EVALUATING THE EFFECTS OF CLEARCUTTING, WILDFIRE, AND BIOENERGY WOOD ASH APPLICATION ON FOREST SOILS TO IMPROVE EMULATION SILVICULTURE

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ABSTRACT

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Keywords: base cations, bioenergy wood ash, biomass, boreal, clearcutting, emulation silviculture, nutrient cycling, pH, soil amendment, wildfire

Ontario's forest management guides promote the use emulation silviculture to manage the province's forests on a landscape scale based on natural disturbance regimes. While clearcut harvesting can have similar effects to wildfire such as the removal of vegetation, creation of edge habitat, as well as increasing nitrogen cycling and decomposition rates, it lacks the chemical impacts associated with fire and ash deposition. This thesis compared published studies from North America, Europe, and Asia and found that there are similarities between harvesting and wildfire on boreal forest floors and soil characteristics. Harvesting and wildfire can have a similar effect on base cation pools such as calcium, as well as forest floor and soil pH, though fire's impacts are more substantial. Upon examination of European and Canadian bioenergy wood-ash trials, the application of ash on post-harvest forest soils could benefit certain sites and improve current emulation silviculture techniques.

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1.0 INTRODUCTION

The Ontario Ministry of Natural Resources introduced the Forest Management Guide for Natural Disturbance Pattern Emulation in 2001 which provided direction to forest management practitioners on how to manage forest landscapes in a manner that better emulates natural fire-created landscapes (OMNR 2001). The guide acknowledges that the application of the directions and guidelines in the document will not mimic the results of fire on the landscape because harvesting is a mechanical process whereas fire is a chemical one. The Natural Disturbance Pattern Emulation Guide would later be replaced by the Forest Management Guide for Boreal Landscape and Forest Management Guide for the Great Lakes-St. Lawrence Landscapes, which work in conjunction with the Ontario Stand-and-Site Guide and Silviculture Guides to manage the province's forests on a coarse filter and fine filter scale. The Ontario Forest Management guide to Silviculture describes several silviculture systems that are meant to emulate the effect of a natural disturbance on a forest's composition and structure. Silviculture systems however are the result of a mechanical disturbance that removes material from a forest, which therefore interrupts nutrient cycling, and negatively impacts nutrient availability in forest soils. Whereas wildfire, the disturbance that a clearcut is meant to emulate, recycles the forest biomass into the soil, volatizes nitrogen and consumes forest floor carbon.

Furthermore, the use of residual materials from forestry operations as fuel for bioenergy has increased substantially over the last few decades, increasing the removal of organic matter from cut-blocks, potentially compromising site productivity and biodiversity, among other valued ecosystem services (Natural Resources Canada 2018; Thiffault et al. 2011). This residual biomass material harvested includes the tree branches and tops, cull logs, and unmerchantable stems that are usually left at the roadside processing site or piled into slash piles and burned on site (Hannam et al. 2017). Wood removed during salvage operations after an insect outbreak or wildfire is also utilised for bioenergy (Hannam et al. 2017). However, the wood ash produced as a by-product of the combustion reaction within energy-producing boilers is also a growing concern, with most of the waste ash being disposed of in approved landfill sites, which also represents an economic burden to the bio-energy sector (Couch et al. 2020). More recently, there has been a reduction in the amount of wood-ash being landfilled in Canada; 82% of the ash produced in power and recovery boilers at pulp and paper mills was landfilled in 1995, decreasing to only 63% in 2013 (Hannam et al. 2017). However, field studies have shown that ash can be used as an effective tool as a soil amendment, improving a soil's water-holding capacity, increasing soil pH, as well as increasing available macronutrients for plants (Hannam et al. 2017).

This review compares the effects of clearcutting and wildfire using McRae et al. (2001)'s review as a baseline and will examine the effects of emulation silviculture and wildfire on forest floor biomass and forest soils using updated literature published since the McRae et al. review. The practice of emulating natural disturbances has been utilised in Ontario for over two decades, however, little is known regarding how effective this management paradigm has been in managing the province's boreal forest. Using data from numerous studies conducted in North America, Europe, and Asia, this paper will examine the impacts of wildfire, clearcut harvesting, and wood-ash application on forest soil characteristics such as base cation concentrations and soil pH, which can greatly impact vegetation in terms of stand development following a disturbance. The effects of these disturbances on forest floor nitrogen, acidity, and base cations will be examined and discussed. The effectiveness of emulation silviculture management techniques will be examined and compared to the natural disturbance condition it is meant to emulate on the forest floor and forest soil. At present, there is little literature on the effectiveness of the management practice, therefore, this paper aims to examine if the process emulates wildfire effectively and what aspects could be improved upon to better mimic natural disturbance processes on boreal forest floor biomass and soil characteristics.

1.1 OBJECTIVES

The purpose of this thesis is to analyze the past and present literature comparing the ecological impacts of clearcut harvesting and wildfires on forest soil characteristics to examine the efficacity of emulation silviculture as a management tool. This summary will interpret the potential benefits and drawbacks of utilizing silviculture systems that emulate natural disturbances as a stand-and-site management option. Moreover, by utilizing and comparing research from North American and European bioenergy wood ash trials, this paper will examine if ash as a soil amendment tool is an effective and possible substitution for prescribed burning for preserving stand nutrient capital and emulating the effects of fire on soil chemical properties.

2.0 METHODS AND MATERIALS

Utilizing a comprehensive review comparing the effects of clearcut harvesting and wildfire published in 2001 by McRae et al. as a basis for research, studies referenced in the review were researched and analyzed for this thesis. This research was further updated with more recent publications and studies to further improve upon the work completed by McRae et al. over 20 years ago. As a recommendation, to keep this paper a reasonable length, this thesis will focus on the effects of one core component of the environment, thus the paper’s focus on forest floor biomass and forest soils. Furthermore, the original concept of this thesis was expanded to include research conducted on biomass wood ash soil amendment. Publications from AshNet, the

Canadian Government, and the Ministry of Natural Resources were analyzed to collect information about the current research being conducted about wood ash use in Canada. Research studies on the impacts of ash amendment, wildfire, and clearcut harvesting on forest floors and soils in North America, Europe, and more, were examined to compare the data and analyze the results of the three processes on soil characteristics.

For this literature review, a variety of studies examining the impacts of harvesting and wildfire were utilized, as well as studies regarding the effects of bioenergy wood-ash application on forest soils. These sources are also compared and examined in the following results and the discussion sections of this thesis. The studies used were conducted on a diverse number of sites across different continents with the breakdown of where the harvesting and wildfire data is from being displayed below in Figure 1.

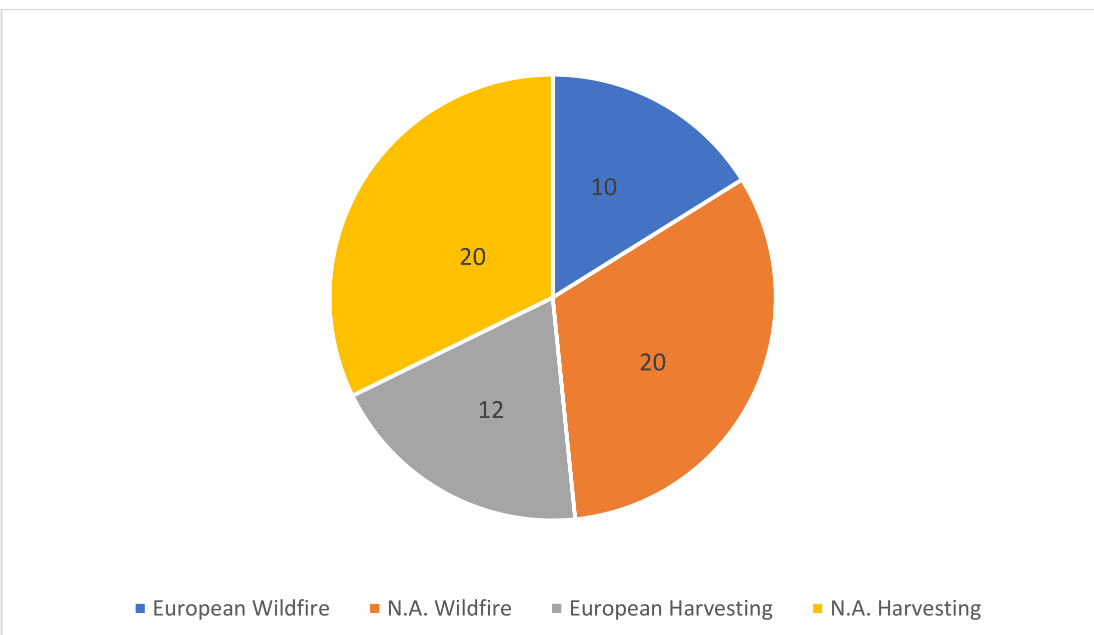

Figure 1 Number of studies utilised from Europe and North America for the literature review.

As seen in Figure 1, the majority of wildfire and harvesting studies have been conducted in North America. However, although not pictured, the majority of ash-trials have been conducted in Europe, though North American trials are beginning to become more common.

3.0 LITERATURE REVIEW

3.1 COMPARING HARVESTING AND WILDFIRE

A forest management approach that became popular in the 1990s was the concept of emulation silviculture; timber harvesting should be designed to imitate natural disturbance regimes in their respective forest types, such as fire and windfall which naturally shape the structures of forest ecosystems (Hunter Jr, 1993). In terms of frequency and distribution, wildfire is the most important stand-replacing natural disturbance in Canada's boreal forest (Webber and Flannigan, 1997). In the boreal forest of Canada, the species in those forests have been interacting with fire for about 30 million years since at least the Miocene era, therefore, a silviculture system that imitates the ecological dynamics of Canadian forests should result in more ecological forest management (Webber and Taylor, 1992).

In Ontario, emulation silviculture has been the basis of the coarse filter requirements in the province's Forest Management Guide for Boreal Landscapes and the Great Lake-St. Lawrence Landscape Guide since the early to mid-2010s. However, as stated by McRae et al. (2001) in their review comparing wildfire and forest harvesting, an impediment to emulation silviculture is that forest dynamics vary greatly among and within biophysical regions affected by various factors such as climate, topography, species distribution, past forest use, and more. Current research in fire ecology and silviculture has focused on specific forest regions and/or plant community types but has ignored the overall picture of the Canadian forests and landscapes (McRae et al. 2001). Therefore, as a general rule, it is inappropriate to apply generalized practices across broad forest regions or even between ecosystem types within the same forest region as fire and logging disturbances may impact them differently. For example, a clearcut in the northern boreal forest in Ontario will not necessarily have the same impact as a clearcut in the coastal rainforests of British Columbia because these forests have adapted to different stand regenerating disturbances. To imitate natural disturbances, emulation silviculture needs to consider the ability of key species to tolerate and regenerate truly effectively after various levels of fire intensity and severity. Furthermore, management systems must account for natural stand-replacing and non-stand-replacing fire regimes to develop suitable landscape patterns, as well as natural age class and species distribution (McRae et al. 2001). Ecosystem functions such as site productivity and carbon storage potential and capacity should also be accounted for.

3.2 EFFECTS OF FIRE ON BIOMASS/ORGANIC MATTER

Wildfire consumes and removes a large majority of the surface biomass and litter on forest floors. The amount of biomass consumed depends highly on fire intensity and fuel moisture at the time of burn based on multiple studies (Viro 1974; Freedman et al. 1996; Kimmins 1997; Stocks and Kauffman 1997). For example, a study conducted in Finland found that wildfire decreased forest floor biomass in the boreal by about 20% (Viro 1974). Furthermore, experimental burns in the boreal forest resulted in decreased thickness of the forest floor by 27 to 63 percent in Alaska (Dyrness and Norum 1983), 79 and 91 percent in northwestern Ontario (Smith 1970), and even up to 100 percent in northeastern Ontario (Stocks 1987). Research conducted by Shorohova et al. (2009) concluded that in boreal regions, wildfires greatly affect the forest's functions and structures as they can cause 15 to 55% biomass loss above ground and 37 to 70% loss below ground due to combustion. A study by Boerner et al (2000) found that relatively low-intensity fires typically result in the unconsolidated litter and fine woody fuels being burned, leaving the humus and upper soil layer untouched. Litter loss from a single fire resulted in a 30 – 80% loss depending on landscape position and fire temperature, however, the hummus layer remained unaffected by fire in the study (Boerner et al 2000).

Typically, the forest floor and upper soil layer have warmer temperatures after a wildfire which occurs due to the combined effects of a darker surface colour, which reduces albedo, and a higher intensity of insolation through a thinned or destroyed overhead canopy (Viro 1974). McRae et al (2001) use an example from a study in Finland where an average mid-day summer forest floor temperature was 30°C on a burned site compared with an 18°C in an unburned spruce stand. Temperature increases in the soil can stimulate microbial activity and can speed up the decomposition rate of litter and organic matter on the forest floor (McRae et al. 2001). In a laboratory incubation study, raising the temperature from 6˚C to 12.5˚C resulted in a doubling in the rate of decomposition, and raising the temperature to 20˚C quadrupled the rate (Viro 1974). The increase in temperature and removal of biomass also modifies soil respiration output from OM decomposition – a key ecosystem process that refers to the carbon dioxide emissions from soil and the biological activity of soil organisms that is a major flux within the global carbon cycle, contributing to roughly ten times the amount of global atmospheric CO_2 than fossil fuel combustion (Bond-Lamberty and Thomson 2010; Le Quéré et al. 2014; Raich & Schlesinger 1992). Essentially, soil respiration is the combination of plant respiration occurring in the roots below ground, the soil's rhizosphere, and soil-dwelling microbes releasing CO_2 into the ground results in soil respiration. Wildfire has been found to negatively affect soil respiration levels by destroying the litter and upper organic layer while further causing severe damage to the underlying humus layer depending on fire severity. For example, in a study conducted on multiple sites in Northwestern Estonia, the highest soil respiration values were recorded in the unaffected control plot which had more than twice the value of respiration than burned areas (Parro et al. 2018). The soil horizons destroyed or damaged by fire are where the most soil respiration occurs in the form of decomposition and root respiration; therefore, fires can significantly impact respiration rates by removing carbonaceous materials and reducing root mass (Parro et al 2018). A similar study conducted in 2004 and 2005 at three boreal forest sites in central Saskatchewan found that the removal of the forest floor resulted in a reduction of soil respiration by 17% to 38% depending on the site and that soil respiration was positively linearly related to the fine root biomass at all sites, thus concluding that variation in root biomass has a larger effect on soil respiration than differential floor organic layers on variation in soil respiration in young boreal post-fire forests (Singh et al. 2008). Therefore, the deeper a fire burns, the more impact it will have on soil respiration levels, also resulting in a higher number of trees killed.

In addition to affecting soil respiration, the removal of shrubs and vegetation whose root mats keep the forest floor porous can result in a compression of the forest floor in subsequent years following a burn (Viro 1974). The aforementioned increase in decomposition and the increase in compression, in combination with decreased leaf litter during the initial stages of stand initiation after a forest fire, can contribute to a decrease in the thickness of the forest floor (McRae et al. 2001). According to Viro (1974), these post-fire influences can persist for as long as 20 years until the next stand develops and matures. There was not, however, any correlation between soil respiration levels and the thickness of the forest floor organic layer according to a study conducted in Saskatchewan (Singh et al. 2008).

3.3 EFFECTS OF HARVESTING ON FOREST FLOOR BIOMASS

Biomass on the forest floor can be impacted and affected by clearcutting and other harvesting systems, however, their effects largely depend on forest type, disturbance type, aspect, slope, as well as other ecoclimatic factors (McRae et al. 2001). Similar to natural fire-based disturbances, decay rates are affected by harvesting through the reduction of litter deposition. Decomposition is increased due to higher surface temperature caused by a decrease in canopy shade, an increase in moisture availability due to less evapotranspiration occurring, reduced canopy interception and the physical mixing of the organic substrate via logging machinery operating on forest soils (McRae et al. 2001). A study of a montane conifer-dominated forest at four sites in Alberta found that clearcutting results in a combination of increased soil wetness following harvesting and a reduced air-filled porosity with increasing levels of soil compaction that cause decomposition rates to increase (Startsev et al. 1998). Furthermore, the study found that soil respiration increased by roughly 15-25% with soils subjected to skidder traffic providing the highest respiration rates, apparently due to on-site biota adapting to low soil aeration and periodic anaerobiosis (Stastsev et al. 1998). A study done on three sites on Vancouver Island, ranging from low elevation to montane, found that the decomposition rate on the surface was not increased by clearcutting operations when compared to their reference conifer forest, however, the rate of decomposition was 3 to 5 times faster deeper in the organic layer profile and at its interface with the upper mineral soil horizon (Binkley 1984). Drier conditions occurring on the top surface of the forest floor post-harvest were presumably the cause of this difference. Another study done on Vancouver Island compared decomposition rates of various silviculture treatments and an old-growth forest, concluding that the overall tendency was for decomposition to be highest in the old growth followed by the clearcut (Prescott 1997). Generally, decomposition is considered to be faster in clearcuts than in undisturbed forests due to higher temperatures and moisture conditions. The results of this study suggest that summer moisture may be more critical to decomposition in the study area's ecosystem (Prescott 1997). A study completed in Brno Czech Republic found that clearcutting impacted soil decomposition processes and fungal community composition by affecting the rhizosphere causing it to more closely resemble bulk soil (Kohout 2018). Decomposition in soil decreases over time, indicating the potential importance of root activity for the decomposition of recalcitrant soil organic matter (Kahout 2018).

On the other hand, some studies have not found any correlation between clearcutting and the increased rate of decomposition of organic matter in the forest floor. Although not in the boreal forest, no significant effect on the decomposition of leaf litter due to clearcutting was found in studies of a chrono-sequence of hardwood stands in Nova Scotia (Wallace & Freedman 1986). Wallace and Freedman concluded that difference in results compared to a similar study done in New Hampshire may have been a result of intra- and inter-stand variation in forest floor weight in the study (1986). In terms of soil respiration, a study by Mallik and Hu (1997) found that soil respiration was not significantly different in their clearcut sites compared to their uncut control sites. The study reported changes in soil respiration patterns that were attributed to changes in soil moisture and organic matter content associated with the various treatments included in the study – those treatments being clearcut without site prep; clearcuts followed by organic matter and soil mixing; screefing; and the uncut control sites (Mallik & Hu 1997). Increased respiration in the soil of the cut and mixed treatments were likely the result of the accelerated activity of the existing microbial population according to Mallik and Hu (1997). A study conducted in jack pine forests in Ontario comparing the effects of clearcutting, scarification, and prescribed burning on leaf litter decay rates found that the biggest differences among treatments were observed after one year of field incubation with differences decreasing substantially after 3 years (Duchesne & Wetzel 1999). Furthermore, the decay rates of the burnt-over plots at various intensities did not differ from the decay rates of clearcut, scarified, or the control plots three years post-disturbance (Duchesne & Wetzel 1999).

Harvesting removes tree biomass and associated nutrient stores from the site. A Scandinavian study noted that nutrient removal may vary greatly depending on the growth model, biomass equations and nutrient concentrations found in different tree compartments (Raulund-Rasmussen et al. 2008). For example, de Jong et al. (2022) found that harvesting logging residues at final felling increased nutrient removal by 20% for calcium removed with Scots pine, and up to 128% for phosphorous with Norway spruce in Dutch softwood species. However, on-site nutrient loss can be somewhat mitigated by delaying the harvest of logging residue by 6 months which can be effective for potassium levels leached from leaves, needles, and branches (de Jong et al. 2022). This method is not as effective for calcium, phosphorous, and magnesium levels because hardly any of these nutrients leach from needles and branches in that span of time (de Jong et al. 2022).

3.4 EFFECTS OF FIRE NUTRIENT CYCLING

It is well documented that wildfires can have a substantial impact on nutrient cycling in forest soils resulting in a relatively even deposition of inorganic nutrients across a burned area with the presence of calcium, magnesium, potassium, and phosphorus in ash (McRae et al 2001; Gonzalez-Perez et al. 2004; Johnson & Curtis 2001; Certini 2005). Moreover, there is a deposition of woody debris which contains organic nutrient contents which are released over time through decomposition (McRae et al. 2001). The decomposition of organic material combined with the deposition of ash and heat created by wildland fires all play an important role in modifying forest soils during and post-disturbance. The deposition of ash results in a decreased acidity of the remaining organic layer and upper mineral soil which can impact nitrate production through bacterial nitrification (McRae et al. 2001; Viro 1974). Utilizing a post-fire chronosequence in a study conducted in northwestern Quebec, Brais et al. (1995) noted a decrease in pH from the recent post-fire stand (pH 5.5) to the mature stand (pH of 3.65). The same study found an increase in the concentration of potassium, calcium, and magnesium following wildfire with calcium and magnesium levels decreasing linearly over time and exchangeable potassium increasing up until 75 years post-fire, then decreasing out to age 231 (Brais et al. 1995). A study conducted utilizing 12 sites throughout the U.S. found that pH levels were significantly higher in soils that had been treated with mechanical and fire treatments when compared to the untreated soil during the first-year post-treatment (Boerner et al. 2009). The same study found an increase in pH during the first post-treatment year on their burn sites with pH declining rapidly in the second year (Boerner et al. 2009). Furthermore, the sites with the greatest fire severity were found to have the most significant changes in soil pH and extractable calcium (Boerner et al. 2009). According to a review by Certini (2004), there is an inexorable increase in soil pH through soil heating during a fire as a result of organic acids denaturation. Significant increases only occur at high temperatures between 450 and 500°C in coincidence with the complete combustion of fuel and the release of bases into the soil (Certini 2004; Arocena & Opio 2003). Moreover, Khanna et al. (1994) found that the capacity of ash to decrease soil acidity is correlated with the sum of the concentrations of base cations in the ash content itself. According to studies conducted in Finland, the amount of total calcium in the forest floor increased by about 65% during the first six years after a fire, with the total amount of magnesium increasing by about 30% (Viro 1974). Exchangeable calcium and magnesium levels tripled and doubled respectively in the first-year post-fire (Viro 1974).

Fire can also greatly impact nitrogen cycling due to the low-temperature threshold making the nutrient easily volatilized. During combustion, the nitrogen content of forest floor biomass and stored N in foliage/fine branches, is largely oxidized into gaseous nitric oxide and ammonia which are lost to the atmosphere (McRae et al. 2001). According to Raison et al. (1985), the amount of total nitrogen volatilized during combustion is directly proportional to the amount of organic matter combusted. However, according to Grier (1975), this relationship may not remain true at lower fire temperatures due to organic matter being able to decompose without volatilizing nitrogen, therefore, nitrogen loss is not necessarily proportional to organic matter loss. Non-volatilized nitrogen remains on site either as unburnt fuels or as inorganic ammonium-nitrogen (NH_4-N) in the soil (DeBano 1991). DeBano (1991) also explained that nitrogen availability is commonly increased by the translocation of nutrients downward through the soil during a fire which occurs due to steep temperature gradients in the upper soil layers during litter combustion. Surface soil temperatures may exceed 1000˚C during a fire, however, due to poor heat conduction by the soil, temperatures typically reach less than 200˚C within 5cm of the soil surface (DeBano 1991). As a result of this temperature gradient, some of the vaporized organic matter and ammonium-rich nitrogenous compounds released during combustion are forced downwards through the soil where they condense upon reaching the cooler underlying soil layer (DeBano 1991). Therefore, although a large amount of total nitrogen is lost during a fire through the loss of plants and litter, available ammonium is typically higher in the underlying soil layer following a wildfire because of this nutrient translocation mechanism (DeBano 1991). However, the immediate amount of ammonium following a fire appears to be linked to the soil temperatures reached; extremely hot, high-severity fires will volatilize most of the nitrogen on a site resulting in only a small amount being transferred downward into the soil whereas under cooler soil-heating regimes, a substantial amount of ammonium can be found in the ash and underlying soil (DeBano 1991). A study conducted in Arizona involving prescribed burning in a ponderosa pine forest found immediate increases in NH_4 levels; increases from 2.3 to 45.1 mg kg^{-1} in the old growth substands, 1.3 to 26.7 mg kg^{-1} in the pole substands, and 1.3 to 8.3 mg kg^{-1} in the sapling substands (Covington and Sackett 1992). The short-term increase in available NH_4 in the forest floor and upper mineral soil combined with increased soil temperature and increased soil pH can result in a stimulation of nitrification which can lead to an increase in nitrate for several years post-fire (McRae et al. 2001; Viro 1974; Brais et al. 1995). Nitrite is however highly susceptible to leaching, which can be a concern regarding water quality. Nitrification is a microbial process wherein reduced nitrogen compounds, such as ammonia, are sequentially oxidized into nitrate and nitrite (USEPA 2002). This increase in nitrate is why post-burn sites typically support large populations of nitrophilous herbaceous plants such as raspberries and fireweed (McRae et al. 2001). According to Certini (2005), prompt plant recolonization is important for the conservation of soil nitrogen in burnt areas. Furthermore, if the vegetation regrowth includes nitrogen-fixing species, a complete recovery of the original pool of organic nitrogen can be quite rapid (Certini 2005). Moreover, the concentration of organic nitrogen in the soil during the stand establishment stage can often exceed the pre-fire levels (Johnson and Curtis 2001).

An important bi-product of wildfire is the creation of charcoal which several studies have shown can have a positive impact on plant regeneration and nutrient cycling in forests. A study conducted on 12 sites in Sweden examined if charcoal absorbed the phenolic compounds of a late successional dwarf shrub, *Empetrum hermaphroditum*, which has very important inhibitory effects against tree seedling growth and establishment, mycorrhizal function of other species and probably the soil biota (Zackrisson et al. 1996). The authors concluded that activated charcoal younger than 100 years was effective at reducing the phenolic effects of the shrub productivity (Zackrisson et al. 1996). They also found that charcoal could impact plant litter decomposition as well as potentially catalyze soil processes in early-successional boreal forests all of which ultimately may have important long-term consequences for ecosystem function and stand productivity (Zackrisson et al. 1996).

Forest fires do not impact phosphorus levels as severely as nitrogen due to the nutrient's higher temperature threshold, making volatilization and leaching losses smaller. In fact, the combustion of vegetation and forest floor litter can result in positive modifications to the nutrient's biochemical cycle with burning by converting the organic pool of soil phosphorus into orthophosphate which is the sole form of phosphorus available to soil biota (Cade-Menun et al. 2000). Furthermore, with the peak bioavailability of phosphorus being around pH 6.5, any increase in soil pH towards neutral has a positive effect on P availability for vegetation recolonization (Cade-Menun et al. 2000). However, according to a study conducted in a cedar-hemlock forest located on Northern Vancouver Island, the changes in pH and phosphorus are ephemeral with available phosphorus and pH levels returning to pre-burn levels within 10 years (Cade-Menun et al. 2000).

3.5 EFFECTS OF HARVESTING ON SOIL AND NUTRIENT CYCLING

Similar to fire, harvesting forests can also greatly impact nutrient cycling with the most immediate and obvious effect being the removal of large quantities of organically bound nutrients contained in the harvested biomass. During a full tree clearcut, also commonly called a whole tree harvest the stem is removed taking the nutrients contained within the wood and bark with the remainder being piled into slash piles and burned on site. According to McRae et al. (2001), if a whole tree harvest is conducted, the nutrient depletion is at least doubled because of the removal of the nutrients from the branches and foliage. Although this additional removal is typically represents about 30% more biomass, these live crown components contain relatively high concentrations of nutrients (McRae et al. 2001). Whole tree clearcuts result in an additional yield of biomass which can be used to make additional wood by-products or used as a source of combustible energy. A study conducted on a regional level in Sweden found that whole tree harvesting in spruce forests led to substantially higher net losses of potassium and calcium than stem harvesting (Holmquvist et al. 2007). The whole-tree harvesting scenario estimated yearly net losses of calcium, magnesium, and potassium to be at least 5, 8, and 3% higher respectively, for the pools of exchangeable base cations, at 25% of the analyzed sites (Holmquvist et al. 2007). Furthermore, the authors conclude that losses of this magnitude could lead to very low base saturation of the forest soils which could result in negative effects on soil fertility, runoff water quality, tree vigour, and tree growth within a forest rotation in certain parts of Sweden (Holmqvist et al. 2007). However, a study conducted in Quebec comparing the effects of wildfire and harvesting on soil nutrients found no significant nutrient loss following clearcut harvesting in any of the study areas (Simard et al. 2001). With respect to soil pH levels, the same study found an increase in pH in one of their clearcut sites compared to their unharvested control (Simard et al. 2001). A study in southern Sweden also found an increase in pH level in the humus layer during the first two years following a clearcut and can stay elevated for up to 10 years following harvesting operations (Gronflaten et al. 2008). Several factors could lead to a pH increase following clearcutting such as enhanced decomposition rates of organic material and the transformation of humic substances as previously mentioned in this paper (Gronflaten et al. 2008). Nitrogen mineralization is also typically increased shortly after a clearcut due to the increased soil temperature and increased decomposition caused by the lack of forest canopy (Gronflaten et al. 2008). Similar to the effects of wildfire, nitrogen uptake by plants is reduced and increased levels of ammonium are frequently observed in the soil following clearcuts (Binkley and Richter 1987). Moreover, the increase in nitrogen availability and higher mineralization rates following a clearcut have been attributed to the fresh input of organic matter, the mixing of mineral soil and forest floor layer by machinery, the increase in soil temperatures, as well as the increased moisture availability from a reduction of the vegetation on site (Simard et al. 200; Keenan and Kimmins 1993). However, not all studies have observed this increase in inorganic N following clearcutting. For example, a study of a chronosequence of hardwood forests in Nova Scotia did not find a significant change in nitrate or ammonium concentrations in the forest floor following clearcutting (Wallace and Freedman 1986). This difference in results could be due to the methodologies used or perhaps a difference between coniferous and Acadian Forest hardwood sites post-clearcut as the other studies examined were conducted in boreal coniferous stands.

Unlike wildfire, soil compaction caused by heavy machinery during harvesting operations can negatively impact soil characteristics. The level of compaction is affected by soil moisture content, with dry soils being less affected than moist ones (Conlin and van den Driessche 1996). In a study conducted in British Columbia examining the effects of compaction on the growth of lodgepole pine and Douglas-fir seedlings, the authors found a decrease in base cation uptake due to soil compaction and increased moisture content (Conlin and van den Drissche 1996). Furthermore, they also noted a reduced uptake of N, P, and K (Conlin and van den Drissche 1996). Root growth of both species was also affected by soil compaction due to the increase in bulk density and gravimetric moisture content (Conlin and van den Drissche 1996). A study by Wert and Thomas (1981) found that growth reduction in trees due to soil compaction on skid trails has been reported to last for as long as 32 years after harvesting operations.

A review study of data compiled from field experiments from northern European sites conducted by Clarke et al. (2021) examined the effects of intensive biomass harvesting on forest soil nutrient contents, the results generally supported that whole-tree harvesting had a greater reduction in nutrient concentrations, soil organic carbon, and total nitrogen compared to stem-only harvesting in northern temperate and boreal forest soils. Another study that aggregated results collected from experimental forests indicated that intensive harvesting can have negative consequences on soil carbon stocks which can potentially have an impact on carbon budgets (Achat et al. 2015). Their modelling simulations suggested carbon losses between 5 to 17 Tg-C year $^{-1}$ depending on the scenario with the most severe scenario resulting in approximately 57% of the carbon sink being offset by unintended losses due to a reduction in soil sink potential (Achat et al. 2015). Furthermore, the removal of logging residues had other negative impacts on forest soils, negatively impacting nutrient availability which could affect tree growth and site fertility (Achat et al. 2015).

3.6 ASH SOIL AMENDMENT STUDIES

Canada has been experimenting with the idea of using biomass wood ash generated from co-generation boilers burning forest residues as a forest soil amendment. Research is being conducted by AshNet, a network composed of Canadian government employees, academic, and industry researchers, foresters, and policymakers into the potential benefits of diverting wood ash from landfills to forest soils (Hannam et al 2017; Natural Resources Canada 2018). AshNet currently consists of 10 research groups with a total of 14 established sites located across 4 vegetation zones in Canada (Figure 2).

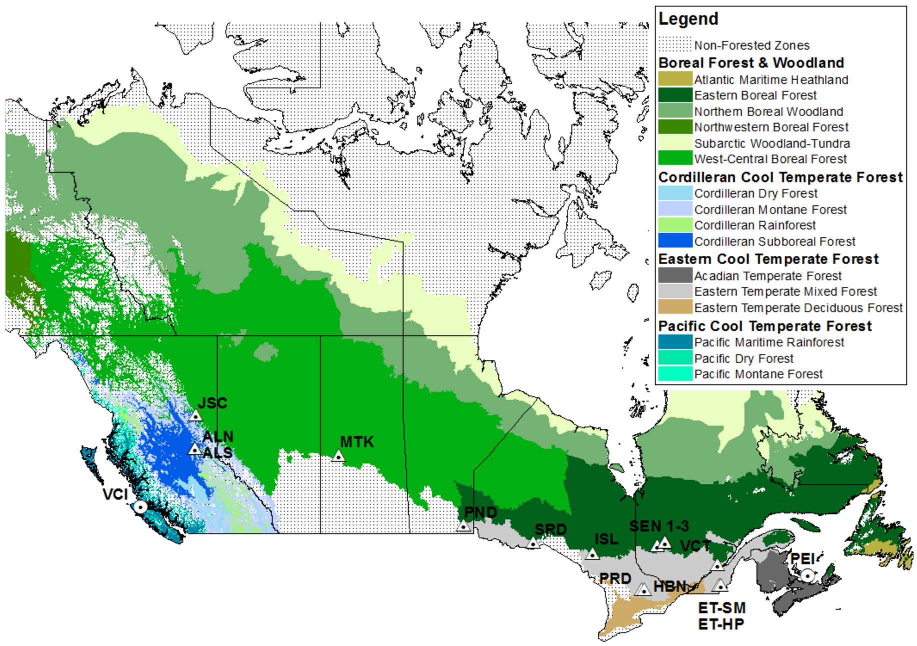

Figure 2 Current AshNet study locations across Canada (triangles) along with two historical ash amendment trial locations that are no longer maintained (circles) (Emilson et al. 2018).

Hannam et al. (2017), list a number of potential benefits associated with using wood ash as a forest soil amendment in Canada. Emulation silviculture management practices are promoted as a means of accommodating the conflicting demands for ecological and economic values in Canadian forests. As previously established, wildfire of varying intensity and severity is the predominant natural disturbance in many Canadian forests and although wood ash application does not impose the same high surface soil temperatures or rapid oxidization of the forest floor associated with fires, it can elevate soil pH and enhance concentrations of calcium, magnesium, and potassium (Hannam et al. 2017; Nave et al. 2011; Augusto et al. 2008; Huotari et al. 2015; Reid and Watmough 2014). In a study comparing research on wildfire and bioenergy ash in North America and Europe, Hannam et al. (2019) suggested that their results support the concept of ash application as a fine filter tool for preserving stand nutrient capital and emulating the effects of wildfire on some soil chemical properties as a substitute for prescribed burning.

Wildfire and bioenergy ash application have distinctly different effects on upland forest soil C and N pools. This is primarily due to the process of ash application lacking the extreme temperatures associated with wildfires that cause the combustion of forest vegetation and volatilizes nitrogen and oxidizes carbon from the forest floor and surface mineral soil (Hannam et al. 2019). Their meta-analysis of bioenergy ash application studies found that the process does cause a small but significant loss of carbon from the forest floor as well as a similar, though not statistically significant, reduction of forest floor nitrogen levels (Hannam et al. 2019). The accelerated decay of organic matter, as well as increased nitrification have been observed in several ash trials and has been attributed to increased soil pH and higher microbial activity (Hannam et al. 2019; Baath and Arnebrandt 1994; Fritze et al. 1994; Zimmerman and Frey 2002; Maljanen et al. 2006; Rosenberg et al. 2010). The apparent increase of both carbon and nitrogen in ash-treated mineral soils in the 10 to 30 cm depth suggests that leaching of these nutrients from the forest floor into the deeper horizons is also probably important (Hannam et al. 2019).

As previously mentioned, wildfires produce highly aromatic forms of pyrogenic carbon in the form of charcoal that can be resistant to decay and contribute to long-term carbon storage in forest soils. Similarly, incompletely combusted bioenergy ash can also contain polycyclic aromatic hydrocarbons with similar effects, promoting carbon and nitrogen mineralization (Hannam et al. 2019). However, further work is required to better understand the net effect of carbon-rich aromatic compounds generated from wildfire and bioenergy ash on long-term soil carbon storage, as well as nutrient cycling (Hannam et al. 2019).

The meta-analysis study found that bioenergy ash application had a temporary positive effect on extractable phosphorus levels which tended to disappear after about 5 years (Hannam et al. 2019). This temporary increase in available phosphorus is likely caused by the increase in soil pH given that phosphorus availability is greatest at around a pH of 6.5 (Hannam et al. 2019). Furthermore, the reasons for the short temporal increase may be due to the applied phosphorus from ash rapidly being taken up by plants, leached from the system, or complexed into less soluble compounds (Hannam et al. 2019; Arvidsson and Lundkvist 2003; Omil et al. 2013; Staples and Van Rees 2001; Tulonen et al. 2002; Jacobson et al. 2004; Gómez-Rey et al. 2013). Moreover, it seems that the application of pre-treated ash, meaning self-hardened, granulated, or pelleted ash, tends to have a greater effect on the concentration of extractable phosphorus in surface soils than untreated ash (Hannam et al. 2019). This is likely due to the reaction between the soil inorganic phosphorus readily reacting with the ash-applied calcium, forming a slowly soluble compound $Ca_3(PO_4)_2$ (Hannam et al. 2019; Jacobson et al. 2004; Gómez-Rey et al. 2013).

Wildfire and the application of bioenergy ash can have similar effects on mineral soil pH and exchangeable calcium, however, the effects of wildfire on the forest floor were more muted compared to those of bioenergy ash (Hannam et al. 2019). A possible explanation for this difference could be the variable nature of wildfires, with forest floor material being left partially combusted during less severe fires (Hannam et al. 2019). In contrast, the forest floor is typically left in place for bioenergy ash application trials, with ash being applied as homogeneously as possible across the soil surface (Hannam et al. 2019; Skogsstyrelsen 2008). Hannam et al. (2019) suggest that ash application rates could be strategically manipulated to emulate the effects of wildfires more effectively on base cation availability and pH in surface mineral soils. The application of less than 6 Mg ha^{-1} of bioenergy ash caused similar increases in surface soil pH to those observed post-fire (Hannam et al. 2019).

Enhanced tree growth has been consistently documented on sites with organic matter-rich soils, where the application of bioenergy ash raises the pH and increases the mineralization of organic matter (Emilson et al. 2019). However, results of wood ash application on upland forest sites have been less consistent in contrast. Studies have reported that ash application on coniferous species planted on upland mineral soils has shown positive, neutral, and negative tree growth-response with these inconsistencies in tree growth responses being attributed to a lack of nitrogen in the applied ash on sites with nitrogen limitations (Emilson et al. 2019; Jacobson et al. 2014). A study conducted on multiple sites with varying soil characteristics across Canada found that tree growth response was found to vary by tree species, highlighting the importance of selecting stands for bioenergy ash amendment (Emilson et al. 2019). In their study Emilson et al. (2019) found that jack pine benefited the most from ash amendment, whereas white/hybrid spruce and black spruce were less responsive. Furthermore, a marginal negative growth response in black spruce was noted, similar to a reported negative diameter growth response found in a study conducted in Quebec across a gradient of increasing wood ash application rates (Brais et al. 2015). However, another study conducted in Thunder Bay examining the short-term effects of high-carbon and low-carbon boiler ash concluded that there were no short-term negative effects on either white or black spruce seedlings after applying wood ash (Couch et al. 2020). Furthermore, the study also concluded that low carbon ash, which generally had a higher pH and higher macronutrient concentrations compared to the high carbon ash, had a greater effect on surface soil chemical properties (Couch et al. 2020).

According to the conclusions of multiple studies, bioenergy ash amendment applications can have similar effects on surface soil pH and nutrient availability compared to wildfire, however, more long-term research is required regarding dosage rates, ash content, and ash pre-treatment methods, to effectively meet management objectives (Hannam et al. 2019; Couch et al. 2020; Emilson et al. 2019). With the increasing interest in removing harvesting operation debris from sites for use as bioenergy, and the reduction of prescribed burning, the application of bioenergy ash could be a valid fine filter tool for preserving forest soil nutrient capital and emulating some of the chemical effects of wildfires on forest ecosystems (Hannam et al. 2019; Paré et al. 2016).

4.0 DISCUSSION

4.1 COMPARISON OF OVERALL EFFECTS OF WILDFIRE AND HARVESTING ON FOREST FLOOR AND FOREST SOIL CHARACTERISTICS

Clearcut harvesting is intended to emulate high-intensity forest fires and their effect on the landscape in Ontario's northern boreal forest in terms of pattern emulation. The effects of both disturbances on boreal forest floor and soils share similarities though differ quite drastically in some regards as summarize in Table 1.

Table 1 Summary of similar and unique effects of wildfire and harvesting on various forest soil characteristics.

Effect On	Wildfire	Harvesting
Forest Floor Biomass	Can consume about 20% of forest floor biomass depending on fire intensity. However, highly variable.	Not a significant amount of biomass removed during conventional clearcut. Impact increased if biofuel harvesting occurs.
Forest Floor Thickness	Reduced by 27 to 100% depending on location and fire intensity.	Not significantly impacted by clearcutting. Impact increased if biofuel harvesting occurs.

Decomposition Rate	Increased due to the increase in soil albedo post-fire.	Increased due to higher temperatures caused by the removal of the forest canopy post-harvest. Some studies have found no changes to decomposition rates following harvesting.
Soil Respiration	Reduced by 17 to 38% due to the removal of the organic layer and root systems.	Increased by soil compaction from skidder trails and heavy machinery. However, some studies have reported no change in respiration levels.
Soil Compaction	Increase in soil compaction caused by combustion of vegetation.	Increased by skidder trails and heavy equipment. Can increase soil bulk density.
Soil pH	Increase in pH reducing soil acidity post-fire. Effects are ephemeral, typically declining rapidly over time.	Reported increases in pH due to increases in decomposition rates and soil temperatures.
Base Cations	A large increase in Calcium and Magnesium. An increase in pH closer to 6.5 results in a short-term increase in phosphorus availability.	Stem-only harvesting does not significantly impact base cation concentrations. However, whole-tree harvesting can negatively impact on-site calcium, magnesium, potassium, and phosphorus levels.
Nitrogen	Losses depend greatly on fire intensity and severity. Lower-temperature fires volatilize less nitrogen and can increase available ammonium levels in surface soils for example. Post-fire conditions encourage on-site nitrification.	Reduction in nitrogen uptake by plants, an increase in nitrification, and conflicting reports of available ammonium levels increasing in mineral soil.

4.2 COMPARISON OF THE IMPACT OF CLEARCUTTING, WILDFIRE, AND WOOD ASH APPLICATION ON SOIL ACIDITY

Comparing the data from various North American (Simard et al. 2001; Brais et al. 1995) and European (Grønflaten et al. 2008; Levula et al. 2000) studies on the effects of wildfire and clearcutting on the forest floor and mineral soil pH indicate that wildfire has a far more substantial effect on acidity levels (Figure 3). The effects of wildfire result in a consistently significant increase in mineral soil pH whereas clearcutting saw an increase of only a few decimals in the forest floor, hardly impacting mineral soil acidity levels.

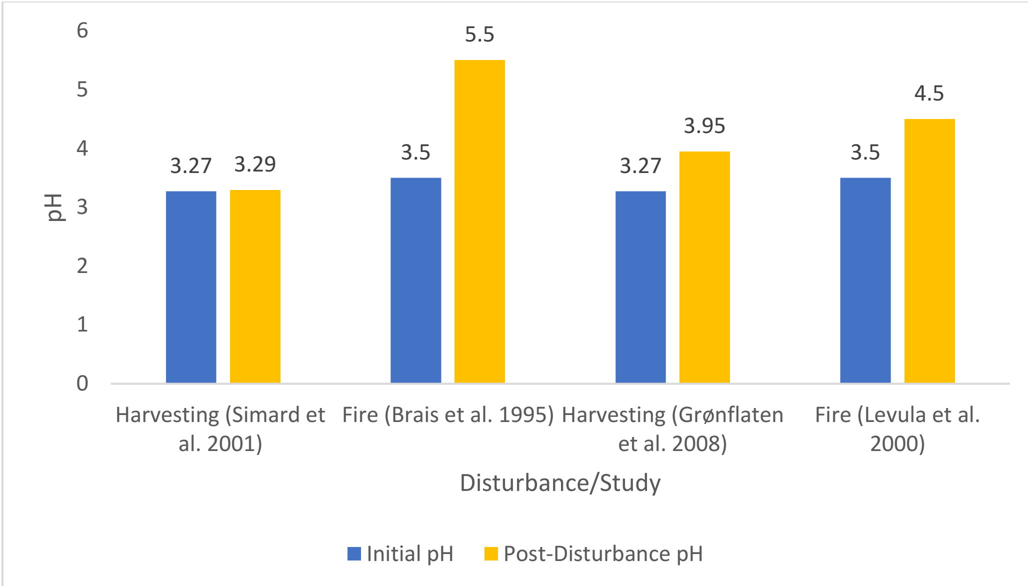

Figure 3 Impact of either wildfire or clearcutting on boreal forest floor and soil pH levels according to multiple North American and European studies.

Utilizing data from various ash amendment studies conducted in European locations (Zimmerman and Frey 2002; Levula et al. 2000; Kepanen et al. 2005; Maljannen et al. 2006) as well as a South Korean (An and Park 2021) and Canadian (Staples et al. 2001) study, there is a clear impact on soil pH as illustrated in Figure 4, with each soil sample decreasing in acidity after wood ash application. The pH increases reported in the studies were averaged to account for multiple research plots and sites in each study examined.

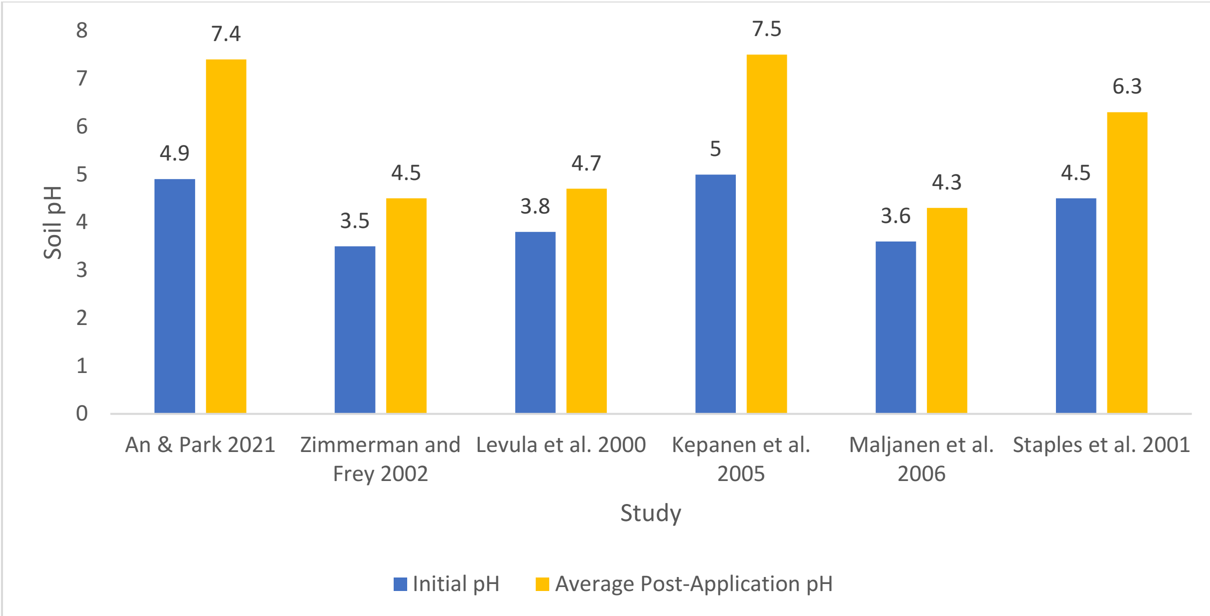

Figure 4 Average mineral soil pH increase observed in a variety of wood ash amendment studies in Europe, South Korea, and Canada.

It is important to note that when interpreting and comparing data from various papers, that a consistent and uniform methodology was not implemented when conducting these studies. A substantial amount of variability, including but not limited to types of wood ash utilized, wood ash content, site, and soil type, as well as the amount of ash applied must be considered. For example, the study conducted by An and Park (2021) in South Korea applied 5000, 10,000, and 20,000 kg ha^{-1} across three different soil types, whereas the study by Levula et al. (2000) occurred in a 100-year-old Scots pine stand in Finland and utilized three levels of ash fertilization, 1000, 2500, and 5000 kg ha^{-1}. The research conducted by Kepanen et al. (2005), examined the effects of two different fly ashes, bottom ash, self-hardened ash, and granulated ash on a field site in Finland as well as an incubation experiment. The study reported no statistically significant increase in pH levels in the field soil trial, however, in the incubation experiment all ash treatments significantly impacted soil pH, with one of the fly ash applications having the greatest effect on soil acidity. Regardless of the variation in methods and study areas, the data consistently suggests that bioenergy wood ash amendment is a valid method of decreasing soil acidity levels and that increased ash doses have a more severe impact on the pH level.

4.3 COMPARISON OF THE EFFECTS OF WILDFIRE, CLEARCUTTING, AND WOOD-ASH APPLICATION ON FOREST FLOOR AND SOIL CALCIUM CONCENTRATION.

The data from various studies examined shows that there is a clear increase in forest floor calcium concentrations as harvesting, wildfire, and bioenergy wood ash application can all have a significant impact on base cation concentrations in the forest floor (Figure 5). Fire from a prescribed burn increased calcium concentrations substantially in the Levula et al. (2000) study, increasing concentrations on the burned plot to 6000 mg kg^{-1} in the forest floor, which is three times higher than the unburnt control plot. However, applying 5000 kg ha^{-1} of wood ash on their study plot increased the concentration fivefold to 10000 mg kg^{-1}. Wood ash had a similar, but lesser impact in the Maljanen et al. (2006) study, increasing calcium concentrations from 5170 to 8710 mg kg^{-1} with the application of 7000 kg ha^{-1} of loose wood ash. The Simard et al. (2001) study comparing the effects of clearcut harvesting and fire found that clearcutting increased forest floor calcium concentrations from 1068 to 2700 mg kg^{-1} with fire increasing concentrations to more than three times compared to the control, increasing from 1068 to 3470 mg kg^{-1} in the burned plots.

Although there was variability in the treatment effects among the studies examined, likely due to variability in the wood ash utilized, stand type, dosage rates, and time elapsed since the ash was applied to the site, bioenergy wood ash application has a clear impact on forest floor calcium concentrations that exceed the effects of clearcut harvesting and fire. Hannam et al. (2019), reported that while wildfires can cause a small reduction in exchangeable calcium content in the forest floor, it does not affect concentrations. Moreover, wildfire increased exchangeable calcium by approximately 50 percent at both the 0 to 10-centimetre and 10 to 30-centimetre mineral soil layers (Hannam et al. 2019). The same study reported increases in forest floor calcium content and concentrations by 264 and 216 percent respectively, with an increase of 116 percent in the 0 to 10-centimetre mineral soil layer and a 69 percent increase in the 10 to 30-centimetre layer (Hannam et al. 2019). The strategic application of wood ash could therefore be an invaluable tool in emulating the effects of wildfire on the forest floor and mineral soil base cation levels if the correct dosage is applied.

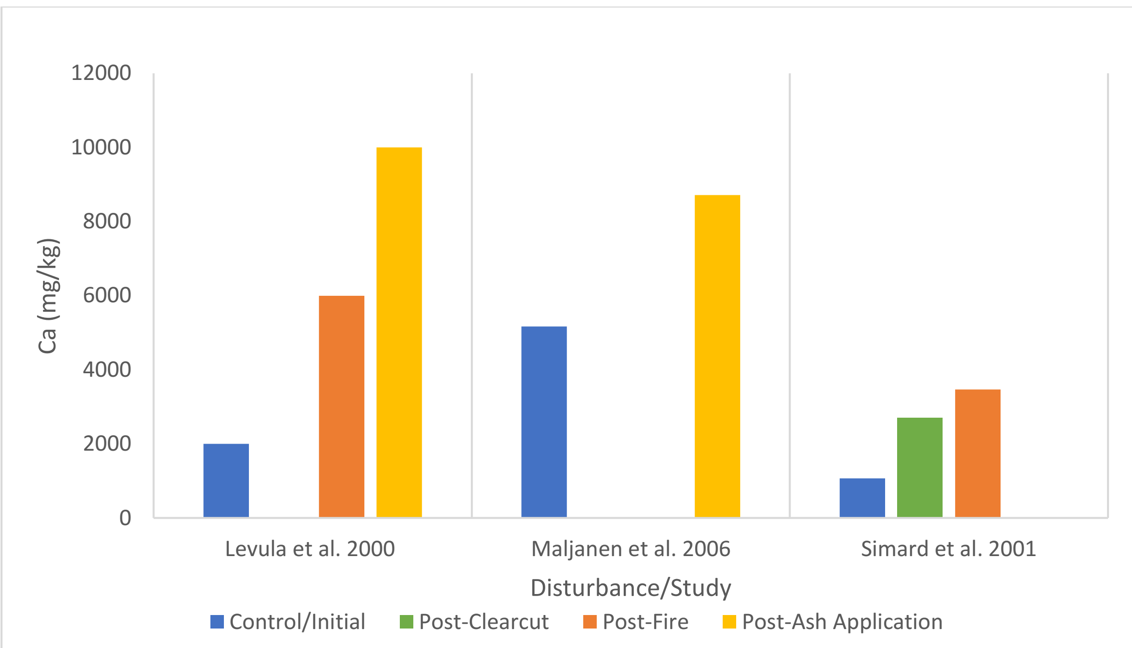

Figure 5 Impact of clearcutting, wildfire, and wood ash application on the calcium concentrations of the forest floor layer according to multiple studies.

4.4 NORTH AMERICAN AND EUROPEAN STUDIES ON FOREST FLOOR AND SOIL NITROGEN

Comparing North American and European data on the effects of wildfire and harvesting on forest nitrogen pools was difficult due to the use of different study methods as well as extreme variability in the results in each paper. For example, North American studies into the effects of wildfire estimate that between roughly 300, 580, and 855 kg ha^{-1} of nitrogen is lost depending on site and fire temperature with clearcutting resulting in an initial 310 kg ha^{-1} being removed from the site during a whole-tree harvest (McRae et al. 2001; Freedman et al. 1986; Viro 1974; Grier 1975; Kimmins and Feller 1976; Johnson et al. 2009). A European study conducted in an Aleppo pine forest found that fire decreased total nitrogen content by 34% at 250°C and by 86% at 600°C in the A soil horizon (0-5cm) which was also confirmed by a study conducted in Nevada (Kutiel and Shaviv 1992; Rau et al. 2010).

A study examining the effects of clearcutting in a mixed boreal forest in Finland reported a substantial decrease in the nitrogen pool of ground vegetation, with contents decreasing by 72 and 54% in their respective plots; plot one decreased from 45.3 to 12.7 kg ha^{-1} and plot two decreased from 42.1 to 19.2 kg ha^{-1} (Palviainen et al. 2005).

Regardless of the method impacting nitrogen levels on a site, it seems that this loss does not have a long-term impact on forest floor biomass and soils, with nitrogen levels typically returning to pre-disturbance levels within a short period. For example, the amounts of nutrients in the ground vegetation returned to initial levels within 4 to 5 years post-clearcut in the Palviainen et al. (2005) study conducted in Finland.

4.5 NORTH AMERICAN AND EUROPEAN STUDIES ON SOIL ACIDITY

As the results show in Figure 3, wildfire has a far greater impact on increasing soil pH values post-disturbance when compared to data from studies on the impacts of clearcutting. As mentioned in the study by Simard et al. (2001), although others have reported a minor decrease in soil pH following clearcutting (Mroz et al. 1985; Mann et al. 1988; Johnson et al. 1991), their study found that the forest floor pH was greater in one of their clearcut stands compared to the control stand. In temperate forests, the minor decrease in pH has been attributed to increased rates of nitrification and the production of hydrogen associated with that process following a clearcut, however, because of the colder climate and the acidic nature of boreal forest soils, nitrification is slowed which could explain why the Simard et al. study reported contrasting results (Simard et al. 2001; Dahlgren and Driscoll 1994; David 1997). In this regard, clearcutting poorly emulates the effects of wildfire on the forest floor and mineral soil.

4.6 MANAGEMENT IMPLICATIONS

While a great deal of research has been conducted on the effects of wildfire and harvesting on forest soils, there has yet to be a review examining the effectiveness of emulation silviculture management in the boreal forest and its long-term effects. This is most likely because this management approach has only been implemented by the province in the last two decades and therefore no long-term data is currently available. As stated in the Forest Management Guide to Silviculture in the Great Lakes-St. Lawrence and Boreal Forests of Ontario under section 6.1, silviculture is an art and science with a wealth of information from long-term plot networks, research trials, and operational monitoring, physiological studies, theoretical studies, experiential knowledge, and more that can be utilized to form and test a hypothesis (OMNR 2015). It is an art in that it is dealing with a large multi-dimensional matrix of desired knowledge with many gaps and variables that are difficult to predict to form that hypothesis (OMNR 2015).

Nolet et al. (2017) conducted the first worldwide ecological comparison of the effects of even and uneven-aged silviculture based on multiple indicators. Most studies at the time comparing the two approaches simply focused on the response of a small group of species, the indicator approach, which the authors of the review found to be inadequate with there being a need to move to a more holistic evaluation of the effects of even and uneven-aged silviculture (Nolet et al. 2017). As reiterated by Nolet et al. (2017), the assumption that biodiversity can be protected by having harvesting operations emulate natural disturbance regimes and natural forest structures remains quite popular, with this hypothesis leading to diverse silviculture methods which result in even or uneven-aged forest stands. While there are theoretical and partially evidenced pathways to support this hypothesis, these pathways are far from confirmed (Nolet et al. 2017).

However, the Canadian government did establish the Ecosystem-based Management Emulating Natural Disturbances (EMEND) project in 1998. The project, located in Northwest Alberta's boreal forest, is a century-long experiment meant to examine the long-term effects of emulation silviculture on a working industrial forest. For example, a study conducted on retention patches found that retention areas that are 1.8 to 4.4 hectares or larger can help conserve beetle species and microclimate conditions that are characteristic to mature forests (Pyper et al. 2010). Several experiments are in progress focusing on biodiversity, primary forest productivity, silviculture systems, forest fire ecology, and more (Government of Canada 2020). Furthermore, soils are being monitored to better understand how harvesting and fire affect them (Government of Canada 2020).

Although silviculture systems are not meant to mimic nature and only emulate its effects, as the name suggests, the approach can be improved upon. Additional management tools that can be applied on a stand scale to mimic the effects of wildfire more effectively, such as the use of bioenergy wood ash for soil amendment, may improve the effectiveness of silviculture systems to better retain the ecological functions in managed stands over the long-term. With the increasing interest in removing harvesting debris from stands to be burned off-site to produce bioenergy resulting in greater losses in stand nutrient capital and the ash generated during energy production commonly being landfilled, ash-borne nutrients such as calcium and phosphorus, are permanently removed from the ecosystem (Hannam et al. 2019). However, Hannam et al. (2019) reported in their meta-analysis of European and North American wildfire and bioenergy ash research that bioenergy ash application is a potentially valid fine filter tool for preserving nutrient capital and emulating the effects of wildfire on certain soil chemical properties, such as pH, and base cation concentrations and availability.

However, the long-term effects of ash application on forest soils and forest productivity require more study. Moreover, very little research has been conducted on the effects of trace metals and potentially hazardous compounds in wildfire and bioenergy ash on forest soils (Hannam et al. 2019). Work must also be done to develop methods for optimizing ash quality for use as a soil amendment due to the highly variable nature of the chemical and physical properties of bioenergy wood ash; properties that are strongly affected by moisture content, the physical form, and tree species composition of the feedstock, the physical point of origin within biomass boilers, and more (Hannam et al. 2018). Moreover, in Canada, the process of obtaining regulatory approval remains a significant barrier to wood ash application on forest soils, however, by utilising the framework established by European countries where the process is standardized, Canada can develop similar guidelines to ensure that ash application is done safely, effectively, and efficiently (Hannam et al. 2018).

5.0 CONCLUSIONS

Although the effects of wildfire and harvesting on soil characteristics and forest floor biomass can differ substantially, emulation silviculture does emulate aspects of wildfire and its effects on stand level scale, focusing primarily in terms of pattern (spatial configuration, amount, tree retention, patches, etc.). However, many of the similarities, such as harvesting's impact on calcium concentrations and soil acidity are far more subtle than the effects of wildfire. Utilizing the principles of adaptive management that guide the development of the suite of Ontario's forest management guides, policy needs to be developed and implemented to allow for bioenergy wood-ash application to be used as a tool that could be applied to forest soils to help replace the nutrients lost during timber harvesting and biomass removal, which could also potentially improve tree growth. This management practice could be implemented as a fine filter tool to help replace the effects of prescribed burning, which has become less common across Canada due to concerns regarding fires escaping and air quality. Because bioenergy wood-ash application can have a similar impact on soil base cation pools and pH as wildfire, the use of wood ash could allow managers to better mimic the effects that current silviculture practices attempt to emulate. At present, the majority of ash studies have been conducted in Europe, therefore, more long-term trials conducted in North America in similar forest types are required to better compare the impacts of wildfire and wood-ash application on the province's forests.

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