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

by Julien Fortier and Christian Messier

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

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...
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. Second, 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

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.

In the late 1980s and during the 1990s, new herbicide compounds were tried (imazapyr, sulfometuron, metzulfuron) 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 spraying. 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.

<table>
<thead>
<tr>
<th>Sustainable development aspects</th>
<th>Chemical treatments</th>
<th>Mechanical treatments</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Direct ecological impacts on flora</strong></td>
<td>Aerial or ground application</td>
<td>Brushsaw</td>
</tr>
<tr>
<td>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).</td>
<td>Less drastic change in vegetal richness and structure compared to herbicides (Locasio et al. 1991, Lautenschlager et al. 1998).</td>
<td></td>
</tr>
<tr>
<td>More impact on relative species dominance than on species composition or diversity (Boyd et al. 1995, Miller et al. 1999).</td>
<td>Species richness, diversity and turnover of the herb, shrub, and tree layers are not significantly affected (Lindgren and Sullivan 2001).</td>
<td></td>
</tr>
<tr>
<td>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).</td>
<td>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).</td>
<td></td>
</tr>
<tr>
<td>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.</td>
<td>Heavy equipment</td>
<td></td>
</tr>
<tr>
<td>Ground application (glyphosate)</td>
<td>May induce more significant changes in species composition than manual brushing (Balandier et al. 2006).</td>
<td></td>
</tr>
<tr>
<td>After a two-year post-treatment study, no differences in fungal fruiting biomass among controls and herbicide-treated plantations (Gagné et al. 1999).</td>
<td>Brushsaw</td>
<td></td>
</tr>
<tr>
<td>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)).</td>
<td>Brushsaw and heavy equipment</td>
<td></td>
</tr>
<tr>
<td>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).</td>
<td>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).</td>
<td></td>
</tr>
<tr>
<td>* Songbirds</td>
<td>Aerial or ground application (mainly glyphosate)</td>
<td>Brushsaw</td>
</tr>
<tr>
<td>Brushsaw and heavy equipment</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Nesting success of open-cup nesting species was higher in the brushsaw-treated areas compared to glyphosate (Easton and Martin 1998).</td>
<td>Bird communities were more homogenous after an herbicide treatment while manual brushing had no effect (Easton and Martin 1998).</td>
<td></td>
</tr>
<tr>
<td>* Small mammals</td>
<td>Aerial or ground application (mainly glyphosate)</td>
<td>Brushsaw</td>
</tr>
<tr>
<td>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).</td>
<td>Glyphosate and brushsaw did not affect deer mouse abundance but they reduce Eastern chipmunk abundance (Lautenschlager et al. 1995).</td>
<td></td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Impact on fungus</th>
<th>Ground application (glyphosate)</th>
<th>Brushsaw</th>
</tr>
</thead>
<tbody>
<tr>
<td>After a 2 year post-treatment study, no differences in fungal fruiting biomass among controls and brushsaw-cut plantations (Gagné et al. 1999).</td>
<td>Heavy equipment</td>
<td></td>
</tr>
<tr>
<td>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.</td>
<td>May induce more significant changes in species composition than manual brushing (Balandier et al. 2006).</td>
<td></td>
</tr>
</tbody>
</table>
Table 1. Comparisons of some possible ecological, social and economical impacts of using chemical vs. mechanical release treatments in intensively managed tree plantation (continued).

<table>
<thead>
<tr>
<th>Sustainable development aspects</th>
<th>Chemical treatments</th>
<th>Mechanical treatments</th>
</tr>
</thead>
<tbody>
<tr>
<td>Sex ratios, body weights, reproduction, recruitment and survival of deer mouse are similar for all treatments (glyphosate and brushsaw) (Runciman and Sullivan 1996).</td>
<td>Brushsaw and heavy equipment</td>
<td>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).</td>
</tr>
<tr>
<td>Brushsaw</td>
<td>Conifer release (brushsaw and glyphosate) did not affect habitat use by hare (de Bellefeuille et al. 2001).</td>
<td></td>
</tr>
<tr>
<td>Mid-sized and large mammals</td>
<td>Aerial or ground application (mainly glyphosate)</td>
<td>Brushsaw and heavy equipment</td>
</tr>
<tr>
<td>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).</td>
<td>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).</td>
<td></td>
</tr>
<tr>
<td>• Invertebrates</td>
<td>Aerial or ground application (mainly glyphosate)</td>
<td></td>
</tr>
<tr>
<td>Terrestrial invertebrates, insects, arachnids, gastropods and microbial processes seem relatively unaffected by treatments (Lautenschlager and Sullivan 2002).</td>
<td>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).</td>
<td></td>
</tr>
<tr>
<td>• Amphibians</td>
<td>Aerial or ground application (mainly glyphosate)</td>
<td>Brushsaw</td>
</tr>
<tr>
<td>No population change in the short term (Bogart et al. 1995, Lautenschlager et al. 1998).</td>
<td>No population change for all treatments (brushsaw, machine and herbicides) compared to control (Bogart et al. 1995).</td>
<td></td>
</tr>
<tr>
<td>There is uncertainty concerning the impact of glyphosate commercial formulation on amphibians found in forest pounds.</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Other ecological impacts</td>
<td>Ground application (mainly glyphosate)</td>
<td>Manual brushing</td>
</tr>
<tr>
<td>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.</td>
<td>Brushsaws and chainsaws are powered with a two-stroke engine, which produces some highly toxic gases (Dost et al. 1996).</td>
<td></td>
</tr>
<tr>
<td>Brushsaw and heavy equipment</td>
<td>The impact of the noise on fauna and green gas production are not documented, but are likely to be important.</td>
<td></td>
</tr>
<tr>
<td>Heavy equipment</td>
<td>Utilisation of heavy equipment such as a tractor can lead to soil compaction and could increase the production of N₂O (Douglas and Crowford 1993).</td>
<td></td>
</tr>
</tbody>
</table>
Table 1. Comparisons of some possible ecological, social and economical impacts of using chemical vs. mechanical release treatments in intensively managed tree plantation (continued).

<table>
<thead>
<tr>
<th>Sustainable development aspects</th>
<th>Chemical treatments</th>
<th>Mechanical treatments</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Social acceptability</strong></td>
<td>Aerial or ground application</td>
<td>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.</td>
</tr>
<tr>
<td></td>
<td>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).</td>
<td>Manual brushing In Ontario, 90% of acceptability was reached for manual cutting in both general public and timber-dependant communities (Wagner et al. 1998).</td>
</tr>
<tr>
<td></td>
<td><strong>Aerial application</strong></td>
<td>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).</td>
</tr>
<tr>
<td></td>
<td>In Ontario, 82% of the general public and 77% of timber-dependant communities found aerial herbicide unacceptable (Wagner et al. 1998).</td>
<td></td>
</tr>
<tr>
<td></td>
<td><strong>Ground application</strong></td>
<td></td>
</tr>
<tr>
<td></td>
<td>In Ontario, 63% of the general public and 65% of timber-dependant communities are opposed to ground application (Wagner et al. 1998).</td>
<td></td>
</tr>
<tr>
<td><strong>Worker health and safety</strong></td>
<td>Aerial or ground application (glyphosate)</td>
<td>Ergonomic problems due to equipment weight and site features caused frequent injuries (mainly falls, sprains and back injuries) (Dubeau et al. 2003).</td>
</tr>
<tr>
<td></td>
<td>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).</td>
<td>Working with heavy and sharp tools can be hazardous when performing a hard labour (Powell 1998).</td>
</tr>
<tr>
<td></td>
<td>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.</td>
<td>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).</td>
</tr>
<tr>
<td></td>
<td><strong>Aerial or ground application (2,4-D)</strong></td>
<td>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).</td>
</tr>
<tr>
<td></td>
<td>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).</td>
<td>BAPE (1997)’s commission recognized that mechanical release presents higher short-term risks in terms of worker health and safety.</td>
</tr>
<tr>
<td></td>
<td>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.</td>
<td><strong>Heavy equipment</strong> Very low risk of injuries.</td>
</tr>
<tr>
<td></td>
<td><strong>Backpack spraying</strong></td>
<td></td>
</tr>
<tr>
<td></td>
<td>Frequent injuries caused by falls and sprains (Dost et al. 1996).</td>
<td></td>
</tr>
<tr>
<td><strong>Job creation</strong></td>
<td>Aerial spraying</td>
<td>Manual brushing Creates more jobs for local communities than aerial spraying.</td>
</tr>
<tr>
<td></td>
<td>Low job creation for local communities.</td>
<td>Heavy equipment Low job creation for local communities.</td>
</tr>
<tr>
<td></td>
<td><strong>Backpack spraying</strong></td>
<td></td>
</tr>
<tr>
<td></td>
<td>Good tool to promote regional economic development.</td>
<td></td>
</tr>
<tr>
<td><strong>Public health and safety</strong></td>
<td>Aerial or ground application</td>
<td>Manual brushing and heavy equipment No known risk for population</td>
</tr>
<tr>
<td></td>
<td>The risk for population, fishers and hunters is negligible in the short and long term (BAPE 1997).</td>
<td></td>
</tr>
</tbody>
</table>
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-enolpyruvoylshikimate-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).

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

<table>
<thead>
<tr>
<th>Sustainable development aspects</th>
<th>Chemical treatments</th>
<th>Mechanical treatments</th>
</tr>
</thead>
<tbody>
<tr>
<td>Economic aspects</td>
<td>Aerial or ground application</td>
<td>Brushsaw</td>
</tr>
<tr>
<td>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).</td>
<td>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 (RAPE 1997).</td>
<td></td>
</tr>
<tr>
<td>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).</td>
<td>Heavy equipment</td>
<td></td>
</tr>
<tr>
<td>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).</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Costs ($ / ha) for one treatment</td>
<td>Aerial application</td>
<td>Brushsaw</td>
</tr>
<tr>
<td>300 (Boateng 1996)</td>
<td>530 (Boateng 1996)</td>
<td></td>
</tr>
<tr>
<td>200–250 (Thorpe 1996)</td>
<td>750-800 (Thorpe 1996)</td>
<td></td>
</tr>
<tr>
<td>Ground application (backpack spraying)</td>
<td>510 (Boateng 1996)</td>
<td>598 (D’Anjou 1996)</td>
</tr>
<tr>
<td>450–500 (Thorpe 1996)</td>
<td>875 (Jean-Marc St-Amant 2006)</td>
<td>Heavy equipment</td>
</tr>
<tr>
<td>No data</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

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 | Brushsaw |
| 300 (Boateng 1996) | 530 (Boateng 1996) |
| 200–250 (Thorpe 1996) | 750-800 (Thorpe 1996) |
| 510 (Boateng 1996) | 598 (D’Anjou 1996) |
| 450–500 (Thorpe 1996) | 875 (Jean-Marc St-Amant 2006) | Heavy equipment |
| No data |
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 (Horsey 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. Coutre 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 deprivation), 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 (Envirizons 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 of 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 (Provdendier 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 (glysophate 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 CO₂ 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 N₂O (Douglas and Crawford 1993), a greenhouse gas that has an impact on the global changes 310 times grater than CO₂ (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 (DuBeeu 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 (DuBeeu 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.

References
Effects of
The state of boreal forestry and the drive for
Trees and weeds. HMSO Publications Centre. Review of 2,4-
L.J. Audus (ed.). The physiology and biochemistry of
In
Élaboration de systèmes de boisement
Étude intégrée des
P.G. Comeau, G.J. Harper, M.E. Blache,
Herbicides are more cost-
Eucalyptus dunnii
P.G. Comeau, G.J. Harper, M.E. Blache, J.O. Boateng and L.A.
Toxicology and
In
Modifying the
and
P.J. Burton, C. Messier, D.W. Smith, and W.L. Adamowicz
1989 National survey on
42 1–40. NRC Research Press, Ottawa, ON.
J.O. Boateng and L.A. Gilkeson. Integrated Forest V egetation
Boulet-Gercourt, B. 1999. Élaboration de systèmes de boisement
et d'éducation des arbres objectifs par un accompagnement ligneux.
ACTA. Report n° 96/02. IDE, Rennes, France.
Boyd, R.S., J.D. Freeman, J.H. Miller and M.B. Edwards.1995. Forest
herbicide influences on floristic diversity seven years after broadcast
Brian, R.C. 1964. The classification of herbicides and types of
toxicity. In L.J. Audus (ed.). The physiology and biochemistry of
Des forêts en santé. Rapport d’enquête et d’audience publique sur la
Stratégie de protection des forêts. Commission sur la protection des
forêts, gouvernement du Québec, Québec (Qc). 277 p.
Programme de dégagement de la régénération forestière. Rapport
d’enquête et d’audience publique, gouvernement du Québec,
Québec (Qc). 133 p.
Burton, P.J., W.L. Adamowicz, G.E. Weetman, C. Messier, E. Prepas,
and R. Tittler. 2003. The state of boreal forestry and the drive for
1–40. NRC Research Press, Ottawa, ON.
Campbell, R.A. 1990. Herbicide use for forest management in Canada:
where we are and where we are going. For. Chron. 66: 355–360.
Compendium of Canadian Forestry Statistics. Ottawa, ON.
Available at http://nfdp.ccfm.org/compendium/pest/tables_index_
e.php
Belowground competition between hybrid poplar and the
herbaceous vegetation in plantation established on previously
logged forest sites in southern Quebec. (In submission).
Collet, C., F. Ningre and H. Frochot. 1998. Modifying the
microclimate around young oaks through vegetation manipulation:
effects on seedling growth and branching. For. Ecol. Manage. 110:
249–262.
des impacts du glyphosate utilisé dans le milieu forestier. Ministère
des Ressources naturelles, Direction de l’environnement forestier,
Service du suivi environnemental, Québec. 199 p.
D’Anjou, B. 1996. Chemical and Manual Treatments – Coastal B.C.
In P.G. Comeau, G.J. Harper, M.E. Blache, J.O. Boa teng and L.A.
Gilkeson. Integrated Forest Vegetation Management: Options and
Applications. Proceedings of the fifth B.C. Forest Vegetation
Management Workshop, November 29 and 30, 1993, Richmond,
B.C. pp. 59–60. FRDA report 251. Joint publication of the Canadian
Forest Service and the British Columbia Ministry of Forests,
Victoria, B.C.
Clear-cutting and regeneration practices in Quebec boreal balsam fir
trial case study: Implement harvesting inspired by natural
disturbance. Poster Presentation. In Eastern CANUSA Forest Science
Conference, University of Maine, Orono, Maine, USA.
Dost, F., J. Boa teng and J. Stobie. 1996. Worker Safety in Forest
Vegetation Management. In P.G. Comeau, G.J. Harper, M.E. Blache,
J.O. Boa teng and L.A. Gilkeson. Integrated Forest Vegetation
Management: Options and Applications. Proceedings of the fifth
B.C. Forest Vegetation Management Workshop, November 29 and
of the Canadian Forest Service and the British Columbia Ministry of
Forests, Victoria, B.C.
sward to wheel traffic and applied nitrogen. Grass and Forage Sci. 48:
91–100.
Dreyfus, P. 1984. Substitution de flore après entretien chimique des
ouvriers sylvicoles débroussailleurs au Québec. Ministère des
Ressources Naturelles de la Faune et des Parcs, Direction de la
Recherche Forestière, Ste-Foy (Qc.). Note de recherche forestière
128. 6 p.
of clear-cutting and plant competition control methods on carabid
(Coleoptera: Carabidae) assemblages in northwestern Ontario.
Env. Mon. and Ass. 56: 87–96.
management on breeding bird communities in British Columbia.
Canadian public opinion on forestry issues. Unpublished report.
Environics Research Group Ltd., Toronto, ON.
Fava, L., M.A. Orrù, A. Crobe, A. Barra Caracciolo, P. Bottoni and E.
Funari. 2005. Pesticide metabolites as contaminants of groundwater
resources: assessment of the leaching potential of endosulfan sulfate,
2,6-dichlorobenzonic acid, 3,4-dichloroaniline, 2,4-dichlorophenol
involved in aerial application of 2,4-D: Exposure and urinary
Franz, J.E., M.K. Mao, and J.A. Sikorski. 1997. Toxicology and
environmental properties of glyphosate. In Glyphosate: A unique
Chem. Soc., Washington, DC.
Frochot, H. J.F. Picard and P. Dreyfus. 1986. La végétation herbacée
Forest Stewardship Council (FSC). 2003. FSC Principles & Criteria
of Forest Stewardship. Available at http://www.fsc.org/en/about/
policy_standards/princ_criteria.
Garabrant, D.H. and M.A. Philbert. 2002. Review of 2,4-
Dichlorophenoxyacetic Acid (2,4-D) Epidemiology and Toxicology.
Gagné, N., L. Belanger and J. Huot.1999. Comparative response of
small mammals, vegetation, and food sources to natural
regeneration and conifer release treatments in boreal balsam fir
George, P.D. and B.H. Brennan. 2002. Herbicides are more cost-
effective than alternative weed control methods for increasing early
growth of Eucalyptus dunnii and Eucalyptus saligna. New Forests
Graham, J.D. (ed.). 1990. The weight of the evidence on the human
carcinogenicity of 2,4-D. Program on Risk Analysis and Environ-
mental Health, Harvard School of Public Health, Boston, MA.
Planted green ash (Fraxinus pennsylvanica Marsh.) and herbaceous
vegetation responses to initial competition control during the first
herbicide and mulch mat treatments for reducing grass, herb, and
shrub competition in the BC Interior Douglas-Fir Zone – ten-year
Harris, L.D. 1984. Substitution of clover after entrenchment of


