# Ecological Sustainability of Winter Harvesting in the Duck Mountain Provincial Park, SK: The Effects of Skidder Traffic, Slash Loading, and Cumulative Effects on Soils and Aspen Regeneration

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# Abstract

In over-mature trembling aspen (*Populus tremuloides*) forests, like those of the Duck Mountain Provincial Park (DMPP), mechanical harvesting has been shown to be an effective source of disturbance to re-establish a healthy and productive forest. However, harvesting operations can result in a degree of unwanted disturbance that could threaten the success of regeneration. The overall goal of this study was to assess, on a landscape scale, whether winter harvesting of the old growth aspen forests in the park is an ecologically sustainable practice for successful aspen regeneration. Skidder traffic intensity, slash coverage, and vegetation indices were calculated for six harvested blocks using Global Positioning Systems (GPS), Unoccupied Aerial Vehicles (UAVs) and Geographic Information Systems (GIS). Based on this information, soil bulk density and early sucker growth was measured to assess the effects of winter harvesting. Soil bulk density increased significantly following 1-5 skidder passes (1.39 g cm$^{-3}$) compared to unharvested controls (1.29 g cm$^{-3}$) but remained relatively constant as skidder traffic continued to increase. In areas of high skidder traffic (51-100 passes) aspen sucker density decreased by approximately 50% while sucker height decreased by over 20 cm compared to areas with less traffic. Soil bulk density, vegetation indices, and slash coverage (up to 60%) showed no relationship with the level of aspen regeneration in harvested blocks. To assess cumulative effects, principal component analysis, principal component regression, and fuzzy logic analysis were used to determine the regeneration suitability across harvested blocks. This analysis indicated that the majority of a harvested block (51-71% of the area) occurred with a rating of low to below average regeneration suitability. On average, low suitability areas had significantly more traffic and slash compared to the other levels of suitability, experiencing 27 more skidder passes and 6% more slash cover compared to high suitability areas. Aspen sucker height, root collar diameter, and dry leaf biomass were also significantly higher in areas with high regeneration suitability compared to areas with low suitability. Therefore, skidder traffic and slash must be properly managed and distributed throughout harvested blocks to ensure the sustainability of future aspen forests in the DMPP.

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# 1 GENERAL INTRODUCTION

The boreal forest (Taiga) is the world's largest continuous terrestrial biome, stretching round the entire northern hemisphere. Canada's boreal forest, which is composed of various cold-tolerant coniferous and deciduous tree species, accounts for roughly 55% (552 million ha) of the country's total land mass and represents 70% of the country's forested land (Brandt et al., 2013). A deciduous genus of particular importance is *Populus*, which belongs to the family Salicaceae and consists of several distinct species. Within Canada, nearly 80% (31.5 million ha) of all *Populus* forests are located in the boreal forest ecosystem and account for approximately 11.7% of the forested lands in that ecosystem (Government of Canada, 2013). Trembling aspen (*Populus tremuloides*) is one of the most common and widely distributed *Populus* species, spanning across the entire country.

In the Prairie Provinces, trembling aspen is a relatively short-lived species with an average lifespan between 100 and 120 years (Navratil, 1991) and like the rest of the boreal forest, is dependent on sporadic disturbances such as forest fires to maintain its health and productivity (Brandt et al., 2013). As a pioneer species, trembling aspen is often one of the first major tree species to return following a disturbance and is most often taken over by more shade tolerant coniferous species such as white spruce (*Piceae glauca*), black spruce (*Picea mariana*), and balsam fir (*Abies balsamea*) until the next disturbance event. In pure aspen stands however, the lack of successional species or disturbance results in over-maturity and the rapid decline of the forest, as young trembling aspen are incapable of competing with the dense understory shrubs (Peterson and Peterson, 1992). Unfortunately, this rapid state of decline is the current situation for much of the forests in Duck Mountain Provincial Park, Saskatchewan.

The Duck Mountain Provincial Park is located along the eastern border of Saskatchewan just to the northeast of Kamsack on highway 51 (Fig. 1.1). It was established in 1931 and encompasses approximately 26,300 ha of forested upland. This forest is predominantly trembling aspen with sporadic white spruce scattered throughout the park. The last major wildfires to affect the park occurred in the late 1880-90's and consequently, the forest is in need of rejuvenation as the current cohort of aspen is reaching its maximum longevity and stand breakdown is accelerating. With this accelerating breakdown, park management is concerned that without the implementation of an immediate management strategy, the majority of the forest will subside to a shrub and grass dominated ecosystem. Therefore, the Saskatchewan Ministry of Parks, Culture and Sport is working with Weyerhaeuser Canada Ltd. and Louisiana Pacific to actively manage the decadent aspen forest through mechanical harvesting. Both companies are using a tree length harvesting operation, which involves cutting the tree at its base, then transporting it to a centralized landing location next to roads where the crown and branches are removed and the tree is cut to specific lengths before transportation to the mill. With this method, only the stem wood of the tree is taken, while the treetop and branches are redistributed throughout the harvested block as a sustainable way of maintaining the cycling of nutrients.

Mechanical harvesting is both an economically and ecologically viable method to mimic the disturbance of fire and stimulate regeneration in aspen forests. Over the past decades, the commercial importance of trembling aspen has increased substantially and accounts for approximately 34% of the total annual allowable harvest in Saskatchewan (Government of Saskatchewan, n.d.; Peterson and Peterson, 1992). Harvesting aspen forests also creates an environment suitable for aspen regeneration by removing apical dominance, eliminating the competing understory shrubbery, and exposing the forest floor to increased solar energy to increase the soil temperature (Navratil, 1991; Peterson and Peterson, 1992). However, improper harvesting

**Fig. 1-1:** Locator map for the Duck Mountain Provincial Park, Saskatchewan.

methods can result in unwanted disturbance to the site which can impede aspen's ability to regenerate successfully (Navratil and Bella, 1988; Smidt and Blinn, 2002; Berger et al., 2004). In particular, machine traffic disturbance and slash redistribution represent the greatest risks to soil integrity and aspen regeneration caused by harvesting. Not only can heavy machine traffic compact the underlying soil and alter soil processes, the physical scarification to the forest floor from repetitive machine traffic can damage the shallow aspen roots responsible for aspen regeneration (Navratil, 1991; Frey et al., 2003; Renkema et al., 2009). While slash loading can drastically alter the soil temperature regime as well as act as a physical barrier to aspen suckers coming from the parental rooting system (Bella, 1986; Lieffers-Pritchard, 2004). These shallow roots are sensitive to surface soil compaction and slash loading, as both having been shown to reduce the density and growth of aspen suckers (Bella, 1986; Lieffers-Pritchard, 2004; Zenner et al., 2007). Therefore, to ensure sustainable forest management, minimizing soil disturbance and properly distributing slash across a harvested block are important considerations when harvesting in ecologically sensitive areas such as provincial parks. It is for this reason that winter harvesting is being used rather than summer harvesting, as it has been shown to cause the least damage to the soil and forest floor (Block et al., 2002; Berger et al., 2004; Kolka et al., 2012). Nevertheless, the question is raised as to whether it is possible to manage this forest through careful ecological winter harvesting to minimize disturbance and still obtain adequate aspen regeneration.

To date, the majority of research examining the success of aspen regeneration following disturbance has been conducted using assessment plots placed throughout a harvested block (Sheppherd, 1993; Lieffers-Pritchard, 2004; Puettmann et al., 2008; Kabzems, 2012). However, the area covered by these assessment plots is small in comparison to the area of the entire harvested block. Consequently, important information regarding the success of aspen regeneration across the block may be overlooked or misconstrued due to the inadequate coverage of the small assessment plots. In order to reduce this uncertainty, newly developed remote sensing and unoccupied aerial vehicle (UAV) technology may offer the solution. Over the past decade, the use of UAVs and high resolution optical remote sensing in the agricultural sector has been proven as a useful tool for assessing crop health (Barnes et al., 2000; Stanton et al., 2017) and this technology is slowly becoming more prevalent in the forestry sector. Several studies have looked at using UAV derived remote sensing data to measure and map forest inventory, composition, stand density, canopy height and pest infestation (Gamon et al., 1995; Lehmann et al., 2015; Tang and Guofan Shao, 2015; Torresan et al., 2017; Hird et al., 2017). However, it is unknown if similar technology can be applied to successfully monitor the regeneration of aspen one year after harvesting at a harvested block scale.

The following research examines the influence of machine traffic intensity and slash loading on the success of aspen forest regeneration one-year post winter harvest, and demonstrates the potential of unoccupied aerial vehicles (UAVs) and remote sensing technology as tools to access regeneration success on a landscape scale. The overall goal of this research was to assess whether winter harvesting used for these old growth aspen forests in Duck Mountain Provincial Park, SK is an ecologically sustainable practice for successful aspen regeneration. To obtain my goal, the research objectives were:

1. To examine the relationship between the number of machine passes over an area, the severity of soil compaction, and its effects on aspen sucker density, height, root collar diameter (RCD), leaf area index (LAI), dry leaf biomass, total nitrogen (N), and total phosphorus (P) following one summer of growth.
2. To examine the feasibility of UAV-based multispectral remote sensing as a tool for assessing the effects of machine traffic intensity on aspen regeneration.

3. To develop a method to estimate the level of slash coverage (%) in harvested areas using aerial imaging, remote sensing, and image processing.
4. Assess the effects of the % slash coverage (determined during Objective 3) on the level of aspen regeneration (sucker density, height, root collar diameter (RCD), leaf area index (LAI)).
5. To develop a method to assess cumulative effects on aspen regeneration for a winter harvest block using fuzzy logic suitability mapping.
6. To determine which factors are responsible for controlling the level of aspen regeneration.
7. To examine aspen regeneration intensities for varying degrees of regeneration suitability (determined during Objective 5)

This thesis is written in a chapter format and contains six chapters: a general introduction to the project, a detailed literature review, three research chapters that cover the four objectives, and a general discussion and synthesis chapter of all the results and conclusions. Below is a brief outline of these chapters.

Chapter 2 is a detailed literature review focusing on the factors that influence aspen regeneration following disturbance. In addition, this chapter will also examine the use of UAVs and multispectral remote sensing as new technical solutions for monitoring vegetation health.

Chapter 3 examines the effects of machine traffic intensity on the level of soil compaction and aspen regeneration (Objective 1). This chapter also examines the relationship between regeneration levels and UAV multispectral derived vegetation indices (Objective 2).

Chapter 4 examines the assessment of slash loading through UAV captured aerial imagery and image analysis (Objective 3) and examines the effects of slash loading on the level of aspen regeneration (Objective 4).

Chapter 5 examines the use of principal component analysis (PCA), principal component regression (PCR), and fuzzy logic to determine the potential cumulative effects on the level of aspen regeneration (Objective 5, 6, 7).

Chapter 6 is a general synthesis and discussion of all results and conclusions from the project and their implications for the harvesting of aspen forests in ecologically sensitive locations such as those in the Duck Mountain Provincial Park.

# 2 LITERATURE REVIEW

## 2.1 Aspen forest life cycle and succession

Trembling aspen (*Populus tremuloides*) is a major broadleaf pioneer tree species found throughout Canada's boreal forest, with approximately 80% of all aspen in the country found in this ecosystem (Government of Canada, 2013). Following a disturbance, trembling aspen is often the first tree species that dominants a site; however, it is a relatively short-lived species with an average lifespan of 100 -120 years in the Prairie Provinces before it begins to succeed to a more shade tolerant coniferous species (white spruce, black spruce, balsam fir) ecosystem (Navratil, 1991; Peterson and Peterson, 1992). Trembling aspen, like most boreal forest species, are largely dependent on sporadic disturbances such as forest fire to maintain the health and productivity of the species (Brandt et al., 2013). Without fire or the presence of successional coniferous species, pure aspen forests often enter into a state of over-maturity and rapid stand breakdown, as regenerating aspen are incapable of competing with the dense understory and eventually succeed to a grassy shrub dominated ecosystem (Peterson and Peterson, 1992). As mentioned earlier, this is the reality for much of the aspen forests in the Saskatchewan Duck Mountain Provincial Park. Attempts at controlled burns to stimulate aspen regeneration in the park have failed primarily due to poor environmental conditions as well as the aspen forest's inability to maintain a fire strong enough to eliminate the over-mature aspen cohort. Mechanical harvesting has been shown as an effective alternative to fire for creating optimal conditions for aspen regeneration (Navratil, 1991, 1996; Frey et al., 2003) and the growing commercial importance of aspen over the past decades has made harvesting an economical viable management option to stimulate stand regeneration (Peterson and Peterson, 1992).

## 2.2 Aspen methods of regeneration

Following disturbance such as fire or harvesting, aspen are commonly the first species to colonize a site due to their rapid growth and ability regenerate both sexually and asexually (Peterson and Peterson, 1992). Once aspen achieve sexual maturity at approximately 10-20 years of age, they are able to produce upwards of 1 to 1.5 million light-weight seeds per tree per year, which can be dispersed by wind several kilometres to nearby disturbed sites (Maini, 1968; Navratil, 1991; Peterson and Peterson, 1992). Although seed production is intensive, high levels of regeneration through sexual reproduction is uncommon in the prairie region, as numerous site conditions required for regeneration are rarely met. Following seed dispersal, seeds must come in contact with a continuously moist mineral seedbed, be exposed to moderate temperatures, and have little competition from other vegetation in order to survive. However, due to their short viability period and growth inhibitors in seed hairs, the above conditions are rarely met (Navratil, 1991; Peterson and Peterson, 1992). Therefore, following disturbance the majority of aspen forest regeneration occurs through asexual reproduction.

The asexual reproduction of aspen following a disturbance is driven by a vast interconnected rooting system belowground that can spread horizontally up to 30 m from a parent tree (Day, 1944; Stone and Kalisz, 1991). While the majority of these roots were found within a depth of 1.2 - 1.5 m (Strong and La Roi, 1983; Van Rees, 1997), aspen roots have been found to extend downwards greater than 3 m depending on soil texture (Stone and Kalisz, 1991). Although aspen roots can extend to great depths within the soil profile, roots deeper in the soil profile are unlikely to be those primarily responsible for regeneration. Compared to root cuttings placed at 5 and 20 cm depth, aspen suckers from cuttings placed below 40 cm were unable to reach the soil surface before the roots energy reserves were exhausted (Wachowski et al., 2014). According to Peterson and Peterson (1992) and Navratil (1996), the roots responsible for the majority of suckering following harvesting were generally found within the first 8-15 cm from the forest floor; however, Lieffers-Pritchard (2004) found the majority of root suckering occurred even closer to the surface at around 4.6 cm depth from the forest floor surface. This variation in depth could be the result of different site, climatic, or clonal properties; however, both studies indicate that the majority of suckering occurs within the forest floor (LFH) or just below the LFH - mineral interface and not deeper in the soil profile.

To stimulate the asexual reproduction of aspen forest, natural disturbance or harvesting must first eliminate the aboveground tree. By removing the aboveground portion of the tree (breaking apical dominance), the flow and balance of hormones traveling throughout the tree are disrupted. The two hormones of particular importance for controlling regeneration are auxin and cytokinin, which suppress and stimulate sucker initiation, respectively (Eliasson, 1971; Navratil, 1991; Peterson and Peterson, 1992). Auxin production occurs primarily in the above-ground tissue and buds of the tree and is transported by phloem down into the root system, where it promotes root elongation and inhibits sucker initiation (Eliasson, 1971; Frey et al., 2003). When the aboveground tree is removed, the flow of auxin into the rooting system stops and the levels of cytokinin, which is produced by actively growing root tips, begins to accumulate in the rooting system. This accumulation of cytokinin activates suppressed buds, newly initiated meristems, and pre-existing primordium on the rooting system, signaling them to suckers (Schier, 1973; Schier et al., 1985; Frey et al., 2003). It is not uncommon for this suckering process to generate over 100 000 suckers ha$^{-1}$ in the first year following disturbance; however, a natural thinning process gradually decreases this stocking density down to less than 3000 suckers ha$^{-1}$ by 20 years of age (Peterson and Peterson, 1992). Because these suckers originate from the rooting system of the previous forest, they are genetically identical to their parent. As a result, aspen forests are often composed of even age stands of genetically identical clones (Day, 1944; DesRochers, 2000). These new suckers begin to produce their own new rooting system; however, the initial interconnected parent rooting system remains of vital importance for the survival of the sucker as it supplies the young sucker with nutrients and water (Zahner and DeByle, 1965; DesRochers, 2000). Nevertheless, several factors can influence the initial production and growth of suckers following a disturbance and potentially cause under stocking of the subsequent forest.

## 2.3 Factors affecting aspen regeneration and forest soils

Following a natural disturbance, factors such as soil temperature, root carbohydrate reserves, severity of root damage, quantity of residual aspen remaining, and clonal abilities to sucker have been found to influence the initiation and growth of aspen suckers (Zahner and DeByle, 1965; Navratil and Bella, 1988; Navratil, 1991; Peterson and Peterson, 1992; Frey et al., 2003). The anthropogenic mechanical harvesting of aspen forests can also have a strong influence on these factors, resulting in further inhibition or stimulation of aspen regeneration depending in the level of disturbance to the site.

### 2.3.1 Season of harvest

As a way to minimize negative harvesting effects on aspen regeneration, harvesting during the winter months is a common practice in northern regions. The practice of winter harvesting is supported by several studies that have monitored not only its influence on soil properties, but carbohydrate and regeneration levels of aspen suckers as well (Schier and Zasada, 1973; Frey et al., 2003; Kolka et al., 2012). During the winter months, soils are generally frozen and covered with a protective layer of snow that increases the soil's ability to resist compaction from harvesting machinery; however, depending on frost depth and snow cover, the risk of soil compaction is still present especially in areas with excessive traffic. Following winter harvesting, Berger et al. (2004), found that the level of soil disturbance on skidder trails was significantly higher compared to off skidder trail areas. This same study also found that landings expressed higher levels of soil disturbance compared to off skidder trail areas; however, the two were not significantly different. Similarly, Holman et al. (1978) found that in the first growing season following winter harvesting, the average bulk density between 2.54-7.62 cm depth on skidder trails (1.42 g $cm^{-3}$) was significantly higher than the adjacent unharvested stand (1.25 g $cm^{-3}$). Although these and many other studies have found significant increases in soil bulk density or soil disturbance following a winter harvest, the severity of compaction/disturbance is often much less compared to sites harvested during the summer (Holman et al., 1978; Bella, 1986; Block et al., 2002; Berger et al., 2004; Kolka et al., 2012). The reason these winter sites may still be experiencing significant increases in soil bulk density/disturbance is due to the fact that the soils may not have been completely frozen during the winter months. As Lieffers-Pritchard (2004) found, mineral soil at a depth of 10 cm from the forest floor and mineral interface expressed a mean daily soil temperature near 0 °C during the winter months (December-March). Therefore, air temperatures may be below 0 °C during the winter months but the soil may not be frozen, leaving it susceptible to machine traffic compaction.

Once a soil is compacted, there are several natural processes through which soil can de-compact (Holman et al., 1978). Over time, soil freeze-thaw, wetting and drying, organism activity, and vegetation growth will restore the bulk density and soil strength back to their original state. Because winter harvested areas do not express as severe of soil disturbance compared to summer harvesting, the length of time required to restore these soils back to their natural state may be reduced. Holman et al. (1978) found that three years post-harvest, the bulk density (2.54-7.62 cm depth) of skidder trails on summer harvested sites (1.42 g $cm^{-3}$) were still significantly higher compared to the adjacent undisturbed soil (1.23 g $cm^{-3}$), while the bulk density (2.54-7.62 cm depth) of skidder trails on winter harvested sites (1.32 g $cm^{-3}$) were no longer significantly different than undisturbed soil (1.26 g cm$^{-3}$). However, a study by Page-Dumroese et al. (2006) found that the level of bulk density recovery five-years post-harvest ranged from full recovery to no recovery depending on the soil properties. Sites with coarser textured soils often saw significant recovery five years post-harvest, while most finer textured soils experienced very little recovery with one site actually seeing an increase in bulk density over the five years post-harvest (Page-Dumroese et al., 2006). Therefore, the rate of soil bulk density recovery is not a fixed rate and varies between sites and although season of harvest may influence the level of site disturbance, it can also have significant effects on the level of regeneration.

Though Bella (1986) found that sucker density was greatest following summer harvest; studies by Peterson and Peterson, 1992; Bates et al., 1993; Berger et al., 2004; Puettmann et al., 2008 all indicated that aspen density was greatest following winter harvesting rather than summer harvesting. However, Steneker (1976) states that in the prairie provinces the effects of season of harvest on aspen density are insignificant, as aspen density was similar on winter and summer harvested sites two-three years post-harvest due to the natural thinning process. Bella (1986) also found that aspen density in winter and summer harvested sites to be virtually the same 5 to 6 years post-harvest. Nevertheless, sucker density is not the only factor to be considered when assessing the effects of season of harvest on regeneration levels.

Aspen height, crown closure, total sucker volume, etc. are also important indicators of aspen regeneration. In the study by Bella (1986), aspen height was consistently highest in winter harvested sites compared to summer harvested sites. Likewise, the results in Lieffers-Pritchard (2004) show that at the end of the second growing season aspen sucker height in winter harvested sites with no slash had nearly double (81.8 cm) the growth compared to sucker found in comparable areas harvested during the summer (45.4 cm). In this same study, total sucker volume (cm$^3$ m$^{-2}$) was also nearly five time higher in winter harvested sites even though sucker density showed no difference between winter and summer sites. Lastly, Bates et al. (1993) not only found an increase in sucker density following winter harvesting, but also an increase in sucker height and crown closure when compared to similar areas harvested during the summer. This increased vigor of aspen suckers on winter sites could be attributed to the lower degree of soil disturbance; however, it is likely that there are a combination of several factors.

Following a disturbance, carbohydrate reserves in roots are essential for aspen sucker growth as they provide the only source of energy for the plant until suckers emerge and begin to produce their own energy through photosynthesis. The levels of carbohydrates in aspen roots are known to fluctuate seasonally; therefore, harvesting at different times of the year may influence aspen's ability to regenerate to its fullest potential. Carbohydrate levels are generally lowest during the spring, increasing over the summer months until they peak during the fall, and then slowly decreases over the winter (Schier and Zasada, 1973). Therefore, it is expected that the greatest levels of regeneration would occur when aspen are harvested during the fall or early winter when root carbohydrate levels are at their highest. Yet studies by Tew (1968) and Schier and Zasada (1973) concluded that carbohydrate levels were not significantly correlated with the number of sucker produced. Though carbohydrate levels did not affect the number of suckers produced, this does not mean carbohydrates are not an important factor for the successful regeneration of aspen forests. Roots containing higher levels of carbohydrates, particularly starch, produced taller suckers with increased biomass, leaf dry mass, and leaf area (Schier and Zasada, 1973; Landhäusser and Lieffers, 2002; Wachowski et al., 2014). Thus, as the above illustrates, season of harvest plays a major role in ensuring optimal regeneration following the harvesting of aspen forests.

### 2.3.2 Harvesting Methods

In aspen forests, the method that is used for harvesting has a direct role in the success of aspen regeneration. As mentioned earlier, the breaking of apical dominance is an important factor for ensuring vigorous regeneration as it disrupts the flow of auxin, a sucker inhibiting hormone, into the root system and allows cytokinin to stimulate suckering (Eliasson, 1971). Due to the interconnected root systems, if there are residual aspen left standing following harvest they will continue to supply auxin to the rooting system and therefore inhibit the level of suckering (Steneker, 1974; Navratil, 1991, 1996; Frey et al., 2003). According to Navratil (1991), there is a clear inverse relationship between the level of aspen suckers and the amount of residuals left standing. Therefore, to achieve successful aspen regeneration clearcutting with a low residual retention rate is considered a more suitable method compared to partial cutting as it ensures apical dominance is broken and the flow of auxin into the rooting system ceases (Navratil, 1991; Peterson and Peterson, 1992). However, clearcutting is also more suitable for achieving successful aspen regeneration as it ensures the maximum amount of incoming solar radiation to the forest floor to increase the soil temperature. By only partially cutting and leaving a high level of residuals, the shade that is created by the canopy blocks solar energy from reaching the forest floor and therefore decreases soil temperature (Navratil, 1991).

### 2.3.3 Soil temperature

Soil temperature is one of the major driving factors that influences aspen regeneration and several studies have examined the relationship between soil temperature and aspen development (Maini and Horton, 1966; Steneker, 1976; Fraser et al., 2002). As Maini and Horton (1966) illustrated in their controlled study, aspen suckering is optimal when soil temperatures were kept between 23 and 30 °C and temperatures above or below this range resulted in a decrease in the level of suckering. However, in northern regions, soil temperatures normally do not reach these levels, yet prolific suckering still occurs. As Fraser et al. (2002) observed, when root cuttings were grown with soil temperatures below optimal conditions (12 and 20 °C), temperature did not have a significant effect on the number of suckers produced but did affect the length of time required for sucker initiation. In soils with a maximum temperature of 20 °C, roots required approximately 11 days to initiate suckering while aspen roots grown under a maximum temperature of 12 °C took approximately 23 days before suckering was initiated. Although temperature may not have an influence on the number of suckers produced, it has been shown to influence the early growth rate of suckers. Maini and Horton (1966), found suckers were tallest when soil temperature was near 23 °C and temperatures above or below this temperature experienced decreased shoot growth. Similarly, Fraser et al. (2002) found that aspen grown at 20 °C had a higher biomass compared to aspen grown at 12 °C. These results suggest that at higher soil temperatures, aspen suckers may gain an advantage over competing vegetation and aid in the successful regeneration of the forest.

Increased soil temperature is also an important factor for driving chemical processes within the rooting system, which in turn stimulate sucker production. Higher soil temperatures have been shown to increase the rate of auxin breakdown in roots as well as increase the rate of cytokinin production thereby stimulating sucker growth (Schier et al., 1985; Navratil, 1991; Frey et al., 2003).

Lastly, harvesting operations can have great influence on the natural soil temperature regime. As a way to maintain the cycling of nutrients following forest harvesting, harvest operations leave non-profitable material such as branches and stems, commonly referred to as slash, throughout the harvested area. Depending on the thickness of this slash layer, it can act as an isolative barrier to the soil and as a result shorten the growing season (Steneker, 1976; Lieffers-Pritchard, 2004). The effects of slash on soil temperature were most notable during the spring as soils under moderate (5 – 20 kg $m^{-2}$) and heavy slash (20 – 110 kg $m^{-2}$) took longer to reach 15°C and mean daily temperature decreased significantly compared to areas with no slash coverage (<5 kg m$^{-2}$) (Lieffers-Pritchard, 2004). This effect of slash on soil temperature may also have an influence on the level of aspen regeneration. In winter harvested blocks, as the level of slash loading increased, the number of aspen suckers decreased significantly from 15 to 1.4 suckers per m$^2$ while aspen height saw a significant decreased from 81.8 to 49.3 cm (Lieffers-Pritchard, 2004). The study by Bella (1986) also illustrated this inverse relationship between slash loading and aspen sucker density and height; however, concluded that under heavy slash loading the level of regeneration would be more than adequate for successful regeneration. Nonetheless, proper distribution of slash across the site may be an important factor for ensuring optimal regeneration is achieved.

### 2.3.4 Harvesting compaction of soils

Soil compaction from harvesting machinery is a serious concern in forests and many best management practices are implemented during a harvesting operation to mitigate the risk of increasing the soil compaction. Soil compaction occurs when the pressure exerted by tires/tracks of heavy machinery exceed the soil's ability to resist the additional pressure. As a result, soil particles are rearranged, soil pore space in reduced, and soil density increases (Greacen and Sands, 1980; Brady and Weil, 2004). This reduction in soil pore space can have serious effects on water infiltration rates, gas exchange, root growth, and much more; however, the susceptibility of soil to compaction is largely dependent on its texture and moisture content (Greacen and Sands, 1980; McNabb et al., 2001; Kolka et al., 2012). Soils with fine texture do not require a large increase in soil strength or bulk density to limit root growth and as a result, they are at a higher risk of experiencing negative effects in relation to machine traffic (Greacen and Sands, 1980; Daddow and Warrington, 1983). Regardless of texture, moisture is a dominant factor when determining a soil's susceptibility to compaction. Liquid water acts as a lubricant between soil particles, allowing them to be rearranged and easily compressed (Greacen and Sands, 1980; McNabb et al., 2001;

Brady and Weil, 2004). Therefore, winter harvesting is a common practice on sites with higher soil moisture content, as frozen water does not lubricate the soil particles and acts as an additional level of support to resist compaction.

During a harvesting operation, compaction can occur with as little as one pass (Brais and Camiré, 1998); however, much of a harvested block will experience several passes throughout the harvesting event. In a study looking at the effects of machine traffic on soils, Zenner et al. (2007) found that the number of passes across a harvested area ranged anywhere from 1 to over 600 passes and as a result, would expect to see an increasing level of disturbance to the soil as the number of passes increased. Several studies have illustrated that with an increasing number of machine passes, the soil strength and soil bulk density generally increase in a logarithmic fashion (Brais and Camiré, 1998; McNabb et al., 2001; Zenner et al., 2007); however, the level at which soil strength and bulk density ceases to increase with the increasing number of passes is disputable. Brais and Camiré (1998) found soil strength and bulk density increased sharply following 1 to 3 cycles (2 - 6 passes) but showed minimal to no increase after 15 cycles (30 passes). Zenner et al. (2007) also found a sharp increase in soil strength after the first pass; however, soil strength continued to increase well after the 35th pass. This discrepancy between studies is most likely due to differences between site properties (soil texture, soil moisture, etc.), thus making comparisons between study sites rather difficult as the number of passes required to compact a soil may vary drastically from one area to the next.

### 2.4 Unoccupied Aerial Vehicles (UAVs) in Forestry

Traditionally, studies looking at the effects of harvesting on forest properties and forest regeneration are conducted using a variety of assessment plot techniques. However, with the increasing technological developments of UAVs and remote sensing, studies are beginning to approach their research in this new direction.

Aerial imagery has been around since the mid 1800's and every year new technological development has not only improved the quality of this information but the feasibility of using aerial imagery in our day-to-day lives. In the past, airplanes and satellite were often used as a means of obtaining an aerial view of the earth; however, these methods often gave low spatial resolution data that was expensive to acquire and did not allow for site-specific information to be gathered (Jensen, 2007; Lehmann et al., 2015). This is where the development of UAVs have proven useful in terms of remote sensing. Fixed wing and rotary wing UAVs are a cost-effective tool that allows a user to collect high spatial resolution site-specific data in a time independent manner, which makes them a practical tool in much of the natural resource sector.

In particular, UAV's are becoming more important in the forestry sector as a new method for improving the monitoring and managing of forest resources. Zhang et al. (2016) found that, UAVs equipped with a high-resolution camera or sensor can be used to measure tree stand information such as, canopy height, canopy closure, species composition, stocking density, which can be used in decision making processes about harvesting operations. More advanced measuring technology such as Light Detecting and Ranging (LiDAR) can also be used in forestry as an accurate way to generate point clouds for 3D measurements of forest structure. Wallace et al. (2012) were able to measure tree height, tree location, and canopy width within an accuracy of 0.05 m, 0.44 m, 0.25 m standard deviations, respectively. UAV technology has also been shown as an effective tool in monitoring pest and disease movement through a forest stand. As Lehmann et al. (2015) found, through the use of multispectral remote sensing imagery, they were able to detect branches on oak trees that were infested with oak splendour beetle versus branches that were still healthy. Recently, a study by Franklin and Ahmed (2017) illustrated how multispectral imagery collected using a UAV and advanced GIS image analysis and classification techniques could be used to classify the canopy of different tree species (*Populus tremuloides, Betula* *papyrifera, Acer saccharum, Acer rubrum*) with an approximate 78% accuracy. Such abilities are useful for the development of site specific forest inventories and vegetation monitoring. However, little to no information is currently available on the use of UAVs and multispectral remote sensing for the assessment of aspen forest regeneration and cumulative effects at a harvest block scale.

## 2.5 Remote sensing of vegetation

Remote sensing is defined as the acquisition of information regarding an object or phenomenon without making physical contact with the object (Jensen, 2007). This is achieved by using a specialized sensor attached to a platform such as a satellite, aircraft, UAV, or simply a handheld instrument. There are two major forms of remote sensing, active or passive. Active remote sensing involves a sensor that generates its own source of energy which it measures once it has come in contact with the object of interest. Alternatively, passive remote sensing collects information about a surface based on its reflectance (optical) or emittance (thermal) of energy that originates from the sun (Jensen, 2007). Of these two forms, passive remote sensing that focuses on measuring the reflectance of energy off the earth's surface are the most commonly used to assess vegetation. To be more specific, optical/reflectance remote sensing involves capturing specific portions (bands) of the electromagnetic spectrum in the visible (VIS), near infrared (NIR), and short wave infrared (SWIR) regions once they are reflected from the earth's surface (Shaw and Burke, 2003; Jensen, 2007). Based on the level of reflectance, it is possible to build a reflectance curve or signature for different types of land cover and use this information to better understand the environment.

### 2.5.1 Remote Sensing Resolutions

There are four types of resolutions that are used to describe a remote sensing sensor: spatial, radiometric, temporal, and spectral. Each of these resolutions are important as they control the properties and quality of the data being collected by the sensor. Spatial resolution refers to the field of view (area captured in an image) as well as the size of each individual pixel within an image. Radiometric resolution refers to the sensitivity of the sensor to differentiate changes in the magnitude of reflectance from the earth's surface. Temporal resolution refers to how often an image is captured for a particular area. Lastly, spectral resolution refers to the number of individual bands a sensor can measure as well as the size/wavelength interval being recorded by each band (Jensen, 2007). Many remote sensing systems are classified based on their spectral resolution or the number of bands the sensor captures. There are three major categories: panchromatic, multispectral, or hyperspectral and of these three, multispectral remote sensing is commonly used for studying vegetation properties and characteristics.

For the assessment of vegetation there are four bands of particular interest: BLUE (0.4 – 0.5 μm), GREEN (0.5–0.6 μm), RED (0.6–0.7μm), and NIR (near infrared) (0.7–1.2 μm) due to their unique reflectance properties that can be used as indicators of plant health. Healthy vegetation absorbs the majority of blue and red light as it used by chlorophyll during photosynthesis, leaving the green light to reflect causing the vegetation to appear green. Conversely, healthy vegetation will reflect virtually all the NIR light to prevent overheating and protein denaturation (Jensen, 2007). This large difference in reflectance between the visible and NIR bands allows for the calculation of many vegetation indices that can be used to further assess vegetation health and discriminate vegetation for other surfaces.

### 2.5.2 Vegetation Indices

Vegetation indices are calculated using two or more spectral bands to extract specific information about an area and the most common index used to assess vegetation health is the Normalized Difference Vegetation Index (NDVI) (Rouse et al., 1974). This index is calculated using the red and near infrared bands NDVI = (NIR-RED)/(NIR+RED) and ranges from -1 to +1 with +1 indicating an area of high vegetation cover while values approaching or below 0 contain little to no vegetation. This index along with many others are heavily used in the agricultural sector as they can be used to assess such things water stress, plant nitrogen status, canopy density within a crop and grain yield (Barnes et al., 2000; Henik, 2012). Similarly when looking at forest vegetation, NDVI showed a high correlation with increasing tree diameter, seed production, standardized tree ring width, LAI and chlorophyll content (Wang et al., 2004; 2005, Eitel et al., 2010; 2011). Wang et al. (2005) found a strong linear regression between NDVI and LAI; however, this relationship varied depending on the phenology stage of the deciduous forest (leaf production, full canopy, and senescence). When NDVI was calculated using the NIR and Red bands, it is known that in multilayer vegetation areas with LAI near 4 $m^2 m^{-2}$, it becomes difficult to predict LAI from NDVI measurements (Wang et al., 2005; Jensen, 2007; Mašková et al. 2008; Gamon et al., 1995). The reason is NDVI values asymptotically approach a saturation level in relation to LAI and do not allow for accurate measurements to be made (Baret and Guyot, 1991; Mašková et al., 2008). Monitoring of multi-layer vegetation such as aspen and surrounding forest vegetation may prove difficult by late summer when vegetation growth is at its maximum; therefore, caution must be taken when analyzing multispectral data to ensure measurements are correct and accurate. To address this issue, several other vegetation indices (Table 1-1) are often calculated from different combinations of spectral bands to ensure a better and more accurate assessment of vegetation properties.

**Table 2-1:** List of vegetation indices used

| Vegetation Index | Equation | Uses | Reference |
|---|---|---|---|
| Normalized Difference Vegetation Index (NDVI) | $= \frac{(\text{NIR - RED})}{(\text{NIR + RED})}$ | - LAI estimation<br>- Differentiating living / dead vegetation | (Rouse et al., 1974; Jensen, 2007) |
| Green Normalized Difference Vegetation Index (GNDVI) | $= \frac{(\text{NIR - GREEN})}{(\text{NIR + GREEN})}$ | - Monitoring vegetation growth | (Gitelson et al., 1996) |
| Normalized Difference Red-Edge Vegetation Index (NDRE) | $= \frac{(\text{NIR - REDEDGE})}{(\text{NIR + REDEDGE})}$ | - Chlorophyll content<br>- Early stress detection | (Barnes et al., 2000) |
| Simple Ratio (SR) | $= \frac{\text{RED}}{\text{NIR}}$ | - Biomass estimation<br>- LAI measurement | (Birth and McVey, 1968; Jensen, 2007) |
| Chlorophyll Index Green (CIG) | $= \left(\frac{\text{NIR}}{\text{GREEN}}\right) - 1$ | - LAI measurement<br>- Green leaf biomass<br>- Chlorophyll content | (Gitelson et al., 2003) |

# 3 SKIDDER TRAFFIC INTENSITY EFFECTS ON SOIL BULK DENSITY, ASPEN REGENERATION, AND VEGETATION INDICES[1]

## 3.1 Preface

Winter harvesting is a common practice used in ecologically sensitive forests to protect the underlying soil and forest floor from compaction and physical disturbance. However with a changing climate, it is uncertain whether winter harvesting offers the same level of protection it once did. Due to the weight and repetitive movements of harvesting machinery, it is important to monitor how these processes influence soil compaction and aspen regeneration. This chapter examines how skidder traffic intensity influences the level of soil compaction as well as the level of aspen regeneration. In addition, this chapter examines the potential of using multispectral remote sensing to assess the level of aspen regeneration across entire harvested blocks.

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[1] This chapter, co-authored with Dr. Ken Van Rees, has been submitted for publication to Forest Ecology and Management. Data collection, data analyses, GIS-analysis, and initial writing of the manuscript were completed by the lead author (Landon Lee Sealey), while editing and review of manuscript was done by the co-author.

## 3.2 Abstract

Following a disturbance, extensive aspen (*Populus tremuloides*) suckering is crucial for ensuring the continued productivity of the future forest. The aim of this study was to assesses the suitability of using winter harvesting in a provincial park as a way to mitigate severe soil compaction and ensure sufficient aspen regeneration to rejuvenate the over-mature forest. Six harvested blocks were selected for this study based on a skidder traffic intensity map which was generated using GPS data collected throughout the duration of the harvesting event. Soil bulk density, aspen regeneration, and vegetation indices were measured across the different levels of skidder traffic intensity. Soil bulk density increased significantly following as little as 1-5 skidder passes (1.39 g $cm^{-3}$) compared to the unharvested control (1.29 g $cm^{-3}$); however, bulk density remained relatively constant as the level of skidder traffic intensity continued to increase. No relationship was found between soil bulk density and the level of aspen regeneration; however, the level of skidder traffic intensity significantly influenced the level of aspen regeneration. Aspen root collar diameter, leaf area index, dry leaf biomass, total N, and total P all decreased as the level of skidder traffic intensity increased; however, none of these factors were significant. Conversely, aspen sucker density and height both were significantly decreased as the level of skidder traffic intensity increased, decreasing nearly 50% and 28%, respectively, in areas with 51-100 skidder passes. Multispectral remote sensing using UAV to assess the level of aspen regeneration across an entire harvested block proved ineffective. Although several vegetation indices showed significant relationships with aspen properties, none of these relationships had a coefficient of determination greater than approximately 0.2. Overall, winter harvesting appeared to have mitigated ecologically damaging increases in soil compaction and provided conditions suitable for healthy aspen regeneration.

## 3.3 Introduction

Mechanical harvesting has been proven as an efficient method for the rejuvenation of over-mature aspen forests (Navratil, 1991; Frey et al., 2003). However, in ecologically sensitive areas such as those in provincial parks, successive machine traffic may pose a risk to the integrity of the soil as well as regeneration success. Repeated heavy machinery movement over forest soils has the potential to increase the soil bulk density resulting in severe compaction (Brais and Camiré, 1998; Zenner et al., 2007). Compaction not only alters soil processes (aeration, infiltration, etc.), it can also impede plant root growth resulting in an overall decrease in the level of regeneration and growth.

Traditionally, regeneration studies involved using small measurement plots to assess regeneration across entire harvested blocks, leaving a high potential for error. Rather than using sample plots to assess regeneration, remote sensing may offer a solution that can accurately assess the level and health of aspen regeneration across entire blocks. Similar research in the agricultural sector has proven the feasibility of using remote sensing to monitor vegetation health and growth (Barnes et al., 2000; Henik, 2012); however, no studies have examined whether these same methods can be applied in a regenerating forest setting with the same level of success.

This chapter assesses whether the use of winter harvesting is a suitable practice to mitigate significant increases in soil bulk density and ensure sufficient aspen regeneration. In addition, this chapter will assess whether unoccupied aerial vehicle (UAV) based remote sensing can be used in a similar way as the agricultural sector to assess aspen regeneration.

The objectives for this study were:

1. To examine the relationship between the number of machine passes over an area, the severity of soil compaction, and its effects on aspen sucker density, height, root collar

diameter (RCD), leaf area index (LAI), dry leaf biomass, total nitrogen (N), and total phosphorus (P) following one summer of growth.

2. To examine the feasibility of UAV based multispectral remote sensing as a tool for assessing the effects of machine traffic intensity on aspen regeneration.

Null hypotheses for this study were:

1. Increasing the number of skidder passes over an area does not significantly increase the bulk density of the underlying soil at a depth of 10 cm following winter harvesting.
2. Increasing the number of skidder passes does not significantly lower a) sucker density, b) height, c) RCD, d) aspen sucker LAI, e) plot LAI, f) dry leaf biomass, g) total N, h) total P of regenerating aspen measured following one summer of growth after winter harvesting.
3. Areas with high aspen regeneration do not have significantly higher vegetation index values (Normalized Difference Vegetation Index (NDVI), Green Normalized Difference Vegetation Index (GNDVI), Normalized Difference Red-Edge (NDRE), Simple RED-NIR Ratio (SR), Chlorophyll Index Green (CIG)) compared to areas with lower levels of regeneration.

## 3.4 Materials & Methods

### 3.4.1 Study area

The harvesting operation took place in the northwest corner of Duck Mountain Provincial Park (Universal Transverse Mercator coordinates system, Zone 14U, 0307591 Easting and 5735089 Northing) (Fig. 3-1) where a 10-year forest management plan has been developed between the Government of Saskatchewan and Hudson Bay Weyerhaeuser to harvest

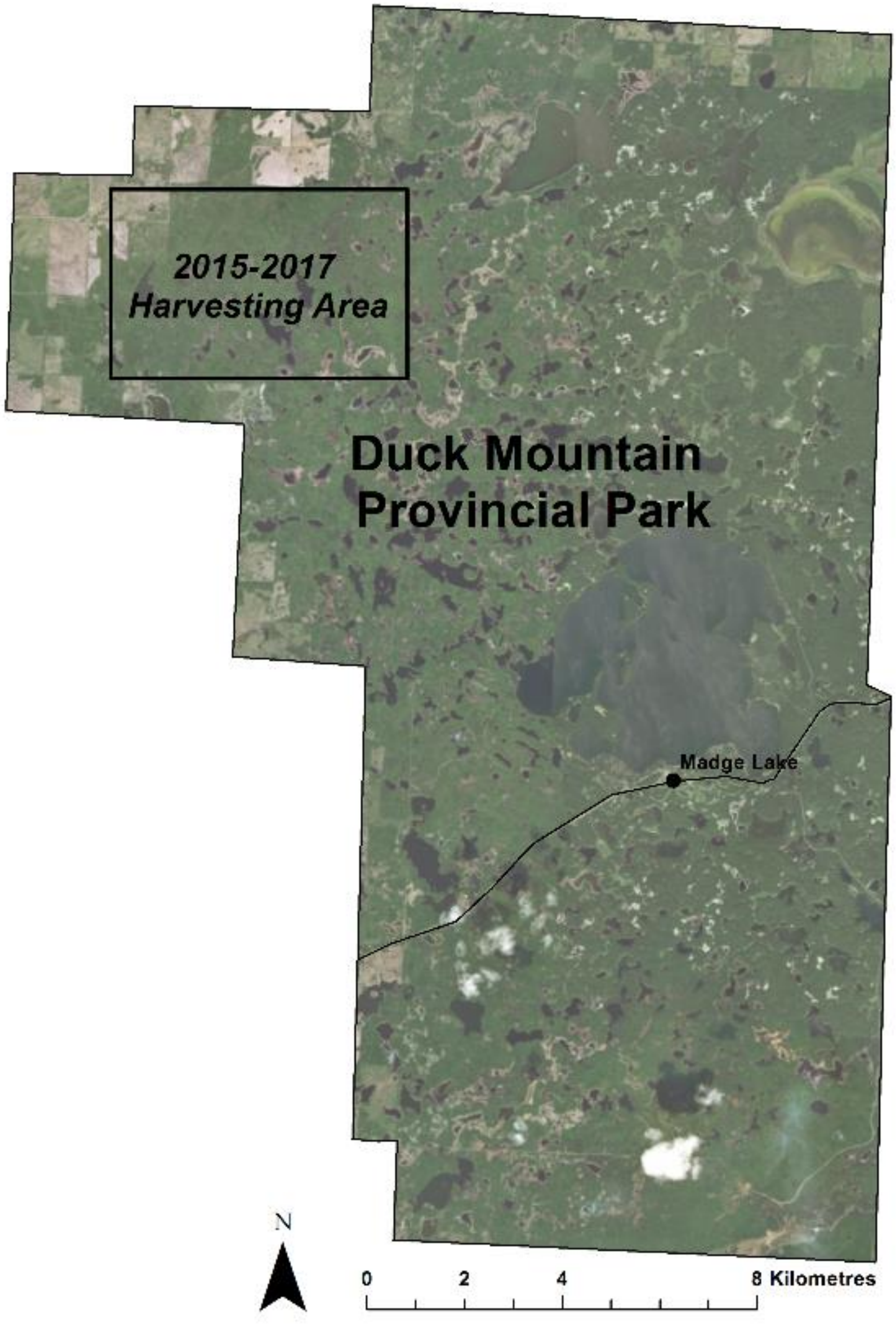


**Fig. 3-1:** Location of Weyerhaeuser harvesting operation within Duck Mountain Provincial Park, Saskatchewan.

approximately 10,000 hectares. In this areas, the forest was largely composed of over mature trembling aspen (*Populus tremuloides*) and balsam poplar (*Populus balsamifera*) (≈120-130 years old) most of which originated after the last wildfires in the late 1880-90s (Government of Saskatchewan, 2015). White spruce (*Picea glauca*) were also present; however, they are sparse and often only found around lower lying areas. The understory was a mixture of beaked hazelnut (*Corylus cornata*), mountain maple (*Acer spicatum*), and several other shrub, grass and forb species. A detailed list of native species found throughout the harvested area can be found in Appendix A.

The landscape in the north end of Duck Mountain Provincial Park is a hummocky terrain with slopes ranging between 5-30% (Saskatchewan Institute of Pedology, 1994). This hummocky terrain also gives rise to several scattered shallow marshes and emergent deep marshes, which range in size between 0.4 and 2 hectares and cover approximately 20-40% of the landscape (Saskatchewan Institute of Pedology, 1994). The soils in the northwest section of the park belong to the Waitville and Northern Light soil associations, which consist mainly of Gray and Dark Gray Luvisols with a loam/clay loam texture (Saskatchewan Institute of Pedology, 1994). A detailed summary of the soils found across the research sites can be found in Appendix B.

In terms of climate (based on 1981-2010 climate normal calculation), the Duck Mountain Provincial Park has a mean annual temperature of 0.7 °C and receives a total of 572.6 mm of precipitation each year. The mean annual maximum air temperature is 6.5 °C and the mean annual minimum air temperature is -5.1 °C. For precipitation, 405.7 mm are in the form of rain while 166.9 mm are in the form of snow (Government of Canada, 2018). A detailed summary of weather data during the winter harvesting operations can be found in Appendix C.

### 3.4.2 Sampling Area and Time

Harvesting in Duck Mountain Provincial Park first began in the winter of 2014-15; however, the areas used for this study were harvested during the winter (December-March) of 2015-16 and 2016-17. Following the winter harvesting of 2015-16, three harvested blocks (1, 2, and 3) were selected based on the range of skidder traffic intensity (described in section 3.2.3) within each block. Soil samples and vegetation measurements for these three blocks were collected between May and August of 2016. Following the winter harvesting of 2016-17, an additional three blocks (A, B, and C) were again selected based on the range of skidder traffic intensity (described in section 3.2.3) within each block. Soil samples and vegetation measurements for these three blocks were collected between May and August of 2017.

### 3.4.3 Calculating Skidder Traffic Intensity and Harvest Block Selection

Prior to the commencement of the winter harvesting in the Duck Mountain Provincial Park, iPads equipped with Avenza PDFmaps (Avenza Systems Inc., Toronto, ON, Canada) were installed on the harvesting equipment (feller-buncher, delimber, and skidder). During the harvesting operation, Avenza PDFmaps continuously recorded machine location and movement (±8 m horizontal accuracy) throughout the harvested blocks; unfortunately, there was an error with the feller-buncher and delimber data collection and therefore were excluded from the analysis of traffic intensity. Therefore, the analysis of traffic intensity was only associated with skidder traffic. After the data was collected, a series of ArcGIS tools and processes were used for the calculation of traffic intensity following the flowchart in Fig. 3-2. Skidder GPS data was imported to ArcGIS (version 10.3.1, Environmental Systems Research Institute, Redlands, CA, USA) where it was used to calculate skidder traffic intensity based on the number of skidder passes over a 0.87 x 0.87 m area. A spatial resolution of 0.87 x 0.87 m was used because GPS units where installed in the

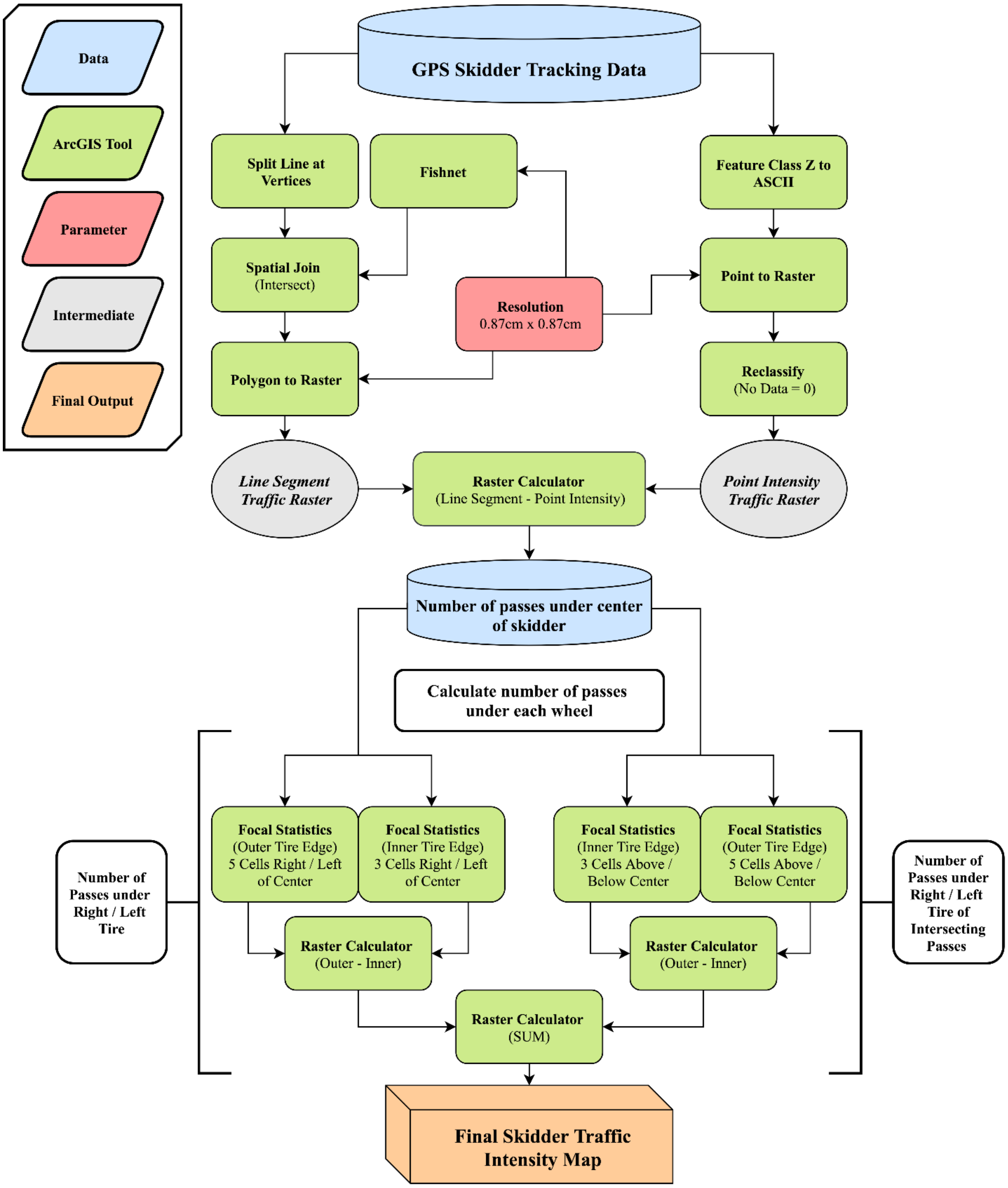


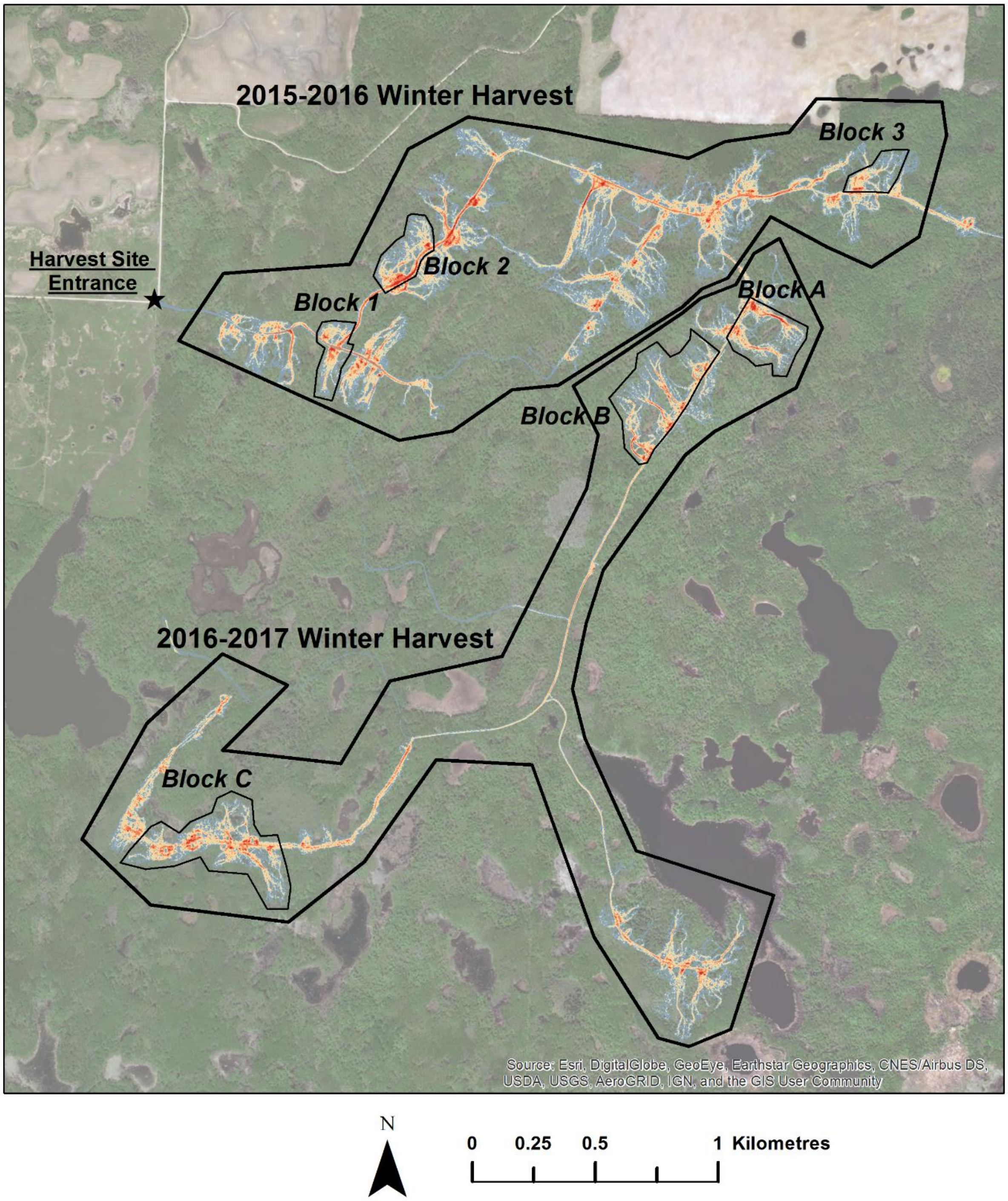
**Fig. 3-2:** Detailed flowchart outlining ArcGIS tool and processes used for the calculation of number of skidder passes across the harvested block.

middle of the skidder and additional calculations based on the width of the skidder were needed in order to calculate the number of passes under each tire.

Once the number of passes across a harvested block was calculated, they were classified into seven intensity classes (unharvested, harvested with 0 skidder passes, 1-5 passes, 6-10 passes, 11-25 passes, 26-50 passes, and 51-100 passes). The decision to classify skidder traffic into seven disturbance classes was based on the literature, which suggested that compaction increased in a logarithmic manner with the largest increase in soil compaction occurring within the first few passes and then diminishing as the number of passes increased (Brais and Camiré, 1998; Zenner et al., 2007). Determining areas that were harvested but did not have any skidder traffic were difficult to define without the feller-buncher data. Thus, it was impossible to know exactly where harvesting occurred; therefore, aerial image interpretation was used to identify areas within the harvested blocks that were harvested but showed no skidder traffic (0 skidder traffic). Following the calculation of the number of skidder passes, six harvested blocks containing all seven disturbance classes were chosen as study blocks (Fig. 3-3) (See Appendix D for detailed traffic maps of each harvested block). As mentioned earlier, three harvested blocks were selected from both the 2015-16 (Blocks 1, 2 and 3) and 2016-17 (Blocks A, B and C) winter harvesting operations that took place between late December and early March.

### 3.4.4 Measuring Bulk Density

Within each of the six harvested blocks, 10 bulk density sample locations per skidder intensity class were chosen at random for a total of 420 bulk density samples (60 samples per intensity class). Soil bulk density was determined using the soil core method (Hao et al., 2008) with a core volume of 68.71 $cm^3$ at a depth of 10 cm from the mineral soil surface. Back in the lab, soil bulk density samples were oven-dried for 24 hours at 105 °C before being weighed for total dry mass using a top loading balance. As coarse fragments (particles >2 mm) are very



Source: Esri, DigitalGlobe, GeoEye, Earthstar Geographics, CNES/Airbus DS, USDA, USGS, AeroGRID, IGN, and the GIS User Community

**Fig. 3-3:** Map illustrating the distribution of harvested blocks used for the study across the entire harvested region in the Duck Mountain Provincial Park.

common in the glacial till soils found in the Duck Mountain Provincial Park, each sample underwent a coarse fragment correction process. First, the dried samples were passed through a 2 mm sieve to remove the coarse fragments. These coarse particles were then weighed using a top loading balance before being submerged in a graduated cylinder to determine their volume. The mass and volume of coarse fragments was then removed from the total dry mass of the sample and core volume, respectively (Vincent and Chadwick, 1994; Page-Dumroese et al., 1999; Hao et al., 2008**.** Samples containing large roots or pieces of forest floor (LFH) were also noted at this time and these samples were removed from the data set prior to statistical analysis.

### 3.4.5 Aspen Regeneration Measuring

In order to assess aspen regeneration and its relation to soil bulk density and skidder intensity, regeneration plots (1 x 1 m quadrat using PVC pipe) were selected based on the sampling locations used for bulk density. In each of the harvested blocks, four regeneration assessment plots were selected at random from the 10 bulk density locations per skidder intensity class, excluding areas that were unharvested. This approach resulted in 24 regeneration assessment plots in each of the harvested blocks for a total of 144 regeneration plots (24 plots per skidder intensity class).

Aspen sucker density (# of sucker $m^{-2}$) was determined by counting all aspen suckers within the boundary of the 1 $m^2$ quadrat. Aspen sucker height and RCD were recorded for each sucker within the plot using a metre stick and a digital caliper, respectively. Next, two measurements of LAI (m $m^{-2}$) were taken for each plot. The first LAI measurements were taken in the field using an AccuPAR LP80 ceptometer (METER Group Inc., Pullman, WA, USA) which converts measures of canopy photosynthetically active radiation (PAR) interception into leaf area for the entire plot along an 84 cm bar (Duursma et al., 2003). To obtain an average LAI measurement of the 1 x 1m quadrat, four ceptometer readings were collected for each quadrat, one measurement reading per quadrat side. Following the ceptometer readings, all aspen leaves within the plot were picked and placed in a paper bag and transported back to the lab where the second LAI measurement was taken using a Li-COR LI3050A area meter (LI-COR Biosciences, Lincoln, NE, USA) to obtain an aspen only LAI. After both LAI measurements were complete, leaves were oven-dried at 75°C for 48 hours then weighed to obtain a measure of total oven-dry leaf biomass (g $m^{-2}$). Leaves were then ground using a high-speed blade grinder in preparation for nutrient analysis. From each plot, 0.25 g of homogenized dry ground leaf was acid digested with 5 ml of $H_2SO_4$ and 2.5 ml (spread over 5 additions) of $H_2O_2$ (Thomas et al., 1967). Following the digest, the extract was analyzed for total nitrogen (N) and total phosphorus (P) using a Technicon AutoAnalyzer (Technicon Industrial Systems, Tarrytown, N.Y., USA).

Due to time constraints, LAI measurements, biomass samples, and nutrient concentration measurements were not collected or determined for the three harvested blocks measurement following the 2015-16 winter harvest (Sites 1, 2, and 3). Therefore, LAI, biomass, and nutrient concentration from the three harvested blocks measured following the 2016-17 winter harvest (Sites A, B, and C) were used for statistical analysis.

### 3.4.6 UAV Remote Sensing of Aspen Regeneration

#### 3.4.6.1 Flight Parameters & Image Processing

A DJI Phantom 4 (Dà-Jiãng Innovations Science and Technology Co. Ltd., Shenzhen, Guangdong Province, China) UAV was used to capture RED-GREEN-BLUE (RGB) imagery of the harvested blocks as well as carry an additional multispectral sensor. The multispectral sensor was a Parrot Sequoia (Parrot SA, Paris, Îles-de-France, France), which captured four individual wavelengths: GREEN, RED, RED-EDGE, and NIR (near-infrared). Prior to any flights, white circular ground control points were placed throughout the harvested blocks and their locations were recorded using a Trimble GeoXT 2005 series GPS (Trimble Inc., Sunnyvale, CA, USA).

These control points were used for geo-correction of both RGB and multispectral imagery during the image processing stage.

This study involved two flight periods over the course of the summer months (May-August) immediately following the harvesting event. The first set of flights occurred at the start of May once all the snow had melted but before any vegetation began to regenerate in the harvested blocks. The data collected from these flights was used for terrain analysis and determination of slope position, as well as calculation of % slash coverage which is discussed in Chapter 4. The second set of flights occurred at the end of August, which allowed a full summer of growth, but was prior to the beginning of senescence. The data collected from these flights was used to assess the levels of regeneration through regression analysis with aspen regeneration measurements made on the ground. Unfortunately, due to technical malfunctions with the multispectral sensor, we were unable to capture imagery from blocks 1, 2, and 3 in August of 2016. Therefore, multispectral data used for the regression analysis and assessment of aspen regeneration after 1 year of growth was only from blocks A, B, and C, which was captured in August of 2017.

All flights were controlled by Drone Deploy (DroneDeploy, San Francisco, CA, USA) to ensure that flight parameters would be consistent between each flight. All flights were conducted between 10 am and 2 pm to reduce the effect of shadow and obtain the best multispectral data possible. All flights were conducted at 60 m elevation above ground level (AGL) which gave a spatial resolution of approximately 1.8 cm pixel$^{-1}$ for the RGB imagery and 7.4 cm pixel$^{-1}$ for the multispectral imagery. Both RGB and multispectral image capturing had approximately 75 % overlap side-to-side and 60 % overlap front to back.

Following flights, all RGB images were uploaded to Pix4D (Pix4D SA, Lausanna, Vaud, Switzerland) where they were stitched (consolidation of overlapping images) to create an orthomosaic of each of the six harvested blocks. The RGB orthomosaics were then exported to

ArcGIS (version 10.3.1, Environmental Systems Research Institute, Redlands, CA, USA) where a geo-correction using the ground control points mentioned earlier was performed. Multispectral imagery was also uploaded to Pix4D in order to create an orthomosaic of harvested blocks A, B, and C. The multispectral imagery also underwent a radiometric correction processing in Pix4D using images of a calibration panel that were collected immediately before and after each flight. The multispectral orthomosaics for the three blocks were also exported to ArcGIS for geo-correction using the ground control points established prior to flight.

#### 3.4.6.2 Terrain Analysis and Slope Position Classification

Due to the hummocky topography found in the Duck Mountain Provincial Park, the soil moisture regime is likely quite variable. As soil moisture can have a major influence on a soils susceptibility to compaction (Greacen and Sands, 1980; McNabb et al., 2001), it was important to determine where in relation to the landscape soil bulk density samples were collected. As different landscape positions are often associated with different moisture regimes, UAV derived data was used to classify the landscape into four slope positions: topslope, shoulder, backslope, and depression based on works by Pennock et al. (1987), Pennock (2003), and Miller and Schaetzl (2014). To begin, Pix4D was used to create a point-cloud of the harvested blocks, which was used to generate a 2 m resolution digital terrain model (DTM). This DTM was then exported to SAGA GIS (Conrad et al., 2015) where the "Relative height and slope position" tool was used to calculate a normalized height output. From this normalized height output, the landscape was classified into upper slope areas (>0.5) and lower slope areas (<0.5). Next, ArcGIS software was used to calculate slope degree (°) of the landscape from the DTM with the built-in slope tool. Based on the studies by Pennock et al. (1987) and Miller and Schaetzl (2014), slope was then classified into three categories, 0 – 1.1°, 1.1 – 3°, >3° which were associated with summit/depression, shoulder/footslope, and backslope positions, respectively. Lastly, the classified normalized height and classified slope outputs were combined and based on the degree slope and whether an area was classified as upper or lower slope, the landscape was classified into four slope positions. As slope position is a qualitative measure, each position was given an arbitrary numerical value /dummy variable (i.e., 1 = depression, 2 = backslope, 3 = shoulder, 4 = summit) so it could be included in the fuzzy logic analysis in Chapter 5.

#### 3.4.6.3 Vegetation Indices Calculation and Extraction

Once the multispectral images were stitched, radiometrically calibrated and geo-corrected, the orthomosaic image of each harvested block were ready for vegetation indices calculation. These vegetation indices were calculated using the raster calculator tool in ArcGIS. Five commonly used indices were selected to assess aspen regeneration: NDVI, GNDVI, NDRE, SR, and CIG (See Chapter 2, Section 2.5.2 for vegetation index equations).

To extract vegetation index values for each regeneration assessment plot, the regeneration assessment sampling points were overlaid on top of each index layer and a digital 1 x 1 m quadrat was created around each sampling point. This digital quadrat acted as a surrogate for the one used during field measurements. The pixels within this digital quadrat were then combined to obtain an average index value for that quadrat and this value was used for regression analysis with the aspen regeneration measurements made on the ground.

### 3.4.7 Statistical Analysis

All statistical analysis for this study were conducted using SAS (version 9.4, SAS Institute Inc., Cary, NC, USA). To evaluate the effects of skidder traffic intensity on soil bulk density, a complete randomized design (CRD) experiment was used. Samples that were collected from the six different harvested blocks were grouped together based on the level of skidder traffic intensity and PROC GLIMMIX procedure was used to perform an analysis of variance. As bulk density samples were collected after two separate winter harvesting events, the year the sample was collected was considered a random effect in the analysis. Slope position was also treated as a random effect in the analysis as samples were chosen at random across the harvested block with no consideration for topographical influence.

To assess the relationship between soil bulk density and the level of aspen regeneration (density, height, diameter, LAI, biomass, total N, total P), simple linear regression was performed (PROC REG procedure). The data used to assess the relationship between soil bulk density and aspen sucker density, height, and diameter was from all six harvested blocks, while data for LAI, dry leaf biomass, total N, and total P data was only from harvested block A,B, and C. For regression analysis, all aspen regeneration measurements for assessment plots where no aspen present were labelled as a zero to indicate no aspen regeneration rather than exclude the point from the analysis. Prior to regression analysis, the dataset was examined for outliers as part of the assumptions for regression using studentized residuals. Data with studentized residual values greater than or equal to 2 were removed from the dataset. Following linear regression analysis, residual normality was assessed with the Shapiro-Wilk test using PROC UNIVARIATE procedure. If residuals were not normally distributed, the data were transformed to achieve normality and the data were re-run.

A CRD experimental design was used to assess the effects of skidder traffic intensity on aspen regeneration. Aspen sucker density, height, and diameter were measured across all six harvested blocks; however, LAI, biomass, total N, and total P were only measured for the three harvested blocked sampled in the summer of 2017 (A,B,C). For regeneration assessment plots where no aspen suckers were present, aspen density was recorded as zero while all other aspen measurements (height, RCD, LAI, biomass, total N, total P) were labelled as a missing value. Therefore, this assessment of the effects of skidder traffic on the aspen only accounts for aspen suckers that were present within treatments. Regeneration data across all harvested blocks was compiled based on the level of skidder traffic and an analysis of variance was performed using the PROC GLIMMIX procedure. Sampling year and slope position were again considered random effects in the model.

Lastly, simple linear regression was used to evaluate the relationship between vegetation indices values (NDVI, GNDVI, NDRE, SR, CIG) and the level of aspen regeneration measured within the assessment plots. For regression analysis, all aspen regeneration measurements for assessment plots that had no aspen present were treated as a zero to indicate no aspen regeneration rather than excluding the data point. Prior to regression analysis, the dataset was examined for outliers as part of the assumptions for regression using studentized residuals. Data with studentized residual values greater than or equal to 2 were removed from the dataset. Following linear regression analysis, residual normality was assessed with the Shapiro-Wilk test using PROC UNIVARIATE procedure. If residuals were not normally distributed, the data was transformed and re-run until residual normality was achieved.

## 3.5 Results

### 3.5.1 Distribution of Skidder Traffic Intensity across Harvested Blocks

The size of skidder traffic classes derived from the GPS data ranged between 0.5 to 43.5% of the harvested area when observed across all six blocks (Table 3-1). On average, areas with 1-5 passes encompassed a significantly larger portion of harvested blocks (≈37%), compared to all other levels of skidder traffic. Areas with 6-10 and 11-25 passes were the second largest skidder traffic disturbance class, accounting for approximately 19 and 24% of the harvested blocks, respectively. No skidder traffic areas and areas with 26-50 passes were the third largest contributor to overall harvested area, accounting for approximately 10 and 8% of harvested blocks, respectively. Areas with 51-100 passes consistently attributed the lowest amount of skidder disturbance to harvested blocks, accounting for just over 1% of all skidder traffic. Areas with more than 26 passes were often associated with landings and major skidder trails used to access secluded portions of the harvested block. The values represented in Table 3-1 do not include the inblock roads that were built as part of the harvesting operation to haul the harvested wood; as they represent an area of higher disturbance from road construction and logging trucks.

### 3.5.2 Effects of Skidder Traffic Intensity on Soil Bulk Density

Although harvesting was conducted during the winter months, the level of skidder traffic intensity had a significant effect on the soil bulk density at the 10 cm depth (Fig. 3-4). With the exception of the intensity classes harvested with 0 passes and 11-25 skidder passes, all other skidder traffic intensity levels indicated a significant increase ($p < 0.05$) in soil bulk density compared to the unharvested control (1.29 g $cm^{-3}$). Areas with as little as 1-5 passes (1.39 g $cm^{-3}$) were significantly higher than the unharvested control; however, the highest average bulk density occurred in areas with 26-50 passes (1.41 g $cm^{-3}$). The change in soil bulk density with increasing number of passes had an asymptotical trend, where following 1-5 skidder passes there was an initial 7% increase in bulk density but then only increased an additional 2% by the time an area had between 26-50 and 51-100 skidder passes.

**Table 3-1:** Harvested block size (ha) and percent breakdown (%) of the harvested block by skidder traffic intensity classes for the six harvested blocks cut during two harvest seasons.

| | Year of Harvest | | | | | | |
|---|---|---|---|---|---|---|---|
| | 2015-16 | | | 2016-17 | | | |
| | Block 1 | Block 2 | Block 3 | Block A | Block B | Block C | **Mean** |
| Harvest Area (ha) | 1.58 | 2.18 | 3.42 | 3.65 | 6.50 | 7.17 | **4.08** |
| | % of the Harvested Block | | | | | | |
| Harvested 0 passes | 6.86 | 8.67 | 6.73 | 13.36 | 13.38 | 13.78 | **10.46c†** |
| 1-5 passes | 38.54 | 34.51 | 26.05 | 41.14 | 43.51 | 35.98 | **36.62a** |
| 6-10 passes | 17.52 | 18.23 | 23.20 | 18.01 | 17.39 | 19.41 | **18.96b** |
| 11-25 passes | 25.21 | 26.23 | 33.22 | 19.56 | 18.99 | 22.92 | **24.36b** |
| 26-50 passes | 10.28 | 10.70 | 9.54 | 6.21 | 6.22 | 6.85 | **8.30c** |
| 51-100 passes | 1.60 | 1.66 | 1.25 | 1.73 | 0.51 | 1.05 | **1.30d** |

† Values with the same letter are not significantly different p = 0.05 using Tukey-Kramer

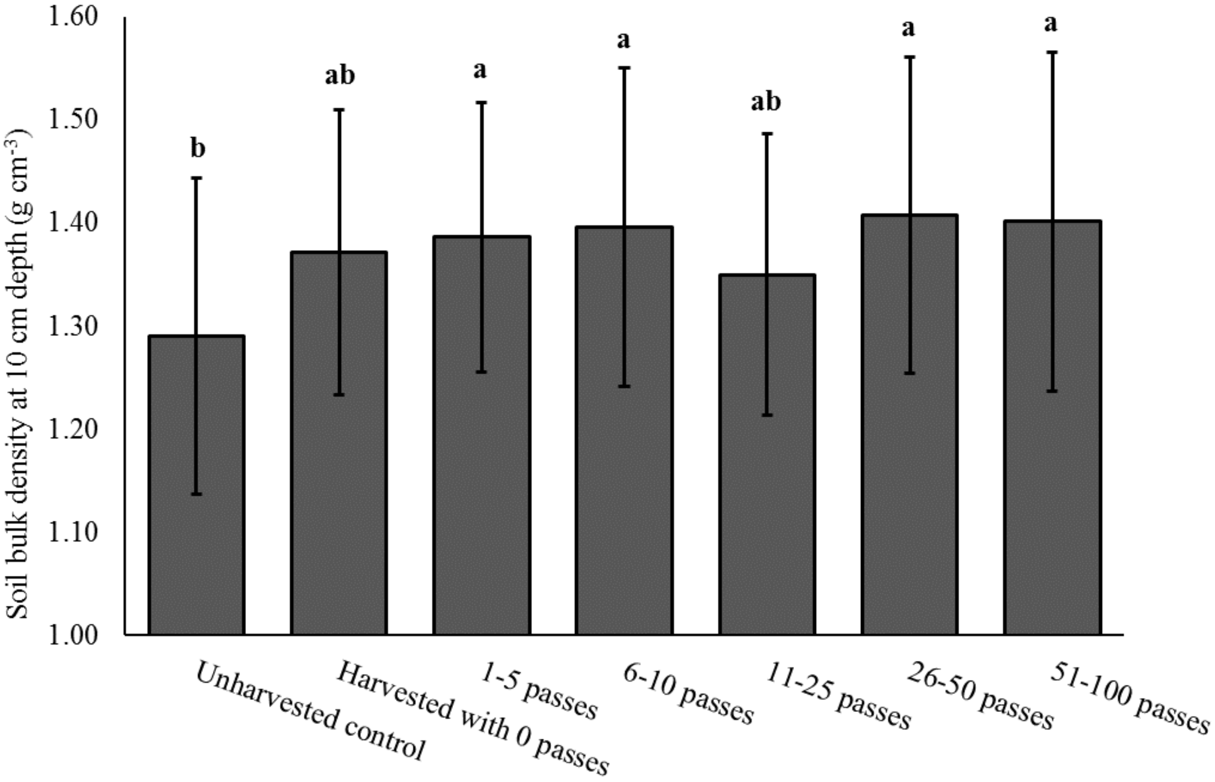


**Fig. 3-4:** Mean soil bulk density at 10 cm depth across skidder traffic intensity classes one year post winter harvest in Duck Mountain Provincial Park, Saskatchewan. Bars with the same letter are not significantly different from each other at $p = 0.05$ using Tukey-Kramer. Error bars represent standard deviation.

### 3.5.3 Effects of Skidder Traffic Intensity on Aspen Regeneration

Increasing the level of machine traffic intensity had significant effects on the density and height of aspen suckers one-year post-harvest (Table 3-2). The average number of aspen suckers decreased significantly from 9.5 suckers $m^{-2}$ (95,000 suckers $ha^{-1}$) for areas with 6-25 skidder passes to 4.7 suckers $m^{-2}$ (47,000 suckers $ha^{-1}$) for areas with 51-100 skidder passes. Although areas with less than six passes had decreased aspen density compared to areas with slightly more skidder traffic, this decrease was not significant. Average aspen sucker height, however, was highest for areas that had 0 skidder passes (85.8 cm) and significantly decreased by approximately 22-25 cm in areas with 11-25, 26-50 and 51-100 skidder passes, 63.9 cm, 62.9 cm, 61.0 cm, respectively. The level of skidder traffic intensity did not appear to have any significant effects on aspen sucker RCD, LAI, Plot LAI, dry leaf biomass, total N, and total P, although the majority of these properties tended to decrease as the level of skidder traffic intensity increased.

### 3.5.4 Effects of Soil Bulk Density on Aspen Regeneration

Although increasing skidder traffic intensity resulted in a significant increase in bulk density compared to the unharvested control, the increase in soil bulk density did not have a negative effect on aspen regeneration properties one year post-harvest (Fig. 3-5). None of the eight aspen regeneration properties (density, height, RCD, LAI, plot LAI, dry leaf biomass, total N, total P) indicated a significant linear relationship with increasing soil bulk density. In addition, none of the coefficients of determination for any of the eight aspen properties was greater than 0.1, further illustrating the lack of any relationship.

**Table 3-2:** Mean aspen sucker density, height, RCD, aspen sucker LAI, plot LAI, dry leaf biomass, total N, total P in 1 $m^2$ monitoring plots across six harvested blocks after one summer of growth following winter harvesting.

|  | Aspen Sucker |  |  |  |  |  |  |  |
|---|---|---|---|---|---|---|---|---|
| Traffic Level | Density (# $m^{-2}$) | Height (cm) | RCD (mm) | Sucker LAI ($m^2$ $m^{-2}$) | Plot LAI ($m^2$ $m^{-2}$) | Dry leaf Biomass (g $m^{-2}$) | Total N (mg $g^{-1}$) | Total P (mg $g^{-1}$) |
| Harvested With 0 Skidder Passes | 8.1ab† | 85.8a | 8.62a | 0.58a | 1.64a | 57.68a | 28.85a | 3.18a |
| 1-5 Passes | 8.5ab | 77.5ab | 8.26a | 0.45a | 1.34a | 47.56a | 27.16a | 3.07a |
| 6-10 Passes | 9.5a | 68.8ab | 7.66a | 0.51a | 1.99a | 47.29a | 27.36a | 3.07a |
| 11-25 Passes | 9.5a | 63.9b | 7.04a | 0.73a | 1.99a | 62.07a | 26.76a | 3.04a |
| 26-50 Passes | 6.8ab | 62.9b | 6.98a | 0.63a | 1.74a | 55.56a | 28.58a | 2.87a |
| 51-100 Passes | 4.7b | 61.0b | 7.28a | 0.31a | 1.54a | 29.87a | 25.63a | 2.70a |
| **Statistical Analysis** | P Value |  |  |  |  |  |  |  |
| Traffic Effect | 0.0318 | 0.0034 | 0.1052 | 0.3489 | 0.4672 | 0.5437 | 0.1334 | 0.4043 |

† Means in a column with the same letter are not significantly different $p = 0.05$ using Tukey-Kramer

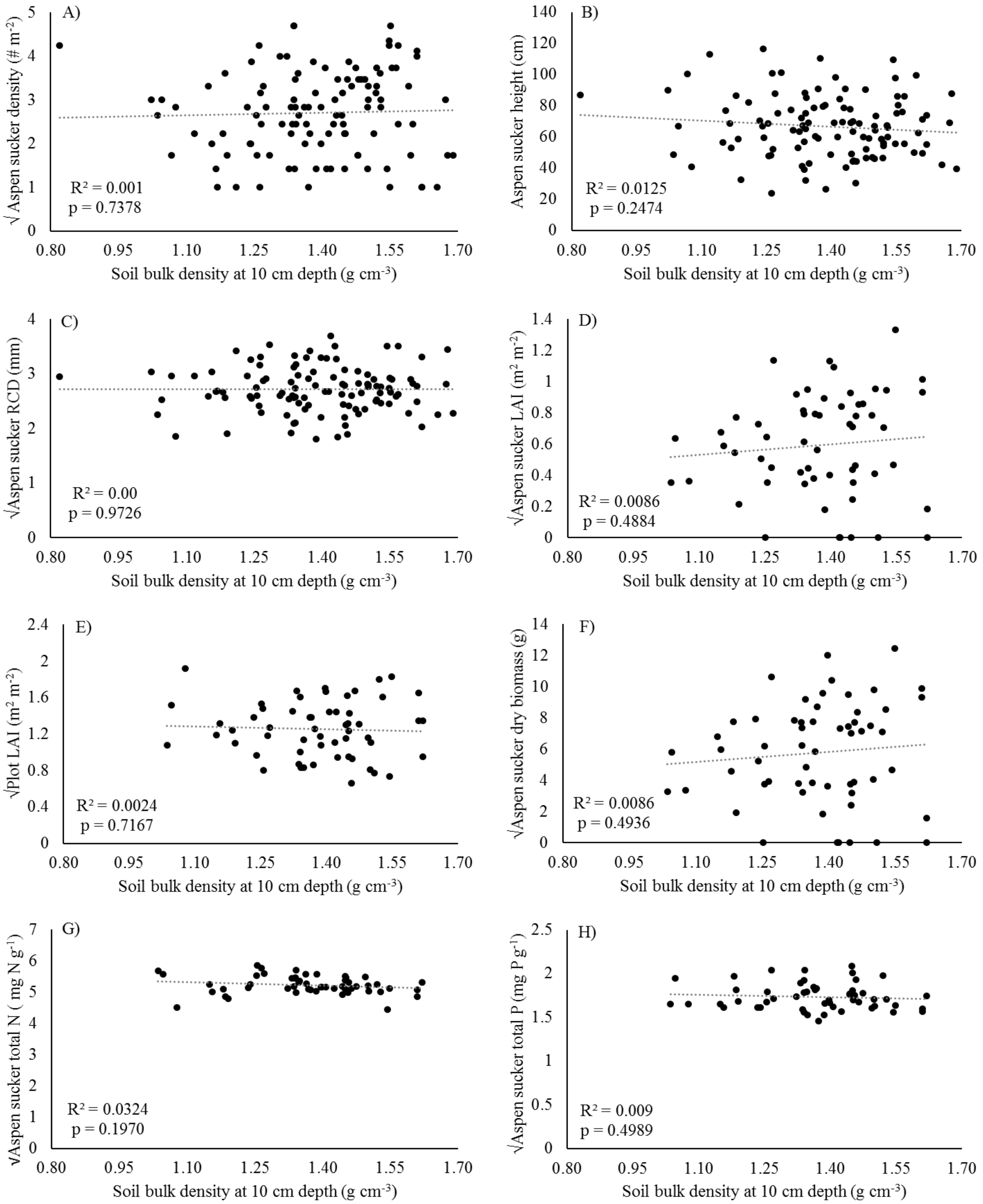


**Fig. 3-5:** Relationship between soil bulk density at a 10 cm depth and aspen sucker regeneration after one summer of growth. A) density, B) height, C) RCD, D) aspen sucker LAI, E) plot LAI, F) dry leaf biomass, G) total N, H) total P. All regeneration measurements, except sucker height (B), are square root transformed.

### 3.5.5 Relationship between Aspen Regeneration and Vegetation Indices

Vegetation indices as calculated using multispectral imagery from a Parrot Sequoia showed that none of the five indices used in this study had a strong relationship with the aspen measurements and therefore could not be used to effectively predict the level of aspen regeneration across the harvested block (Table 3-3). Of the five indices measured, GNDVI and NDVI showed the strongest relationship with many of the aspen regeneration properties and although many of these properties showed highly significant linear regression with the vegetation indices ($p<0.01$), the strength of these relationships was poor. The highest coefficient of determination measured was between NDVI and aspen height with an $R^2$ of 0.2094. These low coefficient of determination values made it impossible to accurately predict aspen regeneration based on any of the vegetation indices. Of all the indices, NDRE was the least sensitive to changes in aspen regeneration as it failed to show a significant relationship with any of the aspen measurement properties.

**Table 3-3:** Coefficient of determination ($R^2$) values of vegetation indices (NDVI, GNDVI, NDRE, SR, and CIG) and aspen regeneration measurements (density, height, RCD, aspen sucker LAI, plot LAI, dry leaf biomass, total N, total P).

| | Vegetation Indices | | | | |
|---|---|---|---|---|---|
| | NDVI | GNDVI | NDRE | SR | CIG |
| Density | 0.0771† | 0.0688† | 0.0235 | 0.0883† | 0.0785† |
| Height | 0.2094†† | 0.1340†† | 0.0183 | 0.0917† | 0.0836† |
| RCD | 0.1909†† | 0.1273†† | 0 | 0.0006 | 0.001 |
| Sucker LAI | 0.1550†† | 0.1434†† | 0.0215 | 0.1172†† | 0.1236†† |
| Plot LAI | 0.0001 | 0.0004 | 0.0043 | 0.0076 | 0.0032 |
| Dry Leaf Biomass | 0.1259†† | 0.1146†† | 0.0118 | 0.0890† | 0.0946† |
| Total N | 0.0022 | 0.1899†† | 0.0194 | 0.0076 | 0.0063 |
| Total P | 0.0021 | 0.2038†† | 0.0035 | 0.0006 | 0.0006 |

† indicates significance at $p < 0.05$

†† indicates significance at $p < 0.01$

## 3.6 Discussion

Overall, assessment of aspen regeneration following winter harvesting in the Duck Mountain Provincial Park indicated that winter harvesting events stimulate vigorous aspen regeneration similar to that found following a natural disturbance such as a forest fire (Brown and DeByle, 1987; Peterson and Peterson, 1992). However, as a result of the mechanical harvesting, small areas (≈ 1% of blocks) experienced an excessive level of disturbance, which lead to significant increases in soil bulk density and significant decreases in both aspen sucker density and height. It should be noted that the level of disturbance for an area was only based on skidder machine traffic due to technical issues; therefore, it was assumed that the feller-buncher or de-limber had limited effect within a harvested block.

Winter harvesting is a common practice used to minimize soil disturbance in ecologically sensitive areas. Several studies have examined the effects of season of harvest and while all have found some degree of soil disturbance associated winter harvesting, it was often significantly less compared to the disturbance experienced during summer harvesting operations (Stone and Elioff, 1998; Block et al., 2002; Kolka et al., 2012). Similarly, the forest in the Duck Mountain Provincial Park were winter harvested, yet certain areas still experienced a significant level of soil disturbance. Compared to unharvested controls, there was a significant increase in soil bulk density at the 10 cm depth with as little as 1-5 skidder passes. However, following the initial 1-5 passes, soil bulk density did not continue to increase significantly as the level of skidder traffic continued to increase, indicating that during the winter harvest, 1-5 skidder passes increased soil bulk density to a level where it was able to resist any further change to bulk density from repetitive skidder traffic. As a result, a typical asymptotic relationship was found between soil bulk density and the level of skidder traffic like those found in many studies (Brais and Camiré, 1998; Williamson and Neilsen, 2000; McNabb et al., 2001; Zenner et al., 2007). Results from this study in the Duck

Mountain Provincial Park further support the findings by Brais and Camiré (1998), Williamson and Neilsen (2000), and McNabb et al. (2001), who found that the majority of the bulk density increase occurred within the first few passes of machine traffic and then remained relatively constant as traffic intensity continued to increase. In terms of forest regeneration following winter harvesting, it was unclear how this slight increase in average bulk density to 1.41 g cm$^{-3}$ in high skidder traffic areas would influence aspen regeneration. Initial thoughts were that increases in soil bulk density would decrease suckering and root growth; however, based on our results it is unlikely that the change to the soil's physical properties were responsible for the decreased aspen regeneration found with increasing skidder traffic.

The highest average soil bulk density found in this study was 1.41 g cm$^{-3}$, however, this is below the growth limiting bulk density of 1.45-1.65 g cm$^{-3}$ stated by Daddow and Warrington (1983) for clay loam to sandy loam textured soils; which are found throughout Duck Mountain Provincial Park. Therefore, the slight increase in soil bulk density should not have influenced the level of aspen regeneration as it was below the growth limiting bulk density. This notion is supported by the results from our study that found no relationship between soil bulk density and the level of aspen regeneration (density, height, RCD, LAI, dry leaf biomass, total N, and total P) one year post-harvest. This same trend was also observed by Zenner et al. (2007), who found no relationship between increasing soil resistance penetration and the level of aspen regeneration (density, height, basal diameter) three years post-harvest. However, as the forest continues to mature, the slight increase in bulk density may have significant effects on the level of aspen regeneration. The study by Kabzems (2012), which had compaction treatments below growth limiting bulk density for the texture of the soil, found no influence of compaction on the initial regeneration level of aspen; however, from four years to ten years post-harvest, aspen sucker height in areas with no compaction were significantly taller compared to areas with intermediate and heavy compaction treatments. Hence, assessing the effects of soil bulk density on the initial level of aspen regeneration may be irrelevant until the suckers begin naturally thinning out and mature. In the Duck Mountains, the highest average bulk density was already below a growth limiting level and the soils are coarser compared to those in Kabzems (2012); therefore, bulk density may not have an effect on the continued growth of aspen as the freeze thaw cycle should de-compact and return the soil to a level similar to their original state over time. The length of time required for de-compaction to occur is debatable, but due to the presence of coarser materials (sand and stones) in these soils, a decrease in soil bulk density within five years would be expected (Page-Dumroese et al., 2006). However, depending on the type of clay and the amount of soil moisture when they freeze, de-compaction can take decades as reported by Corns (1988) in western Alberta. Nonetheless, our study found that increasing the level of skidder traffic resulted in a decrease in aspen sucker density and aspen height one year post-harvest, but if there were no relationships between increasing soil bulk density and regeneration, what other factor(s) could be affecting the initial decrease in regeneration success?

One possibility is the increasing level of physical surface disturbance and scarification of the forest floor associated with increasing skidder traffic. The majority of aspen sucker regeneration occurs on the shallow rooting system found within or just below the forest floor (Navratil, 1991; Peterson and Peterson, 1992; Lieffers-Pritchard, 2004) and are therefore vulnerable to damage caused by the repetitive movement of the skidder. Lieffers-Pritchard (2004) study found that mean suckering depth was only 4.6 cm from the forest floor surface and that only 7% of suckers were initiated from within the mineral soil/below the forest floor. Therefore, any damage to the forest floor may have drastic implications on the level of aspen regeneration. Regions with higher levels of skidder traffic were often associated with landings and major skidder trails used to access harvested trees furthest from the processing area. Although this harvesting operation took place during the winter months when the soil was supposedly frozen and a protective layer of snow likely covered the forest floor, the repetitive traffic in these areas would slowly remove and mix the snow leaving the underlying forest floor susceptible to physical disturbance as seen in Fig. 3-6. There were also several warming periods throughout the harvesting event where air temperature was near or above 0°C (Appendix C), which would have even further reduced the amount the snow cover in these areas. As a result, there would be areas within the harvested block where skidder tires would be in direct contact with the forest floor. In addition to the increased force exerted by skidders when pulling a full load, the hummocky terrain in the Duck Mountain Provincial Park would increase the potential for slippage. Skidder tire slippage on direct forest floor would result in the physical churning or ripping of the forest floor as well as the rooting system within it.

Several studies have examined the effects of aspen root disturbance on the level of aspen regeneration; however, the results are not consistent. Fraser et al. (2004) found that wounding

**Fig. 3-6:** High skidder traffic landing area where the forest floor and ground has been exposed due to the repeated traffic churning the snow and increasing snow melt during periods of increased temperature (photo provided by Mike Andersen, Ministry of Environment, Government of Saskatchewan)

aspen roots nearly doubled aspen suckering as well as increased the height and leaf area of the sucker. However, Renkeman (2009) mentions that the Fraser et al. (2004) study used shovels to inflict their wounding treatments which would not be as representative of the crushing and wounding of aspen roots caused by skidder traffic. Using a tractor to mimic the disturbance of a skidder on aspen roots, Renkeman (2009) found that following winter harvesting, wounding aspen roots decreased sucker density, height, and dry biomass as well as caused a decrease in the % living root and total non-structured carbohydrate concentration within the root. Similarly, a field study by Sheppherd (1993) found that root density, root volume, and sucker density were all lower on skidder trails compared to un-trafficked areas. Therefore, although winter harvesting in the Duck Mountain Provincial Park prevented severe soil disturbance in terms of compaction, excessive levels of skidder traffic may still have disturbed the forest floor and aspen rooting system causing a decrease in the level of aspen regeneration. Though, in our study, it is important to note that the amount of area with significantly lower regeneration levels accounted for < 2% of the entire harvested block (Table 3-1), making it a relatively small area in comparison to the rest of the harvested area.

In addition, areas with significantly lower regeneration still contained on average 4.7 suckers $m^{-2}$ (47,000 suckers $ha^{-1}$) after one year of growth and while this is lower than the 9.5 suckers $m^{-2}$ (95,000 sucker $ha^{-1}$) found in areas with less skidder traffic, this level of early regeneration should be sufficient to obtain a healthy mature forest. During the first five to eight years following a disturbance, there is a rapid decrease in aspen sucker density as competition for resources increases, allowing only the strongest suckers to survive (Perala, 1974; Steneker, 1976; Bella, 1986). However, as Steneker (1976) illustrates, the rate of decrease is much faster in areas with higher initial sucker density compared to an area with low initial density. An area with ≈80,000 suckers $ha^{-1}$ after the first year (similar to high regeneration in Duck Mountain) decreased to

≈40,000 suckers ha$^{-1}$ by the fifth year, while an area starting with only ≈45,000 suckers ha$^{-1}$ after one year (similar to low regeneration in Duck Mountain) decreased to ≈37,000 suckers ha$^{-1}$ by the fifth year (Steneker, 1976). Therefore, higher skidder traffic areas may have a lower initial regeneration level, but as suckers mature and competition begins to reduce sucker density, these areas will likely not decrease at the same rate and over time reach a stocking density similar to each other and the rest of the harvested block.

Accurately assessing any changes in aspen regeneration levels using multispectral remote sensing techniques similar to those used in an agricultural setting were not successful. By simply extracting an average index value for each of our monitoring plots, we were unable to obtain a strong relationship with the level of aspen regeneration (density, height, RCD, LAI, dry leaf biomass, total N, and total P). This lack of relationship is most likely caused by the presence of other vegetation within the monitoring plot. High levels of beaked hazelnut (*Corylus cornuta*), mountain maple (*Acer spicatum*), and other shrubs that were present within the monitoring plots created background noise that overshadowed the amount of aspen and made it impossible to predict changes in the level of aspen regeneration. The best example of this phenomenon occurred in areas where little to no aspen regeneration was recorded. Though no aspen were present, the indices values for these areas were often quite elevated due to the presence of the other vegetation and as a result, no relationships between vegetation indices and aspen regeneration were observed. Therefore, using whole plot multispectral data to assess the regenerative growth and health of aspen forest is not as successful and accurate compared to when it is used in a monoculture agriculture setting (Barnes et al., 2000; Henik, 2012; Van Der Meij et al., 2017). However, in this multi-species setting, additional image analysis processes may be able to increase the accuracy and usability of multispectral data to assess the level of aspen regeneration. Using multitemporal multispectral imagery, a supervised image analysis or object based image analysis could be used to discriminate aspen from the different shrub species (Lisein et al., 2015; Torresan et al., 2017). This would allow for the assessment of aspen regeneration by itself and could be used to determine areas with insufficient regeneration.

## 3.7 Conclusion

Soil bulk density at a 10 cm depth increased significantly with as little as 1-5 skidder passes compared to the unharvested control in the year following the winter harvest of aspen forests in Duck Mountain Provincial Park; however, after the initial increase it remained relatively constant as the number of skidder passes increased. The highest average bulk density was 1.41 g cm$^{-3}$ (26-50 passes), which is below the growth limiting bulk density for the sandy clay loam to clay loam texture of the soil. Following regression analysis, it does not appear that the increase in bulk density is responsible for the decrease in aspen density and height recorded in higher skidder traffic areas, as there was no relationship between bulk density and regeneration. Although not directly measured, the decreased level of aspen regeneration in areas of higher skidder traffic is likely the result of increased damage to the aspen rooting system within the forest floor. While, sucker density dropped over 50% under areas with high skidder traffic, there was still a moderate level of regeneration (47,000 suckers ha$^{-1}$) one year after harvest. Due to competition, sucker density will decrease over the first decade; however, the rate at which mortality occurs is largely dependent on the initial density and as a result, sucker density across skidder traffic intensity levels will likely equalize during this time. In terms of assessing the level of aspen regeneration using UAV based multispectral remote sensing, no strong relationship between vegetation indices and regeneration could be found. This fact was likely due to the interference or background noise from the other vegetation that was present within monitoring plots. In future studies when dealing with a multi-species system, additional image analysis to discriminate between species may prove beneficial in order to assess the level of aspen regeneration.

In terms of harvesting operations and management practices, these findings would suggest that winter harvesting was a feasible solution to stimulate aspen regeneration without causing severe damage to the majority of the harvested block at this site. Visually, landings and skidder trails were identified as areas of potential concern as these areas experienced the most disturbance and had lower regeneration levels compared to areas with minimal disturbance. Winter harvesting appears to have limited the increase in soil bulk density to a level that is below the root growth limiting thresholds stated in the literature. Based on literature, a degree of soil de-compaction should also occur within the first five years post-harvest and therefore, the slight increase in bulk density should not result in decreased aspen regeneration as the forest matures. In order to maximize aspen regeneration across the entire harvested block, our finding would suggest trying to minimize the amount of landings and skidder trails present throughout a harvested block, as these areas were associated with the highest amount of skidder traffic and expressed a lower level of regeneration compared to the surrounding areas.

# 4 RESIDUAL SLASH COVERAGE EFFECTS ON ASPEN REGENERATION AND VEGETATION INDICES[2]

## 4.1 Preface

As a means to supply nutrients to the regenerating forest, residual slash (non-merchantable timber/woody debris) is often left and spread across the harvested block; however, improper distribution of slash can lead to a decrease in the level and success of aspen regeneration. Currently, slash loading intensity is determined manually through a time consuming and tedious process, only to obtain information for a very small area within the much larger harvested block. This chapter examines the potential of using unoccupied aerial vehicles (UAV) obtained imagery and image analysis software as a method for mapping slash coverage across entire harvested blocks.

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[2] This chapter, co-authored with Dr. Ken Van Rees, has been submitted for publication to Journal of Unmanned Vehicle Systems. Data collection, data analysis, and initial writing of the manuscript were completed by the lead author (Landon Lee Sealey), while editing and review of the manuscript was done by the co-author.

## 4.2 Abstract

Proper redistribution of residual slash following harvesting events is crucial for ensuring successful regeneration and continued health in trembling aspen (*Populus tremuloides*) forests. While traditional methods of measuring residual slash loading are a strenuous and tedious process, the objective of this study was to develop a new, faster and more detailed method to assess residual slash distribution for entire harvested blocks. In addition, this study also aimed to assess the influence that residual slash coverage had on the success of aspen regeneration one year after winter harvesting. Using high resolution UAV imagery, maximum likelihood supervised image classification, and confusion matrix analysis, residual slash was differentiated from the underlying forest floor. Overall, classification accuracy ranged between 85 and 96 % with the highest accuracy occurring when aerial imagery was collected at the beginning of the second spring following winter harvesting. The lower overall accuracy for sites with aerial imagery collected during the first spring following winter harvesting was the result of misclassified slash pixels due to their similarity to the forest floor, which caused the producer and user accuracy for these sites to be much lower. Slash distribution was quite consistent across harvested blocks, with 92 % of harvested blocks experiencing less than 33 % coverage. There was no relationship between the level of aspen regeneration following one year of growth and % slash coverage up to 60 %. No vegetation plots occurred in areas with > 60% slash coverage and therefore it is unknown whether aspen regeneration will be affected in areas with higher slash coverage.

## 4.3 Introduction

Tree length harvesting is a common forestry practice throughout much of western Canada. This harvesting practice involves felling the trees then consolidating them near a road where branches and treetops are delimbed from the rest of the trunk. These treetops, branches, and non-merchantable timber, also referred to as slash, are then scattered back across the harvested block area, piled and burnt, or a combination of both as stated in the standards and guidelines legislation (Government of Saskatchewan, 2011). Priority is placed on spreading the slash back into the harvested block as it is an important nutrient source for the growth of regenerating forests; however, the amount of slash being returned must be carefully managed. High amounts of slash loading can act as an insulative barrier to the soil surface, as well as act as a physical barrier that impedes aspen suckering (Steneker, 1976; Bella, 1986; Frey et al., 2003; Lieffers-Pritchard, 2004); therefore, caution is required by forest operators to ensure that this slash is evenly distributed across the harvested block. In addition to the several other factors needed to stimulate aspen suckering, a soil temperature of approximately 15 °C is required before the suckering process is initiated (Maini and Horton, 1966; Navratil, 1991). Thus, increasing levels of slash cover on the soil surface can decrease the level of solar radiation at the soil surface, resulting in a delayed spring thaw warm-up, a lower average soil temperature, and a decrease in aspen suckering (Steneker, 1976; Schier et al., 1985; Lieffers-Pritchard, 2004).

Several methods have been developed to estimate the level of slash loading, downed coarse woody debris, or slash fuel loading in a forest environment (Newman, 1966; McRae et al., 1979; Brown et al., 1982). These mathematical based methods are derived from the line-intercept theory (Newman, 1966), which assumes that the longer an object (piece of slash), the more times that object will cross a series of straight vertical and horizontal lines. To calculate slash loading (kg $m^{-2}$) from the Newman method, each piece of slash within a sampling area is categorized into a diameter class and then multiplied by a multiplication factor; calculated from the mass, length, and diameter of pre-examined pieces. Unfortunately, these methods are very time consuming and labor intensive making it difficult to assess the level of slash loading for an entire harvested block. However, with the continued development of unoccupied aerial vehicles (UAVs) and Geographical Information Systems (GIS) technology, is it possible to develop faster and a more efficient method for measuring the amount of slash left throughout the harvested blocks? Inoue et al. (2014) demonstrated that high resolution UAV imagery can be used to manually map fallen trees in a deciduous forest; but, rather than relying on manual image interpretation, computer based image classification could provide a faster more detailed analysis of slash loading across an entire harvested block. The main difference between a traditional slash loading method and a GIS based analysis of slash will be the unit of measure. Traditional measure of slash loading are calculated as kg $m^{-2}$ while a GIS based analysis of slash will be calculated as percent coverage.

The following chapter examines the feasibility of using UAV and GIS technology as a new method for estimating the level of slash loading across a harvested block.

The objectives for this study were:

1. To develop a method to estimate the level of slash coverage (%) in harvested areas using aerial imaging, remote sensing, and image processing.
2. Assess the effects of the percent slash coverage calculated in objective 1 on the level of aspen regeneration (sucker density, height, root collar diameter (RCD), leaf area index (LAI)).

Null hypothesis for this study was:

1. In winter harvested blocks, increasing the percent slash coverage over an area does not significantly lower sucker density, height, RCD or LAI of regenerating aspen after one summer of growth.

## 4.4 Materials and Methods

### 4.4.1 Study Area

The harvested blocks used for this study were located in the Northwest corner of Duck Mountain Provincial Park (described in Chapter 3, section 3.2.1). Regeneration assessment data for this study was collected across all six harvested block, while multispectral data was only obtained from blocks A, B, and C.

### 4.4.2 Data Collection and Image Analysis

#### 4.4.2.1 UAV Imagery Collection and Image Processing

For this study, a DJI Phantom 4 (Dà-Jiãng Innovations Science and Technology Co. Ltd., Shenzhen, Guangdong Province, China) UAV was used to capture high resolution RED-GREEN-BLUE (RGB) imagery of the harvested blocks. Images were captured in the spring (May) immediately following winter harvest once all the snow had melted, but before any vegetation began to regenerate in the harvest block. This timing allowed for an unobstructed view of the slash that was left behind following the winter harvest operation. Due to technical issues, we were unable to capture images of slash for blocks 1, 2, and 3 in the spring immediately following the winter harvesting of 2015-2016. However, images for blocks 1, 2, and 3 were collected at the beginning of the second growing season (May 2017) along with blocks A, B, and C.

Drone Deploy (DroneDeploy, San Francisco, CA, USA) was used to plan and control all flights to ensure that flight parameters (i.e. altitude, speed, overlap) were consistent between each flight. All flights were flown between 10:00 am and 2:00 pm to reduce the effect of shadow. Flight elevation was set to 60 m above ground level (AGL), which gave a spatial resolution of approximately 1.8 cm pixel$^{-1}$ for the RGB imagery. Image capturing was set to have approximately 75 % overlap side to side and 60 % overlap front to back. After the flights, all images were uploaded to Pix4D (Pix4D SA, Lausanna, Vaud, Switzerland) where they were stitched to create an orthomosaic of each harvested block. These orthomosaic images were then imported into ArcMap (version 10.3.1, Environmental Systems Research Institute, Redlands, CA, USA) where a geo-correction was performed using ground reference points that had been taken prior to flights using a Trimble GeoXT 2005 series GPS (Trimble Inc., Sunnyvale , CA, USA).

#### 4.4.2.2 Image Analysis and Calculation of Percent Slash Cover

A detailed flowchart of the method developed for the calculation of percent slash cover and the ArcGIS tools and processes can be found Fig. 4-1. First, the orthomosaic for each harvested block underwent a maximum likelihood supervised image classification (Franklin et al., 1994). During this analysis, each pixel within the image was classified as either slash or forest floor based on how spectrally similar it was to one of the two cover types. Spectral properties for the two cover types were determined prior to the classification using a series of training polygons place over areas with a known cover type. Once classified, an imaginary grid with a cell resolution of 0.87 m x 0.87 m, based on the cell resolution for traffic intensity, was placed over top of the classified image and the number of slash pixels and number of forest floor pixels within each cell was determined. This information was used to calculate % slash coverage for the entire harvested block. Lastly, using the slash loading visual guide developed by Lieffers-Pritchard (2004) as a base, we categorized percent slash coverage into three slash loading levels: low (0-33%), moderate (33-66%) and high (66-99%) to assess slash distribution across the harvested block.

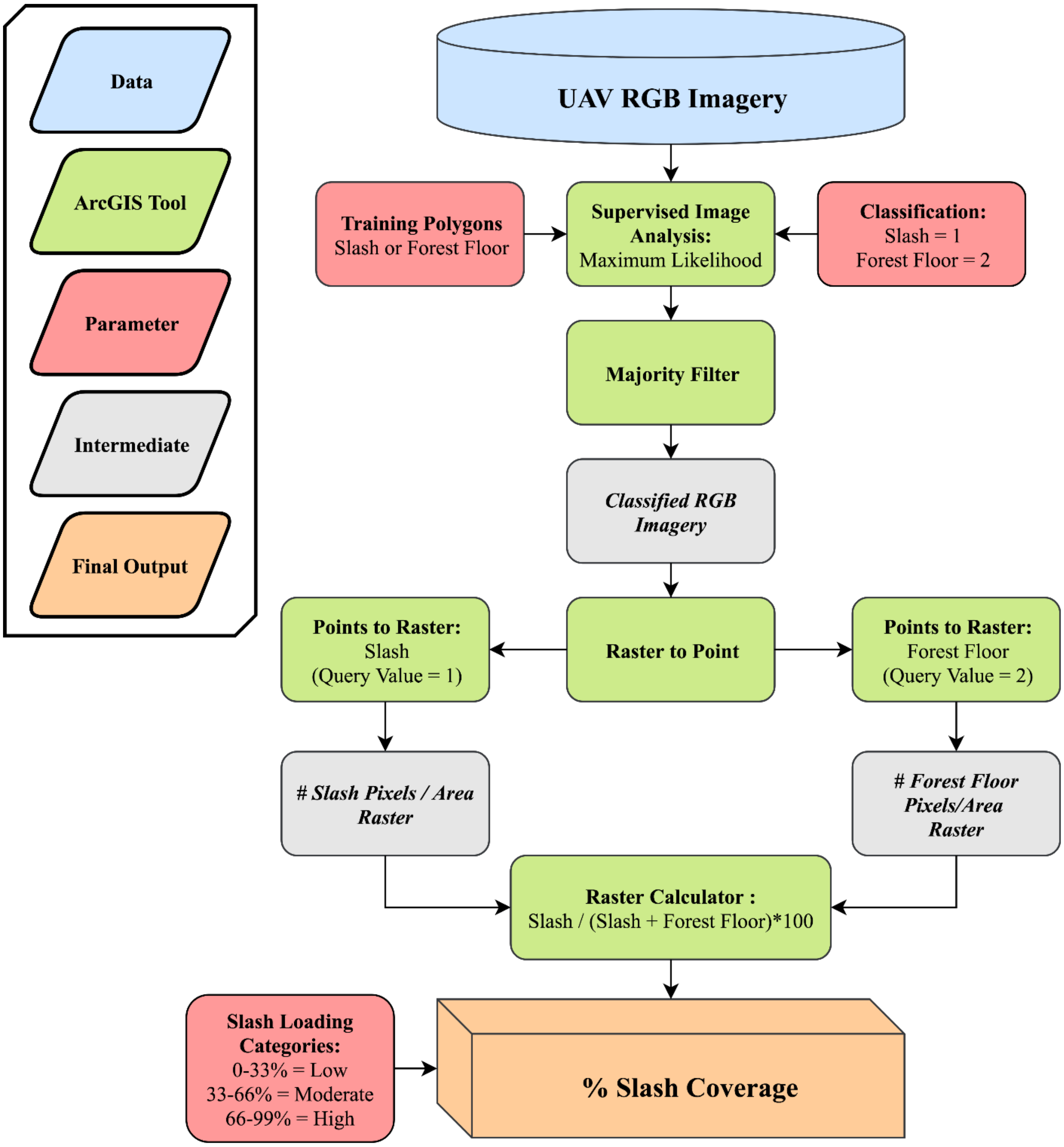

**Fig. 4-1:** Detailed flowchart outlining ArcGIS tools and processes used for the classification and calculation of % slash cover across harvested blocks

### 4.4.3 Aspen Regeneration Measurements:

The aspen regeneration data collected in Chapter 3 was used to examine the relationship between the level of slash coverage and aspen regeneration. Vegetation data from all six harvested blocks were used for this analysis. Refer to Chapter 3, section 3.2.4 for details on how the aspen regeneration measurements were collected.

### 4.4.4 Statistical Analysis

#### 4.4.4.1 Slash Classification Accuracy Assessment

To assess the accuracy of the maximum likelihood supervised image analysis, a confusion matrix (error matrix) was constructed using 50 ground truthing points for both slash and forest floor (Cohen, 1960; Congalton, 1991). A confusion matrix examined the number of pixels that were classified to a category in relation to the category that they were assigned based on ground-truth identification. This matrix was used to calculate several measures of classification accuracy (Table 4-1).

**Table 4-1:** Example of the confusion matrix used for the assessment of slash classification accuracy and the equations used for the calculation of classification accuracy (Congalton, 1991).

| | | **Ground Truth** | | |
|---|---|---|---|---|
| | | Slash | Forest Floor | Total |
| **Classified** | Slash | A | B | C |
| | Forest Floor | D | E | F |
| | Total | G | H | I |

| **Accuracy** | **Equation** |
|---|---|
| Overall | (A+E)/I |
| Producer (Omission) | A/G or E/H |
| User (Comission) | A/C or E/F |
| Expected | ((C*G)/I) + ((F*H)/I)/I/100 |
| Kappa Coefficient | (Overall-Expected)/(1-Expected) |

#### 4.4.4.2 Slash Coverage and Aspen Regeneration

All statistical analysis for this study were conducted using SAS (version 9.4, SAS Institute Inc., Cary, NC, USA). To examine the relationship between percent slash coverage and the level of aspen regeneration (density, height, RCD), simple linear regression analysis was performed using PROC REG procedure. For this analysis, aspen height and RCD were recorded as zero if the assessment plots contained no aspen. Before analysis, the dataset was examined for possible outliers using studentized residuals. Data points with studentized residuals greater than or equal to 2 were removed from the dataset. Following regression analysis, residual normality was checked using PROC UNIVARIATE procedure and the Shapiro-Wilk test. If residuals were not normally distributed ($p<0.05$), the data was transformed and re-run until normality was achieved.

## 4.5 Results

### 4.5.1 Slash Classification and Distribution

Aspen slash was easily distinguishable from the forest floor due to its lighter whitish bark (Fig. 4-2). As a result, a maximum likelihood supervised image classification was able to identify which pixels were slash and which were forest floor (Fig. 4-3); however, slight errors in the classification process reduced the accuracy of the method. Aspen bark is not a solid whitish colour and as a result, several individual pixels along a piece of slash were misclassified as forest floor. A similar phenomenon occurred when classifying the forest floor, as small randomly scattered wood chips were classified as slash and caused a salt and pepper effect across the forest floor. To reduce the severity and influence of these errors on percent slash calculation, a majority filter was used to smooth the image and eliminate individual pixels that were classified differently from the majority of the four orthogonal neighboring pixels. Once converted into a percent slash coverage value (Fig. 4-4), the majority of this example area illustrates having less than 66% slash coverage with only a few isolated areas with over 66% slash coverage (See Appendix E for a complete set of slash classification maps for all harvested blocks).

The percent slash distribution, calculated using this methodology, for all the harvested blocks is presented in Table 4-2. On average, 92% of a harvested block's area was classified as having less than 33% slash coverage, while areas with 33-66% coverage and 66-99% coverage made up approximately 7 and 0.4% of a harvested block's area, respectively.

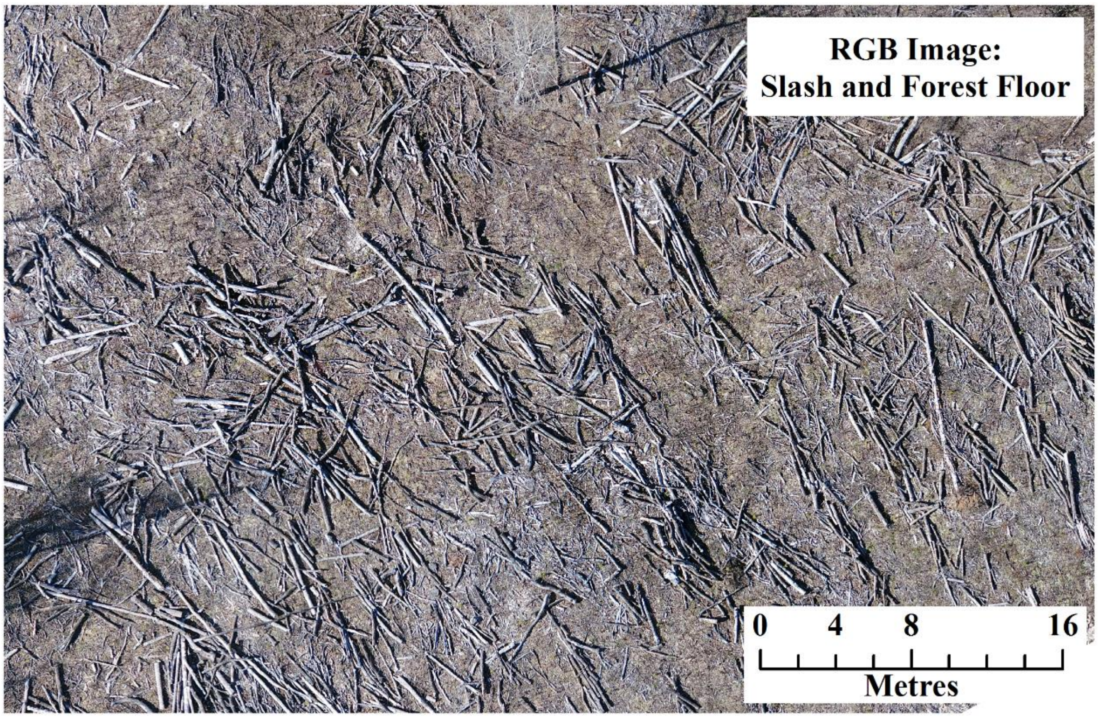

**Fig. 4-2:** RGB image of slash coverage from a portion of harvested block 2 showing visibility of slash in contrast to the forest floor.

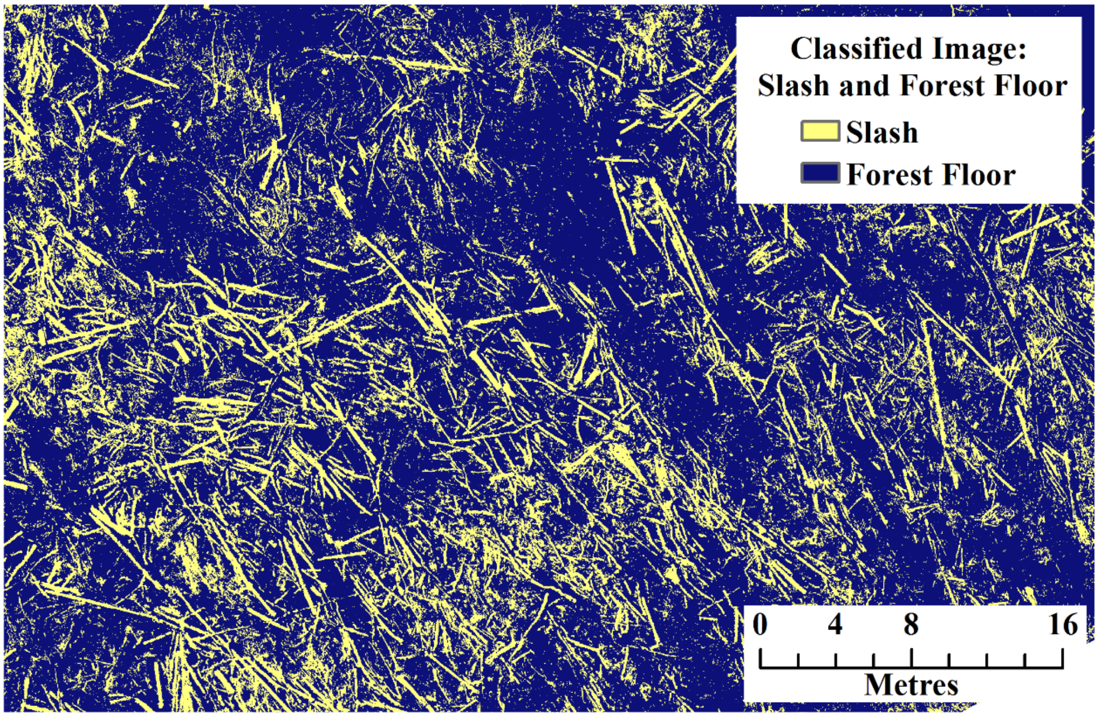

**Fig. 4-3:** Output of maximum likelihood supervised image classification analysis on RGB image shown in Fig.4-2

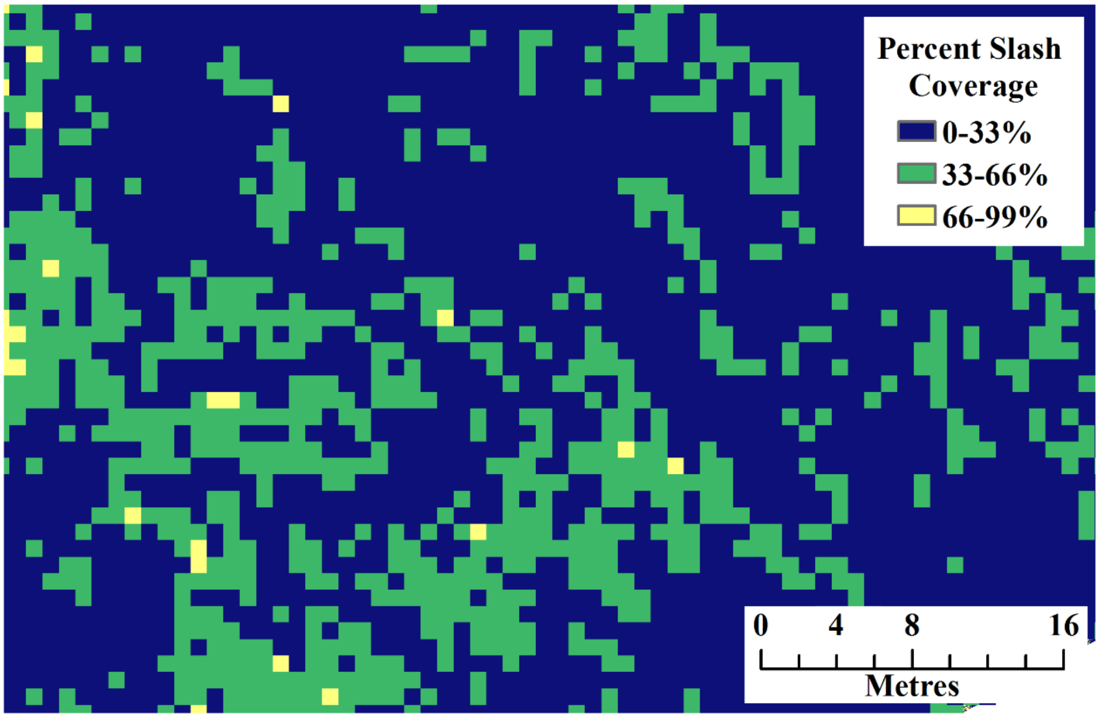

**Fig. 4-4:** The % slash coverage output based on the classified slash displayed in Fig 4-3.

**Table 4-2**: The percent slash coverage distribution for each harvested block.

| | Year of Harvest | | | | | | |
|---|---|---|---|---|---|---|---|
| | 2015-2016 | | | 2016-2017 | | | |
| | Block 1 | Block 2 | Block 3 | Block A | Block B | Block C | Mean |
| Slash Coverage | % of the Harvested Block | | | | | | |
| 0-33% | 92.07 | 92.85 | 84.13 | 92.50 | 95.06 | 97.76 | 92.40 ± 4.17 |
| 33-66% | 7.57 | 6.99 | 13.95 | 7.35 | 4.76 | 2.15 | 7.13 ± 3.59 |
| 66-99% | 0.36 | 0.17 | 1.91 | 0.15 | 0.18 | 0.09 | 0.48 ± 0.65 |

### 4.5.2 Slash Classification Confusion Matrix

The accuracy of using supervised image analysis to assess the level of slash loading across harvested blocks was overall quite good, with the lowest overall accuracy being 85% (Table 4-3 and Table 4-4). Overall, classification accuracy was higher in harvested blocks 1, 2, and 3 compared to harvested blocks A, B, and C. Producer and user accuracy for harvested blocks 1, 2 and 3 were both consistently higher than 90%, indicating a high portion of the ground truthing pixels for both slash and forest were classified correctly. A couple pixels of slash and forest floor were misclassified; however, there was not one cover type being misclassified more than the other.

Conversely, the producer and user accuracy for harvested blocks A, B, and C were far more variable. The producer accuracy for forest floor pixels remained near perfect, indicating that the ground truthing pixels of forest floor were rarely misclassified as slash. However, the producer accuracy for slash was between 72% and 82% due to several slash ground truthing pixels being misclassified for forest floor. These misclassifications of slash for forest floor lowered the user accuracy of forest floor (78-84%) because of the higher degree of uncertainty as to whether a pixel labeled forest floor was actually forest floor.  Due to these misclassifications, the overall accuracy of classification for harvested blocks A, B, and C was between 82 and 90%.

**Table 4-3:** Confusion matrix and accuracy results for harvested blocks 1, 2, and 3.

| **Site 1** | Slash | Forest Floor | Total | User Accuracy |
|---|---|---|---|---|
| Slash | 46 | 1 | 47 | 98% |
| Forest Floor | 4 | 49 | 53 | 92% |
| Total | 50 | 50 | 100 | |
| Producer Accuracy | 92% | 98% | | |
| Overall Accuracy = 95%  Expected Accuracy = 50%  Kappa = 90% | | | | |

| **Site 2** | Slash | Forest Floor | Total | User Accuracy |
|---|---|---|---|---|
| Slash | 48 | 2 | 50 | 96% |
| Forest Floor | 2 | 48 | 50 | 96% |
| Total | 50 | 50 | 100 | |
| Producer Accuracy | 96% | 96% | | |
| Overall Accuracy = 96%  Expected Accuracy = 50%  Kappa = 92% | | | | |

| **Site 3** | Slash | Forest Floor | Total | User Accuracy |
|---|---|---|---|---|
| Slash | 45 | 5 | 50 | 90% |
| Forest Floor | 5 | 45 | 50 | 90% |
| Total | 50 | 50 | 100 | |
| Producer Accuracy | 90% | 90% | | |
| Overall Accuracy = 90%  Expected Accuracy = 50%  Kappa = 80% | | | | |

**Table 4-4:** Confusion matrix and accuracy results for harvested blocks A,B, and C.

| **Site A** | Slash | Forest Floor | Total | User Accuracy |
|---|---|---|---|---|
| Slash | 36 | 1 | 37 | 97% |
| Forest Floor | 14 | 49 | 63 | 78% |
| Total | 50 | 50 | 100 | |
| Producer Accuracy | 72% | 98% | | |
| Overall Accuracy = 85% Expected Accuracy = 50% Kappa = 70% | | | | |
| **Site B** | Slash | Forest Floor | Total | User Accuracy |
| Slash | 41 | 1 | 42 | 98% |
| Forest Floor | 9 | 49 | 58 | 84% |
| Total | 50 | 50 | 100 | |
| Producer Accuracy | 82% | 98% | | |
| Overall Accuracy = 90% Expected Accuracy = 50% Kappa = 80% | | | | |
| **Site C** | Slash | Forest Floor | Total | User Accuracy |
| Slash | 36 | 0 | 36 | 100% |
| Forest Floor | 14 | 50 | 64 | 78% |
| Total | 50 | 50 | 100 | |
| Producer Accuracy | 72% | 100% | | |
| Overall Accuracy = 86% Expected Accuracy = 50% Kappa = 72% | | | | |

### 4.5.3 Percent Slash Cover and Aspen Regeneration

The estimated percent slash coverage calculated using the maximum likelihood supervised image analysis method showed no relationship with the plot data of aspen regeneration collected in Chapter 3 (Fig. 4-5). Aspen sucker density, height, or RCD did not show a significant linear relationship with increasing slash coverage up to 60%. There also does not appear to be any other form of relationship between the level of slash coverage and aspen regeneration.

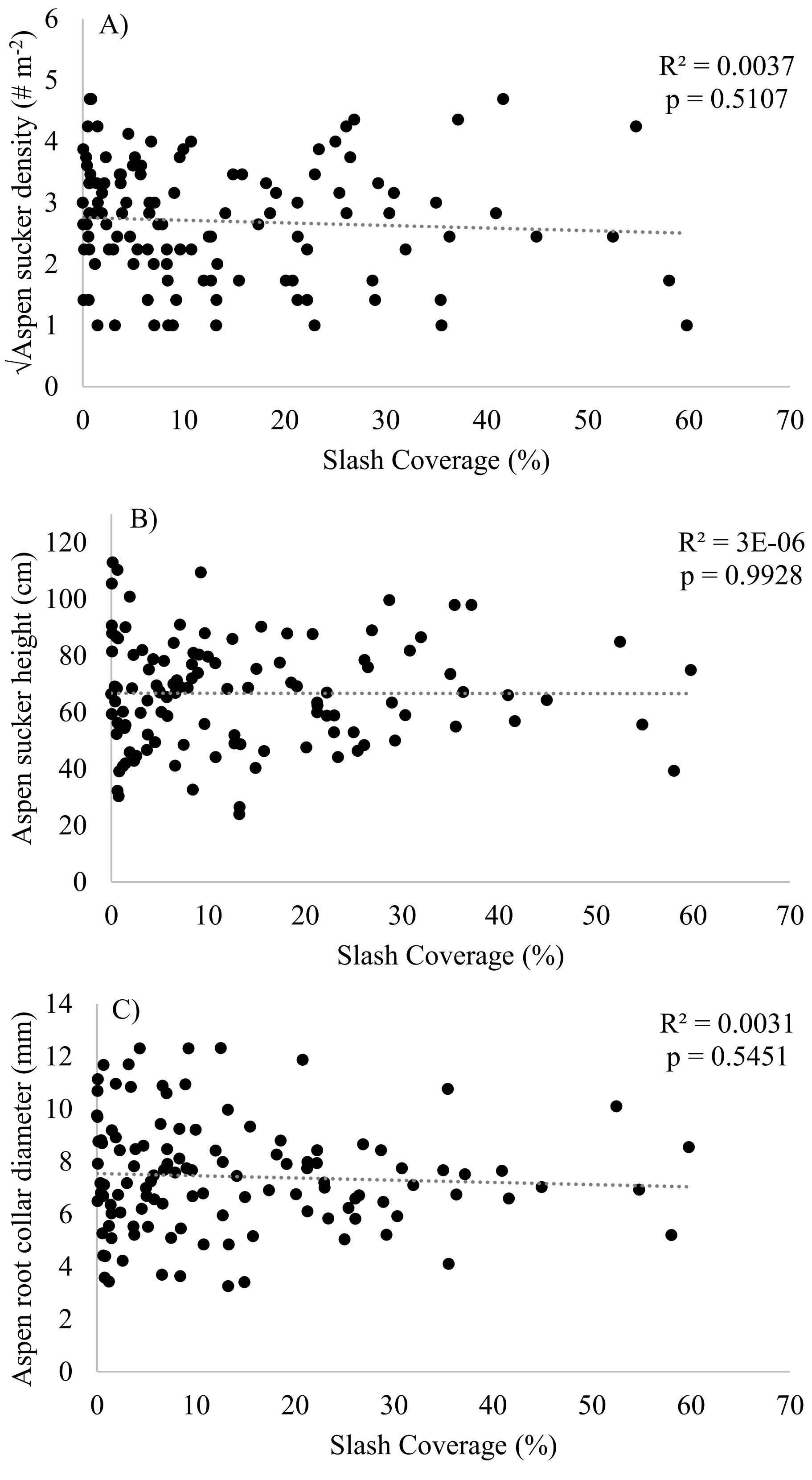

**Fig. 4-5:** Relationship between percent slash coverage and aspen sucker A) density, B) height, C) root collar diameter.

## 4.6 Discussion

As evident through visual examination of the aerial RGB imagery, it is clear that the level and distribution of slash coverage is quite consistent across entire harvested blocks. The vast majority (92%) of a harvested block was covered under low slash levels (0-33%), while only 7% and <1% was covered under a moderate (33-66%) and high (66-99%) slash level, respectively. Therefore, if the effects of heavy slash described in literature (Bella, 1986; Lieffers-Pritchard, 2004; Renkeman, 2009) do have a negative effect on the level of aspen regeneration in the Duck Mountain Provincial Park, the amount of area that would experience a decrease in the level of aspen regeneration and future growth is likely minimal. Areas with moderate or high levels of slash coverage were often associated with landing zones where a portion of treetops, branches, and sawdust would be left following on site processing of the trees. However, a reason why more areas with excess amounts of slash were not prevalent throughout the harvested blocks may be attributed to the presence of slash piles. These slash piles consisted mainly of large tree pieces that were deemed unusable by the operator and rather than spread this material back across the harvested area, it was simply amalgamated into large piles and burnt once dry.

While the practice of slash piling does reduce the amount of slash that would otherwise be scattered throughout the harvested block, these piles create an environment under which conditions are not suitable for aspen regeneration. While the remainder of the harvested block begins to regenerate following the harvesting event, aspen roots underneath these large slash piles will exhaust their carbohydrate reserves in the attempt to produce suckers and eventually will die as no new energy supplies are being returned to the rooting system (Peterson and Peterson, 1992; DesRochers, 2000). Following the burning of the slash pile, it is unlikely that the rooting system will be capable of producing suckers to regenerate this area and will therefore need to rely on seeds to blow in from the surrounding forest in order to regenerate. However, it is unlikely that seedlings will germinate and survive in these burnt slash pile areas due to the harsh growing conditions. A recent study by Rhoades and Fornwalt (2015) found that in lodgepole pine forests, the effects of slash pile burning on regeneration density and soil properties were still evident even after 50 years. Unfortunately, no literature could be found looking at the effects of slash pile burning on the regeneration of aspen.

In terms of aspen regeneration in relation to the level of slash loading, we found that slash coverage up to 66% had no discernable effect of the aspen sucker density, height, or root collar diameter. This would suggest that even in areas with up to 66% coverage, soils were able to obtain a sufficient temperature to stimulate suckering and that slash at this level did not act as a physical barrier to these newly developed suckers. Unfortunately, none of our aspen regeneration plots were located in areas with high levels of slash cover (>66%); therefore, we were unable to obtain a full understanding of how percent slash coverage influenced regeneration in the Duck Mountain Provincial Park and whether high slash coverage would lead to significant changes in the level of aspen regeneration. Based on previous research by Bella (1986) and Lieffers-Pritchard (2004), we expected to see a decrease in aspen sucker density as the level of slash coverage increased. The study by Lieffers-Pritchard (2004) in the Duck Mountains found that aspen sucker density was significantly reduced under moderate slash loading (200-400 t ha$^{-1}$ or 20-60% coverage), while aspen sucker height or root collar diameter were unaffected. The reason our study failed to see a strong relationship between percent slash coverage and aspen regeneration may be the result of the different methods used. While our study measured the level of slash coverage based on aerial imagery, Lieffers-Pritchard (2004) manually measured slash loading using a modified line-intercept method (Newman, 1966).

Our method developed using UAV based RGB imagery measured slash coverage in a two dimensional framework (length and diameter), while traditional field methods for assessing slash loading (Newman, 1966; McRae et al., 1979; Brown et al., 1982) incorporate a third dimension, depth of slash. Although our method is capable of detecting slash lying across the forest floor to create a % coverage estimate, it does not take into consideration slash depth which drastically alters the level of insulation to the soil. For example, an area with a layer of slash covering the soil would not have the same level of insulation compared to an area with three or four layers of slash; however, by only measuring the % coverage, these two areas would be considered equal in terms of the level of slash loading. Therefore, in future studies looking at using UAV based imagery as a method to measure the level of slash loading, it would be advised to incorporate a measure of slash depth to increase the quality of the method.

The presence of sawdust and wood chips from the harvesting operation also made it difficult to get an accurate measure of slash coverage. Due to their bright reflectance, they were often classified as slash and would occur in small clusters of a couple pixels. This created a salt and pepper effect across parts of the forest floor and amplified % slash coverage estimates in certain areas. To address this issue, raster filters were used to smooth the classified image by removing isolated pixels (anomalies) based on the surrounding pixels in the immediate area; however, some areas still contained isolated clusters of sawdust and wood chips. Again, this issue could be aided by incorporating a measure of slash depth as sawdust and wood chips would not be large enough to classify as slash.

The type of forest may also have an influence on the success and accuracy of slash loading estimates made through UAV imagery. The high spectral contrast between aspen and the forest floor made it easy to distinguish between the two covers; however, in a mixed wood or coniferous forest this spectral difference may not be as prevalent. Coniferous species such as spruce (*Picea* spp) and jack pine (*Pinus banksiana*) have a much darker bark, which could make it more difficult for simple colour spectral analysis to detect differences from the forest floor. Future studies could look into the use of an object based image analysis (Blaschke, 2010), rather than simply relying on the spectral differences between land covers to classify the image as it is a more detailed and complex method of classification.

## 4.7 Conclusion

This study illustrated that UAV based RGB imagery could be used to map and measure the distribution of slash left throughout a block following a harvesting event. Although simple maximum likelihood supervised image analysis was capable of accurately discriminating between aspen slash and forest floor, additional research is still needed to improve this method. A method that incorporates slash depth would improve the accuracy of UAV-based slash loading measurements and would make it more comparable to the traditional manual field methods. More detailed and advanced methods of image classification such as object based image analysis could be done in an attempt to better detect pieces of slash rather than simply relying on their spectral signature. In terms of the effects of % slash coverage on aspen regeneration, no significant relationship was observed between any of the aspen measurements (density, height, RCD) and slash coverage. However, it should be noted that our analysis only contained areas with slash coverage up to 60%; therefore, it is unknown whether higher levels of slash loading would result in a decrease of aspen regeneration.

# 5 A CUMULATIVE EFFECTS APPROACH TO ASSESSING ASPEN REGENERATION SUCCESS THROUGH FUZZY LOGIC DERIVED SUITABILITY MAPPING[3]

## 5.1 Preface

Following a harvesting event, aspen regeneration is not controlled by one single factor; however, no studies could be found that assessed cumulative effects at a landscape scale. With the advances in unoccupied aerial vehicle (UAV), remote sensing, and geographic information system (GIS) technology, landscape scale data can now be obtained in an efficient and cost effective manner. This chapter describes the creation of the fuzzy logic suitability mapping method that was used to assess cumulative effects across entire harvested blocks. In addition, this chapter assesses how regeneration varied across suitability levels and attempts to understand which factors were most influential in determining the success of aspen regeneration.

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[3] This chapter, co-authored with Dr. Beyhan Amichev and Dr. Ken Van Rees, has been submitted to Soil Science Society of America Journal. Data collection, data analyses, and initial writing of the manuscript were completed by the lead author (Landon Lee Sealey) while the fuzzy logic method was developed by Dr. Beyhan Amichev. Editing and review of the manuscript was done by the co-authors.

## 5.2 Abstract

Vigorous aspen (*Populus tremuloides*) regeneration immediately following a harvesting event is important to ensuring the continued health and productivity of the future forest. This study aimed to examine the potential of using unoccupied aerial vehicle, multispectral remote sensing, and GIS mapping techniques to develop a comprehensive approach for predicting aspen regeneration success at the harvest block scale. Three winter harvested blocks were studied at Duck Mountain Provincial Park in east-central Saskatchewan, Canada. Ten regeneration predictor variables (number of skidder passes, percent slash coverage, topographic wetness index, slope, aspect, slope position, and four vegetation indices: green normalized vegetation index (GNDVI), normalized red-edge index (NDRE), simple RED/NIR ratio (SR), and chlorophyll index green (CIG)) were determined for 168 measurement plots one year after harvest. Principal component analysis, principal component regression, fuzzy logic analysis, and GIS mapping techniques, were combined for the first time in this study to determine cumulative effects on aspen regeneration. On average, low suitability areas had significantly more skidder traffic (34 passes) compared to below-average (17), above-average (10), and high (7) suitability areas. Low suitability areas also had significantly more slash coverage (13.1%) compared to below-average (8.49%) or high suitability land (7.18%). High suitability areas had significantly higher GNDVI, NDRE, SR, and CIG indices, compared to low and below-average suitability land. Not only does this method of analysis help to assess how a combination of factors may influence aspen regeneration, it can also act as a decision support system tool for industry, or government, to improve aspen regeneration assessments.

## 5.3 Introduction

Following a disturbance event in an aspen forest, vigorous aspen regeneration in the first two years is important to ensuring the continued health and productivity of the future forest. It is well documented that several naturally occurring factors such as clonal ability to sucker, soil temperature, root carbohydrate reserve, and hormonal/chemical imbalances are the driving forces behind the level and success of asexual regeneration in an aspen forest (Maini and Horton, 1966; Schier et al., 1985; Fraser et al., 2002; Frey et al., 2003; Mundell et al., 2008). However, mechanical harvesting events can also influence aspen regeneration through the alteration of soil physical properties (bulk density, aeration, water movement, etc.), soil temperature regime, and disturbance of the shallow rooting system of aspen found in the forest floor that is responsible for the majority of regeneration (Lieffers-Pritchard, 2004; Zenner et al., 2007; Puettmann et al., 2008; Renkema et al., 2009). While these studies are important for establishing our understanding of how these individual factors influence aspen regeneration, they often fail to emulate the natural environment in which several of these factors are acting together to govern the level and success of aspen regeneration.

Mechanical harvesting was shown an effective method for stimulating the regeneration of over-mature aspen forests (Navratil, 1991; Peterson and Peterson, 1992), whereas improper harvesting methods have caused negative effects to site/soil properties and, as a result, reduced regeneration levels (Bates et al., 1993; Lieffers-Pritchard, 2004; Renkeman, 2009). However, most of the studies examining the level of aspen regeneration following harvesting were done at a small scale and fail to consider the significance of the effects at the harvested block scale. In addition, most of these studies only focus on one or two factors and fail to assess the potential of cumulative effects between natural and anthropogenic sources. The lack of past research looking at regeneration levels at a harvest block scale, accounting for the combination of natural and anthropogenic factors, is likely due to the lack of harvest block scale data and methods to analyze said data. However, developing unoccupied aerial vehicles (UAVs), multispectral remote sensing, and geographic information systems (GIS) make the acquisition of useful harvested block scale data possible in both a time and cost effective manner.

The following chapter examines the potential of using UAVs, multispectral remote sensing, and GIS technology to develop a holistic approach for predicting aspen regeneration success across a landscape in relation to several natural and anthropogenic factors, and investigate which factor(s) is/are controlling the level of regeneration following a winter harvesting event. Additionally, using the PCA, PCR and fuzzy logic techniques, several regeneration predictors and influencing factors were amalgamated to generate an overall regeneration suitability map that could ultimately be used to predict the level and success of aspen regeneration at a landscape scale.

The objectives for this study were:

1. To develop a method to assess cumulative effects on aspen regeneration for a winter harvest block using fuzzy logic suitability mapping.
2. To determine which factors are responsible for controlling the level of aspen regeneration.
3. To examine aspen regeneration intensities for varying degrees of regeneration suitability calculated in objective 1.

Null hypotheses for this study were:

1. Increasing aspen regeneration suitability does not significantly increase a) sucker density, b) height, c) root collar diameter (RCD), d) leaf area index (LAI), and e) dry leaf biomass of regenerating aspen measured following one summer of growth after winter harvesting.
2. Skidder traffic intensity, % slash coverage, topographic wetness index (TWI), slope, aspect, slope position, Green Normalized Difference Vegetation Index (GDNVI),

Normalized Difference Red-Edge (NDRE), Simple RED/NIR Ratio (SR), and Chlorophyll Index Green (CIG) are not significantly different between aspen regeneration suitability levels.

## 5.4 Materials and Methods

### 5.4.1 Study Area

The harvested blocks used for this study were located in the Northwest corner of the Duck Mountain Provincial Park (described in Chapter 3, section 3.2.1). All data collected for suitability assessment was gathered from blocks A, B, C.

### 5.4.2 Suitability Predictor Variable Data Collection

#### 5.4.2.1 Skidder Traffic Intensity Calculation

A detailed description of how skidder traffic intensity was calculated can be found in Chapter 3, section 3.2.3.

#### 5.4.2.2 UAV Multispectral Remote Sensing and Indices Calculations

This study used a DJI Phantom 4 UAV (Dà-Jiãng Innovations Science and Technology Co. Ltd., Shenzhen, Guangdong Province, China) to capture red-green-blue (RGB) imagery of the harvested blocks, as well as to carry an additional multispectral sensor. The multispectral sensor was a Parrot Sequoia (Parrot SA, Paris, Îles-de-France, France), which captured GREEN, RED, RED-EDGE, and NIR (near-infrared) bands simultaneously. In May 2017, white circular ground control points were placed throughout the harvested blocks and their locations were recorded using a Trimble GeoXT 2005 series GPS unit (Trimble Inc., Sunnyvale, CA, USA). These control points were used for geo-correction of both RGB and multispectral imagery during the image processing stage.

Two flight events were conducted at each of the three harvested blocks during the summer months (May-August). The first flight event was conducted in early May, before any vegetation began to regenerate, to collect RGB imagery of the harvested blocks and overlying slash. From the RGB imagery, % slash coverage and distribution was calculated for each of the three harvested blocks. In addition, the data collected from these early summer flights was used to generate a digital terrain model (DTM) of the harvested blocks, which was then used to calculate different site characteristics and topographic wetness indices for the blocks. The second flight event occurred in mid-August near the end of the first growing season to capture multispectral imagery of the forest following one summer of growth. Based on the multispectral data, several vegetation indices (described in Chapter 2, section 2.5.2) were calculated as a measure of vegetation presence and health.

Drone Deploy (DroneDeploy, San Francisco, CA, USA) was used as the planning software to ensure that flight parameters would be consistent between each flight. Flights were conducted at 60 m above ground level between 10 am and 2 pm local time to reduce the effect of shadow and ensure proper stitching (i.e., combining of overlapping images) of the overall mosaicked image. Image overlap was set to approximately 75 % overlap side-to-side and 60 % overlap front-to-back.

#### 5.4.2.3 Percent Slash Coverage Calculation

A detailed description of how percent slash coverage was calculated can be found in Chapter 4 section 4.2.2.2.

#### 5.4.2.4 Slope, Aspect, and Slope Position Calculations

The slope and aspect of the harvested blocks was generated based on the Pix4D DTM derived from UAV imagery collected in May before any vegetation began to regenerate. Both slope and aspect were calculated with ArcGIS using the slope spatial analyst tool and aspect spatial analyst tool, respectively. A detailed description of how slope position was calculated can be found in Chapter 3, section 3.2.6.2.

#### 5.4.2.5 Topographic Wetness Index Calculation

A wetness index was developed for each of the harvested blocks because the level of moisture in the soil often has a major influence on not only the amount of plant growth but also the susceptibility of a soil to compaction (McNabb et al., 2001). Using the Pix4D digital terrain model derived from the UAV imagery, a topographic wetness index was generated using a series of functions developed for SAGA GIS (System for Automated Geoscientific Analyses, Hamburg, DE, Germany) (Conrad et al., 2015). First, the slope of the landscape was calculated from the DTM using the Slope, Aspect, Curvature tool. Next, the DTM was run through a fill sink algorithm (Wang and Liu, 2006) to smooth the DTM and remove anomalies before it was run through a multi-flow direction algorithm (Quinn et al., 1991) to calculate catchment area. From the catchment area output, a specific catchment area was derived using the Flow Width and Specific Catchment Area tool. Lastly, the specific catchment area and slope outputs were used together to generate a TWI index with the topographic wetness index tool (Moore et al., 1991; Kopecký and Čížková, 2010).

### 5.4.3 Aspen Regeneration Indicator Data Collection

As an indicator of regeneration, 1 x 1 m aspen regeneration assessment quadrats were used to measure aspen sucker density, height, RCD, LAI, and dry leaf biomass. In addition to the 72 assessment plots that were collected across blocks A, B, and C to assess the effects of machine traffic on regeneration (Chapter 3), another 96 assessment plots were randomly selected based on skidder intensity across the three harvested blocks. Sucker density was measured by counting the number of aspen suckers present within the 1 x 1 m quadrat. Sucker height (cm) and root collar diameter (mm) were measured using a measuring stick and digital calipers, respectively. Aspen

LAI (m $m^{-2}$) was determined by collecting all aspen leaves within the assessment plot and running them through a LI-COR LI3050A area meter (LI-COR Biosciences, Lincoln, NE, USA). Lastly, aspen leaves were oven-dried at 80 °C for 48 hours then weighed to obtain a measure of total oven-dry leaf biomass (g $m^{-2}$).

### 5.4.4 Fuzzy Logic Mapping of Aspen Regeneration Suitability

Fig. 5-1 is an illustration of the new fuzzy logic cumulative effects assessment method, which used PCA and PCR analysis (Lopes et al., 2011) along with fuzzy logic suitability mapping (Akumu et al., 2016; Caniani et al., 2016) to calculate aspen regeneration suitability. This figure depicts in sequence the ArcGIS tools and processes that were used in this method to determine a harvested block's suitability for aspen regeneration.

This method is highly reliant on the combination of PCA and PCR, which are two multivariate statistical analyses commonly used when dealing with large sets of variables and trying to determine which variables are most influential to a process. Principal Component Analysis involves the transformation of variables into a series of uncorrelated principal components (PC), each explaining a different level of variance within the data (eigenvalue). Each PC is also composed of the combination of the variables; however, not all variables exert the same level of importance (eigenvector) within the PC. As a result, PCA is traditionally used not only as a way of identifying which variables are most influential to a process but also as a way simplify data into a few PC which account for majority of variance within data (Pennsylvania State University, 2018). For this study, PCA was used as a way to determine the influence of each suitability predictor and was not used to simplify the data as each PC, no matter how little variance it explained, was important for understanding how the predictor variables related to the level of aspen regeneration. Rather, simplify the number of PCs used to assess regeneration suitability was

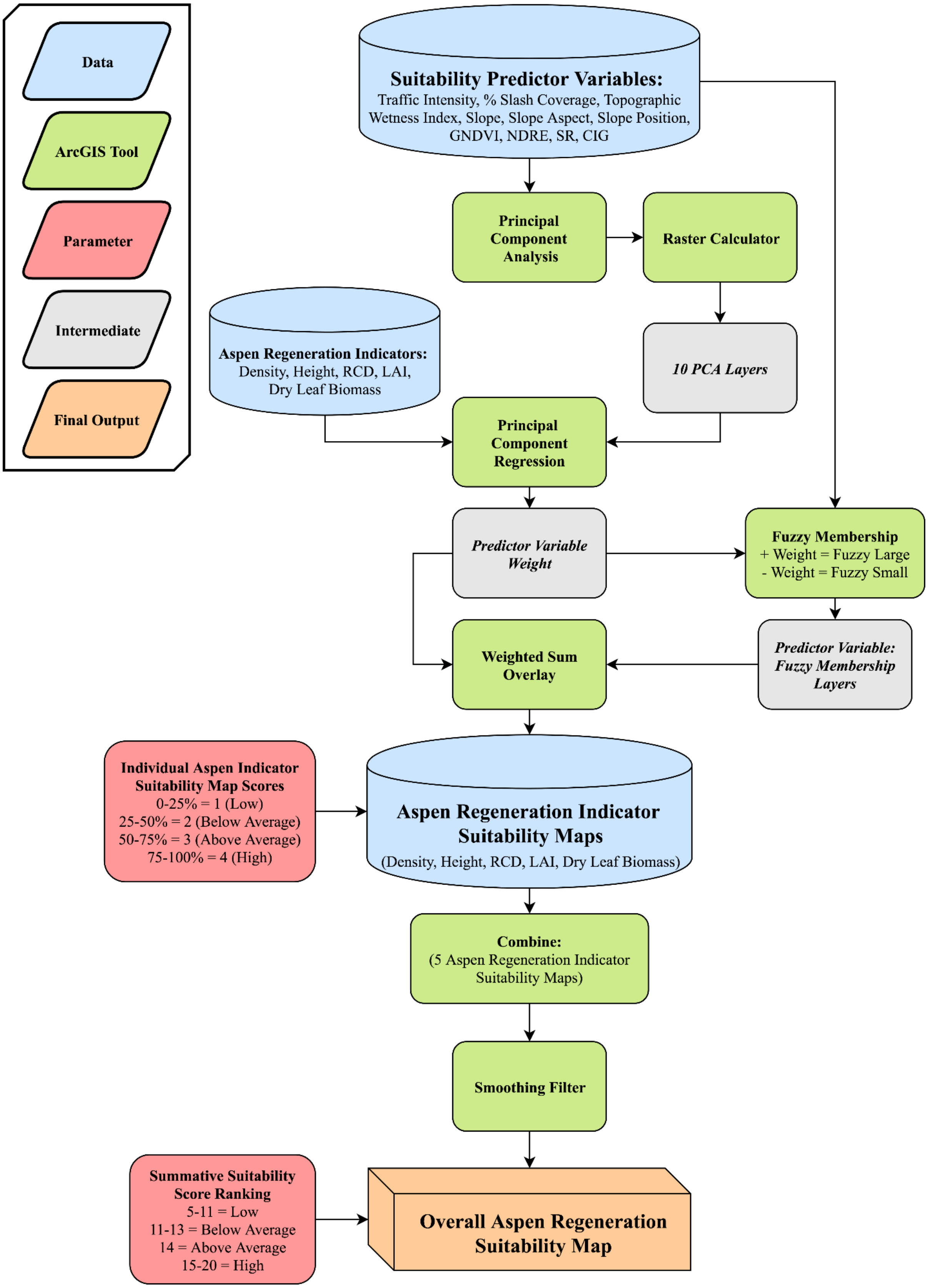

**Fig. 5-1:** Detailed illustration of the PCA, PCR, and fuzzy logic method that was used to calculate aspen regeneration suitability across the harvested landscape.

done using PCR. Principal Component Regression is a method of analysis in which a linear regression model is used with principal components acting as the explanatory variable.

For the analysis of regeneration suitability, the following ten suitability predictors were used: skidder traffic, slash coverage, TWI, slope, slope aspect, slope position, GNDVI, NDRE, SR, CIG. In ArcGIS, these predictor variables were in a raster format and were standardized prior to PCA in order to have a mean of zero and a standard deviation of one. This standardization of variables is a common technique used in PCA analysis when the input variables have different scales as this ensures that each variable receives the same weight during the analysis (Pennsylvania State University, 2018). Following PCA, PCR was used to determine the number of PCs used in calculating regeneration suitability. Principal Component Regression was conducted using the Ordinary Least Square Regression function in ArcGIS where five aspen regeneration indicators were regressed against the ten PCs. Only PCs that showed a significant ($p<0.1$) relationship with the aspen regeneration indicators were kept for future calculations. The coefficient values generated from the ordinary least square regression were used to assess the type (positive or negative) of relationship that the significant ($p<0.1$) PCs had with the aspen regeneration indicators. Depending on the relationship type, the eigenvectors associated with a PC were adjusted by multiplying them with a 1 or -1 to account for a positive or negative relationship, respectively.

As each predictor variable did not contribute the same level of influence when determining regeneration suitability, the weight (i.e., percent relative effect on aspen regeneration) of each predictor variable was calculated. These calculations were also used to determine which fuzzification method/algorithm would be used for each predictor variable. Fuzzification analysis refers to the processing steps of the fuzzy logic approach in which the values of the predictor variables, in their original measurement scales, are transformed to a fuzzy membership scale of 0 to 1, where values close to 0 indicate low membership, and those close to 1, indicate high membership. Predictor variable weight was calculated using Eq. 5-1, Eq. 5-2, and Eq. 5-3 in sequence.

$$Z = \frac{x^2(y)(x)}{|x|} \qquad \text{(Eq. 5-1)}$$

where $Z$ is the weight of a predictor variable belonging to one of the principal components, $x$ is the relationship type adjusted eigenvector, and $y$ is percent of explained variance by the principal component that was determined during the PCA.

The overall predictor variable weight (Eq. 5-2) is simply the sum of a predictor variable's weights across all significant ($p<0.1$) principal components.

$$\mathit{Overall\ Predictor\ Variable\ Weight} = \sum_{k=1}^{n} Z_k \qquad \text{(Eq. 5-2)}$$

Lastly, Eq. 5-3 was used to convert the overall predictor variable weight into a percent value. This was done by squaring the overall predictor variable weights to remove any negative values and then dividing that value by the sum of the squared predictor variables' weights, and multiplying by 100.

$$\mathit{Predictor\ Variable\ Weight\ (\%)} = \frac{\sum_{k=1}^{n} (Z_k)^2}{\sum_{i=1}^{n} \left( \sum_{k=1}^{n} (Z_k)^2 \right)_i} \times 100 \qquad \text{(Eq. 5-3)}$$

#### 5.4.4.1 Fuzzification and Regeneration Suitability Map Calculation

Unlike a traditional binary classification system that would simply classify a landscape into one of two categories (not suitable or suitable) based on whether or not the predictor variables met a set threshold value, a fuzzy logic theory based classification system classifies the landscape across a spectrum of regeneration suitability that ranges from 0 (not suitable) to 1 (highly suitable). To do so, the raw predictor variable data is transformed using a fuzzification algorithm (ESRI, 2016), which assigns new fuzzy membership values (0-1) based on a set of rules outlined in the algorithm. This data transformation step can be done using one of many fuzzification algorithms; however, for this study two algorithms were selected, fuzzy large (Fig. 5-2) and fuzzy small (Fig. 5-3). A fuzzy large transformation algorithm was used when a predictor variable had a positive overall predictor variable weight (Eq. 5-2); therefore, the higher the raw predictor variable value, the more suitable the area was for regeneration. Conversely, the fuzzy small algorithm was used when a predictor variable had a negative overall predictor variable weight (Eq. 5-2), indicating lower raw predictor variable values were more suitable for regeneration. These algorithms were

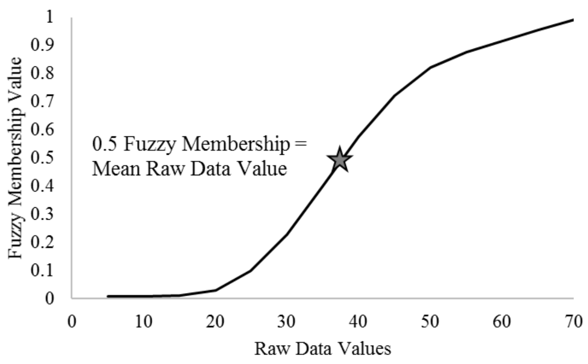

**Fig. 5-2:** Example of a fuzzy large transformation algorithm with raw data.

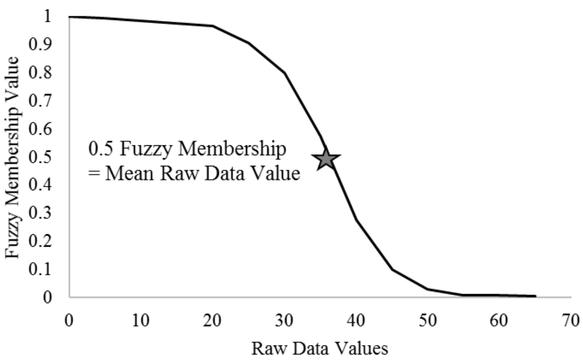

**Fig. 5-3:** Example of a fuzzy small transformation algorithm with raw data.

calculated with the Fuzzy Membership tool in ArcGIS, with the midpoint (0.5 suitability) set as the mean value from the original predictor variable data. All other tool setting were left as default.

Once each predictor variable was run through the Fuzzy Membership tool in ArcGIS, these new fuzzified layers (i.e., layers with transformed values, ranging from 0-1) were run through the Weighted Sum Overlay function in ArcGIS with the weight for each predictor variable being set as the % weight calculated using Eq. 5-3. Through the weighted sum overlay calculation, five aspen regeneration indicator suitability maps (density, height, RCD, LAI, dry leaf biomass) were generated that ranged in value from 0 to 1, where values close to 0 indicate areas not suitable and those close to 1 indicate highly suitable areas for aspen regeneration. These map values were then categorized into four levels of suitability using the Reclassify function in ArcGIS and given the following suitability score (reclassified values from 0-0.25= 1 suitability score, and 0.25-0.5=2, 0.5-0.75=3, 0.75-1=4) before all five maps were summed into one overall aspen regeneration suitability map using the Combine tool in ArcGIS. Once combined, the final map was run through a 3 x 3 cell low pass filter in ArcGIS, to smooth the final raster and remove any anomalies. Based on the sum of the suitability scores from the individual aspen indication suitability maps, the final map ranged in value between 5 and 20; values close to 5 represented an overall low suitability whereas those close to 20 were for high suitability areas. Lastly, the minimum, 1st quartile, mean, 3rd quartile, and maximum values for the final raster were calculated and used to reclassify the final raster into four levels of overall suitability (i.e., reclassified values from 5-11 = Low suitability, 11-13 = Below Average, 14 = Above Average, 15-20 = High).

#### 5.4.4.2 Fuzzy Logic Cumulative Effects Assessment Method Validation and Statistical Analysis

To validate whether this new method of assessing cumulative effects through suitability mapping was capable of accurately predicting areas with higher regeneration rates, the suitability level for each of the 168 aspen regeneration measurement plots was extracted from the final map. An analysis of variance (PROC GLIMMIX procedure) was performed using SAS to assess the differences in aspen sucker density, height, RCD, LAI, dry leaf biomass between the four different suitability levels.

In addition to assessing the differences in the level of aspen regeneration across the four levels of suitability, the predictor variable values (# of skidder passes, % slash coverage, TWI, slope, aspect, slope position, GNDVI, NDRE, SR, CIG) were also extracted for each of the 168 measurement plots. An analysis of variance (PROC GLIMMIX procedure) was performed using SAS to determine whether there were differences in these predictor variables across the four levels of regeneration suitability.

## 5.5 Results

### 5.5.1 Principal Component Analysis and Regression

The level of correlation each predictor variable had on a PC was quite variable (Table 5-1). Overall, the predictor variables with the highest eigenvectors (i.e., correlation) in the first PC (34% of total variance explained) were the NDRE, CIG, SR, GNDVI predictor variables, all with positive relationship, cumulatively representing the overall capability of the area to support vegetative growth, in terms of total green biomass, which was detected via multispectral sensors. High total green biomass in a given area would be highly indicative of soil and climatic conditions that are optimal for plant and tree growth. Therefore, the first PC could be regarded as a surrogate measure of the soil-tree-atmosphere interactions that promote tree growth.

The second PC (16 % of total variance explained) was highly related to slope of the site (positive) followed by TWI and traffic (negative), cumulatively representing the overall site productivity – harvesting interactions of the land. As slope steepness increases, both the TWI and traffic predictor variables will decrease, since the amount of water infiltrating the soil will decrease as more flows downhill (Brady and Weil, 2004) and the machine operators will likely avoid steep slopes during harvesting operations due to the increased risk.

The third PC (12% of total variance explained) was highly related to the slope position and slash predictor variables (positive), cumulatively representing the harvesting effects across the blocks. As slope position (analyzed as dummy variables) moved from a depression to a summit, slash increased as well.

The fourth PC (10% of total variance explained) was dominated by a single variable – slope aspect (negative relationship), depicting contrasting effects of north- versus south-facing slopes, in terms of site productivity. The remaining PCs explained <8% (individually) of the total variance.

However, not all PC showed a significant ($p < 0.1$) relationship with the aspen regeneration indicators (density, height, RCD, LAI, dry leaf biomass) as shown in Table 5-2. Aspen sucker density, LAI, and dry leaf biomass only showed a significant relationship with PC1 and PC7, while aspen sucker height and RCD show a significant relationship with PC1, PC2, PC3, and PC5.

When calculating regeneration suitability across the harvested block for each of the five aspen regeneration indicators, the level of influence (% weight) for each predictor variable was not equal (Table 5-3). The results displayed in this table were calculated through equations #1 – #3, mentioned earlier. Through these calculations it was determined that the predictor variables shared the same level of influence when determining an areas regeneration suitability for aspen sucker density, LAI, and dry leaf biomass, while the influence of the predictor variables on area suitability for aspen height and root collar diameter were slightly different. However, area suitability for all aspen regeneration indicators was largely controlled by the four vegetation indices included in the analysis. Cumulatively, vegetation indices were responsible for approximately 62% - 95% of the decision when determining area suitability and all expressed a

**Table 5-1:** Principal component analysis illustrating which predictor variables were most correlated with each principal component (PC), as well as percent variance explained by each principal component.

| Suitability Predictor Variable | PC Layer | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|
| | PC 1 | PC 2 | PC 3 | PC 4 | PC 5 | PC 6 | PC 7 | PC 8 | PC 9 | PC 10 |
| | Eigenvectors | | | | | | | | | |
| Traffic | -0.170 | **-0.460** | 0.287 | 0.194 | **0.457** | **0.489** | **-0.437** | 0.025 | 0.002 | -0.023 |
| Slash | -0.022 | -0.036 | **0.502** | 0.350 | **0.408** | **-0.617** | 0.263 | -0.083 | -0.015 | -0.017 |
| TWI | 0.011 | **-0.595** | -0.115 | -0.224 | -0.214 | **-0.527** | -0.349 | 0.369 | 0.002 | 0.045 |
| Slope Position | 0.039 | 0.148 | **0.789** | -0.154 | **-0.523** | 0.125 | -0.118 | 0.156 | 0.046 | 0.001 |
| Aspect | -0.145 | 0.103 | 0.142 | **-0.859** | **0.445** | -0.039 | 0.080 | -0.029 | -0.060 | 0.013 |
| Slope | 0.004 | **0.626** | -0.071 | 0.112 | 0.206 | -0.211 | **-0.667** | 0.238 | -0.029 | 0.040 |
| NDRE | **0.403**† | 0.032 | -0.004 | 0.048 | 0.229 | 0.195 | 0.332 | **0.796** | 0.011 | -0.016 |
| CIG | **0.522** | -0.060 | 0.051 | -0.042 | 0.069 | 0.020 | -0.086 | -0.232 | 0.024 | **0.808** |
| SR | **0.508** | -0.059 | 0.042 | -0.045 | 0.001 | -0.004 | -0.125 | -0.197 | **-0.729** | -0.385 |
| GNDVI | **0.505** | -0.034 | 0.010 | -0.101 | 0.087 | -0.043 | -0.142 | -0.222 | **0.679** | **-0.441** |
| Variance Contribution Rate (%) | 34.03 | 16.35 | 11.63 | 10.23 | 7.65 | 7.36 | 6.13 | 4.81 | 1.43 | 0.38 |
| Cumulative Variance (%) | 34.03 | 50.37 | 62.00 | 72.23 | 79.89 | 87.25 | 93.38 | 98.19 | 99.62 | 100.00 |

† Characteristic vectors being larger than 0.4 or less than -0.4 are in **bold** font.

**Table 5-2:** Principal component ordinary least square regression outputs illustrating the strength, type and significance of principal components (PC) with aspen regeneration indicators.

| | PC Layer | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|
| | PC 1 | PC 2 | PC 3 | PC 4 | PC 5 | PC 6 | PC 7 | PC 8 | PC 9 | PC 10 |
| | Density | | | | | | | | | |
| Coefficient | 0.600 | 0.523 | -0.442 | 0.216 | 0.102 | 0.405 | 1.167 | 0.562 | 1.095 | -2.268 |
| p value | **0.031†** | 0.195 | 0.365 | 0.671 | 0.862 | 0.505 | **0.077** | 0.455 | 0.419 | 0.393 |
| | Height | | | | | | | | | |
| Coefficient | 3.558 | 6.741 | -4.613 | -1.882 | -7.463 | -3.330 | 1.105 | 2.133 | 0.289 | -15.602 |
| p value | **0.004** | **0.000** | **0.031** | 0.397 | **0.004** | 0.210 | 0.699 | 0.515 | 0.961 | 0.179 |
| | Root Collar Diameter | | | | | | | | | |
| Coefficient | 0.250 | 0.668 | -0.500 | -0.141 | -0.685 | 0.000 | 0.262 | -0.191 | 0.152 | -0.857 |
| p value | **0.041** | **0.000** | **0.021** | 0.528 | **0.009** | 0.999 | 0.364 | 0.562 | 0.798 | 0.462 |
| | Leaf Area Index | | | | | | | | | |
| Coefficient | 0.051 | 0.017 | -0.042 | 0.015 | 0.002 | -0.010 | 0.100 | 0.055 | 0.060 | -0.111 |
| p value | **0.005** | 0.513 | 0.189 | 0.649 | 0.966 | 0.798 | **0.021** | 0.264 | 0.503 | 0.524 |
| | Dry Leaf Biomass | | | | | | | | | |
| Coefficient | 4.925 | 2.459 | -4.715 | 1.283 | -0.097 | -0.829 | 9.950 | 3.221 | 3.754 | -11.257 |
| p value | **0.003** | 0.307 | 0.106 | 0.673 | 0.978 | 0.819 | **0.012** | 0.473 | 0.642 | 0.477 |

† p values in **bold** are significant ($p < 0.1$)

**Table 5-3:** Percent weight of each predictor variables when determining regeneration suitability for each aspen regeneration indicator and the relationship type (Neg: negative; Pos: positive) each predictor variable had with the aspen regeneration indicators.

| Suitability Predictor Variable | Density/ LAI/ Dry Leaf Biomass | Height/ Root Collar Diameter |
|---|---|---|
| | Overall % Weight (Relationship Type) | |
| Traffic | 1.63 (Neg) | 11.65 (Neg) |
| Slash | 0.06 (Pos) | 4.28 (Neg) |
| TWI | 0.19 (Neg) | 6.62 (Neg) |
| Slope Position | 0 (Pos) | 5.35 (Neg) |
| Aspect | 0.16 (Neg) | 1.26 (Neg) |
| Slope | 2.6 (Neg) | 8.98 (Pos) |
| NDRE | 13.48 (Pos) | 6.29 (Pos) |
| CIG | 29.83 (Pos) | 19.93 (Pos) |
| SR | 26.39 (Pos) | 18.01 (Pos) |
| GNDVI | 25.66 (Pos) | 17.63 (Pos) |

positive relationship with the five aspen regeneration indicators. Therefore, as a vegetation index increased, so did the regeneration suitability of that area. Conversely, skidder traffic expressed a negative relationship with all aspen regeneration, indicating that as the level of skidder traffic increased, the regeneration suitability of that area decreased. While skidder traffic had little influence (1.63%) on determining an area's suitability for aspen density, LAI, and dry leaf biomass, it held a weight of 11.65% when determining area suitability for aspen height and root collar diameter. The other predictor variables (slash coverage, TWI, slope position, aspect, and slope) had minimal influence on determining regeneration suitability as each only held a weight ranging between 0-10%. While the relationship of TWI and aspect with all regeneration indicators was negative, the other three predictor variables were not consistent in their relationship with the regeneration indicators. Slash and slope position indicated a positive relationship with aspen sucker density, LAI, and dry leaf biomass; however, displayed a negative relationship with height and root collar diameter. Lastly, slope had a negative relationship with aspen density, LAI, and dry leaf biomass, but a positive relationship with aspen height and root collar diameter.

### 5.5.2 Fuzzy Logic-Derived Regeneration Suitability Maps

An example of the maps created in ArcGIS, using the predictor variables' weights calculated through PCA and PCR analysis, to derive the overall regeneration suitability map for harvest block C is presented in Fig. 5-4 (see Appendix F for the complete set of fuzzy logic suitability maps). In this example, skidder traffic is transformed using a fuzzy small transformation because of the negative relationship it had with all regeneration indicators (Table 5-3). This same process was carried out for the remaining predictor variables based on their relationship with the regeneration indicators. Once fuzzified, the 10 predictor variables for each regeneration indicator were summed together, taking into account the weight of each predictor variable (Table 5-3), to generate five

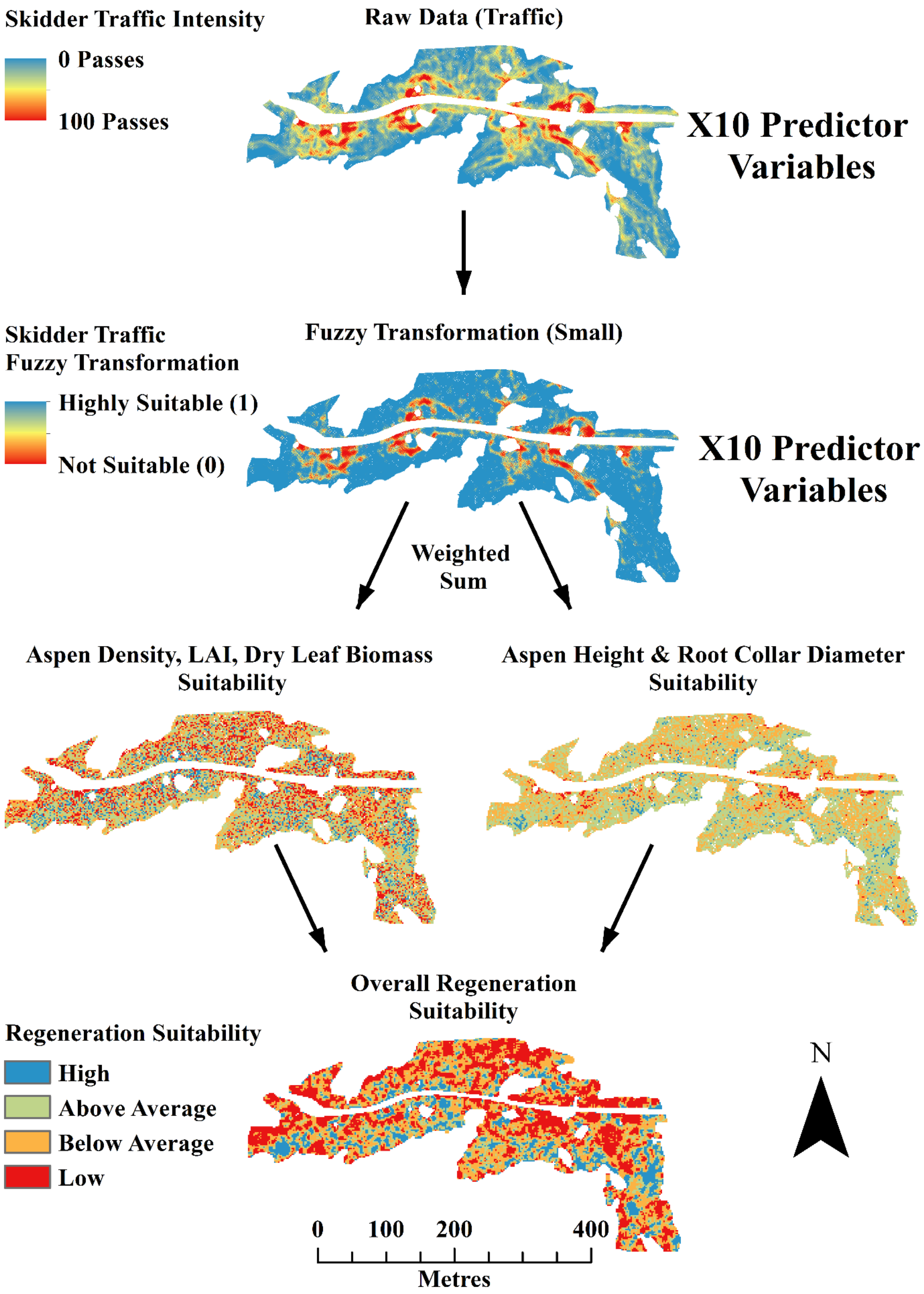

**Fig. 5-4**: Example of the fuzzy logic calculation process through ArcGIS to determine regeneration suitability for harvested block C.

individual suitability maps. Finally, these five individual suitability maps are combined into one suitability map depicting overall regeneration suitability.

From the individual regeneration indicator suitability maps, it is clear that the amount of area categorized as low suitability is much higher for aspen density, LAI, and dry leaf biomass compared to aspen height and root collar diameter. These maps also illustrate how areas of low and high regeneration suitability appear in small clusters scattered throughout the harvested block rather than as large sections. However, once the five individual aspen regeneration indicators suitability maps were combined and smoothed to generate a final overall regeneration suitability map for the harvested blocks, these small clusters were concentrated into large patches that span several meters in size.

The percent area of a harvested block classified under a regeneration suitability level was calculated from the overall regeneration suitability map (Fig. 5-5). For all three of the harvested blocks, low and below average regeneration suitability accounted for over 50% of the harvested area. Harvested block C showed the largest % area being classified as low or below average suitability (71%), while harvested block A showed the largest % area being classified as high or above average suitability (49%).

### 5.5.3 Aspen Regeneration By Suitability Level

The level of aspen regeneration, based on collected field data, found across the overall regeneration suitability maps for all three harvest blocks were compared for statistical differences and presented in Figs. 5-6 to 5-10. Aspen sucker density was not significantly different between regeneration suitability levels ($p = 0.1495$) (Fig 5-6). Aspen sucker height was significantly higher for high regeneration suitability areas (76 cm), compared to low regeneration suitability areas (52 cm). Sucker height in below-average and above-average regeneration suitability areas were not significantly different from either low or high regeneration suitability areas (Fig 5-7). The same

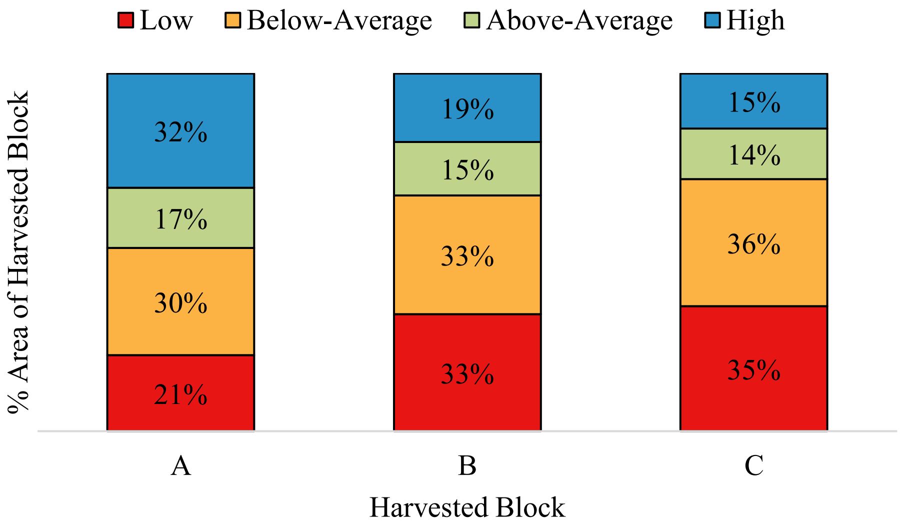

**Fig. 5-5:** Area breakdown (%) of regeneration suitability for harvested blocks A, B, and C.

trend was observed for RCD. Aspen root collar diameter in high regeneration suitability areas was significantly greater (7.4 mm) compared to low regeneration suitability areas (5.6 mm), while differences in below- and above-average suitability areas were not significantly different from either low or high suitability areas (Fig. 5-8). Leaf area index was not significantly different between regeneration suitability levels (Fig. 5-9). Lastly, dry leaf biomass was significantly higher in high regeneration suitability areas (56.6 g $m^{-2}$) compared to low regeneration suitability areas (34.7 g $m^{-2}$) (Fig. 5-10). Dry leaf biomass in below- and above-average regeneration suitability areas was not significantly different from either low or high regeneration suitability areas.

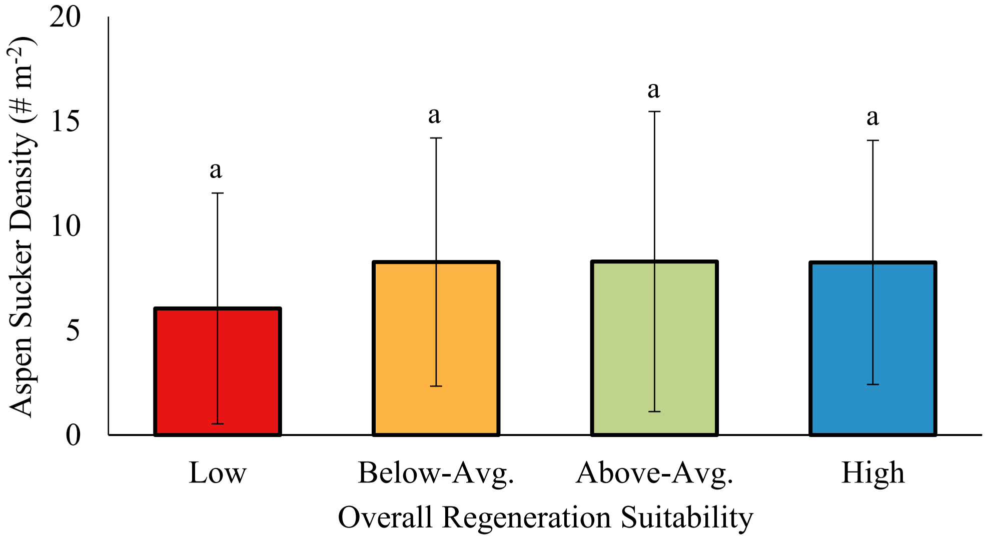

**Fig. 5-6:** Mean aspen sucker density across overall regeneration suitability levels. Bars with the same letter are not significantly different from each other p = 0.1 using Tukey-Kramer. Error bars represent standard deviation.

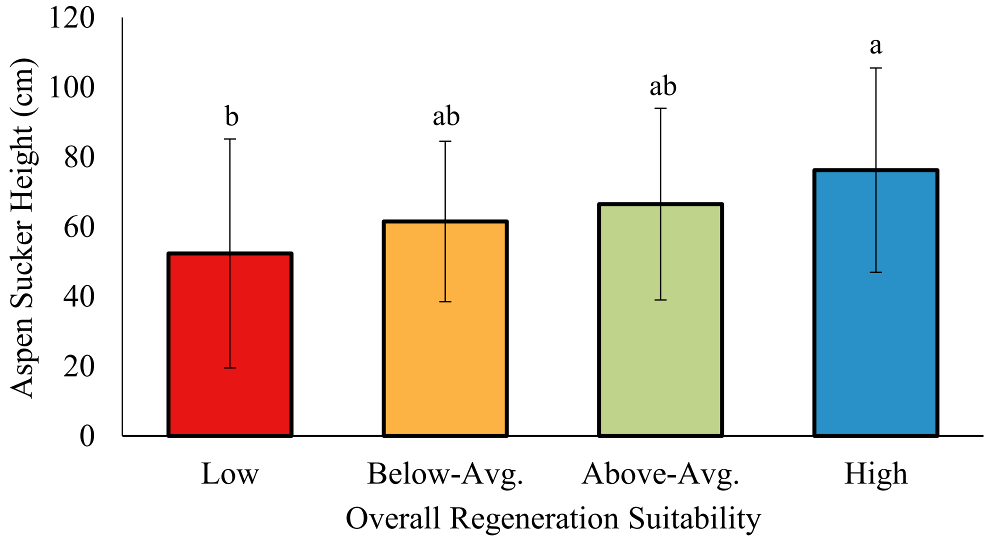

**Fig. 5-7:** Mean aspen sucker height across overall regeneration suitability levels. Bars with the same letter are not significantly different from each other p = 0.1 using Tukey-Kramer. Error bars represent standard deviation.

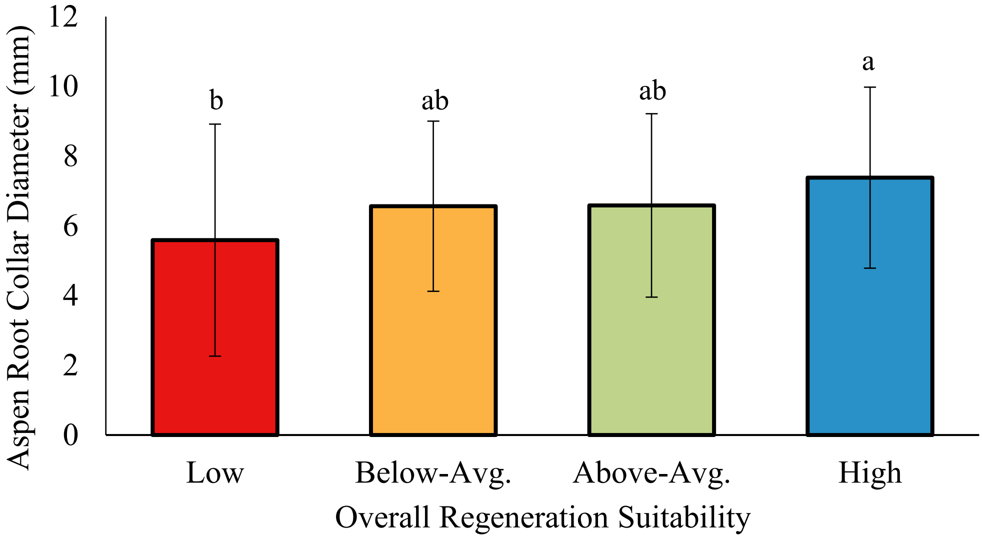

**Fig. 5-8:** Mean aspen sucker root collar diameter across overall regeneration suitability levels. Bars with the same letter are not significantly different from each other p = 0.1 using Tukey-Kramer. Error bars represent standard deviation.

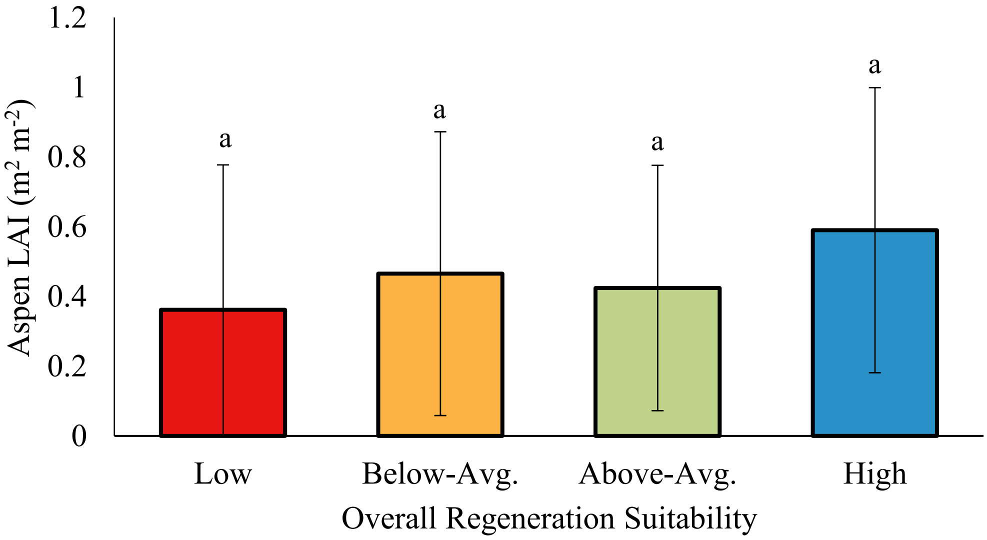

**Fig. 5-9:** Mean aspen leaf area index (LAI) across overall regeneration suitability levels. Bars with the same letter are not significantly different from each other p = 0.1 using Tukey-Kramer. Error bars represent standard deviation.

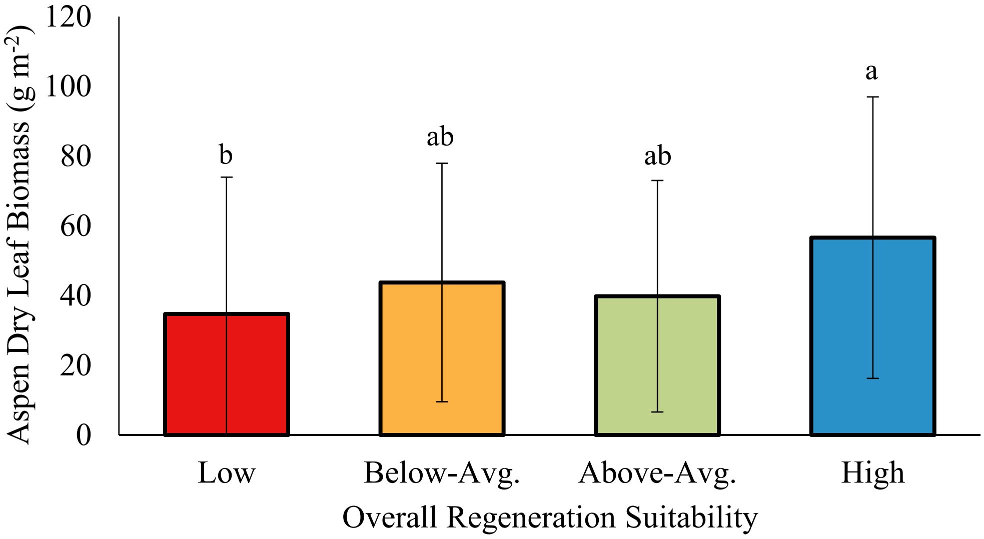

**Fig. 5-10:** Mean aspen sucker dry leaf biomass across overall regeneration suitability levels. Bars with the same letter are not significantly different from each other p = 0.1 using Tukey-Kramer. Error bars represent standard deviation.

### 5.5.4 Regeneration Predictors by Suitability Level

On average, low regeneration suitability areas had significantly more skidder traffic (≈34 passes) compared to areas with below-average (≈17 passes), above-average (≈10 passes), and high (≈7 passes) regeneration suitability (Table 5-4). Areas with low regeneration suitability also had significantly more slash coverage (13.1%) compared to areas with below-average or high regeneration suitability, 8.49% and 7.18%, respectively. No significant differences were found between slope, aspect, and TWI across the four regeneration suitability levels. Low regeneration areas had significantly lower GNDVI values (0.6) compared to below-average (0.67), above-average (0.69), and high (0.7) regeneration suitability areas. Areas with high regeneration suitability had significantly higher NDRE, SR, and CIG values (0.27, 17.46, and 5.59, respectively) compared to low and below-average regeneration. Normalized Difference Red-Edge, SR, and CIG values for areas classified as having above-average regeneration suitability were only significantly different from areas with low regeneration suitability. In areas of above average regeneration suitability, NDRE, SR, and CIG values were only significantly different from areas with low regeneration suitability, while the indices values in areas between low and below average regeneration suitability were not significantly different. As slope position is a qualitative measure, no statistical analysis was performed on this variable; however, sampling locations used to assess areas with low, above-average, and high suitability were primarily located in shoulder positions, while areas with below-average suitability were located on backslope positions.

**Table 5-4:** Mean ± standard deviation skidder traffic intensity, % slash coverage, slope, slope aspect, TWI, GNDVI, NDRE, SR, and CIG across four overall regeneration suitability levels.

| Regeneration Suitability | Regeneration Predictor Variables | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|
| | Skidder Traffic (# of passes) | Slash Cover (%) | Slope (°) | Aspect (°A) | TWI | GNDVI | NDRE | SR | CIG |
| Low | 34±26a† | 13.1±10.2a | 5.0±3.2a | 188.8±104.9a | 5.3±1.3a | 0.60±0.2b | 0.21±0.1c | 10.37±6.5c | 3.73±1.8c |
| Below-Average | 17±18b | 8.5±9.6b | 5.9±2.9a | 221.8±101.3a | 5.2±1.4a | 0.67±0.1a | 0.23±0.0bc | 12.49±5.1bc | 4.35±1.3bc |
| Above-Average | 10±13b | 9.9±10.9ab | 6.3±4.6a | 187.6±110.1a | 4.9±1.1a | 0.69±0.1a | 0.26±0.0ab | 14.44±6.0ab | 4.77±1.4ab |
| High | 7±10b | 7.2±9.6b | 4.9±2.9a | 169.1±98.4a | 5.0±0.8a | 0.70±0.2a | 0.27±0.1a | 17.46±6.5a | 5.59±1.9a |
| **Statistical Analysis** | | | | | P Value | | | | |
| Suitability Effect | <0.0001 | 0.0311 | 0.2391 | 0.1336 | 0.474 | 0.0036 | 0.0002 | <0.0001 | <0.0001 |

† Means in a column with the same letter are not significantly different p = 0.01 using Tukey-Kramer.

## 5.6 Discussion

In the natural environment, the level and success of regeneration following a harvesting event would never be controlled by just one factor. Through the combination of PCA, PCR, and fuzzy logic analysis, it was possible to develop a method that could account for potential cumulative effects associated with harvesting practices on the success of aspen regeneration. Using PCA, 10 predictor variables could be transformed into 10 PCs, which measured cumulatively the importance of the regeneration predictor variables. Then using PCR analysis, it was possible to assess how these components related to indicators of aspen regeneration success and ultimately determine which factors were most influential in deciding regeneration suitability across the harvested block. Based on our search of the literature, this is the first study of the factors influencing forest regeneration that utilized the combination of PCA and PCR analysis, in combination with fuzzy logic analysis and mapping.

The PCA-PCR combined method has been used recently in other research fields. For example, Lopes et al. (2011) used PCA and PCR analysis together to better understand which variables were most important in the formation of beach cusps along coast lines. However, by taking the knowledge gained through PCA and PCR analysis, our study was able to incorporate fuzzy logic predictability mapping (Akumu et al., 2016; Caniani et al., 2016) to assess the effects of regeneration predictor variables on aspen regeneration across the harvested block. By incorporating fuzzy logic into our model, it allowed for the creation of regeneration suitability levels, which were used to delineate the harvested blocks, and better understand the differences in the regeneration predictor variables between the suitability levels. Although this combination of PCA, PCR, and fuzzy logic was able to successfully account for cumulative effects from the 10 factors through the creation of the suitability levels, it was not as successful in determining which individual predictor variables were interacting and causing a cumulative effect on the level of aspen regeneration.

Using the fuzzy logic approach to the data from the Duck Mountain Provincial Park, a large portion of the harvested area contains conditions that are not favorable for optimal aspen regeneration and future growth. On average 30% of harvested blocks were classified as having low regeneration suitability, while an additional 33% were classified as having below-average regeneration suitability. The overall level of aspen regeneration in areas with low regeneration suitability was generally worse than areas with above-average or high regeneration suitability. This decrease in regeneration success is likely the result of an increased level of disturbance experienced in these areas during the harvesting event, in combination with soil and site factors that may be impeding aspen regeneration. Areas with low regeneration suitability did have significantly higher levels of skidder traffic and slash coverage, which are two factors known to have a major influence on soil properties and aspen regeneration success (Bella, 1986; Lieffers-Pritchard, 2004; Zenner et al., 2007; Renkeman, 2009). However, the high level of variability of skidder traffic and slash loading within each suitability level (Table 5-4) suggested that these may not be the only factors determining the success and vigor of aspen regeneration at a harvest block scale, following a winter harvest. Yet the other site properties that were measured (slope, aspect, slope position, and TWI) only contributed a small weight when determining regeneration suitability, and they showed no significant difference between suitability levels, suggesting they had little to no control over aspen regeneration success. However, it is possible that the effects of the factors mentioned above were all accounted for through vegetation indices (NDRE, GNDVI, SR, and CIG) in some way.

As these vegetation indices are highly dependent on the amount and health of vegetation, if site conditions are not suitable for vegetation growth it is likely that the level of regeneration would be lower causing a decrease in the vegetation indices. Hence, these indices act as an indirect measure for many anthropogenic (i.e., forest floor disturbance and severe compaction) and environmental factors (chemical/physical soil properties and climate) that were not, or could not, be directly measured cost-effectively for the entire harvested blocks. To date, several studies have examined the use of vegetation indices as predictors, or surrogate measures, for a specific vegetation property (Wang et al., 2005; Xie et al., 2008; Huete, 2012); however, none have considered using the relationship between vegetation indices and vegetation properties as surrogates for site properties or estimating site suitability. These vegetation indices encompass soil properties that may influence regeneration (i.e., soil nutrient content, soil compaction, soil moisture availability, etc.), environmental conditions during the summer growing season (i.e., temperature, precipitation, etc.), and any disturbance that occurred on the area (i.e., root disturbance, slash loading, etc.). If an area does not have conditions that are favorable for regeneration, it would be expected that the vegetation index for that area would also be lower, as vegetation growth would likely be reduced compared to areas with optimal growth conditions. This is reinforced by the results, which found vegetation indices and the level of regeneration were consistently higher in areas of high regeneration suitability compared to low regeneration suitability, suggesting conditions were more favorable in high suitability area and therefore capable of supporting more regeneration.

There are a few limitations associated with using vegetation indices as predictors of regeneration suitability. The inclusion of vegetation indices into the fuzzy logic model makes it rather difficult to determine which factor(s) are controlling regeneration and trying to assess the potential of cumulative effects between factors. As mentioned above, vegetation indices were a dominant factor in determining the regeneration suitability in this study, which could have overshadowed the effects of the other factors that were measured. Nevertheless, among the four vegetation indices, significantly higher index values were consistently associated with higher regeneration suitability, which justified their use in this study, and warrant their use in future regeneration studies.

Another limitation associated with using vegetation indices in our calculation of regeneration suitability was our inability to differentiate between species; therefore, these indices were not a species-specific measure. Instead, they were a measure of overall vegetation regrowth for all species following the harvesting event. In the Duck Mountain Provincial Park, beaked hazelnut (*Corylus cornuta*) and mountain maple (*Acer spicatum*) are two major understory shrubs that also experience prolific regeneration following a harvesting event and, therefore, created areas with high vegetation indices due to their high reflectance and absorption properties. To resolve this issue, an attempt at differentiating between vegetation species was done using image classification of the multispectral images; however, it was unsuccessful as pixel resolution was not high enough to distinguish individual aspen suckers from the surrounding vegetation. In future studies, higher resolution multispectral images and/or more advanced image classification techniques will be needed in order to differentiate between species and generate species specific indices layers (Lisein et al., 2015; Nevalainen et al., 2017). These new species classified layers could also be used to generate a measure of competition based on species density and distribution across the harvested block. This measure of competition would add an additional predictor of regeneration suitability and could potentially increase the accuracy of regeneration suitability estimations.

It is important to emphasize that the field data available for this study were collected after the first growing season, following harvesting. Despite the data being limited to just one summer of growth, differences in the level of aspen regeneration were found between the different suitability levels, which was the main goal of this study. However, the applicability of these aspen regeneration suitability maps is uncertain for older stands, and was beyond the scope of this study.

Aspen regeneration success across different growing conditions may become less variable in older stands, but this study did not address whether these differences will persist once the forest reaches maturity. As the forest matures, and a natural thinning process begins to remove inferior aspen suckers, thinning rates may differ across growing conditions. Studies by both Steneker (1976) and Bella (1986) found that sucker density decreased at a faster rate in areas with a higher initial density compared to areas with lower initial density, with sucker density reaching a similar level after just five or six years. Nevertheless, this study demonstrated that a holistic approach to determining aspen regeneration suitability can be implemented successfully using the data collection approach and subsequent analyses. This method illustrated how a harvested block can be subdivided into regions of varying suitability and can allow for the identification of factors that threaten the sustainability of the forest. In order to identify which determining factors will persist over time, as the aspen stands reaches maturity, long-term aspen regeneration monitoring studies will be warranted.

Not only does this method of analysis help to assess how a combination of different factors may influence aspen regeneration, it can also be used as a decision support system (DSS) tool for industry, or government, to improve regeneration assessments. Currently, government legislation dictates that regeneration assessments using a ground survey methodology are to be conducted using a transect design, with the beginning of the transect randomly selected, circular plots having a radius of 1.78 m, and the number of plots determined based on the size of the harvested block (Government of Saskatchewan, 2012). As a result, a large portion of the harvested block is left unexamined, and important information about how the entire harvested block is regenerating may be missed, causing the regeneration assessment to potentially over/under estimate actual regeneration. By tracking skidder traffic across the entire harvested block, and the calculation of other site properties based on UAV derived imagery, the harvested block can be run through a fuzzy logic cumulative effects assessment method, similar to the one developed in this study, and generate a regeneration suitability map for the entire harvested block. This measure of regeneration suitability can then be used to delineate the harvested block into smaller assessment areas, which would help to achieve a more comprehensive assessment of regeneration across the entire harvested block. In turn, using the percent distribution of each regeneration suitability level across the harvested block, a weighted average for aspen regeneration (density, height, etc.) could be calculated. This calculation of aspen regeneration based on delineated regeneration suitability regions could help ensure that our current harvesting processes and practices are being conducted in a sustainable manner, as it offers a more in depth analysis of aspen regeneration across an entire harvested block rather than only assessing a small portion of the harvested block.

## 5.7 Conclusion

By combining PCA, PCR, fuzzy logic analysis, and GIS mapping, this is the first study to demonstrate a new and effective method that accounts for cumulative effects between a number of tree growth factors, which was developed and applied to assess regeneration of an aspen forest following winter harvest. This fuzzy logic cumulative effects assessment method offers industry and government agencies a new DSS tool with which they could adjust current regeneration assessment standards to assess aspen regeneration success across harvested blocks in a more detailed and comprehensive manner.

The determination of regeneration suitability was highly dependent on the inclusion of vegetation indices as a predictor variable. These indices were important as they act as a surrogate measurement for the combined effects of several tree growth factors, including soil and climatic properties that cannot be measured cost-effectively across the entire harvested block. Through this new method, entire harvested blocks were able to be delineated into regions based on their regeneration suitability potential which allowed for a more targeted assessment of aspen regeneration. It is unknown, however, as the forest matures whether the difference in aspen regeneration between suitability regions will remain the same and thus will require long-term monitoring to answer this question. Nevertheless, the successful demonstration of this comprehensive approach for aspen regeneration assessment holds great promise for improved forest sustainability monitoring that could be implemented across Canada.

# 6 GENERAL DISCUSSION AND SYNTHESIS

The overall goal of this research project was to assess whether winter harvesting operations used for the old growth aspen forests in the Duck Mountain Provincial Park, SK is an ecologically sustainable practice to ensure successful aspen regeneration. Examination of skidder traffic, slash coverage, and their cumulative effects across the harvested landscape indicated that although certain areas within the harvested block experienced significantly more disturbance and less regeneration than others, the overall level of aspen regeneration across the harvested block was likely sufficient to ensure the continued health and productivity of the aspen forest. The following discussion and synthesis will focus on exploring the key findings from the three research chapters and their implications on the ecological sustainability of these harvesting practices as well as explore how the forestry industry and government could use these findings to improve harvesting practices and regeneration assessment surveys.

Machine traffic is one of the greatest sources of potential disturbance to forest soils and shallow rooting systems due to the size, weight, and repetitive movement of harvesting machinery. To mitigate this source of disturbance, especially on sensitive sites, forest companies often harvest during the winter as the soils are less prone to disturbance and compaction when they are frozen and covered by a protective layer of snow. However, examination of the effects of skidder traffic on soil bulk density in our study and others (Berger et al., 2004; Kolka et al., 2012) indicate that soils are still susceptible to a certain degree of disturbance. In our study, after 1 to 5 passes soil bulk density increased significantly compared to the unharvested control; however, bulk density ceased to increase as the level of skidder traffic intensity increased. Even under areas with the highest level of skidder traffic intensity, average soil bulk density was still well below a root growth-limiting threshold (Daddow and Warrington, 1983) and showed no relationship with the level of aspen regeneration one year after harvest. These findings would suggest that winter harvesting was successful in mitigating potential adverse effects to soil bulk density caused by excessive machine traffic at this site; however, physical scarification and disturbance of the forest floor during harvest by machinery is still an issue of concern as damage to the aspen rooting system within the forest floor can lead to a decrease in regeneration (Lieffers-Pritchard, 2004; Renkeman, 2009).

Examination of aspen regeneration levels in relation to skidder traffic intensity indicates that winter harvesting was unable to mitigate the effects of skidder traffic intensity on aspen sucker density or height. Aspen sucker density was decreased by over 50% under areas with 51-100 passes compared to areas with 6-10 and 11-25 passes, while aspen height gradually decreased approximately 25 cm as the level of skidder traffic intensity increased from no passes to >100 passes. As soil bulk density was found not to have an influence on the level of aspen regeneration, this suggested that the repetitive skidder traffic may have caused damage to the forest floor and aspen rooting system; therefore, resulting in the decreased level of aspen regeneration. As areas with high levels of skidder traffic and lower aspen regeneration were often associated with landings and skidder trails, harvesting operations should attempt to minimize these pockets of high traffic intensity to ensure the greatest level of regeneration. Although these areas with the highest level of skidder traffic (51-100 passes) had the lowest aspen sucker density, they still contained approximately 47,000 sucker ha$^{-1}$ and only accounted for approximately 1% of the entire harvested block; therefore, it is unlikely that this reduction in first-year aspen regeneration will affect the sustainability of the future forest.

Our examination of % slash coverage following winter harvesting indicated that the majority of the harvested blocks were covered with light slash (0-33% slash coverage) and therefore should not experience negative effects associated with heavy slash coverage. Areas with higher % slash coverage (66-99%) only accounted for a very small portion of the overall harvested block and occurred mainly in clusters throughout the landing areas where trees were de-limbed and cut to length. As trees were de-limbed at centralized landing locations, this decreased the amount of slash being left in the harvested block but resulted in excess amounts of slash left in the processing areas. To deal with this excess slash, a portion of the slash is re-spread back into the harvested block while most is simply piled and burnt once dried. While the method of pile and burn helps to control the amount of slash being returned to the harvested block, Rhoades and Fornwalt (2015) found that in a lodgepole pine forest the effects of slash pile burning on the soil and vegetation not only drastically reduced the level of regeneration but the effects persisted for several decades. In aspen forests, it is likely that slash pile burning will have similar effects on the level of regeneration as the intense disturbance and heat will kill the underlying aspen rooting system. Without a valid rooting system for asexual regeneration, these areas then rely on seeds from the surrounding forest to be blown in; however, the large amounts of ash covering the soil is not a suitable environment for seedling germination and growth. As such, harvesting operations should focus on returning as much slash as possible back into the block and reducing the number of slash piles. Forest operations could also look at moving towards a method where delimbing occurs at the stump rather than at centralized landings, which would reduce the traffic at landings and reduce soil disturbance. Lastly, government and industry could examine the potential of finding alternative uses (i.e. bioenergy) for piled slash that does not meet the utilization standards for forest products as a means of reducing the amount of fibre being left in landing areas.

No significant relationships were observed between slash coverage and the level of aspen regeneration. The increasing level of slash coverage did not have any negative effects on aspen sucker density, height, or root collar diameter. Although, it is important to note that the highest level of slash coverage observed at the monitoring plots was only 60%; it is unknown if aspen regeneration would be adversely affected at higher slash levels. While several studies have developed or modified methods for assessing slash loading (Newman, 1966; McRae et al., 1979; Brown et al., 1982; Lieffers-Pritchard, 2004), little to no work has been done examining the potential of using UAV technology to assess slash across harvested blocks. This study was able to develop a method to estimate % slash coverage across a harvested block; however, further research is needed to improve measurements of slash coverage/slash loading from UAV based aerial imagery. Future research should examine the potential of using high-resolution digital elevation models from imagery to measure the depth of slash loadings in addition to slash coverage as the depth of slash will greatly influence soil temperature regimes as well as act as a physical barrier to suckers growth.

The use of vegetation indices to measure aspen density, height, root collar diameter, and LAI proved ineffective in this study. Unlike agroecosystems where multispectral remote sensing can easily be applied to assess the health and productivity of a monoculture crop, a forest ecosystem can be comprised of several species making it difficult to assess the regeneration of one species of interest such as aspen with multispectral remote sensing. Non-target species generate interference by amplifying reflectance signals making it impossible to accurately detect a single species and correlate the regeneration levels to vegetation index readings. However, vegetation indices are a useful tool for identifying which areas within the harvested blocks are experiencing regeneration and those that lack regeneration of any kind, allowing for the identification of potentially problematic locations within a block. Future research should examine the potential of using advanced image analysis techniques to discriminate between vegetation species in order to obtain species-specific reflectance information. If individual species-specific reflectance information could be obtained through multispectral analysis of UAV imagery and validated through field measurements, then the development of relationships between aspen regeneration and vegetation indices readings might be visible on a harvest block level that could be used as a tool for assessment of regeneration standards with aspen.

Lastly, this research demonstrated how a method for the examination of cumulative effects from both environmental factors (climate, soil, slope, etc.) and anthropogenic factors associated with harvesting operations (traffic, slash, etc.) on a landscape scale could be developed. The method developed for this study is the first to use fuzzy logic analysis in combination with PCA and PCR analysis to assess regeneration suitability across harvested blocks. This new method allows us to not only examine which factors are most influential for determining the level of aspen regeneration success across a harvested block, but can also be used as a decision support system for industry or government to improve current planning, management, and regeneration assessment procedures.

Examination of the regeneration predictor variables (traffic, slash, topographic wetness index (TWI), slope, etc.) across the four levels of aspen regeneration suitability indicated that areas with low regeneration suitability had significantly more skidder traffic and higher slash coverage compared to areas with high regeneration suitability. For winter harvesting operations, these findings re-enforce the importance of proper traffic distribution within the harvested block to minimize high traffic areas as well as ensure that slash is evenly distributed in order to ensure the highest level of aspen regeneration possible. The other factors (TWI, slope, aspect, and slope position) did not appear to have any significant effect on determining regeneration suitability.

As vegetation indices are sensitive to not only the abundance of vegetation but the health of the vegetation as well, they are an important factor to include in the analysis of regeneration suitability. Across the landscape, changes to soil properties, environmental conditions, and the level of disturbance from harvesting will have an influence on the abundance and health of vegetation; therefore, in essence these vegetation indices act as a surrogate for factors that were not or could not be measured for the entire harvested block. Thus, areas with higher vegetation index reading likely contain conditions that are more favorable for regeneration and growth compared to areas with low index readings. This notion was observed during the PCR analysis phase of our study as the first PC, which was largely influenced by the four vegetation indices, demonstrated a positive relationship with all aspen regeneration indicators (density, height, root collar diameter, LAI, and dry leaf biomass). Therefore, this phase of the analysis confirmed that areas with a higher vegetation index reading contained higher levels of aspen regeneration.

Although, the examination of regeneration across suitability levels indicated that there were no significant differences in aspen suckering density or LAI, there were however significant reductions in sucker height, RCD, and dry leaf biomass in areas of low regeneration suitability compared to high suitability. This significant decrease in the size of aspen suckers may be the result of increased forest floor disturbance under areas of low regeneration suitability. The majority of aspen suckering occurs within the forest floor (Lieffers-Pritchard, 2004) and disturbance to the rooting system could result in suckering from roots deeper in the soil profile; therefore, shortening the first growing season as the length of time required for suckers to reach the soil surface in increased compared to suckers originating from within the forest floor. The increased amount of slash found in areas of low regeneration suitability may also be delaying soil warm up in the spring as Lieffers-Pritchard (2004) found that high slash loading on aspen sites in the Duck Mountains delayed spring thaw by 21-26 days which would therefore further reduce the growing season.

Although harvesting during the summer and fall can lead to increased levels of disturbance to a site compared to winter harvesting (Bates et al., 1993; Berger et al., 2004), minimizing soil disturbance and ensuring proper slash distribution are still important for ensuring the sustainability of aspen forests following a winter harvesting event. Though increasing skidder traffic resulted in significantly higher soil bulk density and reduced levels of aspen regeneration after one summer of growth following winter harvesting, it is uncertain whether this will lead to long-term effects as the forest matures. As areas that experienced the highest level of disturbance and a reduced level of regeneration only account for a very small portion (1-2%) of the harvest block, it is unlikely that these changes will have a drastic influence on the health and sustainability of the future forest. The soil bulk density in these areas remained below a root growth limiting level and still had a moderate level of aspen regeneration. Although slash coverage up to 60% did not have an effect on aspen regeneration, further research is needed to improve the use of UAVs and remote sensing as a method for the calculation of slash loading. Finally, the assessment of cumulative effects across a harvested block using PCA, PCR analysis, and fuzzy logic analysis is a new method for trying to better understand how different factors (natural and anthropogenic) interact and influence the level of regeneration following a harvesting event. This new method could offer industry and government an effective decision support system from which they will be able to gain a new level of knowledge from current harvesting operations to influence the planning and management of future harvesting operations and ensure the least unwanted disturbance occurs. This new method also offers forest industry and government a new strategy for delineating harvested blocks into smaller management regions to achieve a more detailed and holistic assessment of regeneration across entire harvested blocks. In conclusion, the information and knowledge gained through this research suggests that tree length winter harvesting is an ecologically sustainable practice for harvesting mature aspen stands in the Duck Mountain Provincial Park to ensure that aspen regeneration is adequate to maintain a healthy and productive aspen forest into the future.

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# Appendix A:
# Common names and Latin names of major early successional species

**Table A-1:** Common names and Latin names of major early successional species found across the harvested blocks in the Duck Mountain Provincial Park, SK.

| Common Name | Latin Name |
|---|---|
| **Canopy Species** | |
| Balsam Poplar | *Populus balsamifera* |
| Paper Birch | *Betula papyrifera* |
| Trembling Aspen | *Populus tremuloides* |
| **Understory Species** | |
| Aster | *Aster spp.* |
| Beaked Hazelnut | *Corylus cornuta* |
| Bunchberry | *Cornus canadensis* |
| Canadian Goldenrod | *Solidago canadensis* |
| Choke Cherry | *Prunus virginiana* |
| Dewberry | *Rubus pubescens* |
| Fairybells | *Prosartes trachycarpum* |
| Milkvetch | *Astragalus spp.* |
| Mountain Maple | *Acer spicatum* |
| Pin Cherry | *Prunus pensylvanica* |
| Prickly Rose | *Rosa acicularis* |
| Saskatoon | *Amelanchier alnifolia* |
| Spreading Dogbane | *Apocynum androseamifolium* |
| Sweet-Scented Bedstraw | *Galium triflorum* |
| Western Canada Violet | *Viola canadensis* |
| Wild Raspberry | *Rubus idaeus* |
| Wild Sarsparilla | *Aralia nudicaulis* |
| Wild Strawberry | *Fragaria virginiana* |
| Wood's Rose | *Rosa woodsi* |

# Appendix B:
# Soil characteristics of the harvest blocks in the Duck Mountain Provincial Park

**Table B-1:** Summary of soil characteristics for three blocks harvested during the winter of 2015-2016 in the Duck Mountain Provincial Park, SK.

| Horizon | Horizon Depth (cm) | Texture | Calcareous | pH | EC (µs/cm) | Total Carbon (%) | Nitrogen (%) |
|---|---|---|---|---|---|---|---|
| **Block 1 : Orthic Gray Luvisol** | | | | | | | |
| LFH | (10) | - | Non | - | - | - | - |
| Ah | 0-2 | Loam | Non | 5.94 | 142.8 | 3.21 | 0.18 |
| Ae | 2-7 | Loam | Non | 5.51 | 86.1 | 0.95 | 0.01 |
| Bt | 7-43 | Clay Loam | Non | 6.21 | 119.5 | 0.88 | 0.00 |
| Ck | 43-50+ | Clay | Strongly | 7.74 | 311.0 | 2.61 | 0.00 |
| **Block 2 : Orthic Eutric Brunisol** | | | | | | | |
| LFH | (11) | - | Non | - | - | - | - |
| Ahe | 0-3 | - | Non | - | - | - | - |
| Bm1 | 3-22 | Loamy Sand | Non | 6.06 | 74.5 | 0.54 | 0.00 |
| Bm2 | 22-64 | Sand | Non | 6.39 | 42.7 | 0.20 | 0.00 |
| IIC | 64-72 | Sandy Clay Loam | Non | 5.66 | 99.1 | 0.44 | 0.00 |
| IICca | 72-82 | Sandy Clay Loam | Moderately | 7.56 | 251.0 | 1.00 | 0.00 |
| IIIC | 82-90+ | Loamy Sand | Non | 7.76 | 281.0 | 1.27 | 0.00 |
| **Block 3 : Orthic Gray Luvisol** | | | | | | | |
| LFH | (4) | - | Non | - | - | - | - |
| Ahe | 0-4 | Loam | Non | 5.58 | 117.5 | 2.36 | 0.09 |
| Ae | 4-15 | Loam | Non | 5.31 | 73.5 | 0.64 | 0.00 |
| Bt | 15-35 | Clay Loam | Non | 5.56 | 67.0 | 0.70 | 0.00 |
| Bt2 | 35-77 | Sandy Clay Loam | Non | 5.76 | 67.1 | 0.53 | 0.00 |
| Ck | 77-85+ | Sandy Clay Loam | Strongly | 7.56 | 639.0 | 1.91 | 0.00 |

**Table B-2:** Summary of soil characteristics for three blocks harvested during the winter of 2016-2017 in the Duck Mountain Provincial Park, SK.

| Horizon | Horizon Depth (cm) | Texture | Calcareous | pH | EC (µs/cm) | Total Carbon (%) | Nitrogen (%) |
|---|---|---|---|---|---|---|---|
| **Block A: Orthic Gray Luvisol** | | | | | | | |
| LFH | (7) | - | Non | - | - | - | - |
| Ahe | 0-3 | Loam | Non | 6.48 | 231.0 | 4.10 | 0.31 |
| Ae | 3-11 | Loam | Non | 6.27 | 94.3 | 0.76 | 0.00 |
| Bt | 11-55 | Clay | Non | 5.15 | 87.5 | 0.74 | 0.00 |
| Cca | 55-65+ | Clay Loam | Strongly | 7.78 | 240.0 | 1.71 | 0.00 |
| **Block B : Orthic Gray Luvisol** | | | | | | | |
| LFH | (4) | - | Non | - | - | - | - |
| Ahe | 0-5 | Sandy Loam | Non | 5.7 | 77.2 | 1.35 | 0.10 |
| Ae | 5-16 | Sandy Loam | Non | 6.1 | 77.6 | 0.51 | 0.04 |
| Bt | 16-72 | Sandy Clay Loam | Non | 6.17 | 75.0 | 0.58 | 0.06 |
| Cca | 72-80+ | Loam | Moderately | 7.53 | 410.0 | 2.73 | 0.06 |
| **Block C : Dark Gray Luvisol** | | | | | | | |
| LFH | (7) | - | Non | - | - | - | - |
| Ahe | 0-6 | Sandy Loam | Non | 6.54 | 93.8 | 1.07 | 0.09 |
| Ae | 6-12 | Sandy Clay Loam | Non | 6.23 | 73.2 | 0.78 | 0.07 |
| Bt | 12-43 | Clay Loam | Non | 6.15 | 109.3 | 0.93 | 0.10 |
| Cca | 43-50+ | Sandy Clay Loam | Strongly | 7.39 | 267.0 | 3.17 | 0.06 |

Prior to analysis, all samples were air dried and sieved (2 mm) to remove any coarse fragments. Soil texture was determined using the modified pipette procedure developed by Indorante et al. (1990). Soil EC and soil pH were both determined using a 1:2 soil to water ratio (20 g soil: 40 ml distilled water) following the methods developed by Miller and Curtin (2008) and Hendershot et al. (2008), respectively. For the analysis of total soil carbon and nitrogen, a subsample was ball ground prior to analysis. Total soil carbon and total nitrogen was determined using a furnace combustion method with 0.25 g of soil and furnace temperature set to 1100 °C (Skjemstad and Baldock, 2008).

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# Appendix C:
# Weather during winter and summer

All weather data was collected using Environment Canada Historical Weather Data from both the Pelly 2 (Climate ID # 4086001) and Swan River RCS (Climate ID # 504K80K) weather stations. All values represented below are an average between the two weather stations.

Environment Canada, 2018. Historical Climate Data [Online]. Available at http://climate.weather.gc.ca/ (accessed January 2018). Government of Canada, Ottawa, ON.

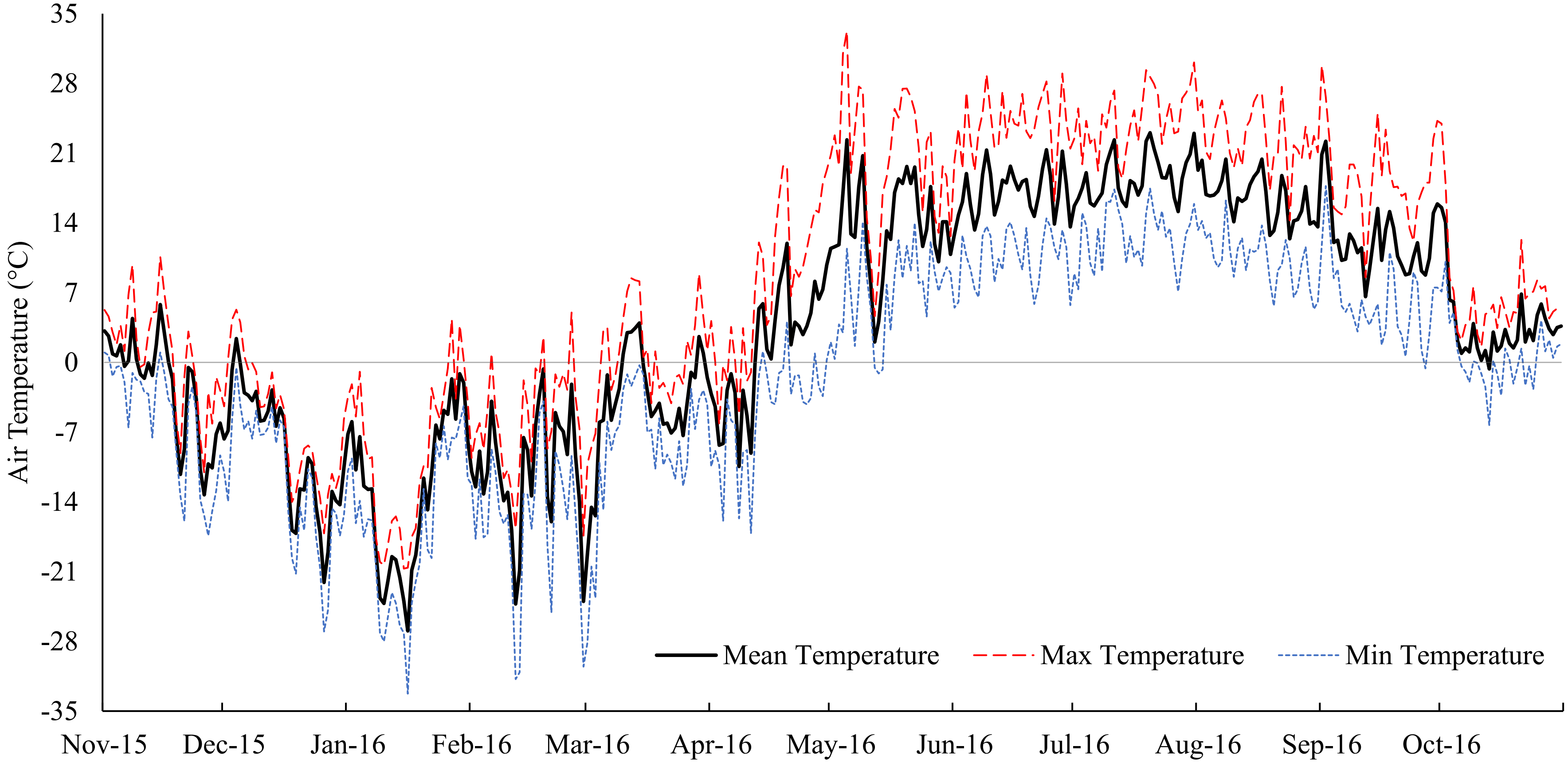

**Fig. C-1:** Daily mean, max, and min air temperature between November 1, 2015 and October 31, 2016 for the Duck Mountain Provincial Park area based on data collected from Environment Canada (Pelly 2 Climate ID #4086001 and Swan River RCS Climate ID # 504K80K).

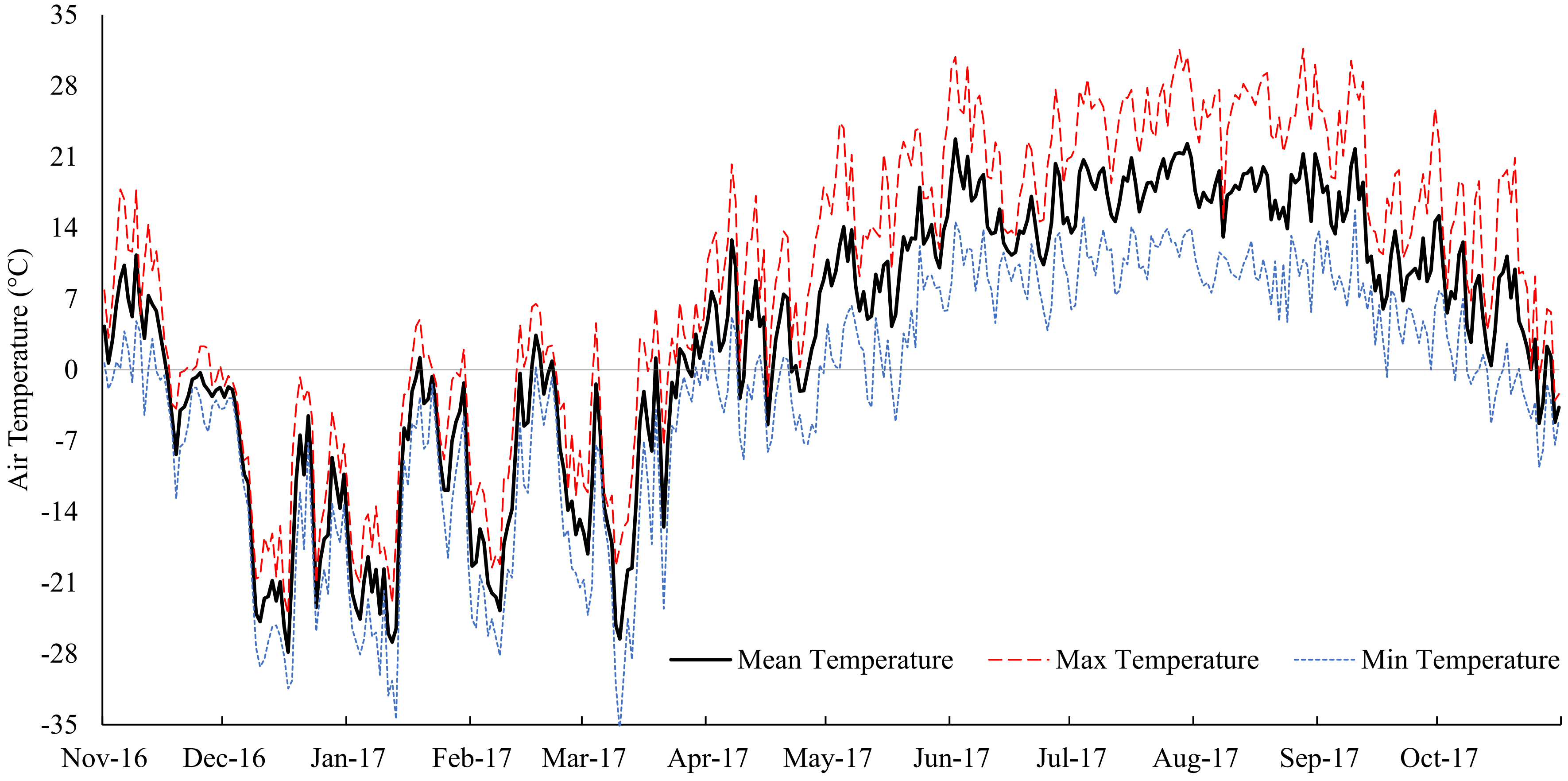

**Fig. C-2:** Daily mean, max, and min air temperature between November 1, 2016 and October 31, 2017 for the Duck Mountain Provincial Park based on data collected from Environment Canada (Pelly 2 Climate ID #4086001 and Swan River RCS Climate ID # 504K80K).

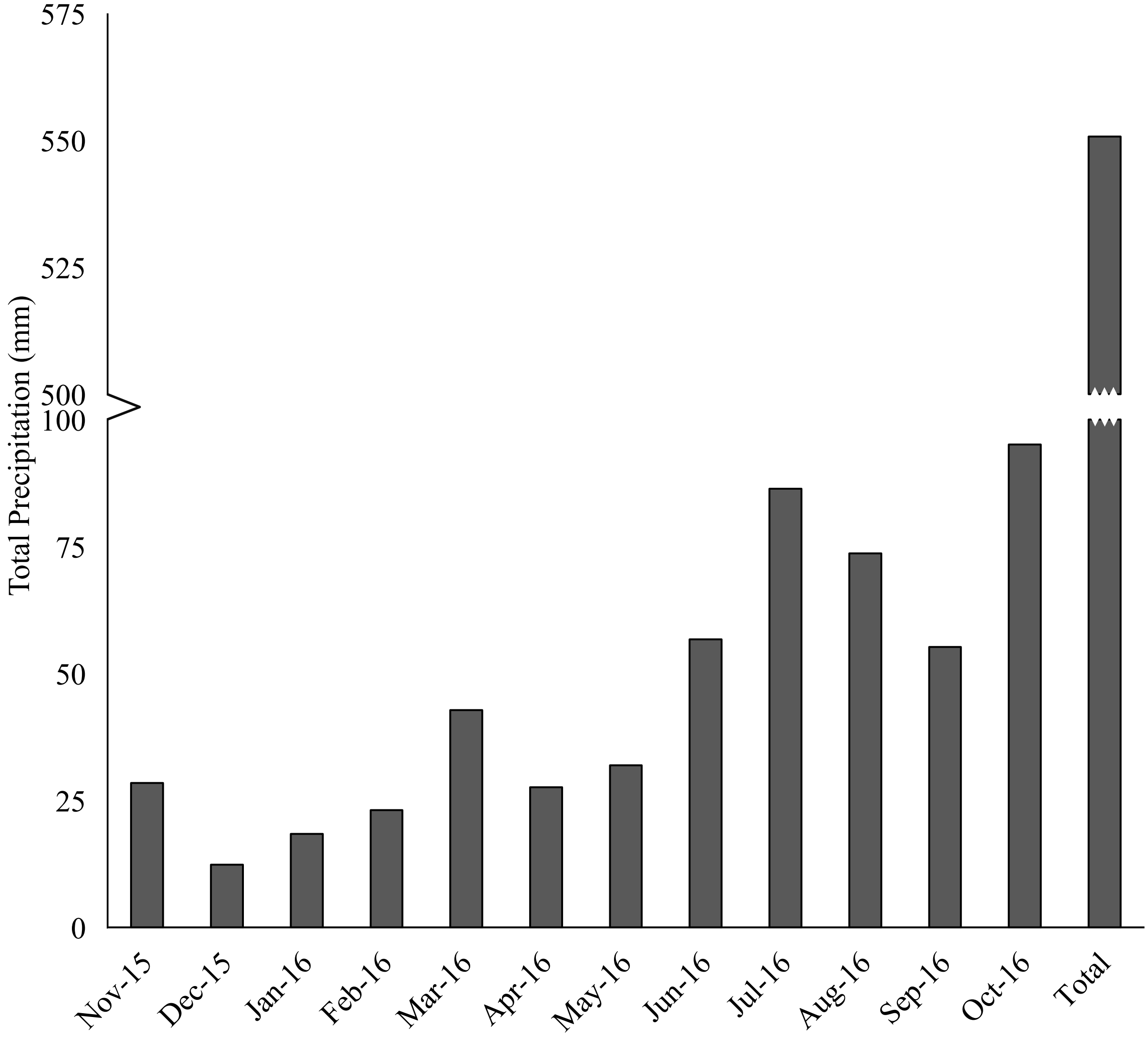

**Fig. C-3:** Total precipitation (rain and snow) by month between November 1, 2015 and October 31, 2016 in the Duck Mountain Provincial Park area based on data collected from Environment Canada (Pelly 2 Climate ID #4086001 and Swan River RCS Climate ID # 504K80K).

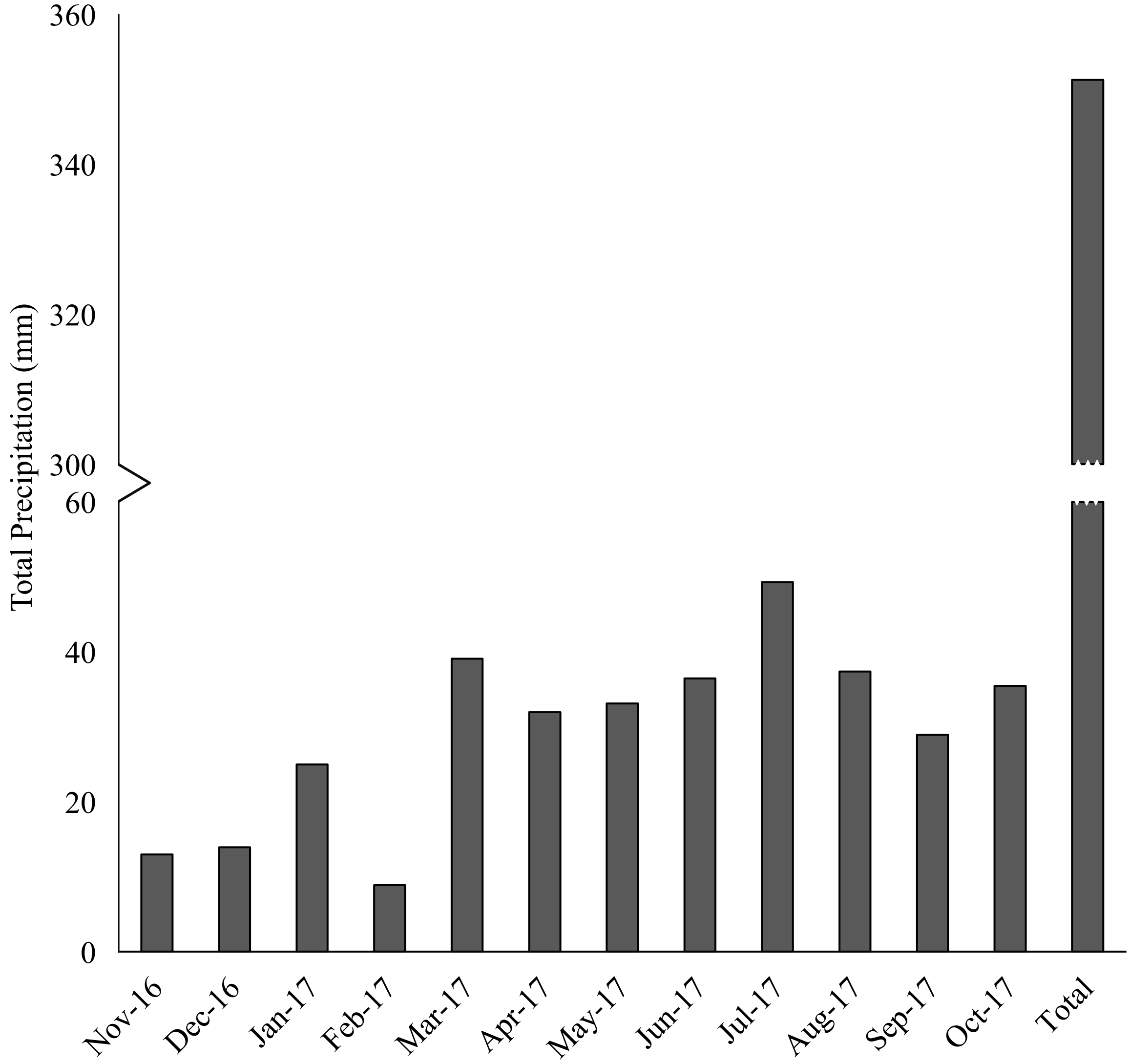

**Fig. C-4:** Total precipitation (rain and snow) by month between November 1, 2016 and October 31, 2017 in the Duck Mountain Provincial Park area based on data collected from Environment Canada (Pelly 2 Climate ID #4086001 and Swan River RCS Climate ID # 504K80K).

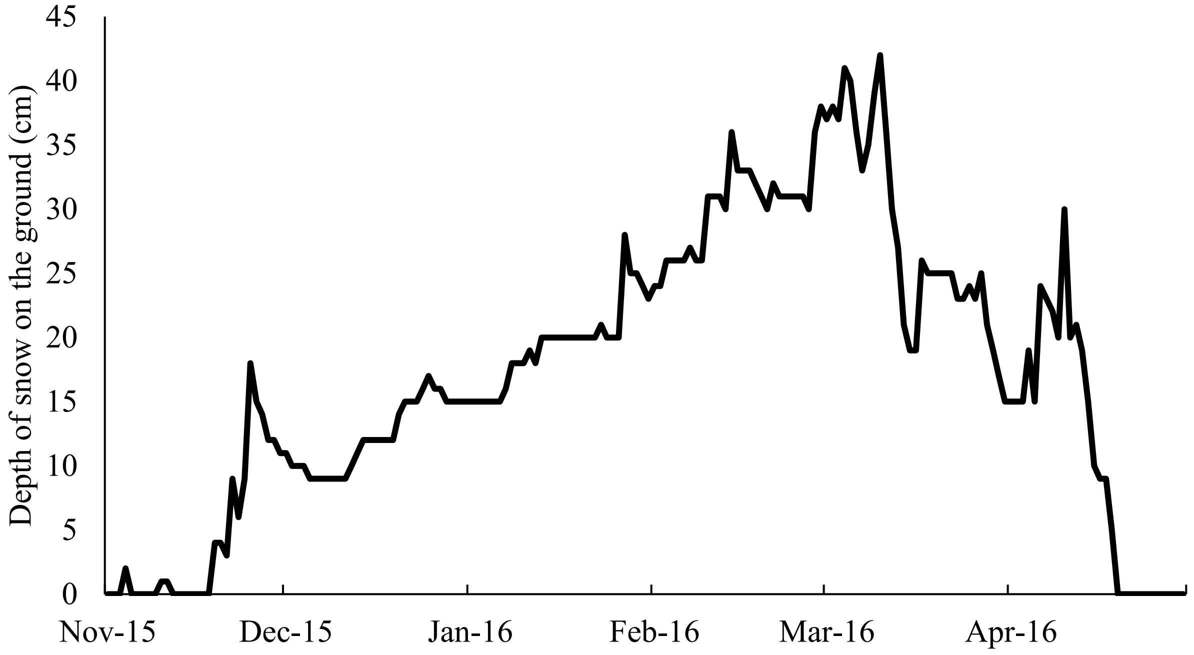

**Fig. C-5:** Depth of snow on the ground between November 1, 2015 and April 30, 2016 in the Duck Mountain Provincial Park area based on data collected from Environment Canada (Pelly 2 Climate ID #4086001 and Swan River RCS Climate ID # 504K80K).

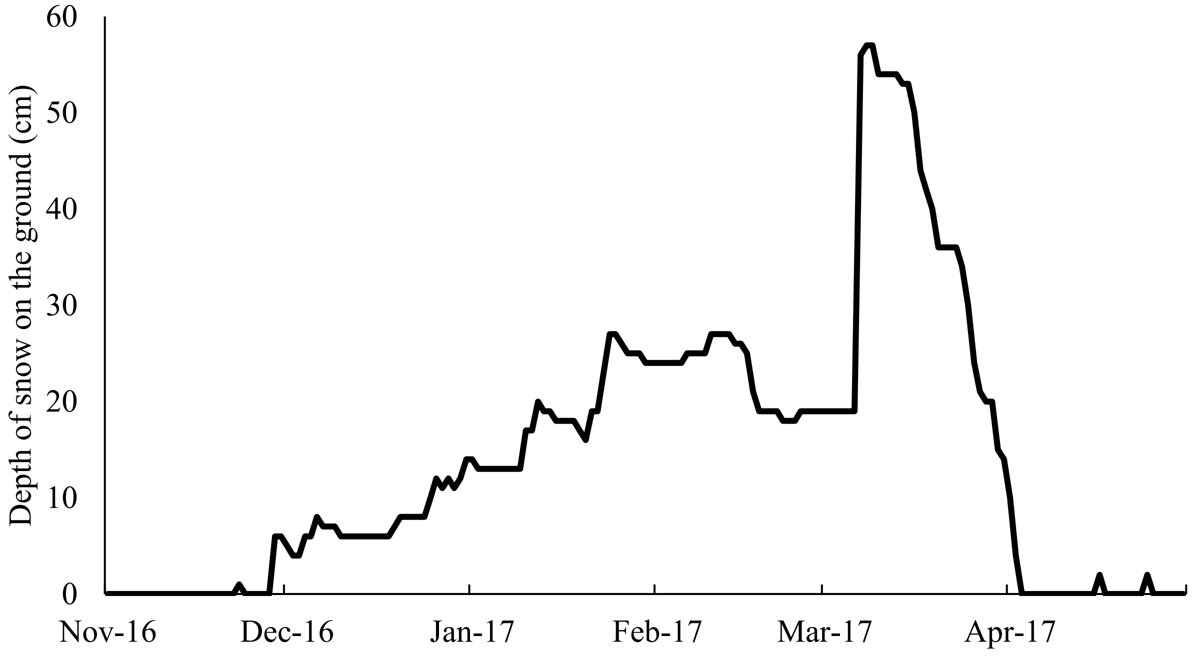

**Fig. C-6:** Depth of snow on the ground between November 1, 2016 and April 30, 2017 in the Duck Mountain Provincial Park area based on data collected from Environment Canada (Pelly 2 Climate ID #4086001 and Swan River RCS Climate ID # 504K80K).

# Appendix D:
# Traffic Intensity Maps

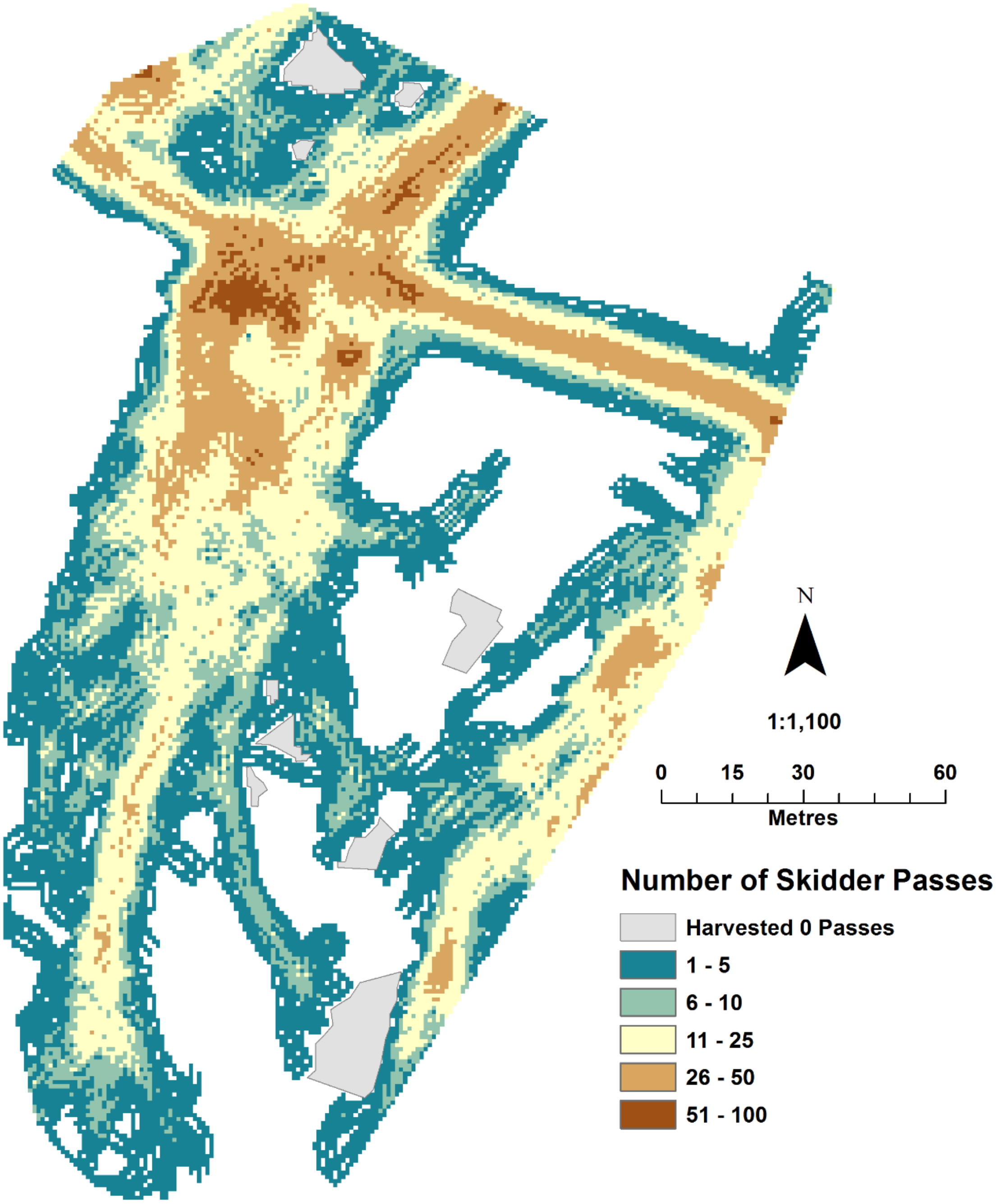

**Fig. D-1:** Skidder traffic intensity distribution across harvested block 1.

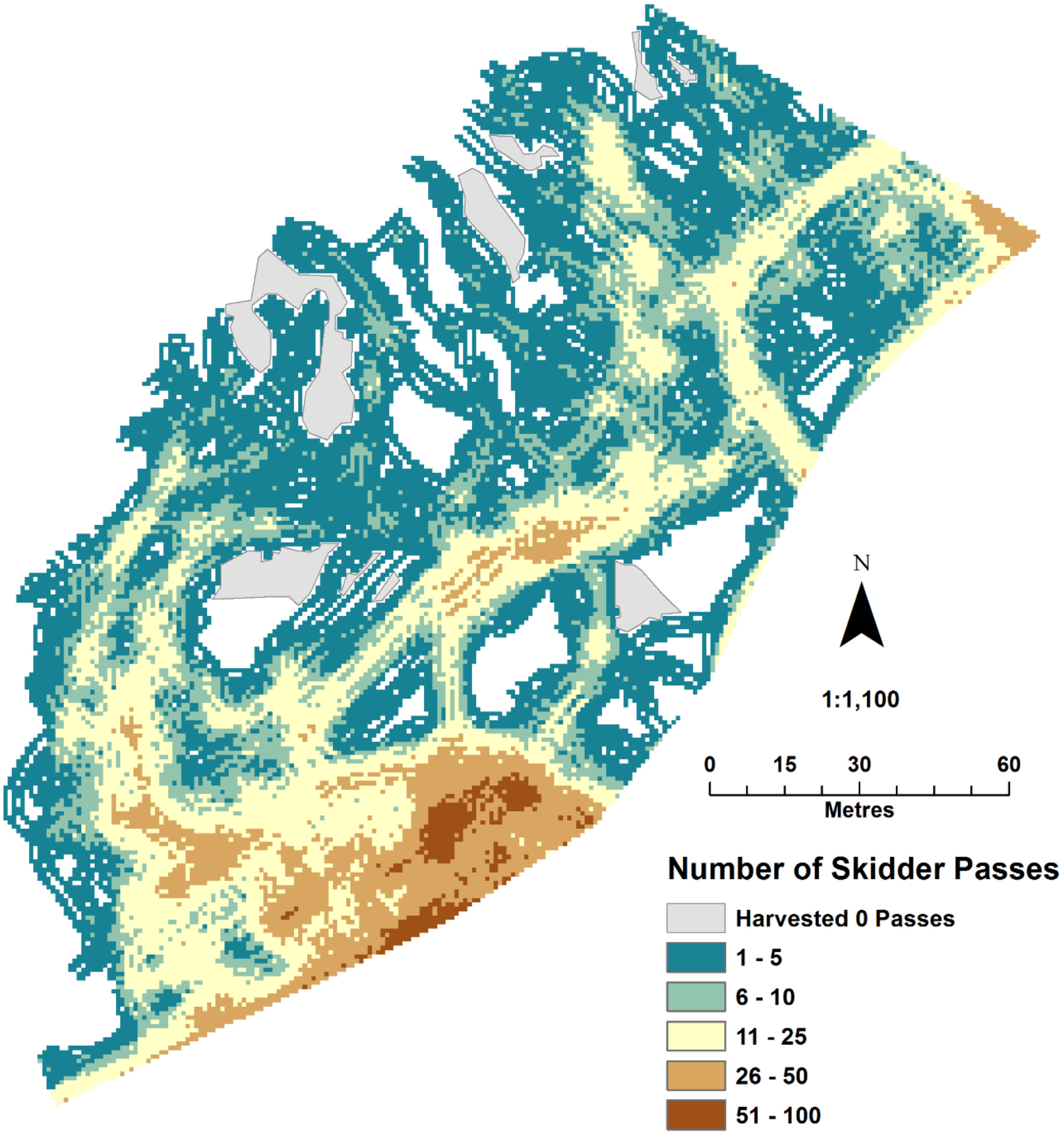

**Fig. D-2:** Skidder traffic intensity distribution across harvested block 2.

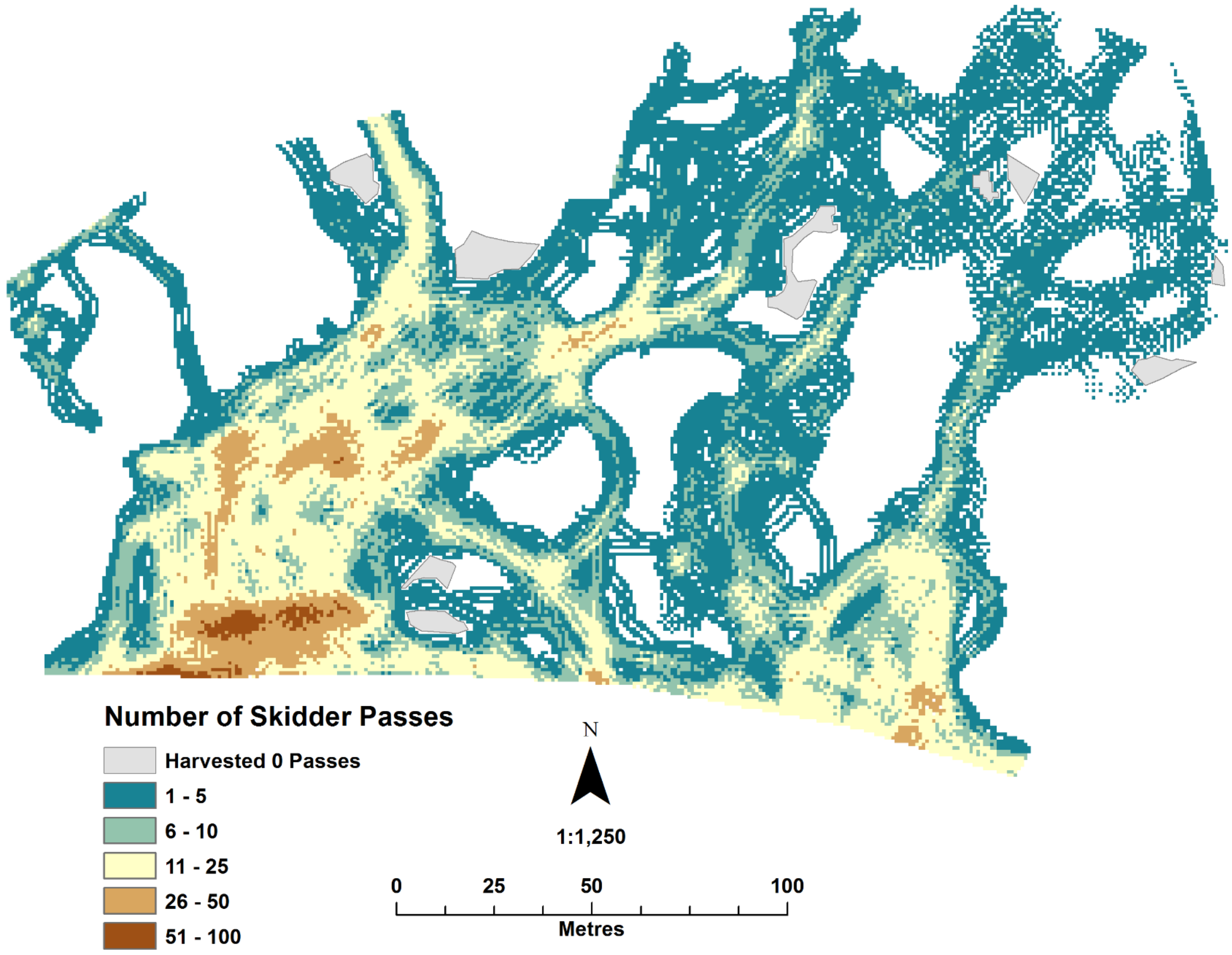

**Fig. D-3:** Skidder traffic intensity distribution across harvested block 3.

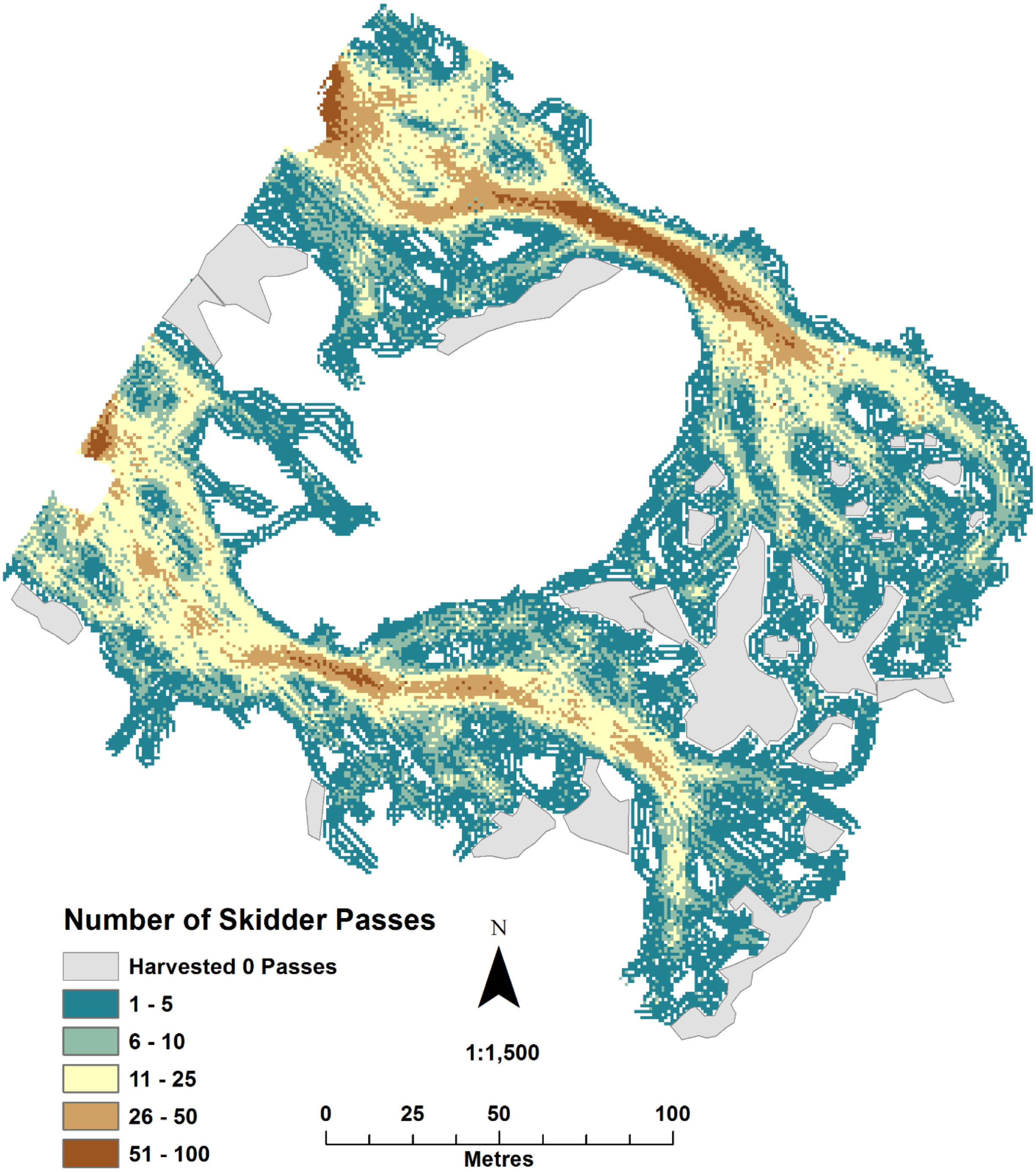

**Fig. D-4:** Skidder traffic intensity distribution across harvested block A.

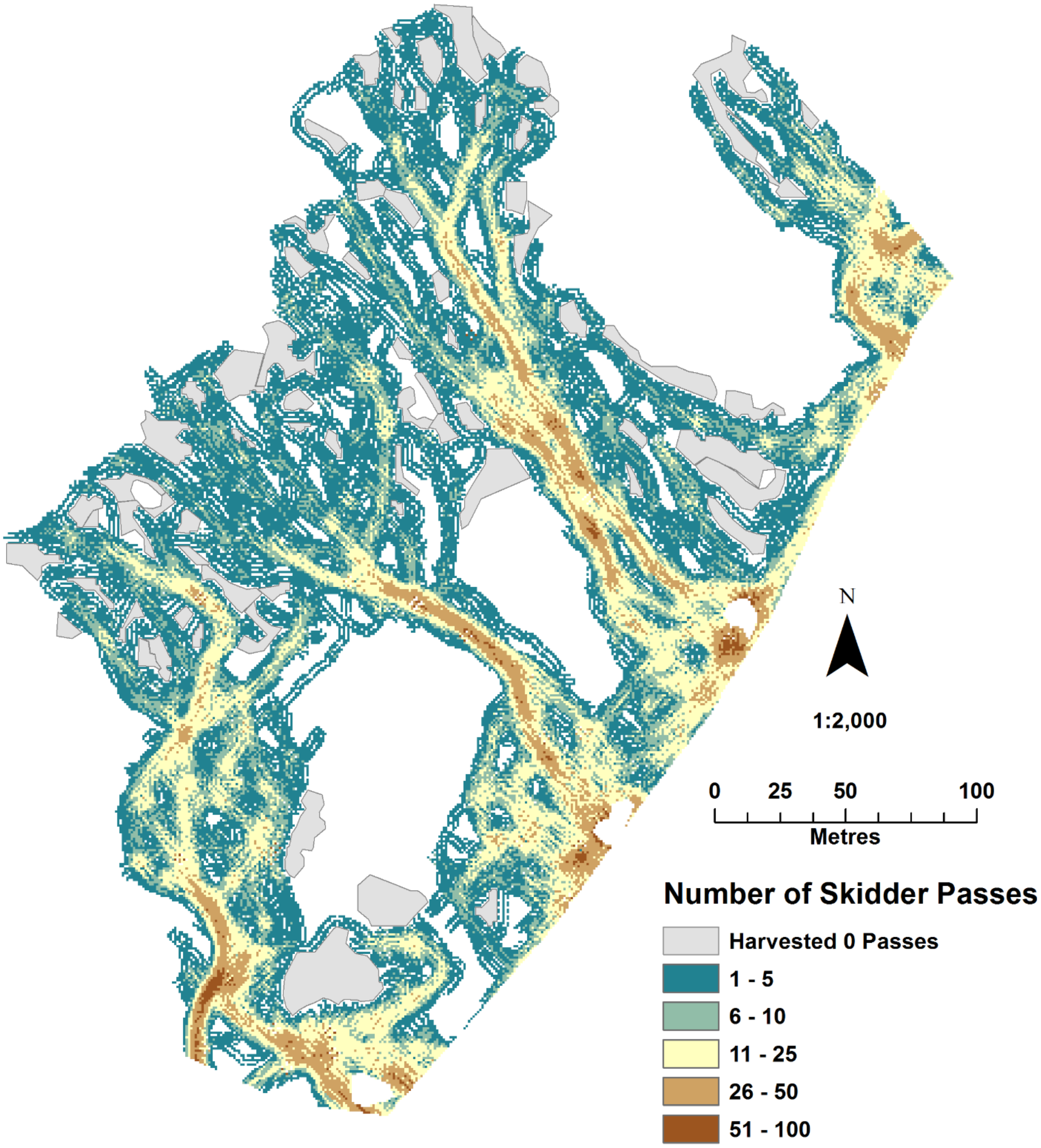

**Fig. D-5:** Skidder traffic intensity distribution across harvested block B.

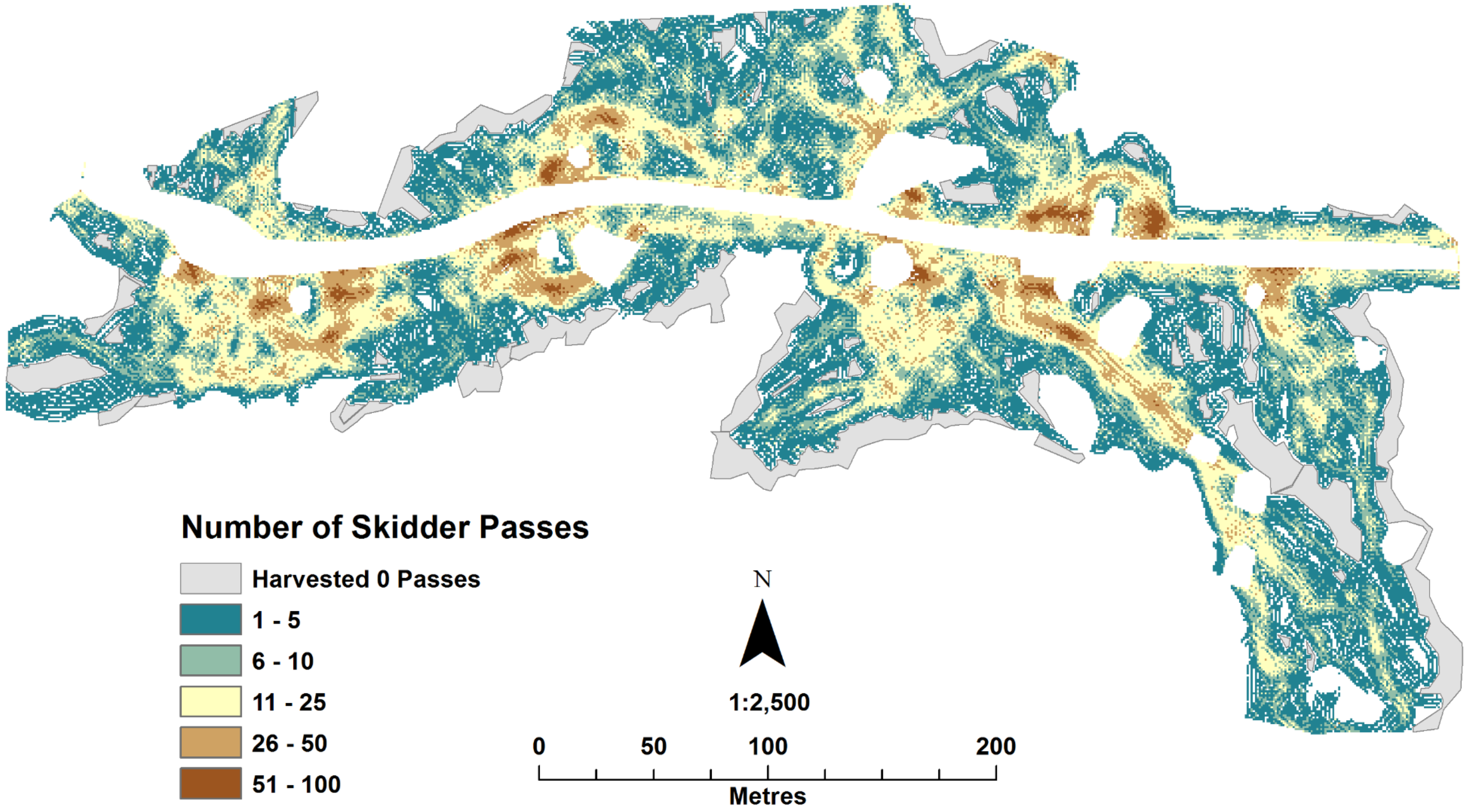

**Fig. D-6:** Skidder traffic intensity distribution across harvested block C.

# Appendix E:
# Slash Coverage

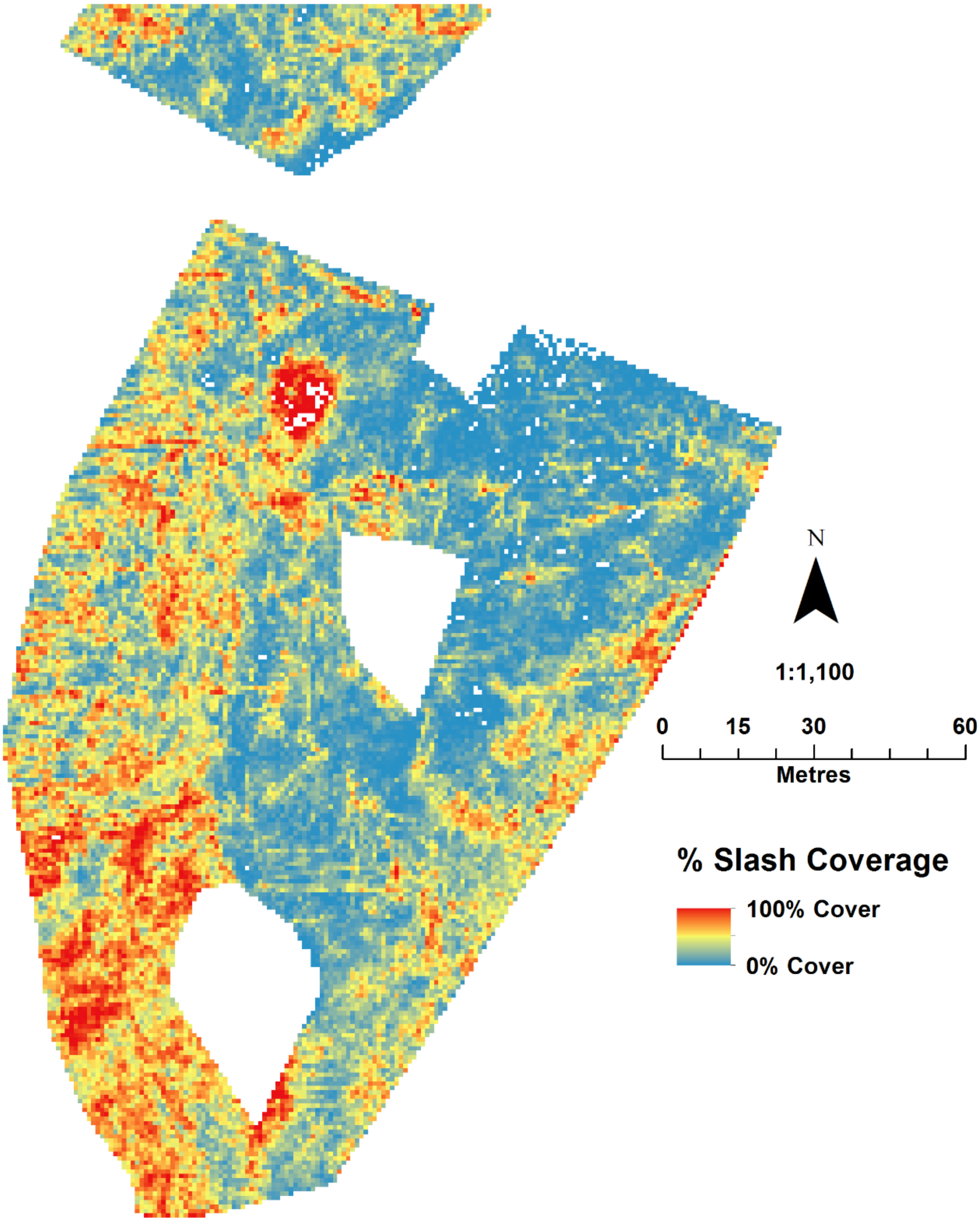

**Fig. E-1:** Percent slash coverage across harvested block 1.

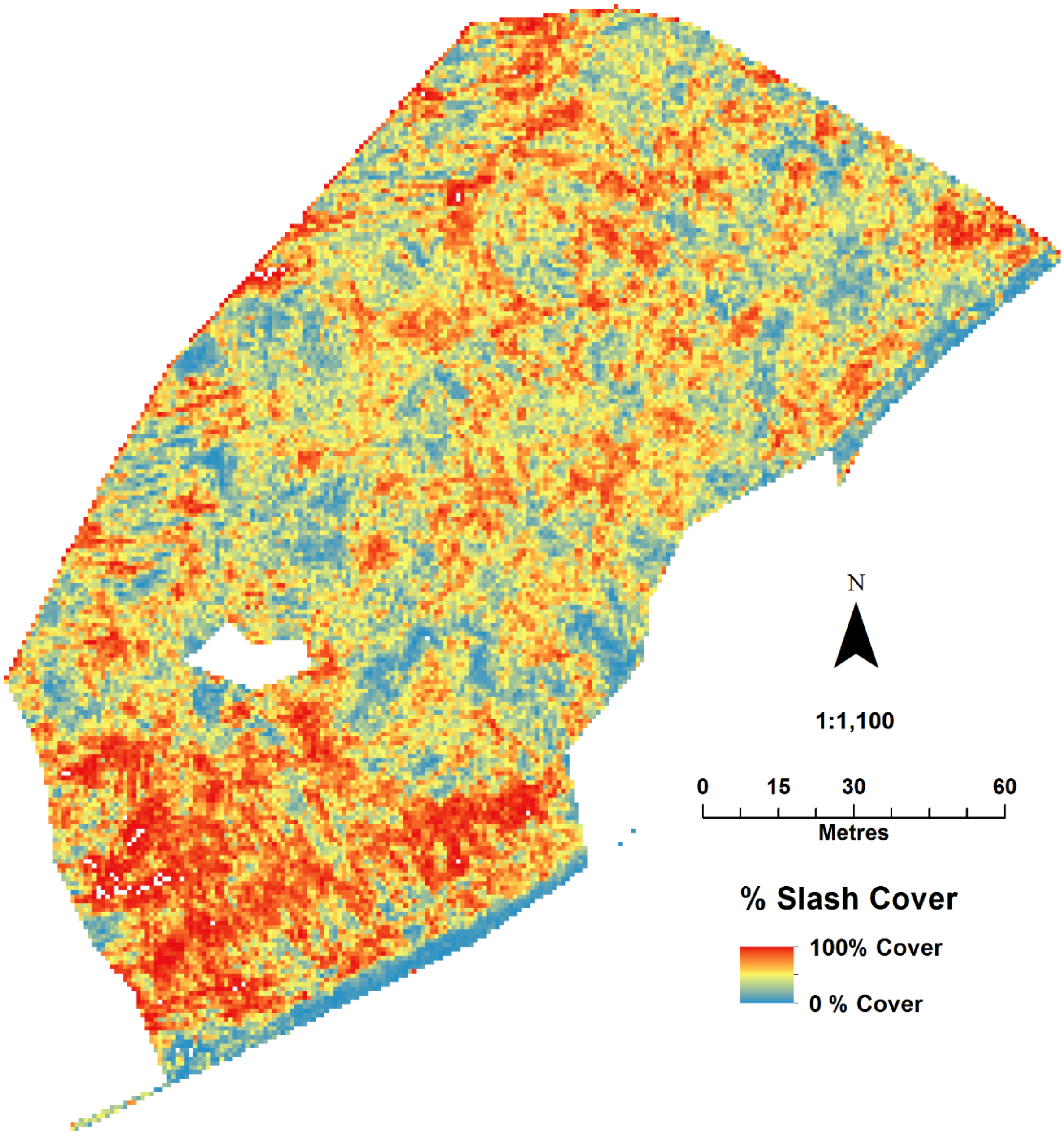

**Fig. E-2:** Percent slash coverage across harvested block 2.

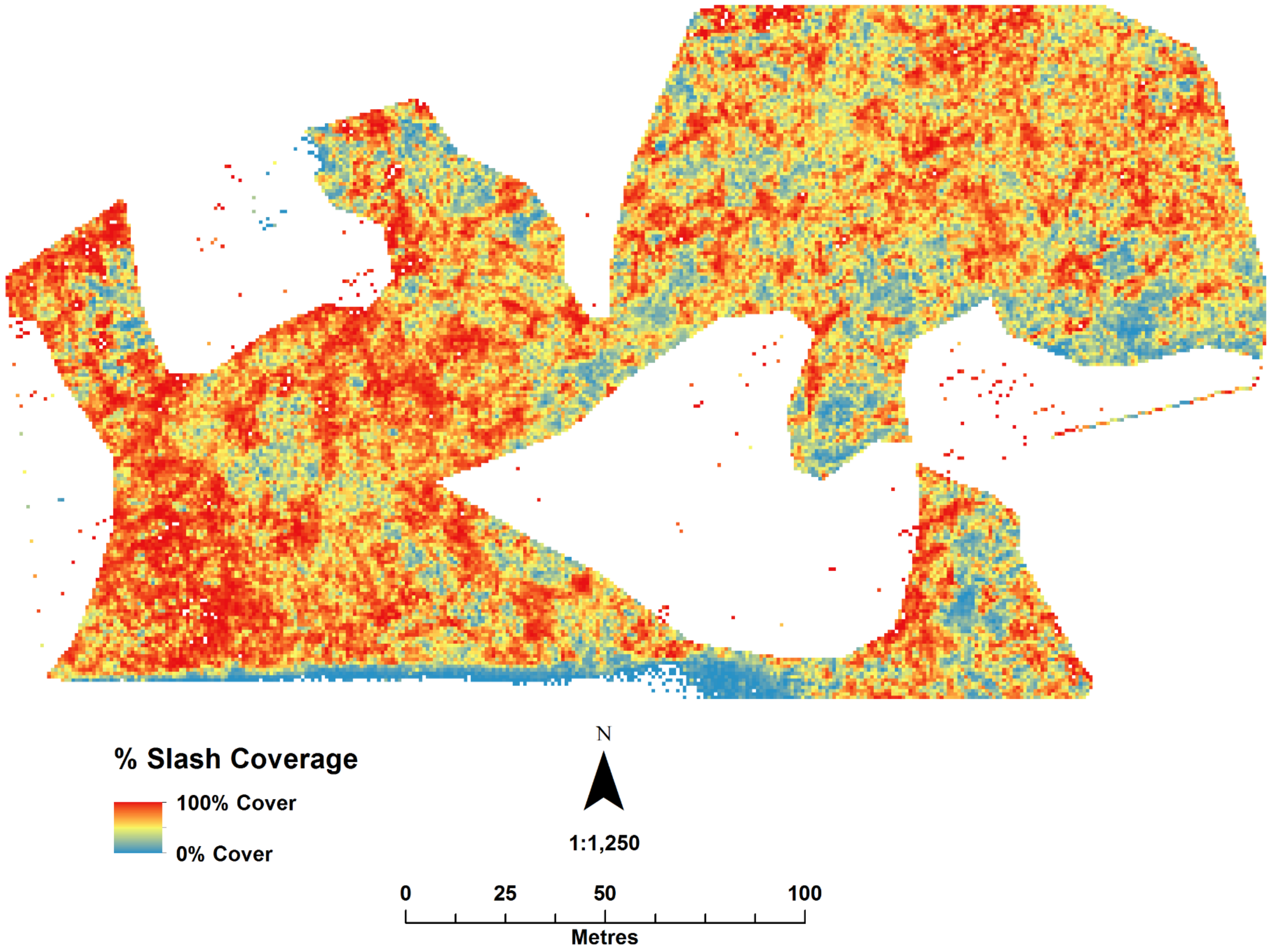

**Fig. E-3:** Percent slash coverage across harvested block 3.

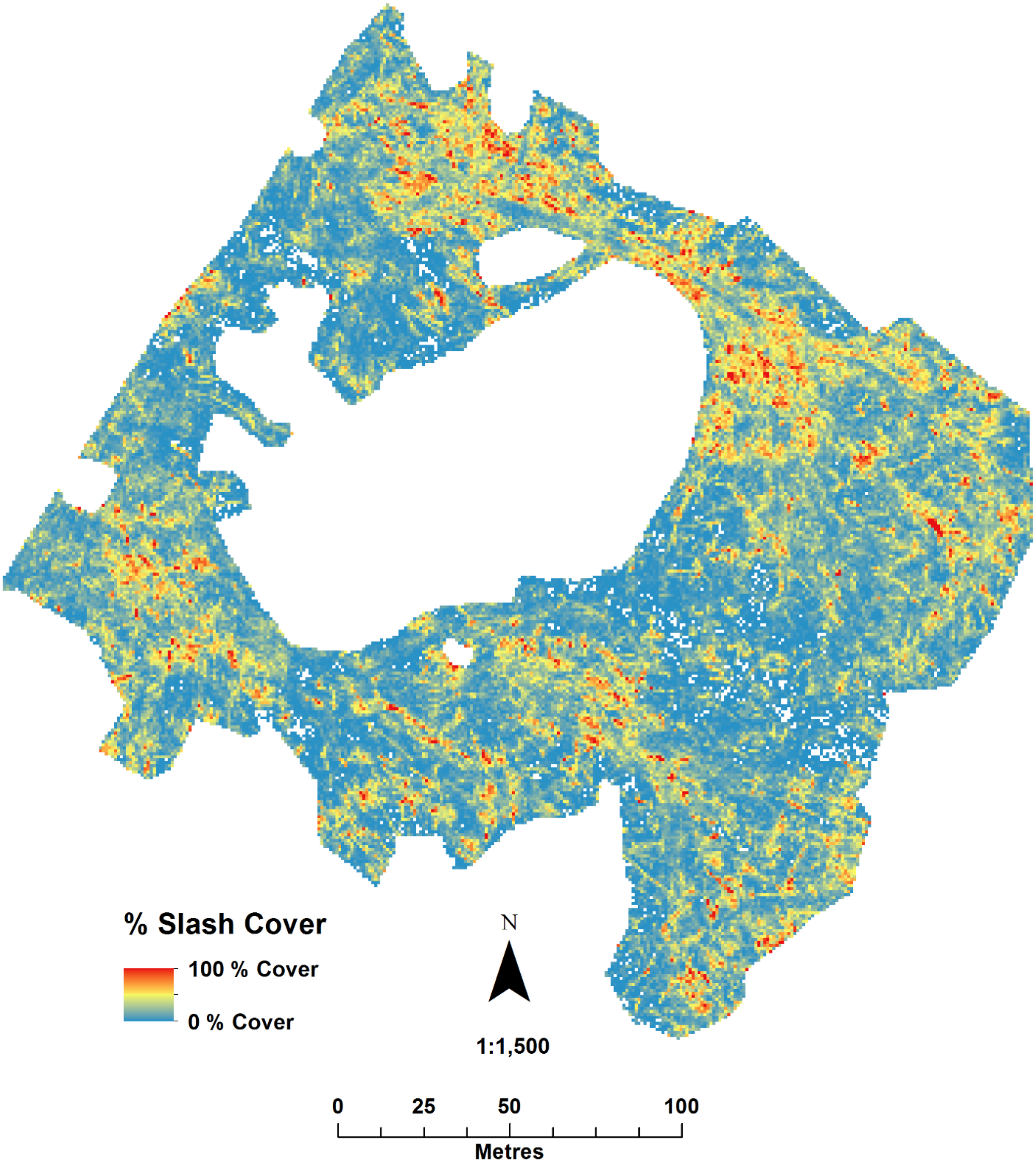

**Fig. E-4:** Percent slash coverage across harvested block A.

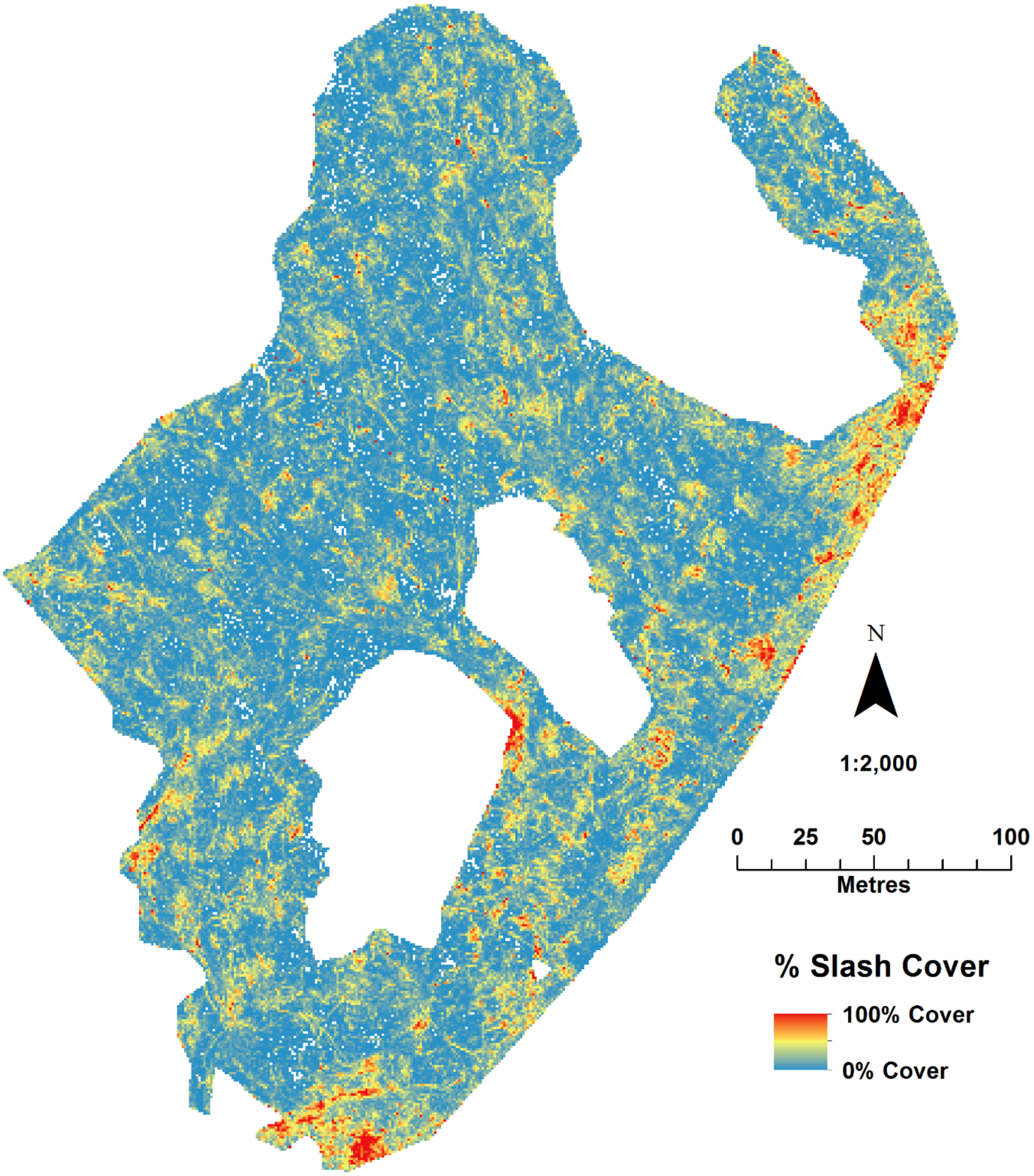

**Fig. E-5:** Percent slash coverage across harvested block B.

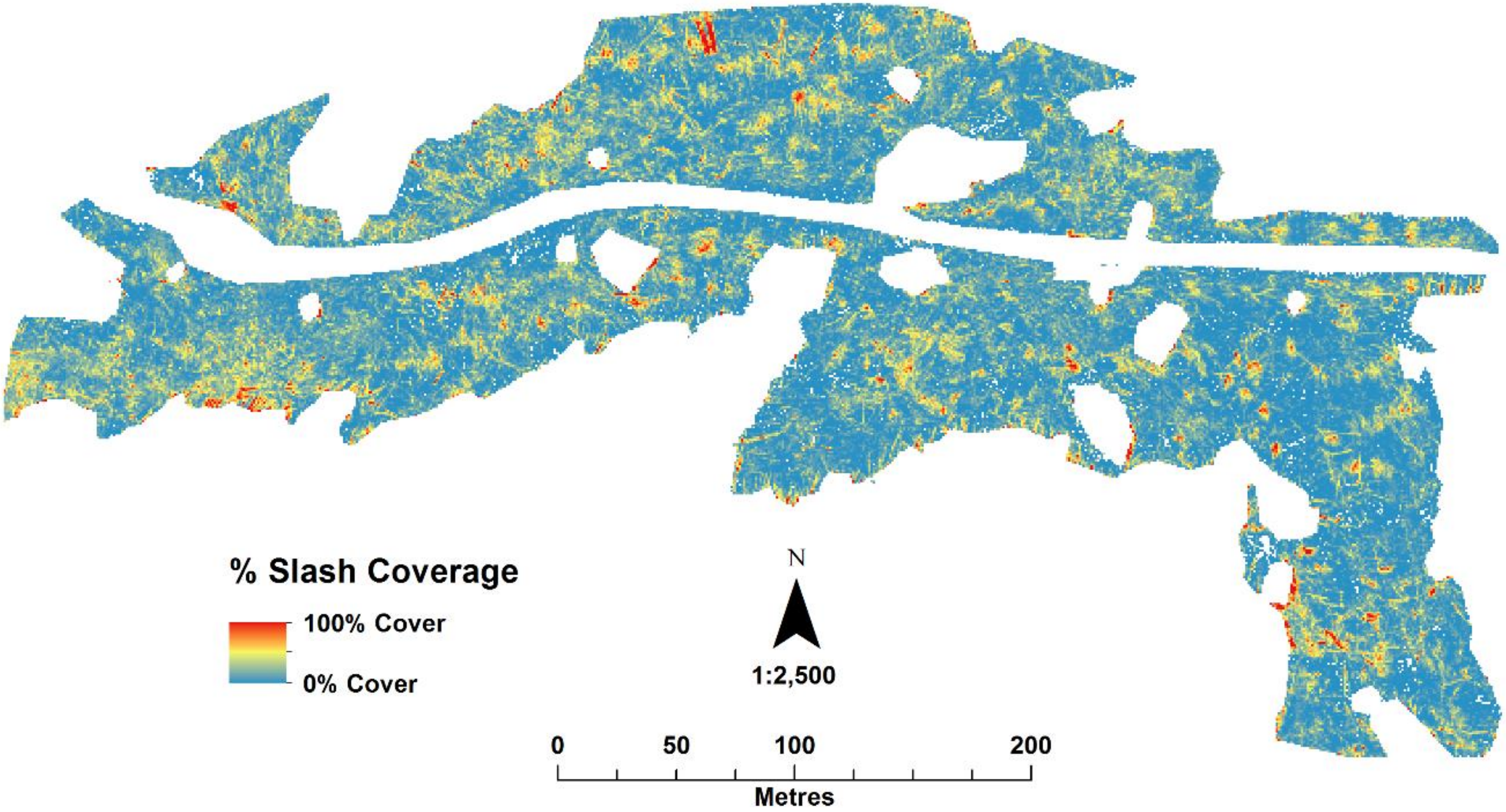

**Fig. E-6:** Percent slash coverage across harvested block C.

# Appendix F:
# Fuzzy Logic Suitability Outputs

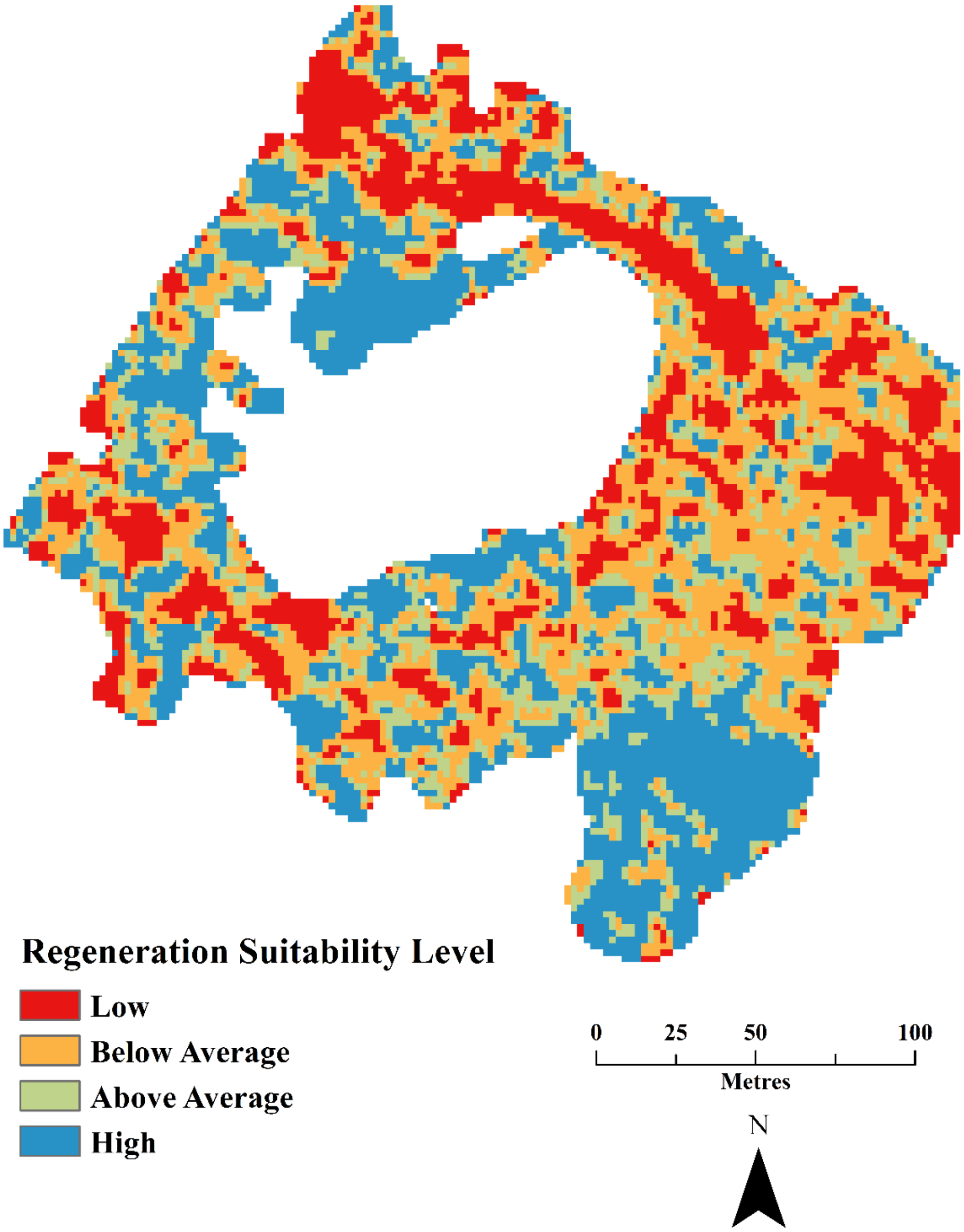

**Fig. F-1:** Regeneration suitability across harvested block A.

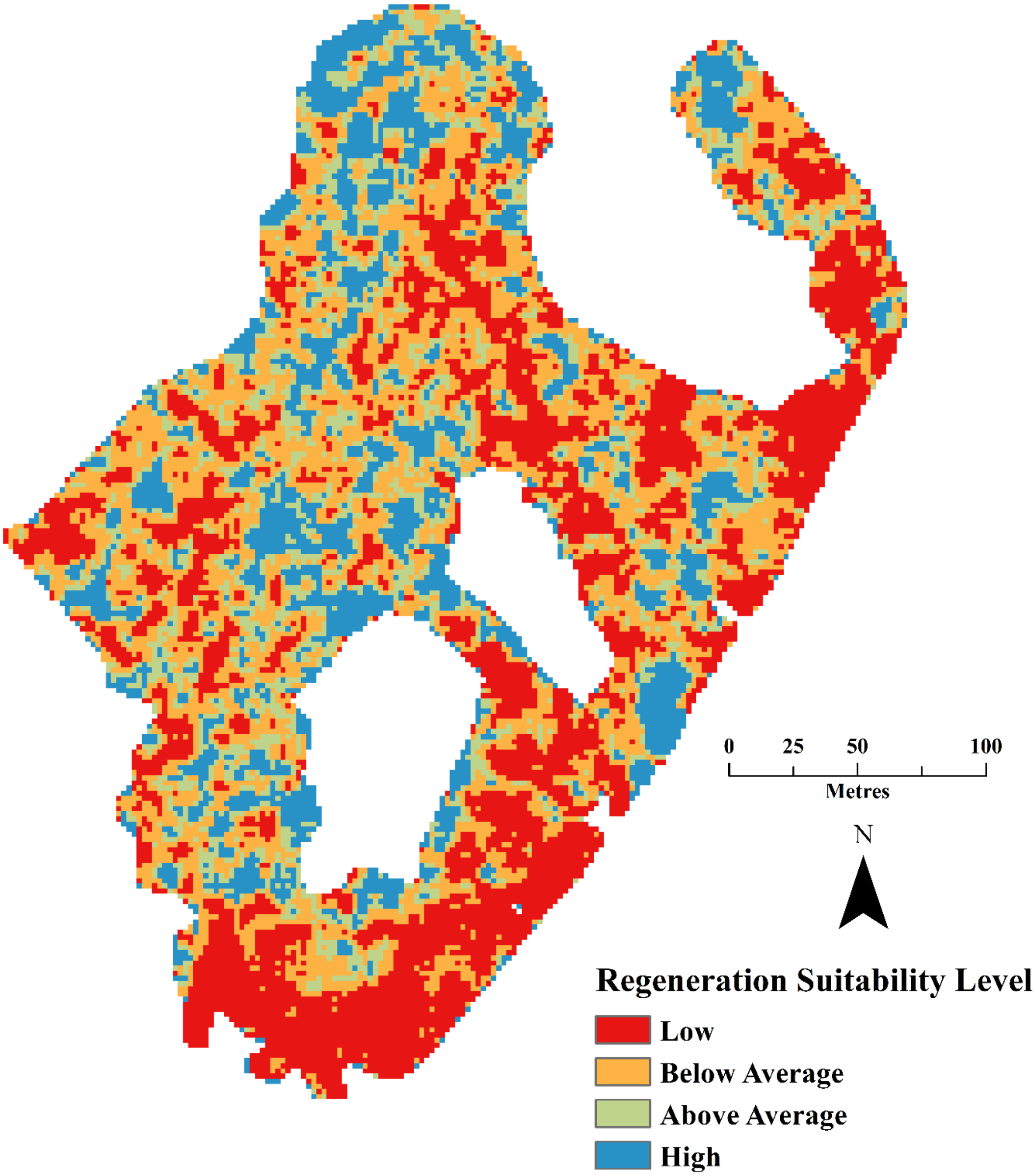

**Fig. F-2:** Regeneration suitability across harvested block B.

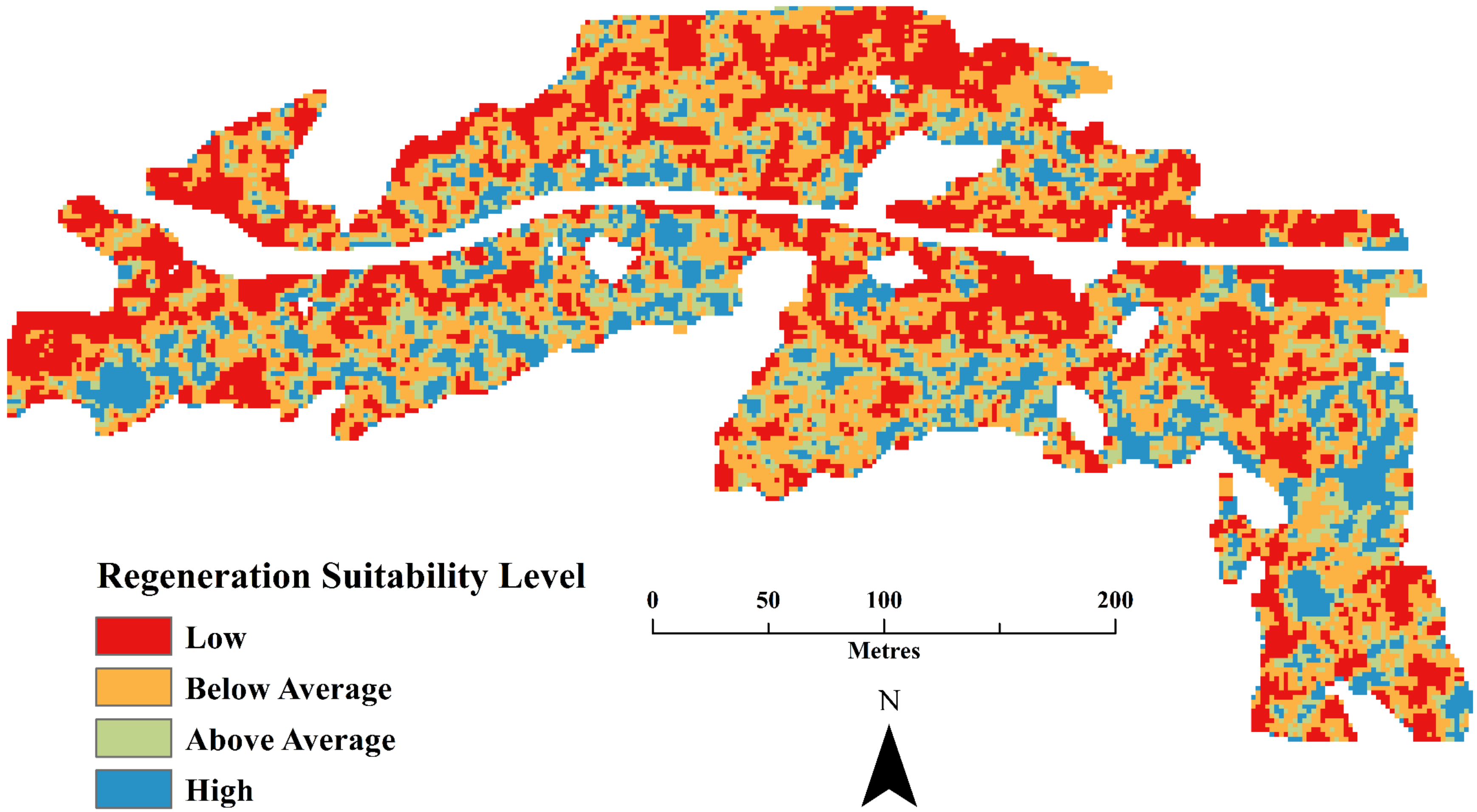

**Fig. F-3:** Regeneration suitability across harvested block C.