CONTROLLING COMPETING VEGETATION FOR FOREST REGENERATION

by

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ABSTRACT

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The timely regeneration of productive forests is vital to maintain timber supply in the forest industry. However, other vegetation can severely hinder forest regenerations. Therefore, effective measures to control the competing vegetation are necessary to ensure the regeneration of new forests. The forest industry develops specific measures and also adopt practices from horticulture, agriculture, and other disciplines to depress vegetation that compete with crop trees during the regeneration phase. Common vegetation control measures are discussed in this thesis with the objective of helping forest manager to select effective vegetation control measures for their specific site conditions. The vegetation control measures discussed include partial harvesting, prescribed burns, livestock grazing, mechanical site preparation, herbicide, mulch, cover crops, and tree shelters. Each vegetation control measure is situation-specific and includes many variables to consider, such as access, labour availability, machinery availability, and implementation cost. By using known vegetation control measures and by researching, developing, and innovating new vegetation control measures, foresters will ensure the success of forest regeneration and steady timber supplies.

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INTRODUCTION

The practice of controlling competing vegetation has been used in forestry, agriculture, landscaping, and horticulture for many centuries, and the techniques used vary (Willoughby et al. 2009). Prolonged presence of undesired vegetation supress the growth of desired trees and lowers the productivity of a forest (Hadley et al. 1990; Thompson and Pitt 2003; Wagner and Colombo 2001). Managing the undesired vegetation allows foresters to maximize the productivity of a forest, while keeping the environmental, economic, and social aspects of a forest balanced. The techniques used have evolved through time thanks to scientific research and innovation (Walstad and Kuch 1987).

Current vegetation control measures used in forestry focus on indirectly and directly altering the land before, during, and after natural or artificial regeneration. Before regeneration, the site is indirectly altered by techniques such as prescribed burns and directly altered by techniques including the use of machines to trench, plow, mound, or till the soil (Thompson and Pitt 2003). During regeneration, herbicide can be used to combat undesired vegetation and allow the desired vegetation to be released and significantly increase its growth (Thompson and Pitt 2003). Indirect techniques used after regeneration focus on inhibiting the growth of vegetation by using partial harvest systems, mulching, cover crops, and tree shelters. Direct techniques focus on the removal of the undesired vegetation and include mechanical site preparation, livestock grazing, and dispersing allowed herbicidal sprays. Vegetation management techniques are situation-specific and are typically completed within five years following harvesting

(Thompson and Pitt 2003). The information of this thesis and further research should assist forest managers to choose a vegetation control measure that is best suited for the site, based on an analysis of the vegetation, soil conditions, and desired tree species to grow (Thompson and Pitt 2003).

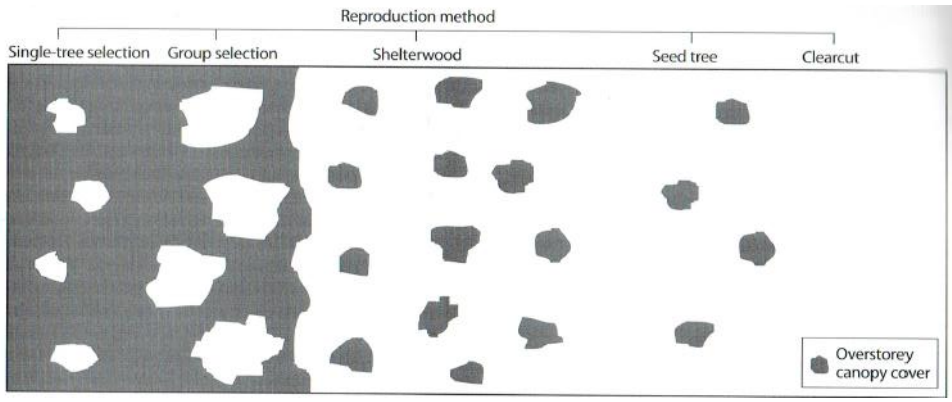
Objective

The objective of this thesis is to synthesize all common means used in different disciplines to control competing vegetation and compare and assess their suitability and potential efficacy for controlling competing vegetation during forest regeneration. With climate change and increased social scrutiny on the rise, it is becoming increasingly important for the forest industry to find environmentally friendly ways to control the competition of other vegetation with new crop trees that allows the desired tree species to establish quickly while maintaining its quality.

VEGETATION CONTROL PRACTICES

Partial Harvest

A partial harvest is when part of the original, dominating canopy, remains after harvest (Thorpe and Thomas 2007). Partial harvesting is best used on mid-tolerant and shade-tolerant tree species due to the overstory canopy being maintained. There are many partial harvest practices that facilitate forest regenerations, such as shelterwood, group selection and single tree selection, and each can be modified to fit the specific needs of the site. Shelterwood methods allow natural regeneration to become established in the understory of existing mature trees while the canopy trees gradually get harvested (Painter and Cooligan 2006; Weetman and Vyse 1990). Shelterwood methods can be completed in strips or distributed evenly over a stand to achieve management of even-aged stands (Wagner and Colombo 2001). Strip shelterwood methods are often used for mid-tolerant species, such as Oak (*Quercus* spp.), and ash (*Fraxinus* spp.), due to increased light conditions, while more shade-tolerant species, such as pine (*Pinus* spp.) and maple (*Acer* spp.), regenerate better under an evenly distributed shelterwood partial harvest (Wagner and Colombo 2001). Group selection methods create small pockets throughout a stand, larger than a single tree, but always smaller than the felled length of two mature trees (Wagner and Colombo 2001). This partial harvest method provides the same environmental conditions as a clearcut while allowing the existing trees to minimize vegetation growth (Wagner and Colombo 2001). The single tree selection method harvests a small number of trees in the stand to replicate small disturbances such as windthrow, pests, or over maturity (Wagner and Colombo 2001). This allows immature regeneration to be released from the understory and maintains an uneven-aged stand (Wagner and Colombo 2001; Province of Nova Scotia 2020). The variation of partial harvest on the landscape can be seen in Figure 1.



Source: Wagner and Colombo 2001

Figure 1. The results after harvest of single tree selection to clearcut harvesting methods.

Partial harvesting does not require specialized equipment but may require more compact and maneuverable harvesting machinery to minimize damage on residual trees (Province of Nova Scotia 2020; Pulkki 2019). Through lectures from Reino Pulkki (NRMT 3211, Fall 2019) he stated that a variety of machines are available to use, and that the forester's choice of machinery will be based on machine availability, labour availability and cost constraints (Pulki 2019; Wiensczyk et al. 2011). Maintained access to the site will be necessary as the harvesting cycle is typically 10-20 years for uneven-aged stands that use partial harvesting methods (Wagner and Colombo 2001).

A partial harvest is used to emulate a variety of disturbances such as mortality, windthrow, insect epidemics, and small or light wildfires, while minimizing the need for vegetation management (Thorpe and Thomas 2007; Wiensczyk et al. 2011). The size of disturbance needed depends on the desired species' shade tolerance, reproduction habits, and other silvics. If the tree canopy is opened too quickly, fast growing vegetation may take over the understory and the desired tree species will have to compete for resources and other vegetation management may be required to release the desired species (Thompson and Pitt 2003; Wiensczyk et al. 2011). Knowing the species of vegetation in the understory will assist in determining the size of canopy desired for tree release and what species the desired tree species will be competing with. Partial harvesting methods can also help control sediment runoff which is a concern with clearcut harvesting (Wiensczyk et al. 2011). The established vegetation decreases the impact of falling rain on the soil, slows runoff water, and traps the water in the organic layer which can benefit soil development (Hadley et al. 1990; Carr 1980). This vegetation control measure works best on shade tolerant species, such as beech (*Fagus sylvatica* L.), fir (*Abies alba Mill*), Scots pine (*Pinus sylvestris*), and sugar maple (*Acer saccharum*), but higher harvesting intensities can accommodate less tolerant tree species (Diaci et al. 2017). Partial harvesting methods are the most successful when used on species that have high seed production and on when it is completed on sites the year prior to a mast seed year (Ferrini et al. 2009).

The use of the partial harvesting methods is increasing worldwide, although clearcutting is still the most dominate method used in Canada's boreal forest (Thompson and Pitt 2003; Thorpe and Thomas 2007; Fuller et al. 2004; Weetman 2004; Ferrini et al. 2009). Partial harvesting methods are used the most in the United States at 61%, and in Norway it is currently being used on 18% of harvest sites with an increase expected (Masek et al. 2011; Floistad, et al. 2009). Spain, Finland, and Sweden have limited use of shelterwood partial harvesting methods but the area that is partial harvested is increasing every year (Coll et al. 2009; Hytönen, et al. 2009).

Further research is needed to show the effects that partial harvesting has on stand development (Thorpe and Thomas 2007). The seedling mortality rates and growth rates from using partial harvesting methods needs to be further analyzed to better understand the capabilities that partial harvesting has to control competing vegetation, while regenerating the stand to its past density (Löf et al. 2009; Ammer et al. 2010). Determining the effects of partial harvesting will also assist in better understanding its economic feasibility (Thorpe and Thomas 2007). These concerns are more concentrated in the boreal forest, where species have adapted to open site regeneration, but would be beneficial for hardwood and mixedwood sites as well (Thorpe and Thomas 2007). Further research is also needed on machine development, low impact and compact machinery is needed to further minimize the damage to residual stands when using partial harvesting methods (Löf et al. 2009).

Prescribed Burns

Prescribed burning has been used as a vegetation control measure and site preparation method in silviculture for centuries (DiTomaso et al. 2006; Wiltshire and Archibald 1998; Thompson and Pitt 2003). A prescribed burn is the controlled burning of an area to rid it of ground debris (Wiltshire and Archibald 1998; OMNR 2003). Different types of burns can be prescribed including, broadcast burns, pile burning, and windrow burning (OMNR 2003). Broadcast burning is the burning of a whole area with scattered debris, while pile and windrow burning consist of dense piles of debris that are lit (OMNR 2003; Environment Canada 1984). Typically, pile and windrow burning are completed near the logging road and away from residual stands to increase fire control and safety (Weber and Taylor 1992). Prescribed burning can be completed before or after harvest (OMNR 2003). Pre-harvest burning is only completed on fire resistant species and is not recommended on mixedwood sites (OMNR 2003). Post-harvest burning is more common and used to further prepare the seedbed for artificial planting or seeding (OMNR2003). Prescribed burning cannot be completed if there are seedlings already established on site. Therefore it must be done relatively quickly after harvest and any advanced growth present on the site will be burned (OMNR 2003). All types of burns require appropriate weather conditions and professional fire personnel to be on site while the burn occurs (OMNR 2003; Weber and Taylor 1992). The cost of performing a prescribed burn is comparable to mechanical site preparation but it has increased risk and capital for potential property damages (Weber and Taylor 1992; Menke 1992). The appropriate weather conditions required to perform a prescribed burn are highly monitored and strenuous, making larger prescribed burns harder to perform (Weber and Taylor 1992; Menke 1992). These two factors deter the forest industry from using prescribed burns as a vegetation control measure.

There are different severity levels of fire and each will have a different effect on the burn site (Johnston and Woodard 1985; OMNR 2003). The Canadian Forest Fire Weather Index outlines the six components they use to categorize fire behaviour which directly align with the fire severity levels (Environmental Canada 1984). Light level severity fires consist of surface fires that do not completely penetrate the organic layer, while severe level fires will penetrate this layer (McLean 1969; OMNR 2003). Revegetation rate after a fire, depends on time of year, severity of fire, and nutrient availability (Hawkes et al. 1990; Weetman 1994). Vegetation will reappear quicker with spring fires, low severity fires, or fires on rich sites (Hawkes et al. 1990). The severity of a fire will determine which vegetative species survives as some have adapted to survive severe fires, while others rely on the regeneration from a seedbank after a low severity fire (Hawkes et al. 1990; Stathers et al. 1990; Lieffer 1994).

Prescribed burning is used to reduce fuel load, improve site access, enhance regeneration, promote biodiversity, and improve habitat, and thus has the ability to change stand dynamics (DiTomaso et al. 2006; Hawkes et al. 1990; OMNR 2003; Wiltshire and Archibald 1998; Methven and Murray 1974). Prescribed burning can be used to reduce the fuel load on high-risk sites, such as sites with a thick duff layer, a significant amount of surface debris, or sites that are close to communities (DiTomaso et al. 2006). This will also improve site access and safety for artificial regeneration (Weber and Taylor 1992). Prescribed burning can enhance vegetation when a fall burn occurs or on site with a rich organic layer because the plants have stored nutrients for their dormancy and will put out a number of new shoots in the spring (DiTomaso et al. 2006; Weber and Taylor 1992). Prescribed burning promotes biodiversity by allowing seeds from the soil seed bank to regenerate on cleared land, which can increase wildlife foraging and shelter use for the site (DiTomaso et al. 2006; Weber and Taylor 1992). Increasing the forgeability and shelter will increase wildlife presence, which further decreases the amount of undesired vegetation from herbivory (DiTomaso et al. 2006; Weber and Taylor 1992). Prescribed burning has also been successful at limiting the spread of invasive species by burning the vegetation with light fires and burning seeds and roots with severe fires (DiTomaso et al. 2006). Prescribed burning for invasive species control works best on late-season broadleaf and grass species but has had success with specific woody species and perennial grasses (DiTomaso et al. 2006). Prescribed burning also improves soil nutrients from burning, raise soil temperatures, making them more attractive for germination, and reduces insect pest populations through burning and displacing host species (OMNR 2003).

In Canada, Ontario and British Columbia use prescribed burning more than the other provinces and territories (Weber and Taylor 1992). Prescribed burning has increased regeneration success in the boreal forest region as species, such as black spruce (*Picea mariana*) and jack pine (*Pinus banksania*) are adapted to wildfires and have evolved semi-serotinous cones (Groot 1994; Weetman 1994; OMNR 2003). When using prescribed burning in the boreal forest late summer fires are recommended, as they provide a high-level severity burn that kills competing vegetation and can help germinate conifer seeds (OMNR 2003). For hardwood promotion, light and moderate severity burns are recommended as it will stimulate sucker sprouts on species like poplar (*Populus* spp.) and allow the seedbed to be receptive of many seeds (OMNR 2003). When planning to use prescribed burning as a vegetation control measure and site preparation method, aligning it with a good seed year will be beneficial and cost effective (OMNR 2003). The "Prescribed Burn Planning Manual" (2019) provides the framework and guidelines to perform safe burns in Ontario (OMNR 2019). Following regional guides and taking the proper precautions will allow safe execution of prescribed burns that will benefit foresters in controlling vegetation. This manual or other similar guides will inform the forester of the required site conditions that a prescribed burn can be performed on (OMNR 2019).

Prescribed burning can be combined with other vegetation control measures, which can decrease the risk associated with prescribed burning and can increase results (Weber and Taylor 1992; DiTomaso et al. 2006). They can be combined with livestock grazing, where palatable species are eaten to allow the burn to be less severe and more evenly distributed (Menke 1992). Depending on the undesired vegetation present, a light level fire may kill the seed and allow more native vegetation growth (Menke 1992). Prescribed burning can be used before and/or after the application of herbicide (Weber and Taylor 1992; DiTomaso et al. 2006). When used before herbicide, the fire will burn the surface vegetation and debris, and may burn part of the seed bed and roots (Weber and Taylor 1992). This will allow the herbicide to act as a long-term vegetation control measure (Weber and Taylor 1992). When used after herbicide, the fire will burn the dead vegetation caused by the herbicide, and a severe burn will take place, burning more of the organic layer and remaining vegetation and roots (McLean 1969; Ditomaso et al. 2006). Prescribed burning can also be used before mulching or cover crop vegetation control measures to prolong the period that a site is free of undesired vegetation (Marble et al. 2015).

There are not many studies being completed on prescribed burning, partially due to their high risk and low usage (Weber and Taylor 1992).

Livestock Grazing

This vegetation control measure is not commonly used in the forest industry (Thompson and Pitt 2003; Willoughby et al. 2009). Livestock grazing consists of a variety of domesticated farm animals grazing on recently harvested and regenerated forest lands (Thompson and Pitt 2003; Willoughby et al. 2009; Papachristou et al. 2009). When forest managers are deciding which animal will graze the harvest area, they should keep in mind the preferred diet of the animal and which vegetation species needs to be targeted (Papachristou et al. 2009). Cattle and horses prefer more herbaceous material, while sheep and goats will eat herbaceous and woody material (Papachristou et al. 2009). The time of graze is important for tree seedlings and vegetation reproduction. Tree seedlings are the most vulnerable within the first year of planting and so grazing in this time period should be avoided (Sullivan et al. 2008). Aligning grazing practices with vegetation reproduction habits will increase the success of using grazing as a vegetation management control measure (Sharrow et al. 1989; Menke 1992). Spring and early summer grazing can remove fast-growing non-native vegetative species and dead stalks, allowing less competitive native species to grow (Menke 1992; Cudlin et al. 2009). This also decreases water competition which then decreases the risk of wildfire (Papachristou et al. 2009).

Livestock grazing benefit certain species more than others. Conifers are generally more suited for grazing, as livestock tend to not graze conifer species due to the needle texture (Papachristou et al. 2009). Studies have been completed on Aleppo pine (*Pinus halepensis*), Calabrian pine (*Pinus brutia*), oak (*Quercus* spp.), hornbeam (*Carpinus* spp.), ash (*Fraxinus* spp.), black pine (*Pinus nigra*), maritime pine (*Pinus* *pinaster*), kermes oak (*Quercus coccifera*), Douglas-fir (*Pseudotsuga menziesii*), and ponderosa pine (*Pinus ponderosa*) (Papachristou et al. 2009; Sullivan et al. 1990). Additional measures may be taken to protect the trees from grazing, and this will reduce damage (Coll et al. 2009).

Understanding the benefits and concerns of livestock grazing can give insight into its use, and why it is not a common vegetation control measure. European countries around the Mediterranean Sea and mountain areas use livestock grazing, especially in plantations of valuable trees (Frochot et al. 2009; Willoughby et al. 2009). Denmark uses sheep, ducks, pigs, and ostrich for livestock grazing (Bensten et al. 2009). In North America, livestock grazing has been used successfully in western states and provinces (Sullivan et al. 1990; Thompson and Pitt 2003). One study completed by Sharrow et al. (1989) showed livestock grazing resulting in a 5% height gain and 7% diameter gain for Douglas-fir plantations. This study concluded that sheep grazing is an effective vegetation control measure and could be implemented into forest management (Sharrow et al. 1989). A major concern with using livestock grazing for vegetation control is their ability to spread disease. British Columbia largely depends on surface water as drinking source and contaminants in water sources are increased with an increased presence of livestock grazing (Newman et al. 2003). This area needs to be researched more to discover all the side effects of livestock grazing (Newman et al. 2003).

Livestock grazing can be used alongside prescribed burns and partial harvesting methods. When grazing occurs before a prescribed burn, the fuel load is decreased and the risk of the prescribed burn getting out of control is lowered (Ditomaso et al. 2006; Menke 1992). When comparing prescribed burns to livestock grazing, natural regeneration prefers burns sites (Papachristou et al. 2009). This is due to less soil compaction. On the other hand, livestock grazing decreases the height of undesired vegetation which allows the regeneration to be released sooner (Papachristou et al. 2009). Choosing between these two methods for a vegetation control measure will depend on the vegetation species' growth and reproductive habits.

Livestock grazing can benefit the forest industry and farmers, but research needs to occur before large-scale integration. (Papachristou et al. 2009). Livestock grazing will benefit both parties because vegetation will be managed while simultaneously producing marketable livestock (Sharrow et al. 1989; Popay and Field 1996). This co-operation will allow low impact management on a harvest site and economic growth in farming. More research in grazing effects on forest ecosystems is needed to ensure long-term stand and seedling damage is not taking place (Papachristou et al. 2009). Damage to the desired vegetation is a severe concern with this vegetation control measure, but multiple studies have shown that little to no damage is done to the desired vegetation when it is an unpalatable species, or it is protected (Popay and Field 1996). If the desired species is palatable for the chosen livestock tree shelters can be used to provide seedling protection (Ferrini et al. 2009). Controlled experiments are needed for multiple reasons, one is to observe the short and long-term effects of livestock grazing on the ecosystem and regenerating stands and another is to develop models for forest responses to livestock grazing (Papachristou et al. 2009). More research is also needed on seedling damage and ways to minimize this damage from livestock grazing (Newton and Comeau 1990). These areas of research will allow livestock grazing to become a common and effective vegetation control measure.

Mechanical Site Preparation

Mechanical site preparation uses various machinery and tools to disrupt the top layer of soil and remove or destroy the plants to allow new desired growth to take place (Marble et al. 2015; Parviainen et al. 1994; USDA 2012; Löf et al. 2012). Mechanical site preparation is completed prior to artificial planting and natural regeneration to prepare the soil and create a suitable microsite for the seedling (Ryans and Sutherland 2001). A beneficial factor of mechanical site preparation is its longer treatment window and larger range of working conditions that allow it to be used more often than other vegetation control methods (Comeau et al. 1996; Wagner and Colombo 2001). When used on sites that are being regenerated naturally, it is beneficial to complete mechanical site preparation the summer or fall before a good seed year (Saursaunet et al. 2018). This will allow the desired vegetation to have access to the best and most microsites. When used on artificial regenerated sites, mechanical site preparation increases microsite availability, decreases competing vegetation, and can increase access to the site (Wagner and Colombo 2001; Saursaunet et al. 2018). Mechanical site preparation is a non-chemical vegetation control measure that increases soil nutrients, sunlight levels, and moisture, while decreasing competition (Wheeler et al. 2002; Thiffault and Roy 2009; Löf et al. 2012; Marble et al. 2015). The various methods of scarification are completed using tools such as a set of chains, barrels, Bräcke scarifier, plow, shear blade, disc trencher, ripper teeth, and mounder (Walstad and Kuch 1987; Thompson and Pitt 2003; Vasic et al. 2009). Disc trenching is the most common, effective, and beneficial in boreal conifer stands and bulldozing, or blade shearing, is the most effective in hardwood forests (Wagner et al. 2004; Holst and Jóhannesdóttir 2009; Bentsen et al.

2009). There are machines that remove surface debris for ease of planting access and to make more planting spot available (McMinn and Hedin 1990). Other machines partially clear the surface and disrupt the upper layers of soil, in varying ways, to remove competing vegetation and create suitable microsites for the desired plants (McMinn and Hedin 1990). The machinery combats competing vegetation by breaking up the roots of perennial vegetation, flipping the organic layer, which decreases the light condition and increasing the amount of mineral soil for artificial planting, and by dragging the seedbed away, putting the seeds in the soil at a disadvantage (Wagner and Colombo 2001). Ryans and Sutherland (2001) provide a detailed analysis of equipment where the main features, treatment objectives, working principle, and general use and comments are outlined and discussed. They also discuss environmental considerations and planning for mechanical site preparation use. Figure 2 shows the results of microsite creation using different site preparation equipment, as presented by Ryans and Sutherlands (2001).

Type of treatment	Operational impediments	Heavy drags[a] plant	Heavy drags[a] seed	Light drags[b] plant	Light drags[b] seed	Powered disc trenchers[c] plant	Powered disc trenchers[c] seed	Patch scarifiers or mounders[d] plant	Patch scarifiers or mounders[d] seed	Blades or plows[e] plant	Blades or plows[e] seed	Choppers or masticators plant	Choppers or masticators seed	Rakes plant	Rakes seed	Mixers or tillers[f] plant	Mixers or tillers[f] seed
Overstorey removed, organic and mineral layers undisturbed (e.g., cut-over)	heavy	—	—	—	—	—	—	—	—	◐	✗	◐	—	◐	✗	—	—
	light	—	—	—	—	—	—	—	—	◐	✗	◐	—	◐	✗	—	—
L layer and part of F layer removed or displaced (e.g., shallow screef)	heavy	●	◐	○	○	●	○	◐	○	○	○	◐	✗	●	●	—	—
	light	◐	✗	●	●	◐	◐	●	●	○	○	◐	✗	●	●	—	—
LFH removed, mineral soil intact (e.g., deep screef)	heavy	◐	◐	○	○	●	●	◐	○	●	●	—	—	●	●	—	—
	light	●	●	●	●	●	●	●	●	●	●	—	—	●	●	—	—
LFH removed, some mineral soil removed (e.g., deep screef)	heavy	◐	○	○	○	●	●	◐	○	●	●	—	—	○	○	—	—
	light	●	○	●	◐	●	●	●	●	●	●	—	—	○	○	—	—
LFH removed, mineral mound on mineral soil	heavy	—	—	—	—	○	✗	◐	✗	○	✗	—	—	—	—	—	—
	light	—	—	—	—	○	✗	●	✗	○	✗	—	—	—	—	—	—
LFH and mineral layers inverted (mineral mound on organic layer)	heavy	—	—	—	—	—	—	◐	✗	—	—	—	—	—	—	—	—
	light	—	—	—	—	—	—	●	✗	—	—	—	—	—	—	—	—
LFH and mineral mixed (e.g., tilling)	heavy	○	○	○	○	○	○	—	—	○	✗	○	○	○	○	◐	○
	light	◐	○	◐	○	○	○	—	—	○	✗	○	○	○	○	●	●
Part of Of removed (e.g., shearblading)	heavy	—	—	—	—	—	—	—	—	●	●	—	—	—	—	—	—
	light	—	—	—	—	—	—	—	—	●	●	—	—	—	—	—	—

Mineral; Organic; ● Very effective; ◐ Moderately effective; ○ Slightly effective; ✗ Treatment to avoid; — Not applicable

a Several combinations available that can affect depth control and product. May be effective in cobbly or stoney soils. Avoid planting in depressions in silty or clay soils as these are prone to frost heaving, frost damage, or flooding.

b Several combinations available. Can be effective in creating minimal disturbance on sites with thin organic layers.

c Avoid degradation on sensitive sites, such as fine sands with thin organic layers or peaty phase soils, by applying treatment when the mineral soil is frozen. Avoid planting in depressions in silty or clay soils as these are prone to frost heaving, frost damage, or flooding.

d Suitable for silty or clay soils where minimal exposure of the mineral soil is desired.

e Controlling blade or plow height can be difficult but is the key to achieving consistent results. Avoid exposing large areas of mineral soil on silty or clay soils.

f Degree of mixing can influence the effectiveness of control of competing vegetation.

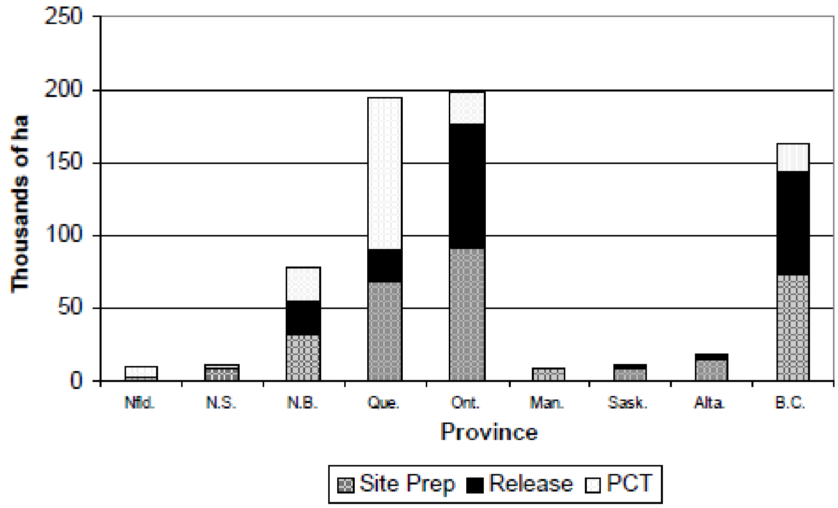
Source: Ryans and Sutherland 2001

Figure 2. Mechanical site preparation effects in ability to create microsites.

Using mechanical site preparation as a method to control competing vegetation is beneficial but can lead to erosion and soil dryness if precaution is not taken (Wiloughby et al. 2009; Kraehmer et al. 2014). Negative aspects to site preparation methods include plant susceptibility to frost damage, flooding and frost heaving, droughts, and competing vegetation (Wagner and Colombo 2001). Frost damage can occur because of the increased soil temperatures and flooding, frost heaving can occur in fine-textured soils, and droughts can occur in areas with coarse-textured soils when periods of no rain occur (Wagner and Colombo 2001). When choosing to use scarification, the site must be analyzed to ensure that no adverse affects will take place (Löf et al. 2006; Wagner and Colombo 2001). This includes ensuring the site does not contain sensitive plant life or archaeological remains (Armleder and Stevenson 1994; Löf et al. 2006). An alternative method used when erosion is a concern is mulching (Willoughby et al. 2009). This will be discussed later. Another downfall to mechanical site preparation is the cost (Kraehmer et al. 2014). Site preparation is time consuming and can be complex with multiple methods used in the same harvest block, which are factors that drastically increase the cost of its use. Deep rooted perennials and larger woody plants may also not be affected by the site preparation and at times it may increase their presence (Wiloughby et al. 2009). Being aware of the impacts that site preparation can have, will allow a forester to make the best decision for individual harvest blocks and give the desired plant the best chance to grow.

The use of mechanical site preparation has increased since it first appeared in the 1960’s (Weetman 1994; Wagner and Colombo 2001). Technology has improved machinery to allow for more control and placement precision, like disc trenchers replacing bulldozers (Wagner and Colombo 2001). In the past site preparation was primarily used on clearcut, even-aged harvest blocks, but it has since been used on many harvest blocks, including small-gapped partial cut systems (Wagner and Colombo 2001; Raymond et al. 2009; Westerberg 1994; Löf et al. 2012). Its use has been found to be more beneficial on sites with deeper organic layers, as it then exposes more suitable microsites for seedlings (Thiffault et al. 2003). It can be used in combination with other vegetation control measures, such as the application of herbicides to further impact competing vegetation, but this also increases the cost (Frochot er al. 2009; Wagner 1993). Some site preparation methods can be modified to include seed and seedling planting while scarifying the soil (Mitchell et al. 1990). This is often more labour intensive than completing the tasks individually but allows for better seed placement control and thus decreases the number of seeds required (Mitchell et al. 1990). In Sweden, mounding and disc trench mechanical site preparation methods are the most common (Löf et al. 2009). In 2006, they completed mechanical site preparation on approximately 170 000 ha and Finland scarified 122 300 ha (Hytönen et al. 2009; Löf et al. 2009). In 2000, Canada completed mechanical site preparation on 306 419 ha, with Ontario using it the most (Thompson and Pitt 2003).

Figure 3 shows the different vegetation treatments used throughout Canada. Thiffault and Roy (2009) combined various scarification studies completed in Quebec to create a collective article on what has been found. One result they discovered was that mechanical site preparation works best on areas with moderate competition, as high competition levels null the benefits of mechanical site preparation (Thiffault and Roy 2009).



Source: Thompson and Pitt 2003

Figure 3. Number of hectares that received site preparation, release, and precommercial thinning in 1999 throughout Canada, by province.

The research completed on mechanical site preparation is vast and has resulted in more refined use. The use of mechanical site preparation has been found to increase seedling survival rate, needle mass, basal area, and rooting (Allen et al. 2005: Wheeler et al. 2002; Walstad and Kuch 1987; Burgess and Baldock 1994; Morris and Lowry 1988). Many studies have compared the effects of one site preparation method to another and found similar results. The use of a disc trencher was found to improve seedling rooting, height, and volume, while decreasing mortality (Morris and Lowry 1988; Wheeler et al. 2002; Walstad and Kuch 1987). Bedding increased nitrogen levels in the soil, and increased seedling height and volume, (Morris and Lowry 1988; Wheeler et al. 2012). The use of mounds as a site preparation method increased *Quercus robur L.* seedling survival (90% compared to 58% on undisturbed soils) and stated that it is comparable to the results from herbicidal spray (Löf et al. 2006). All of these findings are allowing the forest industry to move away from the use of herbicides and to only have to use them when there is no other option to regenerate (Löf et al. 2006). A study comparing tillage to fertilization, and to hand and chemical weed control, found that tillage was most significant with an increase in height and diameter at breast height of 5-36% and 8-130%, respectively (Albaugh et al. 2004). A combination of tillage with fertilization and weed control is also effective, but costly (Albaugh et al. 2004). Many of the studies completed analyze the short-term results of site preparation, but more research on the long-term effects is necessary (Wagner 1993).

Herbicides

Herbicides were introduced to the forest industry in the 1960's (Wagner et al. 2004). Their use has significantly changed regenerating forest stands to have appropriate stocking at an earlier age without damaging the environment, or wildlife (Frochot et al. 2009; Otchere-Boateng and Herring 1990: Newton and Comeau 1990). Herbicides are used to kill and control growth of undesired vegetation and thus assist with seedling survivability and growth (Frochot et al. 2009; Wagner et al. 2004). Herbicides can be used 1-2 years before artificial or natural regeneration takes place (Wagner et al. 2004). This will allow the herbicide to combat hardy competitive species and avoids the desired species needing to be tolerant of the herbicide (Malinauskas and Suchockas 2009; Wagner et al. 2004). Some herbicides can be used 1-2 months before planting to combat herbaceous weeds, or can be used after planting. Herbicides can be used after planting as soon as the next month or up to many years later to assist in desired vegetation release (Malinauskas and Suchockas 2009; Newton and Comeau 1990; Wagner et al. 2004).

Herbicides can be used on slopes, in remote and hard to access areas, areas where soil nutrient depletion may be an issue, sites where erosion is a concern, and on sites where other vegetation control measures would stimulate new growth or sprouting of undesired plants (Otchere-Boateng and Herring 1990; Thompson et al. 2012). Herbicides can reduce invasive species, create snags and downed debris that is useful for wildlife, maintain early successional species composition in late successional stands, and maintain woody and herbaceous species for animal browsing (Wagner et al. 2004). In 1990, 85% of the total herbicides used was for tending, including using it for seedling release, and 15% of the total herbicide use was for site preparation (Campbell 1990).

Herbicides can be applied aerially or by ground application (Willoughby et al. 2009; Otchere-Boateng and Herring 1990). Fixed wing planes and helicopters can apply herbicides from the air in broadcast, banded, or gridded patterns (Campbell 1990; Wagner et al. 2004). Ground applications can include broadcast ground spraying, ground spot treatment, vehicle-mounted spraying, stem injections, and basal spraying, each containing their own set of pros and cons (Otchere-Boateng and Herring 1990; Wagner et al. 2004). Ground application is limited by terrain, site slope, logging debris, and size of target vegetation and the forester should be aware of these to ensure a proper application method is used (Otchere-Boateng and Herring 1990). Aerial spray is most effective in areas with a large quantity of debris and shrubbery, steep terrain, large areas, and sites that are inaccessible (Otchere-Boateng and Herring 1990). Aerial spray is the most common due to its cost effectiveness and timeliness but cannot be used on all sites (Otchere-Boateng and Herring 1990; Allen et al. 2005; Campbell 1990). The application time of the herbicide is important to its effectiveness. Otchere-Boateng and Herring

(1990) created a figure to display the most effective application time for the 5 herbicides that were registered for use in British Columbia (Figure 4) and a herbicide evaluation matrix that outlines damage and effectiveness of herbicides on tree, shrub, grasses, and other vegetation types (Figure 5).

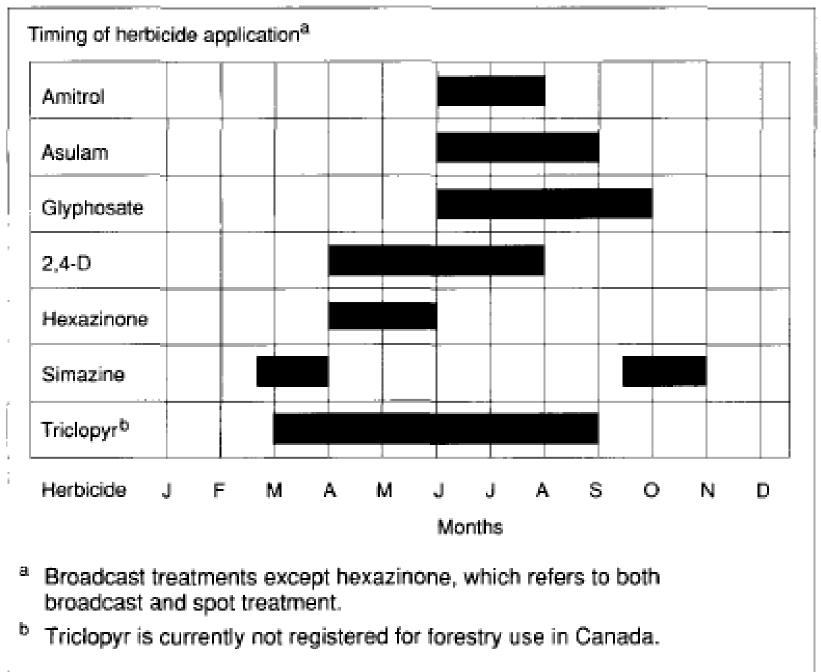


FIGURE 13.2. Optimum herbicide application timing for site preparation.

Source: Otchere-Boateng and Herring 1990

Figure 4. The most effective months to apply herbicides on target species.

TABLE 13.2. Effectiveness of herbicide treatments in British Columbia: interim charts.

Herbicide and application method [a]	Coniferous trees: Douglas-fir *Pseudotsuga menziesii*	Engelmann spruce *Picea engelmannii*	Grand fir *Abies grandis*	Lodgepole pine *Pinus contorta*	Sitka spruce *Picea sitchensis*	Subalpine fir *Abies lasiocarpa*	Western hemlock *Tsuga heterophylla*	Western redcedar *Thuja plicata*	White spruce *Picea glauca*	Deciduous trees: Bigleaf maple *Acer macrophyllum*	Bitter cherry *Prunus emarginata*	Black cottonwood *Populus balsamifera*	Douglas maple *Acer glabrum*	Red alder *Alnus rubra*	Paper birch *Betula papyrifera*	Sitka alder (green) *Alnus viridis*	Trembling aspen *Populus tremuloides*	Vine maple *Acer circinatum*	Willows *Salix spp.*
Vision® (glyphosate) Foliar (July-Sept.)	No visible injury	No visible injury	No visible injury	No visible injury	No visible injury	No visible injury	25 - 60%	25 - 60%	No visible injury	60 - 90%	90 - 100%	60 - 90%	60 - 90%	60 - 90%	60 - 90%	60 - 90%	60 - 90%	90 - 100%	60 - 90%
Vision® (glyphosate) Injection																	90 - 100%		
Velpar L® (hexazinone) Spot (spring, fall)				25 - 60%		No visible injury	25 - 60%	25 - 60%	< 25%			60 - 90%	25 - 60%	25 - 60%	60 - 90%	25 - 60%	60 - 90%		60 - 90%
Velpar L® (hexazinone) Broadcast (spring)			No visible injury	25 - 60%		< 25%	< 25%	25 - 60%	< 25%			25 - 60%	25 - 60%	< 25%	60 - 90%	< 25%	60 - 90%	< 25%	60 - 90%
2,4-D amine Injection												60 - 90%		90 - 100%			90 - 100%		
2,4-D amine, Broadcast (April-June & Aug.-Sept.)								No visible injury				< 25%		90 - 100%	60 - 90%	60 - 90%	60 - 90%	60 - 90%	25 - 60%
Weedone CB® (2,4-D, 4-DP)										90 - 100% [b]									

Herbicide and application method [a]	Shrubs: Devil's club *Oplopanax horridus*	Elderberry *Sambucus spp.*	False azalea *Menziesia ferruginea*	Falsebox *Paxistima myrsinites*	Hazelnut *Corylus cornuta*	Highbush-cranberry *Viburnum trilobum*	Honeysuckle *Lonicera utahensis*	Huckleberry *Vaccinium spp.*	Mountain ash *Sorbus sitchensis*	Oval-leaved blueberry *Vaccinium ovalifolium*	Raspberry *Rubus ideaus*	Red-osier dogwood *Cornus sericea*	Rhododendron *Rhododendron albiflorum*	Roses *Rosa spp.*	Salal *Gaultheria shallon*	Salmonberry *Rubus spectabilis*	Saskatoon berry *Amelanchier spp.*	Snowberry *Symphoricarpos albus*	Stink currant *Ribes bracteosum*	Thimbleberry *Rubus parviflorus*	Twinberry *Lonicera involucrata*	Twinflower *Linnaea borealis*
Vision® (glyphosate) Foliar (July-Sept.)	25 - 60%	60 - 90%	60 - 90%	< 25%	25 - 60%	25 - 60%	90 - 100%	60 - 90%	60 - 90%	60 - 90%	60 - 90%	< 25%	60 - 90%	90 - 100%	No visible injury	25 - 60%	60 - 90%	90 - 100%	60 - 90%	90 - 100%	90 - 100%	60 - 90%
Velpar L® (hexazinone) Spot (spring, fall)					< 25%	25 - 60%			25 - 60%		25 - 60%	< 25%		60 - 90%	No visible injury		60 - 90%	90 - 100%	25 - 60%	25 - 60%	60 - 90%	
Velpar L® (hexazinone) Broadcast (spring)					< 25%	25 - 60%			25 - 60%		25 - 60%	< 25%		60 - 90%	No visible injury		25 - 60%		< 25%	25 - 60%	60 - 90%	
2,4-D amine, Broadcast (April-June & Aug.-Sept.)							60 - 90%															
Asulox F® (Asulam)																						

Herbicide and application method [a]	Grasses: Grasses (general) *Graminae*	Bluejoint *Calamagrostis canadensis*	Pine grass *Calamagrostis rubescens*	Ferns: Bracken fern *Pteridium aquilnum*	Lady fern *Athyrium filix-femina*	Oak fern *Gymnocarpium dryopteris*	Sword fern *Polystichum munitum*	Flowers: False Solomon's-seal *Smilacina amplexicamlis*	Fireweed *Epilobium angustifolium*
Vision® (glyphosate) Foliar (July-Sept.)	90 - 100%	60 - 90%	60 - 90%	25 - 60%	60 - 90%	25 - 60%	90 - 100%	< 25%	60 - 90%
Velpar L® (hexazinone) Spot (spring, fall)	60 - 90%	60 - 90%	25 - 60%						60 - 90%
Velpar L® (hexazinone) Broadcast (spring)	60 - 90%	60 - 90%	25 - 60%				25 - 60%		60 - 90%
2,4-D amine, Broadcast (April-June & Aug.-Sept.)	No visible injury								
Asulox F® (July) (Asulam)				90 - 100%					

Injury
- 90 - 100% (very severe)
- 60 - 90% (severe)
- Insufficient data
- 25 - 60% (moderate)
- < 25% (light)
- No visible injury

a Applications were made using the techniques, rates, and timing recommended on the labels.

b Only above ground vegetation killed.

Sources: The matrices were constructed from the following sources: (a) Operational Treatment Evaluation reports supplied by B.C. Forest Service field staff (District and Regional offices); (b) Reports of various research and operational trials conducted in B.C.; (c) Annual Silviculture Abstracts reported in the Expert Committee on Weeds (ECW) Western Section Research Report for the years 1984 to 1989.

Source: Otchere-Boateng and Herring 1990.

Figure 5. Herbicide evaluation matrix created by Otchere-Boateng and Herring (1990).

When planning to use herbicide on a site a forester can analyze the site pre- and post-harvest to predict which competing vegetation species will be present, what herbicides can be used, and if a combined site preparation method is needed to minimize seedling establishment time (Otchere-Boateng and Herring 1990). Monitoring of the site should take place while the herbicide treatment is taking place, with post-treatment assessments completed to analyze the herbicide effectiveness and long-term assessments to evaluate reforestation objectives (Otchere-Boateng and Herring 1990). The forester's choice of application method will be influenced by herbicide registration, extent and nature of treatment, urgency of treatment, accessibility, labour, cost, and sensitivity of herbicide site (Otchere-Boateng and Herring 1990). The key to effective herbicide use includes appropriate selection of herbicide, herbicide carrier, application rate and spray volume, application season, application method, and monitoring (Otchere-Boateng and Herring 1990).

The most common herbicide that is currently regulated in most countries is glyphosate (Thompson and Pitt 2003). Glyphosate came onto the market in the 1970's with triclopyr, another herbicide (Wagner et al. 2004). Simazine, atrazine, and hexazinone were introduced in the 1960's for forestry use, but they are not used as frequently due to being a more selective and because glyphosate covers the same target species (Wagner et al. 2004). Later, the herbicides imazapyr, hexazinone, sulfonylurea, and metsulfuron were introduced to control specialized vegetation that other herbicides could not control (Wagner et al. 2004). In Canada, there are 5 main herbicides, 2,4-D, glyphosate, simazine, hexazinone, and triclopyr, that are registered for use (Thompson and Pitt 2003). There are also many specialized herbicides registered, but these are in lesser amounts (Thompson and Pitt 2003).

2,4-D is used on broadleaved-herbs and some deciduous species and can be used as a stump or stem injection for spot treatments (Otchere-Boateng and Herring 1990). 2,4-D will negatively affect ponderosa pine (*Pinus ponderosa*) and Douglas-fir (*Pseudotsuga menziesii*) if applied before August (Otchere-Boateng and Herring 1990). When combined with a prescribed burn site preparation treatment, a 1-month gap should take place between treatments to allow herbicide to fully affect area (Otchere-Boateng and Herring 1990).

Glyphosate is effective on deciduous hardwoods and shrubs, grasses, ferns, and herbaceous broadleaf species (Otchere-Boateng and Herring 1990). It has low mobility and degrades quickly, which means no waiting period is required when used as site preparation (Otchere-Boateng and Herring 1990). Conifers are tolerant to glyphosate in the fall and winter after their buds harden and some sites need 1-year post-harvest so the vegetation can recover and the glyphosate to be the most effective (Otchere-Boateng and Herring 1990). Glyphosate accounts for 90% of all herbicide use (Thompson and Pitt 2003). Glyphosate is sprayed on 200 000 ha per year in Canada with Ontario using it the most and B.C. and New Brunswick spraying slightly less (Thompson and Pitt 2003). Its use is most effective during the first year of seedling growth (Pellens et al. 2018). Simazine is most effective on grass species when applied in the late fall (Otchere-Boateng and Herring 1990). It is beneficial to use this herbicide on sites that could have re-invasion from seed germination, making it unique from other herbicides (Otchere-Boateng and Herring 1990).

Simazine is registered for conifer release for white pine and balsam fir species (Campbell 1990). This herbicide has specialized use and only combats herbaceous species in old fields (Campbell 1990). This is the major reason why its use in so low (Campbell 1990).

Hexazinone is a soil-active herbicide and requires some water to move it into the soil of the target area (Otchere-Boateng and Herring 1990). Hexazinone is not recommended for sites that have poor drainage and is a specialized herbicide (Otchere-Boateng and Herring 1990). It must be applied in the spring and is effective on herbaceous broadleaves, grasses, and some woody broadleaves, with some pines being tolerant to it (Otchere-Boateng and Herring 1990). Pine, larch, and Douglas-fir are susceptible to damage from hexazinone so caution must be taken (Newton and Comeau 1990). If hexazinone is to be combined with a prescribed burn treatment, the burning should take place 60-90 after an adequate rainfall to allow the herbicide to be fully brought into the plant (Otchere-Boateng and Herring 1990).

Triclopyr is a growth regulator that suppresses sprouting when applied in the spring (Otchere-Boateng and Herring 1990). Ground applications controls woody species, raspberries, aspen, and maple (Campbell 1990).

Imazapyr is another herbicide that is registered for use and is used in small amounts. It is used on brush and herbaceous weeds and is best used the year before planting takes place, due to a larger conifer tolerance (Campbell 1990).

Herbicide use varies in each country and the registration is controlled by federal and provincial governments (Otchere-Boateng and Herring 1990). Aerial sprays and grounds spraying is regulated separately and the workers applying the herbicide must have an up-to-date pesticide licence and permit and must use pesticides and herbicides as outlined by the manufacturer and label. (Otchere-Boateng and Herring 1990). The development and discovery of new herbicides is limited by the vigorous testing that a herbicide must go through to be registered (Kraehmer et al. 2014). This vigorous testing is expensive, which increases the cost to use the herbicide once registered (Kraehmer et al. 2014). Therefore, a herbicide must be widely used to make it economically feasible (Kraehmer et al. 2014).

Herbicide can be used with other vegetation control measures (Wheeler et al. 2002). In the past it has been used with mechanical site preparation to assist in microsite access and safety for artificial planting as well as allow better growth and survival of seedlings (Otchere-Boateng and Herring 1990). It has also been combined with prescribed burn treatments to stabilize the fuel load, achieve an even burn, and increase safety, as well as target a select species group before or after the burn to better control the vegetation on site (Otchere-Boateng and Herring 1990; Weber and Taylor 1992; Ditomaso et al. 2006). The landscape industry uses herbicide-treated mulches to achieve long term results (Marble 2015). This only works with specialized herbicides, like oryzalin and flumioxazin, and similar results can be achieved by using the two vegetation control measures separately (Marble 2015).

Using herbicides to combat undesired vegetation is effective, easy to apply, and economic (Ferrini et al. 2009; Vasic et al. 2009; Wagner et al. 2004; Thompson et al. 2012). There are many concerns when it comes to herbicide safety and plant evolution. Since the mid 1980's the social acceptability of using herbicides on forest stands has been controversial (Campbell 1990). Since this wide unacceptance, herbicide use has decreased significantly and, in some places, has been banned all together (Wagner et al. 2004; Otchere-Boateng and Herring 1990). Quebec quickly decreased and banned the use of herbicides after social unacceptance and has been herbicide free since 2001 (Thompson and Pitt 2003; Thiffault and Roy 2009). Another reason for less herbicide being used is the increased ability of a forester to better judge when and how much herbicide is necessary and when alternative methods can be used (Campbell 1990). In the forest industry, herbicides are now only used when necessary and when alternative methods cannot be used (Otchere-Boateng and Herring 1990; Wagner et al. 2004).

Considerable research has been completed in this area due to social concerns about herbicide use being detrimental for the environment and wildlife (Frochot et al. 2009). These studies have found no significant damage to unsuspecting plants, environment or wildlife have been reported (Frochot et al. 2009; Otchere-Boateng and Herring 1990: Newton and Comeau 1990). The undesired vegetation developing resistance to herbicides is a concern that has occurred in agriculture and ways to reduce this possibility in forestry are being researched (Otchere-Boateng and Herring 1990). New research on using safeners, or antidotes, and protectants on the desired species to prevent injury from herbicides is being completed (Kraehmer et al. 2014). The outcome is not expected to be significant, but experiments are still occurring (Kraehmer et al. 2014).

Using herbicides has allowed a higher percentage of seedlings to survive and allow the seedlings to have increased stem volume (Wagner et al. 2004; Thompson et al. 2012). Research and technology advancements have improved mitigation techniques and allowed for improved herbicide application (Thompson et al. 2012). In southeastern US forests, volume gains of 65% have been realized with the use of herbicides (Wagner et al. 2004). Many studies have compared herbicide sites to control sites and found an increase in survivability and growth, both in height and diameter (MacLean and Morgan 1983; Albaugh et al. 2004; Burgess and Baldock 1994). Jack pine (*Pinus banksaina*) and black spruce (*Picea mariana*) sites had an increase in seedling survival, height and volume growth, and in needle mass (Burgess and Baldock 1994). A study analyzing the effects of herbicide use on white spruce (*Picea glauca*) found that only minor damage was found on the seedlings, including current year growths stunting, clubbiness of new needles and bleaching of new foilage (Mihajlovich et al. 2004). More research is needed on optimum timing and extent, and duration of weed control required to meet silviculture objectives on specific site types when using herbicides (Thompson and Pitt 2003). More efficient application methods also need to be researched to better use herbicides and policy changes may enable better usage of registered herbicides and allow for better risk and environmental mitigation (Thompson and Pitt 2003). Herbicide use around the world is similar to that of within Canada and the United States, with glyphosate being used the most and many herbicides being heavily regulated and banned in areas (Willoughby et al. 2009). Some countries like Lithuania, Republic of Bulgaria, Italy, Iceland and others have not had to use herbicides as other vegetation control measures are still economical (McCarthy 2009; Ferrini et al. 2009, Malinauskas and Suchockas 2009; Willoughby et al. 2009).

Mulching

Mulching is a vegetation control measure that spreads material, organic or inorganic, around the desired vegetation to combat establishment and growth of undesired species (Marble et al. 2015; Wagner 1993). The material provides a physical barrier against competing vegetation, which allows the desired vegetation to access more of the nutrients and enable it grow more that year (Marble et al. 2015; Wagner 1993). There are many materials that can be used as mulch and a mixture of materials can also be used (Marble et al. 2015). The material chosen will depend on the site and the desired vegetation species (Marble et al. 2015). Organic materials can include wood and bark pieces of different species and sizes, pine needles, pine straw, straw, hydromulch, composted material mixed with wood shavings, sawdust, grass clippings, newspaper, nut hulls, seas shells, and pulp and mechanical slurries (Carr 1980; Marble et al. 2015; Frochot et al. 2009; Ferrini et al. 2009; Guariglia and Thompson 1984). Inorganic materials can include the use of quarry dust, sand, gravel, sheet mulches, paper-based mulches, polyethylene films, gravel, rocks, sand, and other landscape fabrics (Carr 1980; Marble et al. 2015; Frochot et al. 2009; Ferrini et al. 2009; Guariglia and Thompson 1984). Sheet mulches are plastic materials that come in various sized sheets or mats (Siipilehto 2001). They are made of various materials including polyethylene, typar, and plastic fabrics (Guariglia and Thompson 1984; Marble et al. 2015). To apply these materials, it can be labourious and time consuming. Some organic materials are applied using a blow truck, where the mulch is blown through a large pipe onto the site, the other common method is to apply it by hand. The optimal depth of mulch is 7 cm (3 in), but a thicker layer is recommended for sites with hardy competition (Marble et al. 2015).

1000-2000 kg/ha of organic mulch will provide adequate coverage, with the range depending on the mulch size (Carr 1980). The sheet mulch, and polyethylene films and fabrics are applied by hand and require careful placement to ensure that the seedlings are not damaged (Davies 1988). They can be placed between plantation rows or placed over the seedling (Davies 1988; Ferrini et al. 2009). The mats and sheets are impervious and come in varying thickness and do not require a 7 cm (3 in) layer (Davies 1988). These inorganic materials need to be removed from the site as well, which is, again, labourious and time consuming, especially when some competing vegetation makes its way through the mulch (Davies 1988). This vegetation control measure can only be used on sites that are planted or already regenerating as the mulch will not allow anything to grow through it. This is an expensive vegetation control measure that yields desired results (Hytönen et al. 2009; Marble et al. 2015; Wagner 1993). When choosing to implement this vegetation control measure, the forester should evaluate the cost of the material, if the chosen material is allowed for use in a forestry setting, labour intensity, and amount of time needed to install and potentially remove the mulch (Wagner 1993; Marble et al. 2015).

This vegetation control measure is beneficial for desired vegetation growth as it increases soil moisture and decreases temperatures (Carr 1980; Marble et al. 2015; Ferrini et al. 2009; Mitchell et al. 1990; Thomas et al. 2001). Traux and Gagnon (1992) found that the organic herbicide, straw, decreased the soil temperature more than the inorganic black plastic mulch, with each having an average of 24.8 ºC and 34.7ºC, respectively. Adding a layer of mulch decreases undesired vegetation growth because light exclusion takes place, and the soil surface remains out of sight of the sun which allows it to stay at a cooler temperature and hold moisture for a longer period (Marble et al. 2015). These characteristics are beneficial for seedling growth, especially on sites that are dry (Marble et al. 2015; Wagner 1993). Dry sites are also prone to soil erosion and a mulch layer can help the site retain moisture and mitigate water runoff by having a mulch that is made up of larger particles, like a wood nugget or large wood chips (Carr 1980; Marble et al. 2015). In addition to not being easily carried away by the water, these larger pieces of material will not dry out as quickly and block more light (Marble et al. 2015). This will allow the site to hold onto the valuable nutrients that the desired vegetation species needs to grow (Ferrini et al. 2009). By using organic mulches on a harvest site, you are providing protection from competing species initially, and providing nutrients for the future (Ferrini et al. 2009). Organic mulches are also environmentally friendly and are largely socially accepted (Ferrini et al. 2009). The soil being protected can also prevent early frost damage on the trees (Carr 1980). Organic mulching also protects against frost heaving damage in the spring but can also lead to drying injuries and freezing injuries on the seedlings (Daniels and Simpson 1990; Siipilehto 2001). Although mulch does inhibit the growth of competing vegetation species, some materials encourage rodents and other small pest activity, such as mice, voles, termites, and pine weevil (Marble et al. 2015; Hytönen et al. 2009; Ferrini et al. 2009). These animals use it for shelter and feed on the mulch and desired vegetation (Marble et al. 2015; Hytönen et al. 2009). The mulch material used must also be free of seeds to maintain control of competing vegetation (Ferrini et al. 2009). This risk can be minimized by limiting the area that is mulched and by using different types of mulch (Shirish et al. 2013). Mulch can also be used with herbicide or mechanical site preparation. When using mulch with herbicide, studies have found that applying the herbicide before laying the mulch results in increased control of undesired vegetation and the need for less than 7 cm (3 in) mulch layer (Marble et al. 2015). Mulch is typically only used with mechanical site preparation on compact sites and reforestation areas (Frochot et al. 2009). The mechanical site preparation loosens the soil to provide better microsites for seedlings and the mulch allows the site to retain moisture and provides some nutrients to the soils (Frochot et al. 2009; Marble et al. 2015).

Although the results of using mulch are not as significant as other vegetation control measures, they are effective and valuable on specific sites, as well as being generally beneficial for sites (Ferrini et al. 2009). Studies have shown that the undesired vegetation growth has been decreased by 50% (Marble et al. 2015). Organic mulches have an expensive transportation cost and are used locally when the cost is affordable (Ferrini et al. 2009; Siipilehto 2001). Inorganic mulches are cheaper, but the labour to implement the vegetation control measure is expensive. Due to the high cost, mulch is only used on a small scale in some counties, Italy and Finland use organic mulch and Sweden and Germany use sheet mulch (Hytönen et al. 2009; Ammer et al. 2009; Ferrini et al. 2009; Löf et al. 2009). An experiment compared organic mulch depths and found that 7 cm (3 in) was the ideal thickness to combat competing vegetation, while keeping costs down (Marble et al. 2015). The downfall is that reapplication is necessary the following year to maintain control of the vegetation (Marble et al. 2015). Inorganic materials were also compared, and no significant difference was found between the material types, but they all produced increased seedling height (Appleton et al. 1990). When compared 2 and 3 years after application the sheet mulch was the most durable mulch (Siipilehto 2001). The newspaper slurry was the next most durable with wood fibre slurry and wood chip mulch following it (Siipilehto 2001). When mulch was compared to other vegetation control measures the organic and inorganic mulches achieved varying results (Siipilehto 2001). Organic mulches, such as wood chips, wood shavings, sawdust, and newspaper, achieved the overall best results (Siipilehto 2001). Mulching and mechanical site preparation yield similar seedling growth results but are not typically used on the same types of sites (Siipilehto 2001). Soil erosion is increased with mechanical site preparation but decreased with mulching (Siipilehto 2001; Willoughby et al. 2009). This shows that there are vegetation control measures available for many sites. Herbicide yields more significant or similar results as mulching and it is more economic (McCarthy 2009). Chen et al. (2013) compared organic mulches and found the best results occurred when mulch was combined with a herbicide treatment. This is due to the high efficiency of herbicide, and when paired with mulch the site can have an extended competition free period (Marble et al. 2015; Davies 1988). The roots of the competing vegetation provide physical barriers so that water does not carry the soil and the nutrients within it away. Mulch replaces these roots with a low ground, non-intrusive material that allows the above ground portion of the seedling to photosynthesize, while the below ground portion of the seedling can spread it roots without being encroached (Marble et al. 2015). When compared to control sites, mulching improved seedling height growth by 20.0 cm after two years on wood chip mulch sites and newspaper mulch sites (Siipilehto 2001). Mulch use was also found to significantly decrease these species of undesired vegetation including horseweed, dandelions, and annual grasses (Chen et al. 2013). Sowthistle (*Sonchus oleraceus*) populations were increased with mulch use and so foresters should be cautious if this species is present (Chen et al. 2013).

Mulching is typically used on plantation sites, or sites with high-value desired species to help mitigate its high cost (Löf et al. 2012). Research has shown that it is effective on ash (*Fraxinus*), horse chestnut (*Aesculus x carnea* Hayne), European linden (*Tilia x europaea* D.C.), *Pinus patula*, *Eucalyptus grandis*, *Acacia mearnsii*, bur oak (*Quercus macrocarpa*), Douglas-fir (*Pseudotsuga menziesii*), hybrid poplar species (*Populus x*), and hornbeam (*Carpinus betulus*) (Ferrini et al. 2009; Truax and Gagnon 1992; Siipilehto 2001; Davies 1988). Wood chip mulching was found to be beneficial for spruce and birch species and sheet mulch with aspen species (Siipilehto 2001). More research is needed on machinery and equipment to apply mulch at a large scale, and what the effects of using mulch on wet sites are (Ferrini et al. 2009; Wagner 1993). Herbicide pairings with mulch and its efficacy also need to be researched to be better used together at a larger scale (Marble et al. 2015).

Cover Cropping

Cover cropping is planting shrub or low height vegetation to act as a barrier to the growth of undesired vegetation (Frochot et al. 2009; Wagner 1993; OMNR 1994). Cover cropping has been used in horticulture, agriculture, vineyards, and nursery settings but not widely used as a vegetation management tool in the forest industry (Wagner 1993; Frochot et al. 2009; Ferrini et al. 2009; Government of Ontario 2021). A cover crop is most effective on sites that have undesired species that reproduce through seed, rather than roots because the cover crop will be able to better compete (Thompson and Steen 1996). There are a few different ways to apply cover crops and the best results occur when it is paired with mechanical site preparation or prescribed burns because of the improved microsite availability (Thompson and Steen 1996). If using seeds they can be distributed by hand, machine, or aerially (Thompson and Steen 1996; OMNR 1994). The different sized and weighted seeds will be distributed differently, so increased monitoring is required to ensure adequate, even coverage is taking place (Thompson and Steen 1996). Cover crops can also be artificially planted, but this is more labourious, and costly (OMNR 1994). The desired vegetation can also be seeded or artificially planted with or after the cover crop, depending on germination sensitivity (Thompson and Steen 1996; Ferrini et al. 2009). Cover cropping is applied in rows with the desired vegetation in between each row and it can be combined with other vegetation control measures (Thompson and Steen 1996; OMNR 1994). Cover cropping is applied mostly to high-value, broadleaved species on small sites that are reclaimed and/or afforested due to their fast growth, ease of access, and site maneuverability (Holst and Jóhannesdóttir 2009; Ferrini et al. 2009; OMNR 1994). Cover cropping is usually applied mid- to late-summer or fall (Thompson and Steen 1996). When applied in summer, germination occurs within the same year, and when applied in the fall, it is completed as close to the first snow fall to ensure germination is delayed until the spring (Thompson and Steen 1996; OMNR 1994).

Characteristics of the cover crop species include a native species that has trailing or spreading growth habit, covers the soil surface, a low mature height, dense, fast establishment, and is competitive but balanced with the desired vegetation to ensure the desired vegetation is not killed (Marble et al. 2015; Frochot et al. 2009; Thompson and Steen 1996). The site will benefit and maintain its state of being free of undesired vegetation longer, with a cover crop that is a mix of multiple species and includes both annuals and perennials (Thompson and Steen 1996). Other beneficial characteristics of cover crop species includes palatable species for foraging, nitrogen-fixing legumes for foliar mass, and sod-forming species for soil erosion (Thompson and Steen 1996). Common species include native grasses, legumes, and fescues (Carr 1980; Marble et al. 2015; Thompson and Steen 1996). Species that have been studied and are effective include rye grass (*Lolium perenne L.*), clover (*Trifolium spp.*), *Alchemilla mollis*, *Nepeta* x *faassenii*, *Phlox subulata*, *Acaena inermis*, *Muehlenbeckia axillaris*, *Solidago sphacelata*, Alaskan lupin (*Lupinus nootkaensis*), alfalfa (*Medicago sativa L.*), fescue (*Festuca spp.*), and birds-foot trefoil (*Lotus corniculatus* L.) (Carr 1980; Marble et al. 2015; Wagner 1993; Holst and Jóhannesdóttir 2009; Wiensczyk et al. 2011: Thompson and Steen 1996; Government of Ontario 2021; OMNR 1994). Thimbleberry (*Rubus parviflorus*), fireweed (*Epilobium angustifolium* L.), alder (*Alnus* sp.), and cottonwood (*Populus trichocarpa* Torr. & Gray) have been studied and are all susceptible to cover crop species (Thompson and Steen 1996). When choosing the cover crop species mix, local experience and clearly defined objectives should be used, as well as consideration for the cover crops growth habits, if overwintering necessary, sensitivity to herbicide (if necessary), establishment patterns, and pest management (Government of Ontario 2021; Thompson and Steen 1996; OMNR 1994). The amount of seed and species needed will depend on seed availability, allowability, and budget (Government of Ontario 2021).

The main objective of the cover crop is to reduce the impact of undesired vegetation on desired vegetation (Ferrini et al. 2009; Wagner 1993; Thompson and Steen 1996; Government of Ontario 2021). There are many other benefits of using a cover crop, including its ability to reduce soil erosion, soil temperature, soil compaction, invasive species spread, and damage from frost, as well as its ability to maintain and increase nutrients in the soil for the desired vegetation (Frochot et al. 2009; Ferrini et al. 2009; OMNR 1994). Cover crops also allow better access for harvesting and maintenance of productive sites, as well as improve foliar mass, accelerate organic matter replacement, and increase visual green-up (Ferrini et al. 2009; Thompson and Steen 1996).

Some aspects of using a cover crop can appear negative, but there are ways to mitigate the risks and ensure the cover crop is beneficial for the site. Increased vegetation will occur on the site, but less of the undesired vegetation will be present (Thompson and Steen 1996; OMNR 1994). When grass is used as a cover crop, dense patches can damage seedlings as well as rodent and rabbit populations can increase and potentially damage the desired vegetation (Thompson and Steen 1996; Wiensczyk et al. 2011). Livestock grazing and increased habitat for raptors can help alleviate the potential damage to the desired vegetation (Thompson and Steen 1996). Early growth of the desired vegetation has been slowed because of cover crop competition, but once established the desired vegetation has increase growth compared to uncontrolled sites (Thompson and Steen 1996).

Cover cropping is an alternative vegetation control measure to herbicides but can still be combined with other vegetation control measures, and often is. Cover cropping decreases the need for herbicide vegetation control but can still be used on sites that have hardy, competitive undesired vegetation (Wagner 1993; Wiensczyk et al. 2011; OMNR 1994). The use of herbicide can be decreased as much as 50% and having savings of up to $25/ha (OMNR 1994). Cover cropping can also be used with mulch placed around the base of the planted areas (Ferrini et al. 2009). This combination will help combat undesired vegetation further and allow the desired vegetation to have increased growth (Ferrini et al. 2009). It can be used with prescribed fire to establish the site with a desirable vegetation that has less damaging effects on the desired vegetation (DiTomaso et al. 2006). When palatable cover crop species are used, cover cropping can be combined with livestock grazing to further benefit the site (OMNR 1994; Thompson and Steen 1996). This combination may lead to increased wildlife browsing also (Wagner 1993; OMNR 1994).

Cover cropping is not recommended for some regeneration techniques or specific sites. Direct seeding or seedlings that are sensitive when germinating should not use cover cropping because the cover crop species will quickly take over the site and the desired species will not be able to grow (Ferrini et al. 2009). Extremely dry sites should also be avoided because the cover crop will compete for water and if the desired species is not established it will die (Ferrini et al. 2009; Wiensczyk et al. 2011; Thompson and Steen 1996). Lowland sites should be avoided due to their extreme soil moisture negating the cover crop’s ability to grow (Ferrini et al. 2009; OMNR 1994). Silt loam to clay soils should be mechanically scarified the fall before planting and sandy loam and loam soils should be mechanically scarified in the spring, directly before planting (OMNR 1994). This will assist the cover crop in establishment on the site (OMNR 1994).

Throughout the world, the use of cover cropping is low. This is due to the high cost of preparing, planting, and maintaining the site, as well as its effects not being well researched for a variety of cover crop species and climates (Ferrini et al. 2009; Wiström et al. 2018). In Denmark and France, the use of cover crops is being researched (Bensten et al. 2009; Frochot et al. 2009). In France, rye and other grains have been planted with oak and pine seeds successfully (Frochot et al. 2009). Cover crop vegetation control has been used periodically in British Columbia since the 1980's (Thompson and Steen 1996). When grasses and legumes were used as a cover crop the seedling growth was initially negatively impacted, but the forgeability of the site was increased, and the growth was significantly increased a couple years later (Thompson and Steen 1996). The basal area of sessile oak (*Quercus petraea*) and sycamore maple (*Acer pseudoplatanus* L.) were increased with the use of a cover crop, but height was not significantly impacted (Davies 1985). The effects of cover cropping have been successfully experimented on Douglas-fir (*Pseudotsuga menziesii*), yellow pine (*Pinus ponderosa* Laws.), lodgepole pine (*Pinus contorta* Dougl.), Sitka spurce (*Picea sitchensis*), and Engelmann spruce (*Picea Engelmannii* Parry) plantations (Thompson and Steen 1996).New Zealand tested twelve potential cover crop species for the area and found that when planted with a sawdust mulch on fine sandy loam, *Acaena inermis*, *Muehlenbeckia axillaris, Ajuga reptans, Coprosma acerosa, Grevillea lanigera, Juniperus procumbens, Pimelea prostrata, Sedum mexicanum,* and *Veronica peduncularis* were all effective during the 2-year study (Foo et al. 2011).

Research for cover cropping will improve its use, and availability to be used on a larger scale. More research is needed on cover crop species' ability to outcompete undesired vegetation and which species are appropriate to use on specific soils and climates (Marble et al. 2015; Frochot et al. 2009). The introduction of potential cover crop species to a harvest site needs to be studied to assess its impact on the site and the ecosystem (Wagner 1993). Comparison research is needed for cover crops effectiveness against mechanical site preparation and other vegetation control measures (Wiström et al. 2018). A potential cover crop species needs to be evaluated extensively before it is used. The pros and cons, cost, and effectiveness need to be well-researched before cover cropping can be used on a larger scale (OMNR 1994). This research and the funding to provide it are part of the reason that cover cropping is not used as widely as other vegetation control measures (Thompson and Steen 1996; OMNR 1994).

Tree Shelters

Tree shelters are the most complex vegetation control measure and required the most monitoring (Kerr 1995). Tree shelters are structures that are placed around the seed or transplanted desired vegetation, and act as an individual greenhouse (Devine and Harrington 2008; Mitchell et al. 1990). Graham Tuley us the inventor of tree shelters, inventing the first shelter in 1979 (Kerr 1995). The designs of tree shelters vary, but most are plastic, semi-transparent tubes, that can be vented or unvented, and can be different colours (Devine and Harrington 2008; Dominy and Wood 1986; Kerr 1995). They are typically made from polypropylene and degrade over time from ultraviolet radiation, but other biodegradable and photodegradable shelters are available (Dominy and Wood 1986; Kerr 1995; Mitchell et al. 1990). Seeds or seedlings can be used with tree shelters, and they are all hand planted, which is tedious and labour intensive (Mitchell et al. 1990). A lot of materials are used with tree shelters and must be individually placed, which increases the cost (Löf et al. 2019). The tree shelters must be placed over top the desired vegetation, placed into the ground slightly to stop rodents from eating the desired vegetation, then a stake must be placed next to the tree shelter to stabilize it (Dominy and Wood 1986). The tree shelters come in different heights to accommodate the anticipated height growth of different desired vegetation (Defaa et al. 2015).). They can be placed whenever the site has adequate soil moisture and warm temperatures, typically early spring after any chance of frost has passed (Mitchell et al. 1990). Cost, durability, and ease of installation must be factored in when choosing to use tree shelters and when choosing a design (Devine and Harrington 2008; Löf et al. 2019).

The purpose of tree shelters is to improve height and survivability of the desired vegetation (Mitchell et al. 1990; Davies 1985; Kerr 1995). The tube increases soil and air temperature, along with humidity and vapour pressure deficit, which creates optimal growing conditions for the desired vegetation (Ceacero et al. 2014; Kerr 1995). This added growing time allows the desired vegetation to become more resistant to frost and heaving damage (Dominy and Wood 1986). The tube also protects the desired vegetation from direct sunlight, which can decrease the temperature on hot dry days (Coll et al. 2009; Mitchell et al. 1990). The tube protects the desired vegetation from being eaten by rodents as a seed and a young plant and protects it from browsing as it becomes established (Mitchell et al. 1990; Dominy and Wood 1986; Davies 1985). The desired vegetation being protected means less seeds or seedlings need to be planted, decreasing the cost (Mitchell et al. 1990; Dominy and Wood 1986). The tree shelters can be different shapes, colours, have different features and be made of different materials. In Italy, coconut fibre tree shelters were experimented, and in Canada, cone-shaped, mesh tree shelters were experimented with (Dominy and Wood 1986; Ferrini et al. 2009). Once the desired vegetation has emerged out of the tree shelter, 2-3 years after installation, the tree shelter and stakes must be removed, if not degraded (Kerr 1995). Like cover cropping, this vegetation control measure is typically completed on broadleaved species that have a high-value, and sites that are small and easy to access due to its high cost and monitoring needs (Löf et al. 2019; Kerr 1995). The tree shelters must be an adequate height to protect the seedling and have smooth tops, that are slightly arced to not cut into the desired vegetation causing damage (Kerr 1995).

The Mediterranean uses this vegetation control measure semi-regularly with success (Löf et al. 2019). They have used it on Argan (*Argania spinosa*), a species that is endemic to the area and have successfully lessened its risk of extinction using tree shelters (Defaa et al. 2015). The tree shelters increased the survival by 20% for a total survival of 94%, and increased height by 30 cm (Defaa et al. 2015). It has been tested on some conifer species, black spruce (*Picea mariana*), white spruce (*Picea glauca*), and Jack pine (*Pinus banksiana*) and all were improved in height growth (Dominy and Wood 1986). During this study the authors stated that, over the 5-year study 70% of the shelters fully degraded with the highly shaded and dense sites containing the most left over shelters (Dominy and Wood 1986; Kerr 1995). With this information they recommend tree shelters be used only on sites that were cool, exposed, and had little vegetation (Dominy and Wood 1986). Sessile oak (*Quercus petraea*), sycamore maple (*Acer pseudoplatanus* L.), Eucalyptus, cottonwood, walnut, chestnut, ash, beech, cherry, cherrybark oak, and holm oak (*Quercus ilex* L. *ballota*) sites were improved with the use of tree shelters (Davies 1985; Defaa et al. 2015; Ceacero et al. 2014, Sena et al. 2014; Kerr 1995). When used on black spruce, more significant results can be realized on strip cut sites than clear cut sites (Dominy and Wood 1986). In all of these studies the basal area was not increased, this could impact the growth and quality of the desired vegetation in the future (Defaa et al. 2015; Davies 1985; Dominy and Wood 1986). Testing was completed to compare different tree shelter designs on two species, western red cedar (*Thuja plicata*) and Oregon white oak (*Quercus garryana*) (Devine and Harrington 2008). In this study Devine and Harrington (2008) found that mesh-walled shelters were cooler than the solid-walled shelters, the vented shelters did not impact humidity or temperature, and the blue shelters increased the height on both species but hindered the stem diameter growth on Oregon white oak. Tree shelters are seldom used for conifer regeneration because the high cost outweighs the benefits, as conifer regeneration is typically completed on a large scale (Kerr 1995).

Tree shelters are typically incorporated with other vegetation control measures to improve their success (Coll et al. 2009; Ceacero et al. 2014; Kerr 1995). When used with herbicide the desired vegetation has increased growth due to increased sunlight, root growth room, and nutrients availability (Ceacero et al. 2014). Mechanical site preparation will increase available microsites and allow for easier planting and installation of tree shelters (Ceacero et al. 2014). When implemented with livestock grazing, the undesired vegetation can be defeated without concern for damages to the desired vegetation (Ferrini et al. 2009). In Italy tree shelters were used during a thinning treatment to protect the desired vegetation from herbivory (Ferrini et al. 2009). It can be used with mulch, but in a study completed by Ceacero et al. (2014) when they used this combination, it resulted in the least amount of survival and is therefore not recommended.

This vegetation control measure is not used globally due to little research on its effectiveness and species that it can be used with (Löf et al. 2019; Kerr 1995). Sites that have less than optimal temperatures should undergo testing to better understand the capabilities of tree shelters (Dominy and Wood 1986). The long-term effects of the degrading tree shelters on the site also needs to be further researched (Dubois et al. 2000). Tree shelters use in winter climates also needs to be researched to analyze the effects of snowpress and snow presence inside the tree shelter.

CONCLUSIONS

Controlling vegetation is vital for forests to be regenerated in an economical timeframe. The methods used to control vegetation have changed over time with some vegetation control measures fluctuating in use, like herbicide and tee shelters, while other measures have been steadily rising since their introduction, like mechanical site preparation. Each vegetation control measure is beneficial on specific sites and can often be combined with other control measures to obtain increased results. Partial harvesting can be completed with shade tolerant species. Prescribed burns must be completed before regeneration can take place. Livestock grazing is best used on sites where the desired vegetation is protected or is not a palatable species. Mechanical site preparation has many applications because of the variety of machinery that can be use. Herbicide is the most widely used vegetation control measure with glyphosate being the most popular herbicide. Mulch has different application methods each with their own pros and cons. Cover crops are often paired with other vegetation control measures and are expensive to implement and monitor. Tree shelters are also expensive and used on high value sites to offset the cost. A forester’s knowledge to implement the best vegetation control measure is limited by cost, labour and equipment availability, access, among others. By continuing to research and compile scientific information about vegetation control measures the forest industry and foresters will be able to maintain high quality forests while minimizing damages to the environment.

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