COST-BENEFIT ANALYSIS OF SCARIFICATION IN THE BOREAL FOREST

by

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A CAUTION TO THE READER

ABSTRACT

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Keywords: Scarification, soil disturbance, site preparation, scarification benefits, scarification costs, boreal forest, seedling growth, seedling mortality, seedling germination, water quality, and microbial activity.

Soil scarification is a site preparation method that improves growing conditions for seedlings. The practice has associated benefits and costs putting its feasibility into question within the boreal forest. The costs include aspects of environmental degradation in that it causes increased runoff impacting hydrological features and decreases microbial activity within the soil. Additionally, there are economic costs associated with the practice being the cost to purchase, maintain, and fuel scarification machinery, as well as operator wages. This is offset by greatly increased success rates of regeneration. Seedlings experience expedited growth in both the short and long term as well as decreased mortality rates. Ultimately, the benefits of scarification do outweigh the cost in the majority of scenarios within the boreal forest making it a feasible practice. Sites where the benefits may be expected to be dampened include sites with shallow soils, thin organic layers, excessive slope, or sites implementing natural regeneration rather than seeding or planting.

TABLE OF CONTENTS

LIBRARY RIGHTS STATEMENT	i
A CAUTION TO THE READER	ii
ABSTRACT	iii
TABLE OF CONTENTS	iv
FIGURES	v
ACKNOWLEDGEMENTS	vi
INTRODUCTION	1
METHODOLOGY	3
Importance of mechanical site preparation	4
Boreal Forest Soils	6
Types of Site Preparation	7
Ecological effects of mechanical site preparation	12
Effects on seed germination	15
Effects on seedling growth and survival	17
Economic costs to perform mechanical site preparation	21
Variation in species response	24
Considerations to determine site suitability	26
DISCUSION	28
CONCLUSION	32
LITERATURE CITED	33

FIGURES

Figure		Page
1.	Mounding scarification diagram	8
2.	The effect of various scarification treatments in 5 different harvesting methods (SH: shelterwood high, SM: shelterwood medium, SL: shelterwood low, PC: patch cutting, CC: clear cutting) on spots lacking a seedling (Hanssen et al. 2003).	10
3.	Height and length of leading shoot length of Norway spruce as a result of various scarification treatments (Johansson et al. 2013).	11
4.	The impact of clear-cutting and scarification on the phosphorus concentration and quantity of suspended solids in small brooks (Ahtiainen 1992).	13
5.	The effect of scarification and burning on bacterial biomass and fungi biomass in soil (Jiménez Esquilín 2008).	14
6.	Average Scots pine seedling counts on sites that faced various treatments (A: scarification, B: litter burned, AB: litter and humus burned, C: no soil disturbance (Hille and Den Ouden 2004).	15
7.	Average Scots pine seedling height of the top five tallest from each soil disturbance treatment (A: litter and humus burned, AB: litter burned, B: scarified) 23 weeks after seeding (Hille and Den Ouden 2004).	17
8.	Annual height growth of black spruce in response to various scarification treatments (CO: unscarified control, C1: cone single-pass, C2: cone double-pass, D1: disk single-pass, D2: disk double-pass) with different regeneration types (Prévost and Dumais 2018).	18
9.	The effect of various silvicultural treatments on pine weevil caused mortality and severe damage 3 years after seedlings were planted (Petersson and Örlander 2003).	20
10.	Fuel consumption of skidders as they grow in years of use (Kopseak et al. 2021).	23
11.	The effects of scarification on (a) gravimetric soil moisture content and (b) forest floor nitrogen mineralization in Abitibi (warm-dry region) and Côte-Nord (cold-humid region).	28

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INTRODUCTION

Site preparation regarding forestry is the process of increasing the favourability of site conditions to foster the survival and growth of seedlings (Von der Gonna 1992). This may be achieved in multiple different ways. Soil disturbance is a common method of site preparation in which the soil is mechanically altered to expose mineral soil to the surface (Von der Gonna 1992). This is beneficial for the seedlings as the mineral soil holds essential nutrients that facilitate growth. This process is also commonly known as scarification and typically happens 6 months to a year before the planting of seedlings. (Natural Resources Canada 2022). Soil disturbance also combats soil compaction which limits plant growth by inhibiting root penetration (Natural Resources Canada 2022). Another common goal of site preparation is to exterminate competing vegetation (Von der Gonna 1992). Herbicides are used to kill deciduous vegetation to allow for improving resource availability for the desired coniferous trees.

Scarification is a very important process to the success of seedlings. Maximizing the success of seedlings through scarification is also an economically viable practice in many cases. The planting of seedlings is costly so they must be successful to return a profit in the future. Seedlings may face early mortality if they are not planted in mineral soil due to a lack of essential nutrients or available moisture. If they do not face mortality, then at the very least their growth will be stunted. This allows neighbouring vegetation to outcompete the seedling and limits the availability of resources, most notably light as it may shade the struggling seedling out. Depending on the shade tolerance of the given species, being shaded out could cause death yet again further reinforcing the importance of scarification. The cost associated with scarification is offset by the increased success of the replacement stand.

The objective of this literature review is to analyze the costs and benefits associated with performing scarification as a site preparation method in order to determine the lengths at which it is feasible within the boreal forest. If scarification is used on a site, then the seedlings will experience an increased growth rate (Karlsson and Oerlander 2000). This is because the seedlings are more likely to be planted into mineral soil which is more likely to provide the seedling with the appropriate moisture levels and essential macronutrients than the top organic matter layer. This is not to say that trees on sites with scarification are always planted inappropriately. Planters are instructed to exclusively plant seedlings in mineral soil however, for the sake of increasing efficiency, this may be overlooked.

METHODOLOGY

The information compiled in this literature review was primarily found from published research articles. These were found by searching the databases Google Scholar and Web of Science to find articles relevant to analyzing the costs and benefits of scarification in the boreal forest. The citations listed in the literature review were largely sourced from Google Scholar with the exception of Government webpages from the Government of Canada and Ontario. These webpages were found via Google searches.

Price estimates for equipment associated with scarification including the skidder, forwarder, and disc trencher were determined by browsing online listings on various used machinery selling websites. These websites include ForestryTrader, Forestry Equipment Sales, and Machinio. Newer and older models were taken into consideration in order to assign a representative value for each piece of equipment.

Importance of mechanical site preparation

Following the harvest of timber from a forest, the forest is regenerated using various techniques to allow for a subsequent harvest at a later time. The steps taken to regenerate a forest are critical to the success of the process and varies by site. A forester must take into consideration things like soil conditions, current forest conditions, and desired species composition to select an appropriate regeneration technique.

A very common regeneration technique is manual tree planting. This process involves an individual equipped with a shovel and seedlings aged at roughly 2 years that are carried around in large pouches. It has a higher cost than many regeneration methods however this cost is offset by high success rates. Their high rate of success can be attributed to planters being able to select suitable microsites with ideal conditions for the seedling and also unlike a seed that must first germinate, the seedling already has years of preestablished growth.

Aerial seeding is another popular regeneration technique. This process requires an aircraft as well as seed which is dispensed onto the land. For large-scale projects, aerial seeding is much more cost effective than planting by hand. The downsides however are that there is little control over seed placement and seeds may fail to germinate. Both methods are improved by scarification.

Site preparation is the process of creating more favourable growing conditions to foster the creation of the future desired forest conditions (Ontario

Government 2019). The various techniques used are site specific and depend on the reforestation goals. Site preparation is successful if seedlings are given an increased chance of survival as well as faster establishment. The treatments may be mechanical, chemical, or biological.

One goal of site preparation is reducing competition from other vegetation. A very common example in Northern Ontario is the trembling aspen (*Populus trembuloides*). It is capable of vegetative reproduction allowing it to reestablish stands very quickly outcompeting the coniferous seedlings that are typically planted in the region in the early stages of succession. This suppresses the seedlings' growth and increases mortality due to the impairment of their ability to access essential resources such as nutrients, water, and light. A way to resolve this is through the use of a herbicide which is a chemical treatment used to exterminate deciduous vegetation such as the trembling aspen or the employment of scarification which destroys preexisting vegetation.

Another potential goal of site preparation is to alter soil conditions. Soil in its present form may be unsuitable for seedling establishment. The soil is where trees source water and nutrients via their roots so suitable soil conditions are critical for stand reestablishment. Much of the time soil has a thick layer of organic material that has accumulated on top of the soil. Trees planted in organic matter will likely face early mortality. This can be resolved through the use of mechanical site preparation methods blading and scarification which exposes mineral soil underneath the organic layer.

Boreal Forest Soils

The boreal forest is characterized by its cold temperatures as well as the dominance of coniferous tree species. It accounts for 33% of the Earth's total forested area (Natural Resources Canada 2024). The soil in this biome has specific characteristics that introduce various challenges when it comes to stand reestablishment.

The soil in the boreal forest is typically highly acidic. This is caused by the decomposition of needles that have fallen from the trees accumulating on the surface of the soil. The tannins and lignin of the needle release organic acids which are leached into the soil. Vegetation growing in the soil must be adapted to the acidic conditions otherwise it will be outcompeted. Additionally, nutrient availability is low in comparison to other soils. Due to the cold temperatures, the rate of decomposition of organic matter is slow. When the organic matter decomposes, it releases nutrients into the soil, so this means the flow of nutrients into the soil is sluggish. Permafrost is another concern for some parts of the boreal forest, particularly the northernmost regions. Permanently frozen soil impacts soil drainage as well as nutrient availability.

The organic layer otherwise known as the "O horizon" varies in thickness depending on the local conditions however it is usually on the thicker end of the spectrum due to cold temperatures of the boreal forest region causing slow decomposition rates. The O horizon is mainly comprised of needles, leaves, and branches from the trees. Mosses and lichen are also included within this layer. There are ways that the organic layer facilitates the growth of the established stand. It serves as insulation dampening temperature fluctuation in the mineral soil. It also prevents the erosion of the mineral soil by providing a physical barrier from the elements. While it can facilitate tree growth, it inhibits the growth of seedlings and the germination of seeds. There are multiple factors contributing to this. The nutrient availability within the layer is lacking due to microbes present within the layer utilizing the nutrients to further break down organic matter. Additionally, the organic matter may drown out seedlings. The O horizon is great at retaining moisture however this may cause waterlogging which may lead to a lack of oxygen or rot for the seedling.

Unlike organic matter, mineral soil has the necessary qualities to harbour seedling growth. It is composed of the mineral particles sand, silt, and clay. The primary reason that mineral soil promotes seedling growth is nutrient availability. Essential nutrients nitrogen, phosphorus, and potassium are found in the mineral soil from the weathering of rocks and minerals within the soil. These nutrients are used for developing plant tissues as well as photosynthesis. Additionally, mineral soil provides a suitable site for root anchorage creating stability for the trees. Lastly, mineral soil can retain water to be used by trees, but it also has the ability to drain away excess water so that the roots have enough oxygen available for respiration.

Types of site preparation

Scarification is a site preparation process involving the physical alteration of soil. The goal of the process is to create more favourable growing conditions for trees (Von der Gonna 1992). This is achieved by the exposure of mineral soil. There are multiple ways to scarify land. Certain treatments may be more suitable depending on the scenario.

Mounding and trenching are both mechanical methods of scarification. Mounding involves the creation of a bunch of small mounds by displacing soil. Trenching is similar however instead of the creation of individual mounds, it creates long furrows in the soil. This is more disruptive to the site as the impacts to the seedbank are more adverse. Additionally, advanced regeneration is more likely to be destroyed when trenching in comparison to mounding. The size of the mounds and furrows is dependent on the size of the planted trees and the conditions of the soil (Cardoso et al. 2020). The ideal location for growth with both methods is the hinge as seen in Figure 1. The hinge provides optimal moisture and nutrients leading to success for the seedling. Mounding allows for seedling to be planted higher up in comparison to trenching giving seedlings an advantage over non crop vegetation.

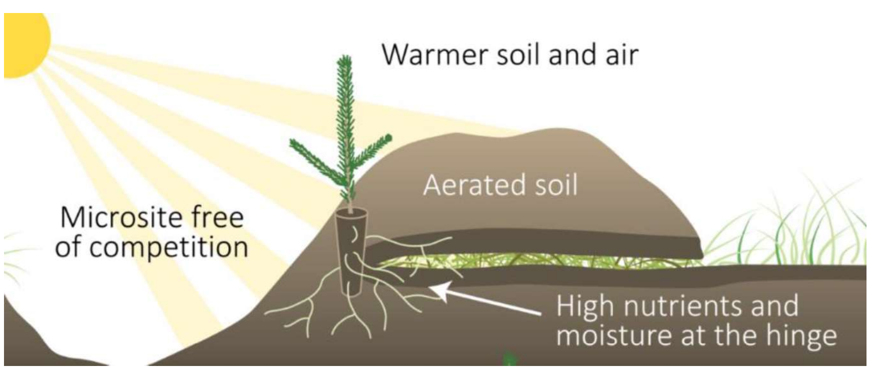

Figure 1. Mounding scarification diagram

A prescribed burn is another scarification method. The burn removes organic matter on the soil surface to expose mineral soil and reduce competing vegetation to aid in seedling development. This also increases nutrient availability at the top of the soil further aiding the seedlings (Sykes and Horrill 1981). Additionally harvesting operations may inadvertently aid in scarification. Heavy machinery and the extraction of logs cause a lot of soil disturbance therefore exposing mineral soil. Lastly, screefing is a manual scarification method which is the process of removing organic matter by kicking or by hand to expose mineral soil (Ontario Government 2019). Screefing is used by tree planters on sites that have not received a scarification treatment.

There are multiple ways to scarify land and these different methods are all put to practice in the boreal forest. All these methods have the same overall objective in that they expose mineral soil to aid in seedling growth, they just do it in differing ways. If there are different mechanical scarification methods, then perhaps there are some that increase seedling performance more than others.

One study compares patch scarification to inverting (Hanssen et al. 2003). The difference between these two methods is that patch scarification simply removes the organic layer whereas with inverting the mineral soil was dug out 30 cm in depth and then dumped back on top of the organic layer leaving it buried. The treatments were performed in areas that used 5 different harvesting methods as well. The harvesting methods were high intensity shelterwood, medium intensity shelterwood, low intensity shelterwood, patch cutting, and clear cutting. The results showed that while the difference in performance between the two scarification methods averaged out to be fairly similar, inverting performed slightly better with the shelterwood systems and patch scarification performed a bit better with patch cutting and clear cutting (Hanssen et al. 2003). The graph below displays how the inverting treatment experienced quite a lot of mortality for the patch cutting and clear cutting sites. It also shows that unscarified sites performed much worse than any scarification method by a large margin. The study also concluded that the seedlings on inverted sites may experience faster growth in the coming years due to the release of nutrients from the buried organic layer. In the 6 years of the study, this was not observed however it has the potential to occur in the future.

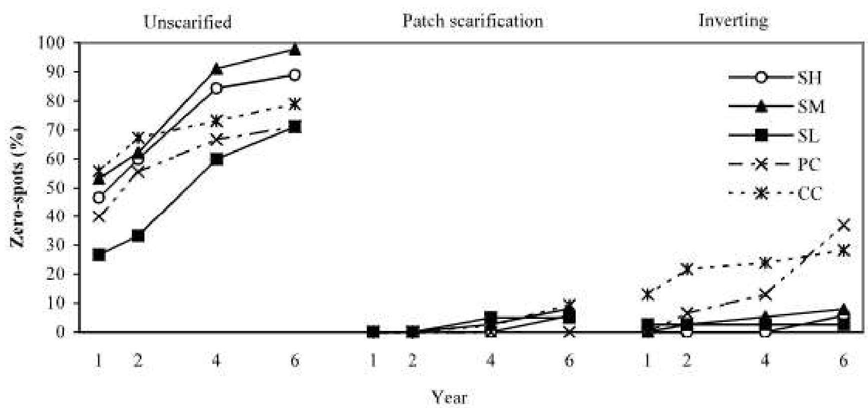

Figure 2. The effect of various scarification treatments in 5 different harvesting methods (SH: shelterwood high, SM: shelterwood medium, SL: shelterwood low, PC: patch cutting, CC: clear cutting) on spots lacking a seedling (Hanssen et al. 2003).

A similar study also explored the effectiveness of different mechanical scarification methods. The success was measured by the height, length of the leading shoot, and mortality of Norway spruce (*Picea abies*). Unlike the previous study, this analyzes the success of the trees at a longer time scale all the way up to 18 years rather than just 6. The three scarification methods compared in this study are mounding, inverting, and intensive inverting. The difference between inverting and intensive inverting is that intensive inverting creates 3500 spots per ha rather than 2500 spots per ha. The same amount of seedlings were planted for each treatment so the additional spots simply provided planters with more available microsites to select from. The results for height and length of the leading shoot were very similar for the three scarification treatments (Johansson et al. 2013). The regular intensity inverting treatment performed slightly worse than the other treatments in terms of growth however not by a significant amount. The unscarified treatment also had increased variation in height. This is likely due to the increased variability of microsites that unscarified land provides. This may cause complications as the stand develops as the shorter trees may receive less resources and remain in the understory.

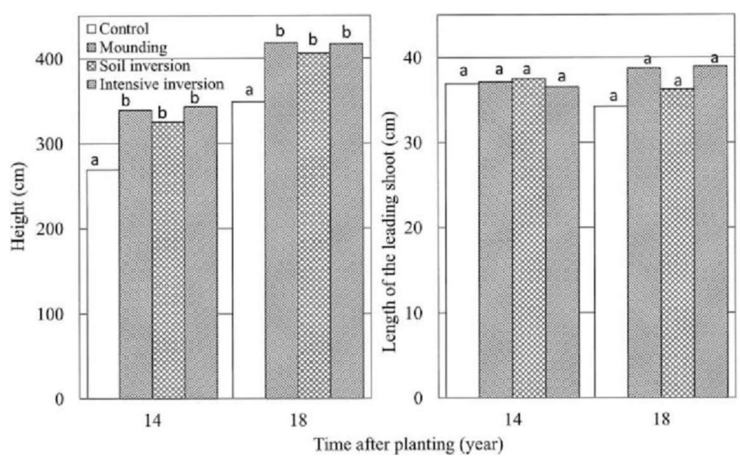

Figure 3. Height and length of leading shoot length of Norway spruce as a result of various scarification treatments (Johansson et al. 2013).

While there was not a significant difference for height and length of the leading shoot, the difference in mortality rate was more significant. The inverting treatments both had very similar survival rates at 77% for normal and 76% for intensive. Mounding however only had a survival rate of 67% which is considerably worse (Johansson et al. 2013). The buried organic layer of the inverting treatment is a likely cause of this as it provided the seedlings with additional nutrients. The majority of the mortality occurred within the first 5 years.

Overall, it cannot conclusively be said that one scarification method is superior to another as certain methods perform better on certain sites. This is because the difference in growth and mortality is negligible in most cases and varies too much between studies on the topic. All scarification treatments have a common goal in exposing mineral soil and reducing interspecific competition. This is why the difference in measurable parameters is fairly insignificant when it comes to comparing treatments. It is likely wiser to select a scarification treatment based on the availability and cost of equipment associated with performing the treatment. It is still arguable that inverting is overall superior due to its ability to provide seedlings with more nutrients.

Ecological effects of mechanical site preparation

While scarification may be effective at creating favourable conditions for seedling establishment, there are downsides to this practice. When prescribing this treatment, one must take into consideration the potential degradation of the local ecosystem.

Scarification increases erosion which is likely to end up increasing turbidity in nearby water bodies (Ahtiainen 1992). After a scarification treatment, the mineral soil experiences increased exposure to the elements as the organic matter is no longer serving as a protective layer. From there the soil ends up in water bodies increasing the quantity of suspended solids. The erosion also causes the concentration of phosphorus, iron, and nitrogen to spike. These combined factors are likely to negatively impact local fish populations. The growth, reproduction, and spawning of salmonoids are negatively affected by increases in suspended solids in the water (Bash et al. 2001). This is why it is important to identify water bodies as areas of concern to mitigate this type of issue.

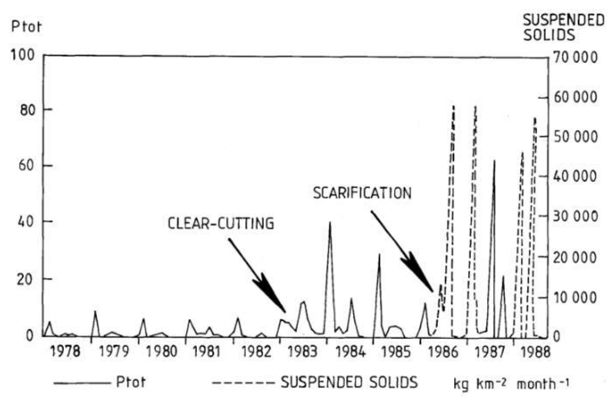

Figure 4. The impact of clear-cutting and scarification on the phosphorus concentration and quantity of suspended solids in small brooks (Ahtiainen 1992).

Another negative impact of scarification is the loss of organic matter and microbial activity within the mineral soil (Jiménez Esquilín 2008). This reduces soil fertility by reducing the nutrient availability. This also means that mycorrhizal fungi quantities are reduced in the soil negatively impacting water and nutrient uptake for the vegetation growing in the soil. Overall, this will lead to decreased forest productivity in the future.

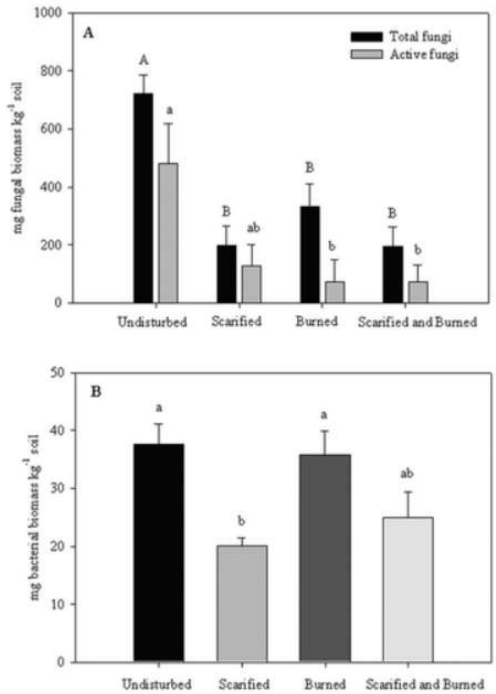

Figure 5. The effect of scarification and burning on bacterial biomass and fungi biomass in soil (Jiménez Esquilín 2008).

Scarification also may negatively impact local wildlife as it alongside harvesting operations alters the habitat creating early successional forest conditions that favour species such as the moose (*Alces alces*), and elk (*Cervus canadensis*) (Finnegan et al. 2021). Scarification destroys lichen that is commonly fed on by the woodland caribou (*Rangifer tarandus*) which hinders foraging availability for them (Finnegan et al. 2021). Sites that are clearcut but not scarified maintain lichens for approximately 2 years whereas scarified sites eliminate the majority of the lichen upon the application of the treatment

(Finnegan et al. 2021). Lichens take anywhere from 60 to 100 years to regenerate upon harvesting which is why strategic land use is critical to ensure that forage availability is high enough for the survival of caribou (Finnegan et al. 2021).

Effects on seed germination

Scarification is also beneficial when seeding is the regeneration method rather than just planting (Hille and Den Ouden 2004). This is especially true with Scots pine (*Pinus sylvestris*) seedlings as seen in Figure 6 as well as lodgepole pine (*Pinus contorta*). The Scots pine is adapted to colonize sites that have been recently burned. The fire burns the organic layer providing easier access to the mineral soil. The reasons that seeds fail to germinate are a lot of the same reasons that seedlings face early mortality for example excessive moisture and poor temperature regulation. For this reason, the soil that did not receive any disturbance averaged a total of 0 Scots pine seedlings per plot 23 weeks after seeding. The other treatments were much more successful notably the scarified treatment averaging 11 seedlings per plot. The second most successful treatment was the burning of litter and humus with 6 seedlings followed by the burning of litter at 4 seedlings. Scarification is also an effective tool when it comes to regenerating stands dominated by lodgepole pine as it greatly enhances their natural regeneration abilities especially at high elevations where competing aspen is absent (Vyse and Navratil 1985).

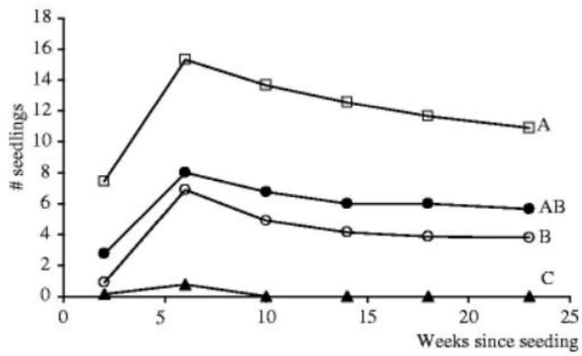

Figure 6. Average Scots pine seedling counts on sites that faced various treatments (A: scarification, B: litter burned, AB: litter and humus burned, C: no soil disturbance (Hille and Den Ouden 2004).

While scarification was more effective at seedling recruitment for the Scots pine, the seedlings there did not experience as much growth as the burning treatments (Hille and Den Ouden 2004). In the case of a forest fire, a large influx of nutrients is added to the top layer of the soil leading to more rapid height growth in the seedlings with burning treatments (Sykes and Horrill 1981). As seen in Figure 4, the litter and humus burning treatment yielded the tallest seedlings followed by the litter burning treatment and the scarification treatment. The treatment without soil disturbance did not have any seedlings upon the conclusion of the 23-week study excluding them from this assessment. The difference in seedling recruitment was more significant than the height growth, however.

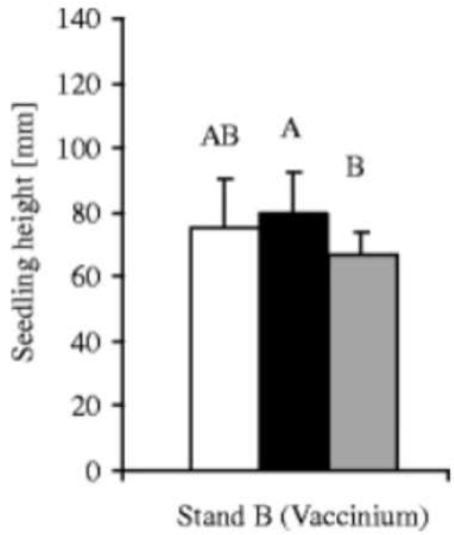

Figure 7. Average Scots pine seedling height of the top five tallest from each soil disturbance treatment (A: litter and humus burned, AB: litter burned, B: scarified) 23 weeks after seeding (Hille and Den Ouden 2004).

Effects on seedling growth and survival

As previously stated, the goal of scarification is to create more favourable conditions for seedlings therefore increasing growth. The seedling response to scarification is dependent on the type of scarification treatment as well as the regeneration method (Prévost and Dumais 2018). The regeneration method that has the most significant response to scarification is planted seedlings as seen in Figure 8. By the end of the 25 years, the scarification treatments had increased height growth by 9.4 cm/year. For pre-established layers and natural seedlings, the response was much less drastic at only a 2.8 cm/year and 2.7 cm/year increase respectively. The previous metrics are all based on black spruce seedlings being grown in the boreal forest. Additionally, the planted seedlings had a much faster response to the scarification whereas with pre-established layers and natural seedlings, it takes roughly 15 years to have a noticeable difference. All of this is due to the fact that planted seedlings are planted in the mineral soil exposed by scarification and for the other regeneration methods it is simply up to chance to determine seed drop location causing many to land in microsites with less suitable growing conditions.

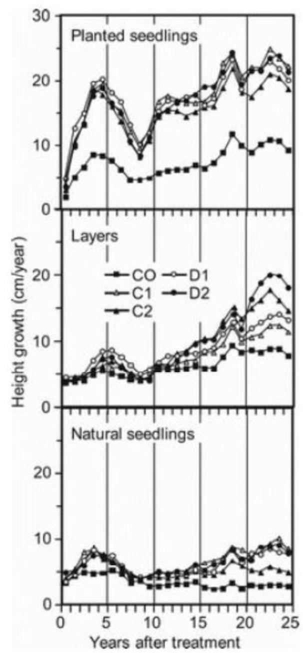

Figure 8. Annual height growth of black spruce in response to various scarification treatments (CO: unscarified control, C1: cone single-pass, C2: cone double-pass, D1: disk single-pass, D2: disk double-pass) with different regeneration types (Prévost and Dumais 2018).

Stands treated with scarification also result in trees with greater stem volumes without any significant effects to wood density (Mattsson and Bergsten 2003). This is greatly beneficial to revenue totals once the stand is ready to be harvested as there is increased merchantable volume without negative impacts on the quality of the timber. Root penetration is also positively influenced by scarification as the treatment breaks up the soil (Martinez et al. 2019). This allows for the development of larger root systems more capable of water and nutrient uptake.

Scarification is also capable of increasing the pest resistance of seedlings greatly increasing their survival rate and protecting future profits. A study compared the effectiveness of scarification, shelterwood, feeding barriers and insecticide in protecting Norway spruce (*Picea abies*) from pine weevil (*Hylobius abietis*) (Petersson and Örlander 2003). It found that scarification was second, only to insecticides. It even outcompeted both feeding barriers Bugstop and Hylostop. Their sole purpose is to prevent insect damage so scarification outperforming them in addition to all the other benefits with scarification really puts into perspective how effective of a site preparation method it is. With this being said, the effectiveness of decreasing damage from pine weevil is much higher for scarification when it is used in tandem with other treatments. When scarification was the only treatment used, about 25% of the seedlings were killed or severely damaged by the pine weevil (Petersson and Örlander 2003). When used in combination with insecticides and a shelterwood system, the mortality and severe damage incredibly nearly fell to 0% however, the study did conclude that the insecticide treatment was surprisingly much more successful than similar studies (Petersson and Örlander 2003).

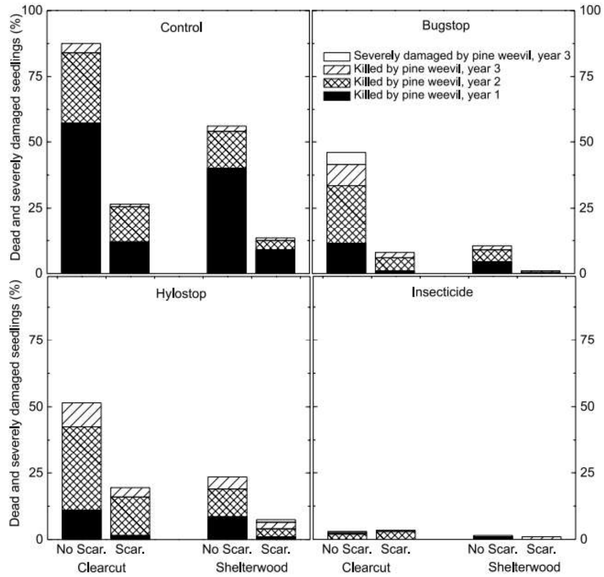

Figure 9. The effect of various silvicultural treatments on pine weevil caused mortality and severe damage 3 years after seedlings were planted (Petersson and Örlander 2003).

The reason that scarification can aid in pest resistance is because the seedlings are more tolerant to stressors. Increased resource availability as a result of scarification allows seedlings to produce increased defences therefore inhibiting herbivory. It also removes the vegetation surrounding the seedling that the pine weevil may use as a bridge to reach seedlings. The removal of these “bridges” prevents the pine weevil populations from dispersing.

Scarification however does not have any significant effect on protecting seedlings from deer herbivory (Bergquist et al. 2001). It is possible that scarification could increase herbivory from deer because scarification removes surrounding vegetation that the deer may have browsed on rather than the seedling (Huss and Olberg-Kalfass 1982). With less vegetation to select from the deer are more likely to select the planted seedlings. Seedlings on scarified sites are more likely to recover from herbivory damage however due to enhanced resource availability. Seedlings also are subject to damage caused by trampling from ungulates grazing in the area. This increases their risk of suffering from fungal disease (Roturier and Bergsten 2006). In the case of the reindeer, the soil disturbance from scarification kills off large amounts of lichen therefore decreasing how often they graze on sites with scarification in the winter months (Roturier and Bergsten 2006).

Economic costs to perform mechanical site preparation

A successful scarification treatment requires money to be performed as the costs are beyond just the potential for environmental degradation. The costs can be categorized as either fixed costs or variable costs. Fixed costs include the cost of purchasing the required equipment used to carry out a scarification treatment. Variable costs include the cost of paying operators, maintaining equipment, fueling equipment, and equipment devaluation. Taking the monetary costs of performing scarification is crucial to determining its feasibility within the boreal forest.

Traditionally in large-scale forest operations, scarification equipment is attached to either a forwarder or skidder, both of which have high upfront costs. The cost of this equipment varies depending on manufacturer, lateness of the model, and the amount of operating hours the equipment has procured. Based off online listings, the prices generally range from $400 000 to $750 000 with equipment in the lower end of the spectrum being multiple decades old with tens of thousands of hours on them while the upper end of the spectrum is occupied by equipment manufactured within the last few years and lesser than 1000 hours. There are pros and cons associated with buying cheaper old equipment in comparison to more expensive new equipment however in most cases the newer equipment will perform better in the long run.

Fuel consumption is another cost associated with scarification. Consumption rates vary based on site conditions like the terrain, the type of harvest that was performed prior to scarification, and the horsepower of the macjinery being used (Kenney 2015). Fuel costs also vary based on the state of the economy meaning that the cost to fuel equipment may fluctuate greatly. A study on skidder fuel consumption found that when skidding in even-aged forests, fuel consumption ranged from 7.81 to 9.34 L/PMH while selective forest consumed 6.49 to 7.10 L/PMH (Kopseak et al. 2021). These consumption rates are based off the extraction process and not scarification so those values may be poorly representative of scarification fuel consumption. Additionally, these consumption rates are based on skidders with much lower horsepower than the ones typically used in Canada. For example, the John Deere 848 consumes roughly 38 L/PMH. Older models of equipment typically consume higher amounts of fuel than newer models (Kopseak et al. 2021). Fuel costs are highly variable. Maintenance costs are another component of the costs associated with skidders and forwarders. Due to the adverse terrain the machines will be subject to, breakage is inevitable. Skidders however do have lower maintenance costs than both harvesters and feller-bunchers (Diniz et al. 2020). Lastly, both skidders and forwarders lose value for resale, as they grow in age and are used for an increasing number of hours.

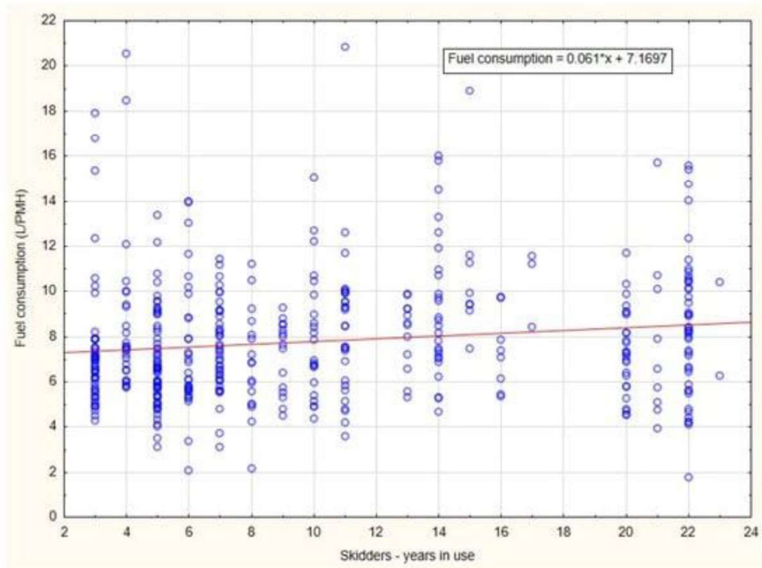

Figure 10. Fuel consumption of skidders as they grow in years of use (Kopseak et al. 2021).

Scarification equipment that is attached to the skidders or forwarders is also quite expensive. The type of scarification equipment is dependent on the type of scarification treatment whether that be mounding or trenching. Disc trenchers, just like the skidders and forwards vary in price based on the condition of the equipment. Based on current listings, commercial grade disc trenchers generally sell for $25 000 to $100 000. There are also costs associated with equipment maintenance, powering the system, and devaluation.

Operator cost is another component of the monetary cost required to perform scarification as automation in the forest industry remains in its infancy for the time being (Visser and Obi 2021). Scarification operator wages are dependent on the skill level of operators and range from $30 to $40 an hour. These operators are expected to scarify roughly 1-2 hectares of land per productive machine hour however this varies based on the equipment being used and site conditions (Gingras and Cormier 2009, Bulley 2000). Additionally, it is also worth noting that not every hour spent by operators will be dedicated to scarification as transportation to the site and other activities must be factored in.

A method used to offset monetary costs is to pay reduced rates to tree planters that are working on sites that have been scarified. This typically means paying a few less cents per tree on scarified land in comparison to land lacking site preparation. Planting on scarified land is much easier for planters as it creates microsites with exposed mineral soil removing the need for planters to manually remove the organic layer for each seedling they plant. This is why the payout reduction is generally agreed upon as being fair as planters a likely to be able to work more efficiently. This in itself does not offset the entire cost of scarification, but it certainly helps.

Variation in species response

With the various tree species in the boreal forest having different requirements for success, they are bound to have differing responses to scarification treatments. The varying responses can be attributed to a plethora of factors specific to each species such as the extent of its ability to tolerate stressors. Species that have a dampened response to scarification may not be valid candidates for scarification as the benefits are not worth the costs of the practice.

A study in Sweden analyzed how scarification impacted various species in a natural regeneration scenario. There is an issue with natural regeneration in regard to scarification in comparison to manual planting. Planters can ensure that seedlings are positioned within the bounds of the furrows and therefore reaping the benefits of mineral soil whereas with natural regeneration it is determined by chance whether seeds will land in the mineral soil. This undoubtably has an impact on the results. The study found that pine seedling density was significantly increased by scarification however, spruce and birch species were not (Karlsson and Nilsson 2005). The species of focus were Scots pine (*Pinus sylvestris*), Norway spruce (*Picea abies*), downy birch (*Betula pubescens*), and silver birch (*Betula pendula*). Scots pine is the only one of the previously stated species that is commonly naturally regenerated in Sweeden which could explain why pine density benefitted more from scarification than spruce and birch given that all species were subject to natural regeneration (Karlsson and Nilsson 2005).

As per Ontario's Forest Management Guide to Silviculture in the Great Lakes-St. Lawrence and Boreal Forests, all commonly planted tree species in the boreal forest are designated with high probability for mechanical site preparation (Ontario Government 2019). This includes black spruce, white spruce, Jack pine, red pine, and eastern white pine. Scarification is a common site preparation method for all of those species in Ontario reinforcing its feasibility across all species. While the species are unique from each other, their need for mineral soil remains constant (Johansson et al. 2007).

Considerations to determine site suitability

The geographic conditions of sites may differ greatly across the boreal forest. With these varying conditions comes varying site suitability for a scarification treatment. Reasons that a site may be unsuitable for scarification are that it would likely cause great amounts of environmental degradation, unfavourable soil conditions, and excessive danger to the operator and equipment.

One site condition that decreases the favourability of scarification is steep slopes. The first reason for this is that it poses a threat to the operator and equipment as it could cause rollovers and slippage (Berkett and Visser 2012). If the manufacturer does not specify the maximum slope steepness, then wheeled machines must not operate on slopes exceeding 30% and tracked machines must not operate on slopes exceeding 40% in accordance with the Approved Code of Practice for Safety and Health in Forest Operations (Berkett and Visser 2012). The steep slope also increases the amount of erosion which is why site preparation is rarely applied to sites with slopes exceeding 25% (Grosh and Jarrett 1994). Scarifying the soil would only exacerbate erosion as the mineral soil would be exposed to the elements. The increased amounts of runoff would eventually end up in water bodies increasing the turbidity (Zhou et al. 2015).

Soil conditions may also hamper the effectiveness of a scarification treatment in multiple different ways. Soils that are very shallow are likely not well suited for scarification because the practice might expose more bedrock than mineral soil. Additionally, rooting space for seedlings is already limited in sites with shallow soil so planting seedlings in furrows even closer to the bedrock only increases the severity of low rooting space. Soil that has a very thick organic layer may also be poorly suited to scarification as the furrows only expose more organic matter rather than mineral soil. These sorts of conditions are not common but can occur often times in the form of sphagnum moss (*Sphagnum spp.*) which can cover forest floors if its habitat requirements are met. It performs best in wet, nutrient-poor sites (Käärmelahti et al. 2023). It accumulates over time creating thick carpets on the forest floor. When scarifying sites like this, it should be ensured that the furrows are actually deep enough to expose mineral soil not just decaying moss. Lastly, a site may be unsuited for scarification if the organic layer is very thin to non-existent. Scarification is redundant if its goal of exposing mineral soil is achieved naturally.

A study in Quebec compares scarification in a somewhat warm and dry region to a cold and humid region. 18 years after the treatment, there was no significant difference in the height growth of the black spruce that was planted however they did find some differences between the regions (Wotherspoon et al. 2020). The cool-humid region had improved nitrogen mineralization as a result of scarification while the warm-dry region did not (Wotherspoon et al. 2020). It is also theorized that the warm-dry climate region may receive benefit in another form as scarification decreases interspecific competition from surrounding vegetation which is more prevalent in the warm-dry region (Wotherspoon et al. 2020).

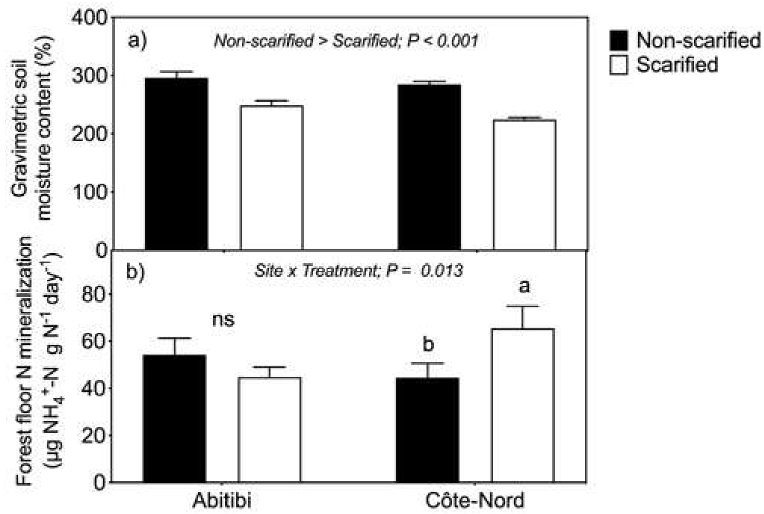

Figure 11. The effects of scarification on (a) gravimetric soil moisture content and (b) forest floor nitrogen mineralization in Abitibi (warm-dry region) and Côte-Nord (cold-humid region).

DISCUSSION

Based on the pros and cons of scarification, the overarching goal of this literature review is to determine its feasibility within the boreal forest. This means that the benefits must outweigh the costs with respect to impacts on the environment and economic gains and losses. Based on the findings, scarification is a viable silvicultural treatment for the majority of sites in the boreal forest.

Its feasibility can largely be attributed to the increased growth rates which in turn yield higher economic returns. For the black spruce, which is a species that is commonly managed for, planted seedlings over the course of 25 years on average experienced an additional 9.4 cm of growth per year in comparison to seedlings planted on a site lacking a scarification treatment

(Prévost and Dumais 2018). 9.4 cm may not seem like a significant amount however, compounded over 50 years, this would be an additional 4.7 m of growth greatly increasing the merchantable volume of the trees. This means that when the site is harvested in the future, revenue would be increased drastically.

Scarification also lowers seedling mortality rates as they have increased nutrient access and improved pest resistance. Sites lacking scarification may face problems with understocking. The negative effects of this are beyond the fact the resulting forest will have fewer trees available to harvest. This is because wood properties are altered when they are growing in stands with low density. It causes excessive taper during tree development (Duan et al. 2016). This is a result of decreased intraspecific competition as trees allocate more resources for secondary growth as there is less competition for sunlight. Boles with high taper have less merchantable volume and therefore decrease the revenue of future harvests.

Tree development in low density stands also experiences increased radial growth of branches. (Mäkinen and Hein 2006). This means that stands with low densities have an increased severity of knots in the bole. Wood strength properties decrease as knot area increases therefore decreasing the quality of the timber (As et al. 2006). Trees that are grown in low density are also more prone to producing reaction wood. The increased size of branches results in compression wood under the branch and tension wood above the branch (Du and Yamamoto 2007). Trees in lower density stands are also more prone to wind blow as there are fewer trees in place to block it. In response to this, trees will produce more reaction wood to brace themselves against the wind preventing blowovers (Gardiner et al. 2014). Just like knots, reaction wood decreases the value of timber as it decreases its strength and causes distortion as cells non-uniformly shrink and swell (Wimmer and Johansson 2013). This further exacerbates why scarification is critically beneficial on many sites when it comes to producing high volumes of quality timber.

The environmental costs of scarification, while present, are rarely severe so long as best management practices are applied. This includes avoiding the use of scarification in riparian zones and steep slopes to avoid large quantities of runoff into watersheds. Microbial activity decreases in the soil after scarification as well however, the fungal and bacterial communities are given ample time to recover between successive harvests and scarification treatments. This means that the effects of scarification are unlikely to compound on microbial communities as the land is continually used for timber production.

Monetary costs are another essential component to determining the feasibility of scarification. The variable costs associated with the practice depend on the area of land that requires the treatment. If roughly 35 litres of diesel are consumed for every productive machine hour, then based on current prices, this would cost $38.50. The price of diesel in April 2024 is 170 cents per litre in Northern Ontario however contractors purchase their diesel in bulk so the cost is deducted by roughly 60 cents (Ontario Government 2024). The average operator cost is $34 an hour however, assuming 80% utilization the cost increases to $40.80 an hour. Assuming operators scarify one hectare per hour, the cost of operator wages and fuel costs results in $74.80 per hectare. This does not take into consideration maintenance costs however this is not an easy parameter to estimate as its variability greatly exceeds fuel cost and operator wages. Most costing models assume that 100% of the purchase price of the machine will be required to maintain it over its lifetime of 5 to 10 years. The actual cost per hectare would be much greater factoring in supervisory costs and maintenance costs. Past studies on scarification become irrelevant due to an ever-changing economy and innovation. A potential future change within the industry is the rise of electric hybrid machinery which would lower diesel consumption as well as reduce emissions, mitigating environmental degradation caused by the scarification process (Šušnjar et al. 2022).

While the monetary cost may discourage the application of scarification, the value gained within an entire hectare of forest is extremely likely to outweigh the cost even if it is likely much greater than $74.80 per hectare with some estimates exceeding $300 per hectare (Gingras and Cormier 2009). The practice also serves as a risk reduction tool. The prospect of mass seedling mortality would be a very costly mishap so applying a scarification treatment would be a wise way to mitigate the likelihood of this occurring. Scarification treatments are likely to cause a large increase in trees, most of which with increased amounts of merchantable volume. This is why scarification is an extremely viable site preparation method and is used widely within the boreal forest.

CONCLUSION

In conclusion, scarification is a widely applicable site preparation method, and its use should be employed when regenerating the vast majority of boreal forest sites. While it does have both environmental and economic costs, these are both negated by the resulting superior stand with enhanced stocking and increased merchantable volume.

The exposure of mineral soil to the surface aids massively in the germination of seeds and seedling growth rates. This is because it provides appropriate drainage, oxygen flow, as well as proper rooting anchorage. In sites lacking scarification, seedlings are less likely to be planted in mineral soil which causes stunted development at the very least, often times mortality. While the practice does cause environmental degradation in a couple of different forms, so long as the treatment is performed many times within short succession in the same area, the impacts are not overly severe. The monetary costs to perform the practice are present however, it is extremely likely that it will pay off in the long-term as the resulting forest will have enhanced profitability. This is why scarification is a feasible silvicultural treatment when regenerating forests.

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