as: provision of food through crop production, timber production, soil water availability, habitat for living organisms, as well as carbon and nitrogen storage (Smith et al. 2015). Studying soil carbon and nitrogen storage including its interaction with the earth's climate system is vital for soil ecosystem function as nitrogen availability often impacts carbon accumulation especially in temperate and boreal forests (Sokolov et al. 2008). Recent study of forest ecosystems and the rising of atmospheric carbon dioxide levels reveals that nitrogen constraints can impact the amount of carbon sequestered by plant woody materials and decomposition; which can affect the terrestrial ecosystems and impact the incremental levels of CO_2 in the atmosphere (Luo et al. 2004). In addition, nitrogen content in the soil can be a major factor in stimulating plant growth, photosynthesis activity, protein production, and the uptake of other nutrients (Novoa and Loomis 1981). Soil carbon is also important and should be well monitored to keep sustaining agriculture/silvopasture production systems, maintaining and even building resilience for climate change adaptation while improving soil quality (Lal et al. 2004). Monitoring carbon storage in the soils is vital as it depends on several factors including: agro-ecological conditions, plant characteristics, soil characteristics and management practices (Howlett, Moreno, et al. 2011). Previous studies have highlighted the key benefits of monitoring soil carbon for sustainable forest management (Fischer et al. 2017); and its advantage in maintaining and contributing to multiple resources such as: biodiversity, ecosystem services, soil water resources, global ecological cycles and other social benefits across the same land base (Kneeshaw et al. 2000).

Forest thinning is one of the sustainable forest management strategies capable of managing multiple concurrent resources (Thomas et al. 1999). Forest thinning increases the resistance and resilience from natural disturbances such as, wildfires and forest insect pests (Hood et al. 2016). Such pests like mountain pine beetle (*Dendroctonus ponderosae)* has impacted up to 10.1 million hectares of British Columbia's lodgepole pine (*Pinus contorta*) forest (Axelson et al. 2009) and resulted in changing forest carbon dynamics and increases in atmospheric carbon emission. The pine beetles has been estimated to impact an estimated amount of approximately 270 megatonnes (Mt) of forest carbon net release over the last two decades, or 36 g carbon m^{-2} yr^{-1} on over 374,000 km^2 of BC forested land (Kurz et al. 2008).

Integrating silvopasture system into forest management after thinning can be an additional tool, offering extra benefits in maximizing land use, including forage and timber productivity as well as carbon sequestration above and belowground level (Howlett, Mosquera-Losada, et al. 2011). The thinning method contributes to amending soil temperature, reducing competition, improving light penetration and soil water content (Saunders et al. 2012). Silvopasture, an integrated forage, livestock and timber management strategy (Shrestha and Alavalapati 2004) which introduces additional grass biomass due to canopy opening; is considered one of the most efficient methods to sequester and store carbon above and belowground (Scurlock and Hall 1998; Feliciano et al. 2018). Grasses store a significant portion of carbon belowground while forested ecosystems tend to accumulate a large portion of carbon aboveground (Post and Kwon 2000).

Despite the value of silvopasture practice for soil carbon sequestration, and as an approach to optimize multiple ecosystem services across the landscape, more research beyond forage and timber production is required on silvopastoral systems on the interaction between livestock grazing and soil (Sharrow 2007). Livestock grazing is a common practice which has been traditionally used, and currently implemented to support people's livelihoods (Gurung et al. 2009). However, overgrazing can create soil exposure to several disturbances, deteriorate soil organic matter (SOM) (Conant and Paustian 2002) and dramatically alter the potential for silvopasture systems to sequester carbon (Silveira et al. 2014; Richardson et al. 2017).

Previous research by Pineiro et al. (2010) tested the effect of disturbance, including grazing, on Soil Organic Matter (SOM) stocks considered as a major reservoir of soil organic carbon (SOC); and soil organic nitrogen (SON) and its impact on soil water availability as well as soil fertility and structure. Referring to their figure (3.1) below, their findings revealed that overgrazing modifies the process of SOM decomposition by changing the net primary production ratio that reaches the soil, which results in reducing SOC and SON stocks.

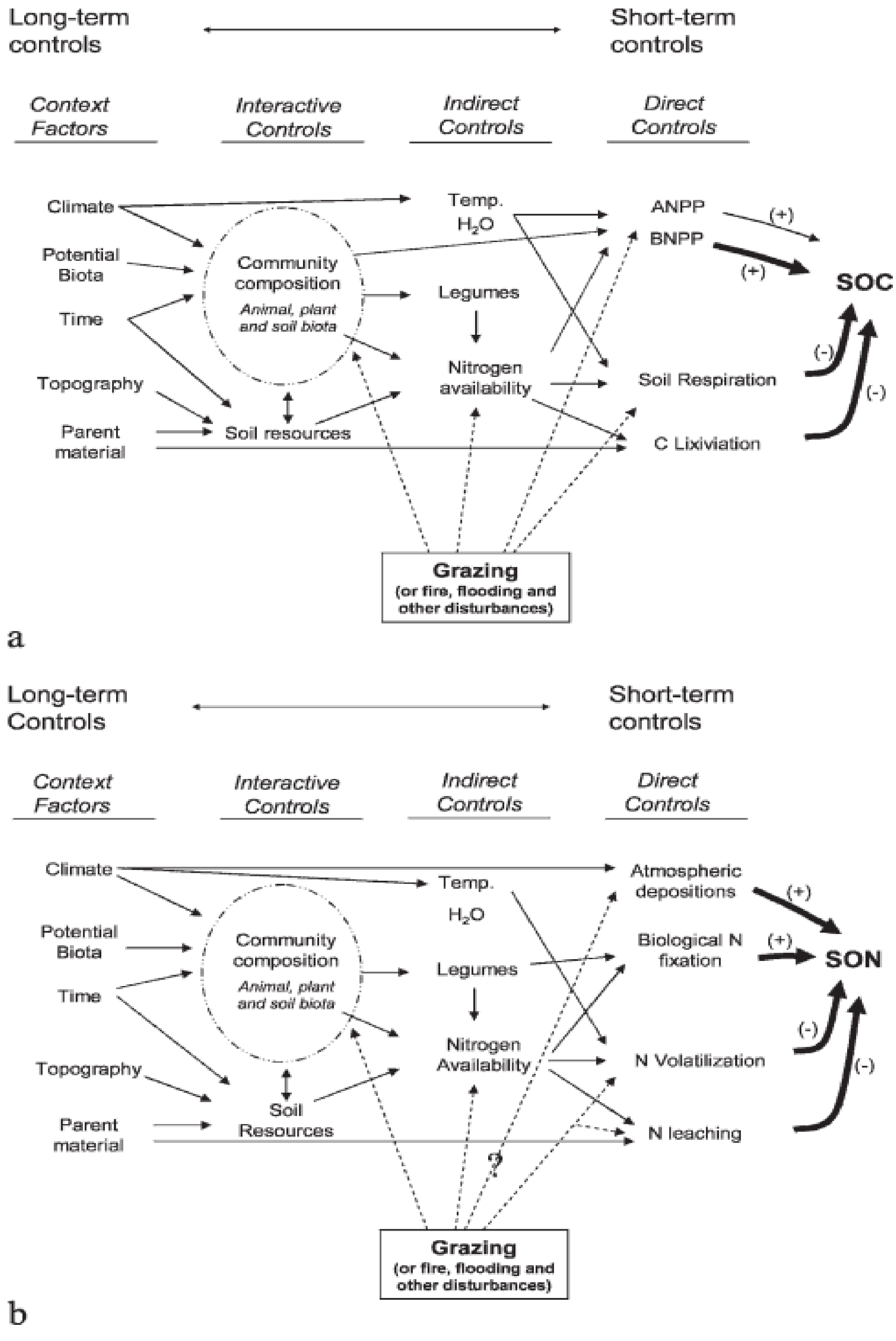

Figure 3.1: *"Soil organic carbon (SOC); a) and soil organic nitrogen (SON); b) controls at different temporal scales. Dashed lines show which controls are affected by grazing. ANPP is aboveground net primary production, and BNPP is belowground net primary production" (Pineiro et al. 2010).*

However, effective grazing management strategies, for example light to moderate grazing, can be a key in improving the accumulation of soil carbon storage by retaining a mix of forage species community composition, increased root production and facilitating soil development (Frank et al. 1995; Richardson et al. 2017).

In our study, we focused on assessing the effects of the silvopasture model of forest management through strip thinning by deploying three different strip widths (10 m, 15 m and 20 m thinned widths), along with the uncut control, on soil organic matter (SOM), soil total carbon (TC) and total nitrogen (TN) as well as the change in soil pH, bulk density and CO_2 flux through soil respiration due to canopy opening. Data was collected both before and after strip thinning of a lodgepole pine forest in three adjacent forested areas; located in the southern interior of BC in order to test the hypothesis that strip thinning would have a significant impact on overall soil carbon and nitrogen stocks.

MATERIALS & METHODS

Site Description & Research Design

Referring to the study site in the Materials & Methods of Chapter 2, the field experiments were conducted in the same area throughout three consecutive seasons (pre-timber harvest 2018, post-harvest 2019 and 2020) in the three adjacent forested areas of Goudie, Kelowna, British Columbia situated at an elevation range between 1340 – 1400 m (Fig 2.1). For data collection purposes, two strips were selected in 10 m, 15 m, and 20 m strips, including two plots in the uncut control areas. The sample data were collected from the center areas of each of the selected strips toward north for strips facing north and east for strips facing east.

Soil sampling for bulk density analysis

Post-harvest 2019 sampling locations were established in each treatment unit for assessing soil compaction caused by heavy machinery during strip thinning activity. A total of 24 samples were collected in the middle areas of the treatment (2 samples per treatment unit) using a core method (Rab 1994). The treatments were re-assessed a year later in June 2020 targeting the entire thinned strip. A two dimensional transect system was utilized to establish random sampling locations throughout each treatment unit. A 90 m transect was placed parallel at 1 m distance from the edge of the strip followed by a perpendicular transect placed across the strip width. 16 sampling locations were randomly selected in each treatment unit (8 sampling points per strip) using both transects which were established lengthwise and widthwise in both open strips and uncut control. At each location, litter, decayed material, and mineral soil samples were collected separately using an excavation method. Mineral soil for bulk density measurement was collected at each location to a soil depth of 15 cm including rocks and other materials found in the excavated plot. A total of 192 soil samples were collected across the three blocks, weighed and placed in a drying oven at 70^{o}C for 96 hours. Dried samples were weighed again and then sieved to remove rocks and other materials larger than 2 mm in diameter. Sieved samples were weighed and the bulk density was calculated based on the mass-volume ratio (Blaisdell et al. 2003; Maynard and Curran 2006).

Soil sampling for pH, SOM, TN & TC analysis

Prior to timber harvesting, soil samples were collected in July 2018 from the four treatments (10 m, 15 m, 20 m strip widths and uncut control) in order to determine soil properties baseline information in each of the three forested areas. Two sampling strips per each thinned treatment unit were selected including two sampling areas in the uncut control (Figure. 2.1). A maximum of 10 sampling points per treatment were recorded and the soils were collected separately from two different depths (0-10 cm and 10-20 cm soil depth). Five samples above 10 cm soil depth and five below 10 cm up to 20 cm soil depth were kept and analyzed separately.

In a similar manner to the July 2018 soil sampling approach, soils were collected post-harvest in July 2019 and July 2020. To better assess the influence of strip thinning at different widths, a total of 480 soil samples were collected (240 samples collected above 10 cm soil depth and 240 samples between 10 cm and 20 cm depth) in the middle areas of the strips using a 50 m transect. The edge effect and road effect were excluded in the sampling procedure as both road disturbance and conifer plantations directly and indirectly influence biological and chemical properties of the soil including: soil carbon dynamics, pH, organic matter, TC and TN (Hofmeister et al. 2013; Deljouei et al. 2018).

Soil pH

Pre-harvest 2018 soil collected in July was analyzed to assess soil chemical property baseline information of the three adjacent blocks. Post-harvest July 2019 and July 2020 soils were collected in each treatment unit to assess the influence of strip thinning at 10, 15 and 20 m widths on soil acidity or alkalinity. 10 g of fresh soil was placed in 50 ml falcon tubes and mixed with 25 ml of distilled water. The mixture was used to measure soil pH with a Palintest 800 PT1350 pH meter after shaking the soil water for 1 min and let it rest for 60 min.

Soil Organic Matter (SOM)

Soil organic matter content was determined using the loss on ignition (LOI) method. 1.5 g of fresh soils were placed into aluminum tin foil pans and heated at 105°C for 12 hours using a YAMATO forced convection constant temperature drying oven (DKN818, Yamato Scientific Co. Ltd) in order to remove soil moisture. The soils were then weighed on an analytical scale and the weights recorded before placing the dried samples into the muffle furnace. The Barnstead-thermolyne 62700 furnace was used to ignite the soils at 500°C for 5 hours and then left in the desiccator for at least 30min until reached the room temperature. Finally, the samples were weighed and recorded again. The soil organic matter was calculated using (Wang et al. 2011; Wang et al. 2012):

Eq. (2)

$$SOM_{LOI}\ (gkg^{-1}) = \frac{Weight105C - Weight\ 500C}{Weight105C} \times 1000$$

SOM final results in gkg^{-1} were finally converted to % for comparison with the total carbon results.

Soil total nitrogen (TN) and total carbon (TC)

Soil samples were carefully prepared using aluminum tin foil pan. Samples were ground and sifted through a 355µm laboratory test sieve (mesh No 45). The sieved samples were weighed in tin containers and then introduced into the combustion reactor from the FlashSmart Elemental Analyzer (Thermo Fisher scientific TM) (Figure 3.2). The FlashSmart Analyzer function based on the dynamic flash combustion technique was used, the produced gases after combustion were carried out by helium flow to the copper reactor, then through a water trap, and finally detected by the Thermal Conductivity Detector (TCD) (Krotz et al. 2016).

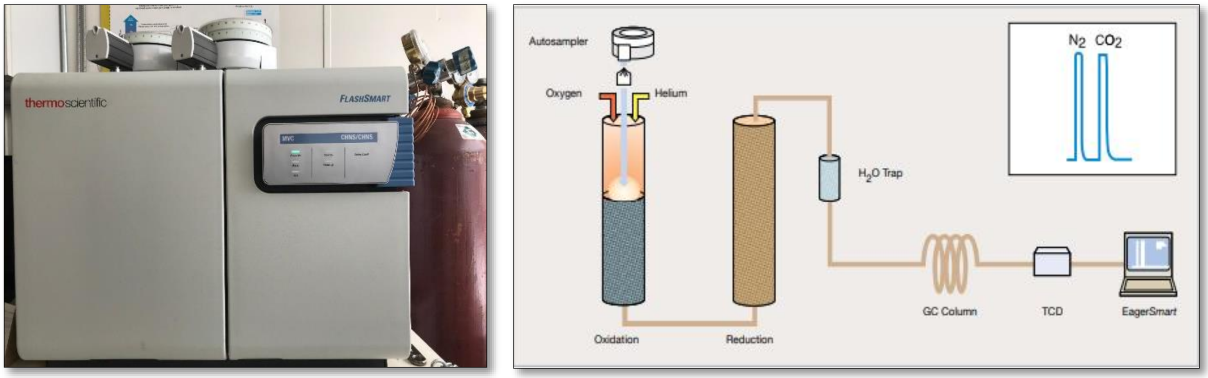

Figure 3.2: *Thermo Fisher FlashSmart Elemental Analyzer Nitrogen and Carbon configuration and analysis process (Krotz et al. 2016).*

Net Carbon Exchange (NCE) through soil respiration

At the ecosystem level, It is important to understand the Net Carbon Exchange (NCE) between the atmosphere and the ecosystem including above and below ground activities such as plant photosynthesis, plant and soil respiration and decomposition (Bhattarai et al. 2016). CO_2 is sequestered through photosynthetic carbon metabolism and utilized for growth and development of plants. Throughout the fixation process, some carbon content is lost through respiration (Li-COR Biosciences 2010a). Several methods can be used to assess the impact of thinning on the rate of CO_2 release from the ground to the atmosphere and our experiment used an automated LI-COR 8100 Soil CO_2 flux system (Figure 3.3) as an approach to quantify CO_2 flux through soil or plant respiration.

The LI-8100 is the most common direct-survey measurement method, using an open and closed chamber system that analyses the fluxes of CO_2 (Fc, µmol $m^{-2}s^{-1}$) from the soil atmosphere out into the bulk atmosphere using the equation (3) (Madsen et al. 2009). The system requires the use of a soil collar (made in polyvinyl chloride- PVC pipe) that is permanently inserted in the soil at least 24 hours prior to conduct any measurement (Figure 3.3). Two strips per each thinned treatment unit including uncut control areas were selected for seasonal flux measurement (see selected strips on figure 2.1). The total of 24 surveys were conducted three times in spring, summer and fall of 2019 and 2020. For the purpose of insuring the accuracy of the instrument data collection, repeated measurements at each sampling location were conducted three times and the average value was recorded using SoilFluxPro software (Li-COR Biosciences 2010b).

Eq. (3) (Madsen et al. 2009)

$$F_c = \frac{PV}{RTS}\frac{dC_c}{dt}$$

Fc = Fluxes of CO_2 (in µmol $m^{-2}s^{-1}$)

P = Atmospheric pressure (Pa),

V = Total system volume (in m^3), including the volume of the chamber, the pump, and tubing in the measurement loop,

R = Gas constant (8.314 Pa m^3 °K^{-1} mol^{-1}),

T = Absolute temperature (°K), and

S = soil area covered by the chamber (m^2).

Figure 3.3: *LI-COR, LI-8100A automated CO2 soil gas flux system with a direct survey chamber ranged between 0ppm to 20,000ppm and an operating temperature range between -20°C to 45°C. A green soil Collar with a 10 cm inside and 11.4 cm outside diameter, and with 10 cm of length inserted permanently in the soil, and a minimum of 2 cm extension above the soil surface (Li-COR Biosciences 2010a).*

STATISTICAL ANALYSIS

All statistical analyses were conducted using R version 3.6.2 (The R Foundation for Statistical Computing). All data sets were checked for normality using Shapiro test and residual plots (Mohd Razali and Bee Wah 2011). Homogeneity of variance was assessed using the Fligner-Killeen test

(Conover et al. 1981), and when necessary, the data were transformed using a natural logarithm or a square root function (sqrt). Analysis of variance was used to assess the differences in SOM, TC, TN, pH level, bulk density and the rate of CO_2 movement between 10 m, 15 m, 20 m strip thinned and the uncut control treatments. Analysis of variance was followed by a Tukey post-hoc test to find treatments that were significantly different from each other at a 5% probability level. Kruskal Wallis tests followed by Dunn's post-hoc test, using the Benjamini-Hochberg procedure to control for multiple comparisons were applied to the data that did not follow a normal distribution and equal variance assumptions. Analysis of covariance (ANCOVA) was also employed to control for a priori effect pre-timber harvest 2018.

RESULTS

Soil bulk density

Soil bulk density measurement conducted in the middle areas of the thinned strips (10 m, 15 m and 20 m width), including the uncut control treatment, was done in May 2019 after soil horizon and texture surveys, as well as coarse fragments content collected in October 2017 (Appendix-A.10& A.11). No effect of heavy machinery utilization on soil bulk density was observed in the middle areas of the thinned strips ($p > 0.05$) (Figure 3.4). In May 2020, soil bulk density was surveyed in the entire strips. The assessment found a significant effect of heavy machinery on soil compaction ($p < 0.001$), with a high bulk density in all thinned strips (Figure 3.4). Uncut controls were significantly different with low bulk density than all of the thinned strip treatments ($p< 0.05$). 20 m and 10 m strips were also significantly different than 15 m strips ($p< 0.05$). No difference was found between 10 m and 20 m strips ($p> 0.05$).

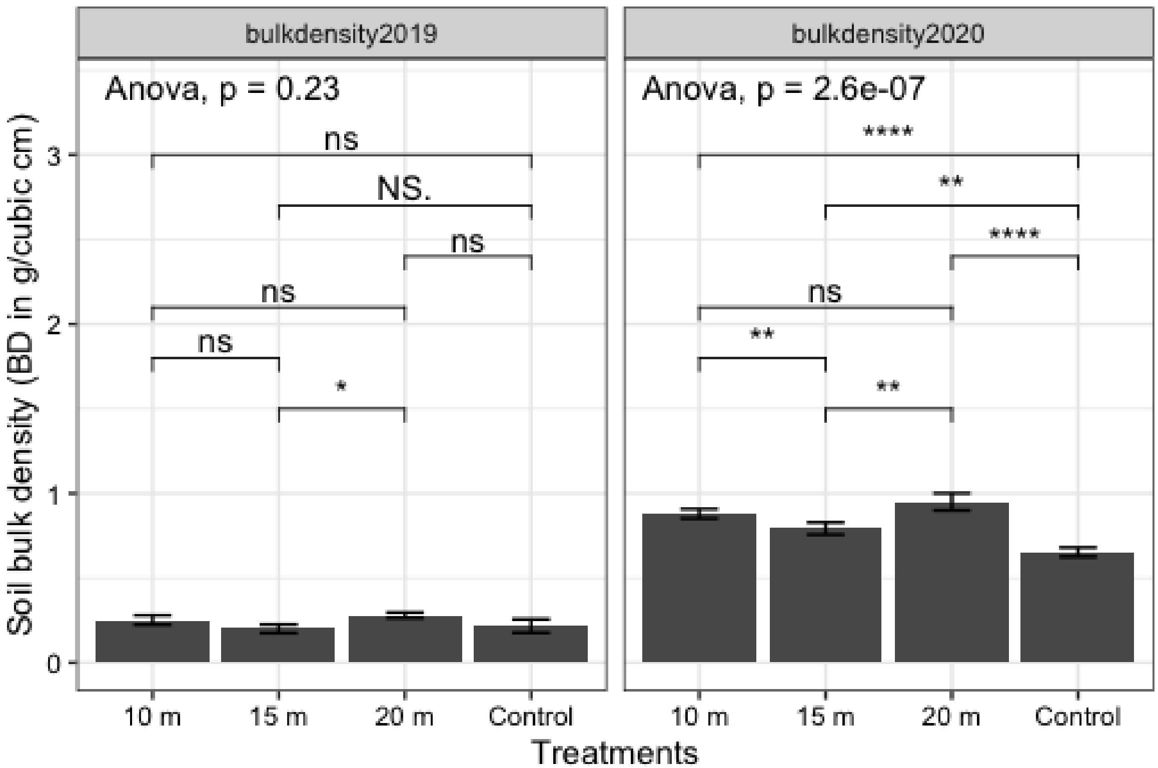

Figure 3.4: *Post-harvest 2019 and 2020 mean bulk density (BD in g cm^{-3}) of each treatment unit in three adjacent block design. Error bars represent standard error of the mean (n= 6 for each group in 2019 and 48 in May 2020). (NS= non-significant; * = p≤ 0.05; ** = p≤ 0.01; *** = p≤ 0.001; **** = p≤ 0.0001).*

Soil pH

The average soil pH of the three blocks in 2018 was 5.6 from 0-10 cm depth and 5.7 from 10-20 cm depth. The mean soil pH for both depths (0-10 cm and 10-20 cm) did not show any statistically significant difference between the treatment units ($p > 0.05$) (Figure 3.5 & 3.6). Apparently, soil pH in the three blocks slightly reduced by 0.1, from year 2018 to year 2019, as the average soil pH in 2019 was 5.5 from 0-10 cm depth and 5.61 from 10-20 cm depth. Post-harvest 2019 thinning activity had a significant effect on soil pH analyzed above 10 cm soil depth ($p < 0.01$) with a high pH in 20 m, followed by the 15 m and 10 m thinned strip treatments and was very low in the uncut control treatment (Figure 3.5); but no significant effect was observed on soil pH depth from 10-20 cm between the three different thinned strip treatments and the control treatment ($p > 0.05$) (Figure 3.6). A similar assessment was conducted again in July 2020 and the analysis did not find any significant different in both above and below 10 cm soil depth ($p > 0.05$)

(Figure 3.5 & 3.6). ANCOVA assessment which included pre-harvest 2018 results as a covariate did not find any effect of pre-harvest condition on soil pH post-harvest 2019 and 2020 both 0-10 cm and 10-20 cm soil depth (p> 0.05).

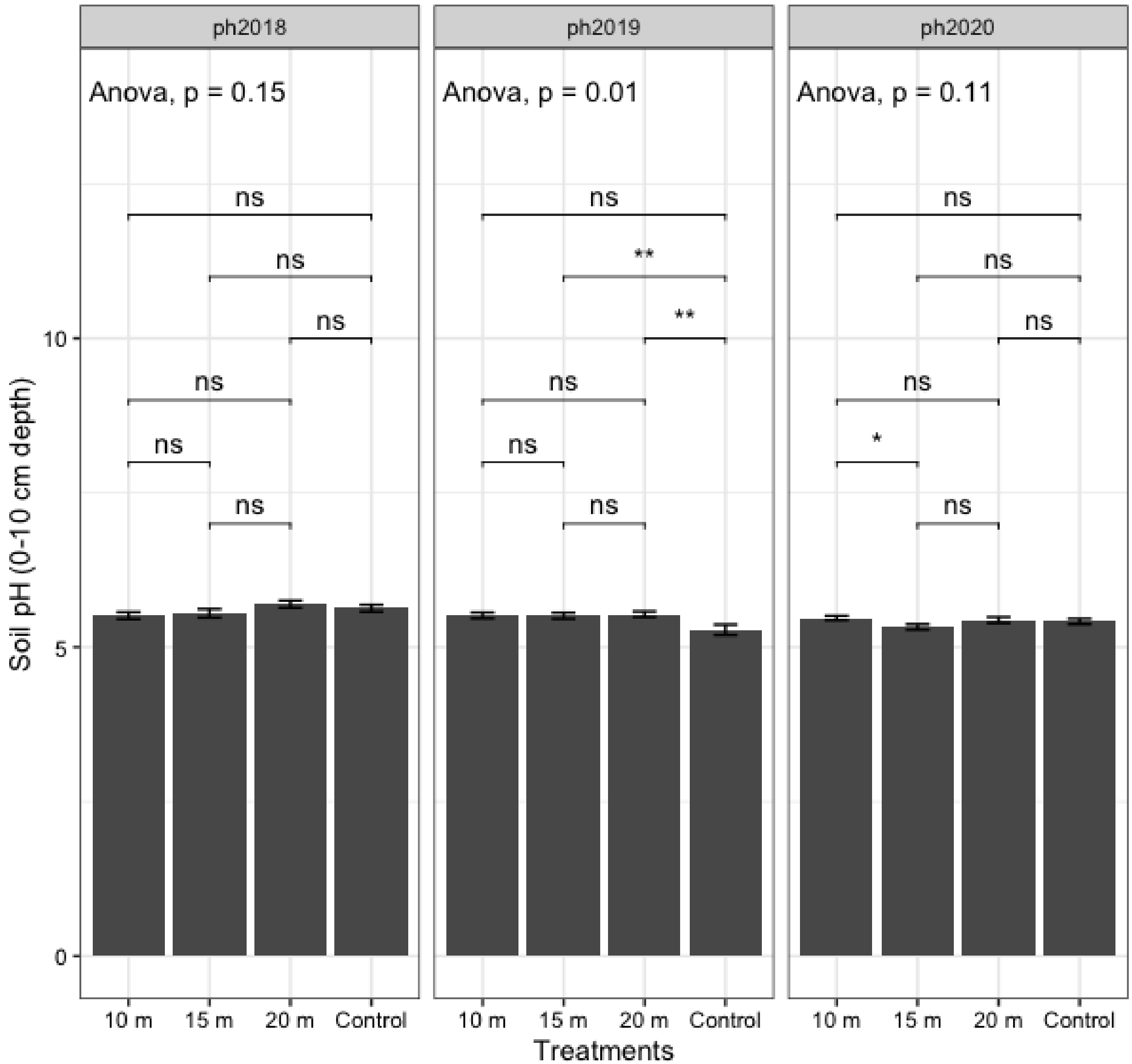

Figure 3.5: *Mean soil pH above 10 cm depth of each treatment unit in three adjacent block designs pre-harvest 2018, post-harvest 2019 and 2020. Error bars represent standard error of the mean (n=30 for each group). (NS= non-significant; * = p≤ 0.05; ** = p≤ 0.01; *** = p≤ 0.001; **** = p≤ 0.0001).*

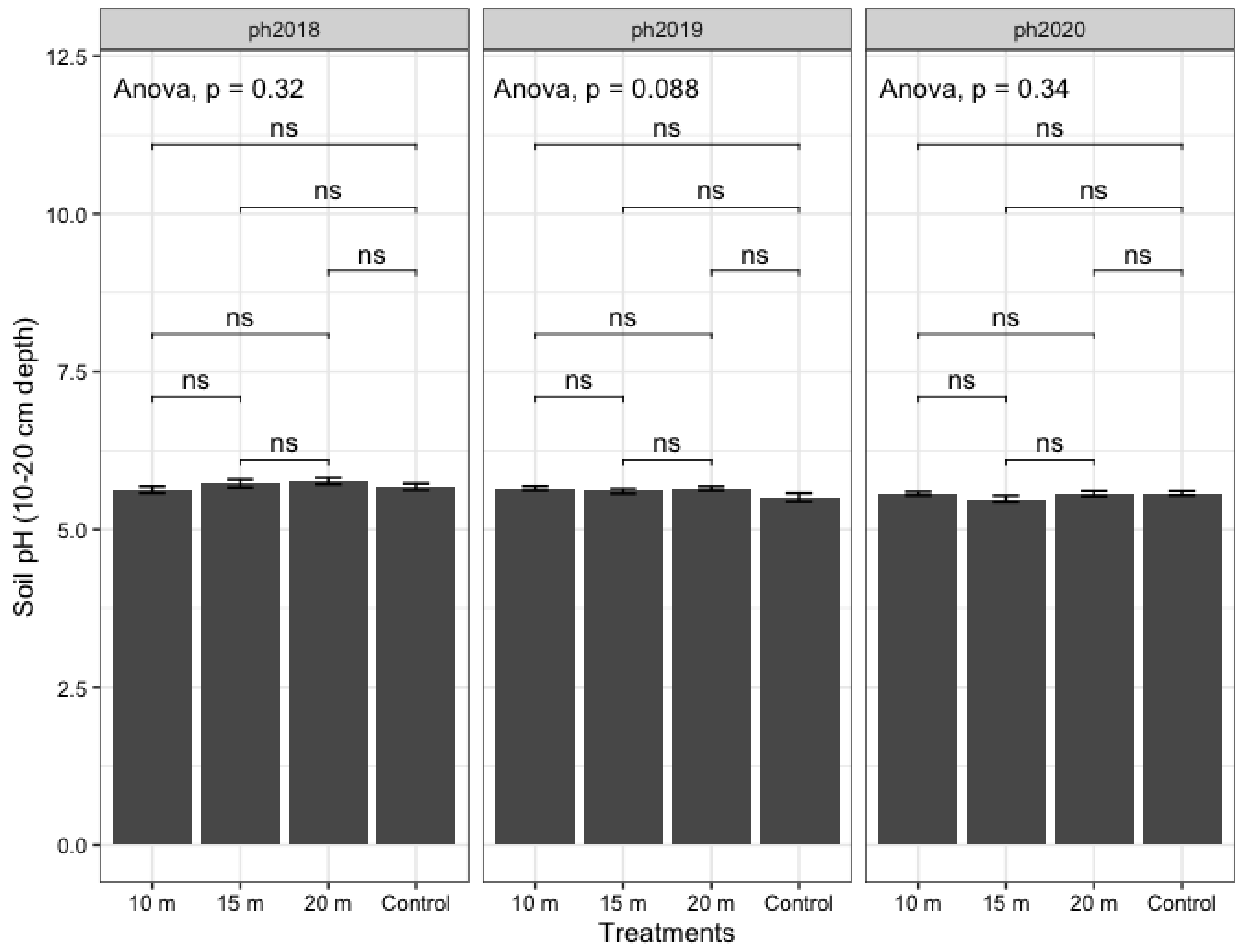

Figure 3.6: *Mean soil pH below 10 cm depth of each treatment unit in three adjacent block designs pre-harvest 2018, post-harvest 2019 and 2020. Error bars represent standard error of the mean (n=30 for each group). (NS= non-significant; * = p≤ 0.05; ** = p≤ 0.01; *** = p≤ 0.001; **** = p≤ 0.0001).*

SOM

The mean SOM level pre-harvest 2018 was at 30.2% and 14.03% from 0-10 cm and 10-20 cm depth respectively in each of the three adjacent blocks. A statistical comparison above 10 cm soil depth between areas allocated to 10 m, 15 m, and 20 m thinned treatments, along with the uncut control treatment, showed a significant difference after a Kruskal Wallis test; as the data was not normally distributed even after performing various transformation tests ($p < 0.05$) (Figure 3.7). Dunn’s test by Benjamini-Hochberg observed a high SOM content in areas allocated to the 15 m thinned strip treatments and a low content in areas allocated to the 10 m, and 20 m thinned and the uncut control treatments. No significant difference was observed below 10 cm soil depth (p. 0.05)

(Figure 3.8); but Dunn's test by Benjamini-Hochberg observed a slightly higher SOM content below the 10 cm soil depth in the areas designed for 15 m thinned treatments and low in the 20 m thinned treatments ($p < 0.05$).

In 2019 post-harvest, the mean SOM decreased by 23.7% and 10.23%, as the mean values were 6.5% above 10 cm soil depth, and 3.8% below 10 cm soil depth. SOM content above 10 cm soil depth was significantly different, and Dunn's test by Benjamini-Hochberg observed a higher SOM content in the uncut control treatment than 15 m and 20 m thinned strip treatments and slightly lower in 10 m thinned treatments ($p < 0.05$) (Figure 3.7). The analysis of SOM content assessed below the 10 cm soil depth did not find any thinning effects across all the treatment units ($p > 0.05$) (Figure 3.8). Similar analysis was conducted once again in July 2020, two years after thinning activities. The overall mean SOM content above the 10 cm soil depth was 12.46% and 7.57% between 10-20 cm depth. Apparently, the mean SOM in 2020 increased by 5.96% above 10 cm soil depth, and 3.73% below the 10 cm soil depth after comparing with the previous year. Kruskal-Wallis did not find any thinning effect on SOM in any thinned treatment at any soil depth including the uncut control treatment ($p > 0.05$) (Figure 3.7 & 3.8). ANCOVA assessment which included pre-harvest 2018 results as a covariate did not find any effect of pre-harvest condition on SOM post-harvest 2019 and 2020 both 0-10 cm and 10-20 cm soil depth ($p > 0.05$).

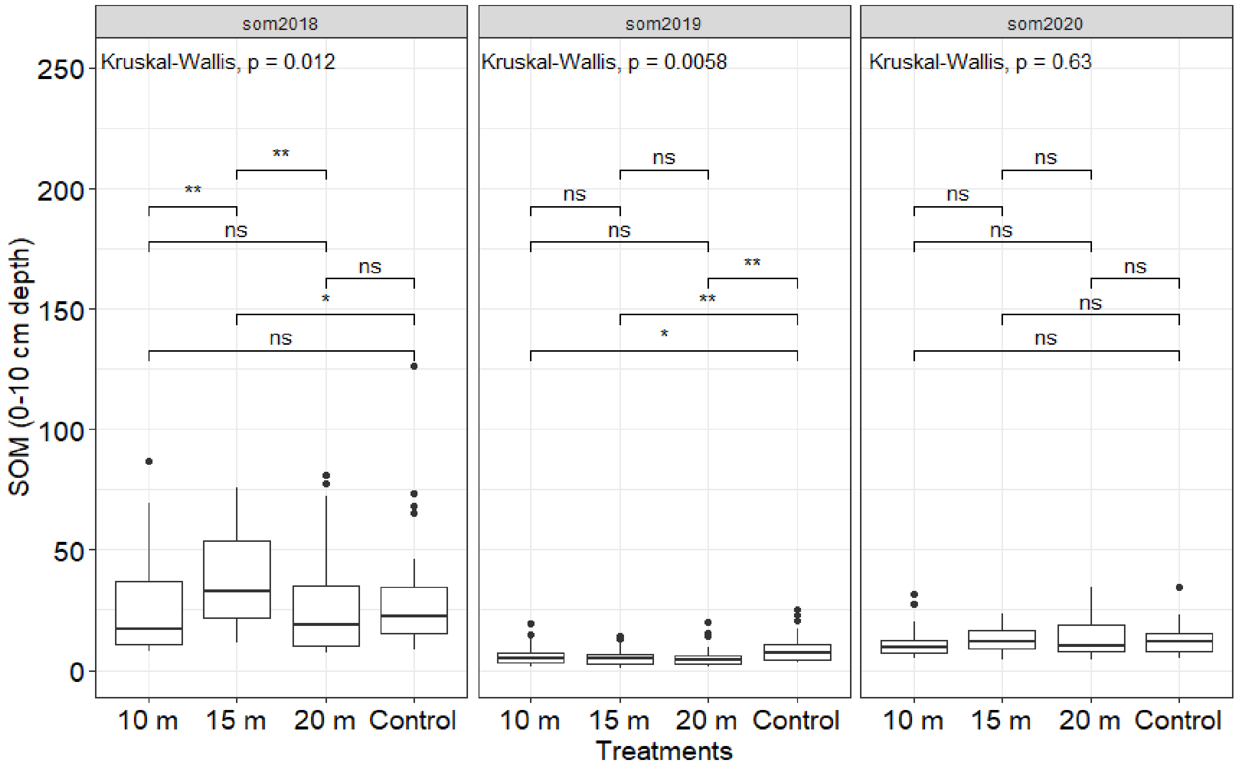

Figure 3.7 *Mean SOM (Soil Organic Matter) above 10 cm depth of each treatment unit in three adjacent block designs pre-harvest 2018, post-harvest 2019 and 2020. Error bars represent standard error of the mean (n=30 for each group). (NS= non-significant; * = p≤ 0.05; ** = p≤ 0.01; *** = p≤ 0.001; **** = p≤ 0.0001).*

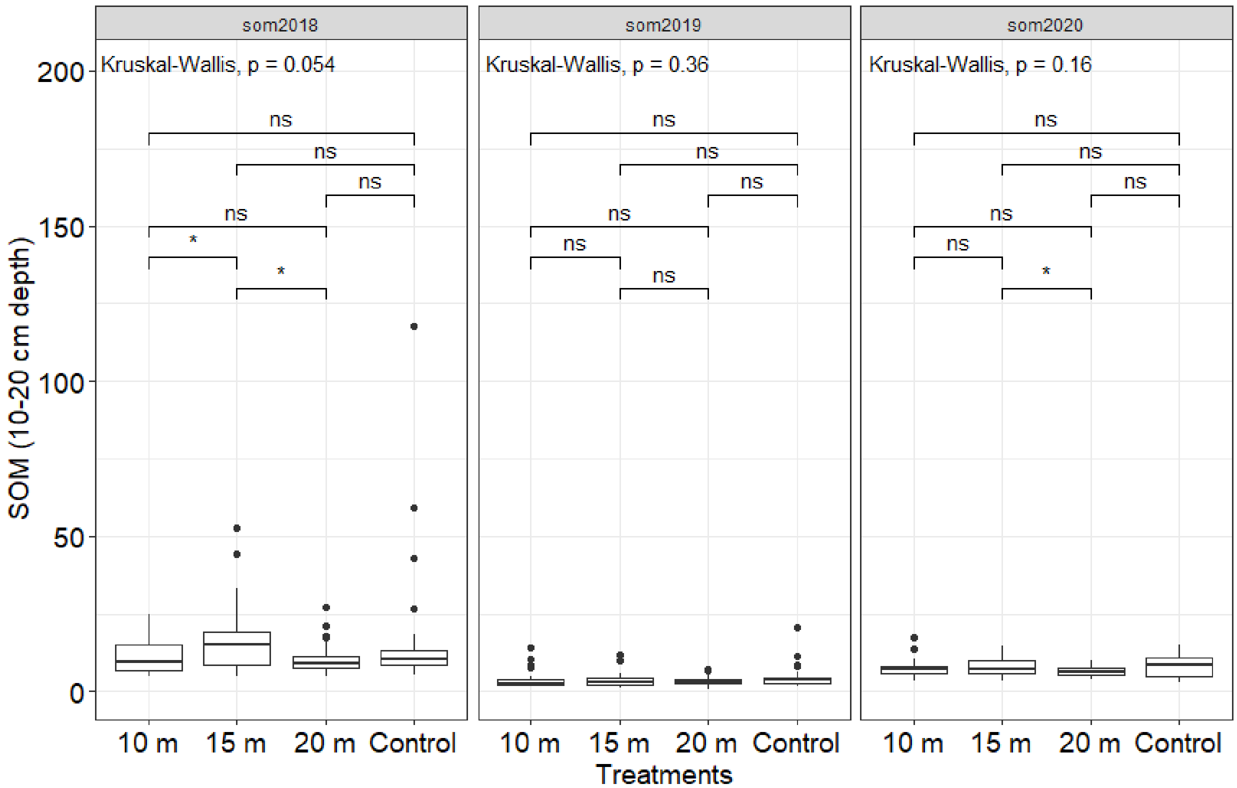

Figure 3.8: *Mean SOM (Soil Organic Matter) below 10 cm up to 20 cm soil depth of each treatment unit in three adjacent block designs pre-harvest 2018, post-harvest 2019 and 2020. Error bars represent standard error of the mean (n=30 for each group). (NS= non-significant; * = p≤ 0.05; ** = p≤ 0.01; *** = p≤ 0.001; **** = p≤ 0.0001).*

Total Carbon (TC)

Pre-harvest 2018 soil TC content above the 10 cm soil depth were 6.31% and 3.35% below 10 cm up to 20 cm soil depth. Soil carbon above 10 cm soil depth showed a significant difference, with a higher carbon content in the areas allocated to the 15 m thinned treatments and lower in other areas allocated to the 20 m and 10 m thinned treatments ($p < 0.05$) (Figure 3.9). Uncut control treatment was also significantly different and higher than the areas allocated to the 20 m thinned treatments in the top soils above 10 cm depth ($p < 0.05$) (Figure 3.9). Comparison conducted below 10 cm soil depth with Dunn's test by Benjamini-Hochberg observed again a higher carbon content in the areas allocated to the 15 m than 20 m and 10 m thinned treatments ($p < 0.05$) (Figure 3.10).

Post timber harvest 2019 carbon content was 4.93% above 10 cm soil depth and 2.61% between 10 cm and 20 cm soil depth. No significant effects of thinning at different strip width were observed on %TC at any soil depth (0-10 cm and 10-20 cm) after comparing 10 m, 15 m and 20 m thinned strip treatments including the uncut control ($p > 0.05$) (Figure 3.9 & 3.10). However, a similar monitoring approach conducted in July 2020 (average TC content of 4.21% above 10 cm and 2.7% below 10 cm soil depth) found a significant change in soil TC level. The change was seen in the deeper soils between 10 cm and 20 cm soil depth, with a higher carbon content in 10 m thinned treatments and lower in 20 m thinned treatments ($p<0.05$) (Figure 3.10). Although the top soils above 10 cm depth was slightly different between 10 m and 20 m treatment widths, no statistically significant difference was observed (at a $p> 0.05$) (Figure 3.9). Analysis of covariance which included pre-harvest 2018 results as a covariate did not find any effect of pre-harvest condition on TC post-harvest 2019 and 2020 both above and below 10 cm soil depth ($p> 0.05$).

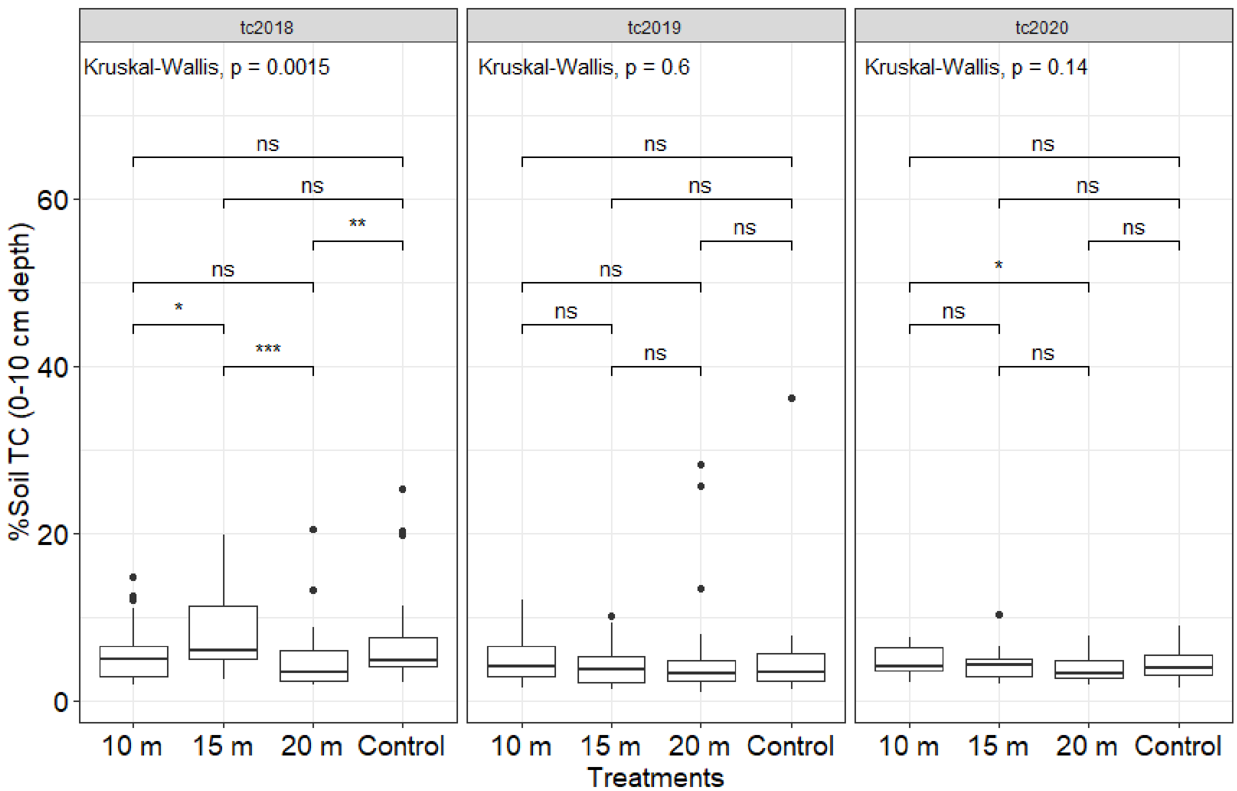

Figure 3.9: *Mean TC (Total Carbon) above 10 cm soil depth of each treatment unit in three adjacent block designs pre-harvest 2018, post-harvest 2019 and 2020. Error bars represent standard error of the mean (n=30 for each group). (NS= non-significant; * = p≤ 0.05; ** = p≤ 0.01; *** = p≤ 0.001; **** = p≤ 0.0001).*

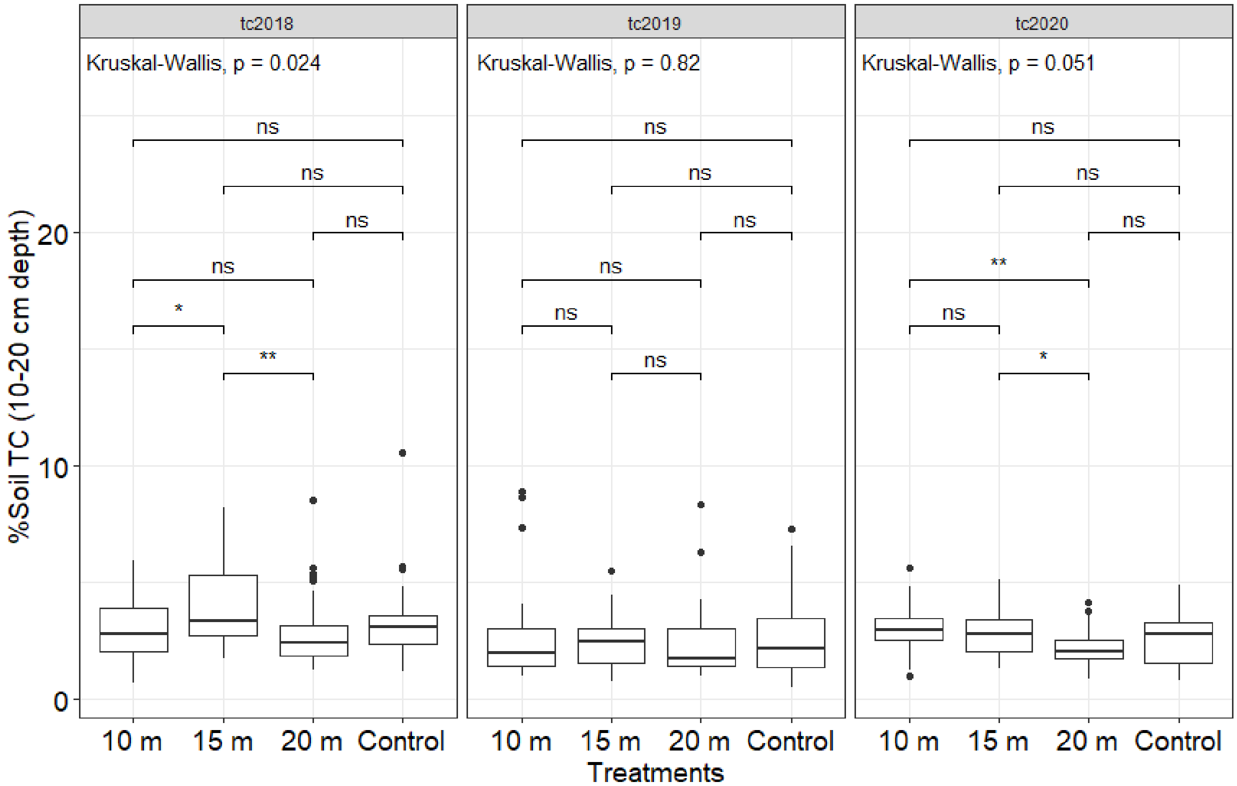

Figure 3.10: *Mean TC (Total Carbon) below 10 cm up to 20 cm soil depth of each treatment unit in three adjacent block designs pre-harvest 2018, post-harvest 2019 and 2020. Error bars represent standard error of the mean (n=30 for each group). (NS= non-significant; * = p≤ 0.05; ** = p≤ 0.01; *** = p≤ 0.001; **** = p≤ 0.0001).*

Total Nitrogen (TN)

Pre-harvest 2018 soil TN content ranged between 0.23% above 10 cm and 0.14% below 10 cm soil depth. The comparison between the four treatments on a soil depth of 10 cm showed a high nitrogen content in the treatments assigned to be harvested at 15 m strip widths and low in other treatments assigned to be harvested at 10 m and 20 m strip widths ($p < 0.05$) (Figure 3.11). The uncut control treatment was also significantly different and had higher TN content than the treatment intended to be the 20 m thinned treatment ($p < 0.05$) (Figure 3.11). Nitrogen content below 10 cm soil depth was still higher in the treatment intended to be the 15 m thinned treatment and lower in 20 m and 10 m thinned treatment ($p < 0.05$) (Figure 3.12).

A similar monitoring approach was conducted post-harvest 2019, which showed a slight variation in nitrogen content with 0.21% above 10 cm soil depth and 0.15% between 10 cm and

20 cm soil depth; but no significant effect of timber harvesting at any strip width treatment including the uncut control treatment was observed either above or below 10 cm soil depth (p> 0.05) (Figure 3.11 & 3.12). However, the re-assessment conducted post-harvest 2020 showed an increment of nitrogen content above and below 10 cm soil depth of 0.81% and 0.17% respectively. A significant effect of timber harvesting was observed above 10 cm soil depth (p< 0.05) with a higher nitrogen content in 10 and 15 m thinned treatments and lower in 20 m thinned treatment and uncut control treatment (Figure 3.11). No effect was noticed in the deeper soil between 10 cm and 20 cm soil depths (p> 0.05) (Figure 3.12). Analysis of covariance found a significant difference only in the top soil (0-10 cm soil depth) (p< 0.05), with a higher TN content in 15 m and 10 m thinned treatments and a lower nitrogen content in 20 m and uncut control treatments (Table 3.1).

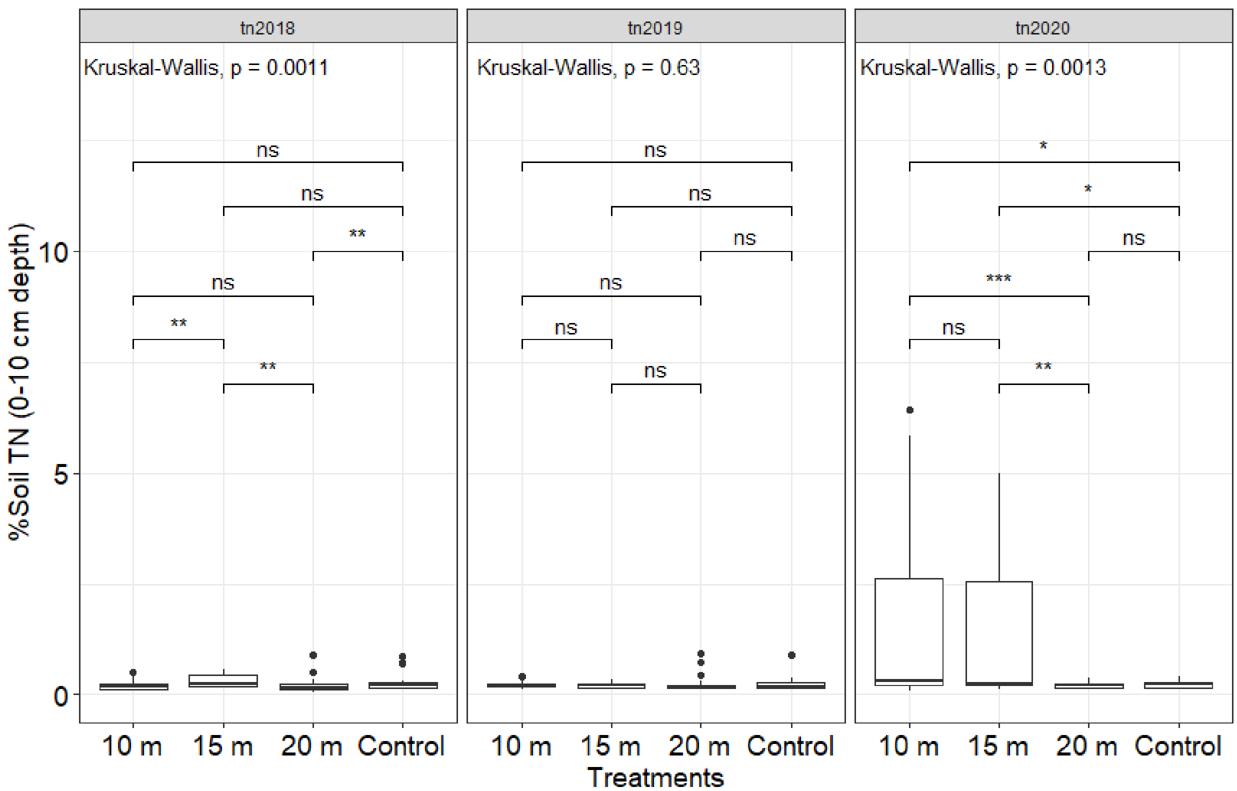

Figure 3.11: *Mean TN (Total Nitrogen) above 10 cm soil depth of each treatment unit in three adjacent block designs pre-harvest 2018, post-harvest 2019 and 2020. Error bars represent standard error of the mean (n=30 for each group). (NS= non-significant; * = p≤ 0.05; ** = p≤ 0.01; *** = p≤ 0.001; **** = p≤ 0.0001).*

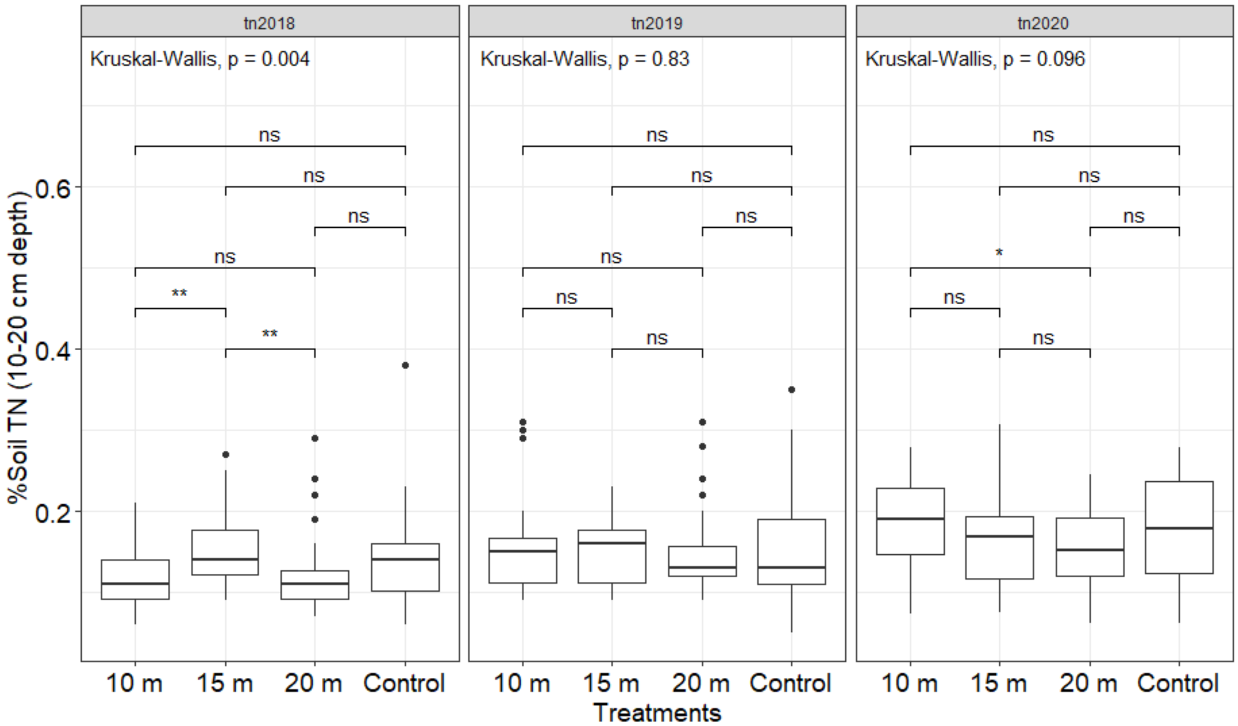

Figure 3.12: *Mean TN (Total Nitrogen) below 10 cm up to 20 cm soil depth of each treatment unit in three adjacent block designs pre-harvest 2018, post-harvest 2019 and 2020. Error bars represent standard error of the mean (n=30 for each group). (NS= non-significant; * = p≤ 0.05; ** = p≤ 0.01; *** = p≤ 0.001; **** = p≤ 0.0001).*

Table 3.1: ANCOVA and post-hoc test results for soil total carbon (0-10 cm soil depth) pre-harvest 2018 and post-harvest 2019-2020.

% Soil TN				
	Estimate	Std. Error	t value	Pr(>|t|)
15 m - 10 m	-0.03262	0.1188	-0.275	0.99276
20 m - 10 m	-0.42047	0.1188	-3.539	0.00267 **
Control - 10 m	-0.39104	0.1188	-3.292	0.00611 **
20 m - 15 m	-0.38784	0.1188	-3.265	0.00641 **
Control - 15 m	-0.35842	0.1188	-3.017	0.01464 *
Control - 20 m	0.02943	0.1188	0.248	0.99465

Net Carbon Exchange (NCE)

CO_2 flux surveyed post-harvest 2019 averaged 2.63 μmol $m^{-2}s^{-1}$ in May 2019, and 3.64 μmol $m^{-2}s^{-1}$ in July 2019, and finally 0.63μmol $m^{-2}s^{-1}$ in October 2019. There was no impact of thinning observed in any strip thinned treatment on CO_2 flux movement in May and July after comparing the four treatments ($p > 0.05$) (figure 3.13). However, a significant impact was observed in October between the uncut control and 10 m thinned treatments with a higher flux in the uncut control and lower in the 10 m thinned treatments ($p < 0.05$) (Figure 3.13).

Post-harvest 2020, CO_2 flux re-assessed in May averaged 0.39 µmol $m^{-2}s^{-1}$, July flux averaged 5.28 µmol $m^{-2}s^{-1}$, and 0.79 µmol $m^{-2}s^{-1}$ in October 2020. The comparison analysis did not find any significant difference across treatments in all seasons (spring, summer and fall) ($p> 0.05$) (Figure 3.14).

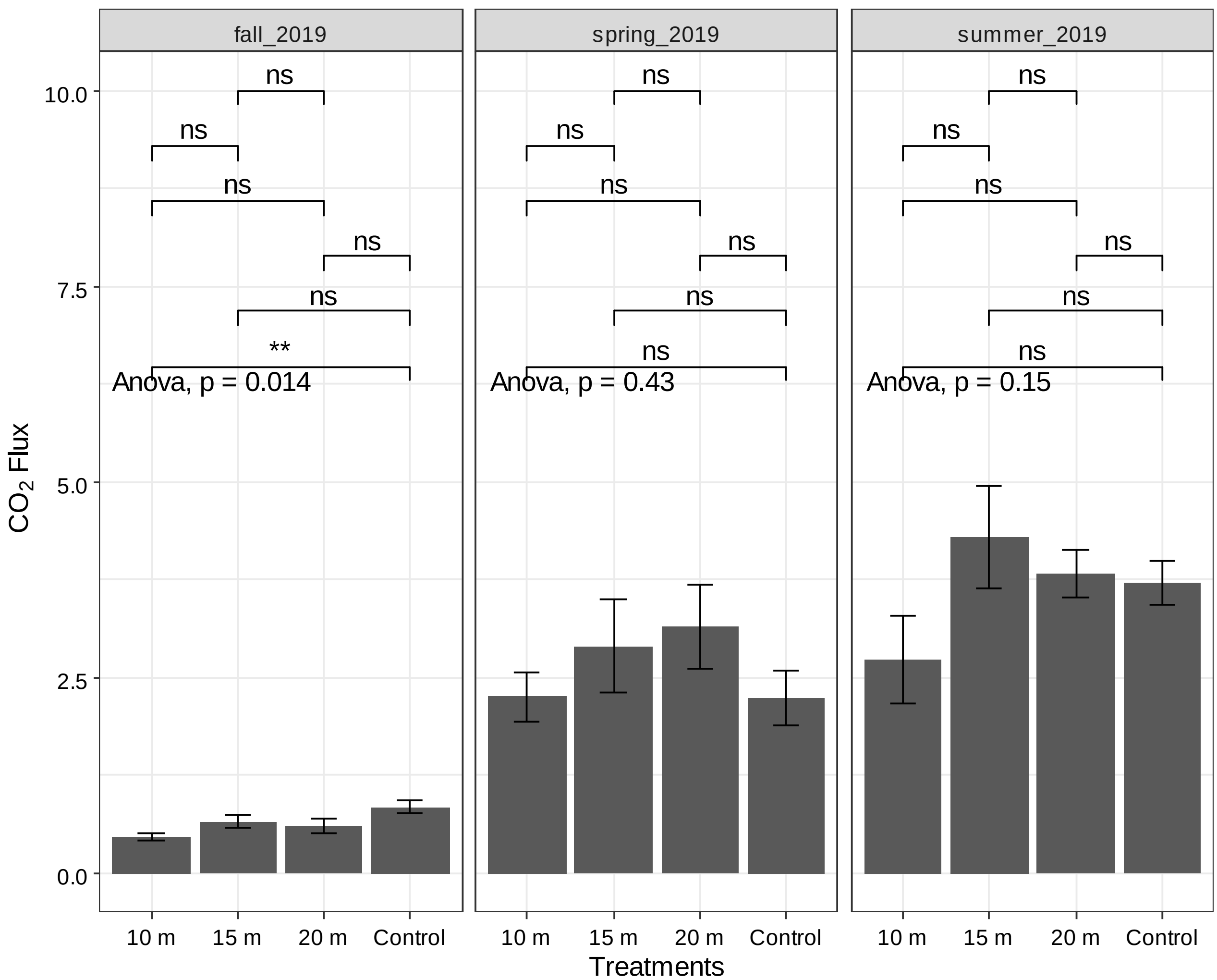

Figure 3.13*: Mean CO2 Flux content of the treatment units in three adjacent study blocks collected in May 2019, July 2019 and October 2019. Error bars represent standard error of the mean (n= 6 for each group). (NS= non-significant; * = p≤ 0.05; ** = p≤ 0.01; *** = p≤ 0.001; **** = p≤ 0.0001).*

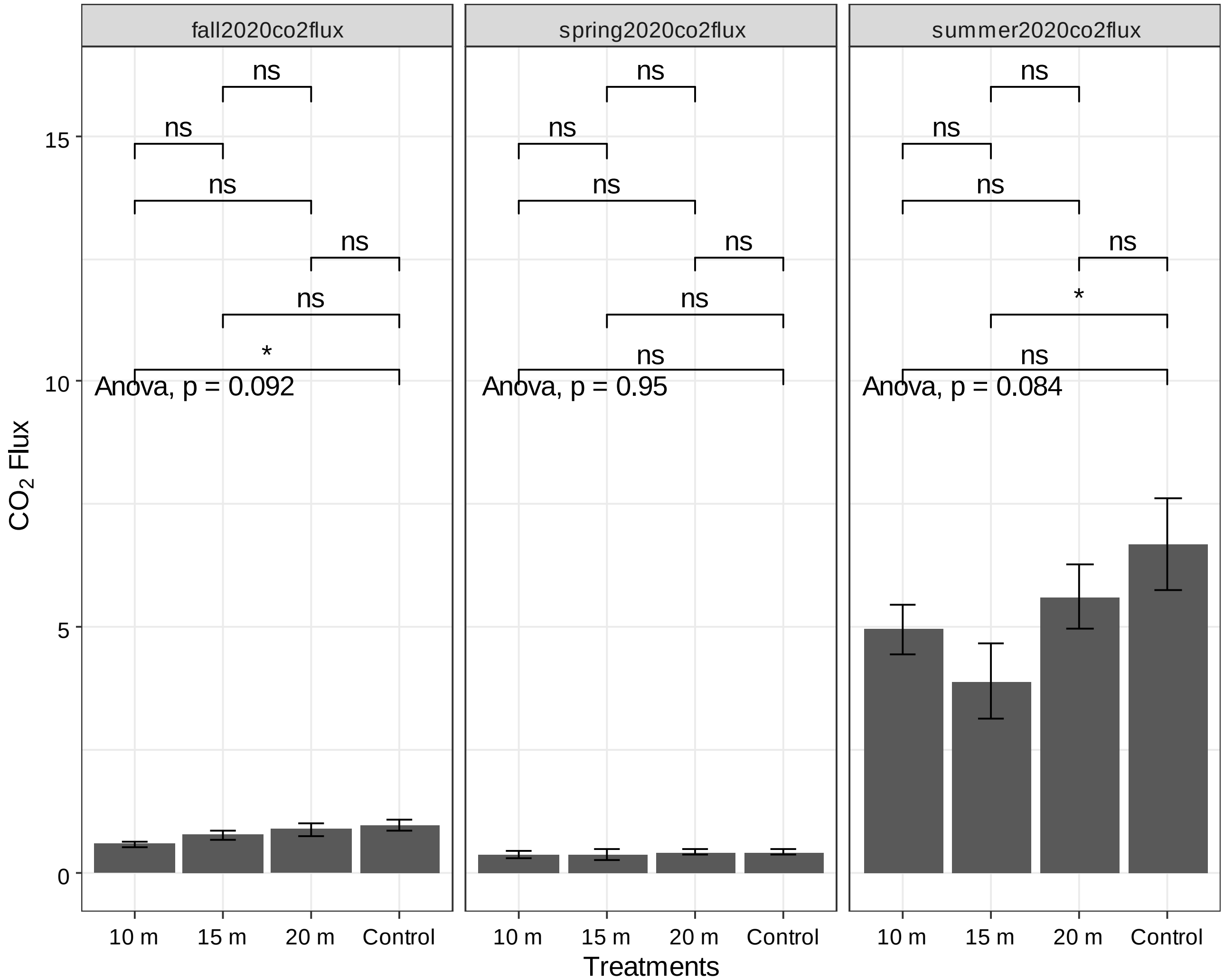

Figure 3.14*: Mean CO2 Flux content of the treatment units in three adjacent study blocks collected in May 2020, July 2020 and October 2020. Error bars represent standard error of the mean (n= 6 for each group). (NS= non-significant; * = p≤ 0.05; ** = p≤ 0.01; *** = p≤ 0.001; **** = p≤ 0.0001).*

DISCUSSION

Effect of strip thinning on soil physical and chemical properties

Bulk density and pH

Strip thinning activity in all three adjacent blocks was carried out using heavy machinery and large tractors, which significantly disturbed the soil in the thinned strips. Soil compaction was visually observed in all harvested strips after an aerial multispectral sensor scanned all experimental research blocks (Appendix- A.13). Bulk density assessment of soil compaction conducted in the middle areas of the thinned strips post timber harvest 2019 did not detected any compaction issue between the treatment units. However, the second assessment that covered the entire strips post-harvest 2020 found a high compaction in all the open strips but the 20 m strips were more affected by compaction, suggesting the 20 m open strips were used more as paths for transporting timber due to their width. A study by Picchio et al. (2012) showed that although thinning is an important practice in managing forest products, it can create several modifications to soil properties including physical properties such as soil compaction which can be caused by the use of heavy machinery and large tractors.

In addition to the above soil physical property, variation in soil chemical properties were noticed after strip thinning post-harvest 2019 with an increment of soil pH in all thinned treatments after comparing them with the uncut control treatment. Lodgepole pine forests have been shown to play a significant role in changing soil chemical properties especially in increasing soil pH levels in an open canopy area, while keeping a low pH in a dense and closed canopy area (Vesterdal and Raulund-Rasmussen 1998; Dingaan et al. 2017). Cheng et al. (2013) found that these variations in soil pH between forested areas and grass areas are caused by the differences in physical and chemical characteristics of soil; and these differences can be seen in a short period of time after land-use change. The increase of soil pH has a greater contribution to forage production, by increasing the availability of nutrients and nodule formation on leguminous species, such as white clover (Rice et al. 1977), and enhancing plant community composition and species richness (Vesterdal and Raulund-Rasmussen 1998; Dingaan et al. 2017). Despite a rapid change of soil pH level due to lodgepole pine (*Pinus contorta*) canopy openings (Vesterdal and Raulund-Rasmussen 1998), thinning activities in forested areas tend to affect more of the soil surface than deeper soils; and our results indicated that soil pH variation was noticed more above 10 cm than below 10 cm soil depth; probably due to lesser amounts of decayed organic matter in top soil, and less disturbance in deeper soils (Zhang et al. 2017). However, soil pH analyzed two years after thinning showed a balanced pH level in thinned and un-thinned treatment units. It seems that two years later, strip thinning did not affect soil pH at any strip width, both above and below the 10 cm soil depths, and it is possible that understory forage growth, and the addition of soil organic matter, might have influenced the results obtained.

Soil Organic Matter (SOM)

Soil pH is often considered as a major influencer in regulating SOM turnover (Kemmitt et al. 2006). A significant increase of soil pH in open strips, and litter clearing by heavy machinery during the process of timber harvesting, might have contributed to a significant reduction of SOM content in 20 m, 15 m and 10 m thinned treatments post-harvest 2019 (Turner and Lambert 2000). According to Turner & Lambert (2000), thinning increases SOM and carbon content after vegetation has fully established through root turnover, rapid litter and root decomposition. Soil disturbance during thinning, and removal of forest floor cover, can negatively affect SOM and carbon content especially above 10 cm soil depth through a slow litter accumulation which explains a significant low organic matter content observed in 20 m, 15 m and 10 m thinned treatments compared to the uncut control treatment. It has been shown that land-use change by opening forest canopies, prior to understory forage growth, reduces SOM and SOC by 42 to 59%, and once vegetation is fully established, accumulation of organic carbon increases at a rate of 300-350kg C ha^{-1} $year^{-1}$ (Puget and Lal 2005). This might explain an increment of SOM and the non-significant differences observed across treatment units in July 2020. Although, understory vegetation in the open strips is not yet fully established, vegetation growth in July 2020 was significantly higher than what was observed in July 2019. A significant growth and the subsequent decay process of plant litter in an agroforestry area could ultimately be a main factor in the formation of soil organic matter (Melillo et al. 1989), and as such vegetation growth needs to be monitored in the future.

Total Carbon (TC) and Nitrogen (TN)

The dominance of conifer tree species in some areas of a forested stand can affect soil carbon and nitrogen as observed pre-harvest 2018; with a significant variation across the designed treatment units (Finzi et al. 1998). It is possible that the difference in litter production, and rate of litter decomposition, due to the amount of tree canopy cover, soil temperature and moisture may have also affected the result obtained pre-harvest 2018 where some of the areas designed for 15 m thinned treatments and control treatments had a significantly higher TC and TN content than some areas designed for 10 m and 20 m thinned treatments (Finzi et al. 1998). However, thinning activities across treatment units post-harvest 2019 did not show any influence on %TC and %TN content; most likely due to the fact that some of the thinned litter materials remained in the open strips, and ended up mixing with the soil after decomposition, like the study published by Bai et al. (2017). The addition of the seed mix and the plant establishment process in the open areas might have added more litter and influenced microbial activities.

Results from this study obtained post-harvest 2020 showed that, assessing long-term effects of forest management on ecosystem pools, including changes in soil carbon and nitrogen, after forest tree removal might take several years (Grady and Hart 2006). The response of soil physical and chemical properties post thinning might be seen in various ways depending on the study sites and assessment periods (Wic Baena et al. 2013). For example, similarities in amounts of soil carbon were observed between treatment units post-harvest 2019 and 2020; as were differences in soil nitrogen with an incremental amount in 10 m and 15 m rather than 20 m thinned treatments and un-thinned control treatments. Soil compaction and high plant root activities, can also affect soil properties such as aeration, water content, temperature and soil microbial activities; especially in sandy loam soils which can influence soil carbon and nitrogen mineralization and nitrification of soil organic matter (Brevik et al. 2002). (Appendix- A.11).

Net Carbon Exchange (NCE)

As mentioned above, the effect of forest thinning on soil respiration can be determined by different inter-related factors including: changes in climatic conditions, soil temperature, microbial respiration, root respiration and decomposition rate from dead branches, and litter to root materials (Tang et al. 2005). In our study, we quantified soil CO_2 flux throughout different seasons (spring, summer and fall seasons) in order to account for the different factors mentioned above. Carbon flux was determined after placing permanent collars (Fig 3.3) in the center areas of the four treatments (uncut control, 10 m, 15 m and 20 m thinned treatments), across the total 101.4 hectares of our three adjacent study blocks. In the three seasons monitored (spring, summer and fall) post-harvest between 2019 and 2020, a significant effect of strip thinning on CO_2 flux was found only in the fall of 2019, with a higher flux level in the un-thinned control treatments, and a lower flux in 10 m thinned treatments. Although, CO_2 flux monitored in all three seasons post-harvest 2020 did not find any significant difference at $p < 0.05$, uncut control treatments showed a slight higher flux than 15 m thinned treatments in summer, and higher than 10 m thinned treatments in fall. Olajuyigbe et al. (2012) showed that vegetation growth and biomass productivity have a strong influence on microbial activities and soil respiration in active trees rather than in dead organic material. Additionally, Tang et al. (2005) showed how delay in vegetation growth is not only explained by soil temperature and soil water, but also by variations in root biomass, ground vegetation cover and soil properties. It seems that the uncut control treatments provided a high flux than thinned areas. It is more likely that the combination of higher forest tree, root biomass and microbial activity, along with soil temperature and other factors mentioned previously might have also significantly influenced our results.

CONCLUSION

This study provides deeper insight on whether the adoption of silvopasture systems established through strip thinning treatments at 10 m, 15 m or 20 m widths respectively, can potentially improve soil carbon sequestration as well as nitrogen storage, ultimately creating more productive and resilient ecosystems for livestock and wildlife. Our findings were not entirely consistent with our hypothesis, and the results obtained did not fully support that the 20 m thinned treatments will sequester more soil carbon and provide more nitrogen than uncut controls or 10 m and 15 m thinned treatments. In contrast, the 15 m and 10 m thinned treatments showed a tendency to accumulate more carbon and nitrogen content than the 20 m thinned treatments. As explained previously in the discussion section, variation in soil pH, soil disturbance and loss of soil organic matter post timber harvesting had a positive effect on carbon and nitrogen decomposition by altering soil microbial abundance and community function (Zabowski et al. 2008; Wu et al. 2019).

Despite the fact that our initial hypothesis was not fully supported, the findings still provide an evidence for optimizing land use in implementing a silvopasture system. As observed not only in this study but by others (Feliciano et al. 2018, Jose et al. 2019), the successful adoption of a silvopasture system through strip thinning has a potential to sequester more soil carbon while enhancing species biodiversity, through a deliberate integration of forage as forage can also sequester carbon not only belowground but aboveground as well.

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CHAPTER 4 – MANAGEMENT IMPLICATIONS AND FUTURE RESEARCH

Forest thinning which is a selective removal of some trees, provides an opportunity to improve the growth and health of the remaining trees or enhance understory vegetation (Verschuyl et al. 2011). Forest thinning is a crucial practice in forest management, as it can be carried out to reduce forest fire fuel loads and can be a factor to slowdown the spread of tree diseases (Smirnova et al. 2021). In addition, the forest thinning approaches applied in the Goudie lodgepole pine forest focused on integrating ranching and forest industries using strip thinning, so that both forest and range products can be fully realized (Appendix- A.14). However, thinning involves the use of heavy machinery and equipment which often results in land disturbance (Picchio et al. 2012). Soil compaction and litter clearing exposes the soil, which can alter soil properties, hydrology and aboveground species development (Kozlowski 1999). It is important to understand all the factors involved and the subsequent benefits in order to make informed and sustainable forest management decisions.

My study assessed the influence of different forest thinning treatments using strips harvesting methods on forage quality and quantity as well as soil carbon storage. The strip-harvested areas were compared to un-thinned areas in order to contribute to a wider understanding of the benefits and effects of forest thinning in British Columbia forested rangeland sites.

Based on our investigation and results, the 20 m and 15 m thinned treatments seemed to influence the most forage growth for livestock and provided higher diverse and richness of understory plant species. Both thinned and un-thinned areas seemed to produce a comparable amount of organic matter, carbon storage and carbon flux. Although the findings of my three years study provided an insight on the potential of improving forage production, and carbon sequestration in a silvopasture system, further research assessing long-term impacts on carbon sequestration and carbon flux in thinned versus un-thinned areas is necessary to determine the full potential of this type of forest management approach.

A long-term experiment should be conducted as well to evaluate at what extent soil bulk density influences forage productivity and carbon sequestration in thinned forested areas and understanding the impact of livestock grazing on forage regeneration and soil carbon.

In addition, it is important to conduct a long-term study on the growth and health response of the remained trees post timber harvesting.

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APPENDIX – A

Relationships between understory species community in the thinned areas Pre-harvest (July 2018) and Post-harvest (August 2019 and July 2020).

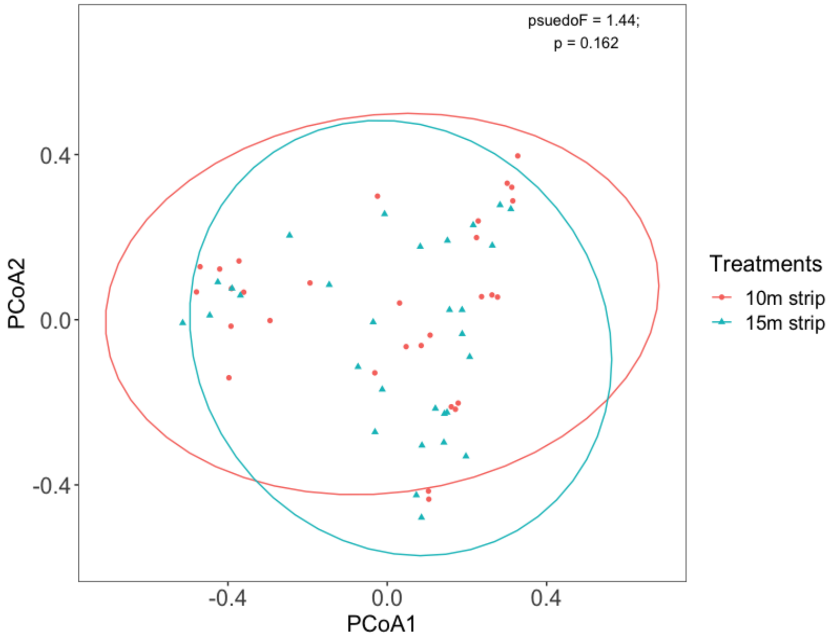


Figure A.1. *PCoA analysis based on Bray-Curtis dissimilarity for July 2018 understory species community composition between areas assigned for 10 m and 15 m treatment widths.*

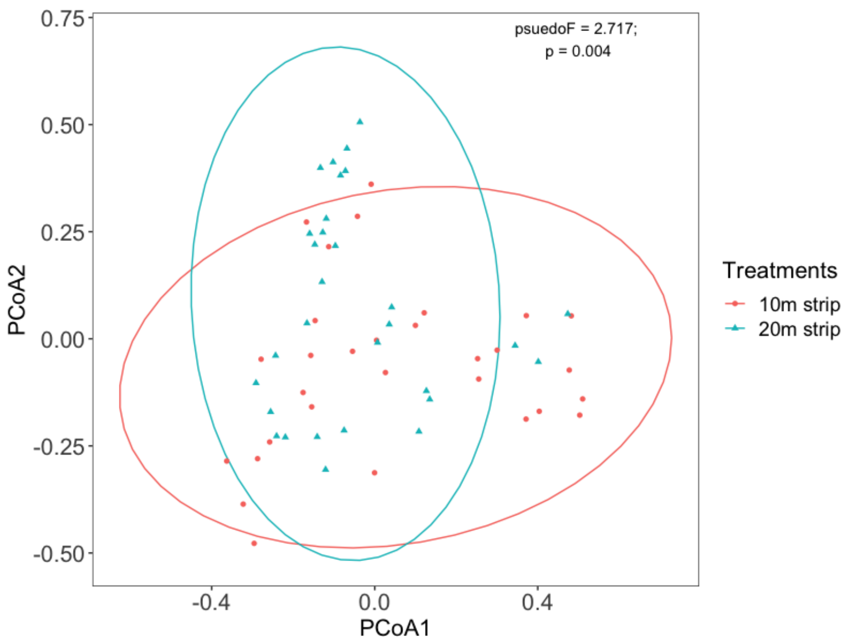


Figure A.2. *PCoA analysis based on Bray-Curtis dissimilarity for July 2018 understory species community composition between areas assigned for 10 m and 20 m treatment widths.*

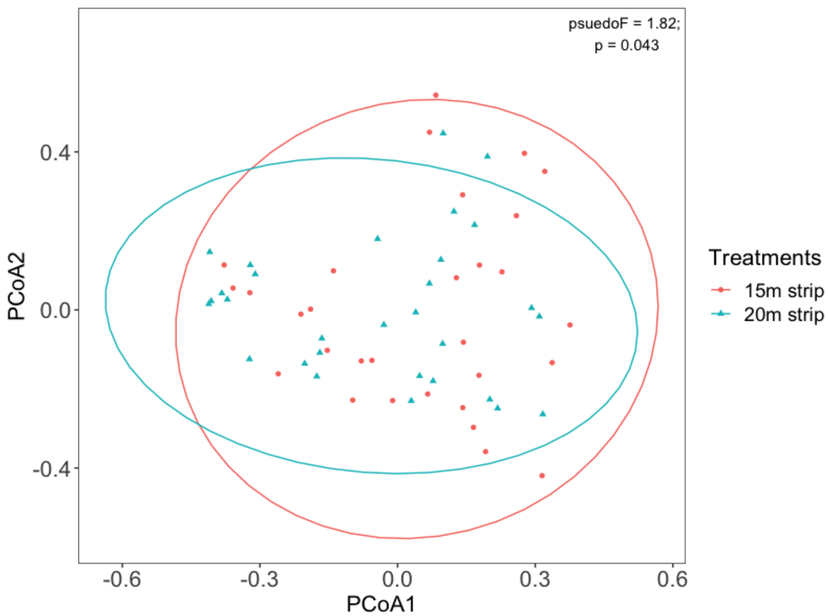


Figure A.3. *PCoA analysis based on Bray-Curtis dissimilarity for July 2018 understory species community composition between areas assigned for 15 m and 20 m treatment widths.*

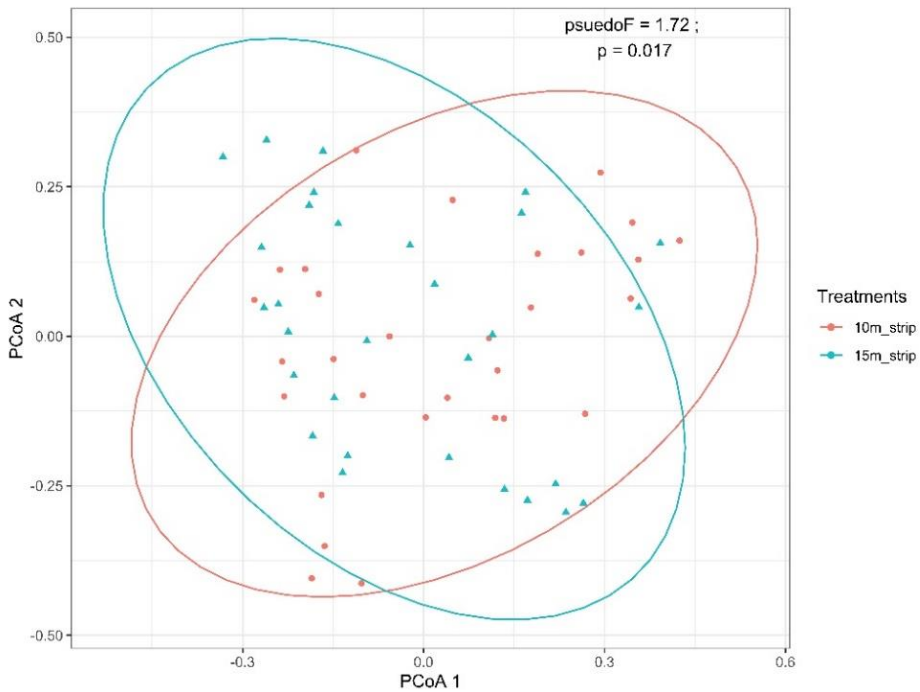


Figure A.4. *PCoA analysis based on Jaccard dissimilarity for August 2019 understory species community composition between 10 m and 15 m thinned treatments.*

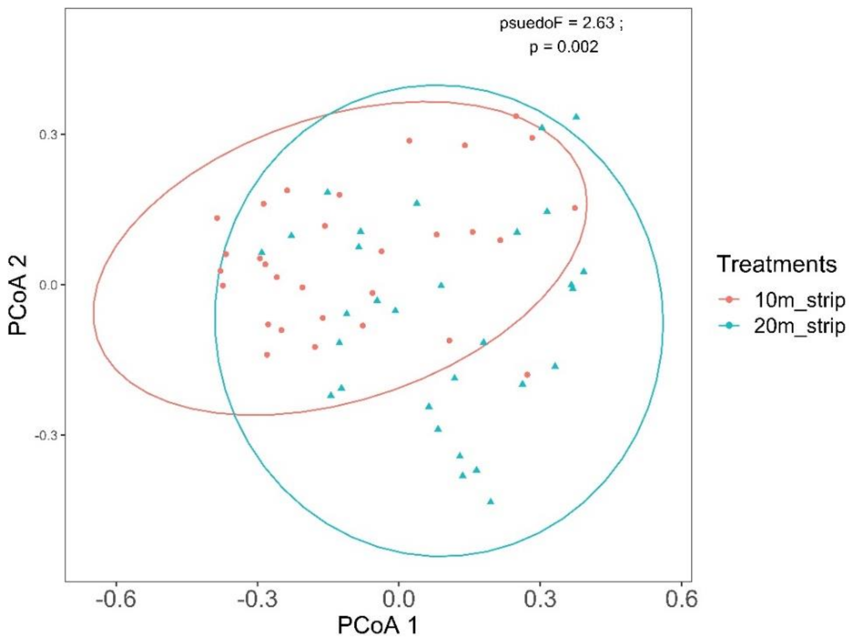


Figure A.5. *PCoA analysis based on Jaccard dissimilarity for August 2019 understory species community composition between 10 m and 20 m thinned treatments.*

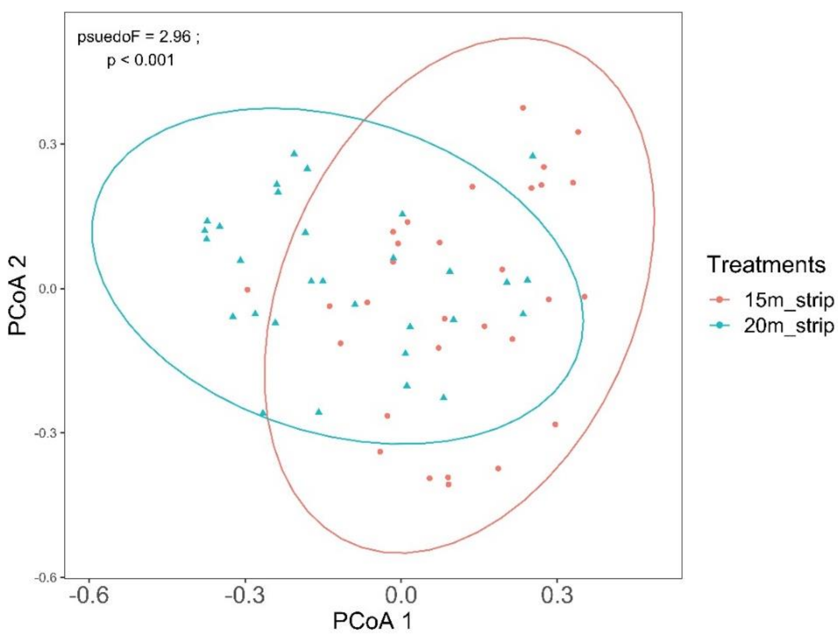


Figure A.6. *PCoA analysis based on Jaccard dissimilarity for August 2019 understory species community composition between 15 m and 20 m thinned treatments.*

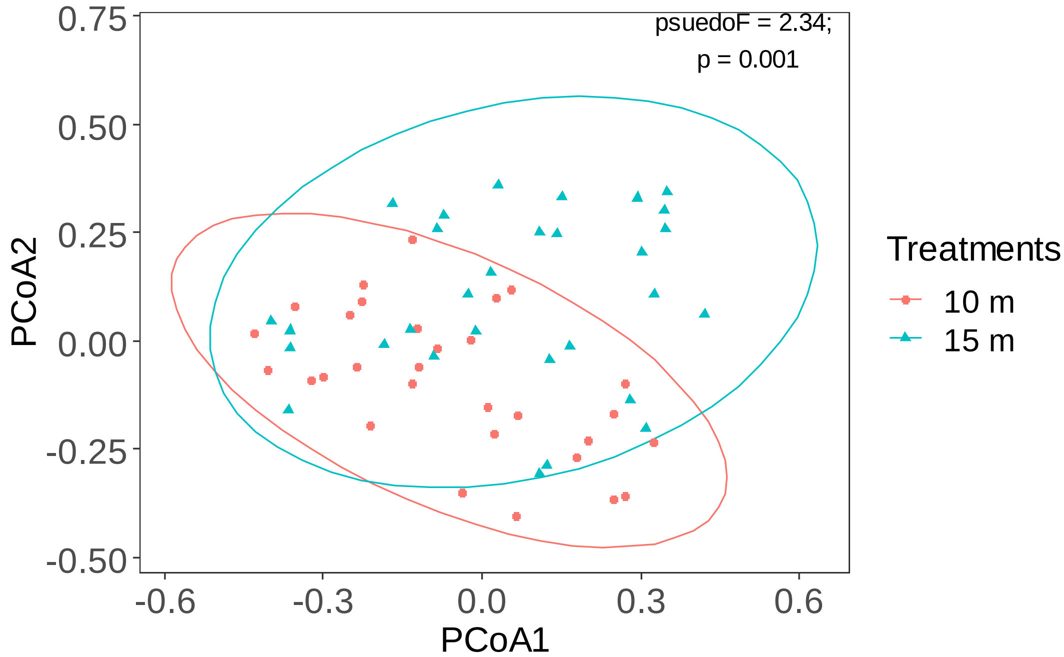


Figure A.7. *PCoA analysis based on Jaccard dissimilarity for July 2020 understory species community composition between 10 m and 15 m thinned treatments.*

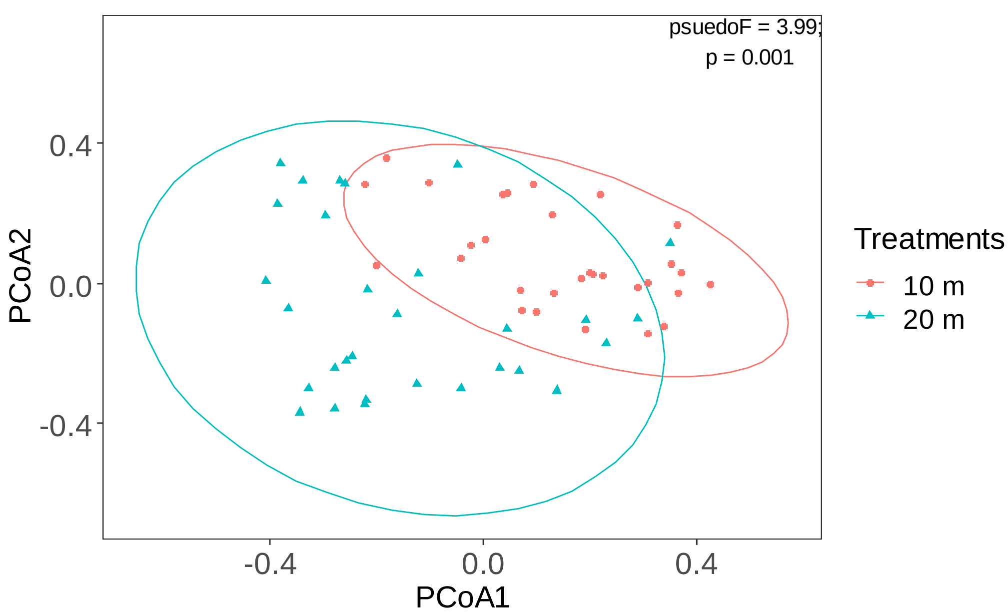


Figure A.8. *PCoA analysis based on Jaccard dissimilarity for July 2020 understory species community composition between 10 m and 20 m thinned treatments.*

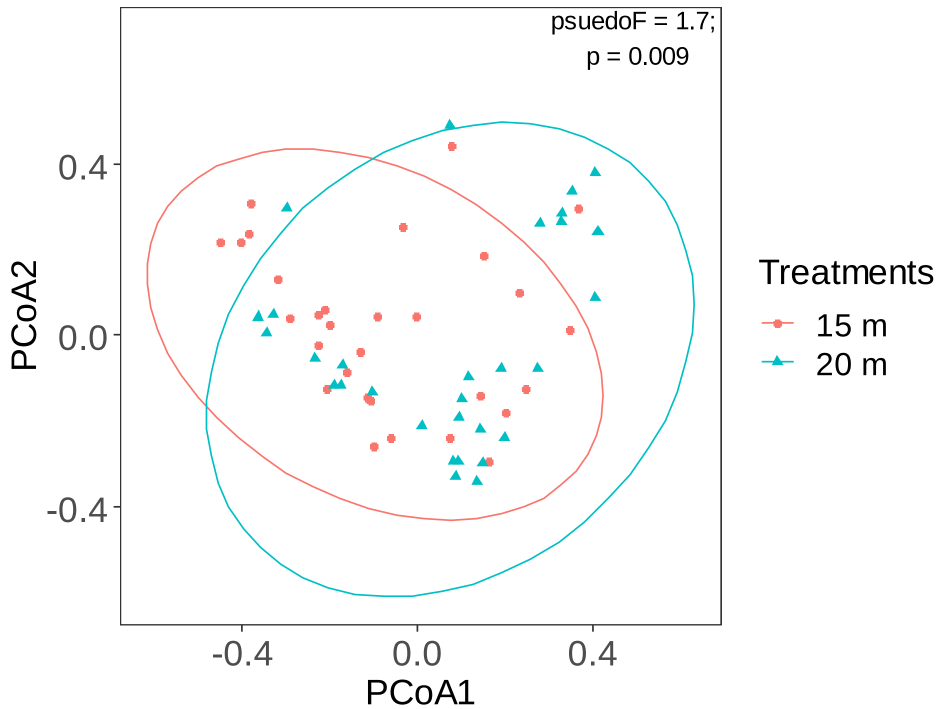


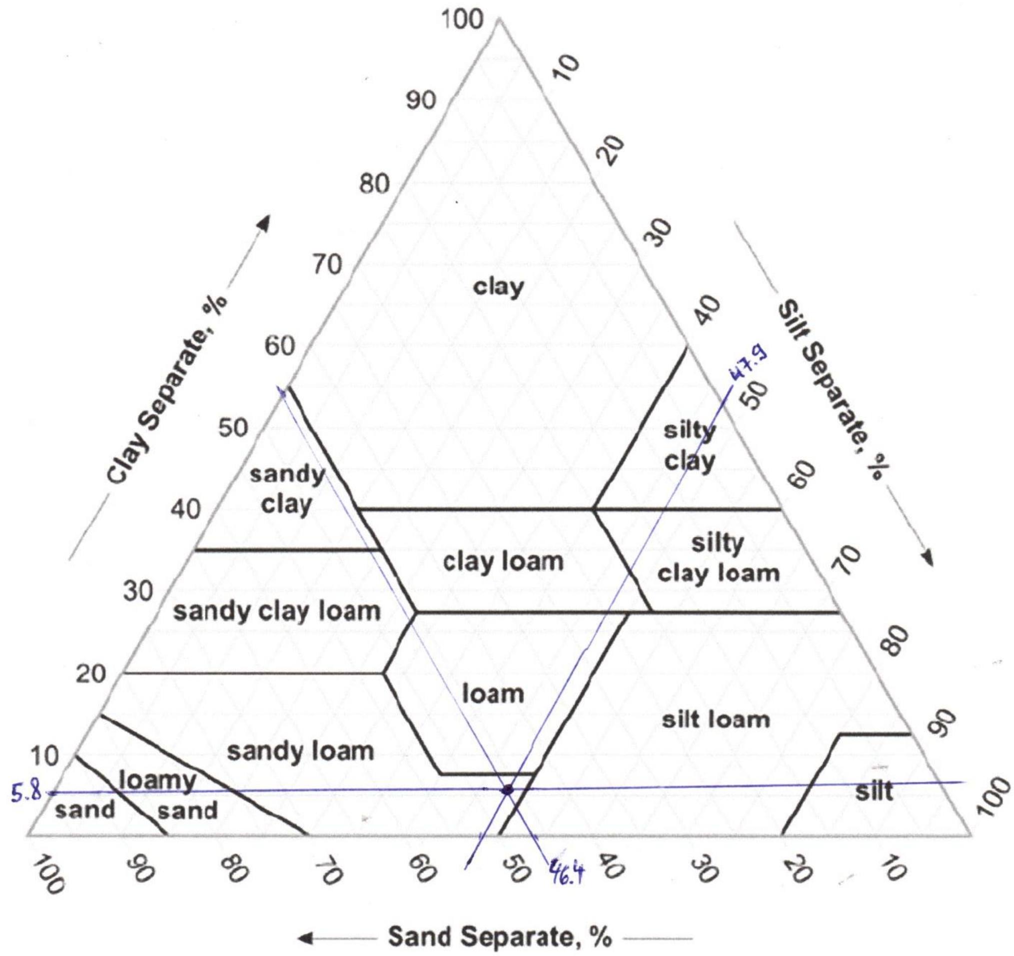
Figure A.9. *PCoA analysis based on Jaccard dissimilarity for July 2020 understory species community composition between 15 m and 20 m thinned treatments.*

Soils

27. Forest Floor Depth (cm) 1 + 1.5 + 1.5 = 4 L F H Total	28. Humus form Mor
35. Rooting Depth (cm) 35	36. Drainage Moderately Well Drained
37. Seasonal Soil Factors (Dates: dry, wet, frozen, snow)	

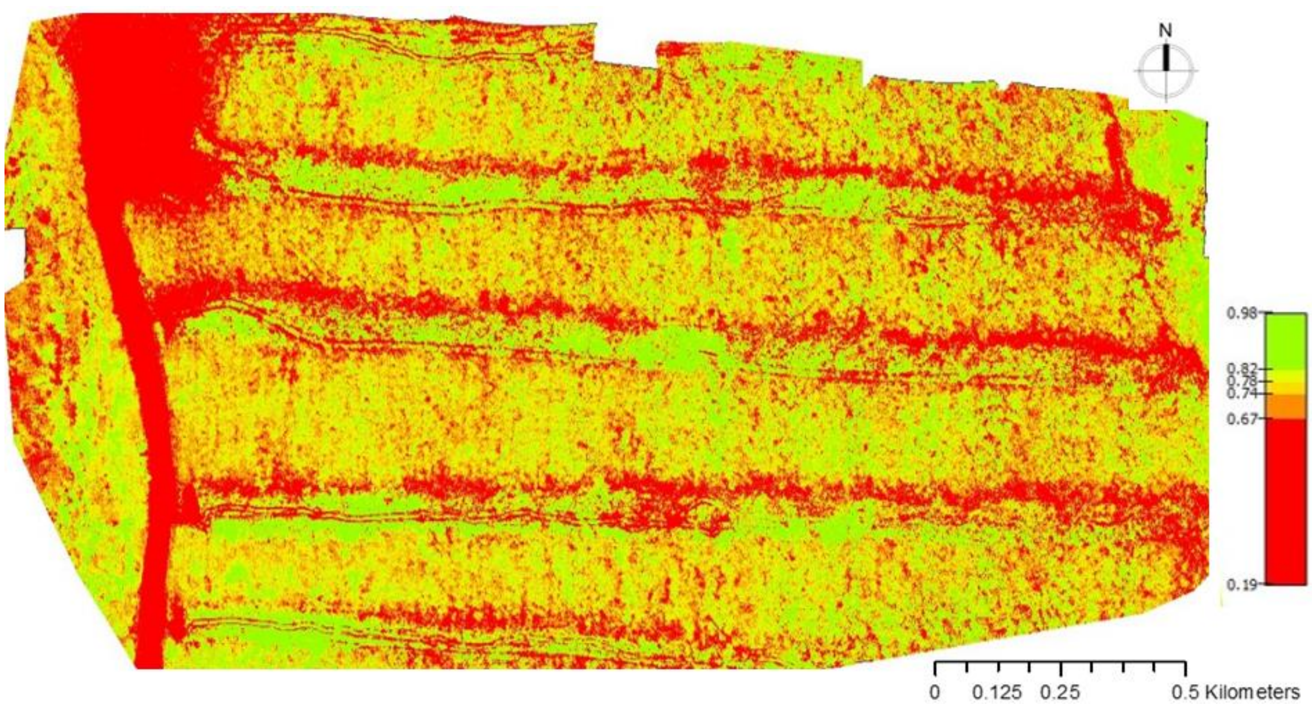
Soil Horizons (Pit Depth______cm)						
29. Horizon	30. Depth (cm)	31. Texture	32. Plasticity	33. C. Fragments %	Size	34. Col/ Moist
Ae	2	FSL				
Bm	2-25	SL		35		
C	25+	SL		45		

A.10. *Soil Horizons, texture and coarse fragment determination pre-timber harvest in three adjacent block design.*



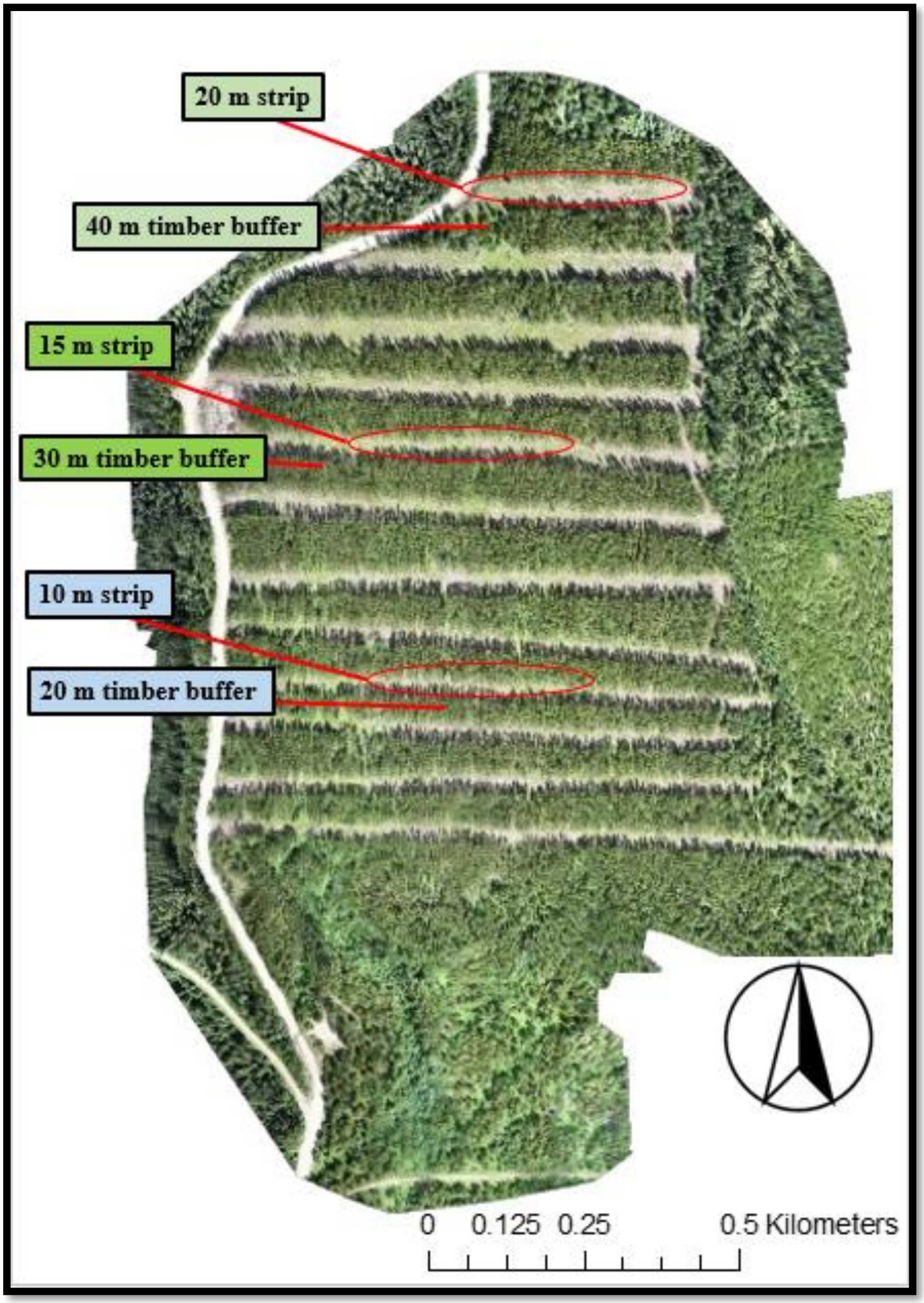
A.11. *Soil texture diagram of Goudie silvopasture research area contains 46.4% sand, 47.9% silt and 5.8% clay.*

A.12. *Excavation method and materials for soil bulk density analysis used post-harvest 2020.*



A.13. *An NDVI map example that shows soil compaction in the strips post timber harvesting.*

A.14. *Integrated forage, livestock and timber approach through forest strip thinning.*



A.15: *Map of one of the experimental design blocks detailing the strip widths and their timber buffers.*

A.16: Plant species identified from all three blocks in Goudie, Kelowna Pre and post strip thinning. (USDA- United States Department of Agriculture 2019)

Seeded agronomic species		Unseeded palatable		Unseeded non-palatable species	
Common name	**Scientific name**	**Common name**	**Scientific name**	**Common name**	**Scientific name**
Orchard grass	*Dactylis glomerata L.*	Kentucky Bluegrass	*Poa pratensis L.*	Graceful cinquefoil	*Potentilla gracilis*
Meadow Brome	*Bromus riparius*	Idaho fescue	*Festuca idahoensis Elmer*	Common snowberry	*Symphoricarpos albus*
Intermediate Wheatgrass	*Thinopyrum intermedium*	Canada Bluejoint	*Calamagrostis canadensis*	Soopolallie	*Shepherdia canadensis*
White clover	*Trifolium repens*	Western fescue	*Festuca occidentalis*	Birch-leaved spirea	*Spiraea betulifolia*
		Pinegrass	*Calamagrostis rubescens*	Falsebox	*Paxistima myrsinites*
		Smooth Brome	*Bromus inermis*	Sitka Alder	*Alnus viridis*
		Sedges	*Carex spp.*	Twinflower	*Linnaea borealis*
		Fireweed	*Chamaenerion angustifolium*	Bunchberry	*Cornus canadensis*
		Dandelion	*Taraxacum erythrospermum*	One-leaved foamflower	*Tiarella trifoliata var. unifoliata*
				Sweet-scented bedstraw	*Galium triflorum*
				Round leaf viola	*Viola rotundifolia*
				Coltsfoot	*Tussilago farfara*
				Prince's pine	*Chimaphila umbellata*
				Utah honeysuckle	*Lonicera utahensis*
				Field chickweed	*Cerastium arvense*
				False solomon's-seal	*Maianthemum racemosum*
				Hawkweed	*Hieracium spp.*
				Tiger lily	*Lilium lancifolium*
				Common daisy spp.	*Bellis perennis*
				Pearly everlasting	*Anaphalis margaritacea*
				Fragile sour weed/Common sheep sorrel	*Rumex acetosella*
				Buttercup	*Ranunculus spp.*
				Thistle	*Cirsium spp.*
				Salsify	*Tragopogon porrifolius*
				Prickly wild rose	*Rosa acicularis*
				Rattlesnake plantain	*Goodyera pubescens*

		black huckleberry	*Gaylussacia baccata*
		Common mitrewort	*Mitella nuda* L
		Salmonberry	*Rubus spectabilis*
		Vaccinum spp	*Vaccinum spp*
		Lodgepole seedling pine tree	*Pinus contorta*
		Columbine	*Aquilegia spp.*
		Mountain sweet cicely	*Osmorhiza chilensis*
		Common Juniper	*Juniperus communis*
		White avens	*Geum canadense*
		One-sided wintergreen	*Orthilia secunda*
		Western meadow-rue	*Thalictrum occidentale*