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Forest vegetation management

Key functions, alternatives to chemical herbicides and challenges

Nelson Thiffault
Canadian Forest Service, Natural Resources Canada,
Canadian Wood Fibre Centre, Québec, QC, Canada

Information Report
FI-X-023
2021

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Cat. no: Fo4-169/2021E-PDF
ISBN: 978-0-660-40936-8

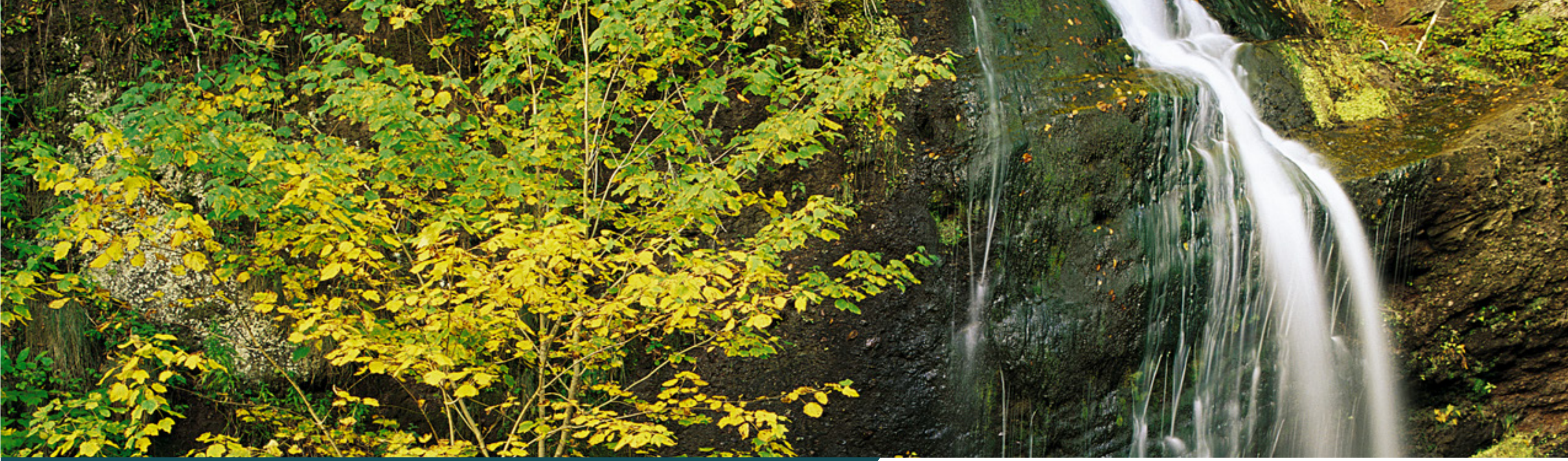
Natural Resources Canada
Canadian Forest Service
580 Booth Street
Ottawa, ON K1A 0E4

A pdf version of this publication is available through the Canadian Forest Service Publications database: http://cfs.nrcan.gc.ca/publications.

Cet ouvrage est publié en français sous le titre : *Gestion de la végétation forestière – Rôles, méthodes de rechange aux herbicides chimiques et enjeux*

TTY: 613-996-4397 (Teletype for the deaf)

Table of contents



Foreword

This report is adapted from a brief that was delivered in May, 2021 to the Standing Committee on Climate Change and Environmental Stewardship, an all-party committee of the New Brunswick Legislature. It was drafted in response to an invitation for proposals on the use of pesticides and herbicides, including glyphosate, in the province.

Summary

Forest vegetation management, initially viewed as efficient environmental resource management that promotes preferred tree species over non-commercial plant species, has been transformed in recent decades. It focuses on managing forest succession to provide a diverse range of ecosystem services. Forest vegetation management is not an end in itself - it is just one of many possible methods for achieving the societal expectations of forests, as identified in the forest management process. Vegetation management typically increases wood fibre production from conifers. However, vegetation management contributes to other objectives, such as the reduced encroachment of exotic species or the spread of disease. Vegetation management involves a preventive loop (e.g., choice of cuts, intervention seasons, debris management), which reduces or eliminates the need for corrective treatments. Mechanical treatments, like brush cutting, enhance the survival and growth of selected trees, even when there's a higher degree of competing vegetation. However, these measures can be costly and hazardous to workers. To guarantee effectiveness, they usually need to be combined with other treatments within an integrated vegetation management strategy. Inadequate integration may fail to successfully establish the preferred species, which in turn may jeopardize the objective. There is no single solution for every context or environment, and no vegetation management approach is inherently good or bad. Deciding on the right approach to vegetation management involves assessing, identifying and addressing issues in the forest management process. Furthermore, our current knowledge of competitive relationships between species and the effects of silvicultural treatments on these species needs to be reviewed in light of climate change. Likewise, a better understanding of ecological facilitation between species could help identify opportunities to conserve or promote companion species, while maintaining or improving the yields of commercially important species. With new insights into complementary ecological niches of species, vegetation management can promote combinations that maximize ecosystem productivity with the optimal use of existing resources. More research is needed to determine effective and efficient approaches to alien invasive species, and combine 21st century science and technology with traditional Indigenous knowledge to devise new approaches to vegetation management.

1. Introduction

The concept of forest vegetation management has adapted over time. In the 1980s, forestry focused primarily on timber production; forest vegetation management was modeled directly on agriculture. At the time, it was seen as effectively managing environmental resources of forest sites (light, water, soil nutrients) to encourage growth of preferred species over non-commercial plant species (Walstad and Kuch 1987). This meant limiting the growth of, or eliminating, plant species that wouldn't contribute to desirable products.

Forest management has adopted sustainable resource management principles as outlined in the Brundtland Report (1987). Consequently, the definition of forest vegetation management broadened to include the pursuit of ecological, economic and social objectives in line with the principles of sustainable forest management, supported by an integrated vegetation management process (Wagner 1994). One feature of integrated forest vegetation management is the competing species' autecology, such as phenology, habitat requirements and reproductive patterns (Bell 1991; Jobidon 1995; Wagner and Zasada 1991).

Forest management paradigms continued to progress during the 1990s and 2000s and are guided by concepts such as ecosystem-based management or EBM. Ecosystem-based management upholds biodiversity and ecosystem viability by reducing gaps between managed and natural forests (Gauthier et al. 2008). This paradigm is central to several Canadian forestry systems, including those of Quebec and Ontario. Forest vegetation management has come to focus on forest succession for various ecosystem services (Bell et al. 2011c), such as maintaining water quality, sequestering atmospheric carbon and providing wildlife habitat.

While these concepts have shifted, timber production remains the primary objective of Canadian forest vegetation management. Even today, with certain exceptions (notably in Quebec and Saskatchewan), Canadian forest vegetation management usually involves chemical herbicides, which have a low level of social acceptability (Ammer et al. 2011; Nadeau et al. 2008; Wagner et al. 1998a; Wagner et al. 1998b) and are incompatible with First Nations perspectives (Kayahara and Armstrong 2015). Municipal and provincial governments, which legislate and regulate these practices within their jurisdictions, are routinely called on for consultation and education in forest vegetation management. Access to scientific knowledge is a key to the success of these processes (Wyatt et al. 2011).

The purpose of this report is to present, in clear and concise language, the context for forest vegetation management and some of its associated scientific concepts. First, we outline and clarify the function of forest vegetation management in silviculture and forest management. We then present the primary documented and available methods of forest vegetation management, with a particular focus on the alternatives to chemical herbicides. Lastly, we highlight various issues, new opportunities and perspectives emerging from the latest ecological research.

2. Why manage forest vegetation?

Managing forest vegetation is a practice used by silviculturists to achieve forest management objectives. The existing forest conditions on specific territories present their own challenges and opportunities, including those related to the intrinsic value of forests for First Nations, timber production, ecosystem conservation, economic activity, carbon sequestration and the fight against climate change, and access to the area for recreation and tourism. Some of the challenges of forest management are to identify these issues and opportunities, weigh them, determine optimal forest conditions and develop strategies to meet consensus-based management objectives (Fig. 1). Forest vegetation management is not an end in itself - it is just one of several instruments for fulfilling societal aspirations for forests.

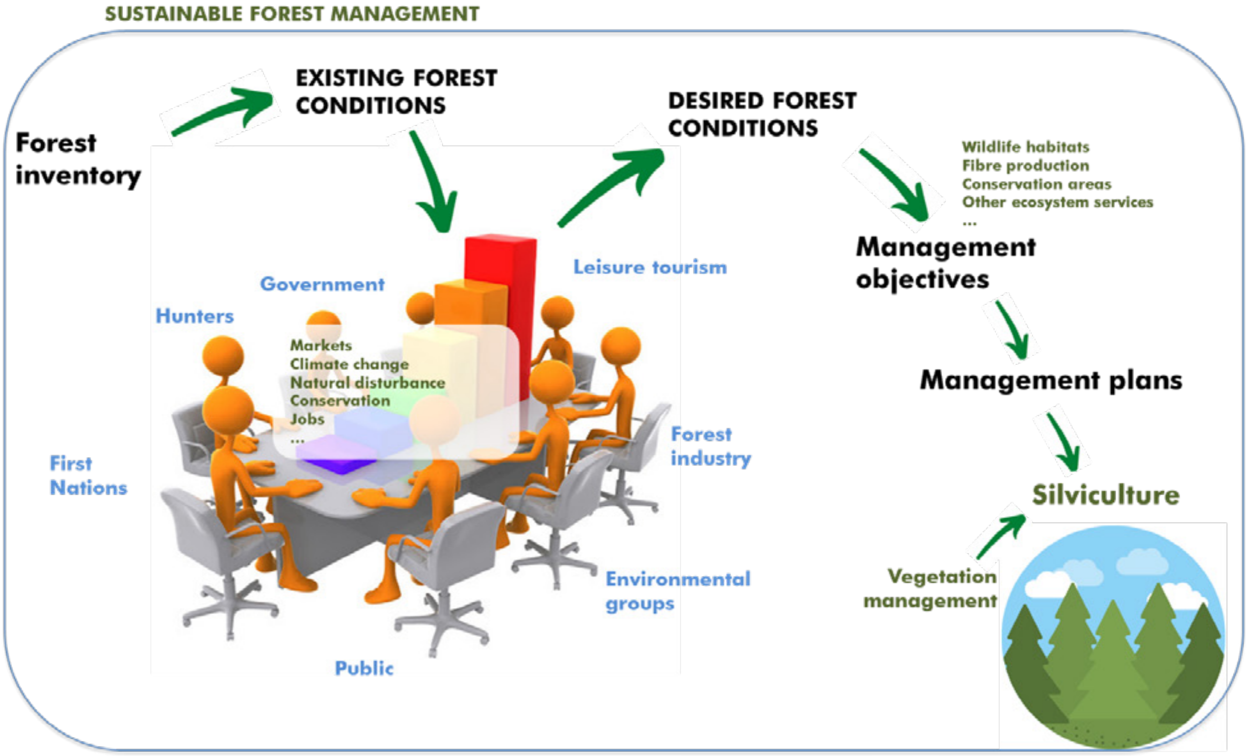


Figure 1. Simplified outline of the forest management process and the role of forest vegetation management. Forest vegetation management is a tool used by silviculturists to address management objectives for a given area. The objectives are established upstream of forest management decisions, based on processes that vary between jurisdictions, usually involving stakeholder consultation or participation. In Canada, forest management on public lands is based on sustainable resource management.

Silviculture uses vegetation management to engineer plant communities and direct them towards achieving management objectives (Bell et al. 2011c). Even today, vegetation management is typically aimed at maximizing conifer wood fibre production (e.g., spruce; *Picea* spp. and fir; *Abies* spp.) after logging (Fig. 2). It has other applications, such as limiting the encroachment of exotic plant species (e.g., glossy buckthorn; *Frangula alnus* Mill.) into natural environments, which threaten ecological integrity (Nagel et al. 2008). It may also be useful in reducing further spread of disease. Controlling *Ribes* spp. in particular is a silvicultural method for fighting white pine (*Pinus strobus* L.) blister rust, a parasite of Asian origin that uses this species to continue its life cycle (Muzika 2017).

Vegetation communities regenerating after logging involve a number of tree and plant species that have adapted to unique environmental conditions at this stage of forest stand development (Bell et al. 2011b). Unlike conditions seen in forest undergrowth before logging, harvested areas receive high levels of sunlight, which warms the air and soil and hastens the decomposition of organic matter in the soil (releasing nutrients for plant growth), the germination of buried seeds and a number of ecological mechanisms (Fig. 3).

Environmental conditions on recently cut sites favour the establishment of plant species that reproduce by seeds, by stump sprouting (new stems growing on or near the stump) or by suckering (new stems growing directly from the root). In all cases, these species grow rapidly (Jobidon 1995; Oliver and Larson 1996). They usually have limited commercial interest, depending on management objectives, and can dominate harvested sites to the detriment of more desired species, such as conifers.

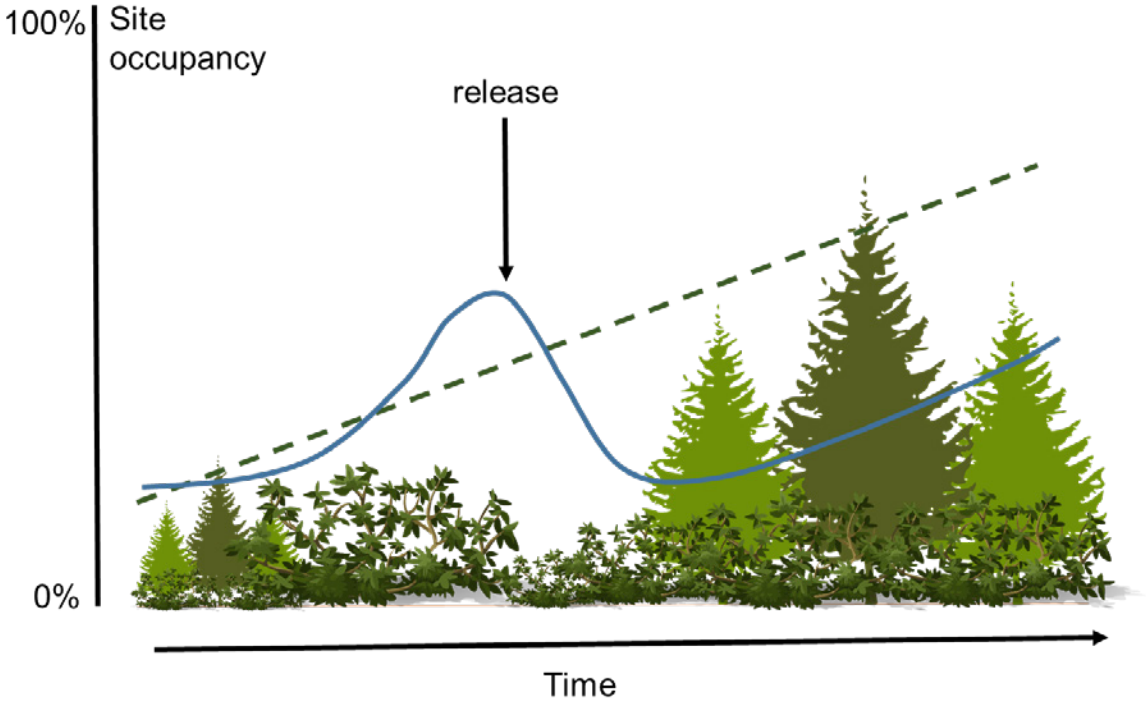


Figure 2. Schematic illustration of forest site occupation by ground cover shrubs (solid blue line) and preferred species, represented here by conifers (dotted green line), in the first decade after logging. Vegetation management, represented by mechanical release, reduces competition and offers an opportunity for preferred species to prevail without eliminating other species. Adapted from Grossnickle (2000).

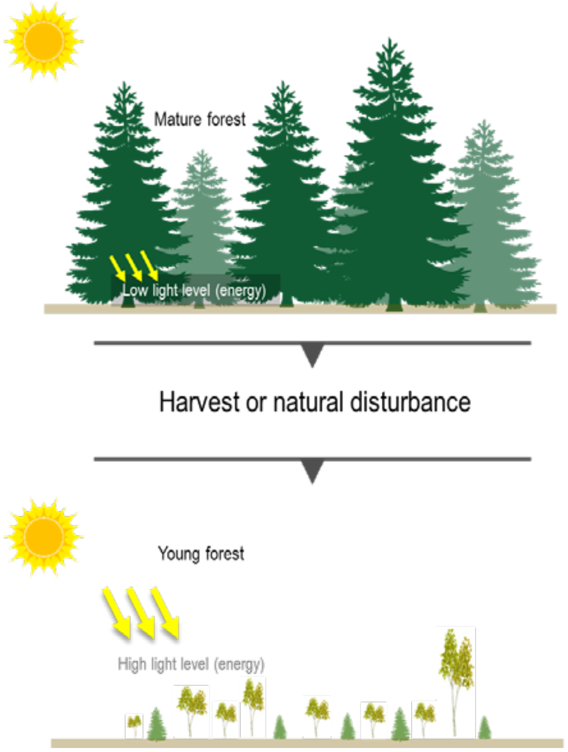


Figure 3. Logging drastically alters the environmental conditions in cut blocks. Certain plant and tree species such as white birch (*Betula papyrifera* Marsh.), trembling aspen (*Populus tremuloides* Michx.) or red maple (*Acer rubrum* L.) have adapted to these conditions and grow very quickly; these are "early successional" species. Other species, such as commercially valuable conifers (e.g., spruce), will grow more slowly and are better adapted to the prevailing conditions later in forest succession.

During the establishment phase of conifer plantations, established natural vegetation will efficiently use environmental resources, in most cases reducing the growth of planted species (Wagner et al. 2001). The effect of companion vegetation on planted species, along with individual species competing for light, water and nutrients, is documented in ecosystems and species worldwide (Wagner et al. 2006). For example, only 5 years after planting, the competition from hardwood species such as white birch, trembling aspen and pin cherry (*Prunus pensylvanica* L.f.) reduced the diameter of planted white spruce (*Picea glauca* (Moench) Voss) by a factor of three (Jobidon 2000) (Fig. 4).

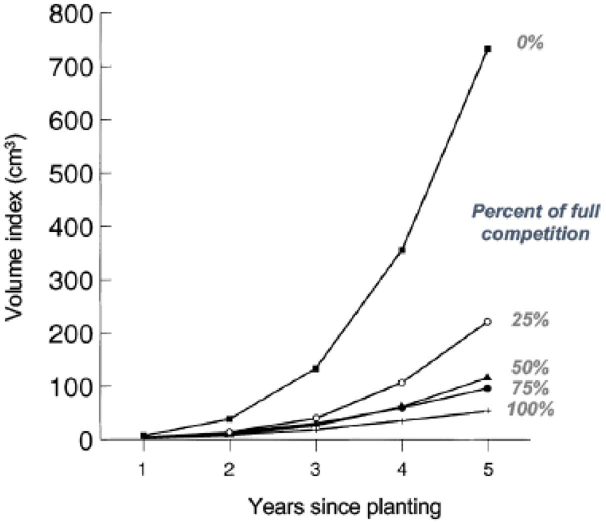


Figure 4. Volume growth of white spruce stems on a recently logged site is directly influenced by shade-intolerant hardwoods such as trembling aspen, which compete for environmental resources (particularly light). White spruce stems subjected to full competition will show linear growth; they lack the typical exponential growth pattern expected in young plantations. Moreover, even a limited competition from light-tolerant hardwoods can significantly reduce growth. Adapted from Jobidon (2000).

Within a forest management context (see Fig. 1) where fibre production focuses on spruce, a competition-sensitive species that requires a high level of sunlight, vegetation management ensures that planted trees grow at a pace that follows production objectives. While other objectives, such as white pine production, which is more shade-tolerant and particularly vulnerable to various insects and diseases in its early life, may require different approaches (e.g., partial canopy maintenance to reduce direct sunlight, coupled with herbaceous vegetation control; Pitt et al. 2016), vegetation management is key to the survival of trees and the achievement of management objectives.

3. How should forest vegetation be managed?

Vegetation management can be split into two loops: preventive and corrective (Fig. 5). As the name suggests, the preventive loop refers to treatments or practices designed to prevent the invasion of forest sites by species that are incompatible with management objectives. Some examples are logging that limits soil disturbance or preserves partial cover, or winter logging that restricts the establishment of species that disperse seeds by wind or which create seed banks in the soil (Wiensczyk et al. 2011). Alternatively, while these practices may protect the regeneration of pre-established species (Waters et al. 2004), they may also favour abundant recovery for other highly competitive species.

Similarly, managing woody debris (harvesting for bioenergy production, stacking it, or distributing it evenly across sites) can either limit or encourage vegetation growth (Gouge et al. 2021). This is because debris creates a physical barrier that decreases soil exposure and affects competing vegetation, micro-climate, and available nutrients (Harrington et al. 2013). Many of these effects vary across sites, including species autecology, soil characteristics, and climate (Trottier-Picard et al. 2014; Trottier-Picard et al. 2016). In-depth understanding and inclusion of species autecology (e.g., Jobidon 1995), along with development and use of an ecological framework and insights that forecast species abundance (e.g., Thiffault et al. 2015) are all crucial to preventive vegetation management. For example, planting scenarios modeled after natural forest successional trajectories will support productive plantations with limited or no clearing requirements (Barrette et al. 2021).

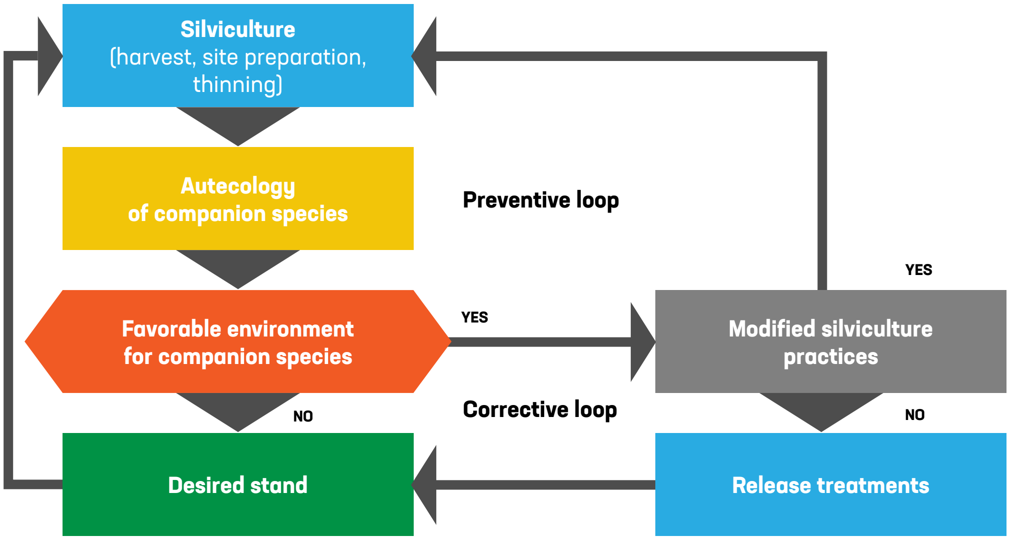


Figure 5. Forest vegetation management decision process. There are two main loops in the process: one maintains conditions that prevent site domination by companion species that limit achievement of management objectives, and one controls companion species once they are established. Adapted from Wagner et al. (2001) and Wiensczyk et al. (2011).

In the corrective loop (Fig. 5), forest vegetation management generally refers to silvicultural treatments that are applied early on to encourage or create conditions for the regeneration of preferred species. There exists a significant body of available literature and review articles that describe the range of forest vegetation management strategies. For example, Bell (1991), Wagner et al. (2001), and Thiffault and Hébert (2013) outline variations and modalities of broad treatment categories and address factors that define their success in the Canadian context. Thompson and Pitt (2003) summarize research efforts in the field and discuss evolving Canadian practices. Wiensczyk et al. (2011) probably offer the most comprehensive overview of available options tested in Canada, emphasizing their capacity to control competing vegetation without harming forest regeneration.

Chemical herbicides and mechanical cutting are the two most popular variants for vegetation management in the corrective loop. There can be significant productivity and cost variations between mechanical and chemical methods (Bell et al. 1997; Fortier and Messier 2006), with the chemical option offering higher benefit-to-cost ratio from a strictly economic perspective (Homagain et al. 2011). Using chemical herbicides, particularly glyphosate-based herbicides, to control forest vegetation is recognized as both effective and efficient (Newton 2006; Wagner et al. 2004). This report does not address the effects of chemical herbicides on forest productivity, biodiversity, or other ecosystem components in greater depth. However, more insight can be gained from a number of available studies and reviews on the topic (e.g., Bell et al. 2011a; Benbrook 2016; Botten et al. 2021; Comeau and Fraser 2018; Dampier et al. 2007; Deighton et al. 2021; Edge et al. 2021; Fu et al. 2008; Man and Bell 2018; Mihajlovich et al. 2012; Peter and Harrington 2018; Relyea 2012; Rolando et al. 2017; Royo et al. 2019; Stokely et al. 2018; Thompson et al. 2012; Urli et al. 2017; Wood 2019).

Manual clearing, by contrast, involves manual methods, using tools such as machetes, axes, brush hooks or pruning shears. These methods may be interesting and effective on a single tree scale, but are rarely applied in large-scale forest management. However, they can be useful in small, sensitive areas.

Mechanical clearing involves motorized methods, such as brush cutters or chainsaws, suitable for operational settings, or tools that are mounted on tractors or log skidders (Wiensczyk et al. 2011). Both manual and motorized methods can enhance the survival and growth of selected trees (Cyr and Thiffault 2009; Deighton et al. 2021) and have the benefit of selectivity; targeted competitors can actually be cut. With integrated vegetation management (described below), mechanical release with brush saws meets production goals, even with high levels of plant competition (Thiffault et al. 2014b) (Fig. 6).

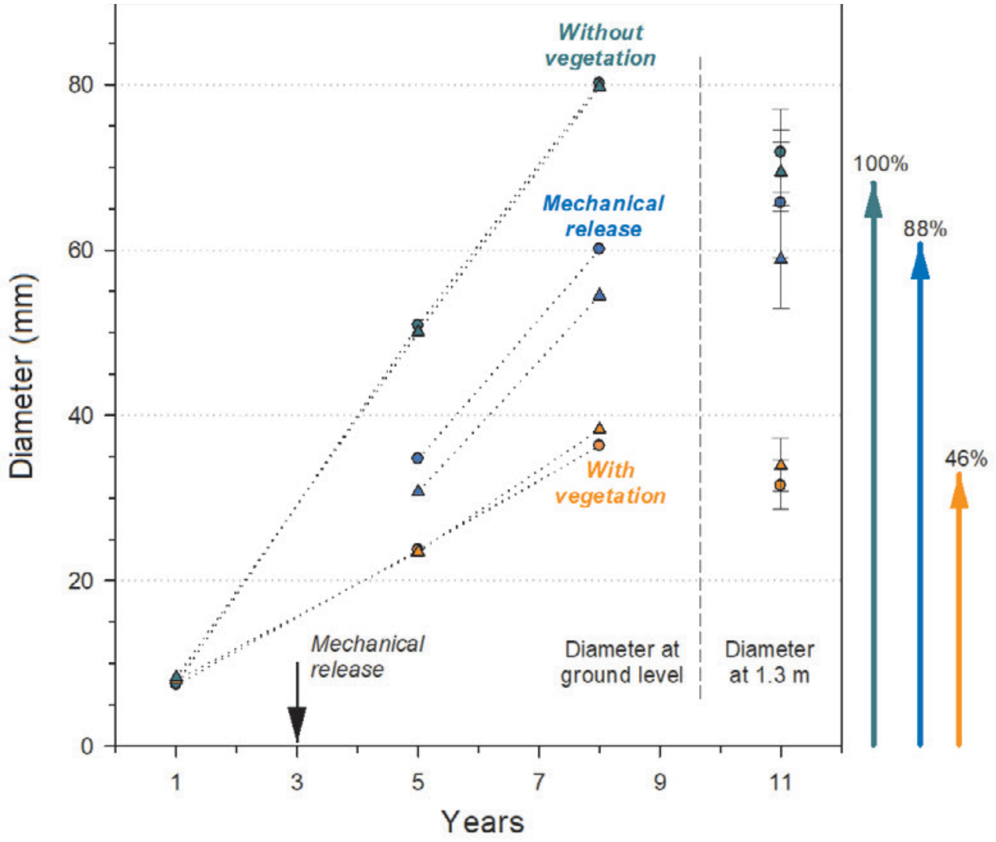


Figure 6. Growth of planted black spruce (*Picea mariana* (Mill.) BSP) seedlings on a site with a high level of plant competition. This experiment compared large seedlings (initial height over 35 cm and initial diameter over 6 mm) that were produced in containers (round symbols) or bare-root (triangular symbols). Seedlings planted the year after logging were subjected to a high competition level in control plots with no vegetation removal treatment (i.e., with vegetation; orange symbols), operational mechanical release with brush saws in year 3 (blue symbols), or an environment with complete vegetation removal (i.e., without vegetation; green symbols). Assuming that the latter experimental treatment reflects the seedlings' full potential, with no competitive growth constraints, mechanical release provides nearly 90% of this productivity. Adapted from Thiffault et al. (2014b).

However, mechanical release involves certain risks, including the accidental cutting of desirable seedlings and exposing forest workers to heavy physical loads that may impact their health (Borz et al. 2019; Sorică et al. 2018; Toupin et al. 2007). Furthermore, competing species are highly efficient in vegetative reproduction (stump sprouting, suckering, or both); mechanical release does not kill the individual plants and the vegetation cover quickly re-forms after stem cutting (Pitt et al. 2000; Pitt et al. 2004). While this may potentially have benefits for biodiversity (Hartley 2002), the rapid vegetative regeneration of cut species may require a second release, with associated high costs.

Research on mechanical release has made it possible to specify the best conditions for its implementation. For example, releasing when the competing species have fully leafed-out (generally July and August) leads to the best growth results for the desired species (Jobidon and Charette 1997). Cutting height also has a significant effect on the effectiveness of mechanical release with brush saws (Bell et al. 1999; Jobidon 1997). Furthermore, the optimal time to perform release with regard to the number of years since harvesting depends on the species to be controlled and the bioclimatic context (Thiffault et al. 2014a); there is no single recipe.

Recent studies show that mechanical release should be combined with other treatments as part of an integrated vegetation management strategy (Fig. 7) for effectiveness in highly competitive situations (e.g., as shown in Fig. 6). In particular, mechanical release should be combined with a thorough appraisal of the need for mechanical soil preparation to ensure that its intensity is sufficient but does not exceed what is necessary for seedling establishment (Buitrago et al. 2015; Thiffault et al. 2003; Thiffault et al. 2017). Early planting of seedlings, in the spring following the final cut, offers conditions that favour seedling establishment and growth, before competing vegetation invades the cut block. It is essential to use plants with initial dimensions that stimulate photosynthetic capacity, growth and improved access to environmental resources, particularly light (Jobidon et al. 1998; Jobidon et al. 2003). The competitive status of planted seedlings should be monitored and seedlings should be released immediately when competition is detected. Several approaches have developed over the years to identify appropriate times for release treatments (e.g., Jobidon 1992; Jobidon 1994; Towill and Archibald 1991; Wagner and Robinson 2006). As a general principle, decision-making criteria should consider the autecology of the target species, accompanying species, relative size or cover, and production objectives.

Failure to integrate these steps can result in plantation failure. An excessively long interval between harvesting and planting, the wrong planting material, inadequate monitoring, or a combination of these errors may compromise production objectives (Office of the Chief Forester 2015; Thiffault and Roy 2011).

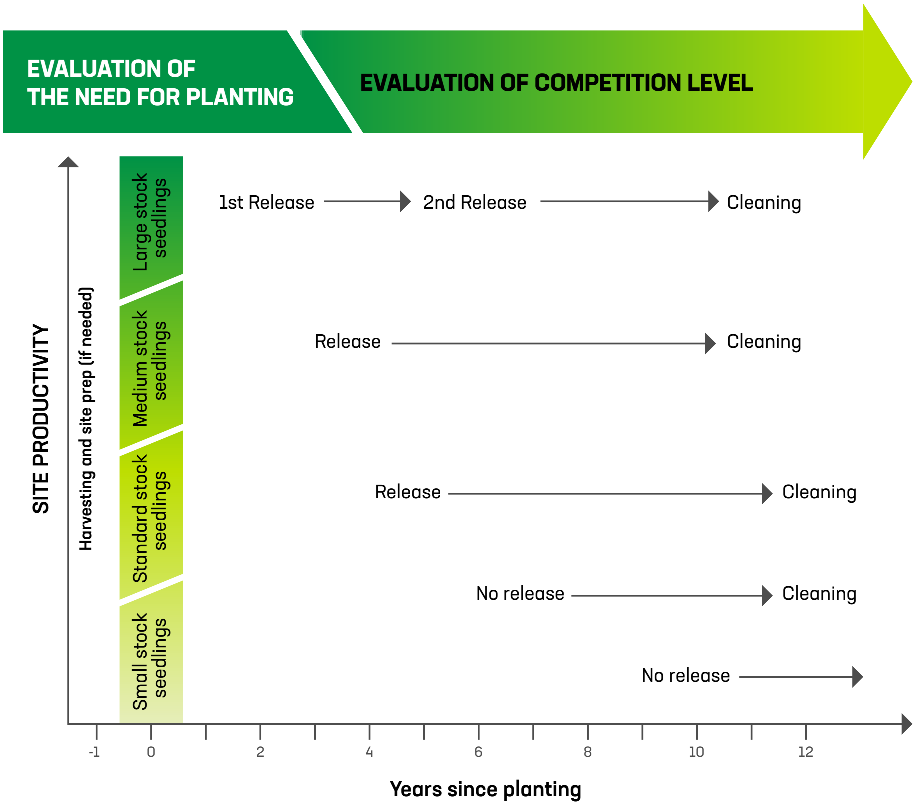


Figure 7 . Conceptual representation of a forest vegetation management strategy in plantations based on forest site productivity (fertility), which influences competition from companion species. The richest and most potentially productive sites need large seedlings, which have more capacity for using environmental resources. The need for release occurs earlier on the most fertile sites and several treatments may be considered in these conditions. In all cases, early planting of seedlings (the year after cutting) provides favourable conditions for establishment and growth, before site invasion by companion species. Reproduced from Thiffault (2010); adapted from Thiffault and Roy (2011).

In summary, the choice of vegetation management methods depends on a number of issues (Deighton et al. 2021) to be identified and discussed (Fig. 1). These can include forest productivity, wildlife habitat and water quality, or the cost-effectiveness of silvicultural treatments and management (Fig. 8). Hence, there is no "one size fits all" solution. Vegetation management treatments are not inherently good or bad; it depends on the objectives and the context (Box 1).

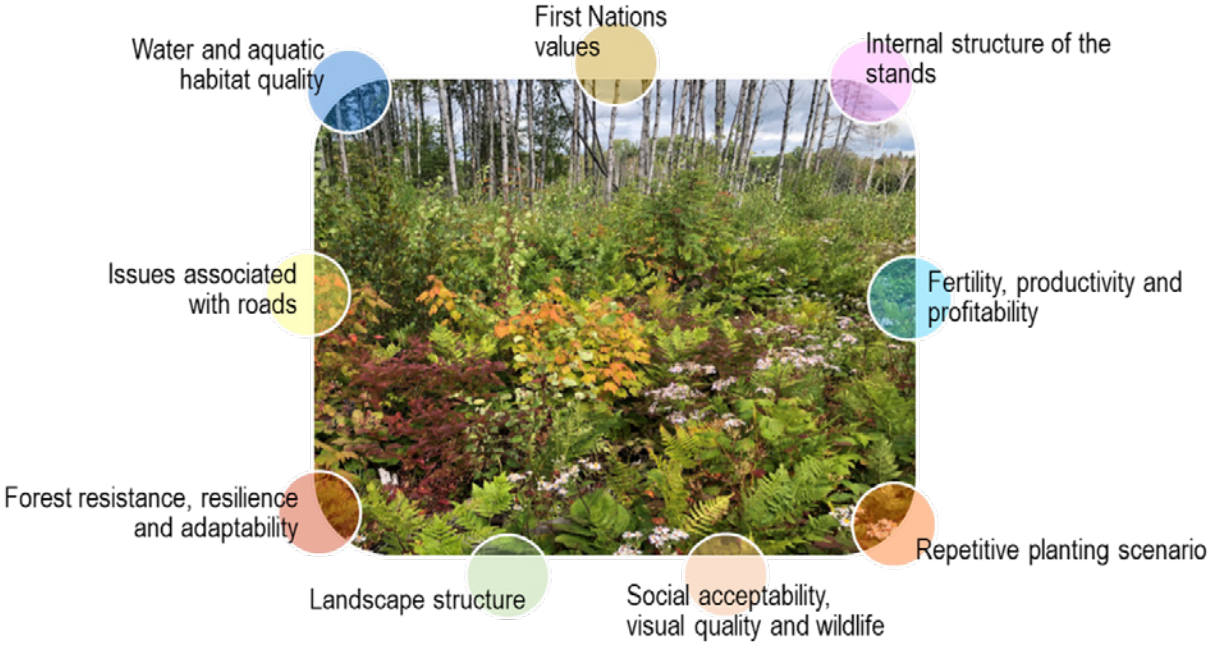


Figure 8. Examples of issues related to vegetation management within a context aimed at maintaining different ecosystem functions and guided by sustainable resource management. Adapted from Barrette et al. (2014).

Box 1. The Saw Analogy

Vegetation management treatments are neither good nor bad on their own. To illustrate, we will draw an analogy: comparing the silviculturist's choice of vegetation management treatments with choices that carpenters make for cutting a piece of wood. Just like a silviculturist, a carpenter has several available tools on the workbench, all with their own pros and cons. For example, a table saw (1) is powerful and fast, and can cut pieces of wood lengthwise. But it's dangerous, noisy and should only be used in controlled environments (workshop). The mitre circular saw (2) can cut precisely at several angle combinations, but is limited in the size of the pieces it can cut. The reciprocating saw (3) is highly versatile and can cut hard-to-reach areas, but has limited control over alignment and cuts can veer from the top to the bottom of the pieces. Finally, the jigsaw (4), with its narrow, small blade, is very handy and can cut rounded shapes or freely chosen patterns, but it is not effective with large pieces.


1. Table saw


2. Mitre circular saw


3. Reciprocating saw


4. Jigsaw

There is no inherent good or bad in any type of saw; the purpose and context of its use determines which is most suitable. Choosing the right saw for the job depends on the objective, e.g., cutting a plank, cutting a board lengthwise, shortening the leg of a piece of furniture, or widening an opening in a wall, and on the context, e.g., a safe and controlled area like a workshop, or an occupied room in a home where other family members are present. Each tool has its own inherent hazards; in all cases, the carpenter must comply with safety rules to reduce exposure and minimize risk. The risks associated with vegetation management treatment, mechanical or chemical, are contingent on its intrinsic danger and the exposure of people, plants, animals or other ecosystem components to its use. While intrinsic danger is an inherent characteristic of methods or tools, the risk can be reduced by controlling exposure.

Intrinsic hazard
Property or capacity of a substance, equipment, work method, etc. that may harm people, animals, or ecosystems.

X

Exposure
The amount and the frequency with which a hazard reaches people, animals, or ecosystems.

=

Risk
The result of exposure to a hazard. For equipment or work methods with a given intrinsic hazard, risks to people, animals, or ecosystems can be reduced by limiting exposure.

On the other hand, there are situations that require a combination of saws to achieve the objective. It is clear that there is no one-size-fits-all solution: no single type of saw is right for every situation. Like the silviculturist, a carpenter relies on a diversified toolbox to do the job.

4. Other issues, opportunities and considerations

The preferences and tolerance limits to the ecological factors of companion species (autecology) are the subject of numerous studies. Bell et al. (2011b) summarize information available for Canada's most important species. Beaudet et al. (2013) drafted comparative charts for a variety of herbaceous, shrub and tree species. However, climate change has the potential to alter the phenology of competing and commercial species (Fridley 2012; Marty et al. 2020). For example, flowering, leafing, fruiting and dormant periods are expected to shift with warming temperatures. This means that we need to review our understanding of competing species and the effects of silvicultural treatments on these species, in order to properly select vegetation management methods and guarantee their success. Because of climate change, the past does not guarantee the future. Silviculture, including vegetation management, will have to adapt to this new reality to maintain resistant or resilient ecosystems, or promote their transition to new compositions for future climates (Achim et al. 2021).

Plant species interact in many ways; competition is just one aspect. Facilitation is another form (Wright et al. 2017), where one species creates favourable conditions for the establishment, survival or growth of another species. Certain species considered as competitors can, under certain conditions, facilitate the growth and survival of targeted species (Thiffault and Hébert 2017; Urli et al. 2020). Our understanding of the mechanisms of facilitation is limited, as well as circumstances where they might override competing interactions. By furthering our understanding of ecological facilitation between species, we can identify opportunities to conserve or even favour companion species while maintaining and enhancing the productivity of commercially valuable species.

Research also shows that plant communities of various species with different above-ground, below-ground architecture and resource requirements use environmental resources more efficiently and boost overall productivity (Justes et al. 2014). This effect is known as "niche complementarity", where the niche is the "position" that a species occupies within the ecosystem. A growing number of research studies point to the positive effects of diversity on forest productivity (Liang et al. 2016; Paquette et al. 2009; Paquette and Messier 2011; Ruiz-Benito et al. 2013; Williams et al. 2017). Drawing on new insights (e.g., Rissanen et al. 2019), vegetation management can be refined to promote species combinations that can maximize ecosystem productivity (Fig. 9).

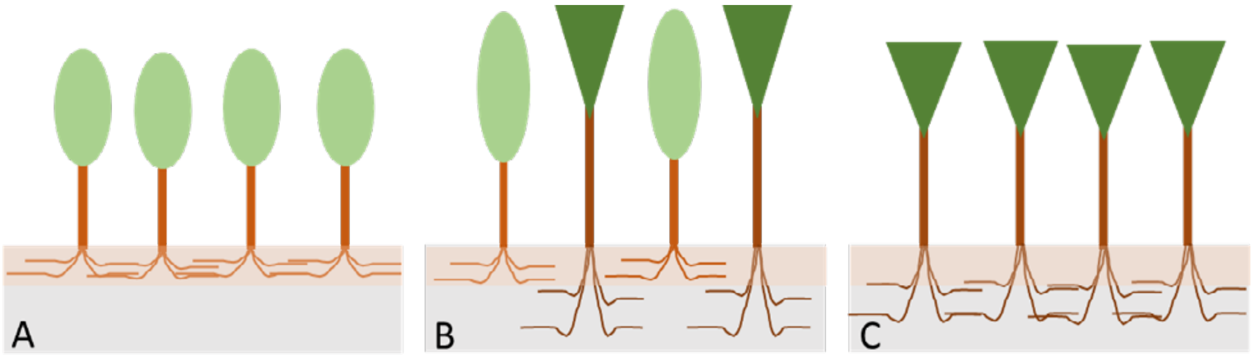


Figure 9. Schematic representation of the niche complementarity effect between two tree species, using different above-ground and below-ground spaces (in B), compared to mono-specific stands of each species, where all individuals use the same resources from the same locations (in A and C). Productivity increases (represented by larger tree size in B compared to A and C) with less competition between different species than between trees of the same species, for more efficient use of ecosystem resources. Adapted from Trogisch et al. (2021).

Global changes, climate change as well as increased trade, can broaden the range of many plant species (Hulme 2009). These species, regarded as exotics, invade ecosystems (Mack et al. 2000) and their presence adversely affects both the biodiversity and functioning of natural ecosystems (Krumm and Vítková 2016; Vilà et al. 2011). Invasive alien species may be more competitive than indigenous species in timber production or restoration contexts (Hamelin et al. 2017; Hamelin et al. 2016; Lanzer et al. 2017). These species, such as glossy buckthorn, pose their own unique challenges (Nagel et al. 2008), especially when chemical herbicides cannot be used (Debar et al. 2018). Further, managing certain indigenous shrub species like *Ribes* spp. that host exotic diseases such as white pine blister rust can also be difficult without chemical use. It is important to continue research in order to determine effective and efficient approaches to this challenge.

Combining 21st century science and technology with traditional Indigenous knowledge is essential for new approaches to vegetation management. These interactions, in line with protocols and with the free, prior and informed consent of Indigenous participants, will create opportunities to expand silvicultural options and fully capitalize on Indigenous and Western knowledge. As a result, the forestry sector gains a reinforced social licence to operate (Moffat et al. 2015), which signals greater commitment to innovation and respect for the rights and values of Indigenous Peoples and communities (Wyatt et al. 2011).

The Herbicide Alternative Program 2.0 (HAP 2.0), which operates in Northeastern Ontario, is a compelling example of this initiative. HAP 2.0 emerged from the original 2011 program (Kayahara and Armstrong 2015), furthering the objective of forest regeneration through alternatives to chemical herbicides. For this purpose, HAP 2.0 promotes collaboration between Indigenous knowledge, ecological and silvicultural research, and advanced technologies. Apart from being a collaborative and co-development platform for innovative practices and decision support tools for vegetation management, HAP 2.0 also co-benefits training and fostering careers in forestry for Indigenous youth, increased community involvement in resource management, and building sustainable and trusting relationships between project collaborators.

5. Conclusion

This report summarizes the role of vegetation management in forest management, an applied science that incorporates principles from several disciplines, including ecology, biology, quantitative analysis, social sciences, economics and political science, to name a few (Larouche et al. 2013). Moreover, silviculture is a scientific discipline in its own right, with evolving paradigms that accommodate new technologies and the realities of climate change (Achim et al. 2021). As such, in this report, descriptions related to these disciplines and the processes involved are intentionally simplified and cannot possibly do justice to their true complexity. Nevertheless, we are hopeful that these descriptions provide an understanding of the relationships between them and their mutual influence.

This report addresses methods that are documented and available for forest vegetation management. We deliberately focused on alternatives to chemical herbicides, as these treatments are generally not as widely recognized as those based on chemical herbicides. The list of treatments described here is by no means conclusive. Alternatives to chemical herbicides, beyond those discussed in this document, have been the subject of studies and reports. For instance, experimental or operational studies have been conducted on: mulches to restrict the establishment and growth of competing vegetation, sowing low vegetation to hinder the germination of other species, grazing by animals, or prescribed burning (Wiensczyk et al. 2011). While these approaches have potential in particular circumstances, they are marginal or require considerable technical planning. There are also organic herbicides that are successful in controlling competing species (e.g., Gosselin et al. 1999; Hamberg et al. 2020). These herbicides use naturally occurring fungi in forest ecosystems to control the stumps of mechanically cut shrubs and limit the number of stump sprouts or suckers. Although conceptually interesting, their actual effectiveness in a forestry context is limited (Laine et al. 2019; Roy et al. 2010; Willoughby et al. 2015). More silvicultural and operational research is needed to improve their performance.

Finally, we identify issues and new opportunities to consider in the evolution of vegetation management. There are significant uncertainties surrounding global change and the challenges of exotic species and diseases. New findings on species interactions open up new opportunities for silvicultural treatments. Integrating traditional Indigenous knowledge with the latest scientific advances will pave the way for a new era in forest vegetation management.

6. Acknowledgements

I thank Ms. Kim Chapman, Mr. Michael Hoepting and Drs. Frank Grenon and Vincent Roy of the Canadian Forest Service (CFS) - Natural Resources Canada (NRCan), as well as Mrs. Isabelle Martineau of the Centre de services scolaires des Premières-Seigneuries, Ms. Laura Thiffault and Ms. Myriam Madore of Université Laval who provided constructive comments on earlier drafts of this report. My thanks also go to Mr. Anthony Bourgoin, for managing the editing process. This report was prepared under the collaborative research project *Fibre production to support the forest sector and the emerging bioeconomy*, within the Canadian Forest Service's *Developing sustainable fibre solutions program*.

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