EFFECTS OF DIFFERENT INTENSITIES OF THINNING ON GROUND BEETLES (COLEOPTERA: CARABIDAE) IN A BLACK SPRUCE PLANTATION

By

Sylvain Flynn

Faculty of Natural Resources Management

Lakehead University

Thunder Bay, ON

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Sylvain Flynn

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Dr. Seung-Il Lee Major Advisor	Dr. Dave Morris Second Reader

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ABSTRACT

Thinning is a silvicultural practice implemented to maximize harvest productivity. However, biodiversity conservation is a growing trend, therefore it is important to understand the short, and long-term effects of thinning on biodiversity. Ground beetles (Carabidae) play an important role as bioindicators of overall forest health. In order for forest managers and policymakers to balance economic growth and sustainability, we must understand how to implement optimal thinning practices. Ground beetles were sampled in replicated (n = 3) 15-year post-mechanical thinning plots ((CC): 100% basal area removal, heavy thin (HT): 45%, light thin (LT): 25%), 62-year-old mature site (controlled (CT)), and an 80-year-old untouched black spruce forest (reference (REF)). A total of 10234 individuals across 21 species were collected. Species richness was highest in reference (REF), and lowest in clearcut (CC). Total catches did not differ statistically among treatments. Heavy thin was found to be within controlled and light thin ordination. This may indicate that ground beetle biodiversity is not negatively affected by heavy thinning. It also illustrates that heavy thinning, light thinning, and controlled intensities share similar community structures. Overall, results conclude that heavy thinning and light thinning show similar recovery patterns, which could indicate that heavy thinning may not negatively impact the long-term recovery of ground beetle assemblages unless denoted as a forest specialist (narrow niche). Although REF and CT share similarities in stand age, there are still major differences in total catches and species composition.

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ACKNOWLEDGEMENTS

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INTRODUCTION

Biodiversity loss has been increasing worldwide, primarily due to anthropogenic factors, such as agriculture, deforestation, and the general degradation of natural ecosystems for human gain (Verschuyl et al., 2010; Haddad et al., 2015). Although conservation-oriented forest management has been steadily increasing worldwide, it is estimated that over a third of all forest cover has been lost over the past three centuries (Haddad et al., 2015). Biodiversity loss is exasperated by fragmentation – the process by which land is divided into smaller disconnected patches or fragments, typically due to clearcut logging, road construction, agriculture, and development. This leads to several issues such as habitat loss and isolation, negative edge effects, reduced ecosystem services, and increased small-scale weather events (Marrec et al., 2021). The rate at which species tend to decline is mostly associated with the ability to immigrate and emigrate within fragments and the overall intra or inter-specific competition found within fragments (de Lima Filho et al., 2020). Species richness and species abundance are strongly associated with the size of a habitat. Also, fragmented populations decline over time due to stochastic events such as a reduction in genetic drift, environmental incompatibility due to edge effects, competition, fire, and resource depletion (Duchesne 1993; de Lima Filho et al., 2020).

Fragmentation in the forestry sector can be limited by commercial thinning. This silvicultural practice improves tree growth and enhances the overall health of the forest by reducing stand density (Tsai et al., 2018). Commercial thinning improves the overall production and timber quality of the stand. Removing smaller and less valuable trees also substantially increases light availability at the understory level due to the formation of larger gaps in the canopy (Tsai 2018). The rapid change in understory species composition leads to an increase in biodiversity. (Bartels 2010; Tsai 2018). Thinning also affects nutrient inputs and soil properties due to understory disturbances. Ultimately resulting in changes in species richness and abundance of insects and microorganisms, primarily due to differences in forest floor structure and decomposition (Tsai 2018). In this study, three different thinning treatments were studied 1) light thin, 25% basal area removal. 2) heavy thin, 45% basal area removal. 3) clearcut, 100% basal area removal.

Insects are the most diverse and speciose class of arthropods on earth with an estimated 5-15 million species, and about 1.06 million species have been described as of 2017 (Scudder 2017). Insects play a critical ecological role in natural resources, agriculture, human health, and ecosystem health and services (Scudder 2017). They are essentially the foundation of all terrestrial ecosystems as they provide a plethora of benefits including sources of food for most taxa, the circulation of nutrients, pollination, soil fertility and structure, and population control (Scudder 2017).

More specifically, beetles (Order: Coleoptera) are the most diverse group of organisms on earth, comprising 40% of all insects (Bouchard et al., 2009; Scudder 2017). Due to the sheer number of species (358,000 described), it remains a challenge to estimate how many are still out there to be discovered. However, estimates point to a range between 850,000-4,000,000 (Bouchard et al., 2009). Among these beetles, the family Carabidae makes up approximately 8% of the whole beetle species with an estimated 40,000 species (Bouchard et al., 2009). Carabid beetles are extremely important in determining the overall health of a forest stand as well as determining the quality of a habitat, specifically in northern temperate regions such as the Boreal (Jopp and Reuter 2015; Duchesne 1993; Bouchard 2009). Specifically, ground beetles (Carabidae) contribute to several critical ecosystem functions, such as controlling pests, eliminating organic materials, dispersing seeds indirectly, preserving soil structure, and nutrient cycling (Gallo, 1997). Carabid beetles have been studied in the past to address important ecological questions in the realm of agriculture, fire management, retention harvesting, clear-cutting practices, soil science, habitat fragmentation, pollution effects, biodiversity conservation, and biogeography/species dispersal (Jopp and Reuter 2015; Duchesne and McAlpine 1993; Bouchard et al., 2009).

For example, a study by Belluz et al., (2022) concluded that carabid assemblages differed within microsites based on understory composition. Belluz et al., (2022) also concluded that carabid species assemblages differed between post-harvest and post-wildfire stands. Also, assemblages did recover to pre-harvest and pre-fire levels over time, but recovery time differed according to species.

Similarly, in the prairies of southwestern Alberta, sites that were prescribed-burned without logging had higher ground beetle species richness than sites that were burned with logging (Gandhi et al., 2008).

A study by Duchesne (1993) suggested that carabid species assemblages vary according to abiotic and biotic factors such as vegetation cover, rates of decomposition soil nutrients, and temperature. Results concluded that burned sites showed the highest value for biodiversity, while clearcut showed the least. However, both sites found an increase of carabid catches 3.9 and 2.7 times that of controlled sites. Finally, results from a study by Wu et al., (2018) states that retention harvest triumphs over clear-cutting practices in terms of biodiversity conservation. However consistent with Belluz et al., (2022), substantial species loss occurred directly after harvest (1-2 years) with clearcut having the largest effect. It is evident that environmental and anthropogenic variables influence carabid assemblages and alter microsite habitat variability and species turnover rates.

The effects of thinning and clear-cutting as disturbances for carabid beetles are not entirely well known. Research gaps include 1) limited observations and low rates of recapture, resulting in short-term dispersal data (Jopp 2015). Long-term multi-year sampling is necessary to ensure accuracy. 2) No environmental data has been acquired. Counts are strictly on species abundance and richness. Future studies are necessary to evaluate beetle dispersal rates according to thinning treatment and microsite conditions. In this case, the effects of light availability on community structure following post-lateral growth canopy closure. As mentioned above, light availability post-thinning is documented, however lacking is long-term post-thinning data on the eventual re-closure of these canopies over time and how they affect understory species diversity (Tsai 2018). 3) Due to the proximity of the plots, species turnover will likely produce larger β-diversity and gamma-diversity numbers. It would be beneficial to research edge effects to determine whether dispersal rates are specific to each treatment.

Forest edges play an important role in maintaining carabid species richness and can act as source habitats for dispersal between treatments (Magura, 2000). Numerous carabid species are commonly found in harvested stands and the interior can migrate to the edge of the forest, thereby populating it with carabids from adjacent stands. This result suggests that forest edges could function as source habitats for species that are considered to be more generalists.

According to a long-term study by Haddad et al., (2010), on the world's forest cover, 70% of the remaining forest is fragmented and vulnerable to degradation within one kilometer of the forest's edge. A summary of fragmentation studies conducted over 35 years, across five continents, numerous biomes, and sizes shows that habitat fragmentation reduces biodiversity by 13–75% and damages important ecosystem services by changing nutrient cycles and lowering biomass. Most importantly, the article mentions that the effects of fragmentation are more prominent in small fragments less than 1000ha.

The current research addresses three relevant objectives: 1) Produce a comprehensive biodiversity report in Northwestern Ontario on ground beetles in both a black spruce plantation and an untouched mature black spruce forest. 2) Provide long-term baseline data for evaluating the impacts of thinning on biodiversity. 3) Compare abundance, species richness, and community structure of ground beetles among different intensities of 15-year post mechanical thinning, clearcut, and uncut forests. I also propose two hypotheses tied to objective three: 1) Ground beetle community structure in light thin is more similar to the beetle community structure of untouched forests. (CT/REF). 2) Beetle abundance and species richness in clearcut would be lower than in light and heavy thinning treatments as well as un-thinned and natural forests.

LITERATURE REVIEW

1.1 FOREST MANAGEMENT AND COLEOPTERA

Lindenmayer (2006) proposes five guidelines for managing forests; maintaining connectivity, maintaining geomorphological and hydrological processes, maintaining stand structural complexity, maintaining landscape heterogeneity, and ensuring that human disturbances are kept as similar as possible to natural disturbances. The current research considers the relationship between ground beetle assemblages and factors influencing guidelines for managing forests and biodiversity. Insects play a vital role in ecosystem services, and more specifically, beetles play a special role in the preservation of important food webs and trophic levels (Jennings and Tallamy 2006). Therefore, we must understand the ecology of microhabitats to better manage forest ecosystems on higher trophic levels.

Maintaining connectivity (Lindenmayer 2006) has been shown to promote biodiversity conservation through techniques such as retention harvesting, which has been steadily increasing over the years as a better alternative to clear-cutting. (Wu et al., 2018). This practice reduces fragmentation by minimizing the total number of felled trees in a stand, therefore increasing the rate at which species assemblages recover from disturbance (Work 2010). Ground beetle diversity and various levels of retention have been studied by Work (2010) (0% clearcut, ≈10%, ≈20%, ≈50%, ≈75%, and 100% uncut). Results concluded that <50% retention did not retain the same species assemblage as an uncut stand, however,>50%-75% showed similar results to uncut stands. Similarly, a study by Wu et al., (2018) concluded that thinning better maintains beetle assemblages than clearcut stands. Also concluded is that beetle assemblages recover much faster in higher retention (such as light thin) stands than in lower retention stands (heavy thin). Wilson and Carey (2000) suggest that leaving snags, logs, dead trees, and other downy debris further increases the rate of recovery to pre-harvest levels and maintains species richness to near old-growth levels.

Furthermore, maintaining stand structural complexity (Lindenmayer 2006) is facilitated by mechanical thinning. The distribution and richness of insects on landscapes are influenced by several factors, including the ratio of habitat edge to interior, the isolation of habitat fragments, patch area, patch quality, patch diversity, and microclimate. (Hunter, 2002)

Mechanical thinning is a silviculture practice in which stand density is reduced to increase forest health, timber quality, maintain ecosystem services, and improve biodiversity conservation (Verschuyl et al., 2010; Tsai et al., 2018). It is used extensively in forest management to meet economic objectives and biodiversity targets (Lindenmayer et al., 2006; Tsai et al., 2018). Thinning allows foresters to remove trees that would otherwise be a risk, such as diseased trees or damaged and insect susceptible trees (Wainhouse and Speight 1989). However, thinning may also increase the chances of root-rot pathogens entering recently cut stumps. This can be mitigated by ensuring that trees are cut in late fall and early winter (Wainhouse and Speight 1989). Lindenmayer (2006) claims that species loss is primarily associated with habitat loss, which is why an emphasis on biodiversity conservation is at the forefront of silvicultural practices.

Speight and Wainhouse (1989) suggests that temperatures fluctuate greatly within forests among the various microhabitats inhabited by insects. One of the most significant contributors to these local variances is insolation, which generates local heating. The sun can shine directly on tree trunks in low-density forest stands, near forest edges, or after thinning, causing local heating. The amount of sunlight that penetrates the forest floor is determined by both tree type and density (canopy closure), and it is often substantially lower in plantations than in natural stands. However, successive thinning improves average light intensity, allowing site-specific ground flora to grow (Speight and Wainhouse 1989).

Mechanical thinning, as reported by Tornamen (2020), has the potential to improve the long-term diversity of understory vegetation by reducing canopy tree density and encouraging regeneration. While one explanation holds that less canopy cover promotes greater ground vegetation, which serves as a host for Coleoptera species, Tornamen's research finds a discrepancy: increases in Coleoptera biomass were connected primarily with increases in bare ground, not ground vegetation. This unexpected find could be related to the fact that many Coleoptera species overwinter in the soil, emerging as late as August. Furthermore, Belluz et al., (2022) observes that the relative abundance of plant species reflects underlying abiotic variables such as soil pH, moisture, and sunlight exposure, all of which influence carabid assemblages on the ground.

1.2 CARABID BEETLE COMMUNITY STRUCTURE AND COMMON SPECIES

Bousquet's (2013) comprehensive checklist of Canadian and Alaskan beetle species accounts for 8237 species, of which 4513 can be found in Ontario. Ground beetles (Carabidae) account for 532 species, and they play an invaluable role in ecosystem services and biodiversity conservation (Bergmann et al., 2012; Bousquet

2013). Carabids are important bioindicators of habitat quality and change related to natural and anthropogenic disturbances. Carabids share a large portion of the soil biomass, making them important predators for invertebrates and other woodland, grassland, and agricultural pests. (Duchesne and McAlpine 1993; Paquin 2008; Bergmann et al., 2012; Busch et al., 2021). Carabid beetles are especially important in the northern climates of the boreal forest as primary biological indicators of forest health, primarily after a major disturbance, such as clear-cutting, natural fire and prescribed burning, windthrow, or disease (Duschesne and McAlpine 1993). Other anthropogenic factors, such as pollution, scarification, fragmentation, land reclamation, climate change, and land management of old and new-growth forests have also been studied alongside beetle community structure (Duschesne 1993 and McAlpine; Bergmann et al., 2012; Scudder 2018).

A study by Duschesne and McAlpine (1993) compared carabid beetle catches collected from undisturbed jack pine stands, clearcut stands, and burned-over stands. Their results concluded that species richness was highest in burned-over sites and was lowest in clearcut sites. However, species abundance was higher in clearcut sites. Furthermore, the authors concluded that species assemblages were significantly different between the three treatments. A study by Tormanen (2020) concluded with similar results, whereas burned-over sites yielded higher species numbers while thinned stands were met with increased Coleoptera biomass, or species abundance. A study by Paquin (2007) also concluded that higher species numbers are more likely on disturbed sites while higher species richness will be found on burned sites.

Saint-Germain et al., (2005) discovered that assemblages were not highly unique to individual environments, but there was significant variation in abundance and species dominance between treatments. Capture rates were found to be higher in logged stands and lower in burned stands.

Similar species found in North America include *P. coracinus* Newm*, P. pensylvanicus* Lec*, P. adstrictus* Eschscholtz*,* and *P. punctatissimus* Randall*.*

P. melanarius and P. coracinus share many similarities, specifically in their morphology and life cycles. The primary morphological difference is in the shape of the pronotum, whereas *P. melanarius* has two pointed edges at the anterior corners of its pronotum, while *P. coracinus* is characterized by a rounded pronotum. They both have one activity cycle per year (May-June until September-October), however, the number of individuals for P. *coracinus* tends to peak earlier than P. *melanarius* (Barlow, 1970). *P. coracinus* is also a summer-autumn breeder, meaning that they share similar niches as larvae and adults (Barlow, 1970). In Canada, *P. melanarius* can be found in every province except LB, while *P. coracinus* can be found in ON, QC, NB, NS, PE, LB, and NF (Bousquet et al.,., 2013)

P. pensylvanicus and *P. adstrictus* are much smaller in size than *P. melanarius and P. coracinus.* They are quite difficult to differentiate due to very minute details such as an extra seta on the inner front tibia, or slightly longer and wider striations near the scutellum. Both species are capable of two cycles per year (climate dependent), however, most females are tenerals during the first two weeks of activity, and by eight weeks the majority of females are already gravid (Barlow, 1970). The range of *P. adstrictus* stretches further north than *P. pensylvanicus*, however both are found occupying the same forest habitats of the Boreal/Taiga. It is believed that the northern range limit of *adstrictus* is due to their capacity for oviposition in colder climates (Goulet, 1971).

1.3 MANAGEMENT OPTIONS FOR *PTEROSTICHUS MELANARIUS*

Forestry Practices

Carabids are often used in forest ecosystem research as they are extremely sensitive (and adaptive) to their environments. Moreover, they are an important indicator species for monitoring different effects of forest management practices on biodiversity due to their generalist nature and predatory instincts (Werner & Raffa, 2000; Thomas et al.,., 2008; Avtaeva et al., 2021)

For example, a study by Thomas et al.,. (2008) on olfaction prey detection of soil-dwelling larvae of *P. melanarius* revealed that not only can adults detect prey through olfaction, but larvae can as well. Results concluded that dead slugs did not induce the same response as live slugs, however, larvae do appear to locate their subterranean prey through olfaction (Thomas et al., 2008). This is important biological information to digest in the presence of the development of biological control agents for specific operations, especially in an agricultural setting to reduce slug populations.

Werner & Raffa (2000) conducted a study on forest management practices on ground-dwelling beetles over a two-year period. They have concluded that it is important to maintain a wide range of forest types to maintain the biodiversity of ground-dwelling beetles. This is largely due to three important factors regarding forest fragmentation/thinning: there is an increase of species that are common in open habitats; a disappearance of forest specialists; and a decline in forest generalists (Werner &

Raffa., 2000). Studies like these are important in determining optimal thinning treatments for specific forest types. That way, we can better implement biodiversity conservation targets into forest management operation guidelines.

Agriculture Practices

P. melanarius is an important species used as biological control agents in agricultural practices due to their predatory nature (slugs, aphids, caterpillars, beetle larvae), as well as their generalist nature and ability to resist some insecticides. However, agricultural tillage may affect their activity density by up to 50% due to the destruction of the top layer of soil, therefore affecting overwintering larvae (Werner & Raffa, 2000; Labrie et al., 2003; Alvarez et al., 2012; Avtaeva et al., 2021; Busch et al., 2021). Preference is given to grain crops such as rye, maize, and wheat, however, pumpkin, tomato, beet, cabbage, and various fruit crops are also important habitats for them (Matalin, 2006).

A study by Alvarez et al., (2012) evaluated the efficiency of *P. melanarius* on the Colorado potato beetle (CPB), L*eptinotarsa decemlineata* (Say). Results concluded that *P. melanarius* adults consumed up to 61 CPB eggs and 24 larvae in a 24-hour period. Results also concluded that a single *P. melanarius* consumed up to 55 aphids in a 24-hour period. Finally, the conclusion was that predation rates were four times higher on the lower portion of crops rather than the upper portions. Overall, the study concluded that *P. melanarius* is a valuable biocontrol agent for potato field pests (Alvarez et al., 2012).

A study by Labrie et al., (2003) evaluated the agricultural impacts of organic and integrated pest management (IPM) orchards in Quebec, Canada on *P. melanarius.*

Results concluded the following: there were no differences in the development stability of *P. melanarius* between IPM and organic orchards; total catches were higher in IPM orchards despite the use of insecticides, which means that natural products such as copper sulphate, diatom powder, or Bt Foray may be even more destructive to carabid species. This is important because it suggests that *P. melanarius* as a biological control agent may be more effective for crop health than previously thought (Labrie et al., 2003).

MATERIALS AND METHODS

2.1 AIRSTRIP COMMERCIAL THINNING SITE AND REFERENCE SITE

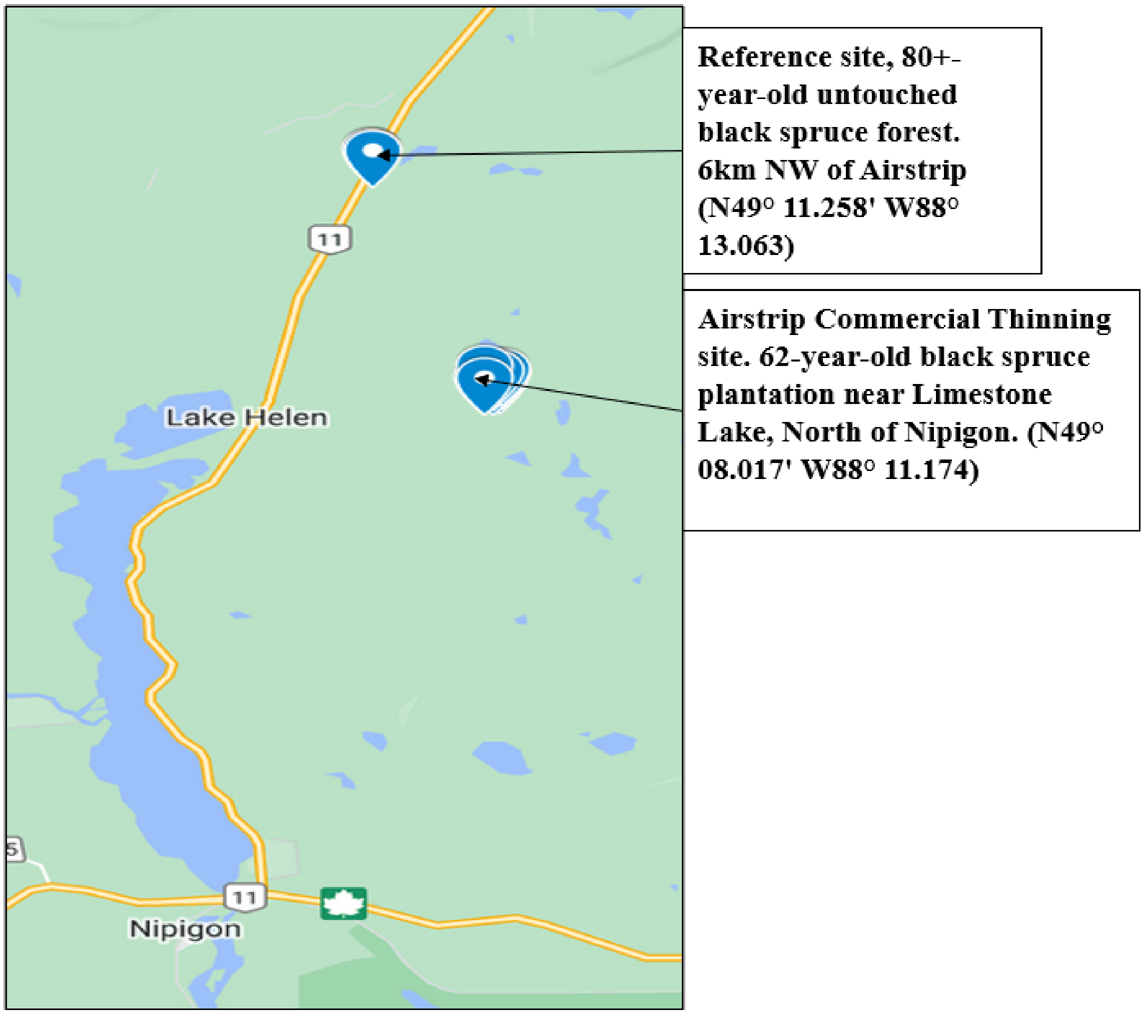

Figure 1: Location of the Airstrip Commercial Thinning Site and Reference Site

The Airstrip Commercial Thinning site is situated approximately 20km north-east of the town of Nipigon. It is a 62-year-old black spruce plantation near Limestone Lake (N49° 08.017’ W88° 11.174). The plantation is situated on a lacustrine clay plain of the Superior Forest and covers Ecoregion 3W of Ontario’s Ecological Land Classification (Reid et al., 2009). It is characterized by its short warm summers and long cold winters. The annual mean temperature is approximately 0.2°C and includes 80 frost-free days (Reid et al., 2009). The site was established by forester George Marek who at the time, worked with the Ministry of Natural Resources. The experimental design used for the site is a popular design known as a Randomized Complete Block Design (RCBD) It is often initiated on small square plots (100m x 100m) to ensure that replicates can be assigned at random such that any differences or variations can be studied in relation to adjacent sites (Brisson 2023, Maxfield 2023). The site has been planted solely with black spruce at a spacing of 5 x 6 feet (Brisson 2023) and includes three levels of mechanical thinning intensities; Clearcut (CC – 100% basal area removal), heavy thin (45% basal area removal), light thin (LT – 25% basal area removal). The site also includes a controlled (CT) treatment which is untouched and treated as a reference site for comparison. These controlled plots were originally harvested in 1962 and have remained untouched since then.

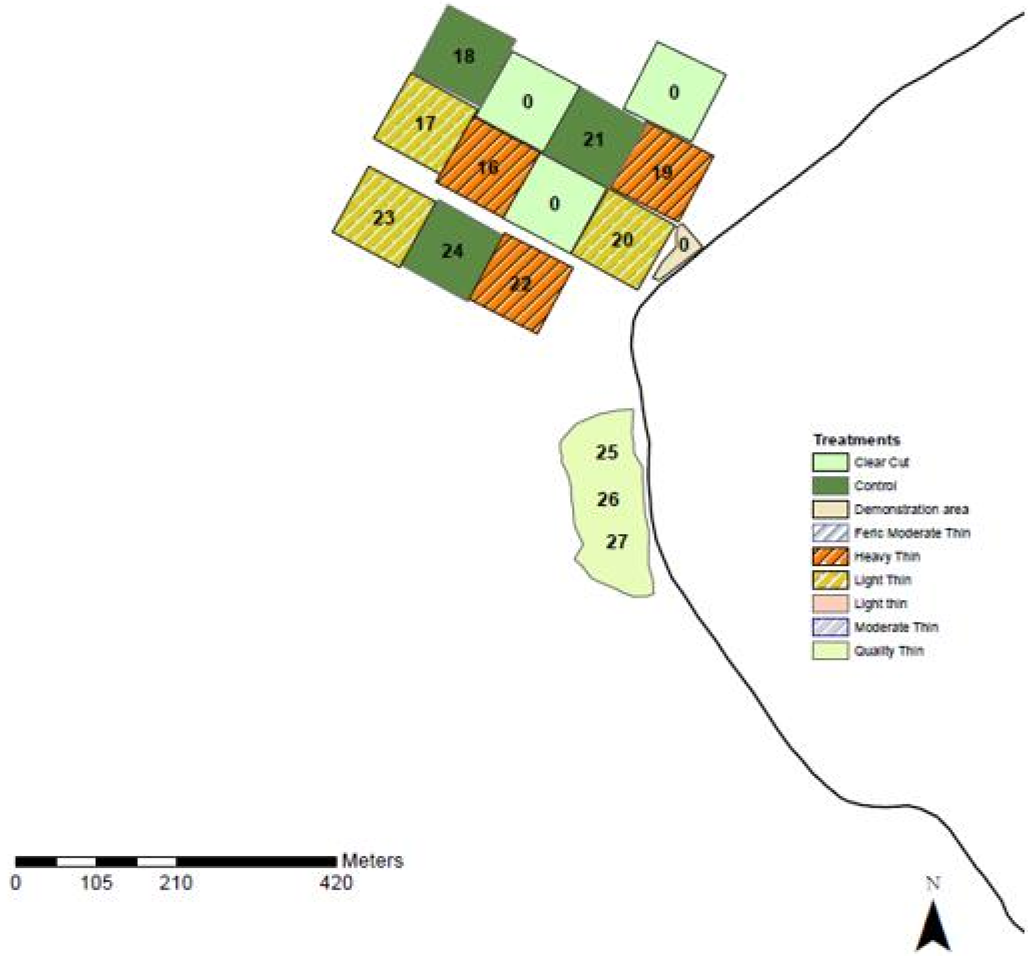

Figure 2: Airstrip Commercial Thinning site. The treatments used in this study were limited to Clearcut, Light Thin, Heavy Thin, and Control.

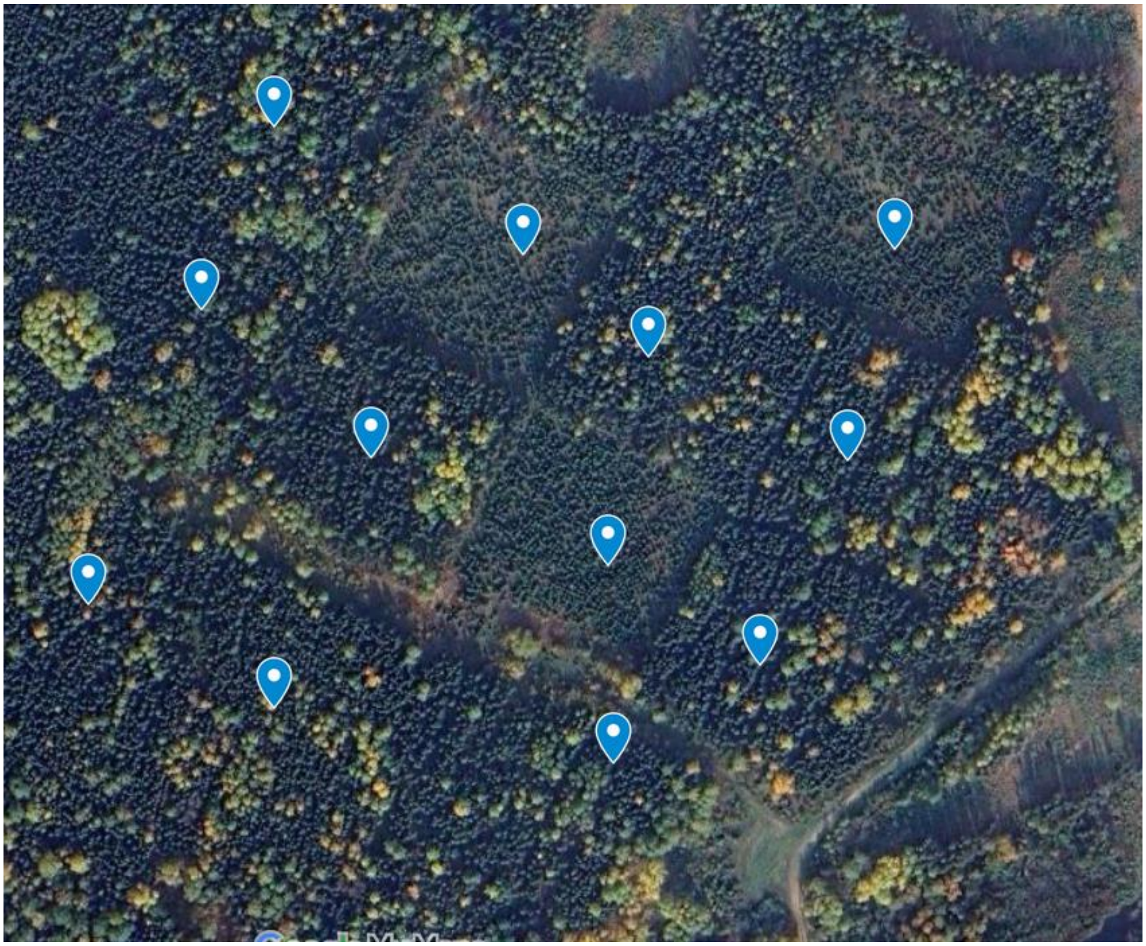

Figure 3: Satellite overview of the Airstrip Commercial Thinning site. Clearcut plots are easily distinguishable from the others.

The reference site is located approximately 6km northwest of the Airstrip Commercial Thinning Site just off Highway 11 (N49° 08.017' W88° 11.174**)**. It is an untouched 80+ year-old black spruce forest. The site was burned in the 1940s and it wasn't until the 1960s that foresters came into the area and initiated permanent growth plot (PGP) locations. However, the area was never thinned or logged. There is a heavy amount of downed woody debris (DWD) throughout, as well as a thick blanket of moss and understory vegetation throughout.

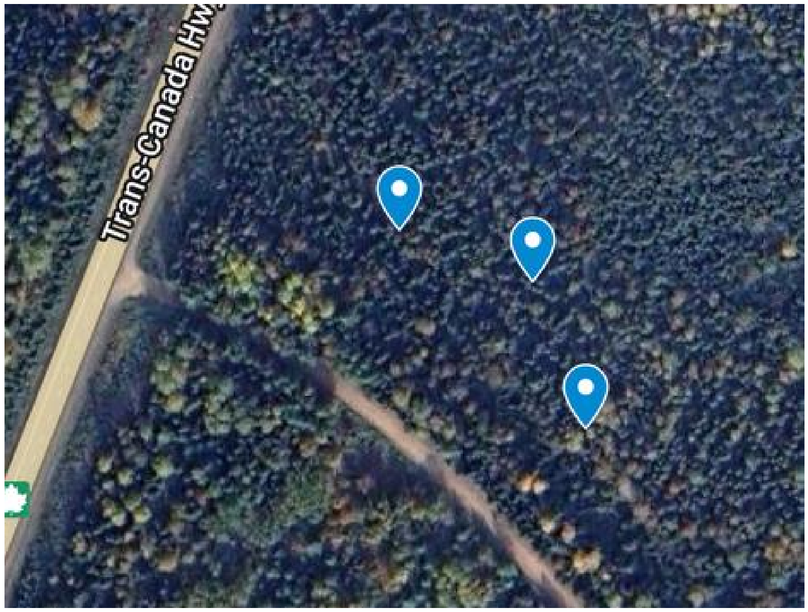

Figure 4: Reference site plot locations

2.2 SAMPLING

Pitfall traps were used to collect ground beetles (Figure 1). They consisted of 16 oz see-through plastic deli containers (11.7cm diameter), filled with propylene glycol as a preservative. Small holes were dug into the soil to insert the cup into the hole flush with the ground. This ensured that the beetles were falling directly into the cup and not avoiding capture by crawling around the lip of the cup. The cups were double stacked to limit the amount of propylene glycol seeping from cracked and broken cups. The damaged cups were discarded and replaced appropriately during the next collection date.

The trap covers were constructed by cutting 15cm x 15cm squares of water-resistant coated cardboard. Metal wires were attached to the covers, and these wires were inserted into the ground above the pitfall trap (Figure 2). This ensured that the traps were protected from rain and fallen debris (leaves and branches), as well as other organisms.

During the collection process, each trap was poured individually onto a piece of cheesecloth (Figure 3) and labelled by date, treatment, and replicate.

Figure 5: Pitfall trap filled with propylene glycol and an assortment of beetles. Airstrip Commercial Thinning site. Uncut control 1-1

Figure 6: Pitfall trap covered with pitfall trap cover. Reference site 1-1

Figure 7: Cheesecloth with beetle catches. Airstrip Commercial Thinning site. Light thin 1-4

2.3 TREATMENTS

Table 1: Collection start and end dates

A total of four collections were acquired over the summer months between June 6th, 2023, and August 14th, 2023. Collection period lengths ranged from 12 to 21 days.

Collection	Start	End	Period (days)
1	20230607	20230623	16
2	20230623	20230713	20
3	20230713	20230725	12
4	20230725	20230814	21

The traps that were set in the Airstrip Commercial Thinning site correlated with permanent growth plot locations (PGPs) previously completed during the initial thinning trials. A trap was set on the edge of each side of the PGP for a total of 12 traps per treatment (4 per replicate). Each treatment was replicated three times for a total of 48 traps.

The traps that were set in the reference site also correlated with previous permanent growth plot (PGP) locations. A trap was set on the edge of each side of the PGP for a total of 4 traps per replicate, or 12 traps total.

Table 2: Number of traps per treatment. Clearcut (CC), Heavy thin (HT), Light thin (LT), Uncut controlled (CT), Reference (REF)

Treatment	Replicate	Number of traps
CC	CC1	4
CC	CC2	4
CC	CC3	4
HT	HT1	4
HT	HT2	4
HT	HT3	4
LT	LT1	4
LT	LT2	4
LT	LT3	4
CT	CT1	4
CT	CT2	4
CT	CT3	4
REF	REF1	4
REF	REF2	4
REF	REF3	4

2.4 ENVIRONMENTAL SITE DATA

Environmental data was previously collected by the MNRF during the initial placement of the permanent growth plot (PGP) locations. Understory vegetation was not collected due to the absence of leaves and other identifiable features early into the fall season. The following data was acquired:

- Elevation (m)
- Age
- Basal area (m2/ha)

- Tree species composition of (% based on basal area)
- Canopy Cover
  - BAF2 prism sweeps to record basal area (m2/ha) and to estimate species composition (%)
  - Increment core to confirm tree age on one dominant tree per species
  - Densiometer to estimate canopy closure
  - Height (m) of one dominant or codominant tree of each species present in the prism plot
- Downed Woody Debris (DWD) Volume
  - Triangular transect (comparable to data collected in PGPs)

2.5 SORTING AND IDENTIFICATION

The sorting and identification process ran between June and mid-September 2023.

1. Collections were sorted and identified periodically as they were collected.
2. Beetles in the family Staphylinidae (rove beetles) were sorted together and excluded from the study.
3. All other beetles not found in the family Carabidae or Staphylinidae were sorted together and excluded from the study (i.e., Silphidae, Scarabidae, Cuculionidae, Nitidulidae, Tenebrionidae, Leiodidae).
4. Spiders were sorted separately and excluded from the study.

A Fisher brand microscope (series 030000xx) was used to identify ground beetles. Specimens that were not identified down to the species level were identified down to the genus level.

Figure 8: Sorting and ground beetle pinning

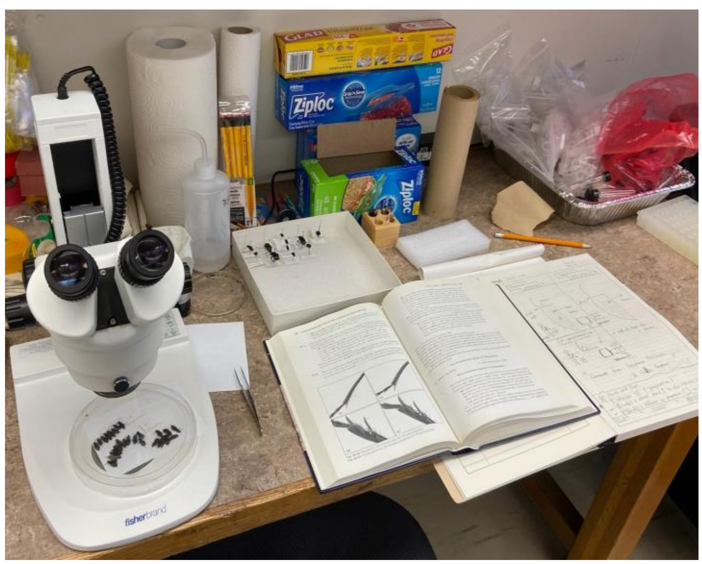

Figure 9: Laboratory desk with microscope, specimens, and guidebook

2.6 STATISTICAL ANALYSIS

Before analysis, I standardized species richness and total catch data to number of species (and individuals)/trap days to reduce the effects of unequal sampling effort due to trap disturbance by wildlife or absence of ground beetles. 38 out of 240 traps (15.8%) were excluded from the analyses.

I used generalized linear models (GLM) with Gaussian distribution of error, to compare species richness and number of individuals for all ground beetles (Carabidae) combined, and for each of the six most abundant species among treatments. Since the data was standardized to trap days, the values were continuous.

Multiple comparison of means (Tukey's honest significance test) was performed to determine which treatments were significantly different from one another in terms of species richness and abundance.

Nonmetric Multidimensional Scaling (NMS) was performed to compare community structure and environmental data within treatments at 95% confidence interval ellipses.

RESULTS

3.1 BEETLE FAUNA

A total of 10,234 adult ground beetles, representing a single family (Carabidae) and 21 species (seven of which were identified down to the genus level, denoted as sp.) were captured for this study.

The genus *Pterostichus* was the most abundant, accounting for 78.4% of catches among only five species. *Pterostichus melanarius* accounted for 57.3% of total catches with 5859 individuals. In contrast, *Pterostichus punctatissimus* accounted for a total of only 17 individuals, all of which came from the reference site. *Pterostichus melanarius, Synuchus impunctatus, Pterostichus adstrictus,* and *Pterostichus coracinus* accounted for 88% of catches.

3.2. SPECIES RICHNESS AND CATCHES

Table 3: Ground beetles (Carabidae) collected from various thinning treatments at the Airstrip Commercial Thinning site and reference site using pitfall traps.

	Clear-Cut			**Heavy Thin**			**Light Thin**			**Controlled**			**Reference**			**Total**
Species	**CC1**	**CC2**	**CC3**	**HT1**	**HT2**	**HT3**	**LT1**	**LT2**	**LT3**	**CT1**	**CT2**	**CT3**	**REF1**	**REF2**	**REF3**	
Agonum retractum					1		1	1			1			17	11	32
Agonum sp.1				1												1
Agonum sp.2														1		1
Amara sp.1		1														1
Calathus ingratus	7	6		7	13	4	49	3	7	13	26	22			4	161
Calosoma frigidum	8	1		21	30	14	100	25	21	18	50	98	1	2	34	423
Carabidae sp.1	1			1	2	1		1			1		1			8
Carabidae sp.2		2	2													4
Carabidae sp.3		6														6
Carabus nemoralis															1	1
Harpalus sp.1		1	1													2
Myas cyanescens													3	1		4
Platynus decentis	13			7	5	3	12	21	14	3	3	5		1	19	106
Platynus mannerheimii															4	4
Pterostichus adstrictus	6			52	92	15	121	57	63	67	160	79	46	16	97	871
Pterostichus coracinus	38	28	15	62	115	21	64	58	43	117	121	54	23	56	55	870
Pterostichus melanarius	351	124	78	158	335	1104	1381	252	513	165	54	1111	27	49	157	5859
Pterostichus pensylvanicus	25	14	1	33	93	20	49	47	17	9	26	31	3	3	42	413
Pterostichus punctatissimus													10	6	1	17
Spheroderus nitidicollis							1						9	5	5	20
Synuchus impunctatus	125	383	97	19	41	55	111	8	4	306	11	130	33	37	70	1430
Total	**574**	**566**	**194**	**361**	**727**	**1237**	**1889**	**473**	**682**	**698**	**453**	**1530**	**156**	**194**	**500**	**10234**

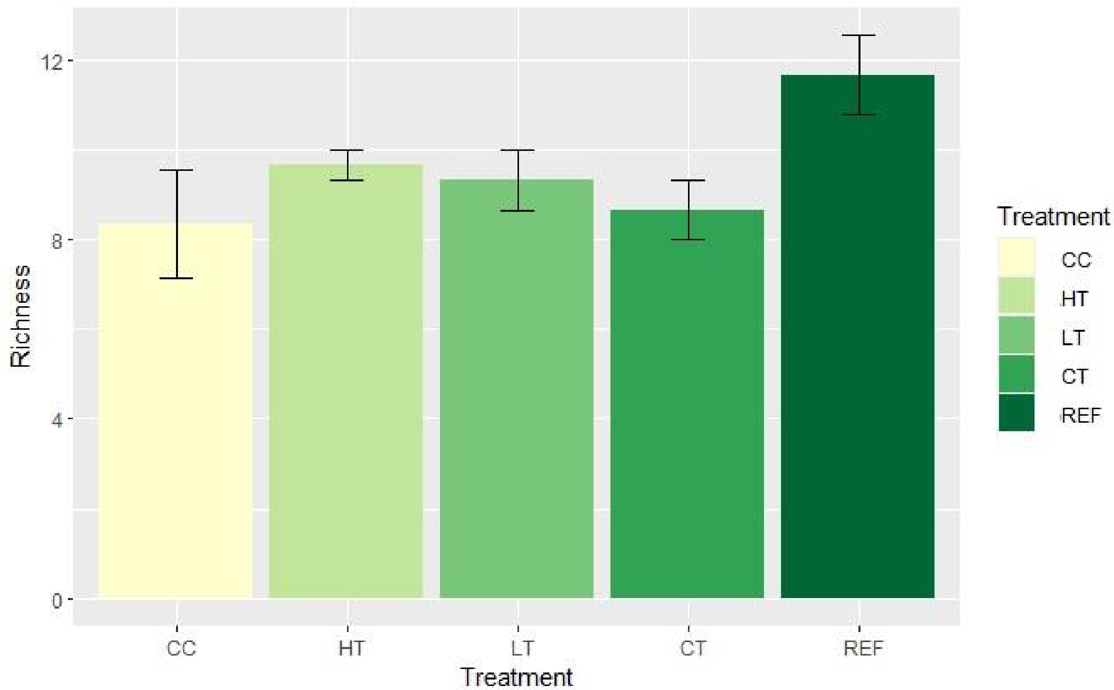

Figure 10: Overall species richness graph comparing number of species per treatment. Clearcut (CC), Heavy thin (HT), Light thin (LT), Uncut controlled (CT), Reference (REF). Error bars represent standard errors.

Shapiro-Wilk normality test determined that species richness did fall under normal distribution (p=0.1551). Species richness tended to be highest in REF. However, multiple comparisons of means (Tukey's HSD) concluded that species richness was significantly higher in REF than in CC (p=0.0273). This may be attributed to the distance and isolation of REF in relation to the other treatments, as well as the difference in stand complexity and understory composition in REF.

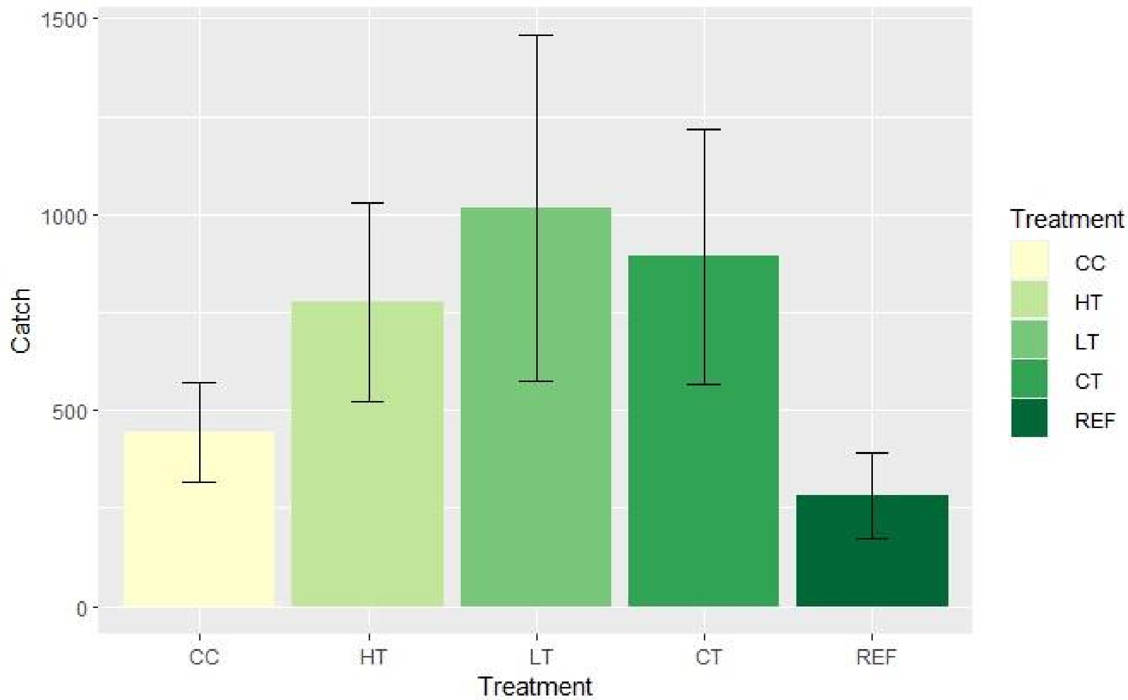

Figure 11: Overall standardized catch between treatments. Clearcut (CC), Heavy thin (HT), Light thin (LT), Uncut controlled (CT), Reference (REF). Error bars represent standard errors.

Shapiro-Wilk normality test determined that standardized catch fits within ordinal distribution (p=0.3272). Total catches did not differ statistically among thinning treatments (deviance = 61.354; p=0.1084).

Table 4: Raw number of catches per treatment

Treatment	Rep	Catches
CC	CC1	574
CC	CC2	566
CC	CC3	194
HT	HT1	361
HT	HT2	727
HT	HT3	1237
LT	LT1	1889
LT	LT2	473
LT	LT3	682
CT	CT1	698
CT	CT2	453
CT	CT3	1530
REF	REF1	156
REF	REF2	194
REF	REF3	500

LT1 was the most active plot with 1,889 catches, while HT3 followed with 1,237 catches. In contrast, REF1 and CC3 were the least active, with 156 and 194 catches, respectively. Overall, LT yielded the most individuals with 3,044, while REF yielded the least number of individuals, with 850.

3.3. SIX MOST COMMON SPECIES

GLM was performed on the six most abundant species. There were three significant differences between treatments: *P. coracinus* (CT-CC (P=0.040); *C. frigidum* (CT-CC (P=0.033); *P. adstrictus* (CT-CC (P=0.012).

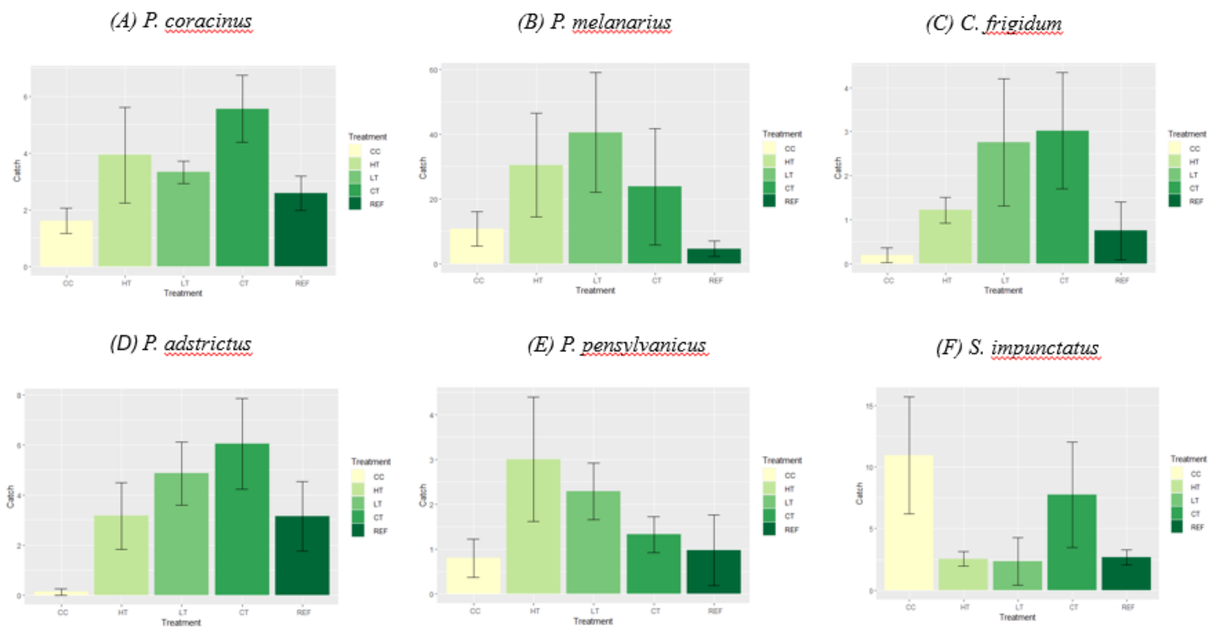

Figure 12: Standardized catch graphs detailing the six most abundant species found between treatments. Error bars represent standard errors.

P. coracinus and *P. melanarius* demonstrate a trend whereas *P. coracinus* was much more abundant in untouched forests, while *P. melanarius* was much more abundant in thinned sites (Fig. 13A and 13B). *P. adstrictus* dominated untouched forests and thinned sites while avoiding clearcut sites (Fig. 13D). In contrast, *P. pensylvanicus* dominated in thinned sites while appearing less frequently in untouched sites (Fig. 13E). *C. frigidum* was most abundant in controlled and light thinned sites (Fig. 13C). This may be due to the proximity of adjacent sites (i.e., controlled sites are found adjacent to clearcut, light thinned, and heavy-thinned sites) producing a species turnover effect. *P. impunctatus* was the most abundant species found in clearcut stands, whereas catches were much lower in other treatments excluding controlled sites (Fig. 13F).

Table 5: Chi-squared results detailing differences between treatments for each of the six most abundant species. Pr(>Chi) signifies the overall relationship between treatments (CC/CT/HT/LT/REF), while Pairwise Comparison signifies which treatments share significant differences.

	Df	Deviance	AIC	Scaled Dev.	Pr(>Chi)	Pairwise Comparison
P. coracinus	4	55.962	66.318	9.555	0.049	CT-CC (P=0.040)
P. melanarius	4	80.684	71.805	7.202	0.126	Not Significant
C. frigidum	4	7.098	35.344	11.866	0.018	CT-CC (P=0.033)
P. adstrictus	4	111.032	76.595	11.575	0.021	CT-CC (P=0.012)
P. pensylvanicus	4	1.134	7.838	7.427	0.115	Not Significant
P. impunctatus	4	17.883	49.206	8.165	0.086	Not Significant

3.4 ENVIRONMENTAL DATA

Table 6: Environmental data acquired for all plots

Overall, elevation was lowest in REF and highest in CC. Basal area and density were highest in CT and lowest in CC (15 years post-harvest). Tree height and canopy closure appear to be highest in CT and thinned sites (HT and LT), however, DWD is significantly higher in REF than any of the other treatments. This is primarily due to the fire that swept the reference site in the 1940s as well as the overall age of the stand (tree mortality, natural disturbance, disease, decomposition)

Site	Elevation (m)	B.A. (m2 ha-1)	Density (sph)	Age	Height (m)	Canopy Closure (%)	Species Composition (%BA)	DWD Volume (m3ha-1)
CC1	271	4.9	1215	15	5.2	<50	Sb 100	19.1
CC2	258	8.3	1126	15	5.9	<50	Sb 86 Pt 14	16.4
CC3	259	6.3	1393	15	5.5	<50	Sb 100	18.3
HT1	263	40.5	1575	62	20.3	79	Sb 90Pt 10	83.1
HT2	256	33.5	1225	62	18.5	77	Sb 87Pt 13	249.5
HT3	257	33.1	1350	62	18.0	89	Sb 91Pt 9	147.6
LT1	265	32.1	1200	62	18.2	75	Sb 88Pt 12	203.9
LT2	247	41.5	1375	62	18.9	95	Sb 75 Pt25	172.8
LT3	233	40.3	1525	62	16.2	85	Sb 88Pt 12	125.3
CT1	263	48.4	2350	62	18.9	90	Sb 82Pt 13Sw 5	45.0
CT2	254	48.1	2400	62	19.3	89	Sb 77 Pt 18Bf 2Bw 2	72.9
CT3	219	49.2	2625	62	17.8	84	Sb 80Pt 20	169.3
Ref1	234	22	N/A	69	20.4	62	Sb 82Bf 18	461.1
Ref2	236	40	N/A	73	20.7	89	Sb 90Bf 5Pj 5	160.4
Ref3	236	30	2275	64	20.5	81	Sb 60Pt 20Pj 7Cw 7Bf 6	304.7

3.5 SPECIES COMPOSITION

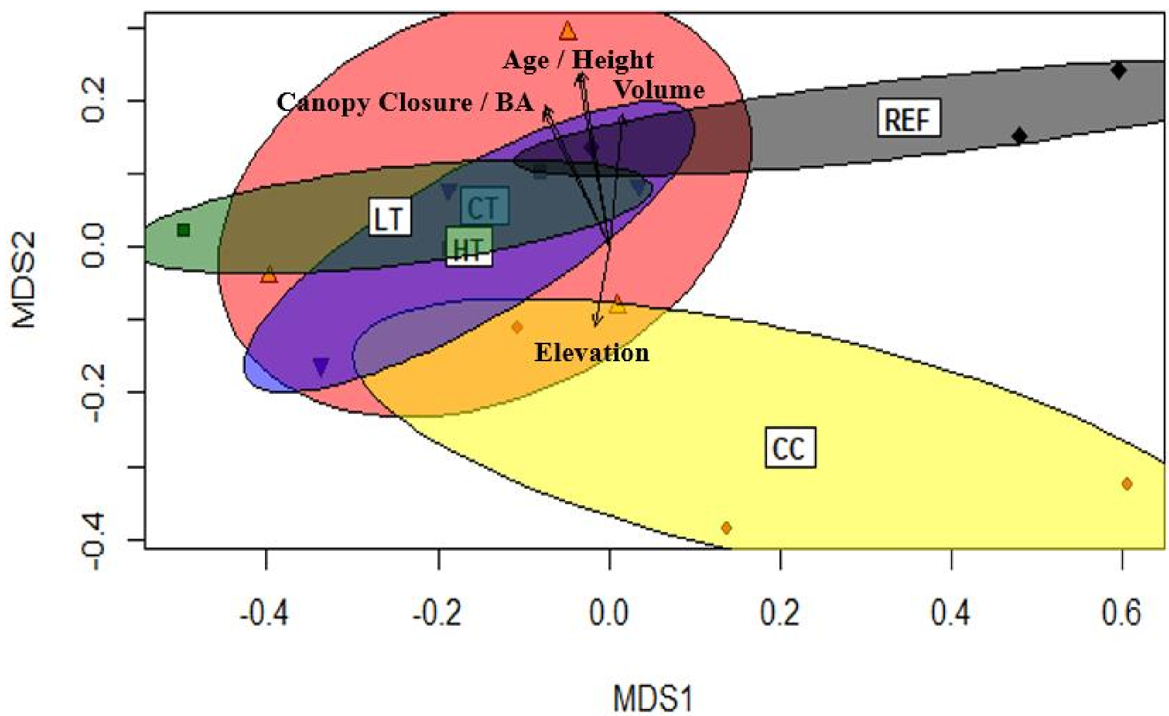

Figure 13: Nonmetric Multidimensional Scaling (NMS) ordination of the community structure between treatments. Ellipses indicate a 95% confidence interval. CC (clearcut) and REF (reference) are significantly different than LT (light thin), CT (controlled), and HT (heavy thin). A stress value of 0.085 was recorded.

Heavy thin (HT), light thin (LT) and controlled (CT) fall within normal ordination, suggesting similar species composition. While clearcut (CC) and reference (REF) suggests major differences in species composition. Although REF and CT share similarities in stand complexity, there are still major differences in species composition between natural forest and managed mature stand.

DISCUSSION

4.1 CARABID BEETLE RESPONSES TO DIFFERENT THINNING INTENSITIES

Results from this study showed that thinning contributes to the maintenance and development of ground beetle community structure in a black spruce plantation. Carabid species are represented by clear habitat preferences and can be classified into habitat generalists, forest generalists, forest specialists, and species of open habitats (Magura, 2000). The variation in carabid catches is influenced by environmental variables such as surface temperature, ground temperature, air moisture, cover of herbs, and canopy closure. Plant cover (understory vegetation) appears to be the most important factor determining carabid species richness (Magura, 2000; Work et al., 2010). Influence of this factor was apparent by the high number of species found in the reference (REF) plots, despite having much lower catch numbers than any of the other treatments.

The comparison of thinning and variable retention does support that partial harvesting can also support biodiversity conservation. Light thin and heavy thin was comparable to ~20% and ~50% retention, respectively. In order to balance harvest removals with biodiversity conservation objectives, we need to understand how thinning intensities and retention harvests affect stand complexity and species recovery over both short and long-term timeframes.

A long-term study conducted by Wu et al., (2020) examined the recovery of a boreal ground-beetle fauna 15 years after variable retention harvest (clearcut, 10%, 20%, 50%, 75%, uncut) in the mixed wood boreal forest of northwest Alberta, Canada. The study was conducted as part of the Ecosystem Management Emulating Natural Disturbance (EMEND) project. The following results were concluded: thinning is preferred over clear-cutting for sustainable forest management; ground-beetle species richness recovers after harvest, however, may be slightly lower than unharvested control plots; species turnover was higher in the harvested treatments than in controls across all four different forest cover-types; ground beetle assemblages in mixed and conifer stands varied more, with some treatments surpassing or equaling the richness of unharvested controls.

My results were similar to those reported in the EMEND study. In our case, Species richness remained largely the same for all harvest treatments, suggesting that recovery of ground-beetle assemblages was not strongly correlated with variation in harvest intensity.

These results correlate with my second hypothesis 'Species richness and catches in the clearcuts would be lower than in light and heavy thinning treatments as well as un-thinned and natural forests'. For species richness, the hypothesis was partially supported. As previously mentioned, REF-CC was significantly different from one another (p=0.0273, Appendix 1). However, the other treatments showed no significant differences (Appendix 1). This may be attributed to the distance and isolation of REF in relation to the other treatments, as well as the difference in stand complexity and understory composition. Therefore, since the other treatments are not significantly different than clearcut, the hypothesis was partially supported.

As for beetle catches, the hypothesis was rejected. Total catches did not differ statistically (p=0.1084) between treatments. However, there was a trend where total catches in REF were lower than the other treatments. This result may be related to two factors. Firstly, the most abundant species in this study were generalists that can thrive in thinned or more open stands; therefore, catches tend to be lower in REF because those species are more likely to be specialists and may have different behavioural patterns and specific habitat niches. Secondly, it is possible that the dominant or most abundant species negatively affect diversity. Since many ground beetles are predators, they may be outcompeting forest specialists (Jennings and Tallamy 2006). For example, *Pterostichus melanarius* and *Synuchus impunctatus* make up 71% of catches, and they are generalists who thrive in open and logged stands (Bergmann et al., 2012). Generally, disturbed forests often display higher species richness than the mature, unmanaged forests (Duchesne et al., 1999).

Magura (2000) suggests that leaf litter may have a negative effect on species preferring open habitats such as *P. melanarius* and *S. impunctatus*. In contrast, leaf litter is a significant positive determinant for forest specialist species. This indicates that species of open habitats are adapted to an environment with limited leaf layers, while the forest specialist species may prefer habitats with dense litter layers and downed woody debris (DWD) (Magura, 2000).

A long-term study on the habitat structure linked to beetle assemblages in a white spruce plantation to evaluate biodiversity conservation was conducted over a 3-year period in northern New Brunswick (Maclean et al., 2015). Overall, the number of beetles were similar in commercial thinning plantations (40% basal area removal) compared to unthinned, older forests. However, unthinned plantations had significantly fewer beetles compared to either the older forests or the thinned plantations. While there were differences in beetle abundance between treatments initially, these distinctions tended to diminish over time since thinning. Predatory beetles were particularly affected, with un-thinned plantations supporting fewer beetles compared to commercial thinning plantations (Maclean et al., 2015). Their findings support the idea that changes in woody debris and canopy openings resulting from commercial thinning of plantations can enhance beetle abundance across various levels. It was concluded that commercial thinning promotes the presence of beetles in the initial three summers following thinning (Maclean et al., 2015).

The post-harvest recovery of beetle community structure (Maclean et al., 2015) parallels those of the current study in essentially all aspects, despite having a ~15-year difference between recovery time. This may signify that ground beetle assemblages recover quickly, then remain largely the same. Similarities in community structure between heavily thinned and unthinned control plots in both studies help to support the current study's prediction that heavy thinning does not negatively affect ground beetle community structure. In fact, our results would suggest that beetle assemblages recover at similar rates across all thinning intensities. Similarly, total catches in our study were higher in thinned stands than the mature, unmanaged reference site, suggesting that large scale disturbances may be beneficial for promoting ground beetle assemblages. However, the rate at which a species recovers may depend on their generalist or specialist nature. Koivula and Niemelä (2003) conducted a similar study on the responses of ground beetle following harvest and concluded that open habitat species increased in abundance one year after logging, but catches in other treatments did not differ. Predatory ground beetles of a generalist nature such as *Pterostichus melanarius*, *Pterostichus adstrictus*, *Pterostichus pensylvanicus*, *Synuchus impunctatus*, and *Calathus ingratus* may have an advantage when choosing suitable habitats. However, a forest specialist species such as *Calasoma frigidum*, *Platynus decentis, Platynus mannerheimi, Pterostichus punctatissimus, Sphaeroderus nitidicollis,* and *Agonum retractum* may not be able to thrive in open habitats and logged stands. (i.e., the abundance of *A. retractum, P. adstrictus, P. decentis*, were severely reduced following clear-cutting and thinning (Duchesne et al., 1999)). These results may suggest that this is due to differences in leaf litter/understory vegetation, canopy cover, and interspecific competition. More specifically, generalists may outcompete specialists.

The current study proposed the following hypothesis : ‘Ground beetle community structure in light thin is more similar to the beetle community structure of mature (CT) and untouched (REF) forests’. This was partially supported. The community structure in the light thin plots was significantly different than REF (Figure 13). However, the light thin and the unthinned control plots were not different (Figure 13). This pattern may be because the light thin plots are more similar to the unthinned control plots, while REF is secluded from the others. REF (mature, unmanaged condition) also has greater stand complexity that creates habitat conditions favourable for other, more unique species. Although REF and CT share similarities in stand age, there were differences ($p=<0.001$, Appendix 1) in total catches and species composition. This may indicate that ground beetle biodiversity was not negatively affected by heavy thinning (45% basal area removal), as it overlaps with the unthinned control and light thin ordination ellipses (Figure 13). Finally, it also illustrates that heavily thinned and unthinned control plots share similar community structures.

4.2 – HABITAT PREFERENCES – COMMON SPECIES

Research is still limited on how forest thinning affects invertebrates at the individual species level. The environmental mechanisms and natural life history responsible for the increase or decrease in individual populations in response to forest thinning are unique to the individual species (Verschuyl et al., 2010; Koivula and Niemelä, 2003). As an example, consider an increase in herbivorous arthropod abundance in newly thinned stands because of increased canopy openings and understory vegetation (food availability) and a decrease in predator populations (such as ground beetles) as a result of declining habitat and food sources on ground level. Overall, thinning that modifies stand complexity might increase the variety and abundance of some insect families (Verschuyl et al., 2010). Clearcut may benefit open-stand generalists such as ground beetles for the first couple of years until regeneration advances enough for the re-introduction of forest generalists (Koivula and Niemelä, 2003).

Open generalists and forest generalists might not recover from thinning at the same pace (Koivula et al., 2019). Due to the time required for vegetation to regenerate and canopy closure to occur, forest generalists that are acclimated to conditions with a closed canopy may require more time to recover. Open generalists, on the other hand, may recover more quickly because they benefit from more light and nutrients. These species thrive in post-disturbance habitats. Evaluating the overall effect of thinning requires understanding the recovery rates of individual species (Koivula et al., 2019).

This section details habitat preferences of individual species and compares them to the current study. Understanding stand complexity, community structure, and recovery rates post-disturbance, are necessary for forest managers to implement the best thinning practices.

Pterostichus adstrictus: The consensus appears to align with catch locations in the current study. Bergmann et al., (2012) captured adults in woodlands as well as in open land, including cultivated fields. In the coastal regions, specimens are relatively independent of forest cover, while in the interior, they are found mostly in tall grassland and in forests. They are most common in open and harvested stands while less common in low elevation forests. They are also found in older fire origin stands. Niemelä et al., (1992) categorized the species as a habitat generalist. Saint-Germain et al., (2005) captured most of their individuals in logged stands, controlled sites, and burned sites.

Pterostichus pensylvanicus: Goulet (1971) reported that it is only possible to find adults of this species beneath leaf litter—not beneath bark or inside decaying logs. Adults can be found in most forest litter areas in southern Quebec, however, are limited to damp soil in deciduous forest litter in central Alberta. In contrast, Belluz et al. (2022) reported that the majority of their captures came from open stands, while Niemelä et al., (1992) reported the species as a forest specialist. When contrasting the results of the current study, it appears that this species is more of a forest generalist as they were collected in all forest cover types.

Pterostichus coracinus: The consensus appears to be very similar to *Pterostichus adstrictus,* denoting the species as a generalist. Found in abundance across grasslands and forest edges, Magura (2000) identifies it as a species of open habitat. While Matalin (2006) correlates the species as dominating in coniferous forests as well as in mixed and frequently disturbed forests.

Pterostichus melanarius: Similar presence as *Pterostichus coracinus*. Found in abundance across forests, grasslands, and harvested stands. They are a species of open habitat (Paquin 2008); however, they can dominate in coniferous and mixed forests as well (Magura, 2000; Matalin, 2006). Is it unclear why *Pterostichus melanarius* accounted for 57.3% of catches. It is suggested that due to its invasive and generalist nature, it has quickly outperformed native species and may have an increased resistance to disturbances (Mulligan et al., 2006).

Calathus ingratus: Catch locations appear to be mixed for this species. Bergmann et al., (2012) found them to be less common in lower-elevated forests as well as grasslands. In contrast, Belluz et al., (2022) counted that 80.7% of his specimens were found in closed forests. Saint-Germain et al., (2005) concluded that this species dominates within logged forests as they were found predominantly in logged and controlled sites. In the current study, most of the individuals were collected in both the unthinned controls and thinned stands.

Synuchus impunctatus: Bergmann et al., (2012) defines this species as an open habitat generalist, most commonly found in open-harvested stands. Jennings and Tallamy (2006) found this species on open ground and in light forest habitats. While Angel (2019) also described the species as a generalist that is common in lightly forested areas. Duchesne et al., (1999) captured this species solely in clearcut stands, while Paquin (2007) captured them in dry forests and forest edges. Overall, this species was caught primarily in clear cut stands and open habitats, which coincides with the current study where catch locations were predominantly in the clearcut plots.

Calasoma frigidum: The genus *Calosoma* is an important predator of Lepidoptera larvae, including species such as the gypsy moth, elm spanworm, and forest tent caterpillar (Saint-Germain et al., 2005). This is interesting considering that the majority of catches found from this study were in the unthinned controls and light thinned plots. It is therefore considered a forest specialist species by Niemelä et al., (1992).

Platynus decentis / Platynus mannerheimii: Life histories of these two species are very similar. They are considered to be mature forest specialists according to Niemelä et al., (1992) and Paquin (2008), and they are found strictly in forests (Jennings and Tallamy 2006). Paquin (2008) characterizes *Platynus mannerheimii* as a species of older maturation stage and is a rare species that is associated with complex soil made of moss, and for that reason it is an indicator species of old growth. This correlates well because most of the catches in the current study came from the mature, unmanaged reference site, although some were also in the light thinned plots.

Agonum retractum: According to Niemelä et al., (1992) this species is found in meadow/moist forests, as well as in mature forest conditions (Saint-Germain et al., 2005). This habitat data correlates well because most of the catches in the current study were from the mature, unmanaged reference plots.

Sphaeroderus nitidicollis: Saint-Germain et al., (2005) captured all of their specimens in mature forest sites. While the majority of the individuals captured in the current study were were also found in the mature, unmanaged reference plot.

Pterostichus punctatissimus has been found in both harvested and unharvested sites (Saint-Germain et al., 2005). This species is characteristic of northern boreal forests, found usually under the bark or moss of tree stumps (Mayry et al., 2018). This corresponds with the high moss cover and DWD volumes found at the reference plots of the current study, as all 17 individuals were captured at the mature, unmanaged reference forest.

4.3 MANAGEMENT IMPLICATIONS

It has been demonstrated that thinning, as opposed to clear-cutting, more effectively supports biodiversity conservation objectives (Jennings and Tallamy; 2006; Magura 2000; Work et al., 2010; Maclean et al., 2015; Pinzon 2016; Wu et al., 2020; Belluz et al., 2022). This is especially true for ground beetles, which recover quickly in plots with higher retention levels. By following methods proposed by Wu et al., (2020), forest managers can find a balance between the overall harvested area required to remain economically feasible and the total amount of retention required for optimal conservation. Three primary strategies are advised for the sustainable management of ground beetle biodiversity, particularly in stands that are predominately coniferous. First, ensure the managed landscape includes some late successional stands that have higher retention levels. Second, post-harvest conifer regeneration can be accelerated by silvicultural techniques (e.g., site preparation and planting), which creates suitable habitats. This is due to the incredibly fast recovery of generalist species and species of open habitat.

Work et al. (2010) suggested that ground beetle composition in higher retention levels (>50%) differ from those of uncut and natural stands. This implies that thinning intensity could be increased higher than what is already the case. This may prove to be economically feasible, as results from the current study found that heavy thinning (45%

basal area removal) and light thin (25% basal area removal) show similar recovery patterns, which may indicate that heavy thinning may not negatively impact the long-term recovery of ground beetle assemblages unless denoted as a forest specialist. An additional consideration is the amount of time assemblages had to recover. Most of the studies presented here were conducted after a recent disturbance (i.e., 1-15 years), however the current study evaluated ground beetle community structure 15-64 years after harvest. Since the results of this study parallel the results of short-term studies (Jennings and Tallamy; 2006; Magura 2000; Work et al., 2010; Maclean et al., 2015; Pinzon 2016; Wu et al., 2020; Belluz et al., 2022), this may indicate that beetle assemblages recover at relatively fast rates (<15 years). This does not, however, take into consideration the recovery time of mature forest specialists and rare species. The importance for future research should focus on the latter.

Another suggestion proposed by Pinzon et al., (2016) is to improve landscape connectivity (i.e., reduce the effects of fragmentation) in order to encourage rapid recolonization of stands harvested at lower retention levels. This will ensure the recovery of habitat features that are appropriate for sensitive species affected by harvest (i.e., specialists and species of closed habitat). This may be achieved with the combination of aggregated and dispersed retention (Pinzon et al., 2016). Similarly, forest edges can contribute to species richness by implementing silviculture techniques such as sowing or planting shrubs and herbs, or by cutting lesser trees to improve light exposure (Magura, 2000). Although, this would prove to be very costly, time consuming, and should be reserved for long-term restoration.

CONCLUSIONS

The main objective of this research was to compare abundance, species richness, and community structure of ground beetles among different intensities of 15-year post-mechanical thinning, clearcut, and uncut forests in Northwest Ontario. I proposed two hypotheses 1) Ground beetle community structure in light thin is more similar to the beetle community structure of untouched forests. (CT/REF). The community structure in the light thin plots was different than REF, rejecting my first hypothesis. However, species composition between the light thin and the unthinned control plots were similar each other. 2) Beetle species richness and abundance in clearcut would be lower than in light and heavy thinning treatments as well as un-thinned and natural forests. For species richness, REF was significantly higher than CC. However, the other treatments showed no significant differences. As for beetle catches, total catches did not differ significantly between treatments. However, there was a trend where total catches in REF were lower than in other treatments.

Overall, results show that heavy thinning, light thinning, and controlled practices may not have a significant negative impact on ground beetle biodiversity in the long term, as indicated by species richness and abundance. However, differences in species composition between untouched forests and mature managed sites emphasize the importance of considering biodiversity conservation in forest management decisions. Thinning rather than clear-cutting is more beneficial for biodiversity conservation, particularly for ground beetles. Forest managers can achieve a balance between economic feasibility and conservation by following strategies such as maintaining late successional stands, accelerating conifer regeneration, and improving landscape connectivity. Further research should focus on the recovery of mature forest generalist/specialists and rare species, while long-term restoration efforts may involve the collaboration of variable retention.

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APPENDIX

Appendix 1:Pairwise comparisons of ground beetle species richness among different thinning treatments, control, and reference sites [Clearcut (CC), Heavy thin (HT), Light thin (LT), Uncut controlled (CT), Reference (REF)]

	Estimate	Std. Error	z value	Pr(>|z|)
CT - CC == 0	0.3333	1.1353	0.294	0.9984
HT - CC == 0	1.3333	1.1353	1.174	0.7660
LT - CC == 0	1.0000	1.1353	0.881	0.9041
REF - CC == 0	3.3333	1.1353	2.936	0.0273
HT - CT == 0	1.0000	1.1353	0.881	0.9041
LT - CT == 0	0.6667	1.1353	0.587	0.9770
REF - CT == 0	3.0000	1.1353	2.642	0.0629
LT - HT == 0	-0.3333	1.1353	-0.294	0.9984
REF - HT == 0	2.0000	1.1353	1.762	0.3963
REF - LT == 0	2.3333	1.1353	2.055	0.2398