Are chemical or mechanical treatments more sustainable for forest vegetation management in the context of the TRIAD?

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ABSTRACT

Chemical and mechanical forest vegetation management (FVM) treatments are analyzed and compared to assess which is the most sustainable in intensively managed plantations in the context of the TRIAD. At the biological and ecological level, herbicides have been found to have more impacts on flora and fauna compared to mechanical treatments, but the differences are of short duration. The effects of noise generated by manual or mechanical brushing on wildlife have not been investigated, however. Local application of herbicide at the base of the tree should further lower these impacts. At the social level, the general public has a negative perception of chemical treatments, while mechanical treatments are well-perceived. However, in terms of worker safety, chemical treatments are less risky than manual brushing (brushsaw or chainsaw). At the economic level, herbicides globally cost less and are more effective at increasing fibre production than mechanical operations. We conclude that it is difficult to assess globally what is the most sustainable option to control competing vegetation. However, the careful use of herbicide may be the most sustainable option if the added productivity thus obtained is used to increase protected areas and ecosystem-based management, as is intended with the TRIAD concept.

Key words: forest vegetation management, chemical release, mechanical release, functional zoning, plantations, ecological impacts, social impacts, economical impacts, intensive management, sustainable forestry

RÉSUMÉ

Les traitements chimiques et mécaniques de gestion de la végétation compétitrice sont comparés afin d'évaluer quel traitement est le plus durable pour réaliser le dégagement des plantations à haut rendement dans le contexte de la TRIADE. Au niveau écologique et biologique, les traitements chimiques ont plus d'impacts négatifs sur la faune et la flore que les traitements mécaniques, mais cet impact est de courte durée. Les effets du bruit sur la faune généré par l'utilisation de la débrousailleuse ou de la machinerie lourde ne sont pas documentés. Un dégagement chimique local, à la base de chacun des semis, réduit considérablement les impacts écologiques associés aux phytocides. Au niveau social, la perception à l'égard du dégagement chimique est fort négative, ce qui n'est pas le cas pour les opérations mécaniques. En matière de santé sécurité des travailleurs, l'usage de phytocide est moins risqué que le dégagement mécanique manuel. Pour ce qui est des bénéfices économiques, comparativement au de dégagement mécanique, l'utilisation de phytocides chimiques est moins coûteuse en plus d'augmenter de manière plus importante le capital ligneux. Nous concluons qu'il est difficile de discriminer quel traitement est le plus durable. Néanmoins, l'usage rationnel de phytocide apparaît comme l'option la plus durable dans la mesure où l'augmentation de la production ligneuse pourrait ensuite servir à l'implantation d'un aménagement écosystémique et à la création d'aires protégées, comme le concept de TRIADE le propose.

Mots-clés : gestion de la végétation, dégagement chimique, dégagement mécanique, zonage fonctionnel, plantations, impacts écologiques, impacts sociaux, impacts économiques, aménagement intensif, foresterie durable

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Introduction

As the Canadian forest is being managed more and more intensively for wood production, conflicts of usages are increasing everywhere (Burton *et al.* 2003). Several authors (Dick *et al.* 2002, Krcmar *et al.* 2003, Messier and Bigué 2003, Schneider and Walsh 2005) have recently suggested the use of the TRIAD (Hunter 1990) as a way to resolve some of these conflicts. The TRIAD principle divides the forest landscape into different management areas with appropriate goals and objectives from full protection to super-intensive fibre production. Many regions of Canada have adopted or are in the process of adopting some form of the TRIAD approach to forest management (Harris 1984, Rowe 1992, Hunter and Calhoun 1996, Alberta Government 1997, Montigny and

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MacLean 2006) However, to be effective the TRIAD approach has to allow increased fibre production on a small portion of the landscape, and this often requires the use of some form of forest vegetation management. This is particularly needed early on during the plantation cycle and for fast-growing tree species such as hybrid poplar and larch. In Canada, two main release strategies are used for forest vegetation management (FVM), mechanical treatments using heavy equipment, manual brushsaw or chainsaw, and chemical treatments using synthetic herbicides.

Despite their common use and high efficiency, herbicide use in forestry has raised a great deal of public concern in North America during the past tree decades. With the increasing role of the public and various stakeholder groups in the decision-making process concerning FVM (Wagner *et al.* 1998, Messier and Kneeshaw 1999), there is a need to objectively compare the possible ecological and biological impacts, social views, and economical costs and benefits of using either chemical or mechanical treatments in intensively managed plantations.

This paper addresses the following question: are mechanical treatments globally more sustainable than herbicides for release operations used in the intensively managed zone of a TRIAD-based forest management regime? Firstly, an overview of FVM chemical and mechanical treatments used in Canada is presented in terms of their ecological, economic and social impacts. Secondly, a comparison between these two types of treatments is proposed in order to establish which treatment may be the most sustainable option for intensively managed areas and high-yield plantation (see Table 1). Our analysis focuses on FVM treatments used strictly for release strategies.

Overview of Chemical Treatments

Historical perspective of chemical uses[3]

During World War II, the phototoxic properties of 2,4-dichlorophenoxyacetic acid (2,4-D) were elucidated. The first aerial application for silviculture took place in 1947 in the northeastern United States. After the war, demands for wood increased and new herbicides were needed. 2,4,5-trichlorophenoxyacetic acid (2,4,5-T) was then developed and tested during aerial trials in the experimental pine forest at Massabesic (Maine, U.S.). During this same period, the first social concerns about the ecological and social risks of using herbicides in forestry appeared. This was principally due to increasing evidence that 2,3,7,8-tetrachlorodibenzo-p-dioxin, TCDD, a highly toxic dioxin contained in some phenoxy herbicides, was having a very negative impact on both human and natural ecosystems.

Anticipation of a possible ban on the use of 2,4,5-T led some chemical companies to increase their research efforts to develop other kinds of herbicides that would be less toxic. In 1974–1975 many experiments took place in the state of Maine to compare the effectiveness of three new herbicides, glyphosate, triclopyr and hexazinone, to the more traditional herbicides (e.g., 2,4-D, 2,4-DP, MSMA). The United States government then authorized the use of glyphosate in forestry in 1980, a measure that was followed by Canada four years later. By this time, both countries had banned 2,4,5-T and 2,4,5-TP.

[3]The information in this section was mainly taken from McCormack (2000).

In the late 1980s and during the 1990s, new herbicide compounds were tried (imazypyr, sulfometuron, metsulfuron) to extend the spectrum of plant species controlled (Wagner *et al.* 2004). From 1990 to 2005, public uncertainty about the safety of herbicide use in forest ecosystems continued to grow and lead to numerous legislative measures throughout North America. Vermont banned herbicide uses in forestry in 1997, which was then followed by the province of Quebec in 2001, while Maine placed a 10-year moratorium on their use in 2001. Ironically, none of these measures have been implemented for the use of chemicals in agriculture, where the use of herbicides is much more intensive.

Today, many countries (e.g., Brazil, Czech Republic, Finland, France, Great Britain, Israel, New Zealand, Norway, South Africa, Uruguay) continue to use herbicides to manage vegetation and promote tree growth in forest ecosystems. However, other countries, like Sweden and Switzerland, have completely banned their use in forestry. In Canada, four herbicides are registered (PMRA 2006) but only two (2,4-D and glyphosate) are currently used for FVM (CCFM 2005). In 2003, glyphosate was used on 126 334 ha and 2,4-D on 2859 ha, representing around 98% of the total herbicide use for forestry (CCFM 2005). Quebec is still the only province to totally prohibit the use of herbicide on publicly owned land, but its usage in Canada is decreasing in all provinces (CCFM 2005).

Methods of application and efficiency

Herbicides in forestry are used for afforestation (agriculture or grass land) and for reforestation of forest stands following harvest (Balandier *et al.* 2006). Many studies report the use of herbicides as a means to decrease the competition from one, several or all herbaceous or woody plants (Reynolds 1988; Knowe *et al.* 1990; Campbell 1990, 1991; Biring and Hays-Byl 2000; George and Brennan 2002; Harper *et al.* 2005). For the release treatment, herbicides can be applied in several ways but aerial spraying is considered most effective, and hence is still popular. In order to diminish herbicide drift, other techniques have been developed, but they are generally more expensive than aerial spaying. Thorpe (1996) observed that stem injection gives mixed results with further treatments often being necessary, whereas cut stump injection and backpack spraying are highly effective. However, none of these methods gives the same coverage as aerial spraying.

As with other ground-based herbicide uses, backpack spraying can have less of an environmental impact compared to aerial spraying because of its localized use. Furthermore, recent studies where backpack spraying was used only at the base of crop trees indicated comparable growth gain to a completely treated plot (Coll *et al.* 2005, Richardson *et al.* 2005).

Generally, herbicides show a high degree of efficiency. The vegetation cover is reduced to between 0% and 80% at the end of the first year following treatment, depending on site characteristics and herbicide residual activity (Balandier *et al.* 2006). The year following the treatment, vegetation composition can be partially or completely altered. These changes in composition and relative abundance are difficult to predict because many variables affect vegetation dynamism: ecological site features, phenological plant stage, application technique, and site preparation (Balandier *et al.* 2006). Sometimes, when the competition from the dominant species is too great, chemical control can be necessary over a number

Table 1. Comparisons of some possible ecological, social and economical impacts of using chemical vs. mechanical release treatments in intensively managed tree plantation.

Sustainable development aspects	Chemical treatments	Mechanical treatments
Direct ecological impacts on flora	**Aerial or ground application** The year after the treatment, vegetation composition can partially or completely differ from the original one (Dreyfus 1984, Willoughby and McDonald 1999, Miller *et al.* 2003). More impact on relative species dominance than on species composition or diversity (Boyd *et al.* 1995, Miller *et al.* 1999). Chemical vegetation control of woody plant for several years can decrease species richness over time despite the initial enhancement of herbaceous richness (Miller *et al.* 2003). Species richness and diversity of vascular plants is unaffected or increased, particularly herbaceous species, following glyphosate application (review of 12 studies by Sullivan and Sullivan (2003)) herbicide.	**Brushsaw** Less drastic change in vegetal richness and structure compare to herbicides (Locasio *et al.* 1991, Lautenschlager *et al.* 1998). Species richness, diversity and turnover of the herb, shrub, and tree layers are not significantly affected (Lindgren and Sullivan 2001). Aspen cover reduction of at least 75% for herbicide and brushsaw treatments. Others deciduous tree and tall shrub species were reduced by all treatments but the reduction was least important for brushsaw (Pitt *et al.* 1999). **Heavy equipment** May induce more significant changes in species composition than manual brushing (Balandier *et al.* 2006).
• Impact on fungus	**Ground application (glyphosate)** After a two-year post-treatment study, no differences in fungal fruiting biomass among controls and herbicide-treated plantations (Gagné *et al.* 1999).	**Brushsaw** After a 2 year post-treatment study, no differences in fungal fruiting biomass among controls and brushsaw-cut plantations (Gagné *et al.* 1999).
Indirect ecological impacts on fauna	**Aerial or ground application (mainly glyphosate)** Globally, negative indirect impacts on animals occur in general during the first three years after treatment, mainly because vegetation abundance is lower compared to an untreated site. After this period, indirect impacts can be considered negligible on fauna. (Review of 30 studies by Couture *et al.* (1995), review of 47 studies by Lautenschlager and Sullivan (2002)).	**Brushsaw and heavy equipment** The impacts of manual and mechanical brushing on the vegetation and on the fauna have not been widely studied (Lautenschlager 1993, Wagner 1993, Richardson *et al.* 2002).
• Songbirds	**Aerial or ground application (mainly glyphosate)** Depending on the specie, herbicides can have a positive or a negative impact in the short and mid term (Couture *et al.* 1995, Lautenschlager and Sullivan 2002).	**Brushsaw** Nesting success of open-cup nesting species was higher in the brushsaw-treated areas compared to glyphosate (Easton and Martin 1998). Bird communities were more homogenous after an herbicide treatment while manual brushing had no effect (Easton and Martin 1998).
Indirect ecological impacts on fauna		
• Small mammals	**Aerial or ground application (mainly glyphosate)** Populations diversity and density seems to be unaffected by glyphosate treatments in the short and mid term (Couture *et al.* 1995, Lautenschlager and Sullivan 2002).	**Brushsaw and heavy equipment** Three and four years after the treatment, small mammals populations had recovered from initial changes caused by mechanical and chemical treatments. For the 4 years of the study, population densities of red-backed voles were 13/ha (control), 10/ha (machine and brushsaw) and 6/ha (triclopyr and glyphosate) (Lautenschlager *et al.* 1997, 1998). **Brushsaw** Glyphosate and brushsaw did not affect species composition markedly (Gagné *et al.* 1999). Glyphosate and brushsaw did not affect deer mouse abundance but they reduce Eastern chipmunk abundance (Lautenschlager *et al.* 1995).

Table 1. Comparisons of some possible ecological, social and economical impacts of using chemical vs. mechanical release treatments in intensively managed tree plantation (*continued*).

Sustainable development aspects	Chemical treatments	Mechanical treatments
		Sex ratios, body weights, reproduction, recruitment and survival of deer mouse are similar for all treatments (glyphosate and brushsaw) (Runciman and Sullivan 1996).
• Mid-sized and large mammals	**Aerial or ground application (mainly glyphosate)** Hares are not affected negatively by the treatment. Deer are unaffected or benefited from chemical release treatments. Moose forage biomass and habitat use is reduced for three to seven years. After this period, forage quality is equal or higher compared to an untreated site (Couture *et al.* 1995, Lautenschlager and Sullivan 2002).	**Brushsaw and heavy equipment** Moose winter use of the study area decreased during the first two years following any release treatments (machine, brushsaw, glyphosate and triclopyr) (Lautenschlager *et al.* 1999). **Brushsaw** Conifer release (brushsaw and glyphosate) did not affect habitat use by hare (de Bellefeuille *et al.* 2001).
• Invertebrates	**Aerial or ground application (mainly glyphosate)** Terrestrial invertebrates, insects, arachnids, gastropods and microbial processes seem relatively unaffected by treatments (Lautenschlager and Sullivan 2002).	**Brushsaw and heavy equipment** Carabid (Duchesne *et al.* 1999) and gastropod (Hawkins *et al.* 1997) abundance was not affected negatively by brushsaw cutting, machine cutting or herbicides (glyphosate and triclopyr).
Indirect ecological impacts on fauna		
• Invertebrates		**Brushsaw and heavy equipment** Gastropod's surface activity on machine and brushsaw cut plots may be recovering more quickly compare to herbicide-treated plots (Prezio *et al.* 1999) Homoptera densities were lower in glyphosate treated plots compared to brushsaw and machine-cut, while the Shannon-Weiner diversity index indicated that carabid diversity was lowest after brushsaw- and machine-cut compared to herbicide-treated areas (Ward *et al.* 1998). **Brushsaw** No significant difference in arthropods abundance between a glyphosate treatment and brushsaw cutting (Gagné *et al.* 1999).
• Amphibians	**Aerial or ground application (mainly glyphosate)** No population change in the short term (Bogart *et al.* 1995, Lautenschlager *et al.* 1998). There is uncertainty concerning the impact of glyphosate commercial formulation on amphibians found in forest pounds.	**Brushsaw** No population change for all treatments (brushsaw, machine and herbicides) compared to control (Bogart *et al.* 1995).
Other ecological impacts	**Ground application (mainly glyphosate)** Within a TRIAD application, ground application of glyphosate in intensively managed plantations can help implement ecosystem-based forest management and increased the percentage of protected areas if the productivity gain is used for conservation purposes.	**Manual brushing** Brushsaws and chainsaws are powered with a two-stroke engine, which produces some highly toxic gases (Dost *et al.* 1996). **Brushsaw and heavy equipment** The impact of the noise on fauna and green gas production are not documented, but are likely to be important. **Heavy equipment** Utilisation of heavy equipment such as a tractor can lead to soil compaction and could increase the production of N_2O (Douglas and Crowford 1993).

Table 1. Comparisons of some possible ecological, social and economical impacts of using chemical vs. mechanical release treatments in intensively managed tree plantation *(continued)*.

Sustainable development aspects	Chemical treatments	Mechanical treatments
		The impact of soil compaction on ecosystem productivity is not documented in the case of FVM, but the authors have observed evident signs of heavy compaction on some hybrid poplar sites where heavy equipment was used for many years after initial plantation to control the competing vegetation.
Social acceptability	**Aerial or ground application** 71% of Canadians are opposed to the use of herbicides in forest, mainly because of the possible risks for wildlife and people living near the treated area (Environics Research Group 1989). **Aerial application** In Ontario, 82% of the general public and 77% of timber-dependant communities found aerial herbicide unacceptable (Wagner *et al.* 1998). **Ground application** In Ontario, 63% of the general public and 65% of timber-dependant communities are opposed to ground application (Wagner *et al.* 1998).	**Manual brushing** In Ontario, 90% of acceptability was reached for manual cutting in both general public and timber-dependant communities (Wagner *et al.* 1998). **Heavy equipment** In Ontario, more than 70% of the general public and timber-dependant communities found heavy equipment very acceptable or acceptable (Wagner *et al.* 1998).
Worker health and safety	**Aerial or ground application (glyphosate)** Quebec's Bureau d'Audience Publique en Environnement concluded that risk of intoxication is low for the workers when safety measures are followed (BAPE 1997). In an exposure study performed on 14 conifer seedling nursery workers, Lavy *et al.* (1992), found that none tested positive for glyphosate after 12 consecutive weeks of urine analysis. **Aerial or ground application (2,4-D)** By a large margin of safety, the calculated absorbed doses by the pilot and the tank mixer were well below the "no observed adverse effect" level (Frank *et al.* 1985, Knopp and Glass 1991). Munro *et al.* (1992) concluded that cohort studies of exposed workers do not generally support the specific hypothesis that 2,4-D causes any form of cancer. **Backpack spraying** Frequent injuries caused by falls and sprains (Dost *et al.* 1996).	**Manual brushing** Ergonomic problems due to equipment weight and site features caused frequent injuries (mainly falls, sprains and back injuries) (Dubeau *et al.* 2003). Working with heavy and sharp tools can be hazardous when performing a hard labour (Powell 1998). Workers' exposure to chainsaw or brushsaw exhaust gases presents a very high risk because they contain several known carcinogens, neurotoxic hydrocarbons, carbon monoxide and various respiratory irritants (Dost *et al.* 1996). There is an uncertainty concerning the effects of manual brushing on health because of the high number of exhaust gases and the multiple potential interactions (BAPE 1997). BAPE (1997)'s commission recognized that mechanical release presents higher short-term risks in terms of worker health and safety. **Heavy equipment** Very low risk of injuries.
Job creation	**Aerial spraying** Low job creation for local communities. **Backpack spraying** Good tool to promote regional economic development.	**Manual brushing** Creates more jobs for local communities than aerial spraying. **Heavy equipment** Low job creation for local communities.
Public health and safety	**Aerial or ground application** The risk for population, fishers and hunters is negligible in the short and long term (BAPE 1997).	**Manual brushing and heavy equipment** No known risk for population

Table 1. Comparisons of some possible ecological, social and economical impacts of using chemical vs. mechanical release treatments in intensively managed tree plantation *(continued)*.

Sustainable development aspects	Chemical treatments	Mechanical treatments
Economic aspects	**Aerial or ground application** After reviewing 23 long-term studies from North America, Wagner *et al.* (2004) observed that most of these studies indicated 30–300% increases in wood volume yield for major commercial tree species. Volume yield gains from effective FVM (primarily using herbicides) were 30–450% in Pacific Northwest forests, 10–150% in the southeastern forests and 50–450% in northern forests. Therefore, herbicides successfully increase wood volume for a wide range of site conditions (Wagner *et al.* 2004). Alternative glyphosate formulation to Vision® (Monsanto) exists. Two new generic formulations, recently registered for forestry in Canada (Glyfos-Forza® and Vantage®) are available. Compare to Vision® generic formulations show similar efficiency for white spruce release treatment (Mihajlovich *et al.* 2004).	**Brushsaw** For black spruce, increases in diameter of 25% to 43% after five years (Jobidon *et al.* 1999) and 24% after 10 years (Jobidon and Charette 1997). Compared to aerial spraying, mechanical brushing is a good tool to promote regional economic development because it offers more jobs (BAPE 1997). **Heavy equipment** Inter-row mechanical brushing with heavy equipment (mowing and disking) can be inefficient for reducing competitive pressure (Kennedy 1981, Davies 1987, Coll *et al.* 2005).
Certification	**Ground application** Forest certification organisms like the Forest Stewardship Council (FSC) tolerates certain kind of herbicides uses, but the managers need to demonstrate that this is the best option and only if they are used in an integrated FVM strategy. "If chemicals are used, proper equipment and training shall be provided to minimize health and environmental risks" (FSC 2003).	**Manual brushing and heavy equipment** Mechanical release is well perceived by certification organisms and therefore is considered a good alternative to chemical treatments.
Costs ($ / ha) for one treatment	**Aerial application** 300 (Boateng 1996) 200–250 (Thorpe 1996) **Ground application (backpack spraying)** 510 (Boateng 1996) 450–500 (Thorpe 1996)	**Brushsaw** 530 (Boateng 1996) 750-800 (Thorpe 1996) 598 (D'Anjou 1996) 875 (Jean-Marc St-Amant 2006) **Heavy equipment** No data

of years and even until canopy closure (Willoughby and McDonald 1999). However, in most cases, the critical period for herbicide application is one to three years after tree establishment (Zutter *et al.* 1987, Newton and Preest 1988, Lauer *et al.*1993, Wagner *et al.* 1999, McDonald and Fiddler 2001).

Characteristics of active ingredients

Glyphosate

Glyphosate (N-phosphonomethyglycine) is a competitive inhibitor of the 3-enolpyruvylshikimate-5-phosphate synthase, a plant specific enzyme (Voet and Voet 1998). Many plant metabolic pathways are disturbed by its action, particularly aromatic amino acids (Hartzler 2001). Hence, glyphosate is a non-selective, systemic and post-emergent herbicide (Franz *et al.* 1997). Many studies have demonstrated that because of its particular mode of action, glyphosate is highly toxic to plants and practically non-toxic to animals (Williams *et al.* 2000, Tatum 2004).

At the toxicological level, no evidence exists about glyphosate's potential neurotoxicity, immunotoxicity and endocrinal disrupting activities when it is used in forest ecosystems (SERA 2002). In fact, this herbicide is currently one of the most studied chemicals and toxicological data are also available for glyphosate metabolites (Williams *et al.* 2000). In the environment, glyphosate shows particular characteristics. It is retained in the soil to a high degree and, therefore, leaching is not significant (Kools *et al.* 2005). Degradation by microorganisms is the major process of biodegradation when glyphosate reaches the ground (Kools *et al.* 2005). Glyphosate's half-life is generally less than 60 days and a complete dissipation is observed within 12 to 15 months (Couture *et al.* 1995). Losses from photodecomposition and volatilisation are negligible (Malik *et al.* 1989, Couture *et al.*1995). Although glyphosate is highly biodegradable, studies on agricultural land show that glyphosate's principle metabolite, aminomethyl phosphonic acid (AMPA), is more persistent in soil compared to glyphosate (IFEN 2003).

2,4-D
This herbicide is a systemic auxin-type phenoxyacetic acid (Brian 1964). Its chemical structure results in the modification of the naturally occurring plant hormone, indol-3-acetic acid (IAA) (Ries 1976). While indole auxin hormones are rapidly inactivated, 2,4-D persists for long periods and blocks fluctuations in hormone levels, which are vital for growth and cell differentiation (Van Overbeek 1964). It has a low toxicity and for this reason, the Canadian Pest Management Regulatory Agency (PMRA) and the US Environmental Protection Agency (EPA), after re-evaluation in 2005, continued to register it for weed control on lawn and turf (PMRA 2006).

During the 1970s, 2,4-D safety was questioned because the herbicide formulations sometimes contained dioxins and furans. Some classes of dioxins and furans are linked to potential cancer risks and as a result, in 1983, the USA federal regulatory body required a modification to its chemical composition to eliminate any 2,4-D contaminants (PMRA 2006). A major review of 2,4-D hazard to human health sponsored by the Harvard School of Public Health came to the following conclusion: "In assessing all of the evidence on 2,4-D, workshop participants were not convinced that a cause-effect relationship between exposure to 2,4-D and human cancer exists" (Graham 1990). In a more recent study that reviewed the epidemiology and toxicology of 2,4-D, Garabrant and Philbert (2002) found no evidence of cancer risks, neurological diseases, reproductive risks or immunotoxicity following a normal exposure scenario.

In the natural environment, this compound is rapidly decomposed. However, in some particular environment, biodegradation can be slow. An experiment conducted by Voos and Groffman (1997) showed that 2,4-D was not detectable in the soil 20 days after its application in a cornfield, a hardwood forest or a home lawn, but still present 80 days after application in the freshwater-forested wetland ecosystems. Furthermore, 2,4-D, and its major metabolite 2,4-dichlorophenol (DCP), presents a low to negligible leaching potential (Fava *et al.* 2005).

These facts concerning the environmental fate of glyphosate and 2,4-D can lead to various interpretations. Studies are generally undertaken in a particular ecosystem within particular soil conditions and precipitation regimes, so generalities concerning the fate of herbicides cannot be easily made unless multiple ecosystems are assessed for a long period of time. Thus, it is important to implement monitoring programs in a variety of ecosystems and always try to minimize its use in natural systems.

Ecological impacts
The main impact following any herbicide application is the partial suppression of vegetation cover. During the post-treatment years, vegetation composition can partially or totally differ from the original (Dreyfus 1984, Willoughby and McDonald 1999). This phenomenon is normally very favourable for tree seedling growth, but in certain cases the new vegetation composition enhanced competition (Horseley 1988, Groninger *et al.* 2004). However, in most situations herbicide application has a greater impact on relative species dominance than on species composition or diversity (Boyd *et al.* 1995, Miller *et al.* 1999, Sullivan and Sullivan 2003). In other words, community structure is the main parameter affected by a chemical treatment. Sometimes, species richness and diversity of vascular plants can be increased, particularly herbaceous species, after a glyphosate treatment (Sullivan and Sullivan 2003). On the other hand, chemical control of woody plant for several years can decrease species richness over time despite the initial enhancement of herbaceous diversity (Miller *et al.* (2003).However, repeated treatment has less influence on herbaceous species richness than woody plants (Balandier *et al.* 2006).

The strong reduction in vegetation cover and, in some cases, changes in species composition can affect the fauna that rely on these plant communities to live. Two studies reviewed the indirect and direct effects of glyphosate and other herbicides on biotic components such as vascular plants, invertebrates, amphibians, songbirds, small mammals and large mammals. Couture *et al.* (1995) concluded, in the context of Quebec forestry, that glyphosate represents no significant long-term risk for the fauna. In the same manner, Lautenschlager and Sullivan (2002) concluded that herbicides are safe tools to use when reintroducing conifers to previously conifer-dominated ecosystems because they have no direct effect on animal health (growth, survival or reproduction). However, in the review by Lautenschlager and Sullivan (2002), out of the 36 studies concerning the indirect impacts of herbicides on animals, none evaluate 2,4D.

Although several authors have classified glyphosate as a safe tool for FVM strategies, there are still concerns about the impact of some glyphosate commercial formulations such as Roundup® on amphibians. Relyea *et al.* (2005) pointed out that amphibian mortality can be quite high following exposure to Roundup® at the manufacturer's recommended maximum application rate. Inversely, another study that evaluated the impact of herbicides (glyphosate and triclopyr) in combination with other natural stressors (pH, food de-privation), but with a different set of amphibians, concluded that "laboratory-based studies tended to over-estimate risks in comparison to field studies where a variety of factors substantially reduced the probability, magnitude and duration of exposures and thereby strongly mitigated against risk to native amphibian larvae" (Thompson *et al.* 2005).

Globally, the negative indirect impacts on the fauna occur during the first three post-treatment years, mainly because vegetation abundance is lower compared to an untreated site. After this period, there is a negligible indirect impact on the fauna. It is important to note that all studies reported in the two previous reviews used herbicides (aerial or ground spraying) on the total surface of the regenerating plot. Therefore, any indirect impact on the fauna or direct impact on the vegetation is likely to be greatly decreased if the herbicide is used only at the base of each crop tree.

Finally, for more than 20 years, scientists have worked on optimizing the use of glyphosate in forestry in order to reduce its impact on the environment (Thompson and Pitt 2003). For example, there is now a streamside management zone where herbicide is not applied (Michael and Hermy 2002).

Based on this review, we conclude that from an ecological point of view, the localized use of herbicides for a few years following plantation is a defensible tool for FVM operation in intensively managed plantations.

Social aspects

Several authors and many public audience reports have concluded that there are a number of concerns about the use of herbicides in forestry across North America (BAPE 1991, 1997; Wagner 1994; Wagner *et al.* 1998; Richardson and Thistle 2005). A national survey reported that 71% of Canadians are opposed to the use of herbicides in forestry, mainly because of the possible risks to wildlife and people living near the treated areas (Environics Research Group 1989). More recently, Wagner *et al.* (1998) examined public perception of risk and acceptability for nine FVM alternatives in Ontario. Their conclusions concerning chemical treatments were as follows:

- The general public perceived aerial herbicide spraying as the most risky treatment mainly because it is hard to control, is potentially catastrophic, will be a problem for future generations, and can cause health problems.
- The next most risky treatments were ground herbicide and biological controls.
- Globally, 82% of the general public and 77% of timber-dependant communities found aerial herbicide unacceptable, while 63% and 65% were opposed to ground application.

In terms of worker safety, most studies found glyphosate to be a relatively safe tool for human health. Following the analyses of the "Centre de Toxicologie du Québec," the commission of the Bureau d'Audience Publique en Environnement (BAPE 1997) in Quebec concluded that risk of poisoning is low for the workers when safety measures are followed. Furthermore, the risks for local populations, fishermen and hunters in the short and long term are negligible (BAPE 1997). In an exposure study performed on 14 conifer seedling nursery workers, Lavy *et al.* (1992) found that none tested positive for glyphosate after 12 consecutive weeks of urine analyses.

For 2,4-D, Knopp and Glass (1991) found detectable concentrations of 2,4-D in forestry worker's urine after four to six days. The higher concentrations were 0.365 ppm for the mixer-loader and 0.052 ppm for the pilot the day after aerial spraying, but absorbed doses were well below the margin of safety at a level where no adverse effect is observed (Knopp and Glass 1991). Frank *et al.* (1985) arrived at the same conclusion concerning 2,4-D toxicity for forestry workers (pilot and mixer-loader). Furthermore, in a review of epidemiological studies, Munro *et al.* (1992) concluded that cohort studies of exposed workers do not generally support the specific hypothesis that 2,4-D causes any form of cancer. In short, there is a very negative public perception regarding herbicide use, but studies on workers exposure concluded that their proper use does not expose workers to long-term health risks. Nevertheless, frequent minor injuries are associated with chemical brushing (Dost *et al.* 1996).

Economic aspects

Herbicides are principally used to increase wood volume yield. After reviewing 23 long-term studies from North America, Wagner *et al.* (2004) observed that most of these studies indicated 30–300% increases in wood volume yield for major commercial tree species. Volume yield gains from effective FVM (primarily using herbicides) were 30–450% in the Pacific Northwest forests, 10–150% in the southeastern forests and 50–450% in northern forests. Therefore, herbicides successfully increased wood volume for a wide range of site conditions (Wagner *et al.* 2004). Moreover, herbicides are the least expensive treatment available when compared to other alternatives. Aerial spraying is by far the cheaper option, but backpack spraying offers more precision and less environmental risks.

In the certification context, organisations like the Forest Stewardship Council (FSC) tolerate herbicides. However, FSC has a clear policy to restrict the use of chemical pesticides, which includes herbicides: "Management systems shall promote the development and adoption of environmentally friendly non-chemical methods of pest management and strive to avoid the use of chemical pesticides. World Health Organization Type 1A and 1B and chlorinated hydrocarbon pesticides; pesticides that are persistent, toxic or whose derivatives remain biologically active and accumulate in the food chain beyond their intended use; as well as any pesticides banned by international agreement, shall be prohibited" (FSC 2003).

In order to reduce herbicide use costs, alternative glyphosate formulations to Vision® (Monsanto) exist. Two new generic formulations, recently registered for forestry in Canada (Glyfos-Forza® and Vantage®) are now available. Compared to Vision®, generic formulations have shown similar efficiency for white spruce release treatment (Mihajlovich *et al.* 2004).

After reviewing 40 studies that compared most of the vegetation management techniques used for enhancing growth of conifer seedlings, McDonald and Fiddler (1993) concluded: "In most instances, forests cannot be managed economically without herbicides if the goal is to grow seedlings at the potential of the site and the plant community includes sprouting hardwoods and shrubs or rhizomatous forbs and ferns."

Overview of Mechanical Treatments

Chemical treatments have proven their efficiency but the social controversies around their use in forests has forced managers to develop other alternatives such has mechanical treatments for release operations. Manual brushing (chainsaw or brushsaw) and mechanical brushing (heavy equipment) are the principle types of treatments used in natural regeneration and plantation release. The province of Quebec, after banning herbicide use in public forests in 2001, mainly uses heavy equipment in high-yield plantation (hybrid poplar) and manual brushing in coniferous plantations. In British Columbia, herbicides are being slowly replaced by manual brushing and sheep grazing (CCFM 2005). Ontario, Alberta and New Brunswick used manual release under certain circumstances, but chemical treatment remains the most popular option for release (CCFM 2005).

Types of treatments and efficiency

Generally, mechanical treatments are an effective way to control woody competitors, like tall shrubs and many species of understorey trees (Balandier *et al.* 2006). They can be used when the goal is to reduce hardwood competition for light while maintaining the beneficial effects of remnant vegetation (Collet *et al.* 1998).

More precisely, manual brushing has proven its efficiency for black spruce growth, with increases in diameter of 25% to

43% after five years (Jobidon *et al.* 1999) and 24% after 10 years (Jobidon and Charette 1997). Usually, when there is competition for light, manual brushing is effective for conifer seedlings release (Thiffault *et al.* 2003). However, it may be necessary to repeat treatments on an annual or more frequent basis (Biring *et al.* 2003).

When competition is mainly for soil resources (from herbaceous vegetation, for example), inter-row mechanical brushing with heavy equipment (mowing and disking) can be inefficient in reducing competitive pressure (Kennedy 1981, Davies 1987, Coll *et al.* 2005). In order to avoid seedlings damage, the tractor must leave an untreated zone at the base of the trees. Many studies have pointed out that this remaining vegetation around the tree is the main source of competitive pressure during the first stage of tree development (Frochot *et al.* 1986, Thomas *et al.* 2001, Coll *et al.* 2005). Furthermore, this technique may, in some cases, enhance the presence of some herbaceous species, like grass, thus increasing vegetation competition (Boulet-Gercourt 1999, Willoughby and McDonald 1999).

In most cases, these treatments remove above-ground parts of hardwood trees and shrubs but the reduction in competition pressure is ephemeral unless root dislodging is achieved (McDonald and Fiddler 1993). Consequently, mechanical treatments have a variable efficiency depending on competing vegetation characteristics (Provendier and Balandier 2004).

Ecological impacts

The impacts of manual and mechanical brushing on the flora and fauna have not been widely studied (Lautenschlager 1993, Wagner 1993, Richardson *et al.* 2002). However, most studies report that mechanical treatments are safe tools with little environmental impacts (Michael and Hermy 2002).

Generally, moderate mechanical treatments such has manual brushing cause less drastic changes in vegetal composition and structure than the more intensive methods such has herbicides (Locasio *et al.* 1991, Lautenschlager *et al.* 1998). However, mechanical mowing may induce more significant changes in species composition than manual brushing (Balandier *et al.* 2006). Gagné *et al.* (1999), in a two-year post-treatment study, found no differences in fungal fruiting biomass among controls, herbicide-treated or brushsaw-cut plantations. However, by the second year, deciduous cover and raspberry cover were much more reduced in herbicide-treated plots compared to manual brushing (Gagné *et al.* 1999). Lindgren and Sullivan (2001) found that species composition, diversity and turnover of the herb, shrub, and tree layers were not significantly different between brushsaw treatment and the control. Pitt *et al.* (2000) observed an aspen cover reduction of at least 75% for herbicide and brushsaw treatments. Other deciduous trees and tall shrub species were reduced by all treatments, but the reduction was the least for the brushsaw treatment (Pitt *et al.* 2000).

In terms of the indirect impacts on the fauna, certain authors compared herbicides to mechanical treatments. In the case of invertebrates, carabids (Duchesne *et al.* 1999) and gastropods (Hawkins *et al.* 1997), abundances were not affected negatively by brushsaw cutting, machine cutting or herbicides (glyphosate and triclopyr). However, gastropod surface activity recovered more quickly on machine and brushsaw-cut plots than on herbicide-treated plots (Prezio *et al.* 1999). Gagné *et al.* (1999) observed no significant difference in arthropod abundance between a glyphosate treatment and brushsaw cutting. Homoptera densities were lower in glyphosate-treated plots compared to brushsaw- and machine-cut plots while the Shannon-Weiner diversity index indicated that carabid diversity was lowest after brushsaw- and machine-cut compared to herbicide-treated areas (Ward *et al.* 1998).

The indirect impacts on amphibian were assessed by Bogart *et al.* (1995). Although only spring peepers and wood frogs were common in the study blocks, there were no population changes for all the treatments (brushsaw, machine and herbicides) compared to the control. However, for songbird populations, nesting success of open-cup nesting species was higher in the brushsaw-treated areas compared to glyphosate and birds communities were more homogeneous after a herbicide treatment, while no negative effect were reported after a manual brushing (Easton and Martin 1998).

In the case of small mammals, mechanical treatments have been found to have very variable impacts. However, those impacts are generally less important than the ones observed following chemical treatments. Gagné *et al.* (1999) observed that any treatment (glyphosate and brushsaw) affects species composition markedly, while Lautenschlager *et al.* (1995) reported that while none of these treatments affected deer mouse abundance, they all reduced Eastern chipmunk abundance. Lautenschlager *et al.* (1997, 1998) observed that small mammal populations had recovered after three to four years from initial changes caused by mechanical and chemical treatments. During the four years of the study, population densities of red-backed voles were 13/ha (control), 10/ha (machine and brushsaw) and 6/ha (triclopyr and glyphosate). Runciman and Sullivan (1996) concluded that sex ratios, body weights, reproduction, recruitment and survival of deer mouse were similar for all treatments (glyphosate and brushsaw). For larger mammals, de Bellefeuille *et al.* (2001) observed that conifer release (brushsaw and glyphosate) did not affect habitat use by hare, while Lautenschlager *et al.* (1999) found out that moose winter use of the study area decreased during the first two years following any release treatments (machine, brushsaw, glyphosate and triclopyr).

Some other indirect impacts can be attributed to mechanical release. Most mechanical treatments can release substantial quantities of CO_2 and other toxic compounds, but these have never been evaluated in terms of environmental impact (Michael and Hermy 2002). For example, brushsaws and chainsaws are powered by a two-stroke engine, which produces various toxic gases (Dost *et al.* 1996). Additionally, the potential impacts of the noise made from these small engines and from heavy equipment on fauna are not documented. Finally, the use of heavy equipment such as a tractor to control vegetation can lead to soil compaction and increased production of N_2O (Douglas and Crowford 1993), a greenhouse gas that has an impact on the global changes 310 times grater than CO_2 (Pérez-Ramírez *et al.* 2003). It is also possible that soil compaction leads to a loss in ecosystem productivity but this impact has not been documented as well.

Social aspects

As Wagner *et al.* (1998) pointed out in his study in Ontario concerning public perception of risk and acceptability of FVM options, mechanical treatments are positively perceived by the general public and by timber-dependant communities. More than 70% of the general public and timber-dependant communities found heavy equipment very acceptable or acceptable while 90% found manual brushing acceptable (Wagner *et al.* 1998). Furthermore, compared to aerial spraying or heavy equipment, mechanical brushing is a good tool to promote regional economic development because it creates more jobs (BAPE 1997), although those jobs are often low-paying. However, it is not clear that manual brushing needs a larger labour force than hand-applied chemicals.

In terms of the impacts on human health, mechanical treatments may not be as harmless as people think. The number of accidents (cuts, bruises, muscle strain, insect stings, poisonous plant and snake injuries, etc.) is high in the forest and workers report that they often experience pain related to their work due to ergonomic problems (Dubeau *et al.* 2003). There is also a significant risk of long-term injuries associated with manual brushing. Manual methods can also pose hazards because workers are dealing with heavy and sharp tools like brushsaws and chainsaws, while performing hard labour (Powell 1998). Moreover, because workers are often paid for the number of hectares treated, they strive for the highest productivity possible, which can be partly responsible for accidents and injuries (Dubeau *et al.* 2003). In addition, when physical characteristics of the site are challenging, a higher physical effort is often required to fill the productivity gap. Accident risks also rise because workers do not always take adequate rest periods, thus reducing their concentration capacities (Roberts 2000).

Additionally, workers' exposure to chainsaw or brushsaw exhaust gases presents a very high health risk because they contain several known carcinogens, neurotoxic hydrocarbons, carbon monoxide and various respiratory irritants (Dost *et al.* 1996). The BAPE (1997) commission did recognize the health risk caused by manual brushing, but it was not able to quantify it.

Although herbicide application seems to be globally safer for field workers, there are certain risks associated with backpack spraying operations as well. Compared to a brushsaw, the equipment for chemical brushing is lighter and more ergonomic, but there are numerous injuries associated with falls and sprains (Dost *et al.* 1996). Moreover, in both jobs — chemical and manual brushing — workers push themselves to their limit because earnings are based on the number of hectares treated.

Economic aspects

Mechanical release is well perceived by certification organizations and therefore is considered a good alternative to chemical treatments. However, many studies (McDonald and Fiddler 1993, Boateng 1996, Thorpe 1996, Wagner *et al.* 2004, Coll *et al.* 2005) report that mechanical treatments are not as efficient as herbicides both in terms of cost and increased yield.

Discussion/Conclusion

The main question addressed in this study was: are mechanical treatments globally more sustainable than herbicides for normal release operations used in the intensively managed zone of a TRIAD-based forest management regime? As this review indicates, the answer is not as obvious as we could have previously thought, especially in the context of a TRIAD approach. Each treatment type has many ecological, biological, social and economical impacts and it is hard to clearly say which one is most sustainable.

From a strictly ecological and biological point of view, at the stand level, this review indicates that chemical treatments generally have a greater short-term negative impact on the local fauna and flora. However, if the chemical treatment is done only at the base of the tree, the conclusion might be different. Clearly, however, aerial spraying is the treatment with the most potential ecological and biological impacts and therefore should be used with great caution. Finally, the direct impacts of the noise made from manual or mechanical brushing should be further investigated.

However, when we include the potential negative health effects of brushsaw and chainsaw exhaust on field worker health, the emission of greenhouse gases and the potential landscape-level gain in protected areas and ecosystem-based management of further increasing growth and yield using herbicide on a small portion of the land as part of the TRIAD approach, then herbicide, especially the less toxic glyphosate, may be the most sustainable solution.

This review does not promote the indiscriminate use of herbicide in forestry. Instead, it provides a global and balance evaluation of the global advantages and disadvantages of using chemical versus mechanical treatments to increase the growth and yield of tree plantations. Our conclusion is that herbicide could provide the most sustainable solution if the economic and growth gain is used to increase protected areas and ecosystem-based management

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