Rapid Understory Restoration of a Thinned Red Pine Plantation in Algonquin Provincial Park

by

Jason Phoenix

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Author's Declaration

This thesis consists of material all of which I authored or co-authored: see Statement of Contributions included in the thesis. This is a true copy of the thesis, including any required final revisions, as accepted by my examiners.

I understand that my thesis may be made electronically available to the public.

Statement of Contributions

This thesis was entirely written by the author, but the contributions of Professor Stephen Murphy should be acknowledged, as he prepared the initial research proposal and experiment design that were presented to Algonquin Provincial Park. Park staff, including Sandy Dobbyn, Jennifer Hoare, and Joe Yaraskavitch,[1] were also heavily involved in the initial planning of this restoration effort. Much of the final experiment design is based on the preliminary planning work done by these individuals. Throughout this thesis, the author has attempted wherever possible to note instances where others have contributed to this work, particularly where the experiment is described in Chapter 2.

[1] These individuals and others who contributed to the restoration work are employees of the Ontario Ministry of Environment, Conservation, and Parks and the Ministry of Northern Development, Mines, Natural Resources and Forestry.

Abstract

By simulating a natural forest environment and facilitating the growth of native species, tree plantations can be used as a restoration tool to quickly re-establish canopy cover in degraded areas. A red pine plantation was established in the 1970s for just this purpose on a bare hillside at Cache Lake in Algonquin Provincial Park, Ontario. Plantation ecosystems, however, are substantially different in composition, structure, and function compared to old growth forests, and their understory vegetation communities develop much more slowly. Therefore, in 2021, the Park began a multi-decade effort to accelerate the restoration of the Cache Lake site by thinning the trees. Their goals were to remove unhealthy individuals, provide space for the remaining trees to expand, and open the dense canopy so understory species could begin colonizing the area. As part of this work, a 4-year project was initiated to rapidly restore the plantation understory by experimentally testing several restoration treatments. This thesis documents the first 2 years of this project, during which the experiment was designed and implemented and some preliminary data was collected.

Two treatments are being applied universally across the site: thinning and invasive species management. Two additional treatments are being tested experimentally using a variant of the randomized complete block design. The first is a simplified version of applied nucleation, where small clusters of plants are placed across the site with the expectation that they will enhance seedling recruitment and spread outwards over time, eventually merging. We transplanted 128 individual beaked hazel shrubs as our nuclei. The second experimental treatment is windthrow guards. This technique, which does not appear in the literature, uses rings of herbaceous plants around woody species (such as our planted nuclei) to protect them from being uprooted by strong winds. Canada goldenrod was used for this treatment, with 768 transplants forming rings around the hazel shrubs. Mortality censuses were conducted one month after transplanting, and it was determined that 99% of shrubs and 87% of goldenrod survived the transplant process. Preliminary results also show that thinning increased average understory light availability to 38.8% of full sun across the site. Vegetation surveys have revealed the presence of native understory species in the plantation, as well as a significant number of non-native species, especially generalist species.

The goals of this experiment are to determine which treatments improve soil quality and increase the rate of native vegetation recruitment. We will also test the effectiveness of the windthrow guards. A final assessment will be issued at the end of the project's four years, revealing whether the experiment has successfully restored a healthy, diverse, native understory. Afterwards, the Park will continue to thin the plantation every 10-12 years. It is expected that the periodic openings in the canopy will allow more understory recruitment, including native hardwood saplings. As the red pines are removed, the hardwoods will dominate, and a young hardwood forest will be established in 30-40 years.

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First and foremost, I want to thank my supervisor, Stephen Murphy, who took a chance on a physics student looking to explore a new field of study. Your guidance, insights, and tutelage have helped me navigate the fascinating world of ecological restoration. Many thanks as well to my advisory committee member, Professor Jeffrey Corbin of Union College, for keeping me on track. Your expertise and experience in this field was very valuable.

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I could not have done this research without the support of Algonquin Provincial Park and its wonderful staff. Many thanks to Alison Smith, Jennifer Hoare, Jason Mask, Peter Mills, Joe Yaraskavitch, and all the others who worked behind the scenes to make this project possible. Your assistance and your work on the initial designs for this project were much appreciated. Thank you as well to Kevin Kemmish and all the staff at the Algonquin Wildlife Research Station for providing myself and my assistants with accommodation and delicious meals during our time in the Park. The relaxing, friendly atmosphere, the clean, pleasant cabins, and (I can't emphasize this one enough) the incredible food made our stays in the Park an absolute delight. This thesis also incorporates some historical images, which were used with the permission of Algonquin Park Archives. Thank you to collections coordinator Emily Welsh for providing high-quality scans of these images for use in this thesis, and thank you for your work in preserving Algonquin's amazing history. Finally, though it feels strange to thank a geographical region, I want to express my gratitude to the Park itself, its ecosystems, and its furry/feathery/scaly inhabitants for providing myself, generations of Canadians, and millions of visitors to this country the opportunity to learn from you and to gaze in wonder at your mysteries, your majesty, and your beauty.

I want to thank my wonderful partner (and field assistant!), Abraham, for your companionship and your sense of humour. I could not imagine a better option for relaxing after long days of working on my thesis than spending my evenings laughing with you. Our thought-provoking discussions/debates on science, philosophy, social issues, and politics have also been a fun way of distracting my tired brain. Thanks, Special One!

Finally, I doubt I would be studying in this field today if it weren't for my parents, Dean and Suzanne. It is from the two of you that I gained my love of animals and nature. I have so many fond memories of growing up in a house in the northern Ontario woods, with bears, foxes, lynx, and birds outside and a plethora of pets inside. Your curiosity and compassion have molded me into the person I am today. You have my thanks and my love.

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List of Abbreviations

AN Applied Nucleation

AN&WG Applied Nucleation and Windthrow Guard

WG Windthrow Guard

Several years ago, I found myself asking a wildlife biologist named Joe Truett to justify his work in exactly such utilitarian terms. We were sitting under an elm tree in a desert grassland preserve in southwestern New Mexico. Bison, which had been brought back onto the landscape, were filing across the sunburned basin. On the horizon, in the craggy Fra Cristobal Range, mountain lions once again hunted a reintroduced population of desert bighorn, and from our patch of shade Truett and I scanned the skies for the aplomado falcon, a bird of prey with beautiful gunmetal-blue and cinnamon markings that had been released in the area as part of an effort to re-establish a U.S. population extirpated in the 1950s. Why, I asked, did all or any of this matter?

Truett answered the question in what is now the usual way: biodiversity contributes to the stability and resilience of the planet; ecological services have economic value; restored landscapes serve as useful reference points for understanding natural potential and the effects of change. None of these arguments was good enough for me that day. I wanted him to somehow prove that the scene we were looking at was as essential as it felt to me in that moment. I wanted a single crowning reason that we should live with more natural abundance, not less, a richer rather than poorer state of nature.

At last, Truett said this: "I like it."

–The Once and Future World by J.B. MacKinnon, p. 146-147

Chapter 1

Introduction

Forests provide vital ecosystem services and jobs for hundreds of millions of people worldwide [1], and the majority of Earth's terrestrial biodiversity (80% of terrestrial species) is found in forests [1–3]. Yet the Earth is currently experiencing significant global deforestation, with just under half of the planet's forests remaining intact and approximately 60,000 km^2 being deforested globally each year [1, 4, 5]. Though temperate forests have been the biome that is most-heavily impacted by humans [4], as of the 1990s, the amount of deforested land in the tropics is now greater than the area of remaining tropical forests [6]. Human-caused deforestation is having immense impacts on local climates, water dynamics, erosion, habitat fragmentation, ecosystem services, and even disease transmission [7], and it is a major source of biodiversity loss and species extinctions [2, 7, 8]. The primary cause of these losses is the transformation of forests into pastureland and agricultural land, especially for cattle grazing, soy crops, and oil palm plantations [1, 4, 6, 7, 9].

In recent years, the ecological community has come to recognise that restoration can be used to complement conservation approaches, so that healthy, biodiverse forests may again grow in degraded landscapes [10, 11]. Although deforestation rates have been slowing in recent years, these losses are still greater than current restoration efforts [1]. As the climate continues to change and threatens to destroy existing ecosystems, reforestation on a global scale is desperately needed to to avoid a significant loss of biodiversity and to sequester carbon [8, 12–15], and large-scale, efficient, cost-effective, scientifically-valid restoration techniques will be required to achieve this goal [14, 15]. One common reforestation option that is currently being implemented on a large scale is the creation of tree plantations [2–4, 8, 11, 16–20]. These plantations can quickly re-establish forest cover and provide numerous ecological and economic services, but they can also have significant negative impacts on ecosystems and can take 100-250 years to develop into old-growth, biodiverse forests [2–4, 6, 10, 11, 16, 18–27]. Therefore, additional treatments are needed to restore plantations, as well as their understories, which are slower to develop and less biodiverse than those of native forests [4].

In the winter of 2021, a 50-year-old red pine plantation in Algonquin Provincial Park was thinned. This was the first step in a multi-decade plan to restore a native forest in an area that has had a long history of intense human activity. As part of this restoration effort, a 4-year project was simultaneously initiated to rapidly restore the understory, which was largely absent after decades of heavy shading by the dense plantation canopy. This understory restoration effort is the focus of this thesis.

The goals of this project are to generate an increase in native understory vegetation, a decrease in non-native species, and an overall improvement in soil quality within the 4-year time frame. Understory succession in North American plantations has not been well-studied [4], so this is an excellent opportunity to expand our scientific knowledge while also actively restoring degraded land in Canada's oldest provincial park. To that end, we will be testing several restoration treatments, including two universal treatments to be applied site-wide (thinning and invasive species management) and two treatments to be tested experimentally with a variant of the randomized complete block design. Of these latter two treatments, the first is applied nucleation, which typically involves manually planting clusters of vegetation that will naturally spread out over time [8]. This treatment is usually conducted using trees, rather than understory vegetation, and it does not appear to have been previously tested in a temperate conifer plantation. The final treatment to be tested is a windthrow guard, which is a ring of vegetation intended to deflect strong winds from the tree or shrub that it surrounds. Windthrow guards do not appear in the literature, so as far as we are aware, this will be the first experimental test of this novel treatment. With this experiment, we therefore have the opportunity to fill several gaps in the literature concerning the restoration of a conifer plantation understory in a northern mixedwood plains ecozone. Other plantations undergoing restoration within Algonquin Park may benefit from these results, and given the swift rate of forest loss worldwide, new forms of rapid understory restoration are urgently needed.

This thesis presents the activities and results of the first two years of this restoration project, focusing especially on the experiment design and implementation. In Chapter 1, we will review the concepts underpinning this research. Section 1.1 discusses how plantations are used and their ecological impacts, while Section 1.2 describes the properties of forest understories and distinguishes them from the unique characteristics of plantation understories. Chapter 1 concludes with Section 1.3, which covers several forest restoration techniques. Chapter 2 contains an extensive summary of the current restoration work in Algonquin Park, as well as some preliminary analysis of the restoration treatments' effectiveness. Finally, the short- and long-term successional trajectories of this plantation are examined in Chapter 3.

1.1 Tree Plantations: Their Uses and Their Ecological Impacts

As natural forests have disappeared over the past century, many have been converted into managed forests, with tree plantations currently composing approximately 5% of global forest cover [2–4, 7, 16]. Pine and eucalyptus are the most common plantation species globally [3]. Single-species conifer stands have typically been the most prevalent type of plantation in the temperate deciduous biome of Europe and North America, although deciduous plantations have begun appearing in recent decades as well [4]. Plantations are primarily created for economic purposes and generate about half of all wood-based products, such as timber and paper [2–4, 16, 21, 22]. That said, timber sales from plantations can actually help fund local restoration projects [6, 21, 22], and they may also assist with soil and water retention [2, 3]. Despite the services they provide and their capacity to reduce pressure on natural forests [2], plantations can cause significant ecological issues due to the homogeneous age, size, and species of their trees [28]. The creation of unnaturally-dense monoculture plantations can lead to degraded habitats, reduced soil quality, more frequent and intense wildfires, a higher prevalence of pests and pathogens, and a sparse understory [28–30].

Plantations and natural forests differ greatly in their structure, composition, and functions [4, 31]. Whereas natural forests are adaptive, dynamic, self-regenerating, highly-complex, interconnected systems composed primarily of native species of many different ages [4], plantations tend to be composed of mono-specific, artificially-spaced trees of equal age and size that form a relatively static and simple system [4, 31]. Planted stands tend to be more dense than naturally-regenerating old-growth forests [31] and may consist of fast-growing, non-native species with a short harvest cycle [4].

The degree to which timber-producing plantations can develop or maintain ecosystems comparable to natural forests remains an open question, as there has been little research in this area [2, 4, 31]. One ecological aspect of plantations, about which there is a fair amount of disagreement in the literature, is how they affect biodiversity [2, 4]. Monoculture plantations evidently have less plant biodiversity than native forests, and there are many examples in which they have been shown to reduce the diversity of animal species as well [2, 28]. On the other hand, plantations can still play an important role in hosting and preserving native species [21–23, 27], even when they are composed of non-native trees [27]. Additionally, as much of the world's timber production takes place in high-density plantations that occupy (relatively) little land area, it has been argued that these practices allow for more land elsewhere to be protected and managed for its ecological and conservation value [4]. There are also several management options that can ensure greater biodiversity within plantations, such as the intentional creation of heterogeneous structures at both the stand and landscape levels [3, 16, 21]. Most industrial plantations host less biodiversity than native, old-growth forests but greater diversity than land affected by other types of high-intensity human disturbance [2, 3]. Overall, it appears that plantations

can have both positive and negative effects on biodiversity, although this can depend significantly on the context [3].

The harvesting of plantations introduces further complications. Plantation harvesting can remove topsoil and reduce soil fertility [32, 33], and the open areas left behind by intense logging operations can allow shrubs and invasive plants to overtake the area, thereby suppressing forest regeneration [28, 33]. Harvests can also impact wildlife by eliminating sources of food and shelter [33], and they may affect nearby water quality through increased sedimentation and chemicals leaching from the soil [34].

Though the public tends to consider them only in terms of logging and agriculture, it has largely been established that the creation of tree plantations can actually act as an effective forest restoration strategy in areas that have experienced long-term anthropogenic disturbance and degradation, such as former agricultural or pastoral land [6, 11, 13, 15, 18–23, 35]. Within a very short period (∼4 years), planted trees can reduce soil density and provide cover and habitats for wildlife and shade-tolerant plant species, including woody plants and herbs [4, 22]. Their root systems can also halt erosion, and they can enhance the nutrient and organic content of degraded soils through fallen branches and leaf matter [6, 19, 20, 23]. By creating an understory microclimate similar to that of natural forests [4, 21, 22], plantations can enhance seed dispersal and plant recruitment processes, thereby fostering the establishment of native seedlings and speeding forest succession [19–22].

Plantations can have a variety of detrimental effects on local ecosystems, especially during and after harvesting. It can take 100-250 years for an undisturbed plantation to reach old-growth status and host significant levels of biodiversity [27]. Nevertheless, despite the apparent downsides of plantations, they can actually perform some useful ecological functions, including hosting native species and sequestering carbon [21–23, 27]. It's even possible to enhance these ecological properties and services without loss of economic value if the plantations are managed carefully [4, 21, 22]. Many monoculture plantations are even created and managed for the specific purpose of aiding in the eventual establishment of native, diverse tree species and promoting forest succession [11, 13, 15, 18–25]. This is the case for the trees planted at Cache Lake in Algonquin Park, where our project is being undertaken. This particular use of plantations will be investigated further throughout this thesis (e.g., Sections 1.3.2, 2.1.1, 2.3.1, 3.2.2) as we discuss the restoration of a red pine plantation to native forest.

1.2 Forest Understories

Forest ecosystems extend from deep underground, where burrowing animals and plant roots interact with fungi and bacteria, to the forest canopy where birds and insects fly among the topmost tree branches. The complexity of a forest ecosystem is generally summarised according to three diversity categories: composition (components of a forest, usually referring to plants), structure (physical arrangement of biological and abiotic components), and

function (processes of and interactions between components) [4]. A healthy and resilient forest tends to be heterogeneous in all of these categories across a range of spatial and temporal scales [36].

In this experiment, we are primarily interested in one particular stratum of the forest ecosystem: the understory. The forest understory consists of all ecosystem components and interactions below the tree canopy and above the ground. Understory plants range from herbs and shrubs to tree saplings [37]. In temperate forests, this layer hosts the greatest diversity of plantlife, and because tree seedlings and saplings have their beginnings here, the understory has a significant impact on the overstory's development and diversity [23]. Natural forests develop large, dense canopies over time, so their understories tend to be dominated by shade-tolerant species [4], although canopy gaps created by fallen trees can provide vital habitats for forest species that need more light [31]. Mature forests usually host understories with large numbers of woody species, as well as spring-flowering herbs that bloom before canopies close over for the summer, and there tend to be fewer non-native species [4, 23]. Forest specialist species often have limited seed dispersal capabilities (such as ant-dispersed spring-flowering herbs), and they are therefore highly sensitive to disturbances and are among the last to colonize a young forest [4, 6, 23, 38, 39].

Non-biological factors are also vital components of forest ecosystems. Light intensity in particular is often considered to be the key factor in determining understory development and forest succession, particularly in mesic forests with dense canopies [22, 40–44]. Light levels affect plant growth both directly and indirectly, in the latter case by influencing microclimate heterogeneity, especially temperature and moisture [10]. If light levels are too high, which could occur with the creation of large canopy gaps, understory species may experience higher temperatures, increased transpiration, and substantial competition from invasive, light-demanding species [10]. This can ultimately lead to changes in the composition and function of forest species as the area becomes more arid [10]. The reverse process can also have harmful impacts, as a dense overstory can shade out important understory species, thereby altering ecosystem composition, structure, and dynamics [4, 22, 23]. Understory plants often respond to shading either by growing larger leaves to collect more sunlight if the canopy is too dense or by simply growing taller if they are being shaded by the surrounding herbs [45]. Overall, light intensity and canopy openness control the dynamics of much of the understory's regeneration process [22].

Other abiotic factors that influence forest understories include water, soil, topography, and disturbance regimes, such as periodic windstorms and forest fires [10, 18, 18, 39, 46–49].[1] Water availability is typically the limiting factor in primary production [10], for instance, while the new environments created by trees blowing down due to intense winds can help drive succession [39, 46, 47]. Spatial and temporal heterogeneity in these abiotic components can have an enormous impact on a forest, especially on the diversity and distribution of species, habitats, and microclimates [18].

[1] Disturbance is actually one of the primary factors that influences ecosystem dynamics and succession [39], although we won't focus too much on it here, since most natural disturbances (e.g., forest fires) have been suppressed within Algonquin Park.

The understory is such a vital stratum of the forest ecosystem that the development of its structure and function can be used as an indicator of overall forest resilience and health [4]. In the case of an artificially-generated forest, it can also act as an indicator of successional progress and likely future trajectories, as we shall see in Section 1.3.5 [4]. Therefore, knowledge of how understories develop and change in native and artificial forests is key to determining the best practices for restoring a plantation to a healthy, self-sustaining forest system [23]. In the following subsection, we will examine the properties of plantation understories, especially in conifer plantations, and we will discuss how they differ from those of natural forests.

1.2.1 Plantation Understories

There has been a lot of research conducted on the properties of plantations and other secondary forests, especially their successional trajectories [23]. Plantations develop more slowly than natural forests [4], and they tend to be more homogeneous in tree age, density, trunk diameter, and height [31]. Monospecific conifer plantations, such as those in Algonquin Park, have also been found to have understories and regeneration pathways that are substantially different from those of natural forests, especially when compared to native deciduous forests [4]. Understories in these plantations have "vegetation assemblages [that are] compositionally, structurally and functionally different from those of naturally regenerated stands" [4].

Land use prior to plantation establishment can have long-term impacts on plant biodiversity, habitat diversity, and soil quality, especially if large equipment or artificial structures were present beforehand [4, 23]. Post-agricultural plantation soil tends to have higher pH, reduced organic content, and altered nutrient levels compared to plantations established in core forest, resulting in reduced herbaceous plant growth [23]. As forest herbs tend to prefer a narrow range of pH levels between 5.0 and 6.0, generalist and invasive species may quickly colonize the plantation understory if the soil is too acidic or alkaline [23]. A loss of microhabitats and fine-scale soil heterogeneity due to compaction by equipment can also inhibit herbaceous regeneration and yield greater understory homogeneity [4, 6, 23]. In such areas, however, the creation of plantations can nevertheless speed the recovery of forest conditions and understory development by increasing soil nutrients, preventing erosion, restoring fine-scale heterogeneity, and facilitating vegetation regeneration [6, 19, 20, 23].[2]

By quickly establishing tree cover, especially in deforested areas such as pastureland, plantations can generate environmental conditions in the understory that are similar to natural forests [4, 21], thereby promoting faster regeneration of native plants [6, 21]. Yet North American conifer plantations tend to have substantially reduced diversity and abundance of native herbs compared to natural forests [4]. There are likely several reasons for this trend.

[2]It should be noted, however, that the planted trees can in turn have long-lasting effects on seedling establishment and resource availability as secondary succession progresses [18].

In sufficiently nutrient-rich, damp forests, the primary limiting factor on understory development is light availability [40–42, 44], so early in the succession process, the understory is dominated by light-demanding species [4]. The increasing levels of shade are an important part of forest succession, and natural old-growth forests tend to have an intermediate level of canopy cover (∼60-85%), which is ideal for most herbaceous plant species and helps maintain a balance between light-demanding generalist species and shade-tolerant forest specialists [23]. Plantations tend to have densely-planted trees [31], however, so as they age and their canopies close over, the abiotic conditions become homogeneous and some species may be unable to establish themselves or persist [4, 18, 22]. For example, native spring-flowering herbs are common in the late-successional stage of natural forests [4], and their establishment is one of the most crucial phases of plantation understory restoration [23]. In deciduous forests, they bloom before the tree leaves emerge in the spring, but in mature evergreen plantations, these light-demanding species may disappear altogether due to the year-round canopy cover [4]. Light is not the only limiting factor, however, as older conifer plantations with substantial canopy cover also tend to have ground cover dominated by acidic, nutrient-deficient needle litter [4]. In dry, infertile conifer forests, soil quality and underground competition appear to be the limiting factors in understory growth, particularly in relation to moisture and nitrogen availability [41, 44]. It should be noted, however, that many native species are better adapted to reduced resource levels, giving them a competitive advantage compared to exotic species, which may not have evolved under such conditions [41].

Another major factor that influences the establishment of understory plants is dispersal, which acts at both the local and landscape levels [4, 6, 23, 39, 41]. Generalist and wind-dispersed species are able to quickly colonize young tree stands [4, 23], but many forest specialists have greater difficulty dispersing themselves to new areas [4, 6, 23, 39]. For example, whereas woody species are typically quite efficient in dispersing themselves [23], many spring-flowering forest herbs are dispersed by ants and therefore have a relatively short dispersal distance [4]. In some cases, these dispersion limitations (among other factors) can result in regenerated understories that are entirely dominated by just a few shrub species, which suppress the growth of other vegetation [6]. Plantations can enhance understory diversity by attracting seed-dispersing animals [6, 22], and although they may also attract species that eat seeds, this can beneficially lead to a heterogeneous plant distribution [23].[3] When directly connected to older forests, plantations have far greater rates of native understory regeneration and of forest specialists colonizing the area[4] [6, 23]. In the short term, isolated plantations (i.e., those not directly connected to intact forests) are usually only naturally colonized by species with long dispersal distances [23]. As they age, isolated plantations do see some increase in the abundance of forest specialists, but a

[3]That said, if large numbers of ungulates are attracted to the area, the increased browsing pressure can destroy the understory structure in some cases [37].

[4]Some animal species, such as bats or large animals, are able to traverse larger distances between plantations and natural forest, so plants relying on these species for dispersal may colonize plantations faster, even when the nearest intact forest is far away [6, 39].

substantial increase in generalist species tends to occur as well due to their enhanced seed dispersal capabilities [23]. Stands closer to native forest see a decrease in generalist species and a much greater increase of forest specialists, with species-specific rates of proliferation affected by such factors as seed properties (e.g., wings) and distance to native forest [6, 23].[5] Levels of ground cover by some specialist species in plantations may be almost identical to those in native forest after several decades [23].

The choice of planted tree species may also impact the regeneration of woody plants and other understory vegetation, with some tree species enhancing the growth and diversity of certain understory species and others having an inhibitory effect [6, 22]. For example, some tree species may create more shade due to their larger canopies, thereby suppressing early-successional species (e.g., grass, ferns), or they may disperse substantial quantities of seeds, which could compete with other plants for resources [6, 22]. The influence of the planted trees can vary substantially by location and species [22]. It has been demonstrated, however, that understory species richness is generally correlated with woody regeneration and can improve with increased prevalence of dead wood [6, 22]. Therefore, those tree species (whether exotic or native) that facilitate the growth of woody species may be the most likely to promote the overall development of a natural forest system and may do so faster than natural regeneration processes [6, 22]. That said, woody regeneration also increases with stand age, so as with a natural forest, time will likely be one of the most important factors influencing plantation succession [23].

Several common trends have been observed in the literature on plantations and their understories. For example, some key plantation properties substantially influence understory cover and the abundance of both specialist and generalist species; these properties include age and canopy cover, as well as spatiotemporal properties like proximity to natural forest [23]. Additionally, average resource availability may have a greater impact on plant growth than localized variations [18]. In general, understory regeneration in plantations appears to be negatively correlated with the abundance of early-successional, light-demanding species [4, 6, 22], and greater canopy shading (provided it's not too dark) results in greater understory richness and reduced numbers of invasive species [10, 22]. As with all complex systems, however, these trends may be context-dependent and vary significantly between sites. For example, the diversity and ground cover of regenerated understory vegetation has in some instances been found to decrease as leaf/needle litter increases [4, 6, 22], while in other cases, biodiversity has increased with litter because of the added soil nutrients [6], and some studies have observed no conclusive correlation between litter and diversity [6]. It may be that only some species are suppressed by leaf litter or that additional interacting factors influence the correlation between litter biomass and understory renewal [6]. This example demonstrates some of the difficulties associated with predicting how complex systems will behave over time.

Understory regeneration pathways have been shown to vary substantially between plan-

[5] In some cases, such landscape-level factors (e.g., proximity to natural forests) may actually have more of an impact on regeneration of timber species than the impacts of the plantation overstory do [6].

tations, even those of similar age and location [6], and the time required to restore the plantation understory to a state comparable to that of natural forest is highly inconsistent between study sites [23]. Some temperate plantations require at least 60 years for the diversity and ground cover of their understory vegetation to match that of natural forest [23], whereas others never reach this state [6]. Overall, there are still many unknowns when it comes to understory regeneration and succession in plantations [4]. Many ecological traits, and their disturbance responses, have yet to be fully characterised and understood, including "seed longevity, soil chemistry requirements and interactions with mycorrhizae, herbivores and pollinators" [4]. These gaps in our knowledge present many challenges when restoring a plantation understory, but each restoration project presents a new opportunity to learn more about these complex systems.

1.3 Ecological Restoration

Over the past several centuries, humans have been impinging upon the world's ecosystems at an increasingly rapid rate, and the natural processes of regeneration can no longer keep pace with human activity. Ecological restoration has therefore been considered as an option for slowing or even halting this trend [12, 14, 15]. Ecological restoration is the process of returning an altered ecosystem to a characteristic state, often one that is self-sustaining, resilient, and has similar properties to some reference system (e.g., similar species, functions, spatiotemporal variations, and disturbances) [10, 12, 41]. It is assumed that by restoring the ecological conditions under which species evolved, they are more likely to thrive [36]. This restored system may mimic the historical state of the ecosystem prior to human interference; it may emulate the state of the system at any point during which humans were present; or it may be a new ecosystem that is better able to weather the current and possible future stressors that will act upon it [10, 41]. Restoration ecology is the branch of science associated with this activity, and its purpose is to understand how systems have been altered, to determine the key factors that influence their behaviour, and to devise strategies for restoring them to a desirable state [10, 41].[6]

There are two main categories of ecological restoration [9, 10]. The first, often called 'passive' restoration, allows natural processes to regenerate the components, structures, and functions of an ecosystem according to "their own recovery pathways, mechanisms, and

[6] As a branch of science, restoration ecology is a rather interesting case where norms and value judgements heavily impinge upon the objectivity and rationality that are typically considered key aspects of scientific research. For example, terms such as 'healthy', 'degraded', and 'desirable' are commonly used to describe ecosystem states in this field, yet these terms inherently imply that particular system states are *preferable* to others. Researchers may also have emotional attachments to the systems they study, something that is perhaps less common in other branches of science. (For instance, it is probably true to say that it is inherently more difficult for a physicist to become emotionally attached to electrons and photons than it is for a restoration ecologist to feel compassion for the animals inhabiting the degraded system they're studying.) I'll make no judgements on whether this level of subjectivity is a benefit or a hindrance to the study of ecological restoration, but it is something of which we should be aware.

timetables, which may not be mirrored in human-driven designs or implementation" [10]. The only human action involved in this strategy is to eliminate any undesirable stressors [9, 10]. This technique is generally the least expensive option because there is minimal human involvement, and as it follows the natural regeneration pathways, it often results in stable, heterogeneous systems [9, 13, 14]. That said, it can be a very slow process; neotropical rainforests, for example, require 20-190 years for their structure to be restored, 60-500 years for the species composition to recover, and millennia for rare species to return [11]. Therefore, an alternative strategy is usually implemented when natural regeneration is too slow for the desired timeline or when the system has been altered to such a degree that it cannot recover to the desired state on its own [10, 11, 38]. This second option, often termed 'active' restoration, involves human interventions to overcome these limitations [9, 11, 14]. Although human intervention to restore the composition and structure of an ecosystem can be beneficial, it is often the restoration of the system's functions and processes that lead to a self-sustaining, self-regulating state [10, 12]. For this reason, a better name for this activity may be 'process-based restoration' [10]. The goal with process-based restoration is to move the system past the necessary thresholds such that it becomes self-sustaining within a reasonable time frame [11]. Although ecosystem structure can sometimes be restored within a few years, recovering the most important processes and functions requires long-term management and monitoring [11], which is why this strategy is often more expensive, labour-intensive, and time-consuming [9, 14]. Overall, both of these methods are effective, but they can have very different results [9], so planning ahead is crucial to producing the desired outcomes.

Although each restoration project is unique, we can glean some general guidelines from the literature. One of the first tasks will always be to set the specific project goals (e.g., to recover a certain level of biodiversity or restore particular processes) [10, 39]. These goals depend on the intentions and desires of whomever is undertaking this project, which may range from the re-establishment of ecosystem services to a desire simply to conserve native species [12]. The project goals are typically specified with respect to a set of reference conditions, i.e., the normal range of spatiotemporal variations in the structure, components, and function of a similar ecosystem [10, 41]. Once goals have been set, the next step is to learn about the system and its current state [10]. Due to the immense complexity of most ecosystems, it is very difficult to determine what causes them to be self-sustaining and to fully understand their internal processes, and we can never have complete knowledge of all their components and inner workings [4]. We must therefore isolate the most relevant and important properties of the system in order to construct a reasonable representation that still accounts for most of the complexity [4, 39]. It is also crucial to determine why and how the system was altered [39]. Human impacts are usually either chronic (i.e., continuous and long-term), acute (a single, short-term event), or some combination of the two [39]. With this knowledge, we can then logically determine the actions that will restore the system to the desired sustainable state [10, 39].

Selecting the best restoration treatments is a complex task, however, as every ecosystem is in some way unique. Restoration is therefore highly context-dependent, and treatments

must be appropriately tailored to the distinctive properties of the system [38]. Site-specific factors will impact timelines [11] and limit possible trajectories for the system [5], which is why it is so important to learn about the system beforehand. Knowledge of the natural recovery times for the different components and processes is key to setting the project timeline [11]. The impacts of the treatments at different spatial scales should be considered, and landscape-level restoration is often recommended to increase large-scale heterogeneity [6, 12, 31, 36, 41]. It is also necessary to consider which components, structures, and functions are absent, which ones need to be manually introduced, and which ones will regenerate naturally [38]. The logistics of each treatment are similarly important to consider during the initial planning stages; these considerations might include treatment costs, labour requirements, and resource availability [38].

Once the treatments have been selected and implemented, the project should then enter a cyclical pattern in which constant monitoring of the system will allow one to determine its current status, to reassess the restoration plan, and to implement new treatments if/when necessary [10]. Indicators such as biodiversity levels, soil quality, and vegetation cover are used to track the progress of the system as the treatments begin to take effect [10]. This cycle of monitoring and reassessment will help keep the project on track and, ideally, prevent the system from entering an alternative, undesirable stable state [10].

Given that this work is highly context-dependent, a common issue encountered in ecological restoration is the limited scope of the reference literature. For example, the research of a particular type of ecosystem may have been entirely conducted in one geographical location, so it may not apply to similar ecosystems elsewhere (e.g., on another continent) due to different species, environmental conditions, management practices, and land-use practices [38]. There may be no literature on the effectiveness of certain treatments, even if they are already commonly in use, or the results may be inconclusive [36, 38]. There may be few studies comparing different ways of implementing a particular treatment (e.g., different methods for reintroducing a particular species), and there are very few papers describing ideal follow-up treatments in the event that previously-attempted treatments fail to achieve the desired outcomes [38]. Additionally, even though restoration is often a long-term effort, long-term research is expensive and time-consuming, so the literature may not include many long-term studies of the treatment of interest [11]. Finally, one of the most difficult challenges is to determine the reference conditions for the restoration. In North America, there are few records known to be reliable and accurate about the historical states of our ecosystems prior to European colonization [41]. Although we can estimate the approximate historical conditions, a perfect recreation is unlikely, and given current anthropogenic influences (such as climate change and habitat fragmentation), it may even be undesirable in some circumstances.

With these guidelines in mind, the following sections will examine some techniques and treatments used to restore native forest understories, especially in the context of tree plantations. We will consider the uses and known effects of these treatments, as well as the gaps in the literature that hint at opportunities for future research. We will conclude this section and this chapter with a summary of the indicators that can be used to determine

the initial state of the system and our progress in restoring the plantation understory.

1.3.1 Plantation-Based Reforestation

Forest restoration often takes place on heavily degraded and modified land, such as agricultural fields, where it can take decades or centuries for trees to re-establish themselves due to dispersal challenges, poor soil quality, seed predation, and exposure to the elements [19–22]. Tree plantations are often used to speed the reforestation process, with the goal of eventually restoring a self-sustaining, naturally-regenerating forest ecosystem that emulates historical conditions [41]. Tree plantations are in fact the most common reforestation technique used in tropical regions [11, 18], and they've been used as a restoration tool in Ontario for over a century [19, 20, 35]. Plantations can hasten the recovery of forest conditions and facilitate understory development by introducing native tree species, recreating a native forest structure, quickly re-establishing canopy cover, increasing soil nutrients, preventing erosion, restoring fine-scale heterogeneity, and promoting the regeneration of herbaceous, shade-tolerant vegetation [6, 10, 11, 18–26]. In areas where the soil is no longer able to support late-successional tree species, due to a lack of organic content and moisture for example, planting early-successional species can assist in soil rehabilitation [19, 20, 35]. This is a common practice in Ontario, where hardy conifers (e.g., white, red and Jack pine) are planted in sandy, compacted, and/or nutrient-poor soil, mimicking the natural, post-disturbance succession process [19, 20, 35]. Over time, their needle and branch litter adds nutrients and organic matter to the soil, their roots loosen compacted dirt and prevent erosion, and their canopies shade the ground, which lowers the temperature and helps with moisture retention [20]. The conifers act as nurse plants by facilitating the growth of other native species in the enriched soil after a few decades [20]. In many cases, plantations result in a much faster forest restoration than would otherwise occur if natural regeneration were allowed to take its course [11, 22].

Plantations are usually established with high-density plantings of fast-growing trees [10, 11, 25, 31]. They are planted so close together because their competition for light causes them to grow very straight and tall, making them economically valuable when harvested [20, 25]. (As we shall see, even plantations used for restoration purposes are often harvested for timber, with ecologically beneficial results.) Depending on the context, it can be advantageous to establish a high-diversity plantation using a mix of different tree species [11, 13, 18, 39]. Such plantations can produce a "greater heterogeneity of habitats for animals and microsites for germination and plant recruitment, facilitate reproduction with conspecific remnant trees and reduce the synchronicity of canopy death" [11]. It can also be beneficial to plant some mid- or late-successional species to accelerate the recovery process [39].

Once the trees have been planted, the development of a diverse, heterogeneous understory is the next stage of restoration [4, 26, 36]. As discussed previously, the understories of conifer plantations tend to develop more slowly than those of natural forests of the same

age and land use history, and they are very different in structure, composition, and function [4]. To recover and sustain a native understory, the conditions must emulate the natural habitats in which understory vegetation grows best [4]. Light intensity has one of the greatest impacts on understory development [40–44], and maintaining canopy cover at roughly 70-80% will create light conditions favoured by a variety of shade-tolerant, slow-growing forest specialists [10, 23]. The initial density of the planted trees can therefore impact the development of a late-successional understory, with species responding differently to overstory structure [31]. As we will see in Section 1.3.2, an alternative option for achieving the necessary light levels is silvicultural treatments, especially thinning the trees by harvesting them for timber [41]. This can have myriad benefits for the understory, including increased understory diversity [41] and disturbed soil that provides seedlings with the necessary microsites for growth [26, 41]. Periodic thinnings and the establishment of the herbaceous and shrub layers should approximate the light levels and structure of mature, natural forests [23, 41]. Seed dispersal is a key factor influencing understory regeneration, so a plantation planted near an intact forest will experience faster colonization by understory species [23]. Understory species can also be manually introduced to circumvent natural dispersal limitations and accelerate understory development. Overall, one of the most important stages in recovering plantation biodiversity is the restoration of the herbaceous understory [23].

In attempting to establish a healthy plantation and encourage understory development, however, there are many issues that must be considered. For example, the germination and growth of tree seedlings and late-successional species can be inhibited by poor soil quality (e.g., acidic, compacted, or nutrient-deficient) [4], especially since high densities of planted trees can result in reduced concentrations of soil Mg, Cu and Zn [21]. Resource competition with overstory trees, generalist species, and non-native plants can also reduce tree recruitment and understory development [6, 18, 21, 22, 41]. The densely-planted trees in a plantation may create a thick canopy that shades out understory species [4, 22, 23], and the trees may become thin, unhealthy, and susceptible to breaking or disease if they continue to grow so close together [19, 24, 25]. The understory could also become entirely dominated by a single species if the appropriate dynamics are not restored [26]. Additionally, wildlife participate in many forest processes, including pollination, seed dispersal, and vegetation consumption, so the restoration of native forest depends on the return of animal species [11]. Finally, there are many non-biological factors to consider, such as moisture levels and hydrology, which could be particularly important for restoring degraded soils [10].

Plantations are often created with the assumption that if the characteristic tree composition and structure can be quickly reconstructed, the natural forest processes and diversity will re-establish themselves shortly thereafter [11, 31]. Many studies have shown, however, that structure and composition are relatively simple and quick to achieve compared biodiversity and forest function, which can take decades or even centuries to recover [11, 36]. Therefore, merely creating a plantation as a quick solution to deforestation can actually slow overall restoration efforts and halt succession if forest processes aren't restored, potentially leading to the creation of an alternative stable state [4, 11].

When restoring normal forest processes within a plantation, it is also important to

consider external forces. One of the key features of any ecosystem is natural disturbance, which plays a vital role in ecosystem dynamics and upon which some species may depend for survival and regeneration [26, 36, 39]. Disturbances vary by type, intensity, and spatiotemporal scale [39]. Forests are impacted by many different disturbances, such as fire, high winds, drought, and insect outbreaks [26, 39]. These disturbances are usually categorized as either top-down (i.e., affecting the canopy first, then the understory and soil), or bottom-up (impacting the understory first) [39]. The actions of these disturbances may alter soil, vegetation, and/or community composition [39] and can result in forest heterogeneity and increased species diversity [26]. Many understory species are adapted to frequently-recurring disturbance, with each species responding differently to different types of disturbance [26, 36, 39]. The absence of disturbance in plantations can therefore alter ecosystem dynamics and species dominance, and if the disturbance regime is not restored, the ecosystem may begin to degrade once more [26]. Many restoration techniques attempt to imitate the effects of specific forest disturbances by creating canopy gaps, restoring structural heterogeneity, producing dead wood, and mixing the soil layers [20, 26, 36]. Such techniques include tree thinning and burning [26, 36], as we will discuss in the following subsection. Ultimately, these disturbance-mimicking treatments are not perfect substitutes, as the vegetation response may not be identical to that which is produced by natural disturbances [26]. In areas where natural disturbances are suppressed (such as forest fires in parks), however, these artificial imitations may be the best option for maintaining natural forest structure, composition, and function.

Overall, plantations can be a useful tool for quickly reforesting an area, but they do have many associated complications. Although their overstory structure and diversity usually follows a predictable trajectory, their understory regeneration pathways are often highly inconsistent and may not result in diversity levels that are comparable to native forest [6, 11]. One option for overcoming these drawbacks would be to apply several different landscape-level treatments, including the creation of plantations, so as to generate a spatiotemporally-heterogeneous mosaic [36]. Alternatively, we might consider the creation of a plantation to be the first step in a restoration project, to be followed by additional management activities that can help the ecosystem overcome the limitations mentioned above. One commonly-used method is tree thinning.

1.3.2 Plantation Thinning

Overstory structure in plantations is very different from that of old-growth forests [31]. Natural old-growth stands tend to have a heterogeneous canopy structure with trees of different heights and sizes [23], as well as canopy gaps that have a large impact on the development of understory shrubs and herbs [31]. Plantation canopy cover is typically very dense, however, due to the small, regular spacing between planted trees [31]. Plantation canopies can also close over completely after a few decades and shade out many forest specialist species that are crucial to the successful establishment of a native forest understory [4, 22, 23, 35]. In many areas, selective tree harvesting is therefore one of the

most common practices for restoring plantations [26]. Although thinning is often used for other purposes as well, including economic gain [31], wildfire prevention [36], and reducing the spread of pests [36], it can nevertheless have important ecological impacts, even when this is not the intended goal [36].[7] By imitating natural disturbances such as fire or trees falling due to wind or heavy snow [26, 36], thinning can accelerate succession and understory regeneration by recreating the heterogeneous overstory structure of old-growth forests and the intermediate levels of canopy cover that promote ground-level vegetation growth [4, 21, 23, 31, 36, 41]. Overall, thinning appears to accelerate forest succession in plantations to a greater degree than leaving the planted trees intact [21].

The thinning treatment is usually applied so as to create an overstory structure and understory conditions that are akin to those of natural forests [4]. In North America, thinning is sometimes used to create forests that imitate ecosystem properties from before European settlement and the interference of modern forestry practices [36, 41]. From a logistical perspective, the immediate goal of this treatment is usually to achieve a specific tree density or structure, such as reducing total basal area by a particular amount [24, 25, 36]. Typically, every third or fourth row of trees is removed entirely to allow access for the thinning equipment, and then the remaining rows are thinned to the desired density [19, 35]. The remaining trees can provide shade and protection for the understory and perches for birds, which act as important seed dispersers [21]. Depending on the purpose of the thinning, the left-over slash[8] may be removed, burned, turned into wood chips, or scattered across the site [36]. In general, thinning procedures should be planned so as to reduce damage to saplings, and logging young rather than old plantations is better for the understory, as it is still developing and can more easily recover [21]. Longer periods between thinnings can allow a mature understory to develop [4].

When a forest or plantation is harvested for lumber, usually a specific species is removed, with a focus on economically-valuable trees that are tall, wide, and straight [20]. In the case of a restoration project, however, unhealthy, insect-infested, and non-native trees will usually be removed first [24, 25], while large, healthy, native trees will be retained [36]. One of the primary differences between thinning for commercial purposes and as a restoration tool is the retention of dead wood in the latter case [26]. Dead wood acts as a habitat for many plant, animal, and fungal species [21, 26, 46], and stumps and fallen logs can protect tree seedlings from wind and animal browsing [26, 46, 48]. Snags[9] retained after thinning may also benefit tree and shrub species that are dispersed by animals [21]. It has even been suggested that one could measure the success of a thinning operation by the subsequent changes in species that depend on dead wood [21].

[7] Even when thinning is conducted for ecological purposes, the sale of timber can yield economic benefits [6, 21, 22, 31]. Forest restoration can be quite expensive, making large-scale efforts logistically unfeasible in poorer regions, so the profits of these timber sales can assist with the cost of restoration projects [6, 21]. Some countries, such as Costa Rica, use timber sales to encourage farmers to restore their unused fields using fast-growing tree species [6].

[8] Slash is the wood debris left behind after harvesting trees. It can include logs, branches, and bark.

[9] A snag is a standing dead or dying tree.

By selectively removing some trees, the thinning treatment is designed to increase the structural heterogeneity of the plantation overstory [26, 31, 41]. Although an old-growth structure can eventually form naturally in an unthinned plantation, frequent thinnings of different intensities may be needed in the short term to simulate natural canopy gaps [31]. As canopy openness increases, so too does light heterogeneity and availability in the understory [6, 20, 25, 26, 36, 36, 41]. It is generally expected that the increased light intensity will result in greater diversity and cover of understory vegetation [26, 36]. Finding the appropriate level of understory light is a delicate task, however, as ferns and grasses may dominate the understory vegetation if light levels are too high, suppressing the growth of woody species [6]. On the other hand, if light levels are too low, the ground may be covered by a thick layer of leaf litter, which also suppresses the regeneration of woody species [6]. To avoid these outcomes and generate a diverse understory, it is recommended that regular low-intensity thinnings be used to maintain a canopy cover of 70-80% [6, 23]. That said, some research has shown that boreal forest understories do not experience significant effects from changes in light levels [26], so thinning may not be as useful in these ecosystems.

The equipment used for mechanical thinning can also have severe impacts on the soil. Large equipment causes soil scarification, resulting in compaction, increased temperatures, topsoil removal, nutrient loss, the elimination of micro-topography, and a layer of sawdust coating the area [21, 46, 50]. The result of this treatment is often a heterogeneous soil disturbance that mixes the mineral and organic layers [36, 50], which can severely reduce soil carbon, organic matter, fungi, and bacteria over the long term [50].[10] The mixing of soil layers does enable rapid seedling establishment of both generalist and specialist species, however, by increasing available microsites and eliminating the thick organic surface layer [26, 36, 50]. Soil moisture and nitrogen content can also be increased by the thinning process [41], and nutrients retained within fast-growing understory species can help quickly re-establish elemental cycling afterwards [51].

With these changes in overstory and understory environmental conditions, there is often a corresponding change in understory vegetation. Native shrubs, saplings, and herbs all benefit from the increased light levels [31, 41], with recruitment, growth, abundance, richness, and cover of understory vegetation increasing substantially in the years following thinning [4, 6, 21, 26, 31, 36, 41]. Understory productivity generally increases after the overstory is thinned [41], and there is much greater community heterogeneity after thinning compared to unthinned areas [4, 36, 41]. Despite the increased competition from newly-arrived species, these effects are often achieved without the loss of the existing understory species [36]. Occasionally, there can be a slight reduction in understory richness initially, followed by an overall increase after a couple of years [41], but in general, thinning can promote the growth of native herbs without resulting in an understory dominated by shrubs or weeds [31]. Within a few years of harvesting, the abundance and diversity of tree saplings increases dramatically compared to unharvested plantations [21]. After 20 years, young stands of trees that have been thinned tend to have understories that are

[10] Regardless of applied treatments, it is also expected that secondary forests will always require a long time to recover their deep litter layer and mycorrhizae [31].

more similar to old-growth forests than unthinned stands, especially in terms of late-seral herb growth [31]. Animals, such as deer, may also spend more time in the area after this treatment due to the increase in understory herbs, which can aid with dispersal [31]. Studies comparing thinned and unthinned stands have found that these changes in the understory are primarily attributable to changes in the environmental conditions (e.g., light, moisture, temperature) after the canopy is opened [21, 31, 36], changes in resource availability (e.g., soil nutrients, water) [31, 41], and reduced competition belowground from the overstory trees [26, 31, 41]. Moreover, the thinning process is non-uniform and yields an uneven gap distribution, which creates patches of early and mid-successional habitats [36]. This large-scale spatial heterogeneity promotes species diversity [35, 36] and spatiotemporal variations in seedling regeneration across the landscape [21].

Research into this area has not been entirely consistent, however, with many studies yielding inconclusive results as to whether thinning improved or inhibited understory recovery, especially in the long term ($\sim$20 years) [6, 31]. In some cases, no change in vegetation cover or richness was found in the years following thinning [26, 36, 41], and there were no observed impacts on the persistence or extirpation of species [36]. Other studies have found outright negative impacts from thinning, such as the increase in cover and richness of disturbance-adapted exotic and generalist species [4, 31, 36, 39, 41, 46], large-scale decreases in shrub cover and diversity [41], and reductions in late-successional species (particularly in mesic habitats) [10, 36]. These undesirable outcomes are caused by several interacting factors. For example, the increase in canopy gaps leads to changes in air pressure, temperature, and humidity, which increases plant transpiration [10]. These changes to the understory environment can ultimately lead to changes in species composition and ultimately the establishment of a xeric alternative stable state [10]. Alternatively, the development of a dense layer of shade-tolerant saplings can cause understory regeneration to stagnate [31]. Thinning equipment, especially large vehicles, can also damage or destroy understory vegetation and its root systems, which will slow the restoration process [4, 21, 26, 39], and understory cover may temporarily decrease if the plants are covered by slash [41]. Each species responds differently to the impacts of thinning due to their differing abilities to adapt to the changes in the environment and resource availability [21, 26, 31]. Species' responses may also vary depending on the type and intensity of thinning [26, 31]. Some research has shown that late-successional and mesic species do well after intense thinning [31, 35], with heavy thinning generally resulting in long-term positive impacts on understory regeneration (e.g., order of magnitude increase in cover) and light thinning having negative impacts [31]. On the other hand, there are indications that the rate of understory regeneration actually decreases as disturbance intensity increases [21], and some studies determined that thinning intensity had no effect on understory vegetation [26]. Some of the discrepancies observed in post-thinning understory regeneration may also be a matter of spatial scale; many studies have noted differences in vegetation cover and richness at the local and landscape levels [36, 41]. These conflicting results therefore suggest the need for more empirical evidence to determine the contexts in which and the degree to which thinning actually accelerates understory regeneration, especially as we do not yet

know the long-term impacts of this treatment [31].

Besides the changes to the understory, thinning operations have numerous impacts on the plantation trees as well. After several decades without being thinned, plantation trees are generally unhealthy, and their tall, skinny trunks are susceptible to breaking under the force of winds and snow loads [24, 31]. It has been found that thinning accelerates vertical growth of the remaining trees, with growth rates correlated to increasing thinning intensity [31]. Conifers are also generally expected to increase in trunk diameter as winds penetrating the interior of the thinned plantation result in increased windfirmness [24, 52], and with more space to expand, the branches, canopy, and root systems can grow larger [19, 25]. That said, the literature does contain contradictory evidence, including one study where in the 20 years after thinning, conifer basal area did not increase compared to an unthinned plantation [31]. The same study also found that thinning did not result in vertical or horizontal canopy heterogeneity, partially because the remaining trees had become more stable and therefore fell less often [31]. Disturbance can also inhibit seedling establishment, with diversity and abundance of tree seedlings dropping by half at sites that have experienced high levels of disturbance [21].

With this information, one can tailor the thinning treatments so as to maximize understory regeneration and ensure the creation of a heterogeneous overstory. In southern Ontario, there is a standard prescription for thinning conifer plantations that have been established to restore abandoned farmland. Roughly 25-30 years after the plantation is established, it is thinned for the first time [19, 20, 24, 25]. The thinning is usually conducted during the winter, as the frozen ground can support the equipment and the tree bark's susceptibility to damage is reduced [19]. The first thinning gives the trees space to grow and expand, and unhealthy/dead trees can be removed at the same time [19, 24, 25, 36]. The openings also allow more wind to penetrate the interior, so the trees become windfirm as they sway in the wind [24, 52]. Afterwards, the plantation is again thinned every 10-12 years [25]. With the second thinning, the canopy begins to open sufficiently for light to penetrate the understory and tree seedlings to establish themselves in the soil that has been enriched and loosened by the early-successional conifers [20, 22, 25]. This process simulates the effects of fire and other natural disturbances that have now been suppressed across much of the province [25, 26, 36, 53]. Such events would naturally create canopy openings, remove dead trees and competing understory vegetation, and burn off the duff layer that prevents seeds from reaching the soil [53]. The soil layer is also disturbed by the thinning equipment, which mixes the surface organic and deeper mineral layers, providing opportunities for new growth [20]. By the third thinning, species from the surrounding forest have usually been dispersed throughout the plantation [25], and the remaining mature pines should be healthy [19]. Over time, more of the planted trees are removed with each thinning, and the young, diverse saplings continue to grow. By the fourth or fifth thinning, all but the largest, healthiest conifers have been removed, and a 30-40 year old native hardwood forest has taken the place of the plantation [25]. This process can therefore establish a young hardwood forest in a formerly barren area in just 60-70 years.

Despite all the benefits of this treatment, many studies have shown that thinning alone

is insufficient to yield the desired levels of understory regeneration. Burning is another restoration option that yields increased diversity and greater soil moisture and nitrogen availability [36, 41]. When burning recreates historic disturbance patterns, the understory regenerates quickly and fire-adapted species are not out-competed [36]. Burning is considered a vital tool for understory development, as it is fast and assists with nutrient cycling [26, 41]. (In mesic habitats, however, it can also increase the cover of generalist species and reduce late-successional species [36].) Some research has been done to study how the removal of understory vegetation impacts tree recruitment (tree recruitment can be suppressed by high-density understory vegetation), but the results are variable and may not be beneficial in early-successional habitats [21]. Ultimately, thinning may yield the best results when used in combination with other treatments, such as burning or storm simulation [26, 36, 41]. The use of multiple variable-intensity/density thinnings and/or multiple other treatments across the landscape might also be the best option for achieving the structural and compositional heterogeneity needed to develop a diverse understory [31, 35, 41]. It may therefore be worthwhile to explore other treatments that can be combined with thinning for best results. In the following subsection, we will explore one such option: applied nucleation.

1.3.3 Applied Nucleation

Forest restoration is commonly achieved either through natural regeneration or high-density, homogeneous plantations of early- or late-successional species [5, 11, 13, 17, 29, 33, 54]. Each of these techniques, however, has significant drawbacks. Though cost-effective, natural forest regeneration tends to be a slow process, its outcomes and timelines are unpredictable, and the growth of desirable plant species, such as native trees, can be suppressed by invasive species and woody shrubs, thereby halting the successional process [5, 8, 11, 13, 14, 29, 33]. This technique is typically limited by the natural availability of seeds from desirable species, especially if there are few nearby forest remnants [5]. Meanwhile, manually planting the entire area can be expensive and labour-intensive, often making the plantation strategy impractical for landscape-level restoration [5, 8, 11, 13, 17, 29, 33, 54]. There is also a tendency to plant dense monocultures or a limited number of species that dominate the forest of equally-aged trees, reducing overall biodiversity, forest structure, and ecosystem function [8, 17, 33, 54]. As with natural regeneration, this type of restoration is a long-term process because native forest species are slow to colonize plantations (see Section 1.2.1) due to seed dispersal limitations [4, 6, 23, 41], dense canopies shading out light-demanding species [4, 22, 31], and poor soil quality [4, 23, 41]. As discussed in the previous section, thinning the plantation can alleviate some of these issues, but it also presents new challenges and requires ongoing intervention.

An alternative restoration strategy is applied nucleation, which is a ∼30-year-old technique that combines the natural regeneration and manual planting strategies [8, 13, 29]. This method takes advantage of the facilitative effects and increased recruitment speed of plantations [4, 5, 8, 14, 15, 17, 21, 29, 33, 54, 55], as well as the economic efficiency, reduced

management requirements, and heterogeneous results of natural regeneration [5, 8, 14, 15, 17, 18, 21, 29, 33, 54, 55]. It begins with the planting of small, randomly-placed clusters of vegetation (typically trees) [8, 13, 15, 29, 54], which are occasionally accompanied by brush piles, transported seed banks, artificial bird perches, and smaller plants [11, 13]. Applied nucleation imitates the natural successional process of nucleation, where a few pioneer plants initially colonize the area in small clusters that spread outwards over time [8, 11, 14, 15, 17, 18, 29, 54, 55]. These artificially-created nuclei facilitate new growth [11] and can help the system overcome dispersal limitations by acting as seed sources, especially for animal-dispersed species [4, 5, 21, 55]. As a general rule of thumb, it may be best to plant those species that are least likely to establish themselves naturally within the desired time frame, such as late-successional, rare, or dispersal-limited species (e.g., ant-dispersed spring-flowering herbs) [4, 15]. The small islands of vegetation also attract insects, birds and terrestrial animals that can help spread dispersal-limited seeds and introduce seeds from species that weren't planted, which improves biodiversity and speeds the increase in (mostly native) forest cover [8, 11, 14, 15, 18, 29, 33, 54, 55]. Through natural recruitment processes, the vegetation will spread radially outwards from the nuclei over time until the clusters eventually merge, forming a single forest with a heterogeneous structure and composition [5, 8, 11, 15, 17, 18, 21, 55]. In the long-term, this technique can also increase the organic content of the soil [55], reduce erosion [5], and restore ecosystem functions such as pollination and nutrient cycling [29].

As restoration work is often limited by available resources, including funding and personnel, applied nucleation is an economical and efficient alternative to large-scale plantations [5, 8, 11, 15, 17, 29, 33, 54]. Average financial cost per unit area can be 30-66% lower for applied nucleation compared to plantation-style restoration, depending on the method of implementation [11, 13, 15]. Seedlings may be sourced from local nurseries or nearby sites where they are naturally regenerated [21]. Tree recruitment rates may be similar ($\pm$20%) in both plantations and applied nucleation sites [13, 15, 33] (and in both cases, regeneration tends to be much faster than natural regeneration [8, 14, 15, 17, 29, 33, 55]), and after the initial nucleation planting, the site usually requires very little management, which further reduces costs [13–15, 55]. Both seeding and transplanting nucleation clusters are effective options [33], and the restoration may proceed faster when other patches of forest are close enough to provide additional, diverse seeds [17, 55]. This technique may be especially helpful in restoring dispersal-limited, late-successional understory species after thinning of the plantation at Algonquin Park, as harvesting equipment can damage or kill much of the understory vegetation [39]. Larger nuclei (50-144 m^2) may be more effective in recruiting seedlings than smaller clusters (4-25 m^2), in part because they attract more seed dispersers [14, 15]. If the resources are available, watering nucleation sites during dry periods may enhance survival in the first couple of years [55].

Despite the claimed advantages of this method, research on the effectiveness of applied nucleation has been quite limited, and there have been very few long-term (>15 years) studies [8, 11, 14, 15, 33, 55]. Therefore, there remain several challenges and unanswered questions associated with this technique. For example, it has been found that applied

nucleation does not always follow the expected pattern of plants slowly spreading out from the nuclei [14, 55]; instead, the inter-nucleus regions are sometimes found to be evenly covered, though the causes of this phenomenon are unknown [55]. Additionally, no research has yet been done to compare the effects of using different inter-nucleus distances [11, 15]. The literature is also lacking studies of different planting designs/patterns, such as circular clusters vs. separated rows [15], and since the most effective nucleus size varies depending on local environmental and biological factors [14], more research is needed to determine ideal nucleus size for different locations and ecosystems [11, 18]. Some authors have also suggested combining the plantation and nucleation techniques by inserting nuclei into plantations or having plantations within large nuclei, but no one has yet tested the effectiveness of these designs [11].

Moreover, it appears this restoration technique is not always effective. In some cases, it does not result in a substantial or rapid increase in native species and may only encourage early-successional species to grow [55]. Some studies show no substantial difference in functional groups between naturally-regenerated and applied nucleation sites in the first few years [14]. Restoration efforts can also be hindered when the planted species are the only ones to return and biodiversity is not fully restored [54], which is why it may be best to avoid clonal plants that spread vegetatively, as they may spread too quickly and suppress other species [39]. Care must be taken to select nucleation species that won't compete for resources with recruited seedlings, although little research has been done to find the ideal mixes of planted species for different systems [15]. There has also been very little research into the claim that applied nucleation creates a more heterogeneous system than plantation-style restoration, and preliminary research in this area has shown that this may not be the case for some aspects of the ecosystem, such as soil nutrients [18]. Additionally, it may be the case that this technique is only effective in areas where there exist suitable microsites for the growth of seedlings [5], and in some cases, there can be biological or temporal limits on propagation and seed dispersal (e.g., seed predation, reduced seed dispersal after a few years, etc.) [14, 18, 55]. There are also issues with invasive species. Invasive plants and insects can be unintentionally introduced during the planting stage, via mulch or hidden on the nucleation plants [55]. In areas that are already dominated by invasive species, the nucleation species must be able to out-compete invasive plants, or else on-going efforts to control invasive species must be implemented [29].

There have been only a few studies that directly compare applied nucleation to other options, such as plantations [11, 13, 15, 18]. In one 6-year study comparing the effectiveness of high-diversity plantations to applied nucleation and natural regeneration, it was found that the plantation plots had greater tree diversity and basal area, as well as higher understory density (mostly consisting of tree saplings) [13]. The basal area within nucleation plots was 80% that of the plantations, however, suggesting that the two could have the same basal area within a few more years [13]. The nucleation plots were also found to have much larger diversity and abundance of recruited trees and a greater abundance of understory shrubs, herbs and vines [13]. Ultimately, their conclusion was that tree recruitment in plantations may be faster (at least initially), but nucleation planting is far more cost-

effective and is more effective in recruiting a diverse understory and new tree species [13]. A similar 15-year experiment determined that after 10 years, both the plantation plots and the nucleation plots had roughly equivalent abundance and richness of various floral and faunal categories, and these were much greater than in the naturally-regenerated plots [15]. In another case, a study examining plantation and nucleation plots 5-7 years after planting found no difference in soil nutrients or recruited tree diversity [18]. They did observe much greater heterogeneity in canopy openness in the nucleation plots, however, as well as soils with far less acidity and greater base saturation [18]. Overall, it appears that more research directly comparing the various techniques is needed, and more long-term observations may be required to fully understand the differences between them [18]. It may also be the case that the ultimate decision of plantation vs. applied nucleation may depend on a project's context, constraints, and desired outcomes.

Applied nucleation is considered a promising technique for large-scale reforestation, although few attempts at large-scale restoration have been attempted using this method [11, 15, 33, 54]. In one long-term study, applied nucleation was used to restore a functioning forest over an abandoned landfill, despite the poor soil and decades of intense human disturbance in the area [55]. In that case, less than 3% of the site was planted and there were no ongoing management activities, yet a dense, mid-successional forest was generated in under 20 years [55]. Another experiment has also shown applied nucleation to be effective in the small-scale restoration of grasslands dominated by invasive species [54]. It has been tested many times in tropical regions, having been used to successfully restore forests on former pasture and agricultural land [11, 13, 15, 17, 18, 29], as well as a clear-cut pine plantation in Uganda [33]. Some preliminary work has been done with applied nucleation in temperate forests [15, 55], but it appears that little to no published research has been done on its effectiveness in the Canadian mixedwood plains ecozone. This research project in Algonquin will therefore fill that particular gap in the literature. We will also be testing the use of small nuclei consisting of understory shrubs rather than the more typical design of large, tree-based nuclei, and we will combine two forest restoration techniques by establishing these nuclei within an existing plantation.

1.3.4 Wood Chips

Another common restoration treatment is the use of wood chips, which can be generated from slash piles leftover from tree harvesting operations. Spreading wood chips on the ground at a restoration site can improve soil quality by reducing compaction, aiding in water retention, and increasing the organic content [56, 57]. Wood chips also release various nutrients into the soil, such as nitrates and magnesium, and since it can take decades for them to completely decompose, wood chips continuously supply small amounts of nutrients to the soil over long periods [32]. Spreading slash chips can significantly reduce the leaching of inorganic soil nitrogen and aluminum from harvested areas, thereby reducing impacts on nearby waterways and maintaining soil quality [34]. This treatment can reduce the growth

of weeds and non-native species during the first 1–2 years after application [32, 54], while also promoting the growth and spread of some native species [54, 56].

There are a few downsides to the use of wood chips as a restoration treatment, however, such as their potential to prevent the growth of some native species [54]. For example, it has been shown that the growth of spruce seedlings is impaired by wood chip treatments, possibly due to nutrient immobilization or the leaching of undesirable chemicals from the slash [57]. In some cases, humus may actually be more effective in stimulating plant growth than chipped slash [57]. Wood chip application can also lead to nitrogen immobilization, which is undesirable in the context of regenerating the understory [34].

Despite these potential drawbacks, wood chip treatments remain a common practice in the field of restoration. They have been used in studies of forest [32, 57] and grassland [54] restoration, and they have been shown to reduce the leaching of nitrates and other chemicals into waterways after industrial logging [34]. In one experiment, wood chips were used to successfully restore forests on abandoned logging access roads in remote areas of British Columbia [56].

1.3.5 Understory Restoration Indicators

Ecological integrity may be defined as: "the capability of an ecosystem to maintain a community comparable to that of a natural habitat for a given region" [4]. It can be used as a framework for gauging the successional process of restored ecosystems [4]. In comparisons of plantations to native forest, the development of an understory can act as a measure of the system's ecological integrity [4].

Short-term forest restoration experiments employ a variety of indicators to determine whether the applied treatments are successful in restoring structure, composition, and function [14]. Common indicators of understory regeneration include the abundance and percent cover of plant species [4, 6, 9, 14, 18, 22, 23, 26, 29, 31, 33, 37, 41, 48, 55], the relative proportions of native and non-native species [29, 41], relative proportions of early- and late-successional species [4, 23, 31], overall biodiversity [4, 6, 13, 18, 22, 23, 26, 31, 36, 41, 55, 58], seedling density [5, 22, 33, 55], and seedling heights and/or basal area [6, 9, 13, 22, 31, 41, 56, 59].

When restoring plantations, forest structure can be an important indicator of progress. Plantations tend to consist of densely-planted, regularly-spaced, mono-specific stands of equal-aged trees forming a closed canopy [4, 22, 31]. Consequently, plantation structure and composition lack the heterogeneity of naturally-regenerated forests. Indicators of plantation restoration may therefore include: light levels [4, 6, 22, 23, 42, 43, 48, 59], canopy openness [6, 14, 18, 23], number of canopy trees [22], and density and heights of planted and non-planted woody species [6, 22, 41]. Examining the spatial variation of these and other properties (e.g., biodiversity, cover, etc.) may also reveal whether structural and compositional heterogeneity is increasing over time [18, 21, 36, 41].

As woody species and spring-flowering herbs are common in mature and old-growth forests but uncommon in conifer plantations, they may be used as indicators of understory restoration [4, 23]. For example, late-successional forest specialist species, such as ant-dispersed spring-flowering herbs, are dispersal-limited and highly sensitive to disturbance, so their presence may indicate advanced restoration progress [4]. Understory species that require a lot of light and have long dispersion distances, however, are indicative of early-successional stages and should ideally decline over time as the forest canopy closes and late-successional species begin colonizing the area [4]. Such light-demanding species may include non-native species, grasses, ferns, and herbs that flower in summer or late summer [4, 6, 22].

Soil quality is an indicator of long-term viability and ecosystem health, and it has been shown to correlate with the growth of native and non-native species [49]. Many restoration projects therefore involve monitoring soil nutrients (e.g., N, C, S, K, Ca, Mg, NH_4, NO_3) [18, 32, 34, 55, 56], organic content [18, 55, 56], compaction and bulk density [56], moisture [34], and temperature [34], among other factors. Leaf litter depth and biomass can also be used as an indicator of plantation understory regeneration [6, 14, 22]. The amount of bare soil or exposed rock may be useful indicators of recovery after disturbance, such as damage done by plantation harvesting equipment [22, 26].

Depending on the scale and duration of the experiment, additional indicators, such as animal biodiversity, may be used, but measurements of soil quality, vegetation, and light intensity appear to be the most common options for short-term reforestation research. Overall, understory development can be a useful indicator of the forest ecosystem's overall ecological integrity [4]. As we lack an accurate picture of North America's forest structure prior to European colonization, however, these indicators can at best only be used to compare the research site to naturally-regenerating forests that currently experience little anthropogenic disturbance [41]. It should also be noted that interannual variability in understory richness and cover can make it difficult to detect which effects are caused by the restoration treatments and which due to uncontrollable disturbances (e.g., storms, droughts, etc.) [23, 41]. In light of these variations, a single survey of the chosen indicators is insufficient; it is instead usually necessary to monitor the site over many years to accurately determine whether the system is following the desired successional trajectory [6].

Chapter 2

Experimental Restoration in Algonquin Provincial Park

Despite its reputation as an untouched wilderness, Algonquin Provincial Park has a long history of human presence. Over the past two centuries, hunting, trapping, logging, and recreation have had enormous impacts on the local ecosystems, and despite its status as a park, humans continue to exert a substantial influence. One area that has played an important role in the Park's history is Cache Lake, where Park Headquarters, a hotel, and a train station were once located on its north shore. In the 1960s, these buildings were demolished and replaced by a red pine plantation (Fig. 2.1), one of many planted throughout the Park to restore degraded areas. Left unmanaged, these plantations have become unhealthy, with many trees at risk of blowing down and posing a risk to visitors [24]. As part of the Park's modern policy to return the landscape to its precolonial state, however, these plantations are to be restored to native forest at last.

The Cache Lake plantation is one of several pine plantations in the Park that have been thinned with a view to natural forest regeneration [24], but this is the only one in which accelerated regeneration is to be tested experimentally. To initiate this restoration, a four-year project began in 2021 in conjunction with the University of Waterloo. The purpose of this project is to experimentally study methods for rapidly restoring the understory of a northern mixedwood plains pine plantation. The project will test two universal treatments, which have been applied across the Cache Lake site: tree thinning and invasive species management. Using a variant of a randomized complete block design, it will also examine applied nucleation, which is a cost-effective method of accelerating natural regeneration. This involves transplanting beaked hazel shrubs into the site and observing their impacts on understory regrowth compared to control plots. Although this technique has been in use at other sites for several decades, it has not been tested under these conditions before. We will also examine the use of 'windthrow guards', a novel treatment that uses small, herbaceous plants surrounding shrubs and saplings to deflect strong winds upward and prevent windthrow. We will be transplanting Canada goldenrod to establish protective rings around the hazel shrubs. A review of the literature shows no explicit tests of this



Figure 2.1: Historic walking trail at the Cache Lake pine plantation.

treatment, making this the first experimental demonstration of windthrow guards as a tool for ecological restoration.

Overall, this experiment will seek to answer 3 primary questions: (1) Which treatments yield the largest and fastest growth/spread of native understory species within the 4-year project timeline? (2) Which treatments restore the major biological and chemical components of the soil? (3) Do windthrow guards reduce mortality among transplanted shrubs? The ultimate goal of this project is to regenerate the native understory, with the long-term goal for the area being the eventual re-establishment of a native, biodiverse forest [24].

To answer the research questions, vegetation cover and soil quality will act as indicators of restoration progress and will monitored across the site. Measurements of light intensities should also yield information on the rate of understory recovery. Transplant survival and health will be monitored to determine whether the windthrow guards are effective.

Beyond the narrow focus of this single site, the results of this experiment may act as a useful guide for the restoration of other plantations within the Park, and more generally, there are potential implications and lessons for the development of rapid, low-cost forest restoration techniques. This work may also serve as a reference for those planning similar restoration projects, and as such, detailed information about the logistics of this experiment has been recorded as well.

In this Chapter, we will examine the initial stages of this project over its first two years, especially the planning and implementation stages. Section 2.1 describes the research site, including its history, climate, flora, and fauna. In Section 2.2, we will examine the various elements of the experiment's design, such as the treatment plan and timeline, with particular focus on why we chose this design. This is followed in Section 2.3 with a detailed

discussion of the restoration treatments, while Section 2.4 covers the experimental methods and the application of the treatments to the site. Finally, we will review the preliminary results of the experiment in Section 2.5, and end with some concluding thoughts in Section 2.6. Chapter 3 will follow up on these early stages of the project with an analysis of the desired trajectory for the plantation ecosystem in the near-term and long-term.

I would like to thank my supervisor Stephen Murphy, as well as Park staff Sandy Dobbyn, Jennifer Hoare, Joe Yaraskavitch, and Alison Smith, for their work on the initial planning for this project. They developed the original plan for this experiment, and the two universal treatments were handled by Park staff and contractors. Many thanks to Steve, Jenn, and Alison for assisting me with my questions about the experiment and the research site. I also very much appreciated the wonderful accommodations at the Algonquin Wildlife Research Station, where I stayed during my fieldwork in the Park. Finally, much of the work and results described in this chapter would not have been possible without my fieldwork assistants, who helped me transplant hundreds of shrubs and herbs. Thank you so much for your help and company: Abraham Dominguez Duque, Eve McLeod Norberg, and Mark Saunders.

2.1 Research Site

The research site for this project is a red pine plantation on the north shore of Cache Lake in Algonquin Provincial Park, Ontario, Canada. This area is within the Unorganized South Nipissing District of north-central Ontario. The site is positioned between Provincial Highway 60 (Frank McDougall Parkway) to the north and Cache Lake to the south. It is bounded to the east and west by two access roads, the latter of which leads to the main public parking lot and boat launch. The other access road leads to the old Superintendent's house and a private boat launch for cottagers. Figure 2.2 shows the site location and surrounding environment. The research site is centered on the coordinates (45°33'08.7"N, 78°35'42.0"W).

Unlike a laboratory experiment, in which most variables can be artificially controlled, field experiments are necessarily impacted by a myriad of factors beyond the control of the researcher. These factors, most of which cannot be directly measured, combine to form a system that exhibits complex behaviour that may be impervious to attempts at detailed predictions of the future. Such factors include weather patterns, plant biology, plant-wildlife interactions, microbe and fungus activity, and long-lasting impacts of historical events. None of these can be controlled, nor are their impacts all 100% quantifiable.

As this experiment is confined to a relatively small area, however, all treatments should be exposed to roughly the same conditions, eliminating differences between treatment plots. On the other hand, the site as a whole will nevertheless be exposed to factors beyond our control. Therefore, in order to accurately characterise the properties of the plantation system and project its approximate restoration trajectory (as we'll be doing in Chapter 3),

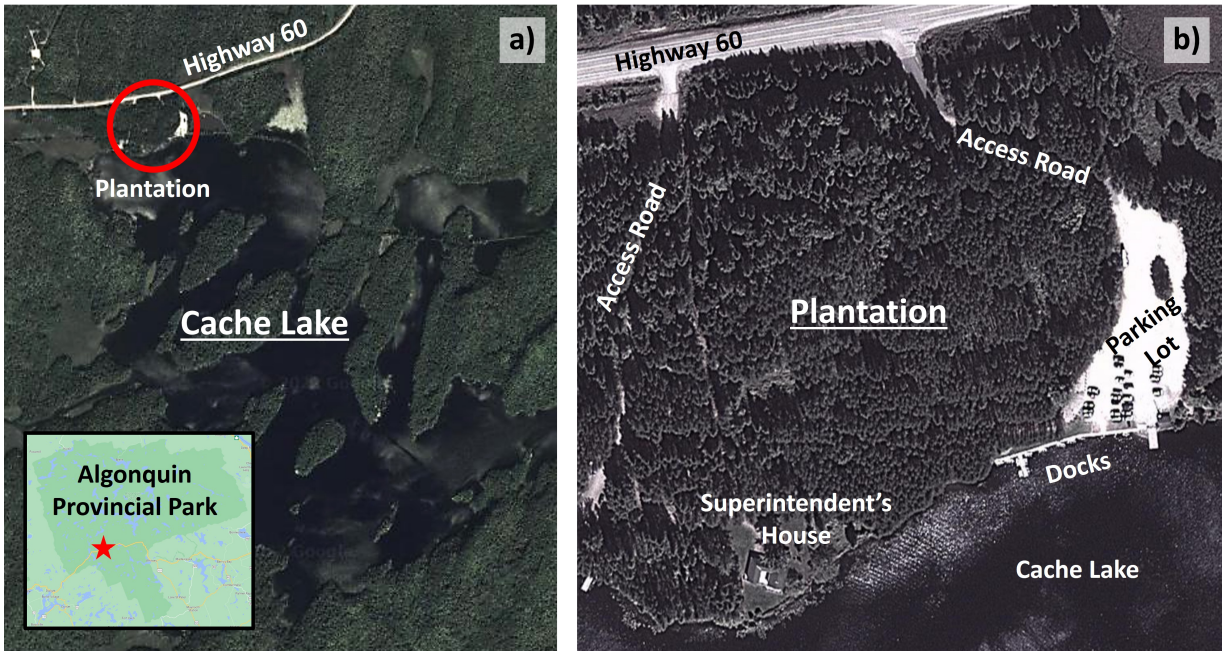


Figure 2.2: a) Location of the research site on the north shore of Cache Lake. Red circle indicates location of plantation. Inset: Location of Cache Lake within Algonquin Provincial Park (red star) [60]. b) Satellite image of plantation with major landmarks labelled [61].

we must first learn as much as possible about it. One factor that will have an enormous impact on the site's future is its history, particularly the legacy of human activity, which extends back thousands of years and has severely altered the landscape. We must also examine the climate conditions, geology, and soil proprieties at the research site, which will affect the health and growth of various plant species. Finally, the native flora and fauna species in the region will determine the types of treatments, particularly transplant species, we can apply to the area.

2.1.1 History

Algonquin Park has a long and fascinating history that cannot be entirely captured in a few pages. While information on the historical ecosystems at the research site may be helpful in determining its future, human impacts on the Park's ecosystems have been progressively increasing over the past 150 years [62]. The native ecosystem at the research site was largely eliminated in the 1890s to make room for Park Headquarters and, later, a luxury hotel. Therefore, although we will briefly cover the precolonial history of the Park, it is more important for our present purposes to study the history of the site from the 1890s onward, as the area's history of human interference currently has the largest impact.

In the following subsections, we will cover the research site's history from the formation of its early geological features to the Park's establishment and the hotel era, followed by

the creation of the pine plantation. This section concludes with a brief look at the site's present state and how its history continues to impact its current condition.

Prehistory - 1893: Geological Formation, Indigenous Inhabitants, Logging, and Establishing the Park

The complete history of Algonquin Provincial Park extends much further back than the arrival or even the existence of its current ecosystems. Algonquin as we know it was shaped first by geological processes, particularly the creation of a mountain range across the western regions of the Park (including Cache Lake) ∼500 million years ago [53]. Over time, the mountains eroded away, leaving Algonquin's iconic hills. A series of four glaciers contributed to this erosion as they moved across the landscape over the most recent one million years, with the final ice sheet retreating approximately 10-11 thousand years ago [53, 63]. Nearly half a millennium passed before the glacier melted completely from the southern tip of the Park to the northern edge [53]. These glaciers carved the river channels and the more than 2000 lakes we see in the Park today, filling them with water upon the final glacier's retreat [63, 64]. The modern ecosystems began establishing themselves shortly thereafter.

Based on archaeological evidence, primarily stone tools, it is believed that humans first arrived in this region in 7,000 B.C.E. [62, 63, 65]. Over the next 8.5 thousand years, a series of hunter-gatherer peoples inhabited the area, and the first Algonquian-speaking people arrived around 700 C.E. [63]. Archaeological evidence has not revealed any large settlements from this era, likely because the nutrient-deficient soils made the area unsuitable for agriculture [65]. Little is definitively known about these early visitors who spent their winters hunting here, aside from that which can be gleaned from oral histories and remnants of stone tools and pottery [62, 63]. In the early 1600s, European explorers such as Samuel de Champlain began to travel this far inland, but they almost invariable bypassed the Park and its rough terrain during their travels [62, 63]. Perhaps the first time European settlers entered what was to become Algonquin Park was in the early to mid-1700s, when French fur traders may have used the rivers as transportation [63].

It wasn't until the 1800s that Europeans really began to spend time in the area [62]. By the 1820s and 30s, settlers and surveyors were regularly travelling through and occupying parts of the modern Park region [63]. Around this time, a series of wars and changes to differential duties had led to an increased demand for timber from British North America to supply English shipbuilders and carpenters [62, 63, 66]. By around 1830-1840, logging within the eastern regions of the modern Park borders had begun, primarily red and white pine in these early years [53, 62, 63, 65, 66]. The timber was transported to the Ottawa River, and then on to the ports in Quebec, by log drives, a highly dangerous practice that resulted in many deaths [53, 62, 63]. As the lumbering business took off, the Park was seasonally filled with hundreds of loggers living in small, unsanitary shacks in the wilderness [53, 62]. The 'untouched' forests of this era held pines more than 40 m tall and 1.5 m wide, but due to the voracious lumbering of the pioneers, these ancient giants were gone from the Park within 70 years [53, 62]. It was a time when people believed Canada had an endless

supply of resources, and as a consequence, the logs were 'squared' for ease of transport by ship, a process that involved removing the rounded sides of the tree and wasting as much as half of its mass [62]. As the supply of the largest pines was exhausted, the sawn lumber industry came to dominate around 1840-1850, helping to supply the new markets across the American Midwest [62, 66]. In 1867, the same year Canada achieved confederation, businessman John Rudolphus Booth bought a large timber limit[1] encompassing most of the southern parts of the modern Park [62, 63]. Owning a vast rail network to move his lumber across the country, Booth would later become a renowned timber baron and one of the country's richest people [63]. He and his businesses feature prominently in the early history of the Park [63, 66]. By 1879, almost the entirety of the modern Park region had been reserved for timber harvesting, and tens of thousand of logs were being sent down the rivers each year [53]. Figure 2.3 shows loggers standing atop a pile of white pine logs harvested in the Park.



Figure 2.3: White pine logging in Algonquin, c. 1910. (APM 1057 Edited, Algonquin Provincial Park Archives & Collections)

By the 1850s, it was expected that this region would be used for agriculture once all the trees had been cleared [62, 66]. Although we might find it surprising today, this plan was actually supported by both the government and the local citizenry [66]. In 1878, Alexander Kirkwood, a chief clerk working for the Ontario Department of Crown Lands, co-published a report indicating that the vast uninhabited areas of northern Ontario could house 500,000 people [62, 63, 66], and township surveys of the future Algonquin Park area

[1] A 'timber limit' is the right to harvest timber within a specific area.

were conducted over the following 18 years [63]. Although farms were established near the future Park, particularly north of Haliburton, fertile soils are uncommon in this region, and less than 20% of the Park's original area had soil that could be used for agriculture [66]. Additionally, with no local markets in which to sell their crops (mostly oats and potatoes), many farmers had difficulty making a profit and turned to winter trapping and lumbering to supplement their income [66]. By the 1880s, many families were leaving the area, and the government acknowledged that the agricultural plan would not be implemented [66].

As new settlements could not be established, the government was left to ponder the future of this large area of land. In 1885, after spending several years reconsidering his previous notions of agriculture and settlement, Alexander Kirkwood suggested the creation of a park to preserve Ontario's wildlife, water resources, and forests [62, 63, 66]. This was not a popular idea in an era when it was still believed that the nation's seemingly-endless natural resources could never be depleted [66]. It was also his recommendation that once resource extraction had been brought under control,[2] the Park could be opened up to tourists, who could stay at camps, hotels and lease cottages [62, 66]. He recommended it be called 'Algonkin Park' in reference to the Algonquian peoples who once occupied the area [62, 63, 66]. Kirkwood hoped "to maintain [the Park], as nearly as possible, in the condition in which it was when they [the Algonquians] fished in its waters and hunted and fought in its forests" [66].[3] The government later concurred with his suggested name; they hoped that this gesture would help to preserve the history and memory of one of North America's most wide-spread Indigenous peoples [63]. The region for the proposed Park was surveyed in 1886 [63, 66], and in 1892, the Royal Commission on Game and Fish presented their final report, in which they accused the Ontario Government of gross wildlife mismanagement and recommended the creation of a provincial park [62, 63]. Finally, that same year, the government established a Royal Commission to explore the possibility of creating a new park [62, 63, 66].

The Royal Commission, chaired by Kirkwood himself, submitted their final report in 1893, and the Algonquin National Park Act was adopted later that year, declaring that 18 townships, covering an area of 3800 km^2, would be reserved for the creation of a new park [62, 63, 66]. The purpose of this new park was: to preserve native forests and help them retain their native state; to preserve the lakes and waterways in the region, which acted as important freshwater supplies (10% of the Park's original area was covered by water); to protect wildlife and increase their populations; to act as a recreational and health resort; and to act as a research site for forestry practices [53, 63, 64, 66, 67]. The extent to which the forests would actually be preserved was to be limited by practical necessity; lumbering was considered perfectly acceptable and was expected to continue for the foreseeable future [53, 63, 66].[4] In fact, the logging industry was very much in favour of the Park's creation,

[2]He suggested timber extraction be strictly supervised by the government, rather than being left to the lumber companies to do as they pleased [62, 66].

[3]By this time, however, the preceding decades of settlement, logging, agriculture, and human-caused forest fires had substantially altered the landscape [62, 63, 66].

[4]The controversy over logging within a provincial park only arose decades later as more visitors arrived

as it would preserve the forests that would otherwise be destroyed by settlements and subsistence farming [53, 62]. Similarly, although the government wished to preserve the native landscape, they were also interested in introducing new plant and animal species to make it more attractive to humans [62–64, 66–69].

Although it was administered by the provincial government from the beginning [62], the Park's original title was 'Algonquin National Park' [62–64, 66]. It became Canada's first provincial park in 1913 when it was officially renamed 'Algonquin Provincial Park' [62, 63, 67] to distinguish it from other national parks, which were administered by the federal government [66]. The original Park boundaries were expanded over time, with surrounding townships being added throughout the 20th century until 1993 [62, 63, 66]. At 7600 km^2, it is now more than twice its original size [62].

1893 - 1959: Park Headquarters and Tourism Destination

Having been within the original boundaries of the Park [66], the Cache Lake area has a recorded history that spans more than a century and has played a very consequential role in the history of the Park itself. The unassuming plantation that today stands on the lake's north shore betrays little evidence to the casual observer that this site was once central to Park administration and tourism.

After the founding of the Park in 1893, Park Headquarters was established at Canoe Lake by the Park's first Superintendent, Peter Thompson,[5] and in 1897, it was relocated to Cache Lake [62, 63]. At that time, Park staff consisted of the Superintendent and four rangers, who patrolled the Park by land and water in two-man teams [64, 66, 68, 70]. While the Superintendent's job was to administrate the Park, the rangers were tasked with cutting ice and wood for Headquarters; cutting portages throughout the Park; 'improving' streams, presumably so they could be used for travel; making canoes and snowshoes for their patrols; preventing poaching, squatting, and other illegal activities; watching for and extinguishing forest fires[6]; and constructing shelter houses throughout the Park for use during their ranging patrols [64, 66, 68–70].

In August of 1898, at the age of 47, George W. Bartlett was appointed as the Park's third Superintendent [62, 63, 66]. Bartlett, who was to become the longest-serving Superintendent in the Park's history (1898-1922) [62, 63], would have an enormous impact on the early success of the Park. By the time he arrived, the Park was already gaining a negative reputation due to rampant poaching by local trappers to the north, who were unconcerned

within the Park [53]. The current strategy for handling this controversy, which was devised in the 1930s, is to segregate the logging and tourism areas [53]. Today, about half of the Park's area is still open to logging [53].

[5] Sadly, Peter Thompson died suddenly of a paralysis-inducing illness in 1895; he was succeeded by one of his rangers, John Simpson [66].

[6] In later years, a separate team of fire rangers was established, but in the two decades after the Park's creation, the Park's limited ranging staff were responsible for fire fighting in addition to their other duties[63, 66].

about potential reprisals by the distant government in the south [66]. Local citizens had been hunting and trapping in the area since long before the Park existed and had little inclination to cease these customs that had now been declared illegal [62]. The rangers of this era were also willing to look the other way and were known to occasionally engage in such untoward activities themselves [66].

With Bartlett's arrival, the Park entered a new era of activity and wildlife protection. In his first year, Bartlett more than doubled the number of Park rangers [63, 66], and it became widely known that illegal activities would no longer be tolerated. They managed to successfully curtail poaching [66, 69, 70], and by 1912, they had only two recorded incidents of illegal trapping during the entire year [69]. This success was attributed to the efforts of the Park rangers, as well as to the overflow of wildlife from the Park into surrounding areas, which satisfied most trappers [70]. The number of rangers increased steadily during Bartlett's tenure, reaching 33 by 1917 [71]. Although poaching would again increase during the Great Depression [63], illegal activities were eventually eliminated when Park staff began patrolling by airplane daily, starting in winter of 1932 [62].

Through the staff's efforts, populations of several game species, including moose, deer, otters, beavers, mink, marten, partridge, and duck, increased over the first couple of decades of the Park's existence [66–70, 72, 73]. In 1911, Bartlett remarked: "[d]ucks are becoming much more numerous, and thousands of them could be seen in our large marshes last fall" [64], and by 1914, visitors could feed the large herds of deer by hand right outside the lodges where they were staying [62, 64, 72]. Fish were sufficiently populous that fishing licenses provided considerable revenue for the Park during this time [64, 67, 72, 73].

Despite early victories, however, this new era under Bartlett was not entirely without controversies. Seeking to maintain this steady increase in wildlife populations, the Park rangers began to trap, hunt, and poison wolves to prevent them from eating the deer [62, 64, 66, 67, 69, 70]. By 1915, roughly 60-100 of these 'pests' were being culled each year by Park staff [73], with a $15 bounty per animal [66]. This successfully resulted in substantial increases in the deer population, to the point that a discernable 'browse line' could be seen along shorelines, and some tree species, such as cedars, lost most of their seedlings to overbrowsing [53]. The practice of poisoning wolves ended in the 1930s [62], possibly because snowfalls would sometimes cover the poisoned bait before it could be eaten [73] and because there was a risk of other, desirable animals consuming it [66]. The large wolf population persisted for several decades thanks to the Park's permeable borders, but their numbers finally started decreasing in the 1930s; only 11 wolves were killed by rangers in 1938 [66]. Wolf hunting by Park staff finally ceased in 1959, shortly after the establishment of Ontario's Wolf Research Program [53, 62, 63], the goal of which was to study the behavioural patterns of a wild population [62]. With the increasing wolf populations, deer populations began to drop significantly and were largely replaced by moose over the following decades [53].

Another issue of contention was trapping. In 1908, Superintendent Bartlett suggested to the Department of Lands, Forests and Mines that a large revenue could be made from the

supervised trapping of beaver within the Park, as the population had increased dramatically [66, 68]. The following year, he noted in his annual report that the Park could even be made self-supporting if fur sales were used as a source of revenue [70]. Soon, several animal species were being trapped regularly by Park rangers, including beavers, muskrats, mink, martens, and otters [66], and the government started auctioning their furs in Toronto in 1910 [63]. Live animals from the Park (especially beaver, mink and marten) were also sold to zoos, private collectors, and fur farms[7] across North America and Europe [66, 72]. The sale of live animals was considered to be a way of fulfilling one of the Park's founding principles: "the multiplication and spread of our fur-bearing animals" [67]. The sale of furs and live animals was providing a large annual revenue for the Park by 1913 [66, 67, 72]. In 1915, during WWI, the Park superintendent noted that the population of beavers had become so large, the Province could easily take at least 500 pelts per year without harming the Park's ecosystems, thereby generating several thousand dollars in revenue [73]. The sale of furs from the Park ended in 1920, however, due to a severe public backlash over the government's hypocrisy [63, 66]. The locals were incensed that the Park was preventing them from accessing their traditional trapping territories while it profited from its own trapping activities there [66]. Some Park rangers were also privately profiting from furs they had illegally acquired within Park boundaries [62, 66]; the public perception was that the rangers were sending half of the pelts to the government and just keeping the rest for themselves [66]. There has been some suggestion that these government trapping policies actually led to an overall increase in poaching during this period [66].

The changes in the Park in these early years were not isolated to wildlife management; human activities were also changing the landscape. Back in the 1870s, the land that was to become Algonquin Park had been surveyed to determine whether it was suitable for the extension of the Canada Central Railway, which was to be connected to the Canadian Pacific Railway and create Canada's first transcontinental railway [63]. Due to its steep terrain, however, the region was bypassed and remained without a traversing rail line for several more decades [63]. In 1892, construction began on the Ottawa, Arnprior, and Parry Sound Railway, which was intended to connect Georgian Bay on Lake Huron to the Ottawa Valley and the Canada Atlantic Railway [63, 66]. Created by J.R. Booth, its purpose was to speed the transport of grain eastward and to facilitate the extraction of timber from the Park, which had previously relied on laborious and highly dangerous log drives along rivers and lakes [62, 63, 66]. The railway reached the Park in 1895 [63], and in October of that year, it extended all the way to Cache Lake and was used to deliver the equipment and materials needed to begin building the new Park Headquarters [66]. Construction of the railway finished in 1896 [63], with the first commercial trains starting in 1897 [66]. By 1900, up to 40 trains were crossing the Park every day, carrying all manner of goods and raw materials [63]. Despite the enormous utility of this line for transporting freight,

[7]Breeding captive animals for their fur was a newly-developing industry at the time. In 1914, Bartlett remarked: "It is now recognized that owing to the increased demand and the steady encroachments which civilization is making on the waste places of the world inhabited by fur-bearing animals, a large part of the fur supply of the future must necessarily be got from animals bred in captivity or under control" [72].

the creation of the railway did have some negative impacts. Most of the Park's forest fires in the early 1910s, including some very large and severe fires, were reportedly caused by the locomotive engines, likely from chimney sparks and/or the dumping of expended hot coals [67, 70, 72].[8] Nevertheless, the creation of this line enabled another very important development in the Park: tourism [62, 66].[9]

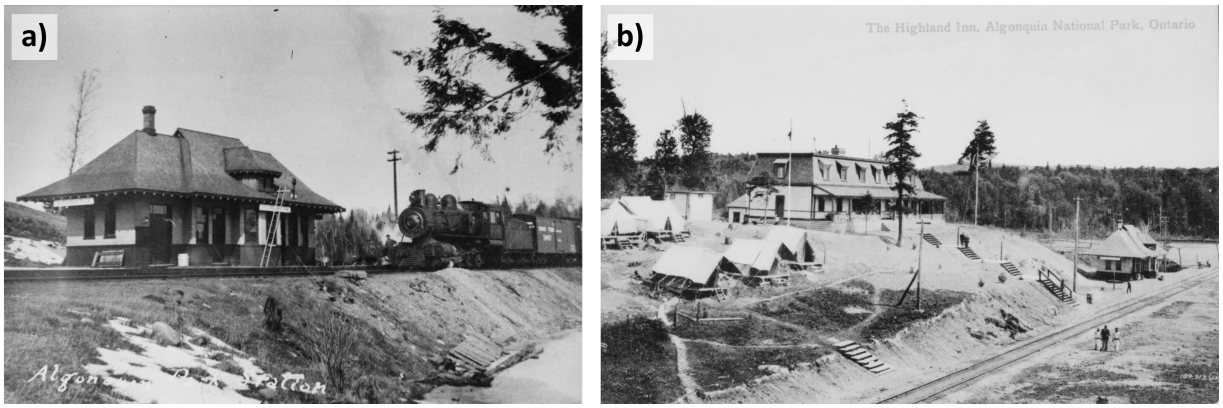


Figure 2.4: a) Algonquin Park Station at Cache Lake, April 1914. (APM 3463 Edited, Algonquin Provincial Park Archives & Collections) b) Original Highland Inn building with overflow tents, c. 1908. (APM 6403 Edited, Algonquin Provincial Park Archives & Collections)

The Park, and Cache Lake in particular, soon became a popular recreational destination, and by 1913, hundreds of tourists from around the world were visiting the Park each year [67]. Art students used the Park for sketching trips [63, 66], girls' and boys' summer camps were established on several lakes[10] [62, 63, 66, 73, 74], fishing competitions and sailing regattas were held at the lakes [63, 72], religious seminars were held at one of the Park's lodges [63, 66], canoeists by the hundreds explored the Park's waterways in summer [69], and dozens of guests even visited during the winter [69]. The Park's first hotel was established by the railway company in 1906 on the north shore of Cache Lake [63],

[8]Superintendent Bartlett suggested in 1914 that all engines passing through the Park be replaced with oil-burning varieties [72]. While this does not appear to have happened at the time, the brush and trees on either side of the railway were cleared [71, 73, 74], and the railway company did create a special car carrying two large water tanks and a long hose in 1915 [73]. This unique vehicle could be pulled along the railway to the site of a fire to help put it out [73], and by 1916, in combination with enhanced communication enabled by the new phone lines, these efforts had begun to substantially reduce the number of extreme fires caused by the railway [74].

[9]The ease of access granted by the railway also permitted the establishment of larger settlements within the Park, such as the now-vanished village of Mowat at Canoe Lake, which in its heyday as a lumber town had a population of over 600 [62, 66]. In fact, during World War I, this line through the Park became the busiest railway in the country as troops and equipment were shipped eastward; at the recommendation of Superintendent Bartlett, the government even authorised deer to be shot in the Park and transported by rail to help stabilise food supplies during the war [62, 63, 66, 71].

[10]Northway Lodge, now called Camp Northway, was constructed on the shore of Cache Lake in 1908 [63]. It is Canada's oldest girls' summer camp and remains in operation to this day.



Figure 2.5: a) The completed Highland Inn, seen from the west with a train pulling into the station. (APM 6401 Edited, Algonquin Provincial Park Archives & Collections) b) Highland Inn seen from the east, near the train station. (APM 4829 Edited, Algonquin Provincial Park Archives & Collections) c) The Highland Inn's dining room filled with guests, c. 1946. (APM 3326, Algonquin Provincial Park Archives & Collections)

where our research site is now located. It consisted of a collection of sleeping tents and a large, open-sided tent that was used as a 50-person dining area [63]. Two years later, the tents were replaced by a real building, the Highland Inn, and a small train station (Algonquin Park Station) was erected beside it to facilitate tourism, as shown in Figure 2.4 [62, 63, 70]. As the popularity of the Park increased, overflow tents were needed to support the number of guests to the Inn [62, 63, 75], and the rail company added a large extension to the building in 1912, increasing its capacity to 150 people [62, 69]. Located in the middle of the Algonquin 'wilderness', we might expect this hotel to have been a rugged wooden structure with few amenities. In fact, the opposite was true: the Highland Inn had a post office [63], well-tended lawns and gardens, a spacious verandah, indoor bathrooms, luxurious dining areas, and numerous sports facilities (e.g., billiards, tennis, and bowling) [62]. The images in Figure 2.5 show the hotel at the height of its popularity. Superintendent Bartlett reported that the Highland Inn had been fully occupied over the summer of 1913 [67]. He noted that "real benefit [was] being derived from the Park as a health and pleasure resort, and that one of the ends for which the Park was set aside [had

therefore] been accomplished" [67]. A year later, he remarked: "We seem to have fewer anglers and more who come for the sake of the life in the woods and the health to both body and mind to be derived from such a life. I feel that the Park is doing a good work as an educator of our people who are learning to enjoy a visit with the wood folk in their natural haunts more than the destruction of them" [72]. Many other hotels, lodges, and camps were soon established throughout the Park, including Bartlett Lodge in 1923, which was founded on Cache Lake near Headquarters by Alfred Bartlett, the son of Superintendent Bartlett [62, 63, 66]. Even during the war years, the Park's accommodations were "filled to overflowing" with guests [74].[11]

Beginning in 1905, the government also started leasing small areas of land to private citizens for the construction of summer cottages [62, 63, 66]. In 1912, Bartlett recommended that no leases be allowed in the northern parts of the Park to preserve its natural state [63, 69], but leaseholds became very common in the southern sections, including along the shores of Cache Lake. At one time, there were over 600 private cottages within Algonquin [62], and their leases formed an important part of the Park's early revenue [67, 73].

With the increased tourism and the expansion of the Park rangers' duties, the north shore of Cache Lake was soon filled with many new buildings, as seen in Figure 2.6. Along the lake shore, near the Inn and Superintendent's house, there was also a boathouse [69], a floating wharf [72], a recreation hall, the ranger's boarding house [62, 66], a waterfront dance pavilion, changing rooms for swimmers, a Park Headquarters office building, quarters for tour guides, and quarters for the hotel's female staff [62, 75]. A water tank was built by the railway company behind the Highland Inn in 1909 [63, 70], and an ice house for cold storage was built at Park Headquarters in 1911 [64]. In 1914, the rangers constructed a concrete building for temporarily holding the live animals that were to be sold; visitors could also observe the captive animals there as examples of native wildlife [72, 73]. Poles supporting telegraph lines, and later telephone lines, were placed beside the railway to facilitate communication in the Park [63, 64, 66]. In the 1930s, under Superintendent Frank A. MacDougall, aircraft started being used regularly for fire prevention patrols, so a fire rangers' station and an airplane hangar were built at Cache Lake near Park Headquarters [63, 66]. A storehouse built behind Headquarters in 1933 hosted a blacksmith shop [75], and a tent erected at Cache Lake in 1947 acted as the first Park Museum [66]. Unfortunately, the increased human activity started to have some negative impacts on Cache Lake's ecosystems. By the 1910s, much of the lake's northern shore had already been cleared of trees to make way for the buildings and lawns, and in 1952, the lake water was determined to be non-potable for humans, likely due to the leasehold cottages and the antiquated septic systems of the Inn and Park Headquarters [63]. In the words of one Algonquin historian: "The people, for whom Algonquin Park was established, were loving the Park to death" [66].

As early as 1916, Superintendent Bartlett suggested that a road be built through the

[11] The only time when the Highland Inn was not filled with guests appears to have been the 6 years during which it was closed due to the Great Depression; it was eventually sold by the railway company to the Paget family from Huntsville and reopened in the late 1930s [63].

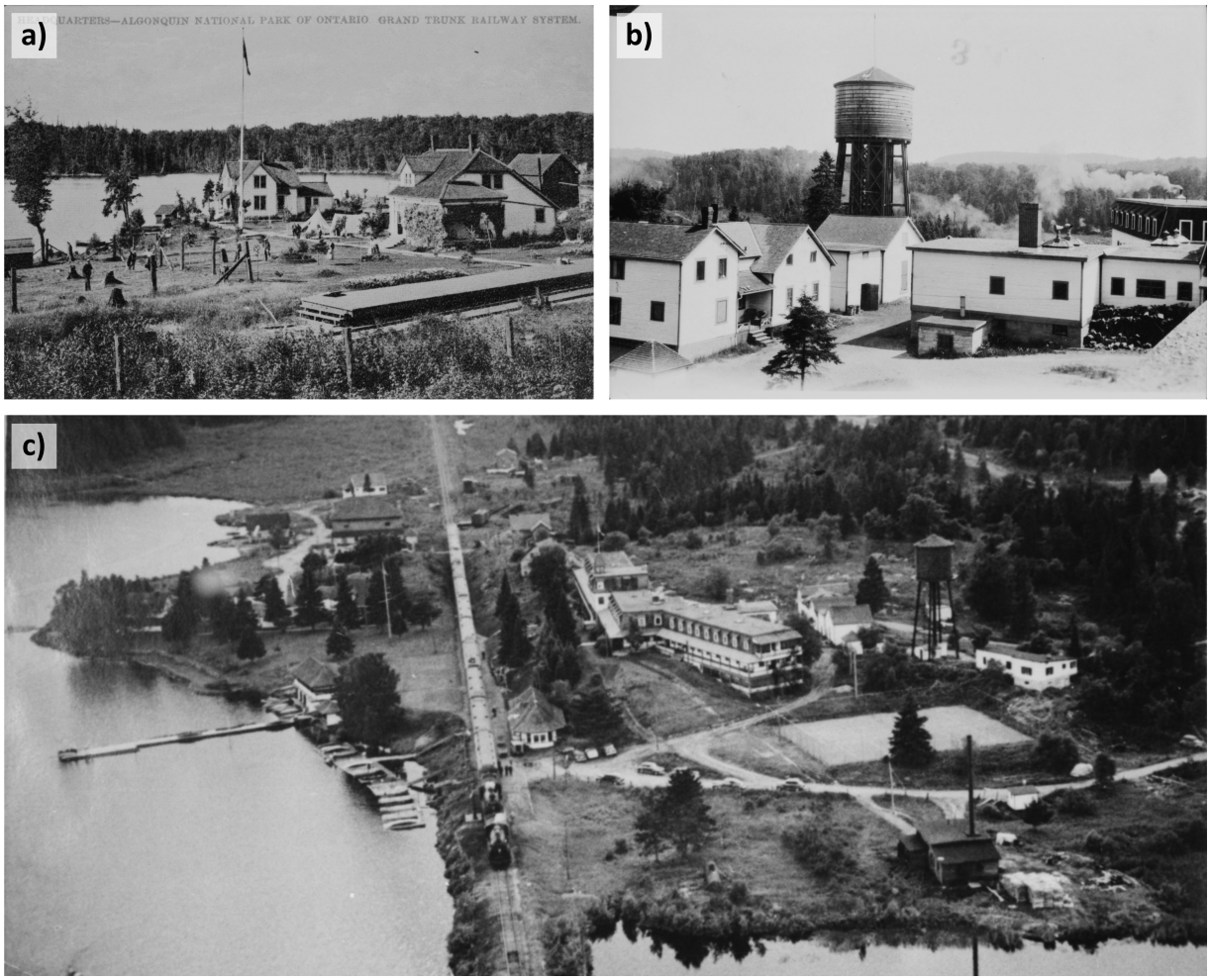


Figure 2.6: a) Park Headquarters, seen from the hill in front of the Inn. The Superintendent's house (centre) and the ranger's quarters (right) would be joined in later years by a small office building and ice house between them. (APM 6423 Edited, Algonquin Provincial Park Archives & Collections) b) Outer buildings behind Highland Inn, including water tower and staff quarters. (APM 2322 Edited, Algonquin Provincial Park Archives & Collections) c) Aerial photo of Cache Lake's northern shore taken sometime after 1943. On the left side of the railway is Park Headquarters, the docks, and the dance pavilion. To the right of the railway lies the Highland Inn and its outer buildings. Highway 60 can be seen in the top right corner. (APM 751 Edited, Algonquin Provincial Park Archives & Collections)

Park to provide motorists with easy access to the lodges and hotels [63, 74]. Finally, in 1933, construction began on King's Highway 60, a dirt road through the Park that would come to be called the Frank MacDougall Parkway in honour of the Park Superintendent during whose tenure it was built [62, 63]. The highway had been proposed in 1930 and was stridently opposed by naturalists and anglers, but by 1933, it was needed as a source

of income for unemployed men during the Depression [62, 63]. In the same year, a large wooden railway trestle east of Cache Lake was condemned, and the railway company had no intention of replacing it because the line was already running at a loss [63, 66]. Trains continued to enter the Park from both ends, but Highway 60 became the only option for uninterrupted travel through the Park when it was completed three years later [62, 63, 66]. Although not paved until 1948, the highway immediately altered recreational activities in the Park [62, 63]. The popularity of the trains, lodges and hotels never really recovered, as 'car camping' slowly became the preferred option for short-term visits [62]. The logging companies also began using the highway for timber extraction [63]. After 40 years as the dominant form of transportation in the Park, the railway had finally been superseded [62]. By 1945, the Park railway east of Cache Lake had ceased operation, and in 1959, the final westward train departed from Cache Lake [63].

Although many of the Park's historians have focused heavily on the tourism of this era, it is important to note that logging continued throughout the Park [62, 63]. The harvests were initially restricted to just white and red pine, but the lumber companies were soon granted permission to begin cutting hardwoods as well [53, 62, 63]. Superintendent Bartlett had worked for J.R. Booth's lumber company before being employed by the Park and appears to have considered logging completely acceptable [62, 66]. During WWI, he recommended to the Department of Lands, Forests and Mines that the government take advantage of the region's sprawling hardwood forests to supply the cities with fuel and provide much-needed revenue [71]. To preserve the Park's natural beauty and use as a place of recreation, Superintendent MacDougall created a 100-foot buffer around Cache Lake in 1930, within which logging was prohibited [62, 63]. This policy was later extended to other lakes and islands [63]. Logging is still permitted today in half of the Park's area, but it has since become highly controversial [53].

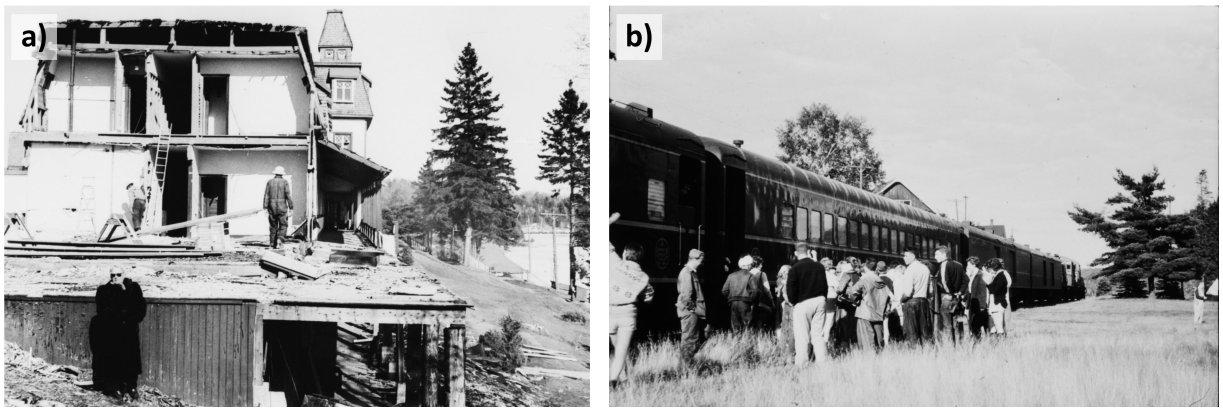


Figure 2.7: a) The western wing of the Highland Inn being demolished in 1957. (APM 4238 Edited, Algonquin Provincial Park Archives & Collections) b) The last train leaving Cache Lake, taking campers home from Camp Tanamakoon in 1959 [75]. (APM 1476 Edited, Algonquin Provincial Park Archives & Collections)

The era of hotels and lodges began its final decline in 1954, when the Park introduced

a major new policy, the purpose of which was to begin restoring the region to its original, natural condition [63, 66]. As Alexander Kirkwood originally envisioned, it was hoped the Park might approximate the Ontario 'wilderness' that predated European colonization [62].[12] To that end, the Park ceased issuing new leases to cottagers and implemented a plan to reclaim land as the leases expired [63]; today, less than 300 cottages remain inside the Park boundaries, with lease extensions having been granted up to the year 2038 [62]. In 1956, the provincial government bought several cottages and hotels within the Park, including the Highland Inn, and the following year, the Highland Inn was demolished (Fig. 2.7a), along with various other hotels and lodges [63]. A new collection of buildings on the eastern boundary of the Park (today called East Gate) was designated as the new Park Headquarters in 1959, and most of the buildings on the north shore of Cache Lake were either dismantled or moved by trailer to the new location [63]. The remaining railway tracks along the Highway 60 corridor were removed later that year (Fig. 2.7b) [63].[13] By autumn of 1959, the north shore of Cache Lake was bare, and its era as a major hub of tourism and the site of Park Headquarters had come to an end.

1960s - 2020: Red Pine Plantation

Following the removal of the buildings on Cache Lake's north shore, the area was likely left unmanaged for several years. With the site having lost most of its administrative importance and tourist popularity, records from this time are difficult to come by. We can surmise that much of the site was likely covered by grass and other plants from the hotel's lawns, and there would have been a lot of compacted dirt and rubble left over from the demolition of the buildings [25]. Based on a comparison of its present topography to historic photos, the locations of the building foundations and the hotel's lower level were likely partially-filled and smoothed over to create a more natural landscape [75].

The site remained in this barren state for another 10 years. In the early 1970s, in an effort to accelerate the process of forest succession, a red pine plantation was established across the site.[14] Red pines are an early-successional species that favour dry, sandy soils in which other trees, particularly hardwoods, cannot grow [19, 20, 35]. Planting them has been a common restoration technique in Ontario for a century, as plantations halt erosion and act as nurseries for hardwood seedlings, which take advantage of the stabilised, nutrient-

[12] It seems that Kirkwood's notions of the land having been an 'untamed wilderness' prior to European arrival were in step with contemporary perceptions. Indeed, this idea is commonplace even today and neglects the presence of the Indigenous populations that inhabited and altered the landscape for thousands of years beforehand [62, 63]. Although there is no evidence of past large-scale Indigenous settlements in the Algonquin Park region [65], we should be hesitant to apply terms such as 'wild' and 'untouched' to the Park's historical state given the long association of humans with this region [63].

[13] The rail line through the northern reaches of Algonquin Park continued to be used for several more decades [63].

[14] While we don't have an exact date for the plantation's creation, we can estimate its age from the remaining pines at the site. Based on counts of the rings on stumps and the number of branch whorls, it's estimated that the plantation is about 50 years old [25].

enhanced soil produced by the conifers [6, 19, 20, 23, 35]. The principle behind this method is that after a few decades, hardwood seeds dispersed throughout the site begin to grow, and the plantation can be slowly thinned over several more decades until the red pines have been removed and all that remains is a mature hardwood forest [20, 25]. The new plantation at Cache Lake was likely planted with these goals in mind, perhaps in addition to a desire to cover the empty, unsightly hillside, which was at odds with Algonquin's popular image as an 'untouched wilderness' [25]. Based on the positions of the trees today, the target planting density was probably one tree per 6 m^2 (8' $\times$ 8' spacing between trees), but the uneven landscape resulted in some areas with one tree per 3.3 m^2 (6' $\times$ 6') [25].

Although its north shore was no longer a site of great activity, the rest of Cache Lake remained a popular tourist destination during this time. Bartlett Lodge and various camps along the lake shore continued to operate and draw in annual visitors. The area formerly occupied by the Highland Inn's tennis courts was converted into a public parking lot, and the docks were moved to provide waterfront access [75]. The former railway corridor to the east became a walking/portage trail, and the original Superintendent's house was eventually replaced with a modern building.



Figure 2.8: The skinny, densely-planted trees of Cache Lake's plantation that remained unthinned in the 50 years after they were planted.

In the following decades, the plantation remained almost entirely unmanaged, except perhaps some efforts to control competing vegetation during the early years, such as grass and shrubs [25]. Pine plantations created to accelerate forest succession are usually thinned after 25-30 years to maintain tree health and create canopy gaps [19, 20, 24, 25]. Although this was almost certainly the original intention for the Cache Lake plantation, in the 50 years following its creation, it was never thinned [24, 25]. Figure 2.8 shows a picture of the skinny plantation trees in 2021. There are several possible reasons for this lack of

management, but a likely explanation is concern over the increasingly controversial nature of logging in Algonquin.

Beginning in the late 1960s, the public became increasingly disturbed by the continued logging within the Park's supposedly-pristine natural areas [62]. Nearby communities, however, were highly dependent on the logging industry for their income [62]. To address the growing antagonism between these groups, the Park Master Plan acknowledged both positions and created a new zoning system when it was published in 1974 [53]. Under this system, logging activities could not be conducted around tourist areas, along lake shores, in the 'wilderness zones', or near areas of historic importance [53]. Given the public's perception of logging and these new rules for timber harvesting, the prospect of logging along Highway 60, right beside a popular public parking lot, was likely quite unpalatable, so the Cache Lake plantation remained untouched for the next 50 years.

Logging continued throughout much of the Park during this era, however, but in 2013, a new amendment was made to the 1998 Park Management Plan [53, 76]. This amendment restructured the previous management zones into four categories: Recreation/Utilization Zones, the only category in which logging is allowed; Development, Historical & Natural Environment Zones, which include a large corridor along Highway 60; Nature Reserve Zones; and Wilderness Zones [53]. Including additional restrictions, logging is today permitted in just 51% of the Park's land area, and the old timber licenses have been replaced by the Algonquin Forestry Authority, which manages all logging activity within the Park [53]. Only 5% of harvesting in Algonquin still involves clear-cutting; the rest is done using other methods that preserve large trees as seed sources and habitats [53]. Interestingly, red pine, which makes up the Cache Lake plantation, is the fourth most-logged tree species in Algonquin, making up about 10% of annual harvesting by volume [53]. Despite all of these changes over the past 150 years, Algonquin Park is still considered a highly-valuable hardwood source for Ontario [62], and timber harvesting remains an important, if controversial, aspect of the Park's operation today.

2020-Present: Understory Restoration

Fifty years after the trees were planted on Cache Lake's northern shore, the site now hosts a dense plantation of 25-metre-tall red pines [25], with few signs of the buildings that once occupied the area (Fig. 2.9). Most of the trees survived, although there are some gaps left from seedling mortality, particularly in locations with compacted soils where the buildings used to be [25]. Unfortunately, the plantation is also deeply unhealthy. Plantations are often planted densely initially so the trees will grow straight and tall (commercially-desirable qualities) as they compete for light [20, 25]. At age 25-30, the plantations are thinned, allowing the remaining trees to grow faster and achieve wider diameters [20]. As the Cache Lake plantation was never thinned, however, the trees grew to become skinny and unhealthy, with small crowns and root systems [24, 25]. In addition to the risk of infection by disease, they are now highly susceptible to bending, breaking, and falling over due to high winds and heavy snow loads [24]. Densely-planted plantations that remain unmanaged

also have thick canopies that create uniform environmental conditions and heterogeneous understory composition [18], which is now the case at Cache Lake. With such a dense canopy, there is little opportunity for understory species to colonize the plantation [24], so much of the ground cover is merely a deep needle layer. Overall, the process of succession at this site has stalled.

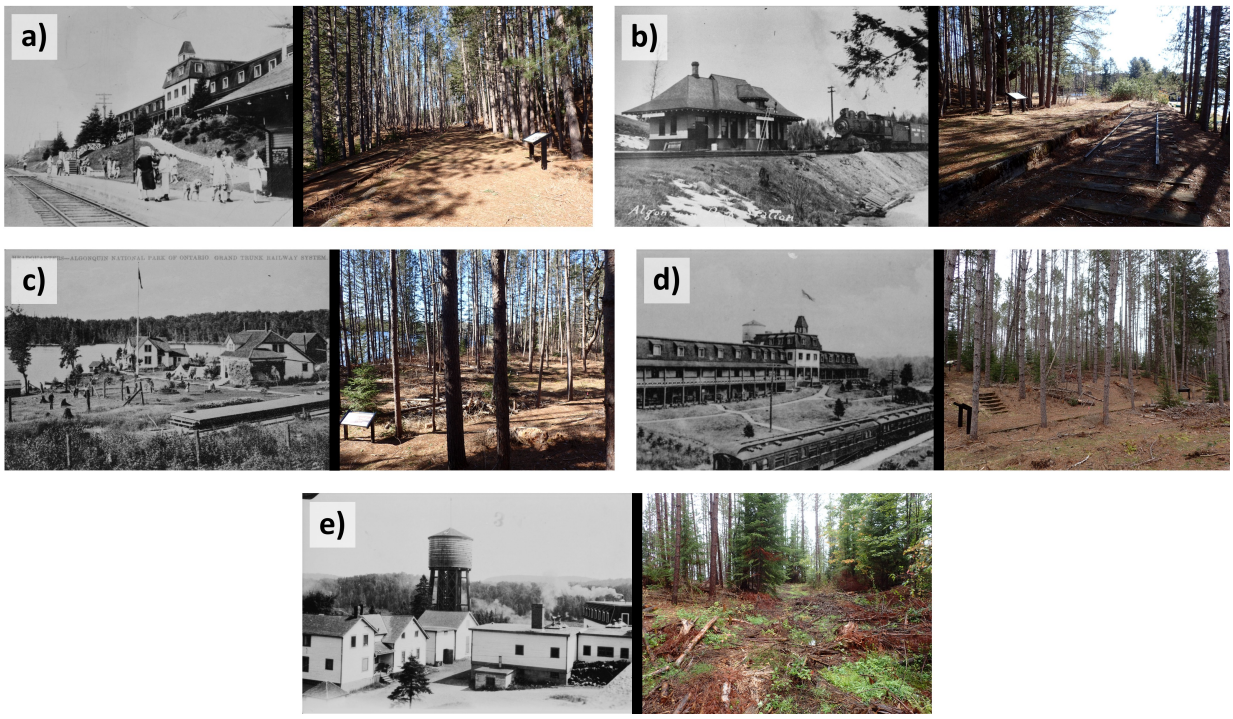


Figure 2.9: Comparison of the past and present on Cache Lake's north shore. a) Looking west along rail platform at the Highland Inn. (APM 4829 Edited, Algonquin Provincial Park Archives & Collections) b) Looking east along the railway at the train station. (APM 3463 Edited, Algonquin Provincial Park Archives & Collections) c) Park Headquarters, looking down from the hotel. (APM 6423 Edited, Algonquin Provincial Park Archives & Collections) d) Facing the hotel from Park Headquarters. (APM 6401 Edited, Algonquin Provincial Park Archives & Collections) e) Behind the inn, looking east. (APM 2322 Edited, Algonquin Provincial Park Archives & Collections)

Most of the evidence of historical human structures at the site have vanished over time, due to a combination of natural forces (e.g., soil buildup, weathering) and intentional removal by humans. As depicted in Figure 2.10, however, some hints of past human activity remain. Concrete pads and blocks that acted as walkways or building foundations can still be found across the research site, especially near the former locations of the inn and train station. There are also several concrete-lined, pipe-filled holes in the ground behind the former site of the hotel. Built in 1916 to replace the original wooden walkway [74], a concrete path running between the railway platform and the Superintendent's house is still just visible above the ground litter in the site's southwest corner. There are a few scattered

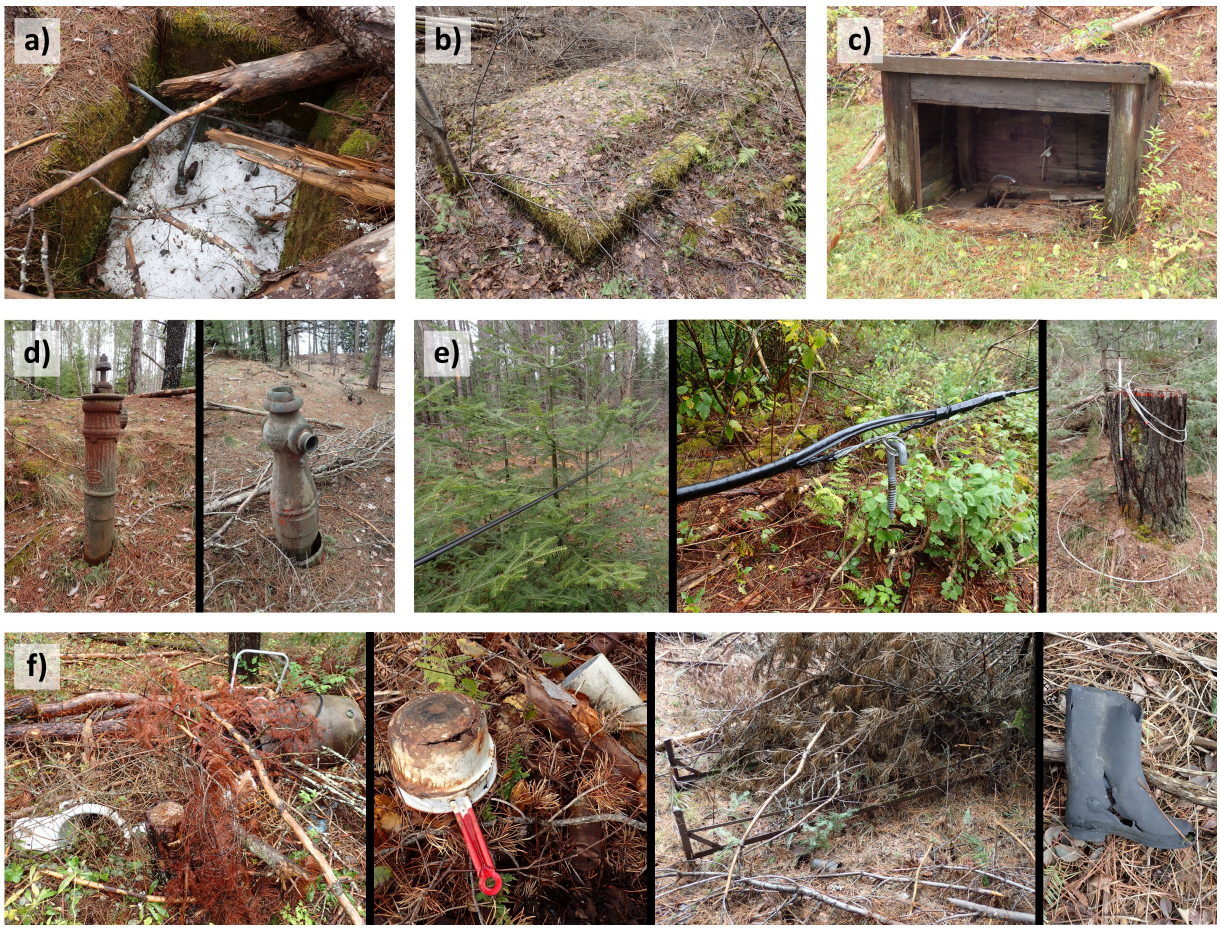


Figure 2.10: Evidence of human habitation at the research site. a) Concrete-lined hole filled with pipes. b) Concrete block (2-3 m long). c) Small shed of unknown purpose (∼2 feet high), housing electrical cables. d) Fire hydrants. e) Downed electrical cables across the site. f) Garbage, including toilet, plastic chicken wire, old pots, cans, pipes, frame of a child's bed, a child's rubber boot, etc.

objects, such as two fire hydrants and a small wooden shed near the former location of the railway. A few areas have large quantities of garbage, some of which may have been left recently by cottagers or tourists, but much of which appears to have been left over from human habitation in the late 1950s. An operational power line still runs to the former Superintendent's house, and a second, non-operating power line runs from the first line, through the site, almost to the tourist parking lot. This second line has fallen into disrepair; while most of the utility poles remain standing, the cables have drooped, and in some cases are held a metre (or less) off the ground by pine saplings. There are a few spots along this utility corridor where random cables are lying on the ground as well. The park personnel in charge of the site have stated that this power line is no longer functional. It may still pose some hazards, however, as I proved on more than one occasion when I unintentionally walked into the low-hanging wires face-first. The original Superintendent's

house was demolished around 1960 [75], and a new building was later constructed in its place, though today it is only used as temporary accommodation by the Deputy Superintendents on weekends [77]. The only other buildings on the north shore are an aging, soon-to-be-demolished boathouse behind the Superindentent's house [77] and a small shelter on the far side of the public parking lot, where visitors wait for transport to Bartlett Lodge. Although one can no longer discern the square outline where the hotel's lowest level cut into the hillside [75], much of the site's topography has been altered by the structures that used to occupy this area. For example, the rail line used to run along the lake shore, and its path is still visible. In the southwestern corner of the research site, a path was carved through a hill for the railway, resulting in very steep 'canyon' with nontraversable rock walls. Finally, as we shall discuss in Section 2.3.2, certain areas of the plantation also suffer from the impacts of invasive species such as non-native honeysuckles (Lonicera spp.) and Japanese knotweed (*Fallopia japonica*), which are remnants of the lawns and gardens that formerly occupied the site [77].

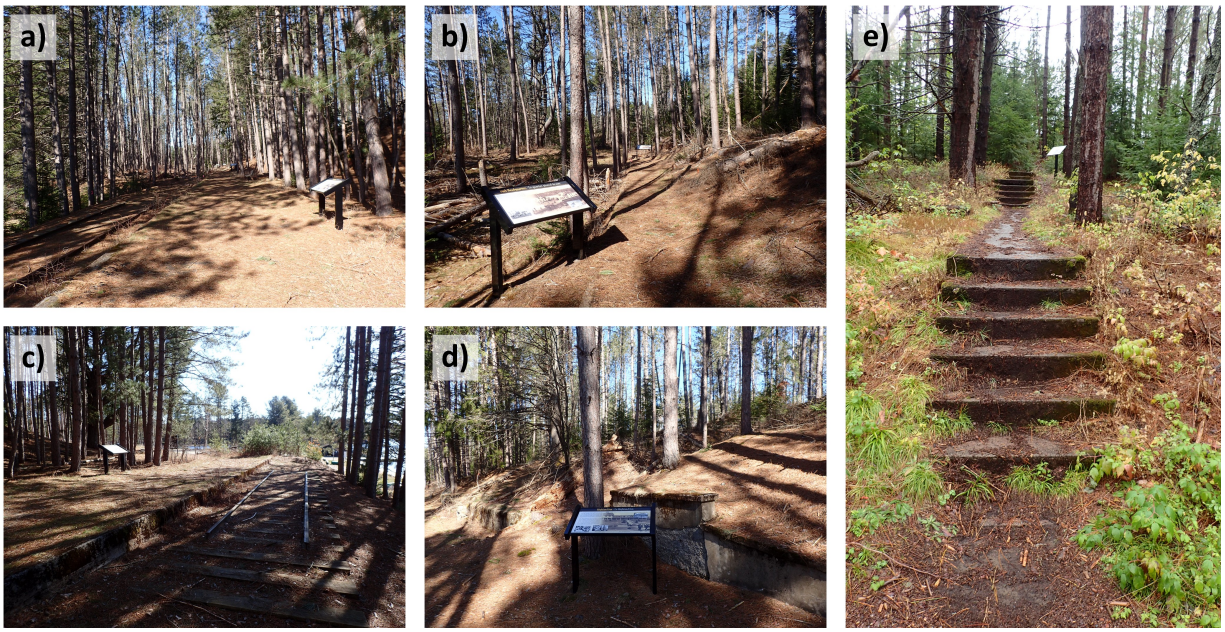


Figure 2.11: Tourist path at Cache Lake Historic Site. a) Start of historic walkway. b) Interpretive sign along path. c) Preserved segment of the railway. d) Concrete wall along railway platform. e) Stairs at the end of the path.

The old concrete railway platform that stretched along the front of the hotel also remains, though it now acts as a ∼150 m historic walkway (Fig. 2.11). Established in 2008 by the Friends of Algonquin Park, this path is meant to commemorate Cache Lake's history as a former hub of transportation, tourism, and administration in Algonquin Park [63]. Along its length are a small segment of rail line and a donated bench, as well as six interpretive signs with details on the history and historic importance of this site. A short concrete wall borders one side of the path, likely built to prevent the hillside from

falling onto the platform when the railway was still operational. The path ends at a set of concrete stairs that formerly led up to the Highland Inn's western wing but which now deliver visitors to the top of a tree-covered hill. This historic walkway is the only section of the research site where tourists frequently walk. As the plantation thinning has opened up the interior of the site, however, we do observe a few individuals and groups roaming the interior each day.

In some cases, these relics of the site's past and the continued tourist presence may impact the success of the restoration treatments. For example, areas with large concrete blocks are likely to experience less vegetation coverage than other areas. It may be necessary to exclude such plots, as well as those hosting the historic walkway, from the final analysis in order to gain an accurate picture of treatment success in a plantation. Overall, these influences may reduce the degree to which the results of this experiment can be generalized to other plantations that do not have a such an extensive history of human occupation.

2.1.2 Climate and Environmental Conditions

Algonquin Provincial Park today encompasses an area of 7,635 km^2 [62], with more than two thousand lakes scattered across its landscape [64]. Given its enormous size,[15] the Park contains a large variety of environments and ecosystems, with the primary factors influencing its climate being the geography and geology. Algonquin extends from about 45° to 46° N in latitude and is located on the Canadian Shield. As described in Section 2.1.1, the west side of the Park was formed from the remains of eroded mountains and has current elevations of 400-550 m above sea level [53]. The research site at Cache Lake is located within this highland region, at an elevation of approximately 450-500 m above sea level [53]. The eastern third of the Park, however, never experienced these mountain-building events and is therefore much lower, at just 100-400 m above sea level [53].

Due to these geological differences, the west side of the Park has a colder and damper climate than the east, experiencing 281 days of frost and 100 cm of precipitation per year, a third of which is snow [53]. In terms of ecology, however, the most important factor is the podzolic soils, which retain moisture more effectively on the west side [53, 65]. As the last glacier moved over the hills during its 70-thousand-year existence, it pulverized the top layers of Precambrian rock into a fine, sandy loam, and as it finally melted, it left behind a layer of coarse gravel on top [53, 65]. Today the soil is Petawawa type: shallow (<1 m deep) and composed of sand and some coarse gravel [78]. Some regions are more silty and can have soil as deep as 3 m [78]. The east side, however, was later flooded by the glacial meltwater, and the vast river that formed deposited substantial amounts of sand across the area [53]. Compared to the shallow glacial till layers above the bedrock on the west side, the deep, sandy soils on the east side have poor moisture retention [53]. Overall, the Park's soils are nutrient-poor, which is why the area was never used as farmland [65, 66].

[15] There are over 30 countries that have smaller areas than Algonquin.

Weather and climate conditions for the area can be found on the Canadian Government's website [79]. Their closest weather station to Cache Lake is in Dwight, Ontario, roughly 40 km from the research site. This station has recorded data for the years 1981 to 2005. The highest temperatures are in July, with a daily average of 18.1°C, while the lowest temperatures are in January, with an average temperature of -11.7°C. The highest recorded temperature was 34°C, and the lowest was -41.5°C. Rainfall peaks in September and October, averaging 110.7 mm during those months. Snowfall averages about 345 cm per year, and between January and March, average snow depth is 59.7 cm. This region of the Park is one of the coldest areas in all of Southern Ontario [65].

2.1.3 Fauna and Flora

Despite its extensive history of human occupation and resource extraction, Algonquin Park's vast wilderness nevertheless retains an enormous variety of plant, animal and fungal species. Perhaps the most significant factors influencing the ecosystems are the region's geography and geology. The ecological impacts of the Park's two different geological states are quite stark; whereas the low-lying east side of the park is dominated by pine forests, the western highlands are primarily covered by hardwood forests [53, 72]. After the last glacier retreated, these species arrived one at a time over thousands of years [53]. In 1911, shortly after the Park's formation, Park Superintendent Bartlett reported the Park was "timbered with birch, maple, beech, hemlock, cedar, spruce, white birch, tamarac, and balsam", and despite extensive logging over the past century, there were "still large blocks of choice red and white pine, while in some sections black cherry [could be] found" [64]. Today, there are 34 native tree species in the Park, most of which are quite common [53]. As they are on the west side of the Park, the regions around Cache Lake contain primarily hardwood forests, though one can often find cedars, firs, and other conifers along shorelines [53]. Figure 2.12 shows examples of Algonquin's mature hardwood forests. Today, some of the most common tree species in this area are sugar maples (*Acer saccharum*), striped maple (*A. pensylvanicum*), red maple (*A. rubrum*), white birch (*Betula papyrifera*), yellow birch (*B. alleghaniensis*), American beech (*Fagus grandifolia*), and black ash (*Fraxinus nigra*) [53].

The Park's hardwood forests have a rich understory, with a variety of shrubs and herbs visible throughout the spring, summer and fall. Spring-flowering herbs in the area include yellow trout lilies (*Erythronium americanum*) [53], red and painted trilliums (*Trillium erectum* and *T. undulatum*), pink lady's slippers (*Cypripedium acaule*), bunchberries (*Cornus canadensis*), northern starflowers (*Lysimachia borealis*), Virginia strawberry (*Fragaria virginiana*), trailing arbutuses (*Epigaea repens*), and mayflowers (*Epigaea repens*).[16] Though they often favour clearings rather than dense forests, there are also many common summer-flowering herbs in this region, such as Canada goldenrod (*Solidago canadensis*), common yarrow (*Achillea millefolium*), common milkweed (*Asclepias syriaca*), and

[16]The plant species listed throughout this section were determined to be present in Algonquin through a combination of literature review, personal observation during fieldwork, and research using iNaturalist.



Figure 2.12: Images a) and b) are pictures of the hardwood forest at Minnesing, primarily consisting of sugar maples and a few large hemlocks. c) Exposed roots of a mature yellow birch on the Track and Tower Trail.

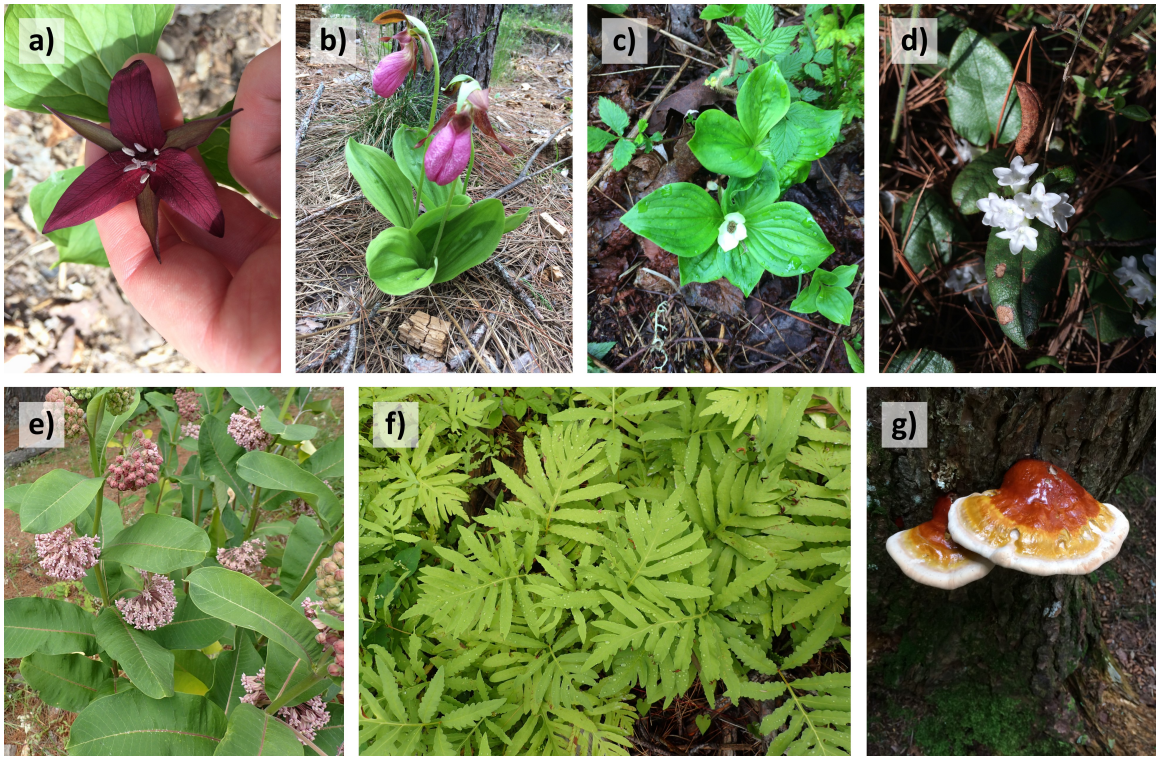


Figure 2.13: a) Red trillium at Minnesing. b) Pink lady's slipper at research site. c) Bunchberry at research site. d) Trailing Arbutus at research site. e) Common milkweed at Cache Lake parking lot. f) Sensitive ferns at research site. g) Hemlock varnish shelf on the Hemlock Bluff Trail.

fireweed (*Chamaenerion angustifolium*). Native shrubs abound in Algonquin, especially around lakes and in bogs and clearings. These include Eastern beaked hazel (*Corylus cornuta* Marsh. var. *cornuta*), American red raspberry (*Rubus strigosus*), red osier dogwood (*Cornus sericea*), leatherleaf (*Chamaedaphne calyculata*), common elderberry (*Sambucus canadensis*), bog Labrador tea (*Rhododendron groenlandicum*), and sweet gale (*Myrica*

gale). Various ferns (e.g., *Onoclea sensibilis*, *Dryopteris intermedia*), clubmosses (genus *Dendrolycopodium*), and grasses can also be found in great quantities. During damp seasons, especially spring and fall, one can observe a variety of fungi throughout the understory, including hemlock varnish shelf (*Ganoderma tsugae*), orange jelly spot (*Dacrymyces chrysospermus*), and northern red belt (*Fomitopsis mounceae*). Figure 2.13 shows off some of the Park's many understory species.

The varied habitats of Algonquin's forests and bogs provide ample space for a range of wildlife, some of which are shown in Figure 2.14. The most abundant mammal within the Park is the deer mouse (*Peromyscus*) [53]. They are commonly documented by the Algonquin Small Mammals research project, which is now in its 70th year [80]. Other small mammals include the eastern chipmunk (*Tamias striatus*), American red squirrel (*Tamiasciurus hudsonicus*), star-nosed mole (*Condylura cristata*), northern flying squirrel (*Glaucomys sabrinus*), American marten (*Martes americana*), fisher (*Pekania pennanti*), American mink (*Neogale vison*), and many others [53, 66, 72, 80]. With so few humans in the area, there are also plenty of larger mammals throughout the Park, such as Canadian beavers (*Castor canadensis*), red foxes (*Vulpes vulpes*), eastern wolves (*Canis lycaon*), and moose (*Alces alces*) [53, 62, 64, 66, 67, 69, 70]. Many species of reptile and amphibian can be found in the Park, such as garter snakes (*Thamnophis sirtalis*), American bullfrogs (*Lithobates catesbeianus*) and spring peepers (*Pseudacris crucifer*), but the prevalence of common snapping turtles (*Chelydra serpentina*) and midland painted turtles (*Chrysemys picta marginata*) is notable, as both are listed as species of special concern in Ontario. Bird species within the Park are too numerous to name, from black-capped chickadees (*Poecile atricapillus*) and northern saw-whet owls (*Aegolius acadicus*) [80] to ravens (*Corvus corax*) and bald eagles (*Haliaeetus leucocephalus*).



Figure 2.14: a) Eastern chipmunk at the Algonquin Wildlife Research Station. b) Moose near the Minnesing utility corridor. c) Common snapping turtle hatchling rescued from the middle of Highway 60.

Although it is a haven for native species, Algonquin also experiences encroachment

by invasive species. There are at least 15 species of non-native trees within the Park, including Norway spruce (*Picea abies*), Manitoba maple (*Acer negundo*) and Scots pine (*Pinus sylvestris*), many of which were planted intentionally over the Park's long history [53]. As we shall see in Section 2.3.2, many non-native understory plants persist in the area, particularly in places with a long history of human activity, such as Cache Lake's north shore. Such species include Japanese knotweed (*Fallopia japonica*), non-native honeysuckles (*Lonicera* spp.) [77], common columbine (*Aquilegia vulgaris*), orange hawkweed (*Pilosella aurantiaca*), and common mullein (*Verbascum thapsus*). Non-native fauna in the Park are relatively rare, with the exception of insects, such as green immigrant leaf weevils (*Polydrusus formosus*), brown leaf weevils (*Phyllobius oblongus*), spongy moths (*Lymantria dispar*), and white satin moths (*Leucoma salicis*).

2.2 Experimental Design

This experiment will test the effectiveness of several restoration treatments in rapidly restoring the understory of the Cache Lake pine plantation. In this section, we will review the design of the experiment, while Section 2.3 will describe the restoration treatments in more detail. To begin, Section 2.2.1 will discuss the plan for applying the experimental (i.e., non-universal) treatments to the site in a randomized grid pattern. Once the treatments have been applied, site monitoring will commence. As described in Section 2.2.2, we will closely observe the soil, vegetation, and light levels of the plantation over several years. We will also monitor the status of our treatments to determine whether the transplanted species survive and whether the populations of invasive species are declining as intended. Once the project's 4-year term has been completed, we can perform a final analysis of the understory's regrowth (Sec. 2.2.3). In addition to the aforementioned activities, those who take over the project in future years may wish to perform additional analyses, such as designing a control-impact study by comparing the research site to other plantations in the area. Section 2.2.4 therefore covers some options for expanding the current scope of the project. Finally, the project timeline is presented in Section 2.2.5.

Importantly, I want to note the contribution of my supervisor, Stephen Murphy, who devised the basic design of this experiment, including: the use of a randomized complete block design, the use of 4 replicate blocks consisting of 8×8 treatment plots, the treatments to be applied to the site, and the use of vegetation and soil surveys to monitor the site over time. Most of this initial design, which was conceived in conversation with Park staff, was retained, with modifications made afterwards due to logistical constraints and additional information obtained once we visited the site for the first time in autumn 2021.

2.2.1 Treatment Plan

This project involves the application of 4 treatments to a red pine plantation: tree thinning, management of invasive plants, applied nucleation, and windthrow guards. The first two

are universal treatments to be applied across the entire site by Park staff. The latter two, however, involve transplanting species to the site and will be applied in a grid pattern with a variant of the randomized complete block design. Randomized block designs are very common for restoration experiments of this nature [6, 13, 15, 18, 22, 36, 37, 41, 81]. They enable the effectiveness of treatments to be assessed by accounting for uncontrollable spatial variations [6], such as differing soil nutrients at different locations, for example. This is achieved by setting up a series of replicate blocks across the gradient of the spatially-varying factor, with each block divided into a series of treatment plots. For this project, the replicate blocks will be used to account for the impacts of spatial variations in soil quality, existing vegetation, and light intensities. See the analysis section (2.2.3) for more details on using the randomized complete block design.

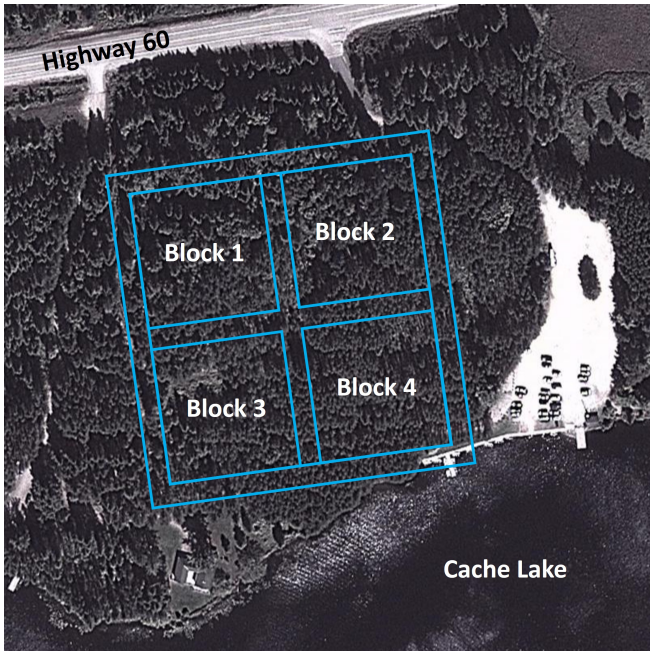


Figure 2.15: Location of experimental grid on Cache Lake's northern shore in Algonquin Provincial Park [61].

The experimental grid fills a 158 m × 158 m square area (24 964 m^2 or ∼0.025 km^2), rotated about 5° west of the north-south axis. The grid's western edge roughly aligns with the utility corridor that stretches from Highway 60 to the Park Superintendent's Residence. Figure 2.15 shows the approximate layout of the experimental grid on the landscape, and the coordinates of the experimental grid are given in Table 2.1.

The grid area has been divided into four 64 m × 64 m replicate blocks (4096 m^2 each). Similar restoration experiments often have 3-6 replicate blocks [13, 18, 22, 26, 31, 41], though some have as many as 12 [36]. Figure 2.16 shows the experimental design, with the dimensions and the four labelled replicate blocks depicted in Fig. 2.16a). Each replicate block is composed of 64 treatment plots arranged in an 8 × 8 grid, and each plot is 8 m

Grid Corner	Coordinates
NW	45°33'10.7"N, 78°35'45.8"W
NE	45°33'11.3"N, 78°35'39.9"W
SW	45°33'05.8"N, 78°35'45.0"W
SE	45°33'06.5"N, 78°35'39.1"W

Table 2.1: Approximate coordinates of the experimental grid's four corners (not including outer buffer).

× 8 m. A treatment area of roughly 50-80 m^2 is common for an experiment of this nature [6, 21, 22, 81], although large-scale restoration experiments may use plots of a few hundred [23, 31] or even thousands of square metres [4, 13, 15, 18, 22, 23, 26, 36, 41]. The white squares in Fig. 2.16b) are the 8 m × 8 m treatment plots. We will be labelling the treatment plots according to the convention: **block/row/column**. For example, the highlighted cell in Fig. 2.16b) is plot 3/7/4. The corners of each experimental plot were marked out at the research site using steel markers and flagging tape. The identification label for each plot is on the marker at its northwest corner. For plot 3/7/4 in Fig. 2.16b), for example, the purple circle indicates the location of its ID label. See Section 2.4.1 for a description of how the grid was set up at the research site in the first year of the project.

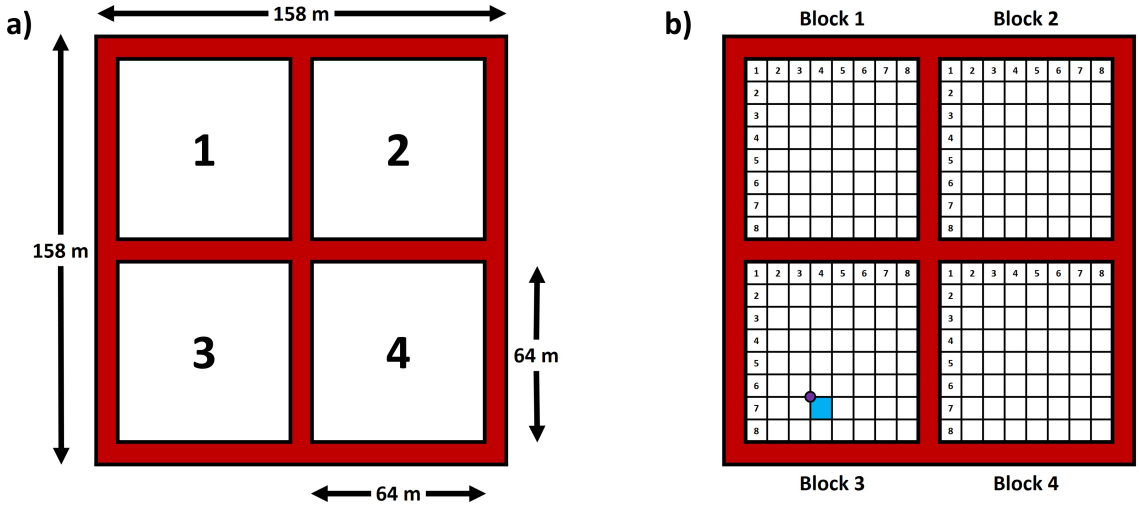


Figure 2.16: Experimental design showing a) the 4 replicate blocks and b) the 64 treatment plots (8 m × 8 m each) within each block. A 10 m buffer zone is shown in red. The replicate blocks and the rows/columns of treatment plots are numbered for easy identification. Plot 3/7/4 is highlighted in b) as an example of the plot identification system (see main text).

The replicate blocks are separated from each other and the external environment by 10-meter-wide buffers. The buffers are to remain untreated, aside from the universal treatments, and they were therefore left as they were after the thinning process; some have plants, some have skid trails, some have portions of the historic walking trail, and some have utility corridors. It should be noted, however, that the nearest continuous, native forest is on the other side of the highway, roughly 100 m from the treatment plots; the experiment buffer does not extend this far. In similar experiments, buffers between experimental plots and continuous forest have varied from 20 m to 2.5 km [4, 6, 23].

Within the experiment grid, two interventions are to be tested in a randomized experiment: applied nucleation and windthrow guards. Both of these treatments will involve the use of transplanted species. To test the effectiveness of the windthrow guards, which are designed to protect the nucleation species from windthrow (see Section 2.3.4 for more details), the applied nucleation must be attempted both in isolation and in conjunction with the guards. As the windthrow guards themselves may influence understory regeneration, they must also be tested in isolation. Finally, we need control plots with neither nucleation nor windthrow guard species, where only the two universal treatments will be applied. Therefore, the four treatments to be tested in the grid are:

Treatment 1: Control

Treatment 2: Only applied nucleation (AN)

Treatment 3: Only windthrow guard (WG)

Treatment 4: Nucleation and windthrow guard (AN&WG)

Note the abbreviations of these treatments, which will be used to simplify the following discussions of the treatment applications. The exact details of these treatments, as well as the universal treatments, will be covered in Section 2.3.

Each of these four treatments is to be applied to 16 randomly-selected treatment plots per replicate block. Treatments were randomly assigned to plots using a pseudo-random number generator, specifically the Python programming language's *random.sample* function. This function randomly selects a list of non-repeated numbers from a sequence of integers. In this case, the treatment plots in each replicate block were assigned numbers from 1–64, and the Python function was used to randomly select half of the plots to have the nucleation species planted. Subsequently, half of these nucleation plots and half of the non-nucleation plots were randomly selected to have the windthrow guard species planted. The resulting treatment plan is shown in Figure 2.17. (See Appendix A for a written list of the plots to which each treatment was applied.)

Similar experiments usually have between 12 and 60 treatment plots [15, 21, 23, 36, 41] (though some may have many more [31]), so with 128 plots and just four test treatments in this experiment, we should have highly reliable results. In each replicate block, each

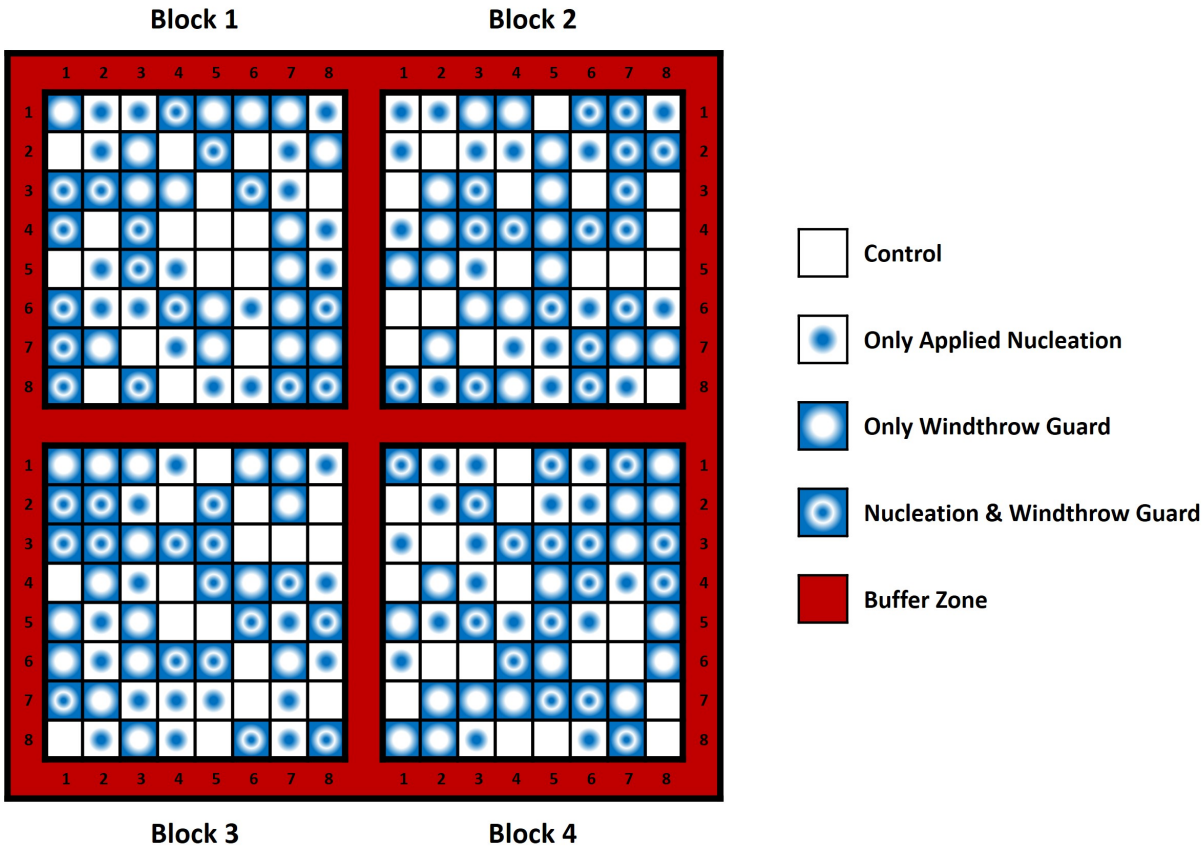


Figure 2.17: Plan for the 4 experimental treatments that were randomly assigned to plots. The numbers of each block's rows and columns are provided for easy reference.

treatment will be repeated 16 times, with an overall total of 64 instances of each treatment in the experiment. This level of repetition should provide sufficient statistical power to achieve reliable results, even if some of the plants die.

It is typical to have some spacing between individual plots and treatments in an experiment to reduce confounding effects [15, 21, 43]. The shrubs to be used for the nucleation treatment will have a diameter of roughly 0.5 m, and the largest treatment, AN&WG, has a diameter of 1.5 m. Within our 8 m $\times$ 8 m treatment plots, we estimate each treatment will influence an area no greater than 4 m $\times$ 4 m during the project's 4-year duration. If the treatments are centered within their plots, the remaining 4 meters between adjacent zones of influence will act as a buffer that should reduce interactions between treatments.

There are a few important things to note about this treatment design. The plans for this project shifted as the needs of the Park changed, and some decisions were also left to the contractors who performed the plantation thinning. Therefore, many of the details of the site were unknown to us before our first visit to the research site in fall of 2021 (almost one year after thinning). Factors of which we were unaware included the site's

precise location, size, density of remaining trees, degree of existing understory, and history. As much of the planning for this project took place before the first visit, some aspects of the current plan do not entirely reflect the properties of the site.

For example, the use of replicate blocks was originally intended for a different setup, wherein thinning and invasive species management could be applied in various combinations to the blocks or some blocks could be placed in other thinned plantations nearby. Although this arrangement did not occur due to the decisions and needs of the many groups involved, it was decided the blocking design would be retained so work on the project could begin immediately and because the areas within the blocks, though adjacent to each other, do each have a few unique physical properties. Figure 2.18 shows some of the unique features of each block. Therefore, there is technically no true replication here, as all of the blocks are located in one site with fairly similar soil, vegetation, and light properties, but it may still yield useful results due to the unique geographical features of each block.



Figure 2.18: a) Block 1: Some large openings, light forest, and a large patch of dense, unharvested forest. b) Block 2: Open forest, many skid trails covered in understory vegetation, some areas with almost no vegetation below pines. c) Block 3: Rocky 'canyon' where railway used to pass through a hill, many open spaces, many pines that have blown down in the wind. d) Block 4: Historic walking path, mostly sparse pines with almost no understory vegetation, skid trails of compacted dirt and logs.

Additionally, in a typical experiment with randomized complete block design, each

treatment would be applied just once per block [13, 41]. Due to the limited space available, however, it was decided to have just four replicate blocks with multiple treatment repetitions in each block, rather than many blocks with buffer zones between them. This is partially because the grid had to be set up early, before the types of treatments had been determined. The original plan was to use wood chips left by the logging company after thinning, which would have brought the total number of treatments to 8 and the number of repetitions per block to 8. There was also uncertainty over whether we could obtain nucleation shrubs of equal size; had we needed to use two separate sizes, these would have been treated as separate treatments, doubling the number of treatments again. Finally, there was no way to know in advance how many of our transplants would survive, so it was preferable to have several repetitions of each treatment per block, rather than having to eliminate entire blocks from our analysis. Therefore, it was ultimately decided to stick with fewer replicates and more plots per block. While this is not a standard design, the increased number of treatment repetitions will nevertheless give us better statistical power when analysing our results.[17] It would have also been ideal to have a much larger research area so that we could have many treatment plots with enough space between them to prevent confounding effects. The limited space, and therefore the limited number of treatment repetitions, is ultimately why we chose to have so few treatments, as this allows for greater statistical power in our analysis.

Overall, the design of this experiment is certainly sufficient to achieve the desired goals, but this does highlight the interesting challenges that arise during the planning stages of an experiment. Adaptability is key to ensuring the success of an experiment in the face of unexpected challenges and changes.

2.2.2 Site Monitoring

Once the treatments have been applied to the site, it is hypothesized that they will help accelerate the regeneration of the plantation understory. To determine the treatments' impacts and the progress of the restoration, the site will need to be monitored for the duration of the project. In particular, we are interested in observing changes in the understory vegetation cover, soil quality, and light intensity, as these are common indicators used to measure the success of short-term restoration experiments (see Section 1.3.5). These factors may also help us understand the survival rates of our transplanted species in the near-term, which we will study via a transplant mortality census (see Section 2.4.5). Monitoring of the control plots will allow us to account for the effects of natural regeneration and yearly differences in weather [41], while the use of a randomized complete block design should help eliminate the impacts of spatial variations.

[17] Nested sampling is an alternative randomized block design that improves statistical rigour by subdividing the replicates into sub-blocks [41], but our design does not conform to this setup either, as the treatment plots are randomly placed within each block. This would have been a good design option, but it unfortunately didn't occur to us in time to implement.

Ideally, monitoring would have commenced in the first year of the experiment, prior to the treatment applications. Baseline data would have been collected both before and after the site was thinned and management of invasive species commenced to account for pre-existing spatial variations when assessing the effectiveness of the various treatments. Unfortunately, due to uncontrollable circumstances (namely the COVID-19 pandemic), this was not possible. Other nearby plantations may act as reasonable approximations of the initial state of the Cache Lake site (see Section 2.2.4), but otherwise, the logged, herbicide-treated plantation will be considered the starting point for this experiment.[18] Ultimately, surveys of vegetation, soil, and light intensity were conducted in Year 2 of the project (2022). Although the invasive species management and thinning commenced the year before, the nucleation and windthrow guard treatments were only applied roughly 1-2 months before the surveys, and therefore should not have had any significant impacts yet.[19] Transplants were therefore ignored and avoided during the vegetation, soil, and light surveys to allow us to assess their impacts in future years. Section 2.2.5 provides further details on the timeline of the project.

Following the application of the restoration treatments in Year 2, each treatment plot will be individually monitored for the remainder of the project. This will provide the data necessary to study the effects of the individual treatments on soil quality and vegetation during the experiment, allowing us to determine which treatment(s) is most effective in encouraging rapid restoration along a desirable successional trajectory. In most restoration experiments, long-term monitoring is preferred, as inter-annual variations may be caused by factors such as weather and animal browsing [23, 41], and predictions of the understory's status over time require an accurate understanding of long-term trends [6]. As the goal of this experiment is to achieve a rapid restoration, however, short-term monitoring over the duration of the 4-year project should be sufficient for our purposes.

The following subsections describe the theory of the data collection process, while the specific methods are discussed in Section 2.4.2, and the survey results and analysis are given in Section 2.5.

Vegetation Survey

Vegetation surveys are a common practice in ecological experiments [6, 13, 18, 22, 23, 26, 31, 36, 37, 41, 42, 48, 58]. Their purpose is to determine the prevalence of particular species and

[18] Park staff did map out the site in 30 m × 30 m plots so they could conduct preliminary surveys of the slash remaining after thinning, honeysuckle stem counts, and locations of other invasive species. They have provided us with this data so that we have some baseline information about the site, which may be useful in our final analysis.

[19] The treatments had to be done before the surveys because we wanted to transplant as many shrubs as possible while they were still in their dormant state. This meant transplanting them mostly in April and early May, and there wasn't time to do the surveys beforehand. Moreover, in April, the ground was still frozen in some parts of the research site, preventing soil samples from being taken, and most of the herbaceous understory had not yet regrown after the winter and therefore couldn't be surveyed.

categories of species within the experimental area. Depending on the type of experiment, the survey may be designed to examine species diversity [6, 13, 18, 22, 36, 41, 58], abundance or coverage area of particular plants [4, 6, 9, 18, 22, 23, 26, 31, 37, 41, 48], and/or the proportion of plants in specific categories, such as size, native vs. non-native, or successional properties [4, 6, 9, 13, 22, 23, 26, 31, 41, 82]. Techniques for vegetation surveys vary and often depend on the type of data under examination. For example, stem counts [6, 31] or line intercept methods [4, 37] are often sufficient for acquiring abundance data. On the other hand, determining abundance or coverage area for densely-populated species may sometimes require a visual estimate of spatial distribution [18, 23, 26, 31, 41]. This technique usually uses a category system to simplify the estimation process (e.g., Category 1 = 0-5% coverage of plot, Category 2 = 5-25%, etc.), and a weighted average is used to calculate the final results. To determine diversity, meanwhile, one may calculate the Simpson index [6, 18, 41], Shannon index [6, 13, 14, 18, 58], and/or use Whittaker plots [36, 41]. The enormous variety of options for data collection means the parameters of a vegetation survey must be tailored to the unique goals and properties of a particular experiment.

In this experiment, the primary goal is to restore a native understory at the Cache Lake plantation, and part of this effort involves removing invasive plant species from the area. Therefore, we are most interested in observing a decrease in the presence of non-native species and an overall increase in native understory species throughout the site. As such, our vegetation surveys will focus primarily on the percent cover of understory plants in each treatment plot, with a particular focus on whether they may be classified as native (endogenous vs. regional) or non-native (low vs. high impact) [29, 33, 41, 55]. This will involve visual estimates of percent cover. This method is useful if speed is important, which is certainly the case for surveying the 128 plots in this experiment, and it allows one to detect species that are easily missed using line intercept methods.

Class	**% Cover**	**Midpoint**
1	0-5	2.5
2	5-25	15
3	25-50	37.5
4	50-75	62.5
5	75-95	85
6	95-100	97.5

Table 2.2: Cover classes of the Daubenmire semi-quantitative method [83].

Visual estimations can be difficult, however, especially with large plots such as these (e.g., does the raspberry patch cover 27% of the plot? 28%? 31.3%?). To simplify the esti-

mation process, we will use the cover classes of the Daubenmire semi-quantitative method [83]. This method uses six cover classes, as shown in Table 2.2. It is far easier to identify which of these cover ranges best describes the coverage of a particular species, rather than attempting to estimate exact percentages. We'll be using a canopy cover technique, where the overall coverage is assumed to be the total canopy cover by the understory species, as opposed to basal cover, for example, which just accounts for the area of the plant stem at its base. With the Daubenmire method, the midpoint of the cover range then gives us the approximate coverage of that species within the plot [18].

A simple calculation can then be used to determine the overall coverage of a particular species within a specific block or across the whole site. We multiply the midpoint of each cover class (M_i) with the number of instances (i.e., plots) where the species was recorded as being in that class (N_i), add them all together, and divide by the total number of plots (T) [83]:

$$\% \text{ cover of species} = \sum_{i=1}^{6} \frac{M_i N_i}{T} \tag{2.1}$$

When performing the vegetation surveys, however, there are a few important considerations to note. For example, many herbaceous species only emerge at certain times of year, so it may be beneficial to survey the site in both spring and summer [23]. As the project progresses, we may also wish to categorize the species according to their habitat/successional preferences to determine the rate of succession [23], although this may perhaps be more relevant to a long-term study (i.e., over several decades). As mentioned above, there are also temporal variations in vegetation induced by variations in weather during different years and seasons, so long-term research sometimes reveals more accurate information about the state of the vegetation [23, 41]. Spatial variations may exist as well, such that it may be beneficial to examine the coverage of various species at different spatial scales [22, 36, 37, 41], e.g., at the level of individual plots, replicate blocks, and site-wide. Finally, obtaining a complete understanding of how and why the understory regeneration is occurring requires additional environmental properties to be examined [23, 31], which in our experiment means surveying the soil quality and light intensity.

Soil Sampling

Soil quality is a vital factor influencing the success or failure of seedling establishment, plant growth, and survival of forest species. Soil analysis is therefore common in many restoration experiments [4, 18, 23, 32, 34, 37, 40, 42, 55, 56, 59, 84], since many soil properties can act as indicators of restoration progress (see Section 1.3.5). In typical restoration experiments, soil cores are taken from each treatment plot, usually with 4-8 cores per plot to ensure accurate results [18, 23, 37].[20] Soil core depth usually ranges from 5 cm [23] to 20 cm [40]

[20] Sometimes the cores are combined into a single, blended sample, rather than tested individually [18, 23].

into the mineral soil. Lab analysis is then used to determine such factors as nutrient content, acidity, organic content, moisture retention, compaction, mycorrhizal density, texture, and many others [18, 23, 32, 34, 37, 40, 42, 55, 56, 59].

In our experiment, soil samples will be collected to a depth of 10 cm, with a minimum of four samples per plot. In the event that there isn't time to obtain samples from every plot, soil will be collected in a W-shaped transect across the site, as this shape prevents spatial autocorrelation between samples, allowing for simpler analysis techniques [85]. The soil samples will be transported back to the University of Waterloo, where they will be refrigerated until they can be analysed. Soil samples will be obtained on a yearly basis to monitor the experiment's progress.

To fully understand the impacts of the restoration treatments, it is necessary to observe a broad range of soil properties. Therefore, the soil samples from the research site will be tested for the following:

- organic matter*
- cation exchange capacity*
- soil moisture*
- bulk density*
- pH*
- nutrients* (P, K, Mg, total N)
- compaction
- seed bank
- surface duff layer
- surface organic debris
- mycorrhizal density
- microbial activity

The items with asterisks in the above list will be analysed by the Agriculture and Food Laboratory of the University of Guelph, while the remainder will be tested at the University of Waterloo. Testing some of these properties, such as microbial activity, requires fresh soil samples. This is an idealized list; depending on available funds and time constraints, it may not be possible to examine all of these properties.

Light Intensity Survey

As we discussed in Section 1.2, one of the most important factors influencing understory development and succession is light availability, particularly in environments that have dense canopies [40–44]. Consequently, studies of forest understories frequently examine light levels below the canopy [4, 6, 14, 22, 23, 42, 48, 59]. Surveys of light levels can either be done by assessing the degree of overhead canopy cover [6, 14, 18, 23] or by directly measuring light intensity within the treatment plots, usually as % of full sunlight

[4, 43, 48, 59]. Measurements are often made 1-2 m above the ground [4, 59] rather than at ground-level, where understory plants themselves add to the shade. As measurements of light intensity are often highly variable due to spatial variation in canopy cover and wind-induced movement of the canopy, it may be preferable to perform multiple measurements per plot, usually at different times/seasons and locations with the plot [6, 43, 59].

In the experiment at Cache Lake, we will be measuring the light intensity within each plot with a light sensor. Our purpose here is to account for light as a factor impacting understory regrowth. We can also use the light data to determine whether it affects the degree of transplant shock experienced by the species used for the nucleation and windthrow guard treatments. These measurements could be conducted periodically to observe changes in overstory density as young trees grow and the canopy begins to re-establish itself, but that is most likely a long-term change that would not be observable over the 4-year duration of this project.

2.2.3 Analysis of Results

Using the monitoring data acquired over the course of the experiment, several analysis techniques will be used to answer the main research questions. In particular, there are three regression models that are commonly used in ecological experiments [86]: general linear models, generalized linear models, and generalized linear mixed models. Linear models, which are so named due to the linear relationship between the measured data and the fitting parameters [87], are commonly used to determine the most effective treatment in a restoration experiment. They are considered appropriate for research that involves only a few sites, a small number of variables, and infrequent data sampling [86], which is an apt description of this reforestation experiment.[21] Each of these models has associated limitations and assumptions that impact their capacity to fit certain types of data accurately and efficiently. The precise choice of model(s) to be used in this experiment will therefore depend on the type and structure of the data, which can only be determined as the monitoring progresses.

General Linear Models

Written in matrix form, the general linear model can be represented by [88]:

$$\mathbf{Y} = \mathbf{X}\boldsymbol{\beta} + \mathbf{E} \tag{2.2}$$

Here, the $n \times p$ matrix $\mathbf{Y}$ is composed of p measured data sets, each of length n. The $n \times m$ matrix $\mathbf{X}$ contains the known values of the m independent variables, and the $m \times p$

[21] Geostatistical models can provide more accurate results for experiments involving frequent monitoring measurements of many sites [86], but given the relative simplicity of this experiment, linear models should suffice.

matrix $\boldsymbol{\beta}$ must be fit to the data to determine its m unknown parameters for each of the p data sets. $\mathbf{E}$ is the $n \times p$ matrix of residuals (i.e. the difference between the measured and expected values) associated with each of the data points in $\mathbf{Y}$. The $\mathbf{X}\boldsymbol{\beta}$ term is therefore the mean value of the data, as represented by the regression line.

There are many potential applications of the general linear model in this restoration experiment. For example, a standard randomized complete block design uses the following regression equation [89]:

$$Y_{ij} = \mu + B_i + T_j + \epsilon_{ij} \tag{2.3}$$

where Y_{ij} is the response of the plot with treatment j in block i, μ is the mean, B_i is the effect of being in block i, T_j is the effect of treatment j, and ϵ_{ij} is the deviation from the mean for this data point.

To determine which treatment is most effective in restoring soil quality and understory vegetation over time, we will attempt to use an analysis of variance (ANOVA). An ANOVA compares the mean values of sub-populations (defined by the independent variables) to that of the overall population [90]. If a sub-population's mean is substantially different from the mean of the whole population, this is an indication that the associated independent variable significantly affects the value of the dependent variable. In restoration experiments, ANOVA tests are commonly used to determine which treatments yield the most significant results [4, 14, 15, 17, 18, 22, 23, 28, 31, 34, 36, 37, 55, 56, 84, 86].

The general linear model has several limitations, however, one of which is that it is only able to fit data with normally-distributed residuals and constant variance [88, 91–93]. It is incapable of fitting bounded or discrete data [91, 92], as these do not have a normal distribution at the boundaries. Most of the quantities to be measured in this experiment, however, have at least a lower bound of zero (e.g., soil nutrient levels), while others have an upper bound as well (e.g., % vegetation cover). This model also demands that the residuals are uncorrelated, meaning that all observations are independent [88, 92, 93]. This would require the measurements across all plots to be completely independent of each other, but there will certainly be temporal correlations between measurements within individual treatment plots. For example, the measurement of soil compaction in a specific plot at time t_1 will be determined by the compaction at time t_0 and will influence the value at t_2. Therefore, a general linear model may not be suitable for analysing all of the monitoring data.

Generalized Linear Model

The *generalized* linear model uses a 'link function', g, to modify the value of $\mathbf{X}\boldsymbol{\beta}$ such that the mean of the regression line fits the error distribution [93]:

$$\mathbf{Y} = g^{-1}(\mathbf{X}\boldsymbol{\beta}) + \mathbf{E} \tag{2.4}$$

The link function is selected based on the error distribution, and as such, this model can handle non-normal distributions and non-constant variance, as well as bounded and discrete data sets [91–93].

Generalized linear models are often used as alternatives to general linear models in ecological research [21, 23, 36, 41, 49]. In this restoration experiment, if an ANOVA cannot be used due to non-normally-distributed data, a Welch's ANOVA or a Kruskal-Wallis test may be a better option [48, 55]. Both perform similar functions to the standard ANOVA, but the former permits normally-distributed data with a changing variance, while the latter permits non-normal distributions with constant variance. It should be noted, however, that generalized linear models still require all observations to be completely independent [91–93], so they may not be appropriate for fitting data from repeated measurements of the same treatment plots over time.

Generalized Linear Mixed Model

To allow for non-independent observations, the generalized linear mixed model introduces random effects [91]. If the $q \times p$ matrix $\boldsymbol{\alpha}$ represents some unknown, normally-distributed random effects associated with the data in $\mathbf{Y}$, then we may write this model as [91]:

$$\mathbf{Y} = g^{-1}(\mathbf{X}\boldsymbol{\beta} + \mathbf{Z}\boldsymbol{\alpha}) + \mathbf{E} \tag{2.5}$$

where $\mathbf{Z}$ is a known $n \times q$ matrix of fixed values that determines how the random effects impact the expectation value [91]. Therefore, $\mathbf{Z}\boldsymbol{\alpha}$ acts as an uncertainty distribution for $\mathbf{X}\boldsymbol{\beta}$ and alters the regression line via the link function, permitting correlation between measurements [91].

Such models have been used often in restoration experiments [15, 17, 26, 28, 29, 82]. The Cache Lake experiment will involve repeated measurements of the same treatment plots as part of the monitoring process, so the use of a mixed model may be necessary if correlations between measurements impact the results. There may also be spatial correlations due to the proximity of the plots to each other. For example, as each block has more than one instance of each treatment, we may need to expand Equation 2.3 to include an additional term $(BT)_{ij}$ that accounts for the effects of interactions between treatments and blocks [89]

Unfortunately, the generalized linear mixed model has a few limitations as well, such as the assumptions that $\boldsymbol{\alpha}$ is normally-distributed and that there are no correlations between $\boldsymbol{\alpha}$ and $\mathbf{E}$ [91]. Provided the data do not deviate significantly from these requirements, this model could be the most appropriate option for analysis of the restoration treatments. Fitting this model is difficult, however, as it typically requires more computationally-demanding approximation techniques compared to standard fitting procedures [91]. Therefore, it is recommended that simpler models be attempted first, but if sufficient accuracy cannot be achieved with them, the generalized linear mixed model may ultimately be the best option for analysing the effectiveness of the treatments.

2.2.4 Suggestions for Additional Actions

The primary goal of this project is to perform a rapid understory restoration by testing applied nucleation and windthrow guards at a red pine plantation that has been thinned and managed for invasive species. With that in mind, there is still plenty of opportunity to expand the scope of the project and investigate additional areas of interest.

One simple addition would be to add another treatment. In the original plan for this experiment, wood chips were to be used to suppress undesirable species and enhance soil quality. Ultimately, this treatment was not used due to logistical issues, but time permitting, wood chips could still be added to the treatment plots in Year 3 (2023). Section 2.3.5 gives a brief introduction to the use of wood chips as a possible future restoration treatment in this experiment.

One ideal option for expanding the project would be to treat it as a control-impact study, wherein other plantations nearby act as controls. The vegetation, soil and light intensity can be measured in thinned and unharvested plantations, as well as plantations with and without management of invasive plants. This would give us a better understanding of how the two universal treatments in our experiment are affecting the restoration progress, rather than treating them as the 'baseline' state of the site.

The geographical size of this experiment is relatively limited, and as such, there are also limits to its implications and the applicability of its results in other contexts. For example, the four replicate blocks are all located in one small area with fairly uniform features, so there is no actual replication. These limitations could be addressed by scaling up the experiment and placing additional replicate blocks in other thinned pine plantations throughout the Park. This would allow us to more accurately compensate for environmental differences (e.g., soil types). It might also enable the use of larger blocks and treatment plots, which could reduce the potential for confounding effects between adjacent plots.

As we shall see in Chapter 3 (Section 3.2.1), one of the methods used to determine the likely trajectory of the research site in the future was a study of a nearby sugar maple forest. The geography of the Park's west side, where Cache Lake is located, causes it to be covered in hardwood forests, especially sugar maples [53] (see Section 2.1.3). By studying nearby forests, we can better determine how the ecosystem of the research site will evolve over time. In addition to studying the interior of a hardwood forest, it may also be beneficial to examine the edges. Lakeshores on the Park's west side often have substantial populations of conifers, including spruce, hemlock, cedar, and fir [53]. Therefore, surveys of shorelines, as well as in the transition zones between the Park's hardwood and conifer forests may provide a more accurate and detailed understanding of the research site's likely future. Stratified random surveys of nearby species pools may also give us an idea of which species are likely to migrate into the research site in the near-term.

Finally, it should be noted that restoration is almost always a long-term effort, and as ecosystems are fluctuating, ever-changing entities, they have no 'final' state. Therefore, although the goals of this project are to achieve a rapid understory restoration within just 4

years, the system will continue to evolve long after the experiment has ended. Therefore, it may be of some interest to again survey the site periodically in the future, perhaps every 5-10 years. Long-term projects are logistically and financially challenging, but they also reveal information about the mechanisms of ecosystem recovery that cannot be observed over short time scales. To scientifically determine the best techniques for ecological restoration, long-term monitoring of sites such as this is important.

2.2.5 Timeline

This restoration project has a 4-year timeline, beginning in the winter of 2021 and ending in fall of 2024. As of this writing, the first two years of the project have now been completed. Below is a chronological summary of completed objectives and milestones for the first two years, followed by the approximate expectations and timelines for the remaining two years.

- **Year 1 (2021):**
  - Plantation thinned over the winter (Dec. 2020 - Feb. 2021).
  - Management of invasive plant species commences. Large stems cut in May, glyphosate spraying in June and August.
  - Site is visited by University of Waterloo student in September for initial walk-through.
  - Experiment grid is established in October.
  - Preliminary soil samples are taken in October.
- **Year 2 (2022):**
  - Nucleation and windthrow guard treatments are applied between late April and mid-June by transplanting nearby species.
  - Surviving invasive species are sprayed with triclopyr in late May.
  - Monitoring of treatment plots begins (vegetation, soil, light) in July.
  - Transplants are surveyed in July to determine survival rates and health.
  - Nearby and historical species pools are surveyed and researched in July.
  - The desired successional pathway for restoration is determined in August based on our knowledge of nearby and historical species pools.
  - Project's first grad student finishes their degree in early autumn.
- **Year 3 (2023):**
  - Project is taken over by another grad student.
  - Invasive species management continues on an as-needed basis.
  - Site monitoring continues throughout the spring, summer, and fall.
- **Year 4 (2024):**
  - Invasive species management continues on an as-needed basis.
  - Final monitoring data is collected.

- Final data analysis is completed to determine most effective treatment(s) and degree of site restoration.
- Final report on the experiment is written.

As noted above, my contribution to this 4-year project will be limited to the first 2 years, which is the duration of my master's degree. Consequently, much of my work has focused on planning the restoration project and initiating the experiment. Additionally, after setting up the experiment and applying the treatments, I have worked on laying out the expected ecological trajectory for the site over the next few years, as we shall discuss in Chapter 3.

Beginning in Year 3, the project will be handed off to an incoming graduate student. Year 4 is expected to involve less fieldwork and, in addition to the last site surveys, will be focused on the final write-up for the project.

Yearly progress reports must also be submitted to Ontario Parks as part of the research authorization agreement. Depending on the amount of effort required to achieve the primary project goals, there may be an opportunity to spend some time studying the effects of the invasive species control compared to other harvested and unharvested plantations nearby. Recommendations for possible extensions to the project were discussed in the previous section (2.2.4). Ontario Parks may also choose to extend the project beyond this 4-year timeline, if sufficient resources are available.

2.3 Restoration Treatments

This project will test the effectiveness of several restoration treatments in the rapid regeneration of a pine plantation understory. This will involve two universal treatments, namely tree thinning and invasive species management, and two treatments to be experimentally tested across the site, namely applied nucleation and windthrow guards. The universal treatments are common restoration tools that have been in use for many years in a wide variety of contexts. Both are being handled by Park staff.

The other two treatments are more recent developments. Applied nucleation, which was introduced in Chapter 1, involves creating 'nucleation' sites, small islands of plants that will spread outwards over time, accelerating natural regeneration. The other experimental treatment is the 'windthrow guard'. This is a relatively novel treatment that uses small, herbaceous plants surrounding shrubs and saplings to deflect strong winds upward and prevent windthrow. A review of the literature shows no known tests of this treatment, making this the first explicit demonstration of windthrow guards as a tool for ecological restoration.

While the treatment plan was discussed in the previous section, the following subsections describe the treatments as they will be applied in this experiment. These descriptions include justifications for why these treatments were selected and the expected benefits of

implementing them in this project. We will also briefly touch on an additional treatment (wood chips) which could be implemented in the future. For the methods used to actually apply the nucleation and windthrow guard treatments to the site, see Section 2.4.

2.3.1 Plantation Thinning

The first treatment to be applied to the site was tree thinning, which is a common restoration treatment for plantations. Pine plantations are often planted with the goal of accelerating natural succession [19–25, 35]. Red pines and other conifers are capable of growing in dry, sandy conditions that are unsuitable for other species, particularly hardwoods [19, 20, 35]. They are planted in dense rows to promote quick growth of tall, straight trees competing for light, as such trees are ideal timber sources [20, 25]. After 25-30 years of uninterrupted growth, thinning is conducted once every 10-12 years, creating the conditions necessary for the development of a mature understory and a diverse overstory [19, 20, 24, 25]. (See Section 1.3.2 for a discussion of thinning as a restoration treatment, as well as a description of the usual timeline for plantation thinning in Ontario.)

Without thinning, however, the succession process stagnates, and the plantation becomes unhealthy. After 45-50 years without thinning, the densely-packed trees become skinny, with small crowns and limited root systems [19]. This is what has occurred to the Cache Lake plantation. The trees here are now at risk of disease, insect infestations, and falling due to wind and snow load [24, 31]. Therefore, Park staff have decided that this plantation needs to be thinned, despite the controversy over logging in the Park. The goal in thinning this plantation is to remove unhealthy trees, open the canopy, and provide space for the remaining trees to grow [24]. This should result in healthier trees with increased windfirmness and greater canopy size; the regeneration of an understory; and improved ecological integrity, biodiversity, and resiliency throughout the site [24].

The preparation for this treatment took many years, however, primarily due to administrative hurdles and the controversy over logging within the Park [25]. The plantation is adjacent to Highway 60 and has a nearby public parking lot, so it is a highly visible site. The initial proposal and public consultations began in 2011-2012, and another 6-8 years were required to complete the environmental assessment [25]. (The proposal also included several other aging plantations along the Highway 60 corridor that needed to be thinned [24].) By late 2020, all necessary approvals had been granted and the site was ready to be thinned.

The Cache Lake plantation was thinned between December 2020 and February 2021 [25]. Basal area at the site was 51 m^2/ha beforehand, and the harvesting successfully achieved the target of reducing basal area by one third, with unhealthy trees and non-native species (e.g., Scots pine) removed first [24, 25]. (Some sources suggest thinning to a basal area of 16-21 m^2/ha may yield the best results for understory sapling abundance [35].) The potential for overthinning was also considered, as this could result in the remaining trees being more susceptible to damage from high winds and heavy snow loads [24, 31].

It is expected that thinning will be conducted 3 or 4 more times at this site, every 10-12 years, in order to continue the restoration process [25]. These future efforts are beyond the scope of this four-year project, although we'll consider their impacts in Section 3.2.2.

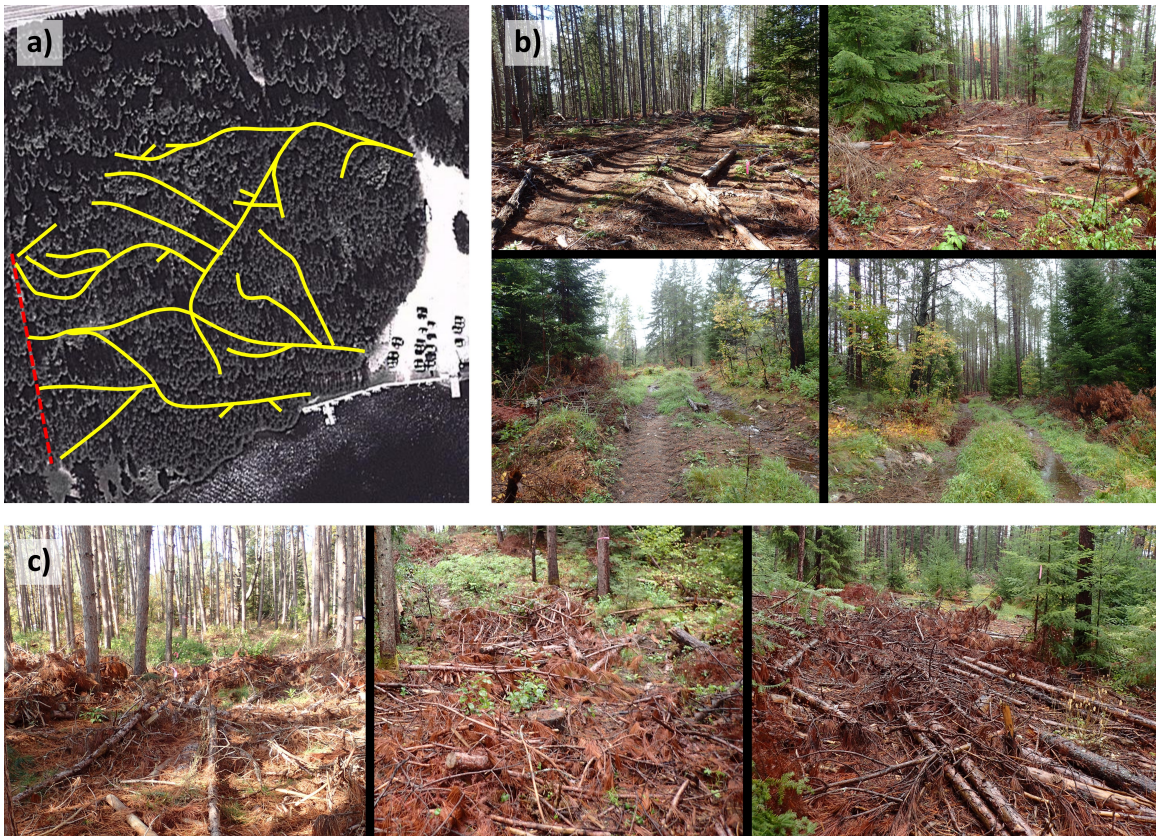


Figure 2.19: a) Map of research site [61] showing the approximate locations of skid trails (yellow lines). Dashed line indicates position of utility corridor along edge of research site; skid trails were not mapped beyond it. b) Skid trails are found throughout the research site. c) Slash piles in the research site.

To provide the harvesting machinery access to the interior of the site, some rows of trees were removed entirely to create skid trails, which are temporary access roads for logging equipment during timber harvest. Figure 2.19a) shows a map of the skid trails across the site. The skid trails have an average width of 3.5 m and consist primarily of compacted soil. In some areas, smaller logs have fallen across the trails or been pressed into the ground by the equipment. Most of these trails are deeply rutted by large tires, and the bedrock has been exposed in some spots. During damp seasons, such as spring and autumn, the deep ruts are observed to form near-permanent puddles that are inhabited by frogs. In the first year after logging, many of these puddles had an oily film on the surface, likely left by the harvesting equipment; in spring of 2022, the water in these puddles was cleaner, so some of the oil was likely washed away by the snow melt. Vegetation levels on these trails vary throughout the site; some skid trails are just compressed sand devoid of all

vegetation, while other trails have retained more topsoil and are covered in grasses and other fast-spreading species. Figure 2.19b) shows some of the skid trails at the site and highlights the variation in their vegetation/debris levels. Due to the extreme levels of soil compaction and vegetation loss along these trails, it is expected that treatment plots on skid trails will recover more slowly than the rest of the site.

Sawdust and slash piles left by the thinning process can negatively impact understory regrowth [21]. While little sawdust has been observed across the site, there are many large slash piles remaining, as shown in Fig. 2.19c). While some dead wood can be retained to act as habitat for insects and other small animals, these dense piles of logs and branches will likely slow the spread of vegetation in some areas. Park staff conducted a survey of slash across the plantation in spring of 2021, and they determined that most of the area required slash management. Therefore, these slash piles may be removed at some point in the future to enhance understory regeneration. It should be noted, however, that research has shown salvage logging (i.e., the recovery of timber from areas damaged by natural disaster) can have extremely negative and long-lasting (15-25 years) impacts on soil and vegetation [48], so given that the thinning process has already had negative effects on the soil, it may be preferable to simply leave the slash where it is.

2.3.2 Invasive Species Management

The second universal treatment to be applied to the research site is ongoing management of invasive species. As discussed in Section 2.1.1, many buildings, lawns and gardens formerly occupied this area throughout the first half of the twentieth century. At the time, the government was happy to introduce any plants that would make the Park more appealing to the public, including shrubs to attract deer and wild rice to attract ducks [66]. By the early 1940s, one could find non-native "timothy, clover, heal-all, ox-eye daisy, yarrow, and orange hawkweed" along the old lumber camp roads [66]. After the buildings on Cache Lake's northern shore were demolished, many non-native species from the gardens were left behind and eventually spread across the site.

Park staff conducted a survey of non-native species at the Cache Lake plantation in spring of 2021 and discovered daylilies, bugleweed, forget-me-nots, ground ivy, lilac, lily of the valley, oregano, and rubarb, among other invasive plants. Non-native honeysuckles (*Lonicera* spp.) have been particularly successful in colonising the site; a systematic survey found that some spots have more than 100 honeysuckle stems per 30 m x 30 m plot. While most invasive species remaining at the site are left over from the hotel and Superintendent's gardens[22] [77], there is also a large quantity of Japanese knotweed (*Fallopia japonica*),

[22]Of interesting historical note is the fact that, besides invasive plants, the park's third Superintendent (George Bartlett) also attempted to introduce non-native wildlife species to Algonquin on numerous occasions [62–64, 66–69]. For example, after he suggested elk be introduced in 1899, ten elk were eventually brought to Cache Lake in 1936 during the tenure of Superintendent Frank MacDougall, although they only survived for a few years [63, 66]. Despite the many species Bartlett and others intentionally introduced

which may have been left by private cottage owners dumping out planters near the access road [77]. A stand of Scots pine can also be found near the old Superintendent's house, with several individuals dotted along the cottagers' access road [77]. Overall, at least 15 species of non-native trees can be found within the Park today, including Scots pine [53].

Several of the Scots pine around the research site were cut down at various times throughout 2021 and 2022 [77], including at least one in the experiment buffer zone between Blocks 1 and 3. Honeysuckle and knotweed, however, are the main focus of the Park's invasive species management activities in this plantation. These aggressive species take advantage of the heavily-disturbed, open spaces left after plantations are harvested [94, 95]. They grow in dense thickets that reduce the light and nutrients needed by native species, and they may have allelopathic effects that prevent other plant species from growing nearby [94–96]. Honeysuckle also appears to have toxic leaf leachates that can harm riparian organisms [96], while knotweed thickets can reduce downstream water supply in rivers [95]. These invasive species can reduce ecosystem biodiversity, reduce the diversity and cover of herbaceous species, slow forest regrowth, and have negative impacts on a variety of endangered native fauna [95–97]. Both are exceedingly difficult to eliminate once established.

After completing surveys across the site in early spring of 2021, Park staff began managing the invasive species. In May 2021, all large stems, particularly honeysuckle stems, were cut, and the following month, all invasive plants were sprayed with glyphosate [77]. Glyphosate, commonly sold under the trade name Roundup, is a chemical herbicide absorbed through the leaves [77]. Put simply, glyphosate operates by inhibiting the creation of an enzyme called 5-enolpyruvylshikimate-3-phosphate synthase (EPSPS) [98]. Without EPSPS, plants cannot create three important amino acids (tryptophan, phenylalanine, tyrosine), which are needed for synthesizing hormones and metabolites [98]. The glyphosate spraying was conducted manually across the research site, with workers carrying backpacks and hand-held pump hoses [77]. The large stems of the invasive plants were cut beforehand to simplify the glyphosate spraying process and to ensure that the chemical, which is applied to the leaves, was not being sprayed up into the air, where it could blow onto other plants or onto the workers [77]. A second spraying was done in August 2021 to kill new shoots from the plant base. The following year, in late May, a third spraying was conducted, this time using triclopyr, also called Garlon [77]. Triclopyr is another herbicide, though it is applied directly to stems rather than leaves [77]. Triclopyr acts as a synthetic auxin, which is a type of plant growth hormone [99]. A large dose of triclopyr results in rapid cell division, eventually leading to organelle death [99]. Plants typically die within a few days of treatment with this product [99]. The combination of stem cutting and application of either triclopyr or glyphosate has been shown to be highly effective in eliminating a variety of invasive species in North America, including non-native honeysuckle [100]. The extensive colonies that have spread throughout the site have necessitated repeated appli-

to the Park over the years, "including [ring-necked] pheasants and two European grouse species" [62], smallmouth bass (introduced in 1899) remains the only exotic wildlife species that was ever successfully established [62, 63, 66].

cations of this treatment, but this technique should ultimately be effective in controlling these species. One can find dead honeysuckle stems throughout the site now, although as we shall see, the vegetation surveys revealed many remaining non-natives.

Ultimately, in addition to the experimental treatments, this research will be conducted in the context of universal invasive species management, which has been shown to improve native biodiversity during forest restoration projects [29]. This effort should enable our applied nucleation species to colonize the area and facilitate seedling recruitment without much competitive interference from non-native plants.

2.3.3 Applied Nucleation

While opening up the canopy and reducing competition from invasive species will provide new opportunities for understory regeneration in the plantation, natural regeneration is a slow process, with numerous limiting factors. Although regeneration will be accelerated by proximity to nearby seed sources, viz. the surrounding forest and wildlife, substantial natural regeneration may not take place within the project's 4-year time frame. The logical solution, therefore, is to artificially introduce native understory species in order to accelerate the process, yet to do so in a manner that is inexpensive and avoids the structural and compositional homogeneity of a large-scale planting. As discussed in Section 1.3.3, applied nucleation is a restoration technique that combines the accelerated regeneration timeline of plantation-style restoration with the low-cost, heterogeneous results of natural regeneration [4, 5, 8, 14, 15, 17, 18, 21, 29, 33, 54, 55]. Based on a review of the literature, it's a technique that has not been previously attempted at a pine plantation in a northern mixedwood plains ecozone, nor has it been used to restore the understory of a plantation. That makes this an ideal opportunity to advance our scientific knowledge while simultaneously fulfilling our restoration goals within the desired time frame. Due to the limited number of treatment repetitions in this experiment, it was decided that testing a single nucleation species would yield more statistically-reliable results.

The nucleation treatment will be tested in 128 plots in total, half of which will also receive the windthrow guard treatment. Although we can hire assistants to help with the transplanting effort, it remains logistically unfeasible to plant more than one shrub per plot. The nuclei also won't have much time to spread out, given the short project time frame. This means we will effectively be testing a simplified nucleation treatment, wherein the impacts of a single planting will be considered, rather than the multiple, clustered plantings that are more typical of applied nucleation [8, 13, 15, 29, 54]. We will also have just a single planting per treatment plot, rather than multiple plantings, so this experiment will not necessarily be testing for the expected pattern of expanding and merging nuclei at the scale of individual plots [8, 11, 14, 15, 17, 18, 29, 54, 55]. If we examine the plantings at the scale of individual blocks, however, we may see this pattern emerge in the future. As we shall discuss in the next section, the windthrow guard treatments could be considered more typical clustered nucleation plantings, especially when combined with the

transplanted shrubs. We will continue to call the treatments 'nucleation' and 'windthrow guard', however, as these remain the basic premises upon which these treatments were designed. Nevertheless, this notion of plantings vs. true nucleation will kept in mind when we discuss the results and conclusions of this experiment.

To determine whether this treatment was successful, we will monitor the plots for evidence of increased seedling recruitment and native vegetation cover compared to the control plots, as well as improved soil quality. Given the size of the individual shrubs (0.5 m diameter), there should be plenty of room within each plot to observe the effects of these plantings and determine whether they are accelerating the changes in the surrounding soil and vegetation. In the short term, we also hope to see high rates of transplant survival, which is necessary for the experiment to proceed. In the long term, we might ideally observe the plantings expand and spread outwards, although this may not occur within the timeline of the project.

Several species were considered for the applied nucleation treatment, including maple-leaf viburnum (*Viburnum acerifolia*) and red-osier dogwood (*Cornus sericea*). Ultimately, the species chosen for nucleation planting was Eastern beaked hazel (*Corylus cornuta* var. *cornuta*). This species was selected for a number of reasons, including its availability; a large colony of beaked hazel was found ∼600 m from the research site, along a utility pole corridor near the parking lot of the Minnesing bike and ski trails, as shown in Figures 2.20a) and b). This proximity has the added benefit of preventing contamination of the research site with invasive/non-native species introduced by transplanting shrubs from outside the Park. The shrubs are also all roughly the same height (1-1.5 m), diameter (0.5 m), and age (3.5-8 years) (see Section 2.4.3). Had they been different sizes, we would have considered each size class as a separate treatment, thereby reducing the statistical reliability of our results. The pine plantation adjacent to the hazel colony is slated to be removed, with a large septic system to be built in its place as the Park's tourist areas are modernized [77]. This is therefore an excellent opportunity to remove the beaked hazel before the area is disturbed, especially as the shrubs may be damaged or destroyed in the process, and the utility corridor will likely be cleared of vegetation in the future anyway, as its power lines are still operational. Figure 2.20c) shows the work commencing at Minnesing; it began in mid-June and continued through July.

Beaked hazel is a common understory shrub that usually reaches 3-4 m in height, though it can grow up to 5 m [42, 102]. Figure 2.20c) shows some of the identifying features of beaked hazel. It has smooth, grey-coloured bark with some lenticels, and the serrated, roughly ovate leaves of varying size (∼2.5-12 cm long, ∼2-7 cm wide) emerge in mid-May [42, 102]. Male and female flowers emerge in April-May, usually before the leaves open, with the male flowers in catkins (⩽5 cm long) that have developed over the previous year [42, 102]. Edible nuts (1.2 cm in diameter) are produced in August and September [102]. Each nut is encased in an bristled involucre (a type of modified leaf) that extends beyond the nut as a thin, wing-shaped protrusion with a toothed tip (hence the botanical term *beaked* in the species name) [42, 102]. These edible nuts act as a food source for many species, including rodents and ungulates [37, 103]. The hazel itself also has a high

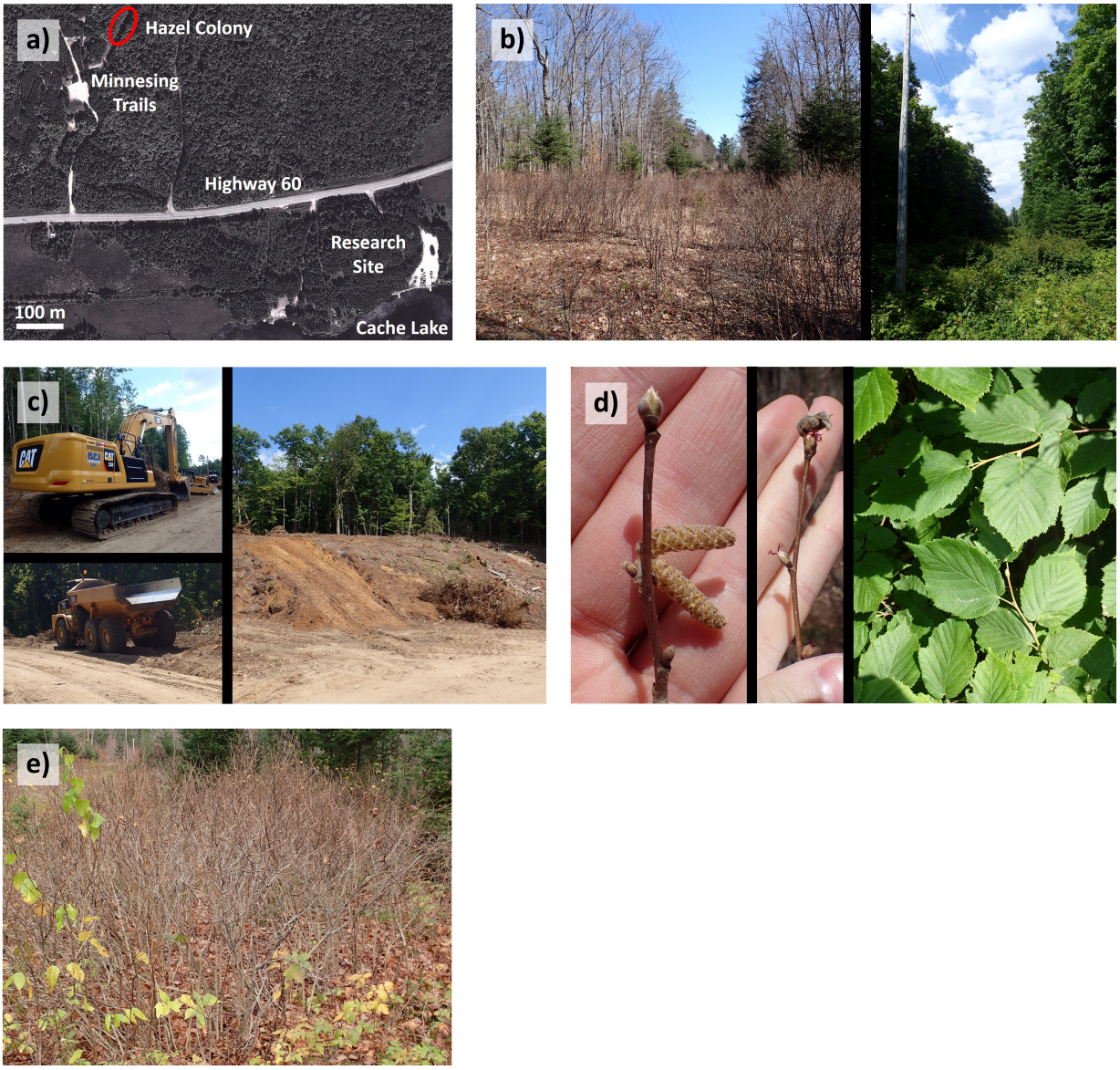


Figure 2.20: a) Location of beaked hazel colony near Minnesing trails [101]. Red oval indicates approximate location of hazel colony along utility corridor. b) Views of utility corridor with beaked hazel colony in April and July. c) Construction work along the Minnesing access road in July. d) Identifying features of beaked hazel: catkins and leaf buds, flowers, leaves. e) Beaked hazel thicket.

tolerance for ungulate browsing [37]. The ability of this species to attract wildlife makes it a desirable nucleation species, as increased wildlife presence in the plantation is likely to accelerate native seed dispersal [8, 11, 14, 15, 18, 29, 33, 54, 55].

This species was also selected for its ecological suitability as an early to mid-successional understory species [42]. Beaked hazel is a widespread native shrub with a geographic range

that spans from Alberta to Canada's eastern coast, and south into the United States [37, 58, 103]. Populations exist throughout much of Southern Ontario, with scattered communities as far north as 50° N latitude [102]. Commonly found in jack pine, red pine and aspen-birch forests [42, 103, 104], it inhabits the intermediate to tall shrub layer (1-2 m in height) [51, 58] at the transition between temperate deciduous and mixed hardwood-conifer forests [37, 42, 58, 102], a description that matches the transitional state of Algonquin Park's forests [53]. A variety of factors can influence beaked hazel growth, including moisture levels, light levels, soil content, climate, intra- and inter-specific competition, levels of browsing, and historical disturbance [37, 42]. It is a mesophytic species that is commonly associated with mesophytic tree species, such as sugar maples, red pines, and eastern white pines [42]. Consequently, it prefers a damp, though well-drained, environment and benefits from higher levels of precipitation [37]. This species also favours open forests with intermediate light intensities [37, 42], and its abundance diminishes as canopy cover increases [37]. Although it can successfully spread in brushland [42], it may go into temporary shock and experience a reduced growth rate if exposed to full sunlight [42, 105]. Stems may even die within a couple of years of long-term exposure to full sun [42]. In general, light levels between 30-40% of full sun are optimal for beaked hazel growth, and levels around 10-30% tend to yield the largest populations [42].[23] Thus, it often prefers forest boundaries or clearings, where some shade is present but competition with trees is reduced [42, 102]. The research site for this project, consisting of a thinned plantation located beside a lake, readily fulfills these required climatic and light conditions, indicating a reasonable chance of transplant success. (The fact that the colony from which these shrubs are being transplanted is less than a kilometer away may also indicate overall climate conditions are favourable.) Moreover, the distribution and density of beaked hazel is directly correlated with successional stages; while highly prevalent in early and mid-successional forests, the populations are much smaller in climax communities, such as maple forests [42]. This makes it a good fit as an understory nucleation species in the red pine plantation, which has been thinned to a mid-successional, partially-canopied state, particularly as the desired end goal for this restoration work is to (eventually) restore a sugar maple forest.

Beaked hazel contains significant amounts of nutrients within its own mass and has particularly high levels of Ca in its leaves [106]. Consequently, its litter contains large quantities of N, Ca, P, and Mn [84, 106], and beaked hazel has been shown to increase the concentration of these nutrients in red pine forest litter [106]. As this litter is blown by wind across the research site, it may enrich the soil with nutrients that are much-needed after a half-century during which the area was dominated by a single species (i.e., red pines). While this species can increase rates of litter decomposition locally in red pine forests, it also has a high turnover rate for soil organic matter and nutrients [106]. Therefore, despite the high nutrient-content of beaked hazel litter, nutrient levels in the surrounding soil may not increase [106], and it has in some circumstances been observed to reduce nutrient availability [40]. Beaked hazel can grow in a variety of soils, and despite

[23] Beaked hazel has some ability to adapt to different light levels: in shaded areas, it produces larger leaves than in full sun, allowing it to collect more light [42].

its nutrient requirements, it is able to grow and even dominate the understory in nutrient-poor soil [40]. It prefers a pH range of approximately 5.1-6.1, with 5.9 being optimum for increased distribution and reduced mortality [42]. Beaked hazel has no particular preference for organic soil content, but it cannot tolerate soils that retain significant moisture levels, such as peat [37, 42]. Overall, well-drained, mesic soils of intermediate density are its preferred growth medium, particularly loamy and sandy soils [42]. This suggests that these shrubs will be able to survive in the soil conditions found at the research site, which range from loose soil rich in organic material, to extremely compacted sand and silt along the skid trails. Most of the research site rests on a hilltop elevated above the surrounding area, so water drains down towards the adjacent access roads, Highway 60, and the lake.

Beaked hazel reproduces through two processes: seeds [42, 102–104] and vegetative cloning via modified underground stems[24] [37, 42, 58, 59, 103–105]. The larger individuals (∼2 m in diameter) begin generating seeds and clones after 7-10 years [42, 103, 104]. Hazelnut seeds are large and wingless and are predominantly dispersed by rodents, rather than wind or water in forest settings [103]. Rapid vegetative cloning, however, is the predominant form of reproduction, allowing the hazel to quickly spread throughout an area [37, 42, 58, 59, 103–105]. Beaked hazel may produce either vertical or horizontal vegetative stems from adventitious buds; the former, activated by any damage to the main stem, will develop into a new aerial stem, while the latter, activated around age 7-8, extends horizontally underground [42]. Once the tip of an underground stem appears aboveground, it develops roots and an aerial stem, and two new underground stems begin to extend from the endpoint of the original after about 7 years [42]. The length of the underground stem prior to developing a new aerial stem is determined by the vigor of the mother stem [42], and each stem lives about 15 years or less [58]. A beaked hazel colony therefore expands outwards from the original stem to fill an area [42], which is roughly the goal of the applied nucleation strategy [8, 11, 14, 15, 17, 18, 29, 54, 55].[25] Except for a single taproot that extends about 60 cm down into the soil, the root systems of vegetative clones are mostly concentrated (92.5%) in the top 15 cm of the soil [42], making them ideal for transplanting. The roots are very thin (0.1-0.5 cm diameter according to my observations), and some are usually covered by mycorrhizae [42]. The dense surface root systems of these shrubs can sometimes prevent other species from establishing themselves [40, 59, 104, 105], such that beaked hazel comes to dominate the soil [42].

During the early stages of its development, beaked hazel grows slowly and sparsely, and it competes with other woody and herbaceous species, including trees [104]. As it develops, however, it can form dense, continuous thickets that prevent other species from growing [37, 42, 58, 59, 102–105], as well as altering soil nutrient levels [104] and leaf litter composition [37]. Hazel densities may be as low as a few thousand stems/ha in low-density populations [105] or as high as fifty thousand stems/ha [59, 105]. (The densest thickets may

[24] These stems are similar to rhizomes, but they do not have distinct nodes from which new roots and stems propagate. Additionally, unlike actual roots, the modified stem has a pith at its centre [42].

[25] Perhaps following resource gradients, the colony tends to extend itself in specific directions, however, rather than following the theoretical model of expanding in concentric rings [42].

have several thousand clones per hectare and more than one hundred thousand stems/ha [103, 104].) Figure 2.20d) shows a hazel thicket in the utility corridor at Algonquin Park. Below dense thickets, as little as 2-7% of sunlight may reach the ground [42, 105], so young stems must compete with each other for resources [37]. The stems may grow taller (∼180 cm) in high-density thickets, likely due to light limitations, while they may only reach ∼70 cm in low-density regions [37, 105]. While the low light levels below hazel thickets is sufficient for many species of tree seedlings, inadequate moisture is typically the limiting factor in seedling survival, as their roots are often unable to penetrate the dense leaf litter and the hazel root mass in the surface soil [42]. Only a few species, such as balsam fir, can successfully reproduce in such conditions; they must be highly tolerant of shade and reduced moisture and be capable of rapidly generating and spreading shallow roots [42]. Thus, in forests right across its range, beaked hazel may eventually dominate the shrub layer, crowding out other species [37, 42, 51, 58, 59, 59, 84, 104, 105] and arresting succession for decades [59]. In this sense, beaked hazel influences other understory species in the same way as mature trees affect it [42]. In the past, wildfires likely maintained hazel densities at a level such that other tree and shrub species could establish themselves, but some areas may now require human intervention to prevent overpopulation [104]. Canopy thinning [105] and prescribed burns [104] may reduce high-density hazel thickets to manageable levels. In some cases, exotic species may supplant beaked hazel over time and dominate the shrub layer [58].

The ability of this species to reproduce vegetatively may increase the chances of it rapidly spreading throughout the plantation, thereby yielding greater recovery of vegetation cover within the project timeline. The dense thickets it forms can also provide security from large predators for birds and small mammals, thereby encouraging them to inhabit the area and aid in seed dispersal. That said, the formation of an impenetrable, homogeneous hazel thicket dominating the understory would be an undesirable outcome, as the project's goals are to restore a structurally- and compositionally-heterogeneous layer.[26] Fortunately, a number of factors at the research site should help reduce the likelihood of this eventuality. Although the plantation was thinned, creating gaps in the canopy, some areas still have substantial canopy cover, which will slow beaked hazel growth [37]. Secondly, the soil has been significantly disturbed across much of the site, particularly along the skid trails. Beaked hazel is capable of growing in such conditions [40], but its rate of spread may be slowed in those areas with nutrient-poor, compacted soils, thereby providing more time for other species, including tree seedlings, to establish themselves throughout the site. As the tree saplings grow and the canopy begins to close, the beaked hazel population will likely decline, having completed its task of facilitating mid-successional understory regeneration.

[26] This would be an excellent example of a misaligned indicator, in which our use of vegetation cover as an indicator of restoration progress could lead us to accept the rapid formation of a dense, homogeneous understory as a successful end result because it maximizes % cover. Such an understory would likely suffer from many of the same ecological problems as the monoculture plantations discussed in Section 1.1, however, ultimately making it an undesirable outcome. Thus, we use multiple indicators, including species richness, in order to guide our interventions so they may yield results that are truly aligned with our objectives.

This is evinced by the observation at the Minnesing site that despite preferring the same soils, there were no hazel shrubs in sugar maple forest surrounding utility corridor, likely due to root competition and lack of light [42]. Finally, a study by Tappeiner in Northern Minnesota red pine stands found that dense thickets tend to form from seedlings filling the gaps between individual shrubs rather than through vegetative spread, which occurred relatively slowly at these sites [103]. As the treatment plan calls for a mere 32 shrubs per replicate block (4096 m^2) and their seed production may be reduced by the poor soils and transplant shock, there will be plenty of opportunity for other species to colonize the area and prevent the formation of a dense, continuous hazel understory.

A very detailed study of beaked hazel and its properties is presented in the frequently-referenced PhD thesis by Hsiung [42].

2.3.4 Windthrow Guard

Windthrow is the term for the uprooting of plants due to high winds, a common phenomenon in boreal forests that can devastate large swathes of established woodland [46, 47, 107, 108]. Figure 2.21 shows several trees at the research site that were killed by windthrow during the winter of 2021-2022. Although plants become accustomed to normal wind conditions as they grow (i.e., windfirm), a sudden, powerful wind event can result in substantial amounts of windfall [47, 52]. The degree of windthrow depends on the type of disturbance; an average storm might bring down a few individual trees, while an extreme weather event could result in large-scale tree and understory loss [46]. The resulting canopy gaps can cause reduced soil humidity and increased temperatures due to increased sun and wind exposure [46, 47].

The impacts of windthrow, however, are not entirely ecologically undesirable. Windthrow is a common and important phenomenon in forest ecosystems [46–48]. It creates areas of dead wood with exposed roots, disrupted soil, altered understory structure, and increased sun-exposure [46–48]. The resulting changes in resource patterns across a wide range of spatio-temporal scales, both below- and above-ground, yield increased habitat heterogeneity and biodiversity [46–48]. Heterogeneity exists even within a single windfall gap due to: differences in sun exposure and direction, such as, for example, the northern side getting more direct light due to the angle of the sun; positions of log piles and leaning trees, which may shade and protect some areas more, as well as alter wind speed and direction; different degrees of soil disturbance; and locations of surviving trees and the surrounding forest [46, 47]. Windthrow can alter soil structure by lifting and mixing the different layers, exposing rocks, and modifying the ground structure into a series of mounds and open pits, the latter of which will collect large quantities of litter [26, 39, 46–48]. Seedlings are able to quickly establish themselves in the newly-created microsites, whereas they may otherwise have difficulty penetrating the duff layer on the surface of undisturbed soil [26, 39]. Figures 2.21c) and d) show the impacts of uprooted trees on the soil, including exposed bedrock and pools of water. Many early-successional, edge, seral, and dead-wood-preferring plant and

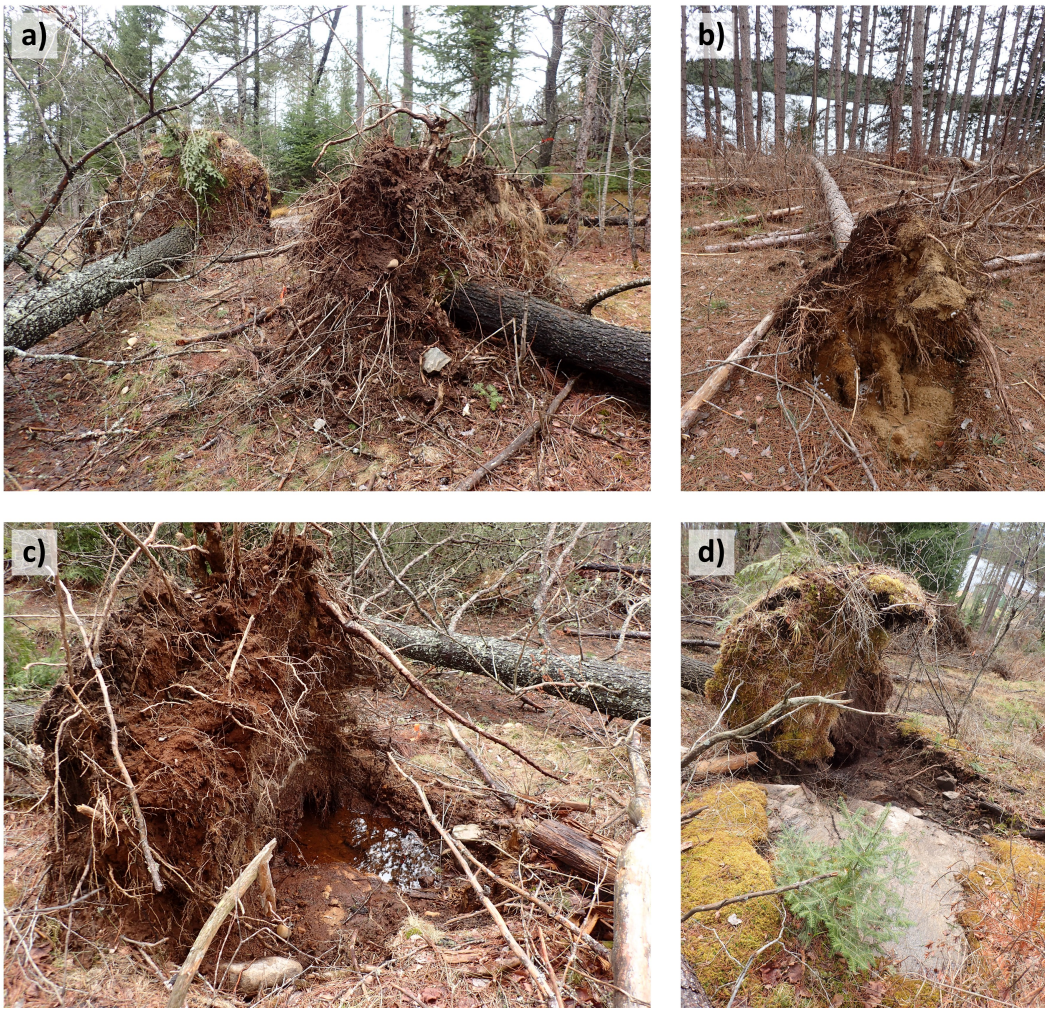


Figure 2.21: a) Trees in Replicate Block 3 blown over by wind during winter of 2021-2022. b) Windthrow just south of Block 4, by the lake. c) Pit formed from uprooted tree, filled with water. d) Exposed bedrock after moss layer and topsoil were pulled off with tree roots.

animal species thrive in the unique conditions created by windthrow, which are otherwise unavailable within climax forest systems [46–48]. Many animal and fungal species rely on dead wood for survival [48], and young trees grow better in canopy gaps due to increased sun exposure [46]. The result of large-scale windthrow disturbances can be that the system either re-establishes its former state or transitions to a new type of ecosystem [46, 47]. Windthrow-induced canopy gaps thereby act as an important component and driver of the successional process, particularly in moist, dense conifer forests [46, 47].

Unfortunately, new growth in recently-harvested plantations is highly vulnerable to windthrow due to the creation of large openings that allow winds to pass through unobstructed at greater velocities [52, 107, 108]. As the present experiment is being conducted in a recently-thinned plantation with disturbed soil and newly-planted shrubs, our restoration

efforts could easily be undone by a single large storm. Although windthrow often presents the greatest risk to trees taller than about 7.5 m [52], shorter species at the research site could be at risk due to the lack of established understory in the plantation. The chosen nucleation species for this experiment, beaked hazel, may be particularly vulnerable to windthrow due to its shallow root system [42], especially in the years following transplanting when its taproot has either been severed or is coiled just beneath the rootball. The utility corridor from which the shrubs were sourced had very little wind, even on days when the plantation experienced a strong breeze, so the hazel may be insufficiently windfirm, making it more vulnerable to windthrow. As the plantation wasn't clear-cut, the remaining trees will offer some protection, but the large openings, particularly along the skid trails [52], still present a risk.

The geography of the site, especially the adjacent lake, may also put the shrubs at greater risk, as large fetches[27] are associated with greater levels of windthrow [52]. That said, the windthrow impacts of a large fetch typically only penetrate up to 30 m into a forest [52], so it may be that only Replicate Blocks 3 and 4 will be impacted, as they are closest to the lake, the parking lots, and the lawn around the Superintendent's house.[28] Indeed, several trees blew down during the winter of 2021-2022 (Fig. 2.21), and it is notable that almost all of them were in Blocks 3 and 4. Additionally, we have observed during fieldwork that that there is little wind on the northern end of the site, even when it is quite breezy by the lake.

To combat the windthrow risk and improve the survival chances of the transplanted hazel, we will be testing a novel treatment we are terming 'windthrow guards'. Typically, wind protection is achieved using stakes or shields (such as burlap tents or snow fences), but these are impractical and undesirable in the context of a forest restoration project. A less artificial option is more appropriate. Therefore, our windthrow guards will be composed of low herbaceous plants surrounding the nucleation species. The conceptual design of this treatment is shown in Figure 2.22. In principle, the presence of these herbs around the shrub should deflect the wind upwards, rather than allowing it to hit the hazel head-on (Fig 2.22a). This should prevent the shrub from being uprooted during extreme weather events. The herbaceous plants can be planted in multiple rings around the nucleation species, with increasing height towards the center to help direct the wind (Fig 2.22b). Due to limitations in materials and time, we will only be testing a single-ring windthrow guard, but in principle, additional rings should offer greater protection.

The origins of this 'windthrow guard' concept are somewhat nebulous. Over the past few decades, informal discussions about this idea have taken place within the ecological community, with the result being that there is no clear 'author' of this idea [109]. The general technique has been used practically in several contexts (e.g., community projects) [110], but a review of the literature shows no known explicit, experimental tests of this treatment

[27] 'Fetch' is the distance over which wind travels unobstructed across an open space.

[28] They also have the lowest tree density. A spatial analysis of future windthrow at the site is therefore warranted, to determine whether hazel location effects mortality rates.

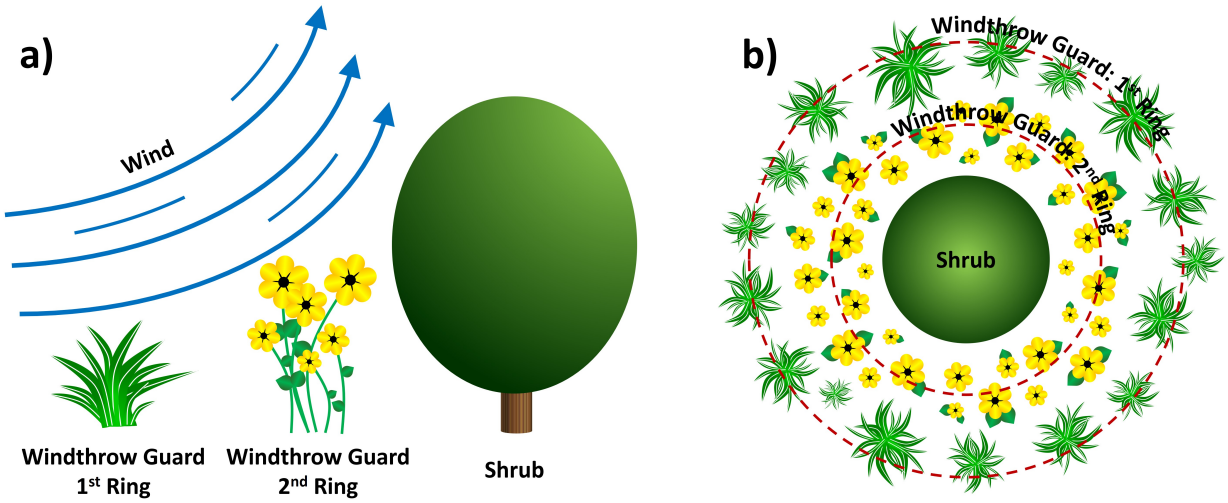


Figure 2.22: a) Windthrow guard principle: planting low, herbaceous species around a shrub, with increasing height towards the shrub, should deflect the wind upwards and prevent windthrow. b) The windthrow guard species can be planted in multiple rings (shown by the dashed circles) around the central shrub.

as a restoration tool. There are some hints in the literature of similar principles, such as the retention of wind-felled logs to protect seedlings [26, 48] and the concept of nurse plants, which are early-successional plants that facilitate the growth of late-successional seedlings, in part by protecting them from the elements [10, 82]. This latter topic was likely the idea from which the windthrow guard concept was derived [110]. The term 'windthrow guard' seems appropriate, although it does not appear anywhere in the literature. Ultimately, this project will serve as the first experimental test of windthrow guard effectiveness.

We should note, however, that this test will only examine whether the presence of the herbaceous species reduces windthrow; it is not proof that the ring design is the best option. For that, we would need to test a variety of transplant patterns, such as rings versus randomized plantings. Moreover, if no windthrow occurs for any nucleation shrubs, we will also have no direct proof of this treatment's effectiveness.[29] Additionally, as noted in the previous section, the nucleation treatment might be better understood as a 'single planting' treatment rather than as true applied nucleation, which typically involves clusters of several

[29]Direct proof of this treatment's effectiveness might need to be done in a laboratory setting. The windthrow guards and the trees/shrubs they are to protect could be planted and allowed time to establish themselves. They could then be exposed to varying wind strengths and directions (from an industrial fan, for example). This would ensure consistency across all repetitions, unlike at the research site, where the topography and existing plantlife will impact the force of the wind experienced by each shrub. It may also be more relevant if this test is done very shortly after planting, when the shrubs are particularly vulnerable to windthrow because their roots have not yet become firmly established.

transplants [8, 13, 15, 29, 54]. The AN&WG treatment, however, might be considered a more typical nucleation treatment, however, as this is a cluster of transplants (although standard applied nucleation experiment usually involve multiple clusters per treatment plot). These potential redefinitions of our treatments will be considered as the project progresses and we analyse our results. The herbaceous plants will also have time to spread during the 4-year duration of the project, whereas the beaked hazel alone will likely only facilitate other species. Using the WG treatment as the control, we could therefore examine whether the shrub in the AN&WG treatment enhances or hinders the goldenrod nucleation planting.

Several species were considered for the windthrow guard treatment, such as fireweed (*Chamaenerion angustifolium*), but it was eventually decided that Canada goldenrod (*Solidago canadensis*) best met the needs of the experiment. This species spreads quickly and can form dense, herbaceous clusters, with individual stems growing to be several feet tall by late summer. Although absent in winter, this nevertheless makes it an excellent choice of windthrow guard species. Low, shrub-like species, such as junipers or Ericaceae, were considered as an option, as these evergreen species would still offer protection in winter, but they may acidify the soil. Ultimately, the deciding factor in favour of goldenrod was its abundance within the Park, making it more logistically feasible to transplant than other species. In fact, several large patches of Canada goldenrod are located by the parking lot of the Minnesing trails, roughly 600 m from the research site (Figure 2.23). By transplanting plants from nearby, we can avoid accidentally introducing invasive or non-native species to the research site.[30] Moreover, as Canada goldenrod is prevalent throughout the Park and the large colony at Minnesing contained more than enough individuals than were needed for transplanting, there was little ecological risk in removing large quantities from the side of this parking lot. Canada goldenrod also has the requisite ecological and successional properties for this project.

Historically, *Solidago canadensis* has referred to a collective of different goldenrod varieties, some of which were eventually re-categorized as separate species, such as tall goldenrod (*Solidago altissima*) [111, 112]. Today, the *Solidago canadensis* species complex comprises several species that share similar properties, including the titular species *Solidago canadensis* [112]. Canada goldenrod is a perennial herb that appears as a straight, vertical stem (∼30-130 cm tall) covered in many thin, serrated leaves (3-15 cm long, 0.5-2 cm wide) [43, 45, 111–115]. These physical characteristics make these tall, leafy plants ideal for forming a protective windthrow guard around the nucleation shrubs. In southern Ontario, the seedlings emerge from the ground between early June and early July, usually spaced 5-12 cm from neighbouring stems, and the typical growing season is June to September [43, 112]. Figure 2.23d) shows a collection of Canada goldenrod stems at Algonquin Park in mid-June. A panicle of many small, yellow flowers at the top of the stem blooms between late July and early October before the above-ground stems die back for the winter

[30] As we will see in Section 2.4.4, there were actually some non-native species in the goldenrod patches, such as tufted vetch. These species, however, were already present at the research site, and efforts were made to eliminate them from the transplants.

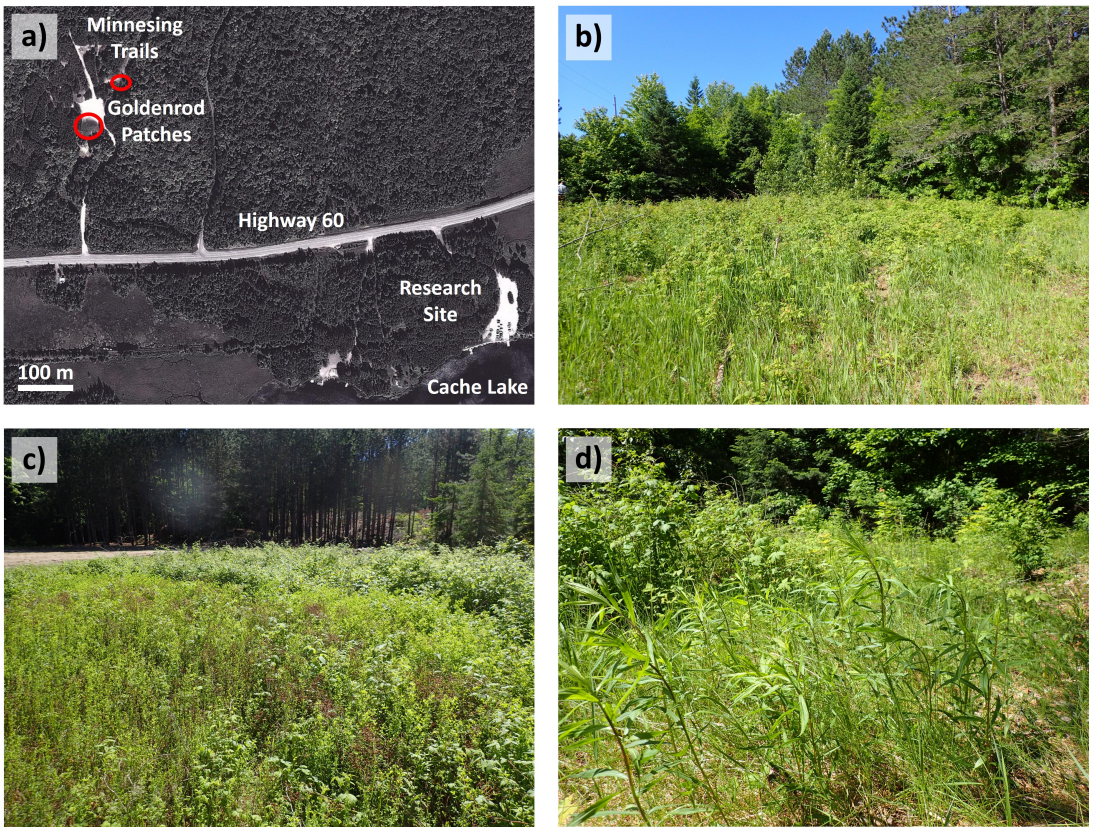


Figure 2.23: a) Location of goldenrod patches near Minnesing trails [101]. Red ovals indicate approximate locations of goldenrod in parking lot (lower oval) and near utility corridor (upper oval). b) and c) Views of the goldenrod and raspberry patch by the parking lot. d) Canada goldenrod at the Minnesing parking lot in mid-June, 2022.

[45, 111, 112, 114, 115]. Although this June-October season means the goldenrod will only provide the nucleation shrubs with protection for about half the year, the dead stems may provide some protection during the winter, especially as the species begins to spread, and in any case, the shrubs will likely be buried in half a metre of snow during the winter months [79]. White-tailed deer (*Odocoileus virginianus*) have been known to graze on Canada goldenrod [112], and hundreds of insect species feed on various parts of the plant, including black blister beetles (*Epicauta pensylvanica*), moths and butterflies (Coleophoridae, Lepidoptera), and native (*Bombus* spp.) and non-native (*Apis mellifera*) bees [112, 114]. Eggs deposited by the goldenrod gall fly (*Eurosta solidaginis*) and the goldenrod gall moth (*Gnorimoschema gallaesolidaginis*) form galls on the stems [112]. The ability of this species to attract and support a variety of species will aid in the understory restoration process at the research site by enhancing biodiversity and supporting pollinators.

A common sight in Canada and the United States, Canada goldenrod is native to eastern North America from the east coast to the Rocky Mountains and from Tennessee and North Carolina to northern Ontario [111–115]. Algonquin Park is near the northern boundary of

its current range. The species can also be found in Europe and Asia, where it is invasive and successfully out-competes other species due to its highly-effective reproductive strategies and allelopathic properties [112, 113]. Its favoured habitats include meadows, tall-grass prairies, old pasture and agricultural fields, roadsides, and open forests [43, 111–115], where it can be commonly found growing alongside several other goldenrod species [111, 114]. Although able to tolerate a wide range of environmental conditions, it prefers light levels between full sun and lightly shaded [106, 112] and grows best in mesic habitats with damp, well-drained soil [43, 111, 112, 114], though it very occasionally inhabits drier areas as well [111, 112]. It cannot tolerate a lack of moisture during the growing season, however, and will disappear from such areas [111]. It prefers soils of 'medium' texture and organic content [112]. The thinned plantation at Cache Lake fulfills these habitat requirements, and plenty of Canada goldenrod stems can already be found across the research site.

Solidago canadensis has two reproduction methods: seed and vegetative growth. Goldenrod flowers, which are self-incompatible,[31] are pollinated by a variety of insects, especially native bees (*Bombus* spp., *Ceratina* spp., *Halictus* spp.), non-native honeybees (*Apis mellifera*), goldenrod soldier beetles (*Chauliognathus pennsylvanicus*), hover files (Syrphidae), and wasps (*Polistes* spp.) [112–114]. Once pollinated, fruits form in autumn, and the seeds are dispersed by the wind over winter, usually to a distance of about 0.3-2.4 m from the source stem [112, 113]. Aside from the impacts of soil conditions, seedlings can be strongly affected by litter and vegetation during their first month of growth [43]. In areas of deep litter and dense vegetation, seedlings are far less likely to emerge and survive to the one-year mark, likely due to heavy shading and difficulty establishing roots[32] [43]. Canada goldenrod therefore prefers open areas with almost full sun exposure during its first year of growth [43]. This may present difficulties for seed-based reproduction at the Cache Lake plantation, as much of the site has a dense layer of red pine needle litter covering the ground.

Goldenrod also reproduces via rhizomatous vegetative cloning [43, 111–115], however, which should enable it to continue to spread at the research site despite the dense litter layer. After a seedling's first year, during which it usually does not flower, it begins to develop rhizomes at the base of the stem, which extend horizontally underground [112]. The rhizomes are dormant for the winter and revive in mid-April [112], whereupon each rhizome can produce one vertical aerial stem, usually at a distance of about 5-12 cm from the mother stem (which has died back by this point) [106, 112]. Fibrous roots will emerge from the base of the new stem between mid-June and July [112] and can extend as far as one metre into the ground [111]. In southern Ontario, Canada goldenrod root systems are usually accompanied by substantial amounts of mycorrhizae (*Endogone* spp.) [112]. Genetically identical and connected by the underground system of rhizomes and roots,

[31] The fact that the goldenrod at the research site was sourced from two separate patches may therefore be advantageous, as goldenrod colonies are typically formed from vegetative clones.

[32] Other relevant mechanisms that may contribute to low emergence and survival rates include: "mechanical impedance by litter or due to fungal infection in the dark, moist conditions under litter, or chemical inhibition resulting from some substance produced by the litter" [43].

the new aerial stems (called ramets) are usually of equal height and will each produce 2-6 rhizomes in the fall, after flowering and fruiting have finished [112]. Vegetative propagation then becomes the dominant form of reproduction for the plant, allowing it to spread quickly [113]. The rhizomes spread out in a circle from the central, seed-established stem, forming a colony of cloned stems [112, 115]. The ramets of a colony will flower simultaneously [111, 114, 115], with the largest colonies having over a million individual flowers [114]. As the rhizomes and root systems continue to survive underground, goldenrod individuals can live quite long [112, 115]; after about 25 years, the colonies can be 2.5 m wide, and a clonal colony estimated to be over a century old has been found in Iowa [112]. The centres of the oldest colonies may die, leaving a large (10 m) ring of ramets [112].

The reproductive success of Canada goldenrod may be assisted by its allelopathic effects [81, 112, 113]. One of the first goldenrod allelopathy studies showed that Canada goldenrod releases a chemical nutrient called choline into the soil, which suppresses the germination and seedling growth in several tree species, including sugar maple (*Acer saccharum*), black cherry (*Prunus serotina*), and jack pines (*Pinus banksiana*) [81]. Other research has found allelopathic impacts on the seeds and seedlings of other herbaceous plants [112, 113]. Overall, however, the results of this research have been somewhat mixed [113]. In some cases, the allelopathic effects were found to be only tissue-specific [113], and one study even demonstrated that leachates from the goldenrod can inhibit its own seeds from germinating [112], thereby reducing competition for other species [113]. In many cases, allelopathy found in a laboratory setting has not been replicated in field tests [113]. This may be because some allelopathic chemicals are metabolized by soil microbes at the field sites before they can have an impact, because soil nutrient levels are sufficient to offset allelopathic effects, or because allelopathic chemicals are washed away by rain before reaching a critical concentration in the soil [81, 113]. While it may have some negative impacts on other species, recent research has shown Canada goldenrod allelopathy does not significantly reduce biodiversity or mortality of its plant community; in fact, goldenrod may actually stimulate growth and diversity of other species [113].[33]

Although it will usually start to appear within the first few years of secondary succession, Canada goldenrod is predominantly a mid-successional (seral) species [106, 113]. Its density and biomass will increase over time, usually peaking around 10-20 years after the disturbance [113]. Due to its ability to reproduce vegetatively, it can quickly out-compete other plants and become the dominant species in abandoned fields after the first decade [112, 113]. After 30-40 years, in later successional stages, goldenrod biomass and cover starts to decrease as woody vegetation takes over [45, 106, 113]. These successional properties nicely match our goals at the Cache Lake research site. Currently, the plantation is an open forest, with minimal understory. This should allow the goldenrod to spread and thrive, thereby fulfilling its purpose of protecting the nucleation species from windthrow during the first few years. In the long term, as shrubs and saplings come to dominate

[33]The caveat is that this only applies within its native range; in Europe, species unaccustomed to these allelopathic chemicals are heavily impacted, which contributes to the success of Canada goldenrod as an invasive species there [113].

the understory and the canopy begins to close, the goldenrod population should decrease, giving way to late-successional forest herbs.

A detailed summary of Canada goldenrod properties was published by Werner et al. in 1980 [112].

2.3.5 Optional Future Treatment: Wood Chips

Spreading wood chips on the ground is a common restoration treatment, as described in Section 1.3.4. The initial plans for this project included testing wood chips as an experimental treatment in combination with applied nucleation and windthrow guards. Ideally, the slash that remained after logging would have been run through a chipper, and several piles of slash chips would have been available for use as part of the restoration treatments. Unfortunately, much of the slash was cleared after the harvest, and a lack of time prevented us from hauling slash out of the plantation and passing it through the Park's chipper. Therefore, due to the lack of easily-accessible chips, as well as time constraints imposed on fieldwork by the pandemic, it was decided that wood chips would not be included as part of the initial experiment. If desired, however, they could be added to some of the treatment plots at a later stage in the project, either by chipping whatever slash remains in the areas surrounding the research site or by bringing in chips from elsewhere. Wood chips are already being used to assist with the rehabilitation of the lawn surrounding the old Superintendent's house near the southwest corner of the site [77].

2.4 Methods and Fieldwork

The fieldwork conducted during the first two years of this project had four main components: setting up the experiment, gathering baseline data, applying the restoration treatments, and surveying transplant deaths. Fieldwork commenced in September and October 2021 with 2 weeks of preliminary activity. After pausing for the winter, fieldwork resumed during the last week of April 2022. Subsequently, approximately 2 weeks of fieldwork were organized per month from May through to the end of July.[34]

To accelerate the laborious and time-consuming process of transplanting 128 shrubs and 768 goldenrod stems, several assistants were hired by the university throughout the spring and summer of 2022. Two of these individuals, Eve McLeod Norberg and Mark Saunders, are fellow master's students from the University of Waterloo's School of Environment, Resources and Sustainability. Abraham Dominguez Duque, who is not a current student, also assisted with the project. Many thanks to these individuals for offering their time, as

[34]Longer fieldwork stints would have been ideal, but I had to schedule around the availability of my transplanting assistants and the availability of accommodations within the Park.

without their assistance, the fieldwork schedule would have likely been extended by several additional months.[35]

In order to conduct the fieldwork in a provincial park, we required the approval and co-operation of Ontario Parks, which is operated under the mandate of the Ontario Ministry of the Environment, Conservation and Parks. The fieldwork was therefore conducted in accordance with the limits and requirements stated in the *Letter of Authorization to Conduct Research in a Provincial Park or Conservation Reserve*, which was initially issued to us in July of 2021. (Subsequent updates to the authorization letter were requested as fieldwork progressed and the project evolved.) The authorization has a 3-year term and may be renewed for the fourth year of the project. The conditions stipulated in the letter include project-specific requirements, such as "Transplants must be species native to Algonquin Park", and general conditions, such as "Leave no garbage or other materials on site", as well as requirements regarding the submission of all data collected to Ontario Parks. All fieldwork within the Park complied with the conditions listed in this authorization letter. Transplant species and sites were identified with the aid of Park staff, who approved the removal of the beaked hazel and goldenrod from the Minnesing site before transplanting commenced.

Due to the ongoing global outbreak of coronavirus disease 2019 (COVID-19), pandemic restrictions prevented the fieldwork from commencing earlier and required additional fieldwork safety protocols to be approved. These measures helped prevent the spread of the virus within the Park, where there are no nearby medical or quarantine facilities. Once pandemic restrictions began to lift and all necessary safety protocols were agreed, the fieldwork could commence. As a consequence of these public and institutional safety measures, only 2 weeks of fieldwork were possible in 2021 before the winter weather began to set in. All transplanting was conducted in spring of 2022, leaving little time for observations of transplant success throughout the summer, and some aspects of the original design for this project could not be done (e.g., collecting site data in Year 1 of the project).

The following sections provide detailed descriptions of the fieldwork that was conducted during 2021-2022. Aside from the standard scientific requirement of recording one's methods, the purpose of presenting this information in such great detail is to provide guidance for anyone who may be conducting similar restoration work in the future. This should also be helpful background information for those who will be completing the final two years of this project and those who may be conducting surveys of this site in the future. The following discussions therefore pay particular attention to the exact steps that were taken, the time and resources required for each step, and any difficulties and setbacks encountered during this process.

[35]Thanks also to the many others who offered to assist; although scheduling conflicts prevented it from working out this time, it would have been a pleasure to have you join us!

2.4.1 Preliminary Tasks

As mentioned above, the field season for Year 1 (2021) of the project was pushed back to the autumn due to pandemic restrictions. These initial trips, while relatively brief, accomplished a lot of the preliminary tasks that needed to be done before the restoration treatments could be applied. Such tasks included taking some preliminary soil samples across the site (see Section 2.4.2) and, with the assistance of Park staff, locating suitable patches of beaked hazel and goldenrod nearby for use in our nucleation and windthrow guard treatments (Sections 2.3.3, 2.3.4).

The first of these fall trips was a 3-day visit in late September 2021, and its purpose was primarily to allow me to familiarize myself with the site and determine where the experiment grid would be placed. This was followed by 2 five-day trips in October, during which the entire experiment grid was set up. The site was also mapped out to determine where the skid trails and unique geographic features were located.

Initial Survey of Site

Having only communicated remotely with Ontario Parks up to this point, the September 2021 visit was the first time I visited the site. Up to this point, we had no firm notion of exactly where the site was located, how large it was, or what type of harvesting had been done (e.g., clear-cutting vs. thinning). We were also unaware that it was a historic site, with remnants of its past (e.g., fire hydrants), a historic walking path, and parking lots on either side.

I received a tour of the site from Park staff upon my arrival, then spent the next two days familiarizing myself with the area. As part of this process, I took many pictures of the research site (Fig. 2.24), which later acted as helpful references when planning the next stages of the experiment. GPS (in the form of Google Maps) was used to roughly measure out distances across the site to judge whether the planned 158 m $\times$ 158 m grid would fit between the access roads or whether it would have to be redesigned. One initial idea was that one or two of the blocks could be placed west of the cottagers' access road, as the plantation had also been thinned there. After determining that the area was (just barely) large enough for all four blocks, GPS was used to mark out the approximate locations of the grid's four corners, and pigtail markers were left in those locations to act as reference points.[36] The utility corridor between Highway 60 and the Superintendent's house (bottom left image in Fig 2.24) was used as the western boundary for the grid.

[36]When the grid was marked out, these initial markers were moved slightly to the final positions of the corners, but the preliminary layout was very close to the final location.



Figure 2.24: A first look at the research site in September, 2021.

Laying Out the Experiment Grid

The experiment grid was marked out in mid-October, 2021. Starting with the southwest corner of Block 3, a 30-metre measuring tape was used to measure out the 8 m × 8 m plots. The corners of each treatment plot were marked using 36" galvanized steel pigtail markers (Figure 2.25). Each marker was labelled with a piece of flagging tape, with pink tape around the outer edge of each replicate block and orange tape within. As described in Section 2.2.1, plots are labelled according to the convention: block/row/column. Each plot label is written in permanent marker on the flagging tape at its northwest corner. The southern row of markers lining the bottom of each replicate block is labelled 'Base', while the eastern column of markers is labelled 'E'.[37]

A compass and GPS were initially used to maintain a constant grid orientation. The utility corridor between the Superintendent's house and the highway was used as a reference for the western edge; the southwest corner of Block 3 was placed 5 m from the power lines so the utility corridor could act as the western buffer zone. The grid was tilted 5° west of north

[37]Before I had decided on a standard labelling system, some of the early markers in Block 3 were labelled 'Bottom' instead of 'Base' and used commas and Xs as delimiters instead of slashes. Most of these discrepant labels are no longer legible due to fading. The word 'Base' was written on the bottom row of markers instead of just the letter B because it could easily be mistaken for an eight. The four corners of the grid (inside the buffer zone) also have the labels 'NW Corner', 'SW Corner', 'NE Corner', and 'SE Corner'.

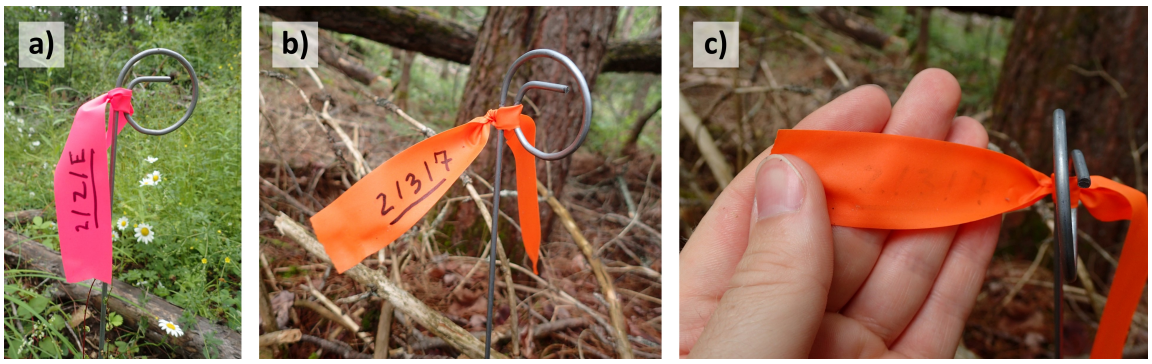


Figure 2.25: a) Pigtail marker 2/2/E was marked with pink flagging tape because it is on the edge of Block 2. b) Pigtail marker 2/3/7 with orange flagging tape because it is *within* Block 2. c) Marker 2/3/7 in July 2022, faded from 9 months of sun exposure.

so as to align with the power lines.[38] Blocks 3 and 4 were marked first, moving column-by-column eastward, followed by blocks 2 and 1, moving westward. The terrain is quite uneven and, in some areas, filled with dense vegetation, slash piles, and concrete pads; in fact, part of Block 3 is a steep artificial gorge through a hill created for the former rail line. Consequently, not all of the markers (∼3-5%) were placed in the exact desired positions, and the treatment plots are not all perfectly square; many are slightly rhombus-shaped due to misaligned columns and rows, especially those that were marked out later in Blocks 1 and 2. Plots 1/1/1 and 1/1/2, which were the last two to be marked, are overly wide by a couple of meters. The use of the compass and GPS had to be abandoned after Block 3, as there were too many minor deviations to keep it perfectly on track. Alignment was partly done by eye thereafter, and for each marker, the eight-metre distance was measured to the nearest markers in the same column and row to try and maintain a square shape. Overall, the dimensions of most plots are estimated to be accurate to within 0.5–1 meter. Figure 2.26a) shows a row of pigtail markers in Block 3 that was set up in fall 2021.

I initially extended and retracted the measuring tape for every measurement, but I eventually determined that it was much faster to simply leave it extended and drag it along behind me (the speed at which I could plant markers nearly doubled). The entire process of laying out the 324 pigtails took approximately 7.5 days, working roughly 8 hours per day. Initially, a piece of flagging tape was stretched between two pigtails near the historic path with a message requesting the tourists not remove the markers (an issue that cropped up within a few days). I replaced it in May 2022 with a tidier, more official-looking sign attached to a log (Fig. 2.26b). Due to time constraints, only the treatment plots were marked out in 2021, not the buffer zone surrounding the grid. The buffer on the eastern side of the grid was established in late April 2022 using unmarked pink flagging tape and pigtail markers placed 16 m apart. The rest of the buffer has yet to be marked, although it is not vital for the success of the experiment.

[38] The power lines do eventually change direction partway along, but they were initially very helpful for establishing Block 3.



Figure 2.26: a) Row of pigtails marking out the experiment grid (Block 3). b) Public sign informing tourists about the purpose of the markers.

Exposure to ultraviolet light causes permanent marker to fade over the course of several months, so upon returning to the site in April 2022, it was discovered that almost all of the labels were illegible, with the exception of those in highly shaded areas. Figure 2.25c) is an example of a faded pigtail marker, albeit one that was in a lightly-shaded area and could therefore still be read. Using fade-resistant permanent markers, the flagging tape labels were rewritten during the spring and summer of 2022. Due to time constraints, this was largely done opportunistically as we moved about the site, rather than systematically. Therefore, all of Block 4's labels have been redone, as have the top few rows of Block 2, but the remainder of the site has a combination of faded labels, rewritten labels, and original labels that didn't fade due to being in shade. It is recommended that the labels be redone on a yearly basis, as this speeds survey efforts and helps reduce errors in identifying plots. Alternatively, the flagging tape could be replaced with something that resists fading for the remaining years of the project.

Mapping Out the Site

During these autumn visits, the other major task that was accomplished was to map out the site in detail. This included wandering along the skid trails to determine their locations, as shown in Figure 2.19a). The skid trails are composed of extremely compacted sandy soils, often containing buried logs and covered in slash. Restoration of these roads will therefore be difficult, so it is important to identify and monitor them.

I also spent time wandering through all the treatment plots to identify their pre-existing conditions and features. I identified and recorded the locations of areas with unharvested trees, enormous impassible logs, garbage piles, utility lines, and historic remnants, such as fire hydrants and concrete blocks. The resulting sketches of each replicate block should help us understand the restoration progress in the treatment plots, which may be affected by these factors.

2.4.2 Baseline Data Collection

To observe the impacts of the experimental treatments and determine the progress of the restoration, the site will be monitored over the next few years. Due to pandemic restrictions, true baseline data for this experiment could not be collected prior to the plantation being thinned and the start of invasive species management. This means we do not have a record of the site's status prior to these treatments, so we cannot determine the full extent of their impacts. From an experimental standpoint, the state of the site after the application of these universal treatments will be taken as the baseline. (Although as mentioned in Section 2.2.4, one could examine other nearby plantations to study the effects of these treatments.)

As discussed in Section 2.2.2, the treatment plots will primarily be monitored for their vegetation coverage, soil quality, and light levels. Some soil samples were taken in October 2021, but the majority of this data was acquired in July 2022. This was shortly after the applied nucleation and windthrow guard treatments were applied, but they were omitted from the data collection.[39] In the following subsections, we will cover the methods used to collect the vegetation, soil, and light data. The survey results are presented in Section 2.5.

Vegetation Survey

The vegetation surveys involved a visual examination of each plot's plantlife and ground cover. Custom, pre-printed data sheets were used to record the vegetation information, as shown in Figure 2.27. On the left-hand side of the data sheet, under the date and location cells, a blank square was provided so a sketch of the plot's vegetation could be drawn. This provided a visual guide when determining the approximate coverage of each plant species. On the right-hand side, spaces were provided for noting the extent of common types of ground cover, such as pine needles, skid trails, and logs (i.e., slash piles). Values were recorded according to the Daubenmire cover categories mentioned in Section 2.2.2. These cells were only used to record bare ground; areas with vegetation cover were noted below, in the native and non-native cells. An additional spot was provided to record overstory details, specifically the number of trees, the type of trees (e.g., mature red pines, sugar maples, etc.), and estimated density (i.e., no overstory, <50%, or >50%).

Therefore, for each plot, the survey began with a quick sketch of all understory plants and ground cover. Cover could then be estimated according to the Daubenmire categories. Any species I could not identify were photographed for future identification using iNaturalist.[40] Mature trees were counted, and the overstory density was estimated. Depending on the amount of cover, it could take between 3 and 15 minutes to record a plot's vegetation data. This time would have been reduced if I were more familiar with native and non-native understory species, as the plot sketches and photos would have been unnecessary.

[39] The reasoning for this is given in Section 2.2.2. In any case, I also surveyed the nucleation and windthrow guard transplants to determine their health and survival rates, so we do have data on them.

[40] I first photographed the plot label on my data sheet so I could identify which photos were associated with each plot based on the order in which they were taken.

Date:	Plot:	Ground Cover (cover class)	Logs:	Needles:
			Grass:	Moss:
			Leaves:	Dirt:
			Rock:	Skid Trail:
			Other:	
		Overstory:		
		Native:		
		Non-native:		

Figure 2.27: Example of data sheet used for vegetation survey.

The vegetation surveys were done on two occasions. One survey was started October 21, 2021, but there was only time to do row 1 of Block 1. A more detailed survey was conducted on sporadic days during July 15-21, 2022, although only Blocks 2 and 4 were surveyed due to time constraints. The July survey was conducted after the transplanting trips, so the transplants were ignored during these surveys.[41]

Soil Sampling

This survey consisted of taking soil samples, packaging them, and analysing them at a later date. Soil cores were obtained using a trowel to dig 10 cm down into the soil and extract a roughly cylindrical soil sample. Figure 2.28 shows this process. The trowel used for this purpose conveniently had a 10 cm ruler etched into its blade. Four to five samples were taken from each plot depending on the trip, and the locations of each sample within the plot were selected by randomly wandering the area. Each sample was placed in a small paper bag, which was taped shut. Paper bags were used instead of plastic because they allow moisture to pass through, reducing mold growth. A permanent marker was used to label each bag with the sample ID, consisting of the treatment plot ID and the sample number for that plot. A small slip of paper was also included within the bag, with the sample ID and date written in pencil. The entire process required roughly 8-10 minutes to collect all soil samples from a given plot. The samples were carried in cardboard boxes, which I swapped for empty boxes from the vehicle whenever they were full. Since the soil samples included the litter layer, which we'd like to study, the samples will have to be passed through a sieve prior to analysis to separate the soil from from the litter and rocks.

Soil surveys were conducted on two occasions: fall 2021 (October 20 and 22) and summer 2022 (July 22). In both cases, the samples were acquired on dry, sunny days to avoid extra moisture in the bags.[42] The original plan was to acquire four samples per plot, which would have given us 1024 samples per survey. We started this process in October 2021, but due to time constraints, only 46 plots were surveyed at that time. Figure 2.29a) shows the plots

[41] If desired, they can be included in future data analysis, as I also conducted surveys of transplant survival during the same trip.

[42] The exception was October 22, when a very light snow fell while the samples were being taken, but didn't significantly dampen the soil.



Figure 2.28: a) Preparing paper bag and selecting sample location. b) Extracting 10 cm soil core. c) Placing sample in bag and adding paper ID. d) Taping bags shut.

with samples taken October 20th and, after realizing there wasn't time to collect samples from every plot, the samples taken in W-shaped transects on October 22nd. This shape prevents spatial autocorrelation between samples during analysis [85]. The transect across Blocks 2 and 4 was completed, but there wasn't sufficient time to finish the transect across Blocks 1 and 3.

In summer of 2022, after the nucleation and windthrow guard species had been transplanted, another survey was conducted in a W-shaped transect that stretched across the entire site (Fig. 2.29b).[43] I avoided digging in the transplant rootballs where necessary.[44] On this occasion, as fewer plots were being sampled, five samples were taken per plot. There could have been sufficient time to collect samples from every plot on this occasion, but it was determined that taking too many samples would have resulted in prohibitively high costs for analysis. Soil samples were transported back to the University of Waterloo,

[43] As this survey involved sampling the buffers as well, the buffer 'plots' were given special labels. The horizontal buffer was labelled as row 9 of Blocks 1 and 2, and the vertical buffer was column 9 of Block 1.

[44] As the goal is to observe whether the transplants are affecting the soil quality at the site, we are not interested in the rootball soils, per se. That said, soil samples were taken from the transplant source sites at Minnesing to compare to the soil at the research site.

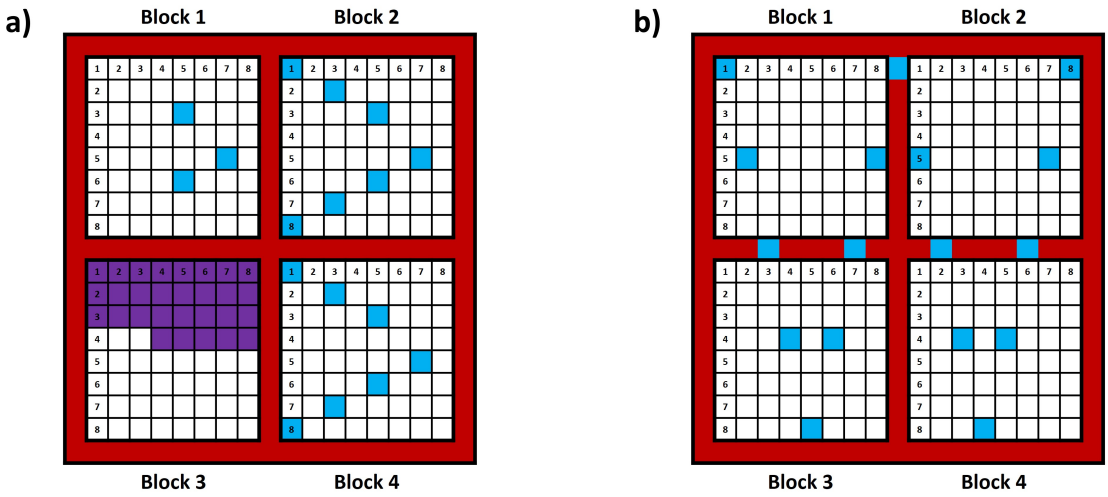


Figure 2.29: a) Plots where 4 soil samples were taken in fall 2021: purple plots in Block 3 were taken Oct. 20, remaining blue plots were taken Oct. 22. b) Locations of soil samples (5 per plot) taken July 22, 2022.

where they were placed in refrigerated storage until they could be sent for analysis in fall of 2022.

Light Intensity Survey

The light survey was conducted at the research site between 10:30 and 13:00 over the days July 14-17, 2022. Measurements were taken in full sunlight, when no clouds were covering the sun. The light was measured using a quantum metre with integrated sensor from Apogee Instruments (model MQ-100), which detects photons in the 400-700 nm range, the wavelengths required for photosynthesis [116]. The sensor is calibrated for full sunlight, and photon flux is measured in μmol/m^2/s. Figure 2.30a) shows the sensor used for these measurements.

Measurements were made with the metre held at chest height ($\sim$1.5 m above ground). These light measurements were recorded after the transplants were added to the plots. As one of the main purposes of the light measurements is to analyse whether sun exposure had any impact on the survival of the transplanted species, measurements were taken directly above the transplants.[45] Light measurements were made in the centre of control plots. For each reading, I positioned myself such that my own shadow would not cover the sensor.

The metre was held vertically, with the sensor pointed directly upwards (Fig. 2.30b), as recommended by the device manual [116]. At this geographic latitude, the noon sun is

[45]In some cases, this means the measurements were not taken in the centre of the plots, as not all transplants could be centred. Therefore, these specific measurements may be more appropriate for an analysis of transplant survival rates rather than general understory regrowth.

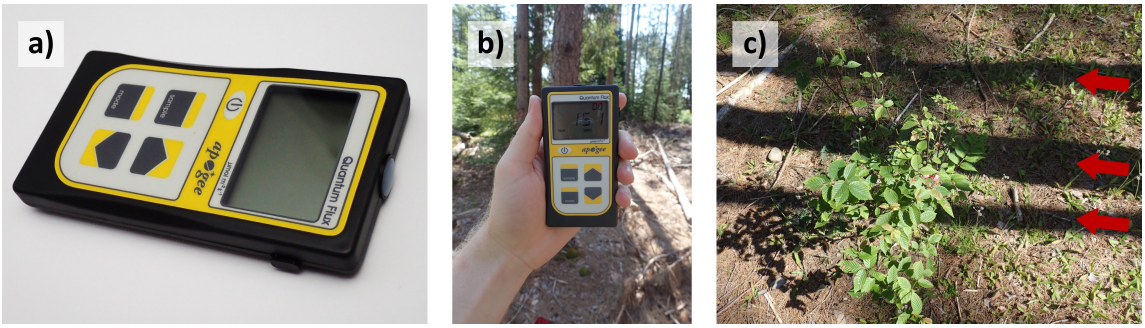


Figure 2.30: a) Apogee Instruments quantum meter, model MQ-100. b) Taking light measurements at the research site. c) Tree shadows that pass over transplanted shrub as sun moves. Red arrows indicate shadows.

roughly 60-70° from the horizontal in July, so measurements with the metre held vertically do not reflect the true value of the sun's intensity. The measurements were conducted in this manner, however, to maintain consistency and to save time, as an attempt to point the sensor directly at the sun for each measurement would be time-consuming and difficult, especially for plots with dense canopy cover. This does mean, however, that measurements were also affected by the precise orientation of the hand-held sensor; even a tiny shift from the vertical alters the readings. We must therefore consider these measurements to be approximations, though they will still give us a good idea of the light levels in each plot. (The measured values would likely not be off by more than a few percent for a minor deviation in sensor orientation.)

The measured light intensity in each plot is most useful when compared to full sunlight, as this gives us a clearer indication of canopy cover. Therefore, background measurements were also taken of full sunlight in the parking lot and in large clearings within the plantation, so our standard unit of light intensity will be '% of full sunlight'. Since the sun moves over time, light measurements were conducted in stints of 16 plots (i.e., 2 rows of a block), with background measurements taken before and after each 16-plot group. Each 16-plot stint took an average of 15 minutes to measure, with the sun intensity changing by an average of 64.57 μmol/m^2/s between background measurements.

Despite efforts to ensure accurate sensor readings, there is one important limiting factor: the small size of the sensor (1 cm diameter) means that the measurements are not spatially averaged over the entire plot. Rather, they are taken at a single location at a single point in time. This means, for example, that a reading taken in the shadow of a tree would be very different than the measurement taken an hour later, when the shadow has moved. Figure 2.30c) shows a transplanted shrub in full sunlight. There are three nearby tree shadows, however, which move across the shrub over the course of the day. Therefore, some measurements may not accurately reflect the overall light levels in the plot, as they may have been taken within a single narrow shadow or patch of full sun that later

moved.[46] Nevertheless, these measurements do represent the sun exposure of the transplants and/or plot centres near midday. Moreover, the areas of full sun and extreme shade may be considered accurate, as neither can occur in the presence of intermediate canopy cover. Intermediate light intensities that were recorded in the presence of a shadow may still be reasonably representative of overall plot exposure, however, as such plots do clearly experience some degree of shade. Therefore, despite this issue and the others mentioned above, the light readings here may still yield useful analytical results.

2.4.3 Planting Nucleation Species

After universal application of the thinning and herbicide treatments in 2021, the first treatment applied in 2022 was the nucleation plantings. As discussed in Section 2.3.3, the species selected for the applied nucleation treatment was beaked hazel (*Corylus cornuta*), because a large colony of these shrubs was found at a nearby site and the species' biological and ecological properties make it ideal for this purpose.

Selecting Hazel Transplants

As different size classes of hazel could be considered separate treatments, the transplanted individuals were carefully selected such that they all shared certain physical characteristics. Each selected individual had a height of 1-1.5 m and a diameter of roughly 0.5 m. These heights should correspond to ages of roughly 3.5-8 years for stems originating from vegetative spread [42]. We can also count the rings of a severed stem [103]; this reveals a 1-centimetre-wide stem (approximately the smallest diameter we transplanted) is 5 years old. These stems are old enough that they should have begun developing their own root systems, which is especially important for those produced via vegetative reproduction to ensure they can survive independently of their mother stems once the underground stems are severed [42].[47] Within our desired size class, we chose individuals that had 1-5 indi-

[46] It might therefore have made more sense to conduct these measurements under the diffuse light conditions of a uniformly cloudy day, rather than on cloudless days [44]. Unfortunately, uniform cloud cover is rare; most cloudy days experience highly non-uniform cloud cover, with clouds constantly moving in the wind. This would render the background measurements a rough guess at best, as the light would constantly be fluctuating unpredictably. Furthermore, sunlight is deflected by the water vapour of a cloud, so it hits the ground from all directions, rather than uni-directionally as it does from the sun. Although this is precisely what reduces the sharp distinction between shadows and shadowless areas on a cloudy day, it also means the sensor measurements would not accurately represent the directional impacts of canopy cover on a sunny day. Such trade-offs are inevitable, given the type of sensor used. Ultimately, as our goal was to measure the percentage of full sun reaching the transplants, it made more sense to conduct the light surveys on sunny days, despite the presence of shadows.

[47] The largest hazel shrubs in the Minnesing utility corridor are roughly 2.3 m tall, but these were logistically difficult to transplant. These large shrubs grow very densely, so it is difficult to isolate individual stems for transplanting. Their size would have also made digging them up and carrying them through the forest prohibitively difficult. The vehicle used to transport the shrubs was a small to mid-sized SUV, so individuals taller than about 1.5 m would not fit in the back.

vidual stems, each 1-2 cm in diameter. We typically attempted to select individuals with more than one stem, as we expect a greater chance of at least some stems surviving after transplanting if multiple are present. Due to the limited availability of the chosen size class, however, some transplants had only a single hazel stem, but these were in the minority. We also selected individuals with reasonably large quantities of leaf buds ($\gtrapprox$30) early in the spring to increase the likelihood of survival after transplanting, and later in the season, we picked individuals with many leaves. As the selected shrubs can be reasonably considered to all be within a single size category, we will proceed under the assumption that only one type of nucleation treatment was applied to the plantation. Figure 2.31 shows examples of beaked hazel in this size category.

The selected individuals were marked using pink or orange flagging tape. The flagging tape was tied to one of the stems in the middle of the shrub using a loose double knot to allow room for future stem growth. The flagging tape was left in place after transplanting to allow us to identify the transplanted shrubs during future vegetation surveys and so the contractors applying herbicide to the invasive species in spring 2022 would not accidentally kill the transplanted shrubs (see Section 2.3.2). Although the Minnesing utility corridor will likely be heavily disturbed when work begins on the new septic facility nearby [77], we attempted to avoid disturbing the undergrowth by following an existing trail along the corridor. The trail was most likely created by a combination of humans (based on the few pieces of litter found along it) and moose (based on the observed feces, browsing evidence, and the sighting of a moose in the adjacent woods during one transplanting trip).

Transplanting Process

After selecting desirable individuals, the shrubs were excavated manually with shovels, as shown in Figure 2.31a). The soil was light and sandy (an ideal soil type for beaked hazel [40]) and therefore easy to dig. As described in Section 2.3.3, the rootballs were very shallow and did not extend very far horizontally. The rootballs for our transplants had an average depth of roughly 10-15 cm and an average diameter of 25-30 cm.[48] As beaked hazel reproduces vegetatively, we had to cut the thick ($\sim$1 cm diameter) underground stems that connected the selected individuals to their mother and daughter plants. This is one of the reasons why we selected older individuals; their rootballs have developed enough that they should be able to survive independently, without relying on resources from their parent stems. The underground stems were severed with shovels during the first two transplanting trips, but as the shovels were not very sharp, pruning shears were used for this purpose instead during subsequent trips. We attempted to select individual shrubs that were at least 0.5 m away from their neighbours to ensure we could collect the entire root mass. Most transplants were accompanied by small quantities of other vegetation on the rootball surface, such as

[48]The rootball diameter was constrained by the diameter of the buckets we were using to transport the shrubs. While larger rootballs could be placed at an angle in the buckets, they were quite impractical; the buckets had to be carried by hand over rough terrain through the woods, and the buckets became too heavy and awkward if the rootballs were larger than about 35 cm wide.



Figure 2.31: a) Digging up a shrub for transplanting. b) Two transplants in early June, after leaves have emerged. c) A transplant in late April, before leaves emerged. d) A shrub placed in a hole at the research site before being buried. e) A transplanted shrub in late April. f) The same shrub 2 weeks later, after its leaves have emerged.

mosses, grasses, ferns, red raspberry (*Rubus idaeus*), clubmosses (*Dendrolycopodium*), and sugar maple seedlings (*Acer saccharum*).

The shrubs were individually transported in (nominally) 19 L plastic buckets (36.5 cm tall, 29.5 cm diameter), as shown in Figures 2.31b) and c). One to two shovelfuls of soil from below each shrub was added to its respective bucket, as the added microbes and fungi from their original home may enhance the survival rate of the shrubs [117]. Some research has also shown that the addition of soils and their associated biological communities from late-successional habitats can help accelerate and steer ecosystem succession along the desired trajectory [117]. The holes left after the shrubs were removed were very shallow (∼10 cm), so they were not filled in.[49] To transport the shrubs to the research site, they were laid horizontally inside the back of a vehicle (a compact or intermediate-sized SUV, depending on the trip), with garbage bags underneath to protect the vehicle and collect debris (e.g., leaves, twigs, sand). Initially, we had five buckets and limited space, so only

[49]We contemplated taking the time to fill in the holes after all the shrubs had been transplanted, but that took several field trips to complete, by which time the leaves had emerged on all species in the utility corridor and various herbaceous species had emerged from the ground. This dense understory reduced visibility and made it impossible to find most of the transplant holes.

five shrubs were transported at a time. We subsequently purchased five additional buckets, so ten shrubs were excavated simultaneously. We were able to fit six buckets in the back of the vehicle (in addition to one person in the back seat), and after transporting those six, two people began planting them while one person returned with the vehicle to retrieve the remaining four buckets.

After driving the shrubs to the research site, they were carried by hand through the plantation to the appropriate treatment plots. See Figure 2.17 for the placement of the 'nucleation only' and 'nucleation & windthrow guard' treatments. The shrubs were planted in the approximate centre of their respective plots (judged by eye), except in those plots where some feature such as a tree or concrete pad obstructed the centre. In such situations, we placed the shrub as close as possible to the centre. Hopefully, despite the off-centre placement of these shrubs, there will still be enough of a buffer between treatments to avoid confounding effects (see Section 2.2.1). As canopy cover and soil quality vary throughout the site, the locale of each transplant is quite different (i.e., some are heavily shaded, some are on skid trails, etc.), the effects of which will be studied as we monitor the site. We manually dug holes with the dimensions of the rootballs (Fig. 2.31d), and the additional soil in the transplant bucket was added to the hole to provide a non-compacted growth medium and soil microbes/fungi from their original home. To reduce the mortality rate from transplant shock [21], we watered the shrubs with ∼5.5-6 L of water taken directly from Cache Lake. Approximately half of the water was placed in the hole before the shrub so the roots could be wet directly when the rootball was lowered into the ground. In most plots, as the soil has been compacted and the bedrock layer is fairly close to the surface, the water did not immediately drain out of the hole, providing sufficient time to place the rootball in the water. After inserting the shrub and covering the rootball with soil, the remaining water was added to wet the upper roots and to shift the dirt so it filled any air pockets.[50] By building a small wall of soil around the stem, we could keep the water in place while it filtered into the ground, rather than it merely draining away over the surface. When filling in the hole with soil, most of the species attached to the rootball were covered over, especially the mosses and grasses. The soil over the rootball was lightly compacted using our feet to prevent it from washing away when it rains and to help fill any air pockets. Figure 2.31e) shows a transplanted shrub.

Transplanting Dates and Weather

Although it is generally considered to be better to transplant in autumn when the shrubs are dormant [118], transplanting did not commence until spring 2022 due to the pandemic delays and restrictions encountered in 2021 (see introduction to Section 2.4). The 'nucleation only' treatments for Block 4 were transplanted April 28-29, 2022. At that time, in

[50]Initially, all of the water was poured over the rootball after planting the shrub, but one of the fieldwork assistants, an experienced transplanter, suggested putting some of the water into the hole first to wet the roots directly. The original watering process was used for all 'nucleation only' transplants in Block 4, as well as 5 'nucleation only' transplants in Block 2.

areas that were heavily shaded at the research site, the soil was still frozen about 10 cm down, and it had snowed just the day before. The daily high was about 8-13°C, and the shrub leaves had not yet emerged. Blocks 2 and 3, as well as half of Block 1, were transplanted May 11-13, by which time the leaves were beginning to emerge and the daytime temperature was 25-30°C most days. The third trip took place from May 31 to June 2, during which all shrubs for the AN&WG treatments were transplanted and the remainder of the AN treatments in Block 1 were transplanted.[51] The daytime temperatures for this final trip were usually between 20 and 29 °C. All leaves had fully emerged and grown to their final size by this time. (Beaked hazel leaves usually require 3-4 weeks to reach full size [42], which aligns with our observations.) Figures 2.31b) and c) compare shrubs being transplanted in April and June, while Figures 2.31e) and f) show a specific transplant before its leaves emerged (April) and after (May). A cursory examination during this third trip indicated that all previously-transplanted shrubs had survived, and the majority appeared healthy. Perhaps a quarter had small, stunted leaves and some dead leaves, mainly among those that had been transplanted during the second trip.

Rate of Transplanting

Thanks to the sandy soils and shallow roots, only about 1 minute was required to dig up an isolated shrub, but if large underground stems needed to be cut, an additional 1-2 minutes were often required. Replanting each shrub at the research site only required 1-2 minutes, depending mainly on the amount of debris present and the degree of soil compaction. Carrying the shrubs (which was awkward given their shape and weight) and the water buckets uphill, through the underbrush, and over fallen logs and debris was the most time-consuming part of the process. Moving the shrubs from the utility corridor to the vehicle required 0.5-2 minutes. At the research site, however, carrying a single shrub, as well as its water bucket, to the pre-determined treatment plot could take up to 5 minutes for the more remote and difficult-to-access plots. Locating the appropriate treatment plots also took a few minutes, as the numbers on the markers had faded over the winter (see Section 2.4.1). When 3 people were working, one person was usually (voluntarily) assigned to fetch water buckets and shrubs while the other two located the relevant treatment plots and started planting. Once all the water and shrubs had been carried into the site, the third person then assisted with planting. This seemed to be the fastest and simplest option.

Once we were familiar with the transplanting process it took an average of 1 hour for one person to identify, dig up, transport, plant, and water 2 shrubs on their own in 10°C weather. The same process required only 1.5 hours for two people to transplant 5 shrubs and 1 hour for three people to transplant 5 shrubs in 29°C weather. Note that this is a general comparison, as many factors impacted the day-to-day speed of transplanting.

[51] A single AN&WG shrub, in plot 1/4/3 was accidentally forgotten and was not transplanted until June 12. This was due to a counting error. During the previous trip, several shrubs had to be replaced, as they were the wrong species, and we neglected to account for one of these replacements, counting it as a regular transplant instead.

For example, Block 4 was the most easily accessible due to the presence of the historic walkway and lack of underbrush, as well as its proximity to both the lake and parking lot. Block 1, however, is accessed by parking along the access road to the Superintendent's house, walking up a skid trail, then hiking along the overgrown utility corridor for the Superintendent's power lines, before finally entering the southwest corner of Block 1. Most of Block 1 is densely forested and contains impassable fallen trees and slash piles. As carrying the water buckets and shrubs was the most time-consuming task at the research site, they had the greatest impact on our speed. When selecting the shrubs from the Minnesing utility corridor, identifying the correct species and finding shrubs in the desired size category took a considerable amount of time. As we removed the most easily-accessible individuals first, we also had to move farther along the utility corridor over time in order to find desirable shrubs, so it became increasingly time-consuming to carry them back to the vehicle.

Species Misidentification

On the morning of May 13, after having transplanted about 3/4 of the 'nucleation only' plots, we noticed that the site from which we were sourcing the shrubs actually contains two different species. Earlier in the season, before their leaves emerged, the bare stems of the two species looked very similar, as they both have smooth, grey bark. During the week of this particular trip, however, the hot weather (up to 30°C) caused the leaves to emerge, making it clear that we were actually dealing with two separate species. The beaked hazel had been identified using iNaturalist and descriptions/images from Ref. [42] and Ref. [102]. The leaf buds, male catkins, and female flowers of the larger individuals were the primary identifying features in the fall and early spring. The stems surrounding the identified individuals all had a similar appearance, so it was tacitly assumed that all the stems in the utility corridor were the same species. Once we moved farther along the corridor and the leaves emerged, however, the second species was easily identified as sugar maple (*Acer saccharum*). Figure 2.32a) shows a cluster of sugar maple stems in mid-May; aside from the leaves, note the similarity in appearance to the beaked hazel (Figures 2.20, 2.31). Figures 2.32b) and c) show the maple leaves in mid-May and late May respectively, which are clearly different from the beaked hazel leaves (Fig. 2.32d). There are many mature maple trees in the surrounding forest, which no doubt shower the utility corridor with their seeds annually. Consequently, about half of the stems in the corridor were actually maple saplings, all roughly the same size, density, and appearance (without leaves) as the beaked hazel in our transplant size category. This revelation should be unsurprising, as maples and beaked hazel share an affinity for the same sandy, loamy soils [42].[52] The two species are shown growing together in the utility corridor in Figure 2.32d).

After making this discovery, the research site was surveyed, and we discovered that 10

[52]The absence of beaked hazel in the surrounding forest is likely due to dense canopy cover and root competition [42].

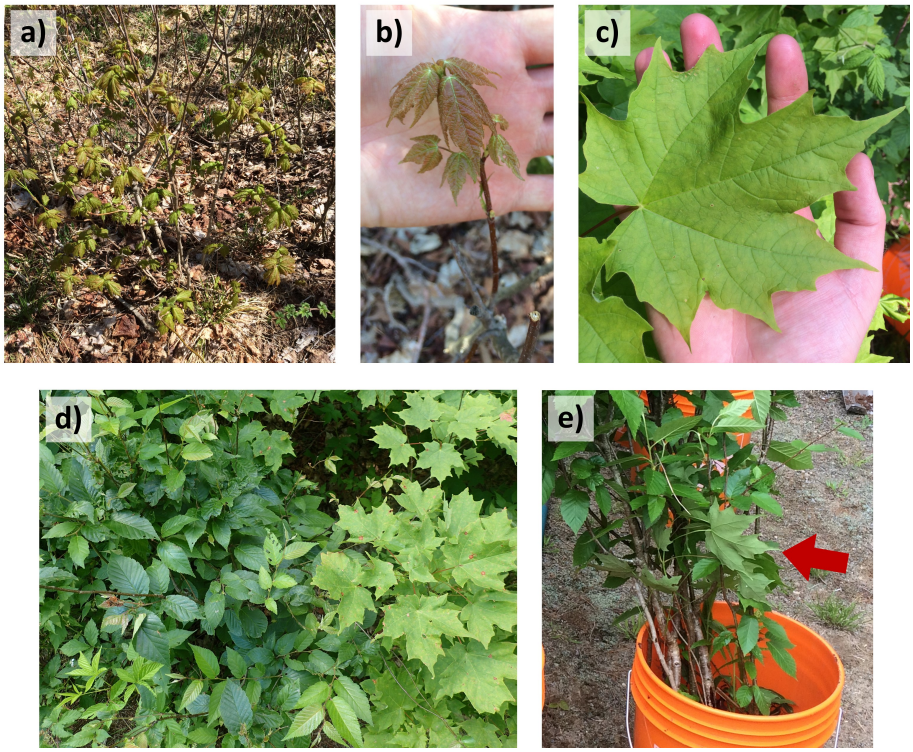


Figure 2.32: a) Sugar maple stems starting to leaf out. b) Sugar maple leaves starting to emerge in mid-May. c) Sugar maple leaf in late May. d) Hazel and sugar maple growing side-by-side in the utility corridor. e) Beaked hazel transplant with young maple stem included. Red arrow shows a maple leaf.

of the 'nucleation only' transplants were actually maple saplings.[53] These were replaced with beaked hazel that afternoon, and the undesired saplings were replanted in the utility corridor.[54] The new shrubs were given the full 5.5-6 L of water when planted, even though those plots had been watered earlier that day and the day before during the first planting.

[53]These were primarily in Blocks 2 and 3, as we had moved into an area of the utility corridor that was densely populated with the saplings while planting those blocks. The affected treatment plots were: 2/8/2, 2/7/5, 2/6/6, 2/2/4, 2/2/3, 2/1/1, 2/2/1, 3/8/7, 3/8/2, and 3/7/7. Plot 2/5/3 had one stem of beaked hazel and one of maple, so it was left in place. Plot 3/1/8 was incorrectly identified as maple. It was uprooted and the plot replanted with beaked hazel, but it was subsequently noticed that the original shrub actually just had several small maple stems included in the root ball; their leaves had emerged, while those of the central beaked hazel stems had not. This particular shrub was later replanted in plot 2/7/5, which may require special monitoring for mortality due to the added stress of being uprooted and planted twice. All of the transplants in Block 1 were beaked hazel, as it was planted using individuals from the mouth of the utility corridor, where there is a dense hazel patch and the original species identification was made.

[54]Planting the beaked hazel in these 10 spots was made easy by the fact that the holes had already been dug, so the process was very fast, even though they had to be carried to very different locations across the site. The saplings that were moved back to the utility corridor were planted in the holes left from previous transplants, and they were not watered, as there was no nearby water source.

The remaining beaked hazel were transplanted in late May and early June, so we were able to positively identify them by their leaves and avoid repeating the same mistake. In some cases, as in Figure 2.32e), young maple saplings were still included with the hazel transplants; a July survey of all 128 shrubs showed that maple stems were included with 10 transplants.

2.4.4 Planting Windthrow Guards

After all the shrubs had been transplanted, the windthrow guard species was planted during June 12-14, 2022. As discussed in Section 2.3.4, the species selected for the windthrow guard treatment was Canada goldenrod (*Solidago canadensis*). The decision to use this species was based on the logistical benefits (a large patch was found at a nearby site) and on the species' biological and ecological properties, which suggest it may act as an ideal windthrow guard.

Goldenrod Source Site

Most of the goldenrod (∼85-90%) was sourced from the parking lot at the Minnesing bike/ski trails, as shown in Figure 2.23a). A large patch of raspberry (*Rubus idaeus*) and Canada goldenrod fills the south side of the parking lot. Based on the compacted gravel and sand making up the soil, this area was likely part of the parking lot in the past or had human-built structures upon it. Other species present in this area included Virginia strawberry (*Fragaria virginiana*), common yarrow (*Achillea millefolium*), and various grasses and mosses. Some goldenrod transplants were accompanied by these species, especially grass and moss, but these accompanying species were mostly buried in soil once the goldenrod was replanted. Common St. John's wort (*Hypericum perforatum*) and tufted vetch *Vicia cracca*, both non-native species, were also present throughout the raspberry patch. While the former was large enough that it was easily identified and excluded from the excavated soil, the latter was removed from the transplants before they were replanted, although some likely remained. As it is already present at the research site and in the surrounding areas, any vetch introduced with the goldenrod is unlikely to have a significant effect on the project. The remainder of the goldenrod was sourced from a smaller patch near the utility corridor where the nucleation species was found[55] and comprises ∼75% of Block 4's windthrow guards. This area also contained substantial quantities of raspberry, grasses, and mosses. Overall, the entire parking lot area, as well as the research site itself, contains substantial quantities of Canada goldenrod.

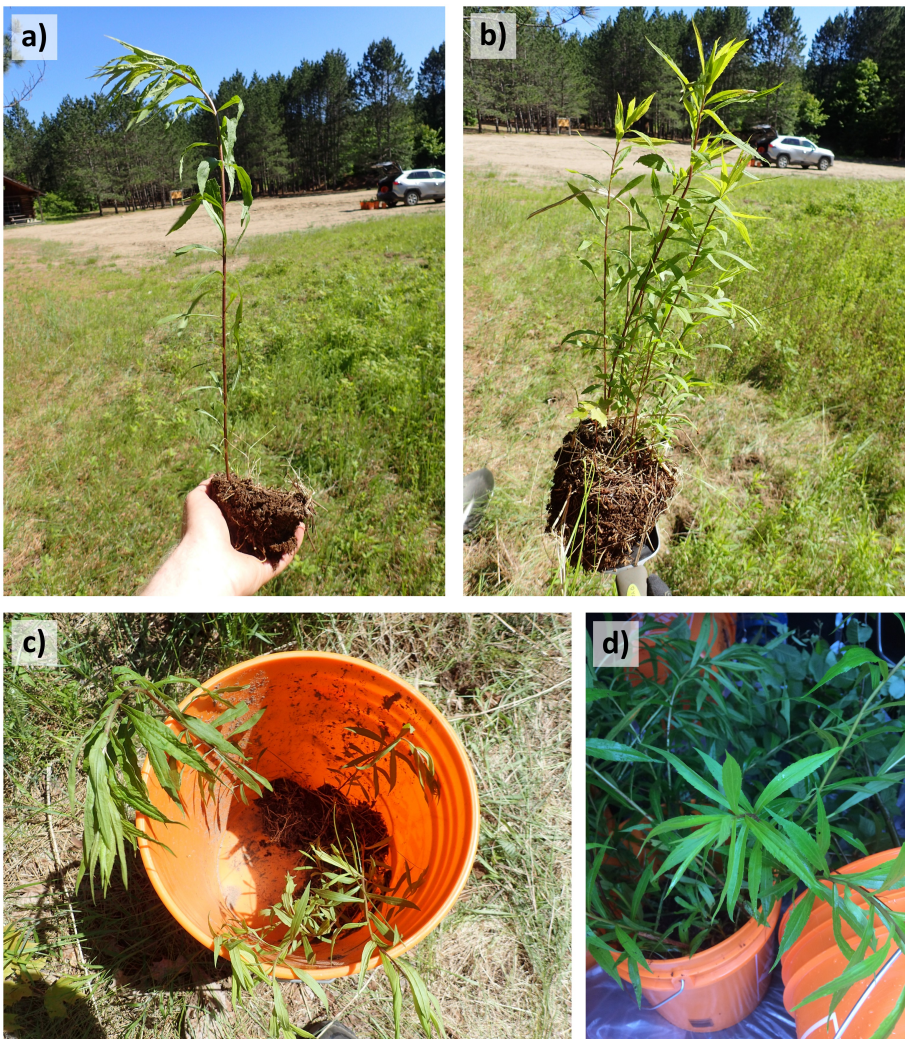


Figure 2.33: a) Single goldenrod ramet and rootball. b) Cluster of ramets that could not be separated. c) and d) Filling buckets with goldenrod.

Selecting Goldenrod Transplants

Based on our observations, goldenrod stems in the Park begin to emerge from the ground in early May. By mid-June, the goldenrod was still developing, with most stems being less than ∼35 cm tall. As the goldenrod had yet to flower, the species was identified by the structure of its leaves and stem using iNaturalist. We attempted to select goldenrod stems that were roughly 15-35 cm tall, as it was hoped that these would have sufficiently large root mass that they could survive the transplanting. For each transplanted individual, the clump of soil containing the rootball had a diameter of approximately 5-15 cm and a

[55]We actually started with this patch, but quickly ran out of viable stems, i.e., those that fell into our desired height class. We subsequently switched to the parking lot patch.

depth of 3-10 cm. As the experimental design called for 768 transplants, we attempted to isolate individual ramets for transplanting, an example of which is shown in Figure 2.33a). Goldenrod often grow in tight clusters, however, making it difficult to isolate individual stems with sufficient attached root mass. Consequently, it was occasionally necessary to collect a group of 2-5 ramets connected by their roots and consider this to be an 'individual' transplant. Such transplants tended to have larger rootballs, and it is therefore expected that they are more likely to survive than some of the single-ramet transplants. See Fig. 2.33b) for an example of a multi-ramet transplant and its large rootball.

Transplanting Process

A review of the literature revealed few documented attempts to transplant individual ramets of wild goldenrod (as opposed to seeding or transplanting nursery-grown seedlings or colonies of many stems), and those papers that do mention such activities are vague about the exact details of the transplanting process (see for example References [38, 115, 119]). Therefore, we attempted several different transplanting methods to determine the best technique. Although this may yield variable survival outcomes, it is preferable to inadvertently using a single ineffective method throughout the site (e.g., one that results in 100% fatality rate). We hope our results prove instructive to anyone attempting the same task in the future.[56]

The main challenge associated with the transplanting process was the goldenrod rhizome structure. The rhizomes extend horizontally underground, then curve upwards to form a vertical aerial stem. Figure 2.34a) shows a stem that has been excavated by hand so that the ground-level curvature is exposed, while Fig.2.34b) shows a stem that has been pulled out of the soil, with the underground rhizome clearly bending 90°. The rhizome connects to other stems, of course, and fibrous roots extend outward from the rhizome beginning roughly 1-5 cm away from the point where the aerial stem meets the soil surface (Fig. 2.34c). Mid-June (when we started transplanting) is when the roots start to extend from the base of the aerial stem [112], and besides those, the only other roots are farther along the rhizome. This structure made it difficult to extract individual ramets without digging too far from the stem, thereby yielding an overly-large rootball, or digging too close to the stem, thus severing the rhizome and leaving the stem without roots. We therefore attempted several different techniques for digging up the stems.

The first technique we attempted was to dig around individual stems using transplanting trowels. This usually resulted in either the trowel cutting too close to the stem and severing the rhizome or an overly large clump of attached soil that reduced the number of stems we could fit into a bucket. As the compacted soil was difficult to dig up using a trowel

[56]That said, due to time constraints and the logistical difficulty of tracking hundreds of individual transplants, we did not record which method was used for each transplant, so we can't definitively state the ultimate survival rate for each method. The following evaluation of the methods used is therefore based primarily on whether they enabled us to successfully extract a large rootball with minimum difficulty and without severing the goldenrod stem.

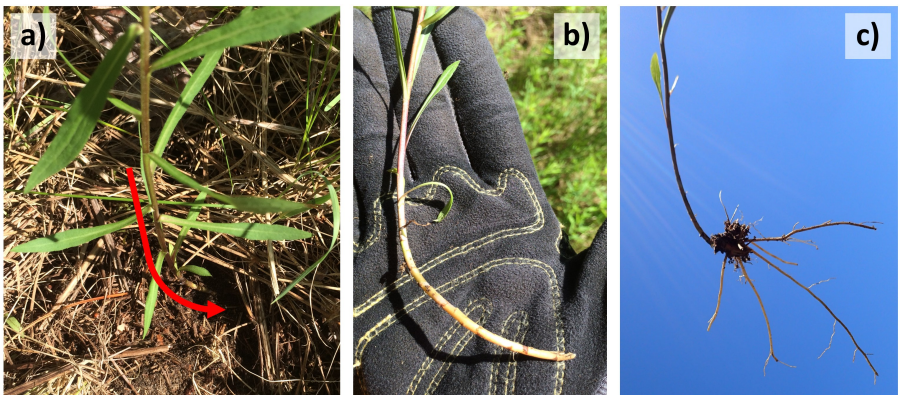


Figure 2.34: a) Goldenrod stem excavated by hand to show underground curvature, as highlighted by red arrow. b) Excavated stem showing 5 cm of rhizome, stripped of roots. c) Roots extending from rhizome.

alone, another method involved digging up large clusters of goldenrod with a shovel. The individual stems could then be more easily separated by hand or with a trowel. This was fairly efficient, although it was still somewhat difficult to achieve a reasonably-sized rootball without severing the underground stems. Ultimately, the technique that may have yielded the best results involved using one's fingers to gently dig down around the stem in order to determine the direction of curvature below the ground, as in Figure 2.34a). Once the position of the rhizome was known, one could cut an oval-shaped patch of soil, with the aerial stem at one end and the underground stem extending towards the other. Figures 2.33a) and b) show the results of this technique, with the the aerial stem(s) near one edge of the soil and the rhizome(s) extending along the length of the oval. The oval-shaped rootballs in this case were usually about 10-15 cm long and 5-8 cm wide, which seemed to be large enough to hold sufficient root mass, while also being small enough that they were easily moved and re-planted. If the aerial stem remained upright in its clump of soil once it was removed from the ground, it likely had a sufficient root mass to survive; if the stem fell over before or after being removed from the ground, the rhizome had likely been severed with no roots to hold it in place. We also attempted a technique whereby we used our fingers to dig down and dig out the roots of the goldenrod by hand without soil. This had the advantage of ensuring that sufficient root mass was retained, but because it risked the roots drying out before the goldenrod could be replanted, it was quickly abandoned.

The goldenrod was transported in 8 L (24.5 cm tall, 22.5 cm wide) and 19 L (36.5 cm tall, 29.5 cm diameter) plastic buckets.[57] Depending on rootball size, the smaller buckets could hold roughly 8-16 individual stems without them crushing each other (enough for 1.5-2.5 treatment plots), while the larger buckets could fit 12-24 stems (2-4 treatment plots). Figures 2.33c) and d) show some of the 8 L buckets partially and fully filled with goldenrod. The holes left after the goldenrod was removed were not filled in because they

[57]The buckets were nominally 8 and 19 L according to the manufacturer; as their dimensions indicate, their total volumes were actually about 20-30% larger.

were very shallow (∼5 cm deep) and will likely be filled with new herbaceous plants by next year anyway, assuming the area is not trampled by machinery during the work at Minnesing. To transport the goldenrod to the research site, the buckets were placed in the back of a vehicle (usually a compact or intermediate-sized SUV, depending on the trip), with garbage bags underneath to protect the vehicle and collect any sand. With 3 people in the vehicle and all but one of the back seats folded down, there was enough room to transport about 10 buckets of goldenrod simultaneously.[58]

Once the goldenrod had been transported to the research site, the buckets were carried to the plots that were to receive the WG and AN&WG treatments (see Fig. 2.17 for treatment plan). Due to time constraints and concerns over the quantity of goldenrod that could be removed from the source patch without exhausting it, the goldenrod was planted in a single ring around the shrubs, rather than the (potentially more effective) 2-ring windthrow guard design. Moreover, as most of the individual transplants had but a single stem, it was decided that six goldenrod would be planted for each windthrow guard. This number should be sufficient to form a reasonably dense ring of herbaceous material around each shrub after a couple of years, even in the event of some fatalities due to transplant shock. Figures 2.35a)-d) depict examples of the transplanted goldenrod surrounding nucleation shrubs. The goldenrod were arranged in an approximate hexagonal pattern centred on the shrub, as shown in Fig. 2.35d). In the case of the WG treatments, the hexagon was arranged around the centre of the plot, an example of which is shown in Figures 2.35e) and f). A stick was planted in the plot centre and used as the point of reference for these treatments.

Each stem was planted at a distance of about 70 cm from the shrub (or plot centre) as measured by the transplant trowels, which were half that length. This distance was selected to offer the goldenrod sufficient room to spread around the shrub without entering into competition with its dense, shallow roots in the near future. The beaked hazel rootballs had an average diameter of about 25-30 cm, so the buffer zone of 55 cm between the two species should provide ample space for the hazel roots to spread out in the coming years without impacting the goldenrod. Additionally, the total diameter of the windthrow guards is therefore 140 cm, which is well within the expected 4 m × 4 m treatment diameter. As discussed in Section 2.2.1, this leaves a 4 m buffer between individual treatments, which should reduce confounding effects. In some plots, debris such as log piles or rocks prevented an exact hexagon from being planted. For these plots, the goldenrod was planted wherever an available spot could be found, while still attempting to form a ring shape. For example, in Fig. 2.35a), the goldenrod was planted much closer than 70 cm from the shrub due to the presence of a tree (top right corner) and a concrete wall at the edge of the old railway platform (below and to the left of the photo frame). For plots where the shrub was planted next to a pile of logs, a fallen tree, or some other large obstruction, the six goldenrod were planted in a partial circle on the opposite side of the shrub, filling

[58] We only transported this many full buckets on a couple of occasions, as that number of buckets was nearly sufficient to complete the goldenrod transplants for an entire replicate block, which could take almost a full day's work.

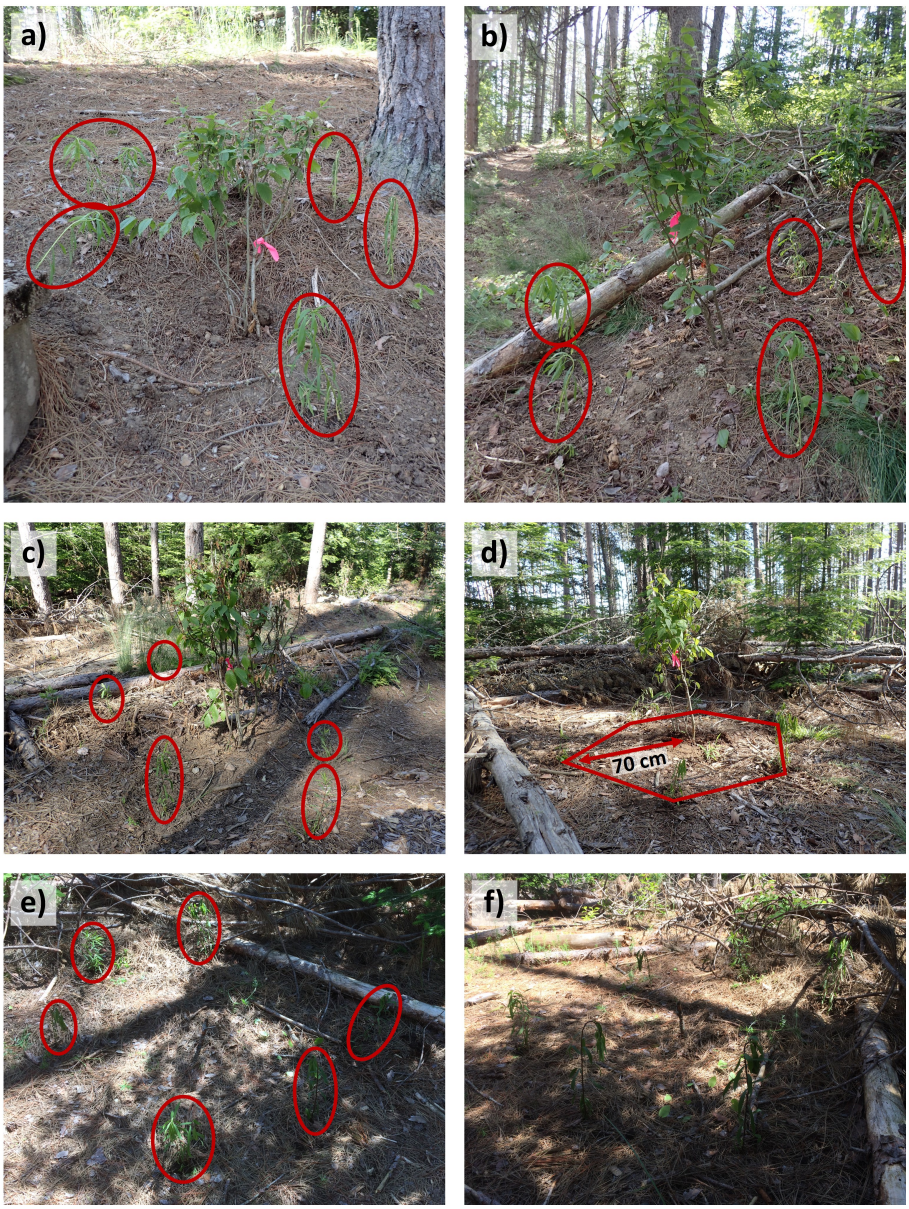


Figure 2.35: Examples of transplanted goldenrod. a)-c) Goldenrod forming windthrow guards around various transplanted nucleation shrubs. The red circles highlight the (visible) goldenrod in each photo. d) Highlighting the hexagonal planting pattern around a shrub. e) A 'windthrow guard only' treatment, with the goldenrod planted around the plot centre. Red circles highlight the goldenrod. f) Same 'windthrow guard only' plot viewed from a different angle.

the available space. Figure 2.35e) shows an example. This planting pattern should still offer reasonable windthrow protection, as the obstruction opposite the goldenrod should partially protect the other side of the shrub. It was decided to plant all six goldenrod in

these cases (rather than, for example, three goldenrod when planting a half-circle), as this maintains a consistent level of introduced plant matter for this treatment type, and some goldenrod may perish after transplanting anyway.



Figure 2.36: a) Transplanted goldenrod. b) Two transplants with wilted stems due to transplant shock.

After measuring out the seventy-centimetre distance from the centre of a plot, all six holes were dug using a transplanting trowel. As with the beaked hazel, water from Cache Lake was added to the holes before the goldenrod were placed in them to dampen the roots directly and thereby reduce potential losses from transplant shock [21]. The amount of water added varied slightly; more was added on hot days and for goldenrod that had been sitting in the transplant buckets for longer.[59] Therefore, each goldenrod received approximately 0.5-1 L of water; as a general rule we simply filled the newly-dug holes to the surface with water. A single one of the small buckets could water 1-2 treatment plots, and the larger buckets, if filled completely (which made them difficult to carry through the site), could water 3-4 plots. After the goldenrod were placed in the holes, their rootballs were covered with available soil, which mostly buried other species that had accompanied the rootballs (e.g., grasses). The soil was pressed down around the goldenrod stem to help hold it in place and eliminate air pockets. Excess soil was also used to hold the stems upright, particularly those that were falling over due to weaker root systems. Figure 2.36a) shows a goldenrod stem after it has been transplanted. Where possible, leaves, moss and needles were used to cover up the stem base to help the soil retain moisture, as shown in Figure 2.36b). In each plot, the planting was typically done in a systematic fashion to speed the process: all six holes were dug, water was added, the goldenrod were placed in the holes, and the rootballs were covered with soil. The goldenrod leaves and the top few centimetres of most stems began to wilt as soon as they were dug up and remained that

[59] As it took several hours to transplant all of the goldenrod, we added water to their buckets after they had been sitting out for a couple of hours. It would perhaps have been better to do so earlier to reduce potential fatalities, but it took a long time to carry water up from the lake, so we didn't want to use up too much of it. Moreover, in the moment, it unfortunately just didn't occur to us to add the water earlier.

way until long after they were replanted. Figure 2.36b) shows three wilted stems. A cursory walk-through of the site on the final day of this trip showed only a few percent of the stems planted 2 days earlier had straightened out again.

Transplanting Dates and Weather

Totaling 768 individual transplants across both the WG and AN&WG treatments, all windthrow guards were planted over the course of three days: June 12-14, 2022. Blocks 1, 3, and 4 were planted June 12-13, and Block 2 was planted June 14. This was just 1.5 weeks after the shrubs had been planted for the AN&WG treatment, and no shrubs were blown down by winds during that time. Given the brevity of this delay between the two species being planted, we can consider the AN&WG treatment to have been initiated all at once in our analyses. The daytime temperature during this period was about 18-22 °C for June 12-13 and 22-27 °C on June 14.

Rate of Transplanting

On average, each individual goldenrod ramet could be excavated in about 20-30 seconds, although this varied depending on the technique used (see above). The pace slowed when the rhizomes were severed without roots, which happened often and required us to switch to a new stem. Overall, including the time required to find individual stems and remove unwanted species from the rootballs (such as tufted vetch), it took about 5-10 minutes to fill each bucket. Fortunately, the vehicle could be parked right next to the goldenrod patches, so no time was lost when carrying the goldenrod to the vehicle. Replanting the goldenrod at the research site took about 3-8 minutes per plot, depending on the density of existing plant material, the presence of obstructive debris, and the soil type (e.g., soft sand versus compacted gravel or bedrock). As was the case with the shrubs, carrying the goldenrod and water to the treatment plots took several minutes and was especially exhausting for the remote plots of Block 1. Once we had familiarized ourselves with the transplanting process, 2 people could complete an average of 5 plots per hour in 25°C weather and 3 people could complete 4.86 plots per hour in 20°C weather. These average rates include the time needed to dig up the goldenrod, transport both the goldenrod and the water to the relevant plots, and replant the goldenrod. This is, of course, an inexact comparison, as numerous factors affect the rate of transplanting, particularly the remoteness of the treatment plots. So although the 3-person rate appears to be barely an improvement over the 2-person rate, it was measured while we were planting in Block 1, which is the replicate block that is farthest from the access roads and lake and is the most difficult to access. The 2-person rate was measured for Block 2, which is easily accessible from the public access road and parking lot.

Despite the fact that we had to move 768 goldenrod, as opposed to just 128 beaked hazel, and although it took longer to plant each plot (about 3-8 minutes for goldenrod versus

1-2 minutes for hazel), transplanting the windthrow guards took far less time overall than the nucleation species. A rough comparison indicates the windthrow guards were planted about 1.5 times faster per plot[60]. A number of factors likely influenced this increased pace. Cooler weather during the three days of windthrow guard planting reduced the physical stress. More importantly, however, the increased efficiency can likely be attributed to the speed with which the buckets were transported. The vehicle could be parked right next to the source locations for the goldenrod, eliminating all travel time during the excavation process. The goldenrod buckets were also lighter than the shrubs, making them easier to carry across the site, and each transplant bucket and water bucket could cover several plots rather than just one each. These combined factors allowed all windthrow guard treatments to be planted in just 3 days, compared to 7 days of shrub transplanting.

2.4.5 Transplant Mortality Census

The success of this experiment requires a sufficient number of transplants to survive their initial planting. 'Transplant shock' is the term for a collection of physiological responses to transplanting, wherein the transplanted individual may experience reduced vitality, slower growth, leaf loss, or death [118, 120]. Although its duration varies depending on the circumstances (a few weeks to a few years), transplant shock will slowly abate as the individual establishes itself and becomes acclimatised to its new conditions [118, 120]. It is usually ideal to transplant a plant during the winter dormancy period, as this reduces the degree of transplant shock [118]. If the plant is dormant, the transplanting process does not interrupt active biological processes (such as leaf growth), and the plant can slowly adapt to its new environment as it resumes its active state. Plants also tend to be more tolerant of water loss during the dormancy period, as transpiration and water uptake may be slowed or halted altogether [118]. To reduce transplant shock in this experiment, each transplant was watered after being planting at the research site, but it was not possible to finish the transplanting during the dormancy period. A mortality census will therefore allow us to determine which individuals survived the transplanting and will provide an assessment of their overall health [82, 121].

Restoration is a long-term process that takes several years to yield substantial results. As the plantation was thinned in 2021 and the hazel and goldenrod were transplanted in 2022 (the year this thesis was written), we expect few changes in the soil quality, vegetation cover, and light levels this year. We can, however, analyse the survival rates of the transplants. Mortality surveys were conducted July 13-14, 2022, one month after the goldenrod were transplanted and 2.5-1.5 months after the beaked hazel were transplanted. The methods used are described in the following subsections, and the census results are presented in Section 2.5.4.

The transplanted shrubs should be surveyed each year to determine their survival rates,

[60]For two people working in 25-29°C weather, five plots planted per hour for the windthrow guards versus just 3.33 plots per hour for the nucleation species.

as they may decline over time [121], and the transplants can only continue to have an impact as long as they remain alive. It may not be possible to survey the transplanted goldenrod stems in future years, however, as they are difficult to find and a new student, who wasn't present when they were planted, will be taking over the project. The original stems should also die back, and new stems will grow in future years as the herbs spread.

Beaked Hazel Census

The 128 beaked hazel were transplanted over a series of 3 trips from April 28 to June 2. At the time of planting, they were given about 5.5-6 L of water, with no further interventions thereafter. In Algonquin Park, beaked hazel leaves begin to emerge in mid-May and are fully extended by early June. Some of the hazel had wilted leaves after being transplanted but had largely regained their vigour within a few days.

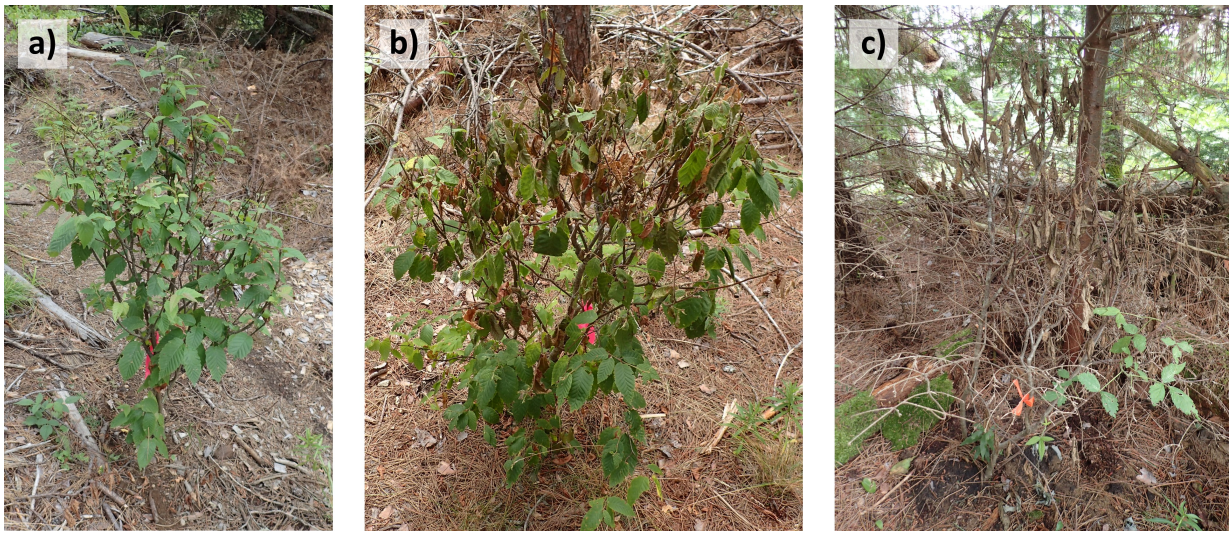


Figure 2.37: a) Hazel bush with nearly all of its leaves still present. b) Hazel with significant leaf death. c) Hazel that has lost all of its leaves.

In mid-July, the beaked hazel transplants were surveyed across the research site to verify they were still alive. During this survey, it was determined that all but one of the transplants had survived, although many had undersized, yellowed, and dead leaves. We will take the state of their leaves as a measure of overall health and the degree of transplant shock experienced. Figure 2.37 shows beaked hazel transplants observed during the census in three states of leaf health.

During the survey, the hazel bushes were visually examined and assigned an approximate 'leaf survival' value in the form of a percentage range. Note that the shrubs were specifically examined for number of visible live and dead leaves; branches without any leaves (alive or dead) were excluded from the visual inspection, as many of the shrubs already had some bare twigs when they were transplanted. Predation by insects was not included

in this assessment. For those transplanted in April, dead leaf buds were also excluded, as they were too difficult to detect during a cursory examination.

Goldenrod Census

The Canada goldenrod were transplanted in a single 3-day trip in mid-June. Each transplant was given 0.5-1 L of water, with no further interventions. All of the goldenrod had wilted stems after planting, with very few having returned to their regular posture by the end of the 3-day planting trip.

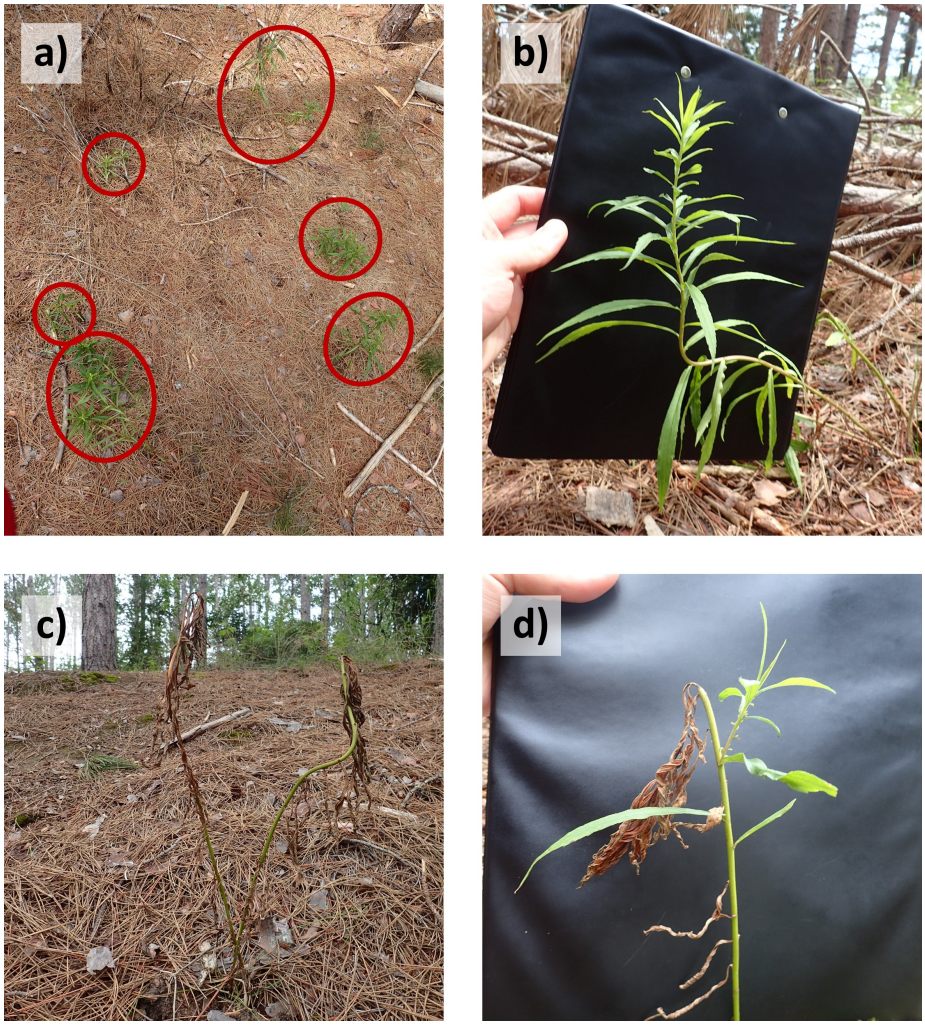


Figure 2.38: a) Ring of 6 surviving goldenrod one month after transplanting. Transplants highlighted by red circles. b) Healthy goldenrod growing in new direction after falling over post-transplanting. c) Dead goldenrod. d) Goldenrod with dead leaves and new growth.

Usually only about one week is necessary to determine whether herbaceous plants have died from transplant shock [121]. In our experiment, the goldenrod were surveyed one

month after being transplanted (in mid-July) to determine how many had survived. For each windthrow guard of 6 goldenrod, the number surviving transplants was counted. A transplant was considered 'alive' if at least one stem had survived and still retained leaves, as shown in Figures 2.38a) and b). It was counted as 'dead' if the stems had lost all of their leaves (Fig. 2.38c) or had only 1 remaining leaf, as the latter were not expected to survive the remainder of the summer and autumn.

While most of the transplants were still alive, an examination of their leaves indicated their health varied significantly [121]. Some had lost most of the leaves along their stems, while others retained their leaves but had lost their inflorescences (i.e., their flowering tips). Quite a few of the goldenrod had begun to branch out, producing new stems after losing their inflorescences, as shown in Fig. 2.38d). The surviving goldenrod were therefore assigned a 'survival category', depending on whether they had a dead inflorescence (usually a few leaves below the inflorescence were also dead), more than a quarter of the leaves on the rest of the stem were dead, or they appeared perfectly healthy. An additional category covered those that had lost both their inflorescence and most of their leaves but were developing new branches with living leaves. For transplants that included more than one stem, the healthiest stem was assessed (although often, all stems in a transplant were in the same state). The majority of the stems had regained their erect posture, but some were lying along the ground, likely because their root system was not sufficient to hold them upright at the time of transplanting (e.g., lower left corner of Fig. 2.38a). For most of those that were tilted or on the ground, the tips of their stems had turned upright and were growing vertically again (Fig. 2.38b).

Despite the losses, most of the stems survived. Although it is unlikely that many of these will go to seed this year due to the lingering impacts of the transplanting process, they should begin to spread vegetatively by 2023. Hopefully, this will result in healthy and effective windthrow guards.

2.5 Analysis of Results

As this is a four-year restoration project, most of the data analysis will come in later years, as we observe the changes that occur throughout the site. Nevertheless, we can perform a preliminary analysis on the data taken during the site surveys in Year 2 of the project (2022), which collected vegetation, soil, and light intensity data. Most importantly, we can also examine the results of the transplant survival census that was conducted 1-2 months after the transplanting trips. Our main focus in this section will be to analyse the light and mortality data, as the soil and vegetation data has not yet been compiled.

The following analyses should reveal the baseline status of the site, as well as the heath and survival rate of the transplanted species. As we don't have data taken over time for these surveys, the analyses here will primarily focus on spatial variations and the pre-existing conditions of the treatment plots.

2.5.1 Vegetation Survey

The vegetation data from this year has not yet been digitised, so unfortunately, it is not yet available for analysis. Some general statements, however, can be made about the type of vegetation observed across Blocks 2 and 4, which were surveyed this summer. Overall, Block 2 has far more vegetation than Block 4. Whereas the ground cover in Block 4 is predominantly needles, slash, and skid trails, with a few patches of balsam fir saplings and sparse understory vegetation, Block 2 has an abundance of understory species across most of its area, including on its skid trails. This difference is quite evident in Figure 2.18. The reasons for this are not immediately clear; for example, we shall see in Section 2.5.3 that these two blocks have nearly identical light levels, so differences in sun exposure are not the cause of these differences in vegetation.

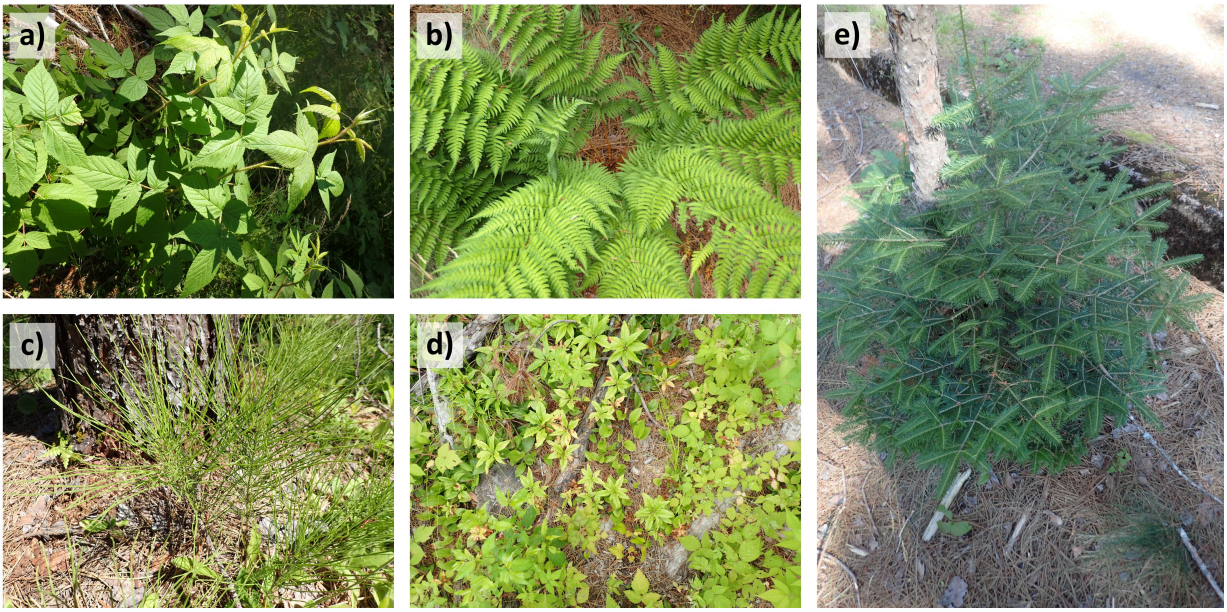


Figure 2.39: a) American red raspberry. b) Interrupted fern. c) Horsetails. d) Northern starflowers and Canada mayflowers. e) Balsam fir sapling.

Figure 2.39 shows native species found across the site. By far the most common understory species across these two blocks is American red raspberry (*Rubus strigosus*), which is present in 86% of the plots in Block 2 and 53% of plots in Block 4. Dense patches take up vast swathes of some plots. Common snowberry (*Symphoricarpos albus*), which is native but may have been planted ornamentally in the hotel gardens, is the second-most-common shrub. Four species of fern were observed: intermediate wood fern (*Dryopteris intermedia*), sensitive fern (*Onoclea sensibilis*), interrupted fern (*Osmunda claytoniana*), and horsetails (*Equisetum*). Common perennials found at the site include Canada mayflower (*Maianthemum canadense*), northern starflower (*Lysimachia borealis*), pink lady's slippers (*Cypripedium acaule*), bunchberry (*Cornus canadensis*), fringed willowherb (*Epilobium ciliatum*), and Virginia strawberry (*Fragaria virginiana*). Canada goldenrod is also present in Block

2. In terms of trees, there are many choke cherry (*Prunus virginiana*), black cherry (*Prunus serotina*), balsam fir (*Abies balsamea*), red maple (*Acer rubrum*), and sugar maple (*Acer saccharum*) saplings. The balsam fir saplings are very widespread across the site, which may cause some issues for the beaked hazel transplants, as they tend to shade out the hazel and compete for root space [42]. Beaked hazel has roughly the same habitat requirements as sugar maple and red pine, however, so it should do fairly well overall at the plantation given the prevalence of these two tree species [42].

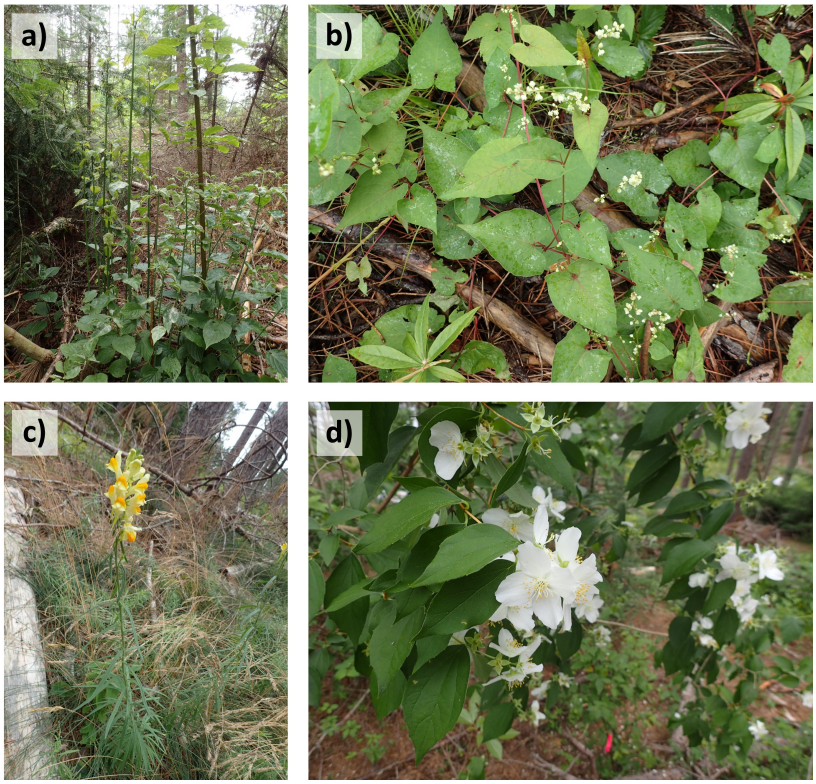


Figure 2.40: a) Himalayan honeysuckle. b) Fringed bindweed. c) Butter-and-eggs. d) Mock orange.

Non-native species are also very common throughout the site, as shown in Fig. 2.40. Non-native herbs observed across Blocks 2 and 4 include: orange hawkweed (*Pilosella aurantiaca*), yellow sweetclover (*Melilotus officinalis*), mallows (*Malva*), bird's-foot trefoil (*Lotus corniculatus*), butter-and-eggs (*Linaria vulgaris*), common columbine (*Aquilegia vulgaris*), heath speedwell (*Veronica officinalis*), tufted vetch (*Vicia cracca*), oxeye daisy (*Leucanthemum vulgare*), common hemp-nettle (*Galeopsis tetrahit*), alsike clover (*Trifolium hybridum*), and common mullein (*Verbascum thapsus*). As discussed in Section 2.3.2, Park staff are most interested in eliminating knotweed and non-native honeysuckle from the site. The knotweed-related species fringed bindweed (*Fallopia cilinodis*) was discovered at the site, especially on the northern end of Block 2, and Himalayan honeysuckle (*Leycesteria formosa*) was found near the centre of Block 2. One of the most interesting

finds was mock oranges (*Philadelphus*) near the historic walking trail in Block 4, where they were likely planted ornamentally during the hotel era.

As the project progresses, it is our goal to encourage the spread of native species while curbing the spread of non-native species. In future vegetation surveys, we therefore hope to see a decrease in the proportion of invasive species relative to native plants, and, ideally, some of these non-native species will disappear altogether.

2.5.2 Soil Sampling

The soil samples taken this year will be analysed in the lab this fall, so this data is not yet available. Qualitatively, it can be said that the soil was quite sandy across most of the site, with some organic content. Some areas have a dense, mossy duff layer, but the remaining plots have a light surface layer of pine needles or (especially on the skid trails) are completely devoid of surface organic matter. The skid trails have very dense, compacted soil, often with buried wood chips and logs. The bedrock is quite near the surface in this region, so some plots have exposed bedrock or soil layers that are less than 10 cm deep. As expected, these findings align with the soil properties typically found on the Park's west side, where Cache Lake is located [53]. Many of these qualities, especially the sandy, mesic, well-drained, shallow soils, make this area ideal for beaked hazel growth [42], so it is expected that the nucleation shrubs will thrive at the research site after the initial period of transplant shock. Canada goldenrod also favours mesic, well-drained soils with intermediate levels of organic matter [43, 111, 112, 114], and this species is already present across much of the site.

2.5.3 Light Intensity Measurements

As discussed in Section 2.4.2, a single light intensity measurement was taken in each treatment plot. Plots were measured in groups of 16, with background measurements of full sunlight taken before and after every cluster of 16 plots. For each plot, we may therefore assign a unique background value by assuming a linear change in sun intensity between background measurements.[61] With these tailored background values, we can accurately calculate the understory light availability relative to full sun in each plot.

Figure 2.41a) shows the measured light intensities across the site as a percentage of full sunlight. The same data is shown in Fig. 2.41b) with a Gaussian filter applied. This

[61] This will not be strictly accurate for two reasons. Firstly, sun intensity follows a (roughly) parabolic curve [116], so the use of a linear slope between background measurements will result in slightly inaccurate values. Moreover, the times between measurements in treatment plots was not equal, as some plots require more effort to enter due to debris and other obstructions. The error from these assumptions is unlikely to have a significant effect on the results, however, especially given the frequency with which the background measurements were made, which was roughly every 15-20 minutes. The calculated background values do take into account the 'zigzag' pattern I used when walking across the site to take the measurements, wherein I would walk east to west across a row, then west to east across the next to save time.

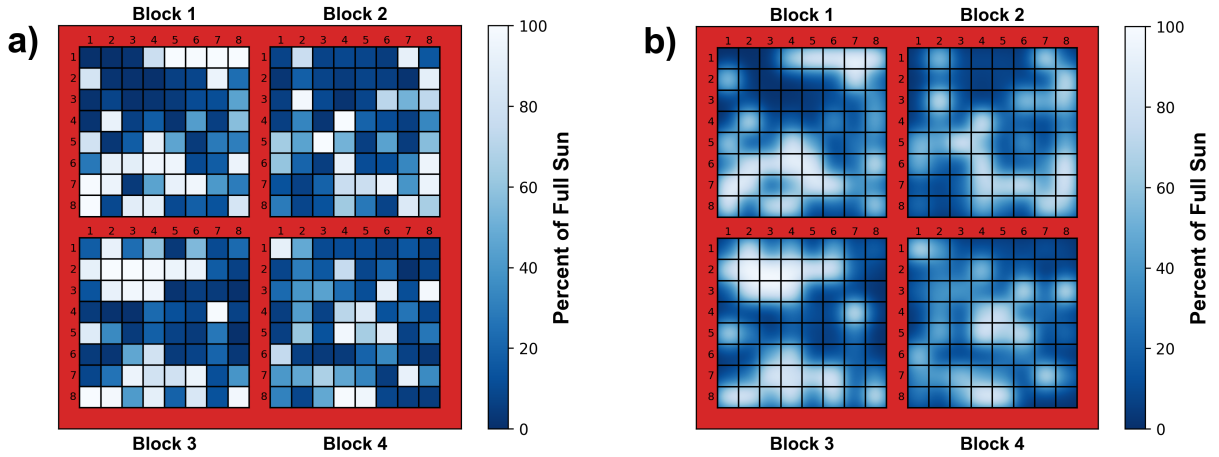


Figure 2.41: a) Survey of light intensity across the research site. b) The same survey data with a Gaussian filter applied.

smoothing makes the map more visually comprehensible by eliminating the sharp distinctions between plots. Effectively, it makes the data look more like an actual map of the site, rather than a low-quality, pixelated image. There are several notable features in this image that align with landmarks at the research site. Note, for example, the large dark patch in the top left corner of Block 1, which corresponds to a dense, unharvested patch of forest at the research site. In Block 2, the 'lines' of brightness are the openings created by the skid trails that crisscross the area, albeit shifted northward from their true positions due to the angle of the sun. The bright patches at the bottom of Block 1 and the top of Block 3 are large openings at the intersection of several skid trails. The centre of Block 3 is dominated by a dark canyon left by the creation of the railway. Block 4 primarily consists of open forest left after the pines were thinned, so intermediate intensities were recorded in this area.

Figure 2.42 compares the measured light intensities across all plots. Fig. 2.42a) is a graph of the photon flux, with the data arranged by the rows of treatment plots in the replicate blocks. (So the first 8 data points are from the plots in row 1 of Block 1, the subsequent 8 are from row 2, etc.) The measured photon flux values ranged between 6 and 1910 μmol/m^2/s, with an average across the entire site of 646.6 μmol/m^2/s. The background levels are also displayed, with an average recorded solar intensity of 1658.58 μmol/m^2/s between the hours of 10:30 and 13:00.

Since the light intensities are being treated as a pre-existing condition, not a treatment, and as we only have a single data point per plot, rigorous statistical methods are of little use in analysing this data. Nevertheless, we can gain further insight into the state of the research site through a simplified, qualitative analysis. In Fig. 2.42b), the measured values are arranged in order of increasing intensity. Note the uncertainty in the measurements, depicted by the light orange shading. This uncertainty arose from fluctuations in the sensor readings, which typically varied by 0-150 μmol/m^2/s depending on the plot. These fluctua-

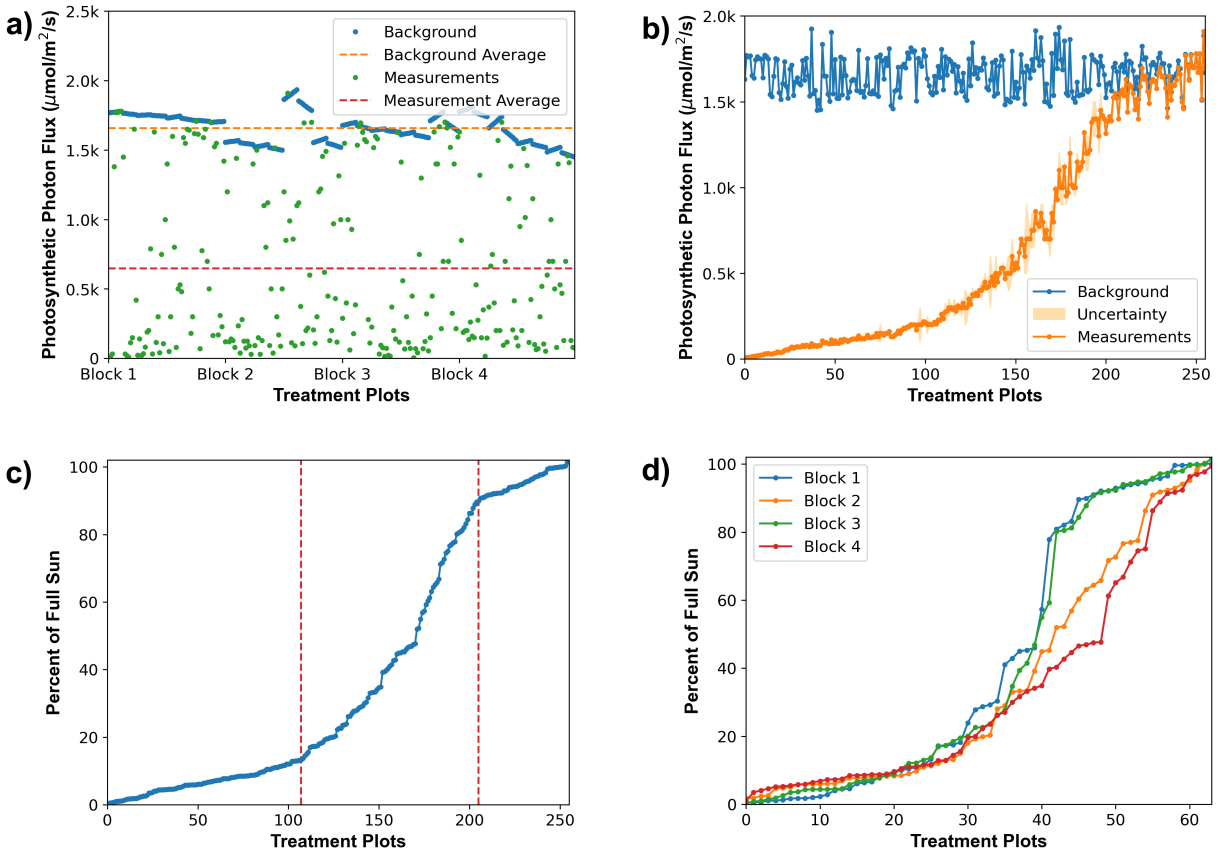


Figure 2.42: a) Measured light intensities across the research site, ordered by rows of treatment plots in the four replicate blocks. b) Light measurements ordered by increasing intensity (when represented in units of % of full sun). Light orange shading represents uncertainty in measurements. c) Light intensities represented as percentage of full sunlight, arranged in order of increasing intensity. Red dashed lines mark points of interest (see main text). d) Light intensities separated by replicate block, arranged in order of increasing intensity.

tions are caused by a combination of overhead leaf/branch movement due to wind and, to a lesser degree, sensor movement (due to my hand not holding it perfectly still). In low-light plots (<100 μmol/m^2/s), the reading would usually fluctuate by 2 μmol/m^2/s or less, while in the brightest areas, sensor readings typically varied by 10 μmol/m^2/s or less. Plots of intermediate light intensity actually experienced the greatest degree of uncertainty. This trend is expected because in bright areas, there were no overhead branches to cause sensor fluctuations, while dense canopy cover meant that the movement of branches had less of an impact, as the sensor was always in deep shade. It is therefore the intermediate canopy cover that yields the greatest uncertainty in the light intensity measurements.

Figure 2.42c) shows the same data, now depicted as percentage of full sunlight.[62] Observe that just over a third of treatment plots (∼100) have intensities below 15% of full sun. Therefore, despite the thinning treatment, substantial portions of the site are still heavily shaded. In the centre of the graph, the slope for the next hundred plots is much greater until it reaches 90% intensity. Given the angle of the sun with respect to the horizon, this section of intermediate intensities likely represents the treatment plots that are north of thinned plots with light canopies. The slope is greater here because there are few plots covering this wide range of intensities. Intermediate intensities are less common because any firm shadow (such as that of a tree trunk, as opposed to the shadows of needles and branches) instantly causes the light intensity to drop to $\lesssim$20% of full sun. Moreover, as most of the overstory trees have only a few remaining branches making up their canopy (see Fig. 2.1, for example), if the tree tops are too far away from the plot, their branches will only block a small proportion of sunlight, and the measured intensity will be quite high. Therefore, there are few plots without 'firm' shadows but with trees close enough for their canopies to create intermediate intensity levels. Finally, the last ∼50 plots have intensities of over 90%; these are the plots with wide skid trails or large canopy openings created by the thinning process and by fallen trees. Plot 1/2/1 in Fig 2.41a) is a good example of a plot made bright by the collapse of a single large tree, even though most of the plot is filled with young, dense trees. It is expected that the high-intensity plots will yield the most substantial increases in understory vegetation over the next few years, as there is reduced competition with the overstory trees [42]. Overall, this wide variation in light levels may be beneficial, as it is likely to produce many different habitats and increase the variety of plantlife that will colonize the site.

Another way we can analyse these results is by separating the data by replicate block, as in Fig. 2.42d). We immediately observe an interesting result: whereas Blocks 2 and 4 reach 15% intensity and then increase steadily towards 100%, Blocks 1 and 3 see a sharp increase above 45%, followed by a sudden plateau at about 90%. Figure 2.41 may provide some insight into these differences. Blocks 1 and 3 both have two large openings due to the thinning operations, one on the north side and one on the south side of each block. They also each have a large dark patch; an unharvested area in Block 1 and a 'canyon' in Block 3. Thus, there are fewer plots of intermediate intensity and many more plots with high intensities. Blocks 2 and 4, meanwhile, have no large openings, and consist primarily of thinned forest. It is perhaps notable that all four blocks have roughly the same number (∼30) of low-light plots (<20% full sun), indicating equal proportions of heavily-shaded plots across all four blocks. That said, Block 4 does have the fewest areas of dense canopy cover and thus has only 1 plot with <3.5% of full sun, whereas Block 1 has a dense forest in its northwest corner and therefore has 9 plots with <2% of full sunlight.

[62] There are 4 plots with values between 100% and 102%. This is likely due to the sensor orientation being slightly different than it was during the background measurements; in these cases it was probably directed more towards the sun during the plot measurements. Moreover, there is likely a slight mismatch between the calculated background intensities and the actual values, as discussed in footnote 61. Ultimately, this has little impact on our analysis, however, and these values are rounded down to 100% in Fig. 2.41.

Beaked hazel has a complex relationship with light, which is the primary factor influencing its density and distribution [42]. It favours intermediate light levels: intensities between 10% and 40% of full sun result in the greatest growth and spread [42]. It is often found along forest edges [42, 102], but sudden direct exposure to sunlight increases transpiration and retards growth [42, 105]. Meanwhile, Canada goldenrod prefers intensities ranging from slight shade to full sun [106, 112], and it is commonly found in open forests and grasslands [43, 111–115]. Given the spatially-heterogeneous light intensities across the site, the needs of both species should be accommodated. Interestingly, however, it may be that the hazel, which prefers darker areas, and the goldenrod, which prefers brighter areas, will thrive in separate parts of the site. We will analyse the impacts of light intensity on our transplant survival rates in the following section.

2.5.4 Transplant Mortality Census

At this early stage of the experiment, one of the most important factors is the survival rate of the transplanted hazel and goldenrod. In the following subsections, we will analyse the health and survival rates of the transplants using the data from the mortality census (see Section 2.4.5). Overall, as the healthier shrubs will likely exert a faster and greater influence on their plots, this census of transplant health will give us a better understanding of the impacts the treatments are having on understory regeneration.

Beaked Hazel Mortality

During the beaked hazel mortality census, the approximate percentage of surviving leaves was recorded for each transplant. As this was a visual estimate, the data was recorded in the form of an approximate percentage range. In the following analyses, we will use the centre of each shrub's assigned percentage range as its 'leaf survival value'. Given the wide margin for error in a visual inspection, I would estimate an uncertainty of $\pm 10\%$ on these values. Despite this large uncertainty, these approximate leaf survival rates should at least give us an idea of each transplant's health.

Figure 2.43a) shows the results of the mortality survey across the site. In Fig. 2.43b) we can see the data arranged in order of increasing leaf survival. Approximately 85% of the transplants (109 shrubs) have leaf survival rates of 50% or more, and 59% (75 shrubs) have retained at least 90% of their leaves. Only 6 transplants ($\sim$5%) were observed to have $\leqslant$10% of their leaves remaining, and of those, only one shrub (plot 3/5/8) was completely dead, with no surviving leaves (Fig. 2.37c). With almost two thirds of the transplants having retained 90% of their leaves and only one confirmed death, the transplanting stage of this project appears to have been a success.

Further analysis is warranted, however, to assist with our projections for the future of this site and to offer guidance to anyone who may be attempting a similar project. We will

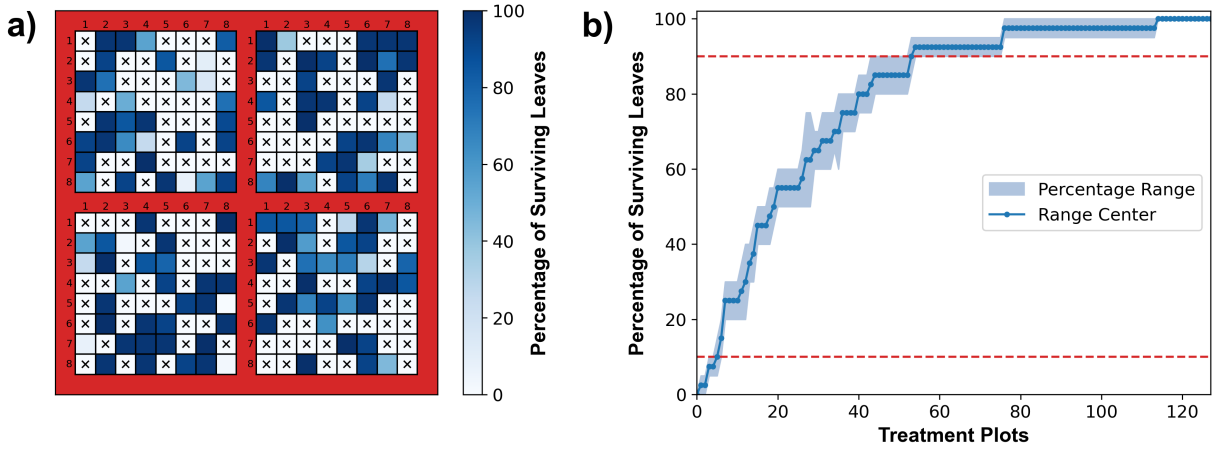


Figure 2.43: a) Survey of hazel mortality, using leaf survival as a measure of transplant health. Small X's indicate plots without transplants. b) Leaf survival of all transplants arranged in ascending order. Blue shading indicates estimated percentage range, and red dashed lines indicate 10% and 90% leaf survival.

therefore analyse hazel health with respect to four key variables: date of transplanting, leaf size, location, and light intensity.

Fig. 2.44a) shows the leaf survival data separated by transplanting dates, and Table 2.3 summarises these results.[63] The differences between the three transplanting trips are immediately apparent. The first trip, in late April, had no shrubs with leaf survival rates of less than 75%, and three quarters of the transplants retained at least 90% of their leaves. The second trip occurred in mid-May, and although 4 transplants lost over half of their leaves, 82% of transplants retained 90% or more. The third trip occurred at the end of May, and these transplants fared poorly compared to those of the previous two trips, with over 20% having lost more than half of their leaves.

Overall, these results appear to indicate that if one is transplanting in spring, it is preferable to move beaked hazel in late April, when the ground has thawed but the leaves have yet to emerge, or in mid-May, when the leaves are just starting to emerge. The shrubs appear to experience reduced transplant shock if they have not yet begun to shift their energies towards leaf growth and are still semi-dormant, as discussed in Section 2.4.5. Note however that dead leaf buds from the April trip, which perished before their leaves could emerge, were not included in the assessment of leaf survival because they were too difficult to locate quickly during the mortality survey. This could potentially have impacted the data such that the April transplants appear healthier, even though they lost many leaf buds.

[63] A single shrub, in plot 1/4/3, was excluded from this particular analysis, as it was planted on its own in mid-June (see footnote 51). It had roughly 50% of its leaves remaining, which aligns with the results of the leaf survival vs. date analysis.

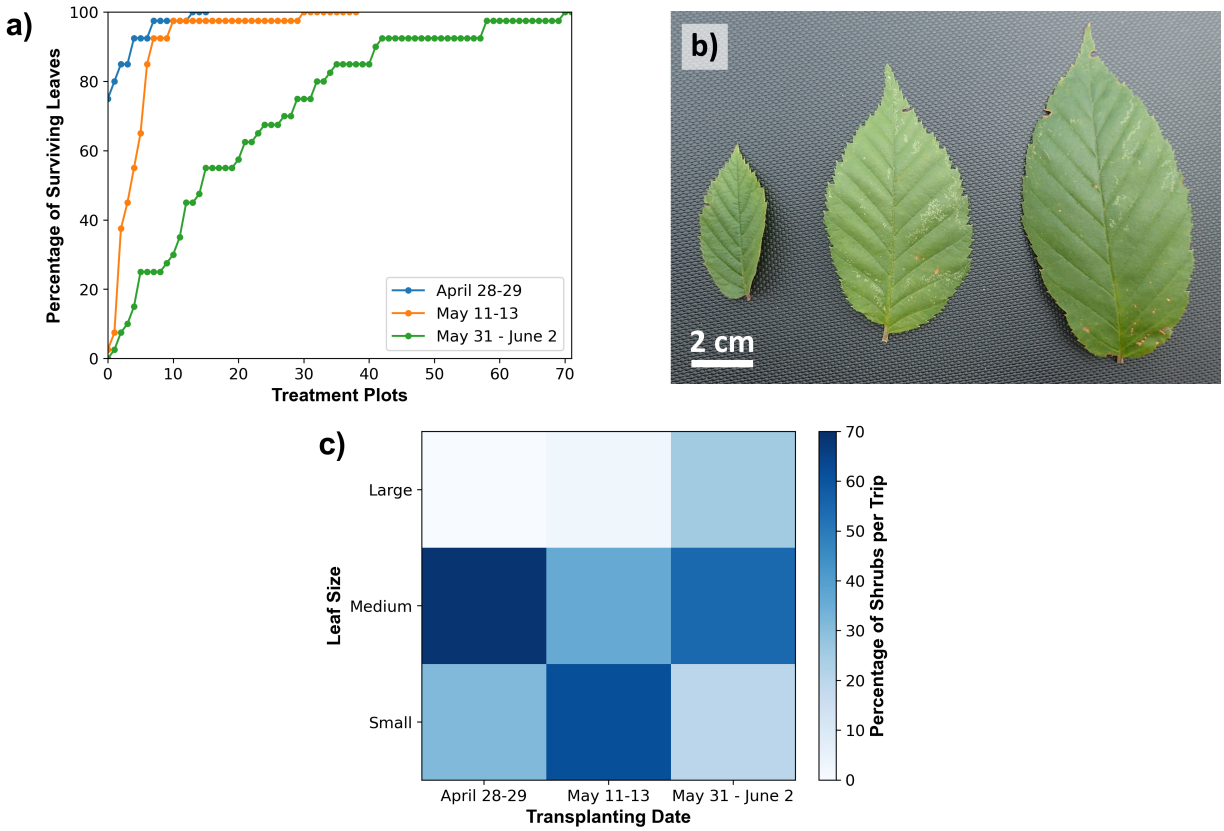


Figure 2.44: a) Leaf survival rates separated by date of transplanting. b) Beaked hazel leaf sizes. c) Two-dimensional histogram of leaf sizes vs. transplanting dates. Values are the percentage of shrubs with the specified leaf size for each individual transplanting trip.

	April 28-29	**May 11-13**	**May 31 - June 2**
Total # of Transplants	16	39	72
Shrubs with >90% Leaf Survival	75%	82%	43%
Shrubs with >50% Leaf Survival	100%	90%	79%

Table 2.3: Hazel leaf survival rates by transplant date.

The date of transplanting also affected the leaf size. Figure 2.44b) shows hazel leaves of three sizes taken from the transplants. From smallest to largest, their lengths are 5 cm, 8.5 cm, and 12 cm. While shrubs with medium and large leaves also tended to have

leaves of smaller sizes as well, we can roughly categorize the shrubs according to to their average leaf size. Figure 2.44c) is a two-dimensional histogram of leaf size vs. transplanting date.[64] Shrubs transplanted in late April, before the leaves emerged, and mid-May, when the leaves were just starting to emerge, tended to have predominantly medium and small leaves. Interestingly, April shrubs had more medium-sized leaves, while the mid-May shrubs had more small leaves. This suggests the April shrubs were able to grow most of their leaves to a reasonable size because the transplanting occurred before the leaves emerged, whereas the mid-May shrubs had the early stages of leaf growth interrupted by the transplanting, resulting in smaller leaf sizes. The shrubs transplanted during the final trip had much greater proportions of medium and large leaves, likely because they were moved after their leaves had nearly finished growing. Therefore, although the late-May shrubs had the fewest leaves remaining, their surviving leaves were much larger than those of the other shrubs. Overall, however, the results of Figure 2.44 suggest that for Algonquin's climate, the ideal transplanting time in spring is late April, before the leaves have emerged, as this yields the greatest proportion of surviving leaves and a large proportion of shrubs with medium-sized leaves. Transplanting in early to mid-May would also yield acceptably healthy shrubs.

As there was a full month between the first and last transplant dates, and the census was conducted just a month and a half after that, these results may be slightly skewed. For example, shrubs planted earlier in the spring have had more time to deteriorate due to transplant shock compared to those planted more recently. This would not change the overall analysis, however, as it would primarily reduce the success of the last transplants, thereby reinforcing the conclusion that beaked hazel should not be transplanted in late May and early June. On the other hand, it may be that the delay between trips gave the dead leaves more time to detach from the earlier transplants and blow away, and so they could not be used to determine leaf survival rates. This could partially explain why the first trip had no shrubs with under 75% of their leaves, the second trip had only a few shrubs with less than 50% leaf survival, and the third trip had many. Unfortunately, with no other census data, there is no direct way of verifying or correcting for this potential issue, aside from conducting a separate experiment to test it.

These results of shrub health, however, are not entirely conclusive, as there were several other factors influencing shrub survival. For example, the hazel was transplanted to different locations across the research site, each of which has a slightly different environment. We should therefore separate the survival rates by replicate block, as has been done in Figure 2.45a). From these results, there appears to be little difference between the four blocks, particularly at the high end of leaf retention. On the low end, the shrubs in Blocks 2 and 4 fared better than those in Blocks 1 and 3. Overall, Block 2's shrubs were the healthiest, with an average leaf survival rate of 84.0%. Block 1 had the lowest average survival rate, at 72.8%. Within the blocks, however, shrubs were planted on different dates, so we should

[64] Two shrubs were excluded from this analysis: the shrub in plot 3/5/8, which had no leaves remaining, and plot 1/4/3, which was planted on its own in mid-June. Note that the leaf size assessment was based on a cursory examination and an estimate of average size, so these results may not be perfectly accurate. Nonetheless, they should provide enough information to assess the general state of the shrubs.

add the temporal dimension of transplant date, as in Fig. 2.45b). Here we see again that Block 2 has the highest leaf survival rates for the last two trips. For trip 3, however, Block 1 actually has higher average survival than Blocks 3 and 4. The higher averages of Blocks 3 and 4 in Fig. 2.45a) are therefore the result of the greater success rates from trips 1 and 2, when the shrubs were reaching the end of their dormant phase. Overall, we may deduce from these results that, again, transplanting in early spring is reduces transplant shock, and Block 2 *may* ultimately see the fastest recovery and growth of beaked hazel.

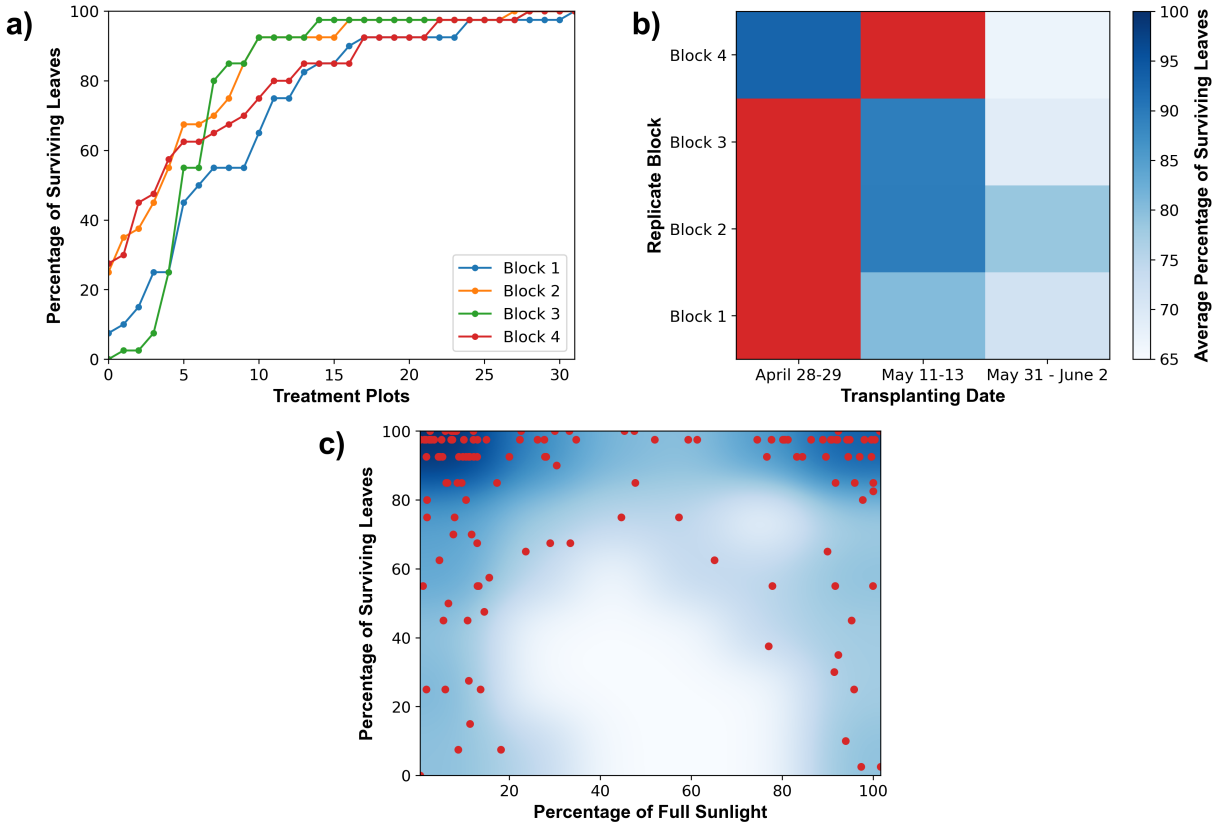


Figure 2.45: a) Leaf survival rates separated by replicate blocks. b) Leaf survival as a function of both location and transplanting date. Red squares indicate instances where no transplanting occurred. c) Leaf survival rates as a function of light intensity. Blue shading is a 2D histogram of data points.

To return briefly to Figure 2.45a), something else of note is that Blocks 1 and 3 are grouped together at the low end of leaf survival, as are Blocks 2 and 4. This is reminiscent of the light intensity analysis in Figure 2.42d), where Blocks 1 and 3 and Blocks 2 and 4 appeared to be grouped together for the higher light intensities. This may suggest that higher light intensities result in greater levels of transplant shock. To examine this possibility, we can graph leaf survival as a function of light intensity, as in Figure 2.45c). A 2D histogram

in the background allows us to assess where the data points are most concentrated.[65] From these results, it appears that the highest leaf survival rates (>80%) occur in very bright and very dark treatment plots, with few occurring in plots with intermediate light intensity. Additionally, all shrubs with leaf survival rates of less than 60% are also in the brightest and darkest plots. There several of ways of interpreting these results. First, we might note that the brightest plots evidently have more sunlight, which the shrubs need, but they also have the least moisture due to evaporation. On the other hand, darker plots have more moisture, but less light. This could potentially explain why we see both the highest and lowest leaf survival rates in both the brightest and darkest plots. It is important to note, however, that the light intensities are invariant; they are merely whatever they are, as determined by the objects within and around the plots. As discussed previously (Section 2.5.3), there are few intermediate-intensity plots, so it is unsurprising here that there are more data points in the darkest and brightest plots. What is perhaps the most notable aspect of this graph is that in all of the intermediate-intensity plots (25-75% of full sun), no shrubs have less than 60% of their leaves.[66] By contrast, nearly a third of shrubs in dark (<25% full sun) and bright (>75%) plots have less than 60% of their leaves. Therefore, we may tentatively conclude that transplant shock is reduced in intermediate light intensities, as there is sufficient shade for moisture retention and sufficient light for photosynthesis.

Further analysis of this data set, such as separating Fig. 2.45c) by block and transplant date, reveals little additional information. An analysis of shrub health with respect to soil quality and surrounding vegetation may be interesting, but the short delay between the transplant dates and the mortality survey means that such analyses would be unlikely to yield useful results. Soil quality, for example, is only relevant if the hazel roots have had enough time to spread significantly beyond their original rootball, and after only a few months, the only relevant factor introduced by the surrounding vegetation is the degree to which it shades the shrubs, which has already been measured. Analysis of this data using regression models also reveals no useful data beyond that which has already been discussed.[67]

Therefore, with almost all of the shrubs having survived and almost two thirds having retained 90% of their leaves, the nucleation transplanting can be considered a success. The results of this analysis also reveal that transplant shock is reduced when the shrubs are transplanted earlier in the season, and Block 2 appears to have the healthiest shrubs. In

[65] A Gaussian filter was applied to the histogram to prevent it from dominating the image with a series of sharp transitions. The histogram data was also exponentiated by a factor of 0.35 so the bins with just one or two data points could still be observed. (Otherwise, the high-value bins would dominate and the low-value bins would disappear into the background as white squares.)

[66] It's possible though that there are merely insufficient data points in this region to observe unhealthy shrubs.

[67] An analysis of the data in Fig. 2.45c) was attempted using a generalized linear model and assuming a Poisson distribution (which yielded a fit with a very low pseudo-R-squared value), but even when separated by replicate block and accounting for interactions between the blocks and light intensities, no meaningful results were obtained. The data does not have a linear form, so linear models are not useful here, and this early stage of the experiment doesn't warrant the use of more advanced models.

the near term, it may be worthwhile to observe the whether plots of intermediate light intensity continue to have reduced shrub mortality rates.

Goldenrod Mortality

The goldenrod mortality census surveyed the number of surviving transplants in each plot where the windthrow guard treatment was applied. The results are shown in Figure 2.46a). In most plots, all six transplants, including the dead ones, were located and recorded. Some areas have very dense vegetation, however, so it was difficult to locate all goldenrod transplants in these plots, even after several minutes of searching. Therefore, Figure 2.46a) indicates the seven plots in which some transplants could not be found, and these plots will be eliminated from the following analysis.[68]

In Fig. 2.46b) we can see the data arranged in order of increasing transplant survival. Approximately 94% of the plots in this analysis had at least 4 of their 6 transplants survive, and over half of the plots (55%) retained all six transplants. No plots were observed with just 2 surviving transplants, and only one plot was recorded with 5 dead transplants. The census also revealed that every single plot had at least one surviving transplant. Overall, of the 768 goldenrod transplants, 665 (86.6%) survived, 13 (1.7%) couldn't be located, and only 90 (11.7%) were confirmed to have died. This is a gratifying result, as we weren't sure during the transplanting process whether any of the goldenrod would survive. Given their small rootballs, the speed at which they wilted, and the amount of time they sat in buckets waiting to be re-planted, high survival rates seemed unlikely at the time. Ultimately, however, it appears that this transplanting effort was a success.

Figure 2.46c) shows the effects of the replicate blocks on survival. The results are summarised in Table 2.4. Overall, Blocks 1, 2 and 3 have very similar transplant survival rates (∼89%), and similar average survival rates per plot (∼5.4 transplants). Block 4, the first to be planted, has the lowest total survival rate (84%) and the lowest average survival rate per plot (5.1), although these values are quite close to those of the other blocks. The only substantial difference is the percentage of plots per block with 6 surviving transplants; Blocks 1 and 4 have 47%, while Blocks 2 and 3 have ∼63%. The reasons for these groupings and the difference between them are not entirely clear, as there are no known properties that link Blocks 1 and 4 and Blocks 2 and 3. Blocks 1, 3, and 4 were planted on 22 °C days, while Block 2 was planted separately on a much hotter day (27 °C), so planting date/temperature are unlikely to be the cause. Therefore, it may be worthwhile to study differences in windthrow guard size between blocks in the future to determine the cause of these results.

We should also analyse goldenrod survival as a function of light intensity (Fig. 2.46d). Survival rates appear highest in both the brightest and darkest plots, but as discussed previously, this may simply be due to the low number of plots with intermediate intensities.

[68] The plots are: 1/7/7 (2 missing), 1/7/8 (2), 2/3/2 (1), 2/5/1 (2), 3/1/7 (1), 3/2/2 (4), and 3/3/2 (1).

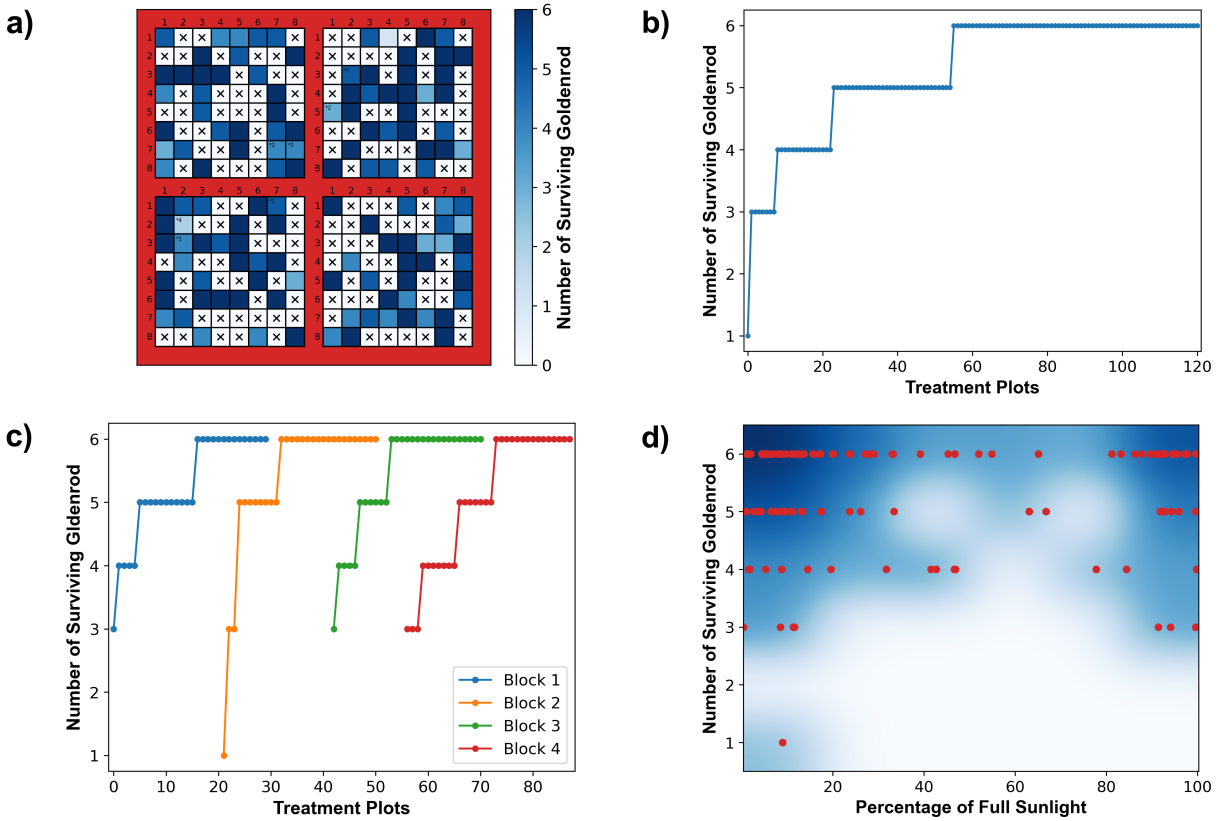


Figure 2.46: a) Survey of goldenrod mortality. Small X's indicate plots without transplants. Plots with asterisks mark the number of goldenrod that could not be located during the survey. b) Number of surviving goldenrod arranged in ascending order. c) Transplant survival rates separated by replicate blocks. Data for each block has been shifted horizontally for easier viewing. d) Transplant survival rates as a function of light intensity. Blue shading is a 2D histogram of data points.

	Block 1	**Block 2**	**Block 3**	**Block 4**
Total Percentage of Survivors	88%	89%	90%	84%
Average Survival Rate per Plot	5.3	5.4	5.4	5.1
Plots with 6 Surviving Transplants	47%	63%	62%	47%

Table 2.4: Goldenrod survival rates separated by replicate block. Percentages account for plots omitted in each block due to unlocatable transplants.

If we divide the experiment into dark plots (⩽25% full sun), intermediate intensities (25-75%), and bright plots (⩾75%),[69] we can more easily assess the impacts of light intensity on transplant survival. Going by the percentage of plots in each intensity category, Table 2.5 shows that light intensity has very little impact on transplant survival. In all three categories, the six transplants have survived in just over half of the plots (53-57%), and more than 90% of plots have 4-6 surviving transplants. As was the case with the hazel, however, we again find that intermediate light intensities are subtly different, with *no* intermediate-intensity plots having fewer than 4 survivors. This suggests that intermediate light intensities may result in the least amount of goldenrod death from transplant shock, although roughly half of the plots will lose at least one transplant regardless of intensity.

	Dark (⩽25% full sun)	**Intermediate (25-75% full sun)**	**Bright (⩾75% full sun)**
Plots with 6 Survivors	35 (53%)	12 (57%)	19 (56%)
Plots with 4-6 Survivors	61 (92%)	21 (100%)	31 (91%)
Plots with 1-3 Survivors	5 (8%)	0	3 (9%)

Table 2.5: Transplant survival rates separated by light intensity.

In addition to the survivor count, the census also assessed each transplant's health based on four categories. The 'lost inflorescence' category denotes transplants where the flowering tip (i.e., the inflorescence) was observed to be dead during the survey. Stems that had lost more than a quarter of their leaves were placed in the 'dead leaves' category. Any stem that had lost most of its leaves and its inflorescence but had small surviving branches is in the 'new branches' category. Finally, there were also many goldenrod that appeared to be perfectly healthy. Figure 2.47a) shows the goldenrod health data. Overall, about half of the surviving transplants (53.8%) had lost some of their leaves, and a third (31.7%) appeared fully healthy. Only a few had lost their inflorescences (7.5%) or had lost all but a few new branches (7%).

We may further study transplant health by dividing these results by replicate block, as in Fig. 2.47b). Note how Blocks 1, 3, and 4 have a particular pattern: large quantities of transplants with dead leaves, fewer that are fully healthy, a small percentage with new branches, and an even smaller quantity with dead inflorescences. Block 2, however, is substantially different, with nearly equal quantities of healthy and dead-leaved transplants (42% and 37% respectively). About 17% of Block 2's surviving goldenrod have lost

[69] Any firm shadow instantly drops light intensity to about 20% of full sun, so if we use 25% as the boundary for the 'dark' category, we should capture most of the heavily-shaded plots, and then we mirror that on the upper end at 75%. Granted, these are somewhat arbitrary intensities to define the categories.

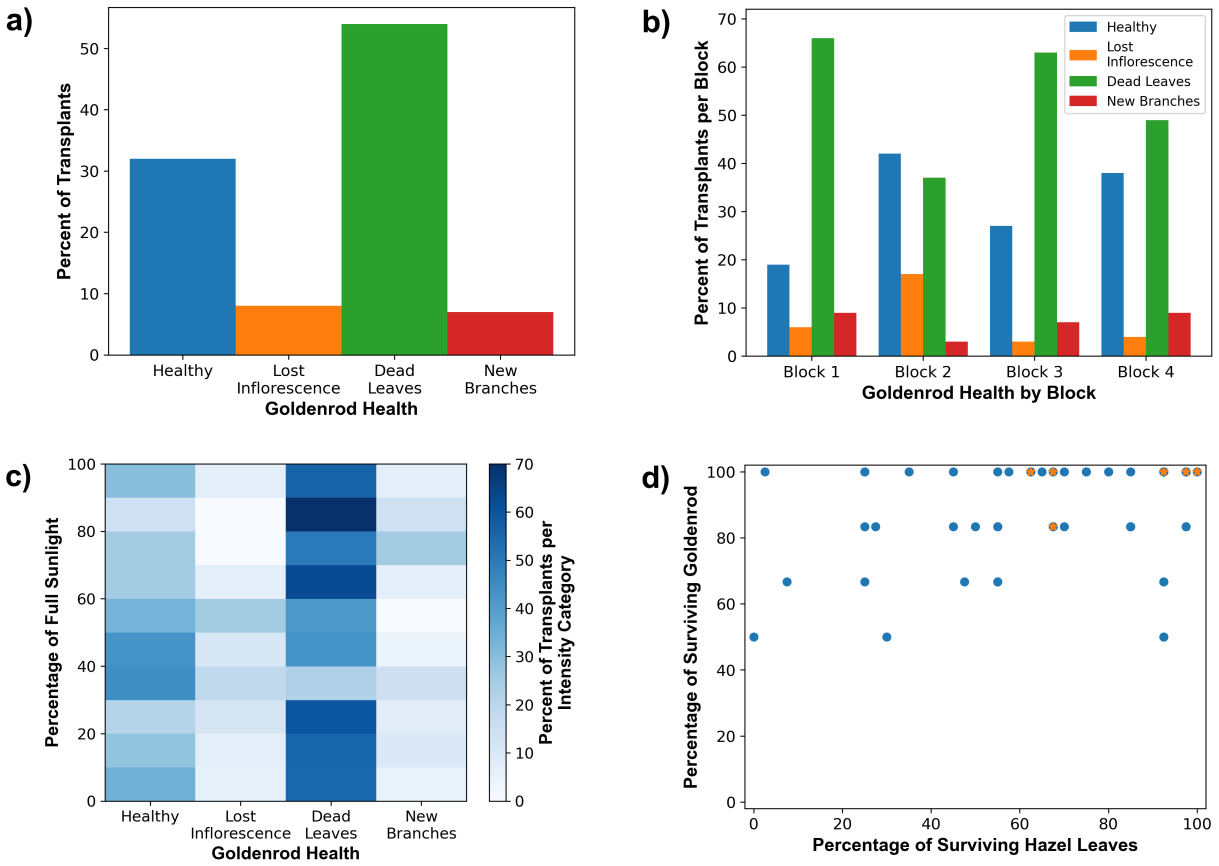


Figure 2.47: a) Proportion of transplants in each of the four categories of goldenrod health. b) Goldenrod health by replicate block. c) Goldenrod health as a function of light intensity. d) Comparison of surviving hazel leaves and goldenrod in AN&WG plots. Points with stars indicate plots of intermediate light intensity (25-75% full sun).

their inflorescences, and a tiny proportion (3%) are only surviving through new branches. Although this could suggest that Block 2 has some unique property affecting goldenrod survival, perhaps a more likely explanation is that Block 2 was transplanted on a much hotter day than the other blocks. Additionally, it was a much slower process because one of my transplanting assistants had to leave that day. Therefore, the goldenrod sat in their buckets for many hours, and we eventually added water to the buckets to keep them alive. The goldenrod wilt from the top of their stem, and it may be the case that their inflorescences are more sensitive to water loss than their leaves during the transplanting process. This could explain why so many of Block 2's transplants lost their inflorescences after sitting in their buckets for many hours. It's also possible that the percentage of completely healthy goldenrod, which is higher than in any other block, may be attributed to the water that was added to the buckets later in the day. Alternatively, it may be that the higher rates of healthy goldenrod are attributable to the new transplanting method that was attempted that day, which involved cutting ovals around the goldenrod stems in order to extract as

much of their root system as possible (see Section 2.4.4). This was suspected to be the best technique at the time of transplanting. Not all goldenrod in Block 2 were extracted using this technique, but if single-stem goldenrod transplanting is being conducted in the future, it may be worthwhile to test whether this method does in fact result in greater survival rates. In any case, while we don't have an exact explanation for this difference in goldenrod health, it at least seems reasonable to conclude that goldenrod transplanting may have better success rates if they are kept watered while being moved.

One final factor to examine is whether light intensity had any effects on transplant health. Figure 2.47c) shows the number of transplants in each health category as a function of light intensity. Each cell is the percentage of transplants in a light intensity category that has a particular health status. For example, in plots with 90-100% full sunlight, 30% of transplants are healthy, 7% have lost their inflorescences, 56% have lost some of their leaves, and 7% have new branches. Overall, the relative abundances of each health category are fairly consistent across the entire range of light intensities, and they match the general trend seen in Fig. 2.47a) and Blocks 1, 3 and 4 in Fig. 2.47b). Based on these results, this appears to be the standard pattern for the health of transplanted goldenrod.

There is, however, a slight change in health at the intermediate light intensities (30-60% of full sun). At these light levels, the proportion of healthy transplants rises to 40%, transplants with lost inflorescences increase to 18%, the number of transplants with lost leaves decreases to 36%, and transplants with new branches remains low at 6%. Remarkably, these values match the results from Block 2 to within a few percent. In the case of Block 2, we can likely attribute the differences to the increased temperature, longer wait times in buckets, and the addition of water to the buckets. The connection between these factors and intermediate light intensities is not readily apparent, as Block 2 has roughly the same number of intermediate-intensity plots as the other blocks (Fig. 2.42d). We might think of both conditions causing the same degree of transplant shock, but what we call 'transplant shock' is actually a collection of many different physiological phenomena, some of which may result in similar responses or may appear to do so [120]. It seems highly unlikely that two unrelated phenomena would yield almost the exact same effects on transplant health. This connection might warrant further study in future experiments. It should be noted however, that these results are by no means conclusive; there are *far* fewer data points at the intermediate intensities (see Table 2.5), and the division of light categories into intervals of 10% is arbitrary and may affect the numbers. Therefore, this intriguing result, though noteworthy, could be merely a coincidence or an artifact of this analysis process.

Finally, we can examine whether the conditions within the plots are having a large effect on the degree of transplant shock by comparing the proportion of surviving hazel leaves and goldenrod in AN&WG plots. A correlation could suggest that they are both experiencing significant effects from the environmental conditions in their plots. Figure 2.47d) graphs goldenrod survival and hazel health for the plots where the two species have both been planted. This graph, however, shows no apparent correlation. This is likely because the species are so different that they respond to transplanting and their new environment in different ways. For instance, we have determined for both species that intermediate light

intensities may reduce transplant shock, but as we see from the available data in Fig. 2.47d), hazel health is highly variable at these intensities while goldenrod survival rates are not. Another possible explanation is that they have not yet been in their new plots long enough to have been significantly affected by them.

Given the limitations of this data, the use of regression methods, in particular linear models, are unlikely to give any additional relevant information. Nevertheless, this simple analysis of the goldenrod census has revealed several interesting results. Despite the challenges of the transplanting process, 87% of goldenrod transplants survived. The replicate blocks seem to have little impact on the number of surviving transplants or the average number of survivors per plot, although there is an unexplained difference between Blocks 1/4 and Blocks 2/3 in the number of plots with 6 survivors. As with the beaked hazel, intermediate light intensities appear to result in the least amount of transplant shock in terms of number of survivors. There appears to be a standard pattern for goldenrod health after transplanting, which we observe across Blocks 1, 3, and 4, as well as at high and low light intensities. Interestingly, however, Block 2 and light intensities between 30% and 60% of full sun have a very different pattern which may be worth investigating further. Although the individual goldenrod transplants are unlikely to provide substantial protection from windthrow this year, such a high survival rate suggests that they will likely spread in future years, surrounding the shrubs with the herbaceous barriers needed to block the wind.

2.6 Conclusions and Lessons for the Future

Over the past two years, we have initiated the first stages of this 4-year project to restore the understory of the red pine plantation at Cache Lake. While Park staff applied the two universal treatments in early 2021, my work involved refining the initial design of the experiment, setting up the experimental grid, locating desirable species for transplanting, and applying the experimental treatments. After getting the experiment started between autumn of 2021 and early summer of 2022, I conducted baseline surveys of the site in July 2022 and assessed the survival rates of the transplanted species.

Although the experiment is just starting, we have already begun to observe interesting results, including the substantial quantities of native and non-native understory vegetation that are already present at the site. Surveys of light intensity have revealed that there are fewer intermediate-intensity plots than there are bright or dark patches, but the thinning treatment has already accomplished one of its goals: to open up heterogeneous canopy gaps so sunlight can reach the understory. Most importantly at this stage, however, the mortality census revealed that the effort to transplant beaked hazel and goldenrod for the applied nucleation and windthrow guard treatments was overwhelmingly successful, despite the challenges associated with this task. With only one exception, all of the hazel survived the first 1.5 months after being transplanted, and 85% of them retained at least half of their leaves. Based on an analysis of hazel health, it appears that the shrubs experience reduced

leaf mortality if they are moved earlier in the spring, although their leaves may not grow to full size that summer. The windthrow guard treatment was also successfully applied, as roughly 87% of goldenrod transplants survived, and in more than half of the plots, all six transplants survived. Goldenrod health tended to follow a particular pattern, with half the surviving transplants losing their leaves, 30% remaining perfectly healthy, 7% losing their inflorescence, and another 7% surviving only in young branches. Interestingly, this pattern was broken for unknown reasons at intermediate light intensities and in Block 2, which was planted on a hot day and involved a new transplanting technique. For both the beaked hazel and the goldenrod, intermediate light intensities appear to reduce transplant mortality, although with so few data points, further research might be required to verify this finding.

As we've seen throughout this chapter, there were many challenges associated with initiating this restoration experiment. In particular, time constraints imposed many limitations on what we were able to do, as did the practical and logistical difficulties. There were many trade-offs to be considered, such as whether to do more replicate blocks or more treatment repetitions, and whether to have more shrub plantings per plot versus more treatment repetitions. These limitations will have ongoing implications for the project, which highlights an interesting feature of ecological experiments: each one can only be conducted once. Whereas an automated physics experiment, for example, could be repeated one hundred times in an hour and can be reset to the exact same starting conditions each time, an ecosystem's unique, complex, ever-changing properties make each ecological experiment a one-time opportunity. Therefore, considering all the limitations and challenges that will inevitably be encountered, forethought and detailed planning are key the successful implementation of an ecological experiment, as it won't be possible to undo your efforts, return the ecosystem to its initial state, and start again if errors are made. Despite the challenges associated with getting this experiment running, however, it has now been successfully initiated, and we can begin to consider its future.

Chapter 3

Establishing the Successional Trajectory of the Plantation

For fifty years, the red pine plantation at Cache Lake has remained unmanaged, its thin, sickly trees looming over ground covered only by a layer of pine needles. With no sunlight reaching the understory, succession was effectively halted, and the ecosystem had stagnated in a state of poor biodiversity and homogeneous structure. In 2021, a restoration project was implemented, with the immediate goals of restoring ecological integrity and re-initiating forest succession by accelerating understory regeneration. The treatments applied to the site were designed to encourage the growth of native understory species by facilitating seedling establishment and manipulating key factors affecting vegetation growth, such as light availability. Although the experiment described in the previous chapter only has a 4-year timeline, restoration efforts will actually continue at the site for several decades. It is expected that eventually the north shore of Cache Lake will once again host a native hardwood forest that matches the surrounding landscape.

The implications of this project, however, extend far beyond the restoration of this single site. Conifer plantations are common in Algonquin Provincial Park and throughout southern Ontario, where they are often used as a method of stabilising degraded soil and quickly establishing canopy cover. Although there are plenty of resources describing the use of thinning as a treatment for restoring these plantations (e.g., Ref. [19] and [20]), there have been few (if any) studies specifically examining treatments for rapid understory restoration of a conifer plantation in a northern mixedwood plains ecozone. There is also little research on the effects of combining multiple treatment types in this context. This experiment therefore seeks to fill these gaps in the literature by testing new treatments and examining how they affect the successional trajectory of this type of system. As Algonquin works to restore old plantations within its boundaries, and given the global efforts to accelerate reforestation using scientifically-tested and ecologically-sound methods, the results of projects such as these can be used to help us tailor restoration treatments to the unique properties of different ecosystems and accurately project the future of these sites. Many of the plantations being restored in Algonquin have been thinned in recent years, but only

the Cache Lake site has also received transplanted shrubs to facilitate understory recovery. If the rate of vegetation regeneration at this site is sufficiently accelerated, the results of this experiment may inform future restoration efforts across the Park and beyond.

With the previous chapter having covered the design, implementation, and preliminary results of the restoration experiment, this final chapter will examine the short-term (∼2 years) and long-term (a few decades) trajectories of the plantation and its understory. While we cannot perfectly predict the future of the site, we can draw some conclusions about probable regeneration pathways based on the literature review in Chapter 1, as well as our current knowledge of the site from Chapter 2. We'll reflect on whether the goals of the research project are likely to be achieved, adaptive measures that can be taken to keep the research agenda on track, and the ultimate state of this plantation as restoration efforts continue and succession progresses.

3.1 Future of the Restoration Experiment

With only 2 years remaining for the project, the research site is unlikely to experience large changes overall. Nevertheless, understory species can spread quickly, so we may observe substantial understory development during this time.

In the following subsections, we'll explore the near-term trajectory of the site and whether it aligns with the project goals. This will involve an analysis of the probable regeneration pathways over the next two years given the impacts of the two universal treatments (thinning and invasive species management). We can then narrow our focus to the experimental restoration treatments (applied nucleation and windthrow guards) to determine what effects they will have and whether they are likely to have the desired facilitative impacts on understory regeneration. Finally, we'll consider measures that can be taken to keep the research agenda on track in the event that the site does not follow the expected trajectory.

3.1.1 Desired Outcomes

The primary goal of this project is to develop a diverse understory, which the plantation is currently lacking. In particular, we wish to observe an increase in the abundance and richness of native understory species and an overall decrease in non-native plants. Wile the thinning treatment should result in an overall increase in understory species, the nucleation treatment is designed to facilitate the recruitment of native species, and invasive species management should assist in reducing the abundance of non-native species.

There are many non-native plants that are not being managed, however, such as naturalised species. Generalist and light-demanding species, which are indicative of an early-successional stage, are also common throughout the site. Ideally, if the goal of restoration

is to accelerate succession, we should also expect to see a large number of shade-tolerant forest specialists colonise the site, such as trilliums and clubmosses. Although this is currently not an explicit goal for the project, we may wish to track the presence of these species as indicators of succession.

Another goal of the project is to improve soil quality. Compaction should be reduced, while nutrient levels and organic content are increased. We also hope to see increases in mycorrhizae and microbial activity. There will be less of a focus on soil quality compared to vegetation in the following subsections, as we have yet to analyse the soil samples taken at the site, but we can still make some general predictions about how it may change in the coming years.

3.1.2 Short-Term Projections

Currently, with the open canopy and prevalence of generalist, light-demanding, and exotic species, the understory at the research site would be considered to be at an early stage of succession [4, 43]. As there has been very little research on understory succession in North American plantations [4], short-term predictions of vegetation development can be quite challenging. As noted in Chapter 1, the complex nature of these systems means that the results presented in the literature are often inconclusive or inconsistent, and the unique properties of each location and ecosystem make direct comparisons impossible. Succession pathways often vary unpredictably due to a combination of stochastic and deterministic processes [11]. There will certainly be spatial variations across the research site, and brief temporal variations (e.g., drought, extreme winds) could have severe impacts in the short-term. Nevertheless, we can predict a *general* trajectory for the site over the next two years based on its properties and the typical patterns of plantation recovery.

To determine the approximate short-term trajectory of this site, we should consider which relevant factors enhance and suppress understory development. Seed dispersal plays a vital role in understory regeneration and can limit the recovery rate [4, 6, 23, 39, 41]. The Cache Lake plantation, however, appears to have ideal conditions for seed dispersal. It is situated 100 m from continuous, intact forest; its remaining trees, their canopy, and the slash piles provide habitat and shelter for a variety of seed-dispersing animals, including moose, squirrels, and birds; and as described in Section 2.5.1, many understory plants are already present throughout the plantation, so they can act as local seed sources for plots with minimal vegetation coverage. The existing understory, though sparse in many areas, also hosts a variety of insects, so pollination should not be an issue. Additionally, although existing patches of dense vegetation can strongly suppresses the emergence of seedlings due to excessive shade and resource competition [43], much of the site has little existing vegetation, with the exception of a few specific areas (e.g., Block 2). Therefore, there is plenty of opportunity for seedling recruitment without excessive competition in the first few years. The large amount of dead wood left behind after the thinning treatment will also enhance the regeneration of dead wood-dependent species [21], and the logs and slash

piles can help protect seedlings from wind exposure and browsing pressure [26, 46, 48]. Active management of invasive species during this project should eliminate most of the highly-invasive non-native plants, so there should be a noticeable drop in their prevalence. Naturalised species, such as oxeye daisy and bird's-foot trefoil, will likely not be eliminated through the invasive management effort, so they will probably persist in the short term.

While most of the factors mentioned above may enhance understory recovery, there are several others that may suppress vegetation growth. Slash piles are present across much of the site, and many of them are several metres wide. Slash has been found to temporarily suppress vegetation growth by blocking sunlight and acting as a physical barrier [41], so we are unlikely to see any growth on top of slash piles for several years. With the planted conifers having loosened and added nutrients to the soil over the past 50 years [20], as well as the mixing of the soil layers by the thinning treatment [26, 36, 50], there should be plenty of opportunity for new growth. As discussed in Chapter 1, however, the soil properties of a plantation are very different from those of an old-growth forest, so despite the ameliorative effects of the conifers, the soil may still be more favourable to generalist and early-successional species, rather than late-successional forest specialists. Moreover, deep litter layers can prevent seedling recruitment [43], and despite the machinery moving through the site during the thinning process, the needle litter that accumulated over 50 years remains undisturbed across much of the area. Additionally, many of the skid trails left by the thinning process currently have heavily-compacted soil, mostly composed of sand, rock, and crushed wood. These areas provide few or no microsites for new plant growth, particularly in the deep ruts left by the machinery tires.

As discussed previously (Section 1.2), one of the most important factors affecting understory growth and succession in areas that have had dense canopy cover is light availability [40–44]. Greater light intensities promote the growth of generalist, early-successional, and exotic species [10, 44], whereas extremely low-light environments can kill off vegetation and result in ground cover dominated by leaf/needle litter [4, 22, 23]. Intermediate light levels, achieved at about 60-85% canopy cover, appear to be ideal for the growth of native, shade-tolerant forest specialists [23]. Due to the thinning treatment at the plantation, the canopy has been opened up in many places, resulting in a patchwork of understory light levels. The remaining trees now have room to slowly expand their canopies [19], but this is unlikely to substantially alter the light levels in the understory during the remainder of the experiment. Aside from wind-felled trees, light availability is therefore likely to remain roughly constant over the next two years. Based on light measurements made in summer of 2022 (Figure 2.42c), more than a third of the experimental plots have light levels below 15% of full sunlight.[1] Although this is quite dark, in many of these plots, we can likely expect native forest specialists to slowly spread, as they may have only transient shadows passing over them during the day.[2] It's likely that generalist species will be unable to col-

[1] Note that light intensity (which we measured) and canopy cover (the units in which the literature gives ideal light levels) are not interchangeable units, but they are correlated.

[2] Recall that light intensity was only measured in one spot per plot, so individual tree shadows had a large impact on the measured values in some cases.

onize these plots due to their light-demanding nature, although many of the darker plots will probably remain without any understory growth over the next couple of years. One third of all plots are exposed to more than 50% of full sunlight, so we should expect to see the quick spread of generalist and non-native species in these plots, particularly naturalised species not targeted by the Park's invasive management efforts. The remaining ∼15% of plots experience intermediate levels of sunlight that are ideal for the growth and spread of native, shade-tolerant forest specialists, so we should see a substantial increase in such species in these areas, along with a few generalist species.

In summary, we will probably see a large increase in understory vegetation during the final two years of the project. The proximity to native forest, as well as the many animal species living nearby, will assist with seed dispersal, speeding understory recovery. Those plots with large slash piles and heavily-compacted skid trails will likely have minimal vegetation growth during this period, as will areas with substantial quantities of undisturbed needle litter (e.g., Block 4). The current light levels suggest that a large proportion of the new vegetation will be generalist and non-native species, as was observed during the vegetation survey in 2022. Forest specialists will most likely spread to a number of plots with low and intermediate light levels that were previously uncolonized. Overall, it seems highly probable that substantial understory recovery will occur across the site in the next couple of years, although without further intervention, it may take much longer to achieve the eventual goal of forest specialist species out-competing generalists.

3.1.3 Experimental Treatments

The purpose of applying restoration treatments to the site is to accelerate succession over the short and long term. In this experiment, one of the treatments used to facilitate understory regeneration was applied nucleation. Rather than using the clustered plantings that are more typical of applied nucleation [8, 13, 15, 29, 54], various limitations and logistical challenges resulted in the use of single plantings of beaked hazel as the nuclei. As discussed in Section 2.3.3, Algonquin's west side has the exact environmental conditions favoured by this species. In the short term, the shrubs will benefit from the relatively open canopy that has resulted from the thinning. They should assist in restoring the plantation soil by reducing compaction and increasing organic content, a task well-suited to their dense root systems [42]. They contain substantial amounts of nutrients in their stems and leaves [84, 106], which will help enrich the nearby soil over the next couple of years. In this early stage, their dense roots may compete for space and nutrients, thereby limiting the growth of other species in their immediate environment [40]. This competition typically occurs in a relatively small area (1-2 m^2) around an individual shrub [103], however, and as it will take time for their roots to expand beyond their transplanted rootball, other species should have time to establish themselves.

Above the ground, the shade provide by these shrubs may help facilitate the growth of tree seedlings and shade-tolerant forest specialists by increasing humidity levels, reducing

high soil/air temperatures, blocking direct exposure to sunlight, and protecting seedlings from browsing [40]. Their role as a food source may attract wildlife from the surrounding forest, thereby speeding seed dispersal (both their own and that of other plant species) [37, 103]. Most of the transplants are already or are approaching the age when they will begin to reproduce vegetatively [42]. It will likely take at least a couple of years for their underground stems to extend horizontally underground and turn upwards. We may therefore start to see a few small hazel clones appearing by the end of the experiment. After a few more years, with these clones fully grown, these groupings of shrubs will have the clustered structure that is more typical of applied nucleation. Their combined presence will have a greater facilitative effect on nearby vegetation, and their combined root systems and underground stems should help reduce soil compaction near the surface, particularly along skid trails. Some of the larger shrubs will also be old enough that they may start producing seeds by the end of the experiment [42]. Overall, we should expect to see an increase in native, shade-tolerant species around the transplants as they create localized environments that favour forest specialists. By the end of the experiment, we may see a noticeable difference in the types and abundance of vegetation in plots with the nucleation treatment and plots without, although it is not possible to predict whether these shrubs will have a substantial effect on the overall understory within the project's timeline.

The windthrow guard treatment was designed to assist with the survival of the beaked hazel, rather than to facilitate the growth of other vegetation. That said, we are also testing it in isolation to determine whether this treatment enhances or suppresses the growth of other species. In the near term, the impacts of the goldenrod on the soil and the shade it provides could be beneficial to native forest species. On the other hand, goldenrod appears to release some allelopathic chemicals, although they are not always effective in field conditions [113]. Goldenrod is also strongly suppressed by deep litter layers and shade from dense vegetation [43]. Therefore, this light-demanding, late summer-flowering herb, which is currently present throughout much of the site, will likely begin to disappear over time as succession progresses and woody species start to dominate the understory [4, 43].

As for the effectiveness of this treatment in blocking windthrow, we will have to wait for data to be collected before a determination can be made. It should be noted, of course, that if no shrubs are observed to experience windthrow, this is not conclusive proof of this treatment's effectiveness; some shrubs will need to experience windthrow, and only then can we determine whether the damage is statistically occurring more frequently in the plots without guards.

3.1.4 Adaptive Measures

For the remainder of the experiment, the site will be monitored to determine how the understory is developing. Although there are only 2 years remaining in this project, it is possible that the ecosystem may not follow the desired trajectory. For example, the current abundance of non-native species at the site (see Section 2.5.1) is a worrying trend, as many

are generalist species that favour the high light intensities now present across much of the area. Therefore, as we monitor ecological indicators at the site, we should also consider adapting our management strategies to handle undesirable changes in the understory. This is a challenging prospect, as the literature rarely covers tests of secondary treatments to apply after the initial treatments have failed [38], so there is little guidance available. Nevertheless, by contemplating our options in advance, we will be prepared in the event that this occurs, and we may be able to augment the literature with our results.

If the applied nucleation treatments are not resulting in an increase in understory vegetation, we could consider increasing the number of transplants per plot to create a clustered planting. This may enhance the facilitative impacts that the hazel is expected to have on seedlings. If the windthrow guard treatment is ineffective in preventing windthrow, we might consider adding another ring around the shrubs or using different species. We could also augment the existing rings, especially if the most-impacted shrubs are the ones whose rings experienced the greatest degree of transplant shock.

Overall, if we observe a poor understory response to the applied treatments, such as a lack of change in native understory species, we may have to consider transplanting additional species to the site. This could overcome dispersal limitations and difficulties in seedling establishment. Further thinning the overstory may help, but it will also encourage the growth of non-native and generalist species, so it should only be considered as a last resort.

If coverage by non-native species continues to increase, particularly naturalised species that aren't currently targeted by invasive species management, we may have to adapt our management strategy. Mowing or spraying these species could help reduce their abundance, but at large scales, these treatments can also harm desirable native species. As noted in Section 1.3.4, wood chips can be used to suppress invasive species, allowing native species to spread [32, 54, 56].

Finally, it should be noted that some undesirable pathways may only be temporary. For example, the prevalence of non-natives may decline as the canopy re-establishes itself over time. Therefore, before implementing a new strategy, we should consider whether the system may ultimately converge with the desired trajectory without further intervention.

3.2 Future Trajectory

Although this understory restoration experiment will end two years from now, restoration efforts will continue at this site for several decades. Eventually, the Park's goal is to transform the plantation into a native hardwood forest. In this final section, we will therefore examine the expected restoration trajectory of this site over the coming decades. To assist with this analysis, a small survey was conducted in a nearby intact forest to direct our projections for the future of the research site.

3.2.1 Survey of Hardwood Forest

To guide the long-term restoration work for this area, we can use the surrounding forest as an approximation of the research site's status prior to the construction of the buildings in the early 1900s. The surrounding area can therefore act as a reference for our projections of the site's successional trajectory. To make the comparison, however, we will have to determine the current conditions of the nearby forest, including the light levels, soil quality,[3] and understory vegetation.

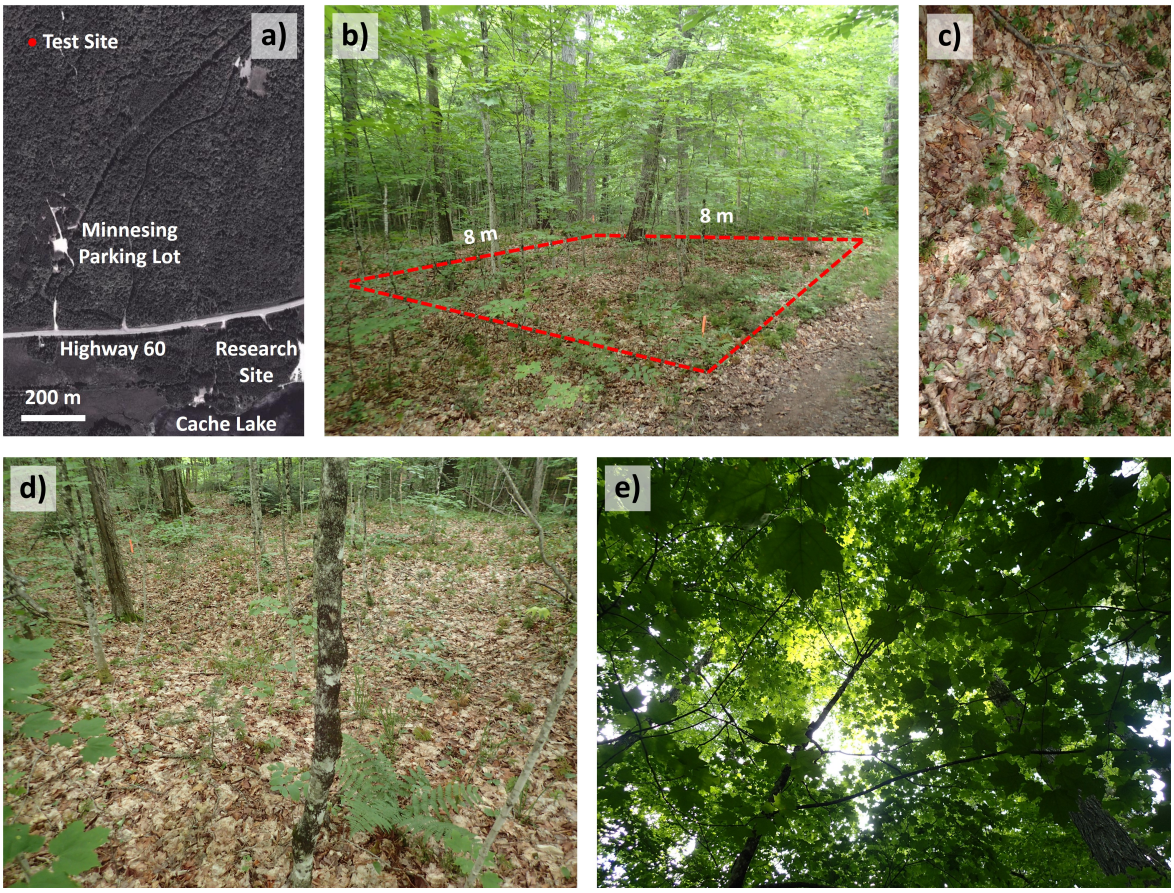


Figure 3.1: a) Location of hardwood forest survey at Minnesing trails [122]. Red circle indicates approximate location of 8 m × 8 m plot. b) Experimental plot at Minnesing staked out using pigtail markers, indicated with dashed red lines. The trail can be seen in the image's lower right corner. c) Typical ground cover within the plot. d) A wider view of the plot's understory. e) Dense overstory composed entirely of sugar maples.

On July 16, 2022, a single 8 m × 8 m experimental plot was staked out in the sugar maple forest ∼1.13 km northwest of the research site (Fig. 3.1a). Figure 3.1b) shows the

[3] Although soil samples were collected from the forest at Minnesing, they have not yet been analysed, so those results will not be included here.

plot, which was located by the side of the Minnesing bike/ski trail. This site was selected at random while walking down the trail. It is sufficiently far from the parking lot and the associated pine plantations that it can be considered a relatively undisturbed area that is typical of the Algonquin highlands hardwood forests. There may be some edge effects, as the plot was placed directly beside the trail, but these impacts should be minimal, since it is a simple dirt trail. To avoid harming the delicate forest ecosystem, it was also decided that wandering further into the forest away from the trail would be inadvisable. Light, soil, and vegetation surveys were conducted in the plot using the same methods as at the research site (see Section 2.2.2).

Cover Type	**Species**	**Cover Class**	**Estimated % Cover**
leaf litter	-	3	37.5%
clubmoss	*Dendrolycopodium*	2	15%
false Solomon's seal	*Maianthemum racemosum*	2	15%
sugar maple saplings	*Acer saccharum*	2	15%
balsam fir saplings	*Abies balsamea*	1	2.5%
beaked hazel	*Corylus cornuta*	1	2.5%
bladder sedge	*Carex intumescens*	1	2.5%
Canada mayflower	*Maianthemum canadense*	1	2.5%
intermediate wood fern	*Dryopteris intermedia*	1	2.5%
northern starflower	*Lysimachia borealis*	1	2.5%
red trillium	*Trillium erectum*	1	2.5%

Table 3.1: A summary of results from the vegetation survey conducted at the Minnesing test site.

The results of the vegetation survey are presented in Table 3.1, where they are ordered by Daubenmire cover class and the associated % cover (see Section 2.2.2). The most prevalent species were clubmosses, false Solomon's seal, and sugar maple saplings, which each had an estimated coverage of 15% of the plot. The plot also had several spring-flowering herbs, including false Solomon's seal, mayflowers, starflowers, and trilliums. Many of these species were observed to be flowering at Minnesing earlier in the spring, before the canopy had closed over with new leaf growth. All species discovered within the plot are native, shade-tolerant species. Note the presence of beaked hazel, which was used in our nucleation treatments. As highlighted by Fig. 3.1c), all exposed ground not occupied by plants was covered in leaf litter from the overstory. This leaf layer was quite deep and may prevent

seedling establishment. This could be one reason why the understory is so sparse, as shown in Fig. 3.1d).

Another factor impacting vegetation growth is likely the canopy cover, which was very dense and entirely composed of sugar maples within the plot (Fig. 3.1e). (Eastern hemlocks, American beech, striped maple, and red maple were also observed nearby.) Measurements[4] taken at the site revealed understory light availability to be just 0.56% of full sunlight, which is far below the tolerance of many species.

These results are quite typical of an old-growth forest, with dense canopy above and a relatively sparse understory containing many shade-tolerant, forest specialists. Although time constraints limited the extent of this survey, it would have been ideal to study several plots, both at this location (to obtain a spatial average) and at other locations (to determine the range of conditions across the nearby landscape). With this information, however, we can begin to construct the expected trajectory of the research site over the long term.

3.2.2 Long-Term Projections

Substantial research has been done on understory development and succession in secondary forests [23], providing a general framework for projecting the plantation's future. In general, light availability appears to be the key factor determining the composition, structure, and function of forest vegetation [40–44], though a number of other factors, ranging from soil quality to disturbance regimes, have significant influences as well. Using the information gathered in Chapter 1 and the Minnesing survey data as references, we can estimate how the research site will develop in the long term. Although there have been few long-term understory studies of conifer plantations in a northern mixedwood plains ecozone, we should be able to construct a plausible timeline for the site.

1-10 Years

Over the next decade, we can expect the understory to take advantage of the new light conditions, and we should see a large increase in understory diversity and abundance across the research site. Initially, generalist species will likely remain common in bright areas, while forest specialists will colonize the plots with greater canopy cover. With on-going invasive species management, most exotic species should disappear from the site over this time period. The transplanted hazel should help improve soil conditions, particularly on the skid trails, and all of these shrubs will reach the age where they can begin to reproduce

[4]Light intensity was measured at the site at around 4:20 pm, half an hour after taking the background measurements in the Minnesing parking lot. The walk from the parking to the site took approximately 20 minutes, and another 10 minutes were required to set up the pigtail markers so the measurement could be made in the plot centre. As usual, the measurements were taken during periods of full sunlight, without clouds.

vegetatively [42]. Small hazel colonies will therefore appear across the site, acting as nucleation sites. These clusters will also act as nurse plants by providing shade and protection for recruited seedlings, thereby facilitating the growth of other understory species. The hazel will attract seed-dispersing animals, as will species such as raspberry and snowberry, which are common throughout the site. The remaining mature red pines, which are currently quite thin and susceptible to bending and breaking, will likely become stronger and more windfirm [24].

After the first several years, the canopy should begin to slowly close over again as the remaining overstory trees expand into the available space [19, 25]. Young saplings will also take advantage of the newly-available growing space and form patches of secondary canopy in some areas. With the increased shade, many generalist species (including naturalised non-native plants, which tend to be light-demanding species) will begin to disappear except in areas with large canopy openings, while shade-tolerant forest specialists will further proliferate and replace them. As discussed in Section 1.3.5, this transition from light-demanding to shade-tolerant vegetation is an important indicator of forest succession [4]. As for the transplanted species from this experiment, the beaked hazel can easily tolerate lower light levels, with 10-40% of full sun being the ideal light intensity for hazel growth and abundance [42]. As a light-demanding, mid-successional herb that flowers in late summer, the goldenrod population will likely decrease towards the end of the decade [45, 106, 112, 113]. By this point, however, the beaked hazel should be well established, and the goldenrod's task of windthrow protection will have largely come to an end. The newly-developed understory should be able to provide sufficient protection from wind for the hazel and any developing saplings.

Alternatively, we may see the pines begin to die off over the next decade. For example, this first thinning has allowed more wind to enter the interior of the plantation, so the skinny trees are susceptible to windthrow and bending/breaking. Indeed, one year after the thinning, I noted several trees had been blown during the previous winter (Fig. 2.21). Therefore, there could be additional losses over the next few years, which would further open the canopy and allow understory vegetation (especially generalists) to flourish. If this is the case, the Park may decide to delay the second thinning, which is currently planned to take place 10 years after the first thinning treatment.

11-35 Years

By the end of the first decade after thinning, diverse and relatively abundant vegetation should fill much of the plantation understory, with native forest specialists supplanting the generalists that are present today. Assuming there isn't a substantial die-off of the remaining pines, however, the thickening canopy and reduced understory light availability could result in succession stagnating. Without restoration treatments, a conifer plantation can take 100-250 years to turn back into native, old-growth forest on its own [27]. Therefore, the Park is planning to continue applying thinning treatments to the site every 10-12 years for the next few decades [25]. The first thinning, which was conducted in 2021, was intended

to remove unhealthy and dying trees and to make room for the remaining trees to grow larger trunks, canopies, and root systems [19, 24, 25, 36]. The second thinning should open the canopy sufficiently for a substantial understory to develop, more so than the original thinning treatment [20, 22, 25]. Since the plantation was not thinned according to the usual schedule (25-30 years after planting), and as there are many large openings in the canopy (Fig. 2.41), there is already a lot of vegetation growing across the site. With the second thinning ten years from now, however, we may see an even greater change in the understory as more canopy gaps are created. Therefore, with each subsequent thinning, openings in the canopy should result in an increase in understory vegetation, particularly light-demanding and generalist species. Saplings will also take advantage of the openings created by overstory removal and will grow to fill those gaps. This will result in decreasing light levels in the years following thinning, which will again eliminate many of the generalist species except below major canopy gaps. Forest specialist species will likely dominate most of the understory by this point, with a few generalists still present. Most of the spring-flowering herbs found in the Minnesing survey are already present at the research site, and they should slowly replace the generalists. The thinning process will therefore help improve diversity and resiliency [24], keeping the restoration on track over the long term and preventing succession from stagnating due to an overly dense canopy.

The research site is located in the Algonquin Highlands on the Park's west side, where the forests are primarily hardwood [53]. This is likely why the vegetation survey conducted in summer 2022 revealed that many of the saplings already present at the site are hardwood species: choke cherry, black cherry, red maple, and sugar maple. Balsam fir is also present and is currently the most common species of sapling at the site. From the survey at Minnesing, we might expect sugar maples to eventually dominate among sapling recruits, especially as several sugar maple stems were included with the nucleation transplants. A shade-tolerant, highly-competitive species [81] and the most common hardwood in Algonquin [53], sugar maples favour the sandy loams present across much of the area [42]. Their need for soils with high moisture retention [53] will be readily fulfilled at the site in areas with deep soils and thick duff layers. Those areas with shallow soil and exposed bedrock, however, may favour other species until the soil eventually builds up. This increase in saplings may attract more moose, which browse on the leaves, and their droppings can help disperse seeds and add nutrients to the soil.

The moose may also be attracted to the increases in beaked hazel, which they sometimes consume [37]. Within the first few decades, hazel colonies should form throughout the site. By this time, they may have formed impenetrable thickets in a few areas, which could choke out other understory vegetation. Balsam fir seedlings can still establish themselves below hazel thickets [42], but this would not be an ideal outcome. Fortunately, as tree saplings mature and the canopy begins to close, hazel invasion should be halted due to limited light availability [103], preventing it from dominating the understory as a dense thicket. Over the years, shade-tolerant forest specialists will have benefited from the protection and shade offered by the hazel, as well as the improved soil quality. The goldenrod forming the windthrow guards should have disappeared after the first few decades, as its abundance

tends to decline with increasing shade and successional progress [45].

35 Years and Beyond

In the long-term, we should expect to see substantial changes to the ecosystem at the research site. Over time, all but the strongest red pines will be removed by the repeated thinning procedures, such that after about 30-40 years (total of 4-5 thinnings), the plantation will have been replaced by a young hardwood forest [25]. Based on the observations at Minnesing, the saplings recruited in the understory at the research site will eventually be dominated by sugar maples, along with other maple species, balsam fir, and hemlock. The remaining red pines can survive for hundreds of years, although they're unlikely to regain dominance except temporarily in the event of a disturbance [53]. Choke cherry trees, which are currently present in the understory at the site, will likely persist, but their reproduction will have largely ceased by this point. Choke cherries are a disturbance-adapted species that only flower in full sun [53], so as the canopy closes once more, their only chance for continued reproduction is if another disturbance occurs at the site. Black cherries are similarly disturbance-adapted and do not grow well in shade, so they may only be able to persist for a time if they can out-compete the maples for light [53]. Shorelines in this region of the Park often have hemlocks, cedars, firs, and spruce, so these species may actually dominate along the lake shore (Blocks 3 and 4), while the northern end of the research site transitions to a sugar maple forest (Blocks 1 and 2). At this point, with the thinning work concluded, a 30- to 40-year-old hardwood/mixedwood forest will now have been established on the site of the former hotel and Park Headquarters.[5] In this environment, the establishment of a hardwood forest indicates the most mature stage of succession [45].

Once a thick layer of leaf litter has been established, as is the case at Minnesing, sugar maples are one of the few species whose seedlings can actually penetrate the leaves and establish themselves [53]. Their high dispersal rates and extreme competitiveness tends to crowd out other species, such that many of Algonquin's hardwood forests are composed of 60-70% sugar maple [53]. With the increase in sugar maples at the site, we should expect to see more deer mice, Algonquin's primary predator of sugar maple seeds [53]. Other species, such as weasels, owls, and foxes, depend on the mice as a source of food [53], and they may therefore begin inhabiting the area as well.

Assuming there is sufficient disturbance (e.g., wind from the lake) to maintain a few periodic canopy openings, the young hardwood forest should be able to sustain a wide array of understory specialist species, including fungi and spring-flowering herbs. We may see the rise of clubmosses, which are very common at Minnesing but are currently not found anywhere at the research site. Generalist and exotic species should have disappeared

[5] This forest will be established 80-90 years after the buildings were removed. Judging by the general lack of mature hardwoods at the site, this is still much faster than such a forest would have otherwise regenerated naturally. That said, if the forest had been managed according to the usual schedule (i.e., first thinning after 25-30 years), it could have taken just 55-70 years [19, 20, 24, 25] and would have been almost there by now.

entirely. At this time, the beaked hazel will likely be in decline as the canopy closes over. Although a single, spindly hazel shrub was found in the Minnesing survey plot, hazel does not favour the deep shade and root competition of a hardwood forest, and it tends to decrease in abundance as succession progresses towards a 'climax' state, such as a maple forest [42]. A quick, informal examination of the maple forest surrounding the utility corridor at Minnesing (where the transplanted shrubs were obtained) showed no beaked hazel below the canopy. After several decades, the hazel will have completed its task of facilitating understory development at the research site, and future changes to understory vegetation will be primarily determined by sugar maple canopy cover.

Although the above projections follow the typical successional pathway expected in this part of the world, we must also account for a major factor that could alter the expected trajectory: climate change. Just as many tree species moved southwards during the last ice age, modern anthropogenic climate change is likely to shift the natural ranges of tree species northwards [53]. Whereas today, Algonquin is near the northern boundary of sugar maples, by 2100, it may be at the southern edge of their range [53]. White spruce, meanwhile, will likely move so far north that it is no longer present within the Park by the end of the century or is at minimum incapable of successfully reproducing there [53]. Therefore, we will likely see new species and perhaps new ecosystems arrive here. Although there is little that can be done to prevent this, careful monitoring and the adaptation of management schemes should help the new ecosystems to thrive in the Park.

3.3 Conclusion

Over the past two years, substantial progress has been made on restoring the plantation at Cache Lake. The thinning procedures conducted in winter of 2021 removed the weakest trees and opened up the canopy. As we saw in Chapter 2, the light intensity survey revealed heterogeneous understory light availability across the site, with a mean intensity of 38.8% of full sun. Vegetation surveys suggest that understory plants have already begun to take advantage of the increased light availability and have now returned across much of the site. Many rare and delicate forest specialist species, such as trilliums and pink lady's slippers, have been documented. Unfortunately, there are also substantial quantities of non-native species introduced during the Park's hotel era, and for that reason, invasive species management is ongoing.

To facilitate the growth of native, shade-tolerant species, we transplanted 128 beaked hazel shrubs to the site in the spring of 2022. A mortality census later in the summer revealed that all but one of the shrubs survived, and the majority lost less than 10% of their leaves due to transplant shock. Now that they're established, these shrubs should create microclimates that are more favourable to native seedlings, and they may eventually develop into nucleation clusters. As this species has a shallow root system, however, they are highly susceptible to windthrow, especially in the years after being transplanted. We therefore transplanted 768 stems of Canada goldenrod to form protective rings around

the shrubs. In doing so, we explored various techniques for moving individual stems, as the literature is quite vague on this subject. The novel windthrow guard treatment does not appear in the literature, and although further monitoring of the site is required in the coming years to verify its effectiveness, we observed an 87% survival rate among the goldenrod transplants. For both the hazel and the goldenrod, transplant shock appeared to be reduced in plots with intermediate light intensities. Overall, despite the logistical challenges, the transplanting efforts were very successful.

With the treatments having been fully applied to the site, we will now commence ongoing monitoring of the vegetation cover and soil quality across the site for the remaining years of the project. It is expected that understory species will continue to proliferate across the site, aided by the increased light levels, reduced competition due to ongoing invasive species management, and beneficial impacts of the nucleation shrubs. Soil quality should also improve as compaction is reduced and nutrients, organic content, bacteria, and mycorrhizae increase in concentration. In the short term, our analysis suggests generalist and exotic species may be relatively common, but as the canopy begins to close again, native, shade-tolerant vegetation should start to dominate. Over the next several decades, the repeated thinning treatments should result in a diverse, native understory, strong overstory trees, and the establishment of a young hardwood forest on the site where the red pine plantation now stands. The combined impacts of the applied restoration treatments should be the restoration of the site's ecological integrity and the accelerated succession of a heterogeneous, native forest. The lessons learned here may then have applications in the restoration of conifer plantations across the northern mixedwood plains ecozone.

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APPENDICES

Appendix A

Treatment Plan: Treatments Assigned to Plots

Table A.1 (next page) provides the coordinates of each treatment in the experimental grid using the labelling convention of block/row/column. Note that the following plots had their treatments swapped from the original design due to transplants accidentally being placed in the wrong plots: 1/8/3 and 1/8/4; 2/3/5 and 2/3/6; 4/3/3 and 4/3/6.

Treatment	Block	Plots
Control	1	2/1, 2/4, 2/6, 3/5, 3/8, 4/2, 4/4, 4/5, 4/6, 5/1, 5/5, 5/6, 7/3, 7/6, 8/2, 8/4
	2	1/5, 2/2, 3/1, 3/4, 3/6, 3/8, 4/8, 5/4, 5/6, 5/7, 5/8, 6/1, 6/2, 7/1, 7/3, 8/8
	3	1/5, 2/4, 2/6, 2/8, 3/6, 3/7, 3/8, 4/1, 4/4, 5/4, 5/5, 6/6, 7/6, 7/8, 8/1, 8/5
	4	1/4, 2/1, 2/4, 3/2, 4/1, 4/4, 5/7, 6/2, 6/3, 6/6, 6/7, 7/1, 7/8, 8/4, 8/5, 8/8
Nucleation Only	1	1/2, 1/3, 1/8, 2/2, 2/7, 3/7, 4/8, 5/2, 5/4, 5/8, 6/2, 6/3, 6/6, 7/4, 8/5, 8/6
	2	1/1, 1/2, 1/8, 2/1, 2/3, 2/4, 2/6, 4/1, 5/3, 6/6, 6/8, 7/4, 7/5, 8/2, 8/5, 8/7
	3	1/4, 1/8, 2/3, 4/3, 4/8, 5/2, 5/7, 6/2, 6/8, 7/3, 7/4, 7/5, 7/7, 8/2, 8/4, 8/7
	4	1/2, 1/3, 1/6, 2/2, 2/5, 2/6, 3/1, 3/3, 4/3, 4/7, 5/2, 5/4, 5/6, 6/1, 8/3, 8/6
Windthrow Guard Only	1	1/1, 1/5, 1/6, 1/7, 2/3, 2/8, 3/3, 3/4, 4/7, 5/7, 6/5, 6/7, 7/2, 7/5, 7/7, 7/8
	2	1/3, 1/4, 2/5, 3/2, 3/5, 4/2, 4/5, 5/1, 5/2, 5/5, 6/3, 6/4, 7/2, 7/7, 7/8, 8/4
	3	1/1, 1/2, 1/3, 1/6, 1/7, 2/7, 3/3, 4/2, 4/6, 5/1, 5/3, 6/1, 6/3, 6/7, 7/2, 8/3
	4	1/8, 2/7, 2/8, 3/7, 4/2, 4/5, 5/1, 5/8, 6/5, 6/8, 7/2, 7/3, 7/4, 7/7, 8/1, 8/2
Nucleation & Windthrow Guard	1	1/4, 2/5, 3/1, 3/2, 3/6, 4/1, 4/3, 5/3, 6/1, 6/4, 6/8, 7/1, 8/1, 8/3, 8/7, 8/8
	2	1/6, 1/7, 2/7, 2/8, 3/3, 3/7, 4/3, 4/4, 4/6, 4/7, 6/5, 6/7, 7/6, 8/1, 8/3, 8/6
	3	2/1, 2/2, 2/5, 3/1, 3/2, 3/4, 3/5, 4/5, 4/7, 5/6, 5/8, 6/4, 6/5, 7/1, 8/6, 8/8
	4	1/1, 1/5, 1/7, 2/3, 3/4, 3/5, 3/6, 3/8, 4/6, 4/8, 5/3, 5/5, 6/4, 7/5, 7/6, 8/7

Table A.1: Treatment plan. Treatment plots are labelled by row/column.