EFFECTS OF FOREST EQUIPMENT ON BOREAL FOREST SOILS: A REVIEW

by

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ABSTRACT

Soil disturbance is an important aspect of forest harvesting operations. Machines that are responsible for the harvesting of trees and wood transportation have a direct effect on the soil that they operate on. Some of these machines can weigh dozens of tonnes, making their effect on the soil considerable; the degree of contact with soil also affects soil integrity. On improperly constructed roads and sensitive soils, these machines are a detriment to not just the soil itself, but the plants and wildlife that reside in the soil play dynamic roles cycling nutrients and organic matter and maintaining the ecology in forest ecosystems. Machine effects on boreal soil have been characterized and synthesized using a literature-review based approach, mainly focusing on western Canada and Ontario.

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OBJECTIVE STATEMENT

This thesis aims to answer the question whether forest machinery negatively affects soils in boreal forests, primarily within Canada. This thesis builds on existing knowledge due to being literature-based and as a result, will serve to implore and justify additional accompanying research in this field.

INTRODUCTION

What is soil?

Soil is not just dirt, as it is truly its own type of ecosystem within an ecosystem. Soil can be interpreted, in short, as a series of layers near the ground surface consisting of unique texture, density, structure, water, and chemical composition (Hillel 1982). Some context is needed to partially understand why soil is important to not just boreal forest ecosystems as I am examining in my thesis, but ecosystems around the world. Soils are important to ecosystems because they are a non-renewable resource that serves vital ecosystem functions. Plant growth, cycling of nutrients and water, biodiversity habitat, and environmental quality are all examples of these core functions (Hou 2020, Drenning 2021, Gama 2023).

Soil classifications and dynamics

Sand (large), silt, and clay (small, <2 micrometers) collectively describe soil texture, and soils often consist of a mixture of these three primary particle size classes (Jaja 2016). Sandy soils will typically have the weakest ability to retain water, and clay will typically have the highest water retention ability (Barbour 1998). Bulk density (and relative rates of soil compaction/loss of soil structure, which varies inversely) also has a significant effect on soil water dynamics along with texture. Water availability, texture, and density all influence tree growth and other ecosystem processes. Soil structure (i.e. how well aggregated soil particles are), compaction and bulk density (which are often closely related) of boreal forest soils also influences the growth of plant life, especially root permeability (Veihmeyer 1948). Soil organic matter content and quality is another critical soil property that influences infiltration rates and water holding capacity, soil structure, bulk density, and soil nutrient cycles (Franzluebbers 2001). Mineral soil texture, soil structure, and soil organic matter (including living roots and microbial mycelia) all influence how susceptible soils are to compaction and erosion associated with forestry (logging/site prep) equipment. The weight of these machines can compact soil, making it difficult for root systems to re-establish after harvest. There is a great deal of variability in how different equipment and forest management practices impact different soils. In some cases, even if mechanical work is done carefully, it still restricts regeneration.

Soils within the boreal forests of Canada

The boreal forest is a vital part of the Canadian ecosphere. In Canada, the boreal forest amounts to approximately 3 090 000 square kilometres of the total land in Canada (Price 2013). Within this exceptionally large part of the global boreal biome, Canadian forest soils are responsible for countless things, with a key role being carbon storage. More specifically, Canada's boreal forest soils hold carbon within itself, preventing additional carbon emissions. Twenty-eight gigatons of carbon are held in various soil sources such as biomass, dead organic matter, and other carbon pools within the soil; along with living boreal forest trees, and standing dead trees (Kurz 2013, van Loon 2022). Twenty-eight gigatons is equivalent to two years of global fossil fuel emissions. Canada's boreal forest soils can also be important sinks or sources of the potent greenhouse gas methane depending on soil moisture and disturbances.

Soils in the boreal and sub-boreal forests of Canada are quite diverse. Based on the Canadian System of Soil Classification, they span across multiple soil orders (Brunisols, Podsols, Gleysols, Luvisols, Organic Soils), including permafrost affected (Cryosols) at the boreal sub-arctic interface (Soil Working Group 1998) Within the realm of commercially managed forests, soils in the Brunisol, Podsol, and Organic (e.g. spruce bogs) orders typically predominate. The diversity of soil taxonomy reflects the diversity of underlying soil forming factors that all influence how soils form and function and how they are impacted by forest equipment.

Figure 1. Brunisol soils in Ontario (left), British Columbia (middle) and Saskatchewan (right) (Soil Working Group 1998).

The chemical composition of soils in the boreal forest is also highly variable. Canada's boreal forests exist across a range of mineral parent materials (from poorly buffered granitic Precambrian Shield environments to calcareous marine and aquatic sediments that weather quickly and buffer pH), and organic matter inputs vary primarily as a function of the dominant vegetation (e.g., with key differences between hardwood and softwood vegetation) (Sanborn 2011). The broad chemical makeup of soils, along with the physical properties described above and the nature of the forest plants and microbes all influence nutrient cycling. In the boreal forest, primary macronutrients are phosphorous, nitrogen, and potassium; while secondary macronutrients include calcium, magnesium, and sulfur (Zewide 2021, Kreutzweiser 2008). Micronutrients are required in less amounts but are still important for the health and wellness of plant life in the boreal forest. Examples of these include boron, zinc, manganese, and copper (Gianquinto 2013). The most significant impacts from logging equipment include changes in soil chemical properties along with changes in nutrient cycling.

Mechanized forestry

Forestry equipment in this context is to be understood as any type of wheeled, tracked, studded, or other forms of mobilized machinery used in active forest harvesting operations and site preparation. Examples of harvesting-related machines include grip harvesters, feller bunchers, skidders, and logging trucks. Types of harvesting in the boreal forest is almost entirely clearcut due to the largely shade intolerant tree composition. Additionally, site preparation machines include disc trenchers and bulldozers will be focused. There is variability in minimum and maximum size or weight limits, empty logging trucks are the smallest of the forest machines in both size and weight. Tree damage was not examined, because of insufficient data regarding the subject.

Figure 2. Single grip harvester in action (Canadian Forest Industries 2017).

CONTEXT

Boreal Forest

The boreal forest is an uneven shape that wraps around the northern hemisphere. In total, the global boreal forest spans an estimated 17 million square kilometres of land (Kayes 2020). Before the introduction of Forest Resource Inventories and remote sensing, it was difficult to perceive the depth and size of the Canadian boreal forest. After these came into the fold, researchers and surveyors were able to receive more accurate estimates of Canadian boreal forest size. Canada has vast boreal forests, estimated to cover between 3 090 000 – 5 520 000 square kilometers, according to several sources. (Price 2013, Statistics Canada 2018, Government of Canada 2020, Wells 2020). The Canadian boreal forest landscape accounts for almost a third of the global boreal forest biome (World Wildlife Fund).

Ontario is one of the largest provinces in Canada in terms of landmass, second only to Quebec. The boreal forest occupies virtually all of northern Ontario, except for the far north region of the province that is absent of trees because of its very large wetland area that spans most of the region (i.e. the Hudson and James Bay lowlands). Ontario is dominated by boreal forests, with ½ of its entire landmass being occupied by the biome (Government of Ontario 2021). These areas of boreal forest are unmanaged because they are above the respective northern limit of the Area of Undertaking. Additionally, the boreal forest accounts for two-thirds of Ontario's total forested land, with 30 million hectares being boreal forest (Schoeder 2002).

Northern boreal forests and their soils are also relevant in the United States, with Alaska being the most prominent example, and moderate expanses of boreal forest can also be found in the northern Midwest US – notably Minnesota. Boreal forests in these states have a considerable amount of boreal forest tree and animal species (Wells 2020). The state of Alaska has boreal forest located within the center of the state with barren tundra surrounding it in most regions except the far south to southeast portion of the state. Because most of the forests of Alaska are underlain by permafrost and isolated due to insufficient road network, conventional forest management and products are typically restricted to the coastal rainforest areas (Todd 2006). However, this has been changing in the past 30 years and with changing climate, management of interior spruce and birch forests in Alaska may become more important.

Boreal forests comprise virtually all of Norway, Sweden, and Finland (Yrjola 2002). Three-quarters of the total amount of land in Finland is boreal forest as of 2021 (Clausnitzer 2023). Only a third of Norwegian land is forested (Salas 2023). Sweden has just over two-thirds of its land occupied by forests (Salas 2023). Lastly, the Russian total forested land amounts to 882 million hectares (Food and Agriculture Organization 2012), 763 500 000 being boreal forest, or 86 percent of Russian forested land (World Wide Fund for Nature 2007).

Boreal Forest Trees and the Soil that they Grow in

Organic and Podzolic soils are the most common soil orders in north/northwestern Ontario (Matthews 1954). Brunisolic soils are another common soil type, especially near the Thunder Bay/Nipigon region of Ontario (Saurette 2020). Mosses (specifically Sphagnum) are the most common part of any organic soil. Organic soil will also consist of leaf and needle litter along with some decomposed animal and insect material. Podzolic soils are found northeast of the Thunder Bay area, extending from just south of Timmins to the Quebec border (Saurette 2020). Brunisolic soils are defined as having A and B horizons that are weak, small, and otherwise underdeveloped (Saurette 2020).

It is common for soils to be similar to each other, as they share many characteristics, especially in localized regions. In Ontario, upland and lowland black spruce prefer to grow in soils that are well-drained and mesic (Krause 2022) but are also capable of growing in much wetter soils than jack pine. In British Columbia and southeast Alaskan boreal forests, the abundant lodgepole pine prefer to grow in well drained soils, a typical trait of all pine trees (USDA Forest Service). A figure of the soil textural triangle has been pasted below.

Figure 3. The soil textural triangle of that describes textures by class for mineral soils (Plant and Soil Sciences eLibrary).

<u>Seasons</u>

Seasons have a large impact on the boreal forest soils, particularly winter because of soil freezing, summer because of hot temperatures, and spring because of wet and muddy soil conditions. The main effect of winter is the decrease of carbon emissions into the atmosphere due to the aforementioned soil freezing. It is more difficult for carbon to be emitted from the soil due to this (Oquist 2008, Haei 2013). Carbon is inputted to the soils from plant litter and root exudates (Lei 2023). Permafrost is a permanently frozen layer of soil, usually near the surface. It is common in the Arctic, where winter temperatures and conditions persist year-round. Permafrost is a trait of Cryosolic soils.

Spring and summer are the prime growing periods for trees in the boreal forest, as they get relief from the extreme cold. As for the spring soil, the melting snow and ice creates excess water, which saturates it. Additionally, soil thawing during warming periods frees up water and other nutrients, explaining the faster rates of growth (Bergh 2001). As for summer, it is found that positive warming effects on soil would be offset by periods of drought. With the soil drying up, it would lose its ability to sequester carbon, and it would be emitted into the atmosphere (Schindlbacher 2012). A scorching summer is the worst soil condition, as it can completely offset winter carbon emission reductions along with positive spring warming effects.

<u>Types of forest machinery</u>

Figure 4. Damaged, unidentified forest machine, likely a processor (Conway 2023).

Large scale machine usage has become increasingly common during the 21st century. Machines such as grip harvesters, feller bunchers, skidders, forwarders, and logging trucks are all crucial in helping modern natural resource industries perform their required tasks. Grip harvesters are typically single or double-gripped. Their heads can cut and process trees to a specific system, such as cut-to-length. Cut-to-length single-grip harvesters are capable of harvesting trees on the ground at a rate of 4.3 – 14.9 m^3 of processed timber for every productive machine hour (Glode 2002, Gerasimov 2023). One head on the double harvester is responsible for controlling trees, while the other is responsible for processing trees above the ground (Glode 2002).

Cut-to-length was typically a long and time-consuming process because logs are initially processed on site, rather than in the sawmill. In the past, this practice fell out of favour because of how much time it would take to process logs on site; taking time, money, and effort away from further harvesting. This was during a period where volume was the main priority, sometimes the only one. In modern times, harvesting machinery is much faster and more refined than 20th century machinery, making cut-to-length favourable again with the time constraints being significantly reduced.

Feller bunchers work in a similar fashion to grip-harvesters, minus the additional processing capabilities. Feller bunchers simply grab the tree and cut it at base stump location, in level with the ground. Tracked-tire feller bunchers allow for increased traction and better stability on steep slopes (Sessions 2017, Andronov 2020). Due to its inclined nature, tracked-tire feller bunchers are better suited for mountainous areas of the globe, such as British Columbia and Norway. Feller bunchers with normal tires are preferred in flatter, more typical forested environments, such as those in Ontario, due to its higher efficiency and work speed (Han 2013).

Skidders typically come with either a grapple or a cable with log chokers at the end. Both types of skidders can take more than one stem at a time, often being used in areas where feller buncher activity is common in the case of grapple skidders (OSHA, USDA Forest Service 1997). Skidders act as a liaison in mechanical harvesting, taking logs from the harvesting site and bringing them to the roadside, where they will eventually be loaded onto logging trucks. On average, skidders can carry up to 5 stems at a time. This is dependent on stem size and size of the grapple/number of chokers.

Figure 5. A grapple skidder moving wood (Canadian Forest Industries 2020).

Forwarders are similar to skidders in terms of moving wood from the harvesting site to the roadside. Unlike skidders however, they have less of an impact on the soil and can carry more logs (USDA Forest Service 2006). In this sense, they may also be viewed as small logging trucks with a mechanical grappling hand attached to the machine as well. Often, forwarders are used to load up the actual logging truck for transport off-site. Once on the logging truck, the vehicle takes them to the sawmill where they are then further processed into refined wood products. Logging trucks often travel in a convoy, with multiple trucks on site. Logging trucks typically have seven to nine axles: three on the cabin, and four to six on the trailer. Logging trucks put the most stress on subgrade soils, mostly due to the sheer number of trucks that drive on the forest roads.

Non-forest vehicles

Pickup trucks and ATVs are the most common examples of lightweight vehicles, at least in comparison to massive forest machinery. They will not be classified as forest machinery, even though they are essential vehicles of forest operation. Pickups allow for labourers and managers to access the site aside from logging trucks. ATVs are small and mobile, allowing for access to places where pickups cannot go.

Tires

Tires are the main contact point between machine and soil; soil damage is mainly transmitted by weight pushing the tires into the ground (discs, tracks, and plates on the front of dozers also can cause damage to the soil). Tires are mainly either normal rubber or reinforced with studs or tracks. They can come in many sizes and are tailored to meet the size of the machine that is using them. Lighter vehicles mostly use bare rubber or winter tires, while heavier machines such as feller bunchers will sometimes have studs or tracks (Andronov 2017). This is not always the case, as heavier machines will not have tracks or studs if they are not needed, for the sake of efficiency.

It is common for machines to weigh between 20 to 30 tons when fully loaded. This causes serious damage to the soil, and mechanical harvesting is bound to cause this (Horn 2004, Ampoorter 2012). Soils that have low densities and low tolerance to stress are put in a highly vulnerable position to further damage by tires (Horn 2004). This leads to a reduction in future forest growth (Horn 2004) because of soil compaction. Compacted soil restricts oxygen, water, and nutrient flow to soil microorganisms and plants, which provide negative consequences for forest growth productivity (Cambi 2014). It is important to take the same tracks repeatedly, so that less overall soil gets damaged (Horn 2004). Compacted soils as a direct cause of tire/track (as well as discs) may also be more susceptible to soil erosion.

Figure 6. Tracked tires on a modified grapple skidder (Tigercat n.d.).

Optimal harvesting time

The best harvesting time is in the winter. This is especially valid in the boreal forest, because of the winter season being longer and colder than forests that are more south. Soil damage is minimized because of the frozen ground, and machines can better access the harvesting sites (Kuloglu 2019). It is not recommended to harvest in wet periods, such as rainfall or meltwater in the early spring. Summer and autumn are also good harvesting periods, but not as great as winter since soil can still be disturbed and displaced by machinery.

The boreal ecosystem and its mechanics

An ecosystem is defined as a community of living organisms within an environment, with every component interacting and functioning together. The health of an ecosystem is dependent on its ability to function at an adequate level, with little to no natural or man-made disturbances (Brandt 2013). Boreal ecosystems span from the 45^{th} to the 65^{th} northern parallels, according to NASA Earth Observatory (Simmon 1999). Additionally, they also provide ecosystem services specifically related to regulation, natural resources, and culture for instance. Disturbances of boreal forest ecosystems include climate change, fire, insect, and pathogen damage (Brandt 2013). Canadian boreal forests are mainly replaced through fire which serves as the main influence of species composition, stand structure, biodiversity, and productivity (Weber 1997, Brandt 2013). Lastly, eight ecozones can be partially/entirely found within the Canadian boreal, including the Boreal Shield (Natural Resources Canada).

Silvicultural systems used in harvesting operations

Silvicultural systems are defined as a planned program of silvicultural treatments over the life of a forest stand to fulfill the needs of the government, landowners, or public. Silvicultural systems are required to be placed within the context of sustainable forest management. Additional purposes of silviculture systems are to control stand establishment, composition, and growth (Graham 1998, Government of Ontario 2015). In the boreal forest, silvicultural systems are used in an even or an uneven-aged context depending on the structure of the forested area (Graham 1998).

There are three main systems that are used in Canada. These systems are clearcut, shelterwood, and selection. Clearcut is the most common system used in the boreal forest, as it is accustomed to large-scale disturbances and shade-intolerant species. Entire areas of forest are removed at once. On average, Canadian logging companies harvest and regenerate 400 000 hectares of boreal forest annually (Natural Resources Defense Council 2022). Regeneration on many sites is difficult, even with the implementation of a system with standards and tree planters. Oftentimes in the boreal forest, this clearcut is done with standards to assist in future regeneration. Shelterwood and selection is used sparingly in boreal forests, unlike in Great Lakes-St. Lawrence forests where the former is the predominant harvesting method.

Aspects and goals of silvicultural systems

Due to the variability of the forest industry, modern silviculture systems seek to achieve various socio-economic and ecological goals. Soil integrity is a goal of most silviculturists. In the boreal forest however, many soils are acidic. Boreal soils are often shallow, poor in nutrients and biotic material, and over half of the nitrogen and ectomycorrhizae are found on the surface of the forest floor (Graham 1998). Organic material is less abundant in the deeper soil layers below the forest floor. Before intentional forest floor disturbance occurs, silviculturists must plan carefully to ensure that the organic layers are maintained for assistance in future regeneration. It is a primary reason why some coarse woody debris is left, as useful nutrients are transferred into the soil, where new regeneration will have easier access. Coarse woody debris is especially important in boreal forests due to the shallow soils (Graham 1998).

Harvesting

In the past, forest stands were overharvested due to a widely held misconception that Canada had an infinite number of trees. Harvesting laws and protected areas had to be made to ensure that Canada’s wood supply could be kept in check. The white pine is an example of a victim of archaic harvesting practices, its current numbers are far below the abundance it once had. Feller bunchers and grip harvesters are used to harvest trees in large scale operations. Chainsaws are the most iconic tree harvesting tool, and they are still used in places where heavy machinery cannot reach. Additionally, they are still a preferred choice in small-scale operations with private landowners. Modern harvesting practices are designed with the purpose of emulating natural disturbances, such as fire and insect outbreaks (Government of Canada 2021).

Site Preparation

Site preparation is used in managed forests to tailor a tract of land towards desired commercial tree species through anthropogenic disturbance of the forest floor (Schmidt 1996). This is achieved by reducing vegetative competition and exposing mineral soil (along with other upper soil horizons) for planted trees (Government of Ontario 2015, Smenderovac 2023). Manual, mechanical, chemical, and prescribed burns are commonly used within the province of Ontario. Mechanical site preparation involves the use of machinery, with the disc trencher being a favoured tool in managed forests across Canada, mainly used to expose mineral soil (Schmidt 1996, Government of Ontario 2015). In chemical site preparation, federally and provincially approved herbicides (glyphosate, hexazinone, etc.) are used to treat the vegetative aspect of competition once the site is already established, and desired tree species have been planted (Chen 2006, Government of Ontario 2015).

Figure 7. A disc trencher disturbing soil, exposing valuable minerals at a cost of quicker consumption (Mendel University 2020).

Oftentimes, multiple site preparation methods are used in forest operations for a higher likelihood of success as opposed to using only one method (Government of Ontario 2015). Through its disturbance of the soil, mechanized site preparation has been known to cause a loss of important nutrients such as carbon, nitrogen, and phosphorous (Schmidt 1996, Sutinen 2019); in exchange for providing new tree growth with easier access to them.

Transportation Systems

Transportation via logging truck is the dominant form of log transport in the boreal forest. It is easier to stock a truck than it is to fly in a helicopter or drive logs on a river. The latter was common in the past, but it has become obsolete. This obsolescence was brought on primarily through the loss of harvested timber (15-50% were lost from harvest site to mill), and because sawmills have dwindled since the turn of the 20th century, when log driving was at its peak (Labrecque-Foy 2023). Additionally, modern sawmills are located closer to cities to have access to consumers. Helicopter logging is more expensive, mostly being used in mountainous terrain rather than in flatter boreal forest land. Talks of using unmanned aerial vehicles/ballons have been discussed, but there is no evidence of success or failure, due to insufficient data of these in boreal forests, similar to helicopters (Prentice 2011).

Forest roads need to be constructed to allow the harvesters to reach the trees. This is built on top of the existing soil subgrade. The roads are then capped with expensive gravel and other road building material (Prentice 2011); these are items that take monetary and human attention away from minimizing soil, environmental, and ecological damage and instead on maximizing profits, an issue that has been around for as long as the industry itself within Canada.

Soil properties in relation to equipment impacts

Soil properties can be divided into three branches: physical, chemical, and biological changes. Major physical soil properties include soil texture (sand, silt, and clay), structure (pores, aggregates) and water content. Other physical soil properties include bulk density, erosion, aeration (the passage of movement and air through soil), and temperature (Hillel 1982, Gardner 1999). The physical properties of soil affect how much damage that they can withstand from chemical, biological, and other physical agents.

Chemical properties of soil include cation-exchange-capacity (CEC) (the maximum amount of cations that a soil is capable of holding), pH value (which is directly tied into the CEC of soils, and plant nutrients (nitrogen, phosphorous, potassium, carbon, etc.). Biological properties of soil include organisms that live within the soils, such as earthworms, insects, and bacteria for instance, including nitrogen-fixing bacteria that is common in environments with alder shrubbery (Food and Agriculture Organization).

An example of a boreal forest soil is Podzol. Podzolic soils are one of the most common soil orders in the boreal forests of Canada, which also includes the boreal forests of British Columbia and the Yukon. (on top of the Brunisolic and Organic soils already mentioned within the Western Cordillera). In Quebec, Humo-Ferric Podzol soils are the most common identifiable soil group (by square kilometres) within the province, followed by Dystric Brunisol soils. Other notable soil groups include Mesisolic, Organic, and Cryosolic soils in the Yukon (Moore 2021).

Table 1. The five most common soil orders in the Quebec boreal forest (Moore 2021).

Group	Order	Area (km^2)
Dystric brunisol	Brunisol	223 940
Turbic cryosol	Cryosol	79 867
Mesisol	Organic	96 848
Humo-ferric podzol	Podzol	463 518
Ferro-humic podzol	Podzol	62 825

Podzolic soil properties are further defined by its diverse B horizon. The B horizon is 10 centimetres thick or more, defined as a yellow-red soil (7.5 -10 YR on the Munsell Scale) at this horizon (beneath the organic leaf and needle litter), becoming more yellow in colour as the soil depth increases. It is coarser than clay, indicating a silt-like texture. Furthermore, the Bf (0.5% organic carbon or more) and Bhf (5% organic carbon or more) sub-horizon is also subjected to the same thickness requirements (Government of Canada 2013). Additionally, Podzolic soils are characterized by their low pH count, due to the mineralogical composition of the sediments, further exacerbated due to the rapid decomposition of acidic coniferous needles. This creates a somewhat harsh microenvironment that is accommodated towards trees that contribute to the acidic soils, such as lodgepole pines (Soils of Canada 2020, Lavkulich 2021).

These properties are relevant to mechanized forestry because of how the machines compact the soil, along with the problems associated with it. Soil compaction affects bulk density, porosity, and water flow. Finally, this results in reduced tree growth and reduced economic flow in long-term forest management. Generally, harvesting companies have become more environmentally conscious regarding the health of boreal soils, to ensure ecological sustainability within the soils, as well as being able to meet economic and volume quotas.

Bulk density and soil strength is increased through soil compaction brought on by forest machinery, with decreased water flow, air porosity and an ability for roots to spread as drawbacks (McNabb 2001). Bulk density is not a reliable method for measuring the ability of boreal soil to compaction by itself (McNabb 2001), but there is an inverse relation between bulk density and water content, indicating that soils with high bulk density are less hospitable to tree growth (due to the lack of water flow) and along with it, some proof that links bulk density to soil compaction to an outside interpreter with surface-level knowledge of the topic. It was also found that compaction of the soil reduced soil air porosity for three to four years. Poorly drained soils are less at risk of their physical properties being significantly altered because of already adequate aeration, or because aeration cannot be further restricted through soil compaction. Well drained soils are most at risk of a reduction in air porosity because of its vulnerability to air porosity restrictions (Startsev 2009).

Due to mechanized forestry changing the porosity of boreal soils, this also has an effect on a chemical level. There are serious concerns of not just nitrogen deficiency, but oxygen deficiency as well for faunal organisms with a respiratory system (Tan 2005). Microbial biomass content (MBC) is not affected compared to nitrogen content in mineral soil. Previous studies stated that mineral soil was compromised in terms of MBC along with oxygen and nitrogen deficiency, indicating that protective soil measures have been making a difference in boreal forests (Tan 2005).

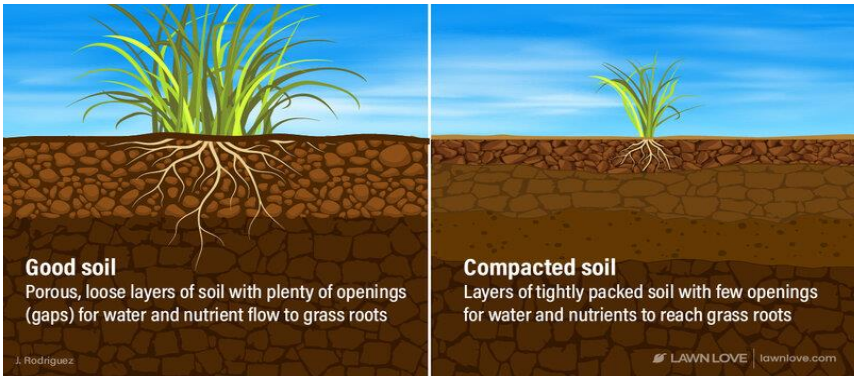


Figure 8. Reduced plant growth in compacted soils (Purnell 2022).

METHODS

Since this is a literature review-based thesis, the methods section has been limited. Instead, most of the thesis can be located within the results and discussion sections. Data has been gathered from reputable peer-reviewed journal sites. These include, but are not limited to: Google Scholar, ScienceDirect, JSTOR, and Springer Link. Government publications will also be drawn from significantly throughout the thesis. The Governments of Ontario and Canada will be cited considerably. Through the citing of the most reputable sources possible in a bountiful amount, the thesis is also reputable and valid itself.

The trees that are studied mainly include spruce, pine, poplar, and birch. These trees are very common in boreal forests throughout the northern hemisphere and have different effects on soil composition and may have their own boreal forest microclimates depending on species and topography. The study was carried out from September 2023 to March 2024. Most of the thesis has been placed on boreal forests within Canada, with primary focus within Ontario and some secondary focus on other global boreal forests.

RESULTS

As mentioned previously, the clearcut system is the most commonly used system in boreal forests across Canada. In Ontario, total clearcuts (each and every stem) are no longer practiced on provincial crown land. Modern clearcuts are now forced to implement some form of conservation, to ensure future regeneration. The table below lists examples of common clearcut methods, and regions that they are commonly practiced in.

Table 2. Clearcut systems used around Canada and the greater global boreal forest biome (Government of BC 1999, Lundmark 2013, Government of Ontario 2015, Government of Yukon 2015, Kuuluvainen 2019).

Clearcut harvest method	Description	Examples of regions practiced
With Standards	Most trees are removed from a large area, some trees are left over to assist in silviculture or other purposes, most common system.	Ontario British Columbia Sweden Finland
Seed tree	Most trees are removed from a large area, some trees are left to assist with natural regeneration.	Ontario
Block	Most trees are removed in a defined pattern, specifically cut and uncut blocks.	Ontario British Columbia
Patch	Trees are removed in irregular shapes; spaced and sized specifically towards the regional terrain and original forest types.	Ontario Yukon
Strip	Trees are removed in narrow strips (10-60 meters), strips are tailored to allow for seed trees and shelter to the cut areas.	Ontario British Columbia Yukon

Multiple clearcut harvesting methods can be used to achieve a universal standard system (Government of Ontario 2015). The reason why the standard clearcut is so common across the globe is because it can be understood as any form (or multiple forms) of carefully managed, but large harvesting operation where most of the trees in an area are removed together.

Along with the equipment previously mentioned along with their roles, equipment is also used to carry out extra components of timber processing and site preparation.

Table 3. Examples of forest machinery used in the boreal forest (Thompson 2002, Lof 2012).

Type of machinery	Purpose
Grip harvester	Harvesting/processing
Feller buncher	Harvesting/processing
Skidder	Transporting (short distances)
Logging truck	Transporting (long distances)
Forwarder	Transporting (short distances)
Disc trencher	Site preparation
Stroke de-limber	Processing
Bulldozer	Site preparation
Excavator	Site preparation

Bulldozers are used along with disc trenchers to clear woody debris (when appropriate) for the purpose of acclimatizing soil by levelling the ground (Gouge 2021, ConocoPhillips 2023). Additionally, stroke de-limbers are used to process trees at the landing site, rather than at stump site, unlike bunchers and harvesters (Thompson 2002).

Table 4. Effects of forest machinery and summer harvesting on boreal soils (Sutherland 2003, USDA Forest Service 2006, Government of Ontario 2015).

Examples within context	Soil impact	Level of soil damage
Cut-to-length harvesting and processing	Slash mats are used for travel, modern machines are able to perform cut-to-length at stump site rather than take	

	extra trips to a landing site (Sutherland 2003, Government of Ontario 2015).	Damage is very minor when compared to other harvesting methods.
Forwarders	Displacement of soil underneath tires or tracks.	Minor: Wide machine tracks and low log height allow for even load distribution; high flotation tires can also be used on wet soils to further minimize disturbance. (Sutherland 2003, USDA Forest Service 2006)
Skidders	Logs are dragged on the surface of the soil by a grapple or a set of cables.	Severe: In the case of grapple skidders, because both tire and log move along the soil (as opposed to just the tires); less severe with grapples because the logs are usually further off the ground.
Feller-bunchers	Displacement of soil underneath tires or tracks.	Moderate: Repeated passes can cause significant damage through rutting but can be minimized with proper spacing and bunching (Sutherland 2003).
Disc trenchers	Erosion risks, due to the extra rutting created by the discs.	Minor: Improper trench creation can alter nutrient cycling in the soil; exposing too much mineral soil may cause future soil to lack in nutrients, especially if organic material is cleared.

Other forms of equipment are used, but these are the most prominent forms of equipment in the boreal forests of Canada and Europe.

DISCUSSION

Forest machinery negatively affects forest soils in Canada, but this is variable and inevitable. Levels of soil damage are dependent on the machinery used, as machines that are in higher rates of contact with the ground will cause more soil damage. Regardless of the type of machine used, it will damage the soil if it is in contact with the ground. Public land use and mitigation of soil damage are important to preserve boreal soil integrity. Good forest road use, increasing aerial logging, and reducing machine weight may also work in reducing soil damage.

Recreational land use in comparison to active operations

Recreational land (i.e. provincial and national parks) is used by the public, usually providing them with a sense of peace and mental well-being brought on through its natural beauty. Its soil is undisturbed by the rutting and other forms of displacement caused by the increasing level of mechanization. Sensitive sites and soils are left largely unattended for, with natural processes left to determine the conservative direction of the soils and the forests. Trees are completely barred from being harvested (except for firewood in contextual circumstances), unable to be cleared by forestry companies to make room for logging access roads, to yield a profit for their own personal or company gain, or for any other reason.

Anthropogenic disturbances are not as spatially widespread as natural disturbances, especially fire. In 2021, 120 000 hectares of forest was harvested, compared to over 793 325 hectares of forest burned just during the span of the 2021 harvesting season (Government of Ontario 2021, Government of Ontario 2023). However, this hides the true damage that humans have on the forest. Increasing mechanization, such as cable skidders, causes severe damage to the soil, even with preventative measures being taken.

Preventative measures need to be taken, such as using wide-tracked forwarders or using flotation tires in sensitive sites. Use cut-to-length harvesting, rather than more harmful alternatives such as full-tree harvesting. Site preparation is largely beneficial for the immediate growth and establishment of trees due to the exposure of mineral soil, but this removes organic horizons and woody debris. Additionally, channels and trenches will increase erosion. Long-term nutrient quantity is not guaranteed, especially in shallower soils. Altered nutrient cycling processes, coarse woody debris removal, and negative effects of soil compaction brought on by mechanized forestry may affect the long-term forest product. Less timber and soil will be damaged if spring harvesting is avoided.

Mitigation methods in western Canada

To avoid soil damage, it is best to harvest in the winter, summer, or fall, rather than in the spring. Harvesting in the spring after winter runoff is not recommended, as this is when the soil is at typically at its wettest. In these circumstances, delay harvesting to a later point in the year. Soil strength is at its peak in the late summer and early fall due to the lack of soil moisture. Ensure that the winter is cold enough to prevent rutting and compaction or ensure that there is not enough moisture to cause significant damage (Sutherland 2003).

For machines, it is recommended to keep the weight and load size as low as possible (Sutherland 2003). The height of the machine should also be considered, as this increases the risk of tipping. These factors are exacerbated through overloading. Some companies choose to cut on time and push the limits of efficiency at the cost of safety. An overloaded or improperly loaded machine (such as a grapple skidder or log) will have its load unevenly distributed, putting added stress on an axle, support beam, or tire (Sutherland 2003). Machines that are not loaded properly serve to damage the soil, primarily due to factors such as excessive weight and uneven load distribution that sways the weight to one side of the machine.

Companies in western Canada also use a tire pressure control system (TPCS). TPCS provides mainly economic and maintenance benefits, but also reduces negative soil impacts. It can be manually controlled by the vehicle operator allowing for environmentally conscious drivers to lower the PSI, essentially turning the normal tires into flotation tires temporarily (Bradley 2023). Wider tires do not affect the soil as severely as narrower tires as pressure is more evenly distributed (Sutherland 2023). It is still not recommended to drive on low-strength soils, even with TPCS and wide tires.

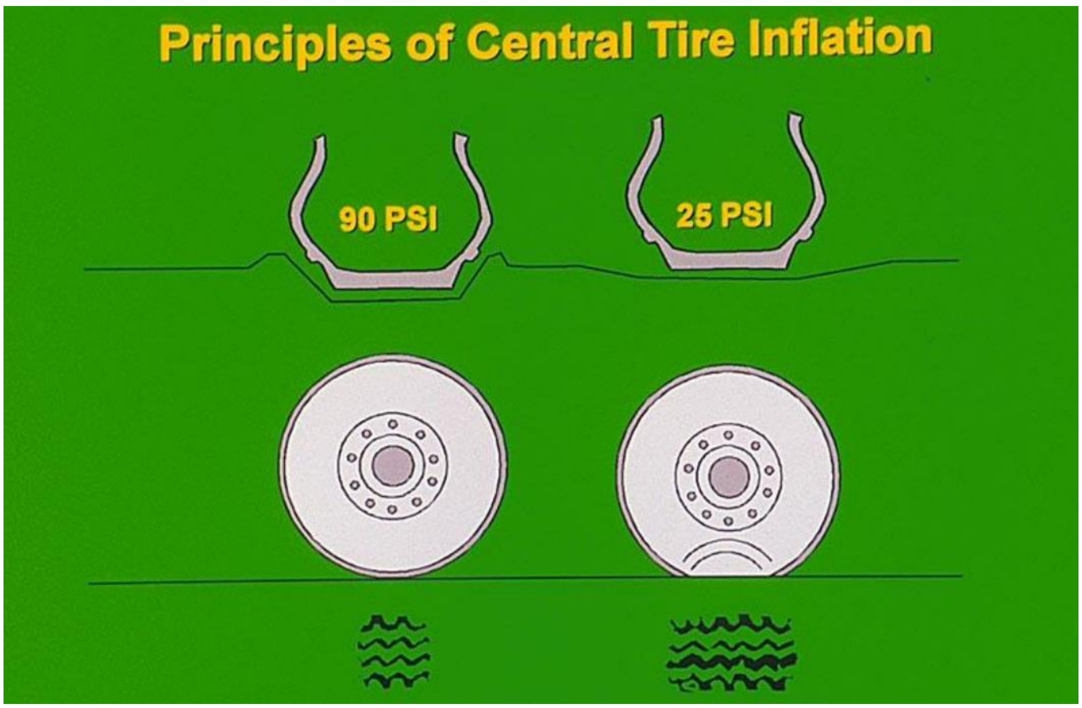


Figure 9. High vs low-pressure tire effects on forest road and soil surfaces, controlled by TPCS (Bradley and Amishev 2023).

Skidders generally have the luxury of being able to switch between tires and tracks depending on the type of soil. Cable skidders usually pull logs from one main cable, or with several smaller cables attached to the main cable (Sutherland 2003). Sometimes, logs are almost entirely dragged along the ground in cable skidding, causing further damage to the soil (especially if the company harvesting is lackadaisical). This is less common in grapple skidding in addition to its efficiency and safety being superior to cable skidding (Sutherland 2003). Meanwhile, forwarders are less prone to losing traction (which would further displace the soil) and are able to travel over slash mats more readily than skidders. They also have increased maneuverability. Its main drawback also relates to soil compaction, as it can carry heavier loads than a skidder.

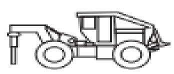
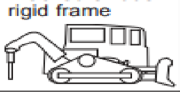
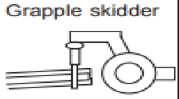
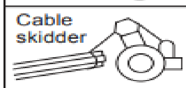
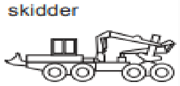
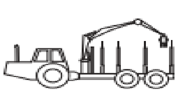
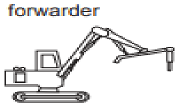
	Effects on the soil	
Equipment	Pros	Cons
Wheeled skidder 	- Can switch to wide tires or add tracks to reduce ground pressure, or add chains to reduce slippage. - The rounded edges of tires are less likely to shear surface layers (i.e., damage roots) than the sharp edges of tracks.	- Capable of high speeds and is therefore subject to bouncing which can increase soil compaction. - Worn tires are prone to slippage. - Articulation while stationary can displace soil and result in considerable damage to soil and roots.
Tracked skidder-rigid frame 	- Tracked machines travel more slowly than wheeled machines so may cause less soil damage. - Can have better traction than tires, so less slippage and rutting occurs.	- Skid steering can cause considerable disturbance. - Track grousers can cause damage to tree roots. - Unbalanced load distribution may result in higher ground pressures than wheeled machines.
Flexible tracked skidder 	- Tracks conform to shape of the ground so weight distribution is maximized. - Low or non existent grousers prevent damage to tree roots.	- Combination of high speed and skid steering can increase soil displacement and root damage. - Unbalanced load distribution may result in higher ground pressures than wheeled machines.
Grapple skidder 	- Less manoeuvring of skidder is needed with swing grapples compared to conventional grapples.	- Must maneuver skidder to the location of each load resulting in more travel over the ground. - May need to reposition several times to collect a full load if bunch size is small.
Cable skidder 	- Can minimize area of ground disturbance when cable is pulled from main skid trail. - Can reduce soil damage if load is released and winched when traversing wet areas.	- Use has been declining in favour of grapple skidders, due to the efficiency and operator safety of the latter.
Clambunk skidder 	- High load capacity requires fewer passes than conventional skidders. - Rotating clam and articulated boom mean less turning and maneuvering are necessary when loading. - Some models have a swing cab allowing machine travel in either direction.	- Not suitable for small confined areas and short skid distances that require considerable maneuvering to build a load. - Very heavy loads can increase compaction.
Forwarder (6 or 8 wheels) 	- Carries rather than drags load so potential for wheel slippage is less than with skidders, and ground disturbance is less. - Usually travels over a mat of slash created by the harvester. - Bogie tracks can be added to reduce ground pressure. - Can maneuver around obstacles easier than a loaded skidder.	- Greater weight of loaded forwarder compared to skidder may increase compaction. - Bogie drive system can skid steer when turning and result in more rutting with heavy loads than four-wheeled machines. - Slash mat can be pushed into soft soil.
Loader-forwarder 	- Machine is stationary while load is forwarded in stages so much less ground disturbance occurs than with other equipment. - Can forward wood from sensitive areas to ground better suited for skidders. - Can corduroy wet spots.	- Equipment is specialized, so it is best used in conjunction with conventional skidders. - Equipment is heavy. - Load imbalances may result in point loading.

Figure 10. Positive and negative mechanized forestry effects on boreal soils, including skidders and forwarders (Sutherland 2023).

Driving patterns are also noteworthy, two driving patterns can be used to mitigate soil damage. In western Canada, foresters can disperse their driving (as in the case of feller bunchers) or they can use a “beaten path” approach. Essentially, a forester can do less damage over a large area, or they can do considerable damage confined to a small trail. “Beaten path” trails can be rehabilitated, though this is not always possible. These types of trails are able to grow trees after several years, and dispersed driving damages natural regeneration. In order to mitigate soil damage, minimize passes for both styles of driving, and travel at low speeds. Take long turns and utilize large turning angles (Sutherland 2003).

If done properly, site preparation will not cause soil damage (but can cause long-term nutrient loss). For site preparation, follow similar guidelines as harvesting. Do not operate on low-strength, wet, or moist soils. Avoid repeat passes when the option presents itself and use wide tires and tracks.

Mitigation methods in Ontario

It is recommended that mechanized forestry be minimized in saturated sites, especially loamy soils as they are more prone to rutting as opposed to sandy soils. Additionally, soils with shallow bedrock are susceptible to nutrient loss. Foresters need to be careful during site preparation to account properly for the lack of soil depth. Best Management Practices (BMPs) are used to negate or mitigate soil damage (Archibald 1997).

Fine-textured soils (such as silty and clay loams) are more prone to compaction and rutting in Ontario. The susceptibility increases as the soil becomes more wet, to the point of saturation. Soil erosion is a cause for concern in sandy and silty soils, due to its lack of a strong chemical bond (such as clay). Shallow bedrock soils are also extremely susceptible to erosion.

Intact organic layers can reduce the risk of erosion (Archibald 1997). It is recommended to leave some coarse woody debris or leaf litter to assist in maintaining the integrity of the organic layer. Improper elimination of understorey vegetation can also lead to site and soil degradation and erosion.

Mechanical site preparation has a similar effect on soils in Ontario as described above for British Columbia (BC). Disc trenchers, bulldozers, and excavators poses significant risks to the physical soil site. Foresters modify the boreal soil to fit micro-site objectives (such as clearing space for jack pine regeneration). It is recommended to use prescribed burn for several sites, as this is the closest emulation to a natural disturbance, when compared to anthropogenic disturbances (Archibald 1997).

Compaction is reduced during winter harvests, but not as significantly encouraged as it is in BC. In fact, Ontario encourages a great snow cover depth to protect the sites adequately as opposed to compacting the snow to allow for frost penetration (Archibald 1997, Sutherland 2003). Ontario also discourages harvesting in fall because of soil moisture. To mitigate soil damages due to harvesting, harvest in the summer or winter.

Similar driving patterns are used in Ontario boreal forests as opposed to those in BC. Ontario also utilizes a dispersed and “beaten path” method, using whichever is appropriate to mitigate the damage to the soil. Skidding and forwarding equipment also poses amplified rutting and soil displacement/compaction due to the load that they carry (Archibald 1997). Chainsaws are used on steep slopes and sensitive sites where machines cannot access. Cable skidders are more commonly used than grapple skidders (unlike BC) due to its increased mobility (Archibald 1997).

Prescribed burn can also mitigate the negative effects of nutrient loss within the soil. Nutrients are unlocked via the burning of wood, and they are able to then be cycled and used for new regeneration. Hardwoods (such as aspen and birch) are more effective at nutrient cycling than softwood due to their better-developed soil profile. Full tree harvesting on poor sites are at the biggest risk of complete nutrient depletion. Cut-to-length should be used, with slash being left behind to supply nutrients and have mulch effects.

Ideas to reduce the impacts of mechanized forestry on boreal soils

One aspect of forest operations that can be changed is the size of the roads. It is not uncommon for roads to accommodate three or more logging trucks driving side by side at its widest points. Not only does this result in more soil being compacted, but it also has major economic drawbacks for forestry companies. Thousands of extra dollars are injected into a project, simply to reach the landing. There is no guarantee that the revenue that the trees will bring in will be the same as the expenses to build the road, let alone make a profit, even with surveying.

The length of the road is also important for multiple reasons. Aside from soil compromises, the longer a logging road is, the farther the distance from the sawmill where the wood will be processed. Logging trucks have to make further trips, which increases the associated costs in gas, maintenance, and trips from the landing to the mill. Additionally, more soil is taken away from regenerating trees as the road gets longer and wider, further impacting future regeneration.

Figure 11. A forest road in Ontario, likely a secondary or branch road (Conway 2023).

The practical solution would be to branch off an already existing set of logging roads, and to build what is needed to reach the desired landing site. Road construction costs are minimal, companies just need to build what is required to reach the forested site specifically licensed to them. New roads that need to be built should be kept as narrow and short as possible to avoid unnecessary soil damage, while not compromising operational efficiency that an extremely narrow road would create.

A second aspect of forest operations that can be changed to benefit the soil is aerial logging. Instead of building extra roads, groups of hand fall logging crews can travel in a helicopter to the landing. They can cut what is needed, do the processing themselves at the stump, and have a feller buncher arrive. Once the buncher has organized the logs, it departs. Some soil is still compacted, but only one machine is travelling on the ground. The logs are then attached to the helicopter via a set of cables, or a basket tailored to helicopter logging. This is common in BC and other steep environments where machinery cannot easily access a site. This is not as common in flatter environments such as Ontario, but it may be able to be used for sites such as large forested isolated islands that bridges cannot be feasibly built to.

A third aspect of forest operations that can be changed to benefit the soil is the weight of the machines. It was briefly discussed regarding the logs that they transport, but this is concerned about the weight of the machines without logs. To mitigate soil compaction, reducing the weight of machines can significantly benefit soil recovery from compaction after harvest. Lightweight metals and materials (such as aluminum and carbon) can consist of a higher percentage of the machine design. In the future, it may be possible that machines are built almost entirely out of aluminum or carbon fibre.

CONCLUSION

Forest machinery does have a largely negative effect on boreal soils. Most of this is inevitable but can be mitigated with proper site preparation and harvesting methods. Knowing what paths to take to get to the stump in certain situations is crucial in maintaining the long-term health and sustainability of not just the forest, but future regeneration. Additionally, knowing when to use tires, tracks, or other forms of mobility on a vehicle is necessary, especially when working in sensitive sites. Early spring harvesting should be avoided, along with other periods of the year with high soil moisture and saturation. To conclude, it should be stated that the forest industry has undergone lots of positive change since the turn of the 20th century. Further reducing road costs, super-light vehicles and increased aerial logging can become a reality one day.

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