TREE DIVERSITY AND TREATMENT COST EFFECTIVENESS RESPONSES OF VEGETATION RELEASE TEN YEARS AFTER TREATMENT

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ABSTRACT

Dampier, J.E.E. 2006. Tree diversity and treatment cost effectiveness responses of vegetation release ten years after treatment

KEY WORDS: biodiversity, glyphosate, herbicide alternatives, plantation, mixedwood, orthogonal contrasts, pesticide, rank abundance plots, triclopyr, vegetation release, weed

This thesis synthesizes two papers in journal article format, on the effects of vegetation release treatments on boreal tree species. For both papers, field data was collected 10-years after alternative vegetation release. The first paper investigates tree diversity responses for six early seral boreal forest plantations in Ontario, Canada, representing three conifer species; black spruce [*Picea mariana* (Mill) B.S.P.], white spruce [*Picea glauca* (Moench) Voss] and jack pine (*Pinus banksiana* Lamb.), 14 release treatments and 94 experimental units. Dominance-diversity curves and Simpson's indices of diversity and evenness indicate tree alpha diversity. I propose a new method for assessing diversity, percentage of theoretical species maximum (%TSM); which is determined by comparing post-disturbance richness (S) with a theoretical species maximum (TSM). Results support the hypothesis that, "alternative vegetation release treatments generally do not significantly reduce diversity levels (%TSM) when compared to untreated plots (*a priori* planned comparisons)." Results also support the hypothesis that "tree monocultures do not develop after vegetation release." Only one out of 94 experimental units developed into a tree layer monoculture (Simpson's reciprocal diversity index = 1) at a site that was intensively treated with annual applications of herbicide.

The second paper utilizes a cost effectiveness analysis to investigate the relationship between white spruce gross total volume, and estimated current treatment costs based on detailed treatment time study data at the white spruce site. Only the white spruce site was included in the cost effectiveness analysis because detailed time-study data was only available for that site. This study is important, since very few cost-effectiveness studies of vegetation management in conifer plantations are reported in the literature. Individual treatment costs were estimated by pricing out 2003 values by consulting silviculture vegetation release companies. The most cost effective treatment was the aerial application of herbicide Vision (\$12.16 m^{-3}), followed by the aerial application of herbicide Release (\$12.18 m^{-3}), cutting with brushsaw (\$38.38 m^{-3}) and mechanical tending by Silvana Selective (\$42.65 m^{-3}). No cost differences were found between the herbicide treatments ($p = 0.998$) or between the cutting treatments ($p = 0.559$). The herbicide treatments were three-fold more cost-effective than the cutting treatments ($p = 0.001$). Since no treatment cost was associated with the control plot, it was not included in the ANOVA.

LIST OF PAPERS

Dampier, J.E.E., N. Luckai, F. W. Bell and W.D. Towill. 2006. Tree-level diversity: Do tree-level monocultures develop after Canadian boreal silviculture? Biodiversity and Conservation, submitted.

Dampier, J.E.E., F.W. Bell, M. St-Amour, D.G. Pitt and N.J. Luckai. 2006. Cutting versus herbicides: Tenth-year volume and release cost-effectiveness of sub-boreal conifer plantation. Forestry Chronicle, accepted.

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ACKNOWLEDGMENTS AND FORWARD

The format of this thesis is somewhat new to Lakehead University's Faculty of Forestry and the Forest Environment. Whereas in the past the Master's thesis was formatted in the traditional (British) book format, I, with the encouragement of my committee have taken a new approach where chapters are formatted into journal article format. The individual chapters are self contained, while the thesis as a whole is an integrated piece of work.

Although I am the sole author for chapters 1 and 4 (introduction and conclusions, respectively), chapters 2 and 3 prepared for peer-review journal submission, were co-authored by committee members and other key researchers. Since the study sites were established in the late 1980s and early 1990s (while I was still in high school), decisions on experimental and sampling design occurred well before my involvement. My contributions to this project included field data collection, collation, analysis and interpretation, with the guidance of my committee members; Nancy Luckai, Wayne Bell and Doug Pitt. Roy Maki of Monsanto Canada, INC. was my NSERC Industrial sponsor who gave me much insight into the forest silviculture industry. I thank Michel St-Amour and Mark Ryans of the Forest Engineering Research Institute of Canada, for providing information and insight into silviculture treatment costing and plantation cleaning machines.

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I never would have finished this thesis if it were not for the encouragement, support and understanding of my wife, Rebecca, who allowed me to move our family from New York to Thunder Bay so I could pursue this study. *In addition to these acknowledgments, chapters 2 and 3 have their own acknowledgements sections.*

1.0 INTRODUCTION:
VEGETATION MANAGEMENT, LOOKING TO THE PAST AND PRESENT TO MOVE FORWARD

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> "The outstanding scientific discovery of the twentieth century [was] not television, or radio, but rather the complexity of the land organism. Only those who know the most about it can appreciate how little is known about it (Leopold 1970)."

Sustainable forest management in Ontario is legislated under the Crown Forest Sustainability Act [CFSA], 1994. S.O. 1994, CHAPTER 25. Under article 68.5.b. of the act, every forest management plan must have, "(i) Crown forest *diversity objectives*, including consideration for the conservation of natural landscape patterns, forest structure and composition, habitat for animal life and the abundance and distribution of forest ecosystems," and "(ii) *social and economic objectives*, including harvest levels and a recognition that healthy forest ecosystems are vital to the well-being of Ontario communities (*emphasis added*) (Anonymous 1994)."

This thesis investigates conifer plantations ten years post vegetation release in the boreal and boreal / Great Lakes – St. Lawrence (GLSL) transition forests of Ontario. In order to determine economically- and ecologically-sound vegetation management practices that are socially acceptable, Ontario Ministry of Natural Resources (OMNR) initiated in 1991, the Vegetation Management Alternatives Program (VMAP) to advance forest regeneration knowledge and further all aspects of forest vegetation management in

Ontario. The program's goal was to, "develop approaches to managing forest vegetation that can reduce dependence on herbicides in Ontario's forests (Wagner *et al.* 1995)." The six studies reported on in this thesis were established under VMAP. In this thesis, I strive to bring forth new knowledge pertaining to how alternatives to silviculture herbicides (i.e. vegetation release treatments) relate to and potentially support *diversity* and *economic objectives*.

Social objectives related to vegetation release (specifically aerial herbicide usage on Crown Forests), although not researched in this study, are still very important because forestry practices on Ontario's Crown Forests have a social mandate. According to surveys conducted in Ontario (Buse *et al.* 1995, Wagner *et al.* 1998), Ontario's public has concerns and possess a "considerable discomfort" with regard to the use of herbicides on publicly-owned forests. They deem herbicide use unacceptable because they feel that the risks are; (1) a problem for future generations, (2) potentially catastrophic, and (3) difficult to control. Conversely, the forest industry has experienced wide success and effectiveness using aerially-delivered herbicides in controlling competing vegetation. Furthermore, Ontario has a tradition of herbicide usage that spans decades and is the predominant vegetation control method in Ontario (Wagner *et al.* 1995), with the majority of herbicides applied to Canadian forests occurring in Ontario (Thompson and Pitt 2003).

1.1 HUMANKIND'S VIEW OF WEEDS AND VEGETATION MANAGEMENT OVER TIME

Thousands of years before VMAP was ever established, there was much concern about controlling weeds and competing vegetation. Biblical references written approximately 3500 years ago depict weeds (i.e. thorns and thistles) as a curse.

> "Cursed is the ground because of you; through painful toil you will eat of it all the days of your life. It will produce thorns and thistles for you, and you will eat the plants of the field (Genesis 3:17-18)."

Another biblical reference warns a curse of "briers and weeds" instead of "wheat and barley" for poor stewardship.

> "If my land cries out against me and all its furrows are wet with tears, if I have devoured its yield without payment or broken the spirit of its tenants, then let briers come up instead of wheat and weeds instead of barley (Job 31:38-40)."

In addition to Judaism, most other societies had deities that were often evoked and prayed to in order to achieve crop protection. For thousands of years, humanity approached weed control with superstition and magic (Smith and Secoy 1981).

Over time however, superstition and magic gave way to a more empirical approach. In the first century A.D., Columella a Roman agriculture worker, wrote "But it seems to me the mark of a poor farmer to allow grass to grow among his crops, for it detracts greatly from the yield if weeding is neglected (*Columella quoted in* Smith and Secoy 1981)." Hand-weeding was one of the most common early weed control methods that led the ancient Romans and Greeks to develop the hoe, sickle and plow to aid in their weed control efforts. Furthermore, Romans were known to use fire to control weeds, and to kill weeds and weed seeds after harvest.

Early chemical control of weeds dates back to 146 BC. According to Smith and Secoy (1981), Romans applied salt as a broad spectrum herbicide to enemy's fields, destroying crops. In England during the late 16th century and into the 17th and 18th century, knowledge of salt as a herbicide increased as experimentation with timing and rates of salt allowed salt to be applied as a selective herbicide on fields and gardens (Smith and Secoy 1981). Salt remained the main chemical herbicide used until the development of synthetic chemicals in the mid 20th century.

1.2 FROM WEEDS IN AGRICULTURE TO COMPETING VEGETATION IN FORESTRY

> "In a garden we should hardly tolerate these bushes, but would rather grub them out as weeds; and yet they are hardly more useful here in the woods, for surely they will never grow into trees, and in all cases may hinder young trees from starting or choke off the seedlings of our useful trees. They are forest weeds, and while we could hardly afford to grub them out, yet we shall try to keep them down; but how (Roth 1902)?"

Gains in agriculture benefited the practice of forestry. Even though foresters started to become concerned about forest weeds near the turn of the twentieth century (Roth 1902), it wasn't until the 1940s and 1950s when the advent of mechanical site preparation, prescribed burning and chemical herbicides gave rise to modern forest vegetation management (Walstad and Kuch 1987a).

Vegetation management has an important role in ameliorating the effects of previous poorly managed forests, where productive confer stands were inadvertently converted to poor quality and low value brush and hardwood sites (Newton *et al.* 1987). The historic pattern of harvesting without intentional reforestation for the past 100 to 200 years exacerbated these problems throughout the Boreal and Great Lakes / St.

Lawrence Forests (Newton *et al.* 1987). Past mistakes have created a need and opportunity for developments in vegetation management to correct some of these problems created from the past.

Although modern Canadian vegetation management is considered a relatively new discipline, as indicated by a relatively small number of published research papers (Thompson and Pitt 2003), the tradition of vegetation management dates back to pre-European contact as Aboriginal people employed vegetation management via prescribed burning. In her personal account of traditional Aboriginal life, Madeline Katt Theriault (1992) documents traditional Aboriginal vegetation management. According to Theriault, in mid-April Aboriginal trappers would look for small patches of exposed land where the snow was beginning to recede. The trapper would ignite a low intensity fire on the exposed land allowing the surrounding snow to act as a barrier to prevent wildfire. Two seasons later, the trapper would return to find blueberries (*Vaccinium spp.*) growing where the fire was.

1.3 WEEDS, PLANTATIONS AND VEGETATION MANAGEMENT

In order to ensure clarity and consistency in this thesis, it is prudent to define "weed" and "competing vegetation." The Weed Science Society of America defines a weed as, "Any plant that is objectionable or interferes with the activities and welfare of humans (Zimdahl 1993)." Plants are given the label weed for a number of reasons. For example, they can be poisonous, they can cause hazardous conditions, they can be aesthetically undesirable or they can cause economic damage in agriculture and forestry crops (Walstad and Kuch 1987b). However, it is important to note that a weed in one context may be benign or perhaps even beneficial in a different context. Weeds in this thesis will be defined as, "Any herbaceous or woody plant species that considerably reduces growth of desired species in regenerating stands." The terms "weed" and "competing vegetation" will be used synonymously.

Competing vegetation in the Canadian forestry context is often controlled by the vegetation management treatment known as "vegetation release." Vegetation release is defined here as a cutting or chemical treatment of nearby competing vegetation to reduce its negative influence on the growth and survival of established conifer trees (*cf.* Newton *et al.* 1992, Sauvageau 1995).

Can a species that was once labelled a weed change status? When the VMAP research sites were originally established, trembling aspen (*Populus tremuloides* Michx.) was considered a weed species, due to its low economic value. Herbicides were used to encourage conifer growth by killing aspen. Since then, aspen has seen an increase in utilization and has gone from being an undervalued weed species in surplus, to being an overcommitted species with the establishment of several new mills in northern Ontario (OMNR 2004).

From 1990 to 2003, the poplar harvest in Ontario has increased one and a half–fold, while the harvest of other traditionally economic species – namely spruce, pine and fir (SPF) – increased at a reduced rate (Figure 1.1). Although aspen has a lower relative value when compared to conifers, it has become an important merchantable species (Hearnden *et al.* 1992), and it is currently used in the production of particle wafer board, veneer, pulp and paper, and oriented strand board. However, Canadian conifer species remain highly important in international trade, and must continue to be a priority (Thompson and Pitt 2003).

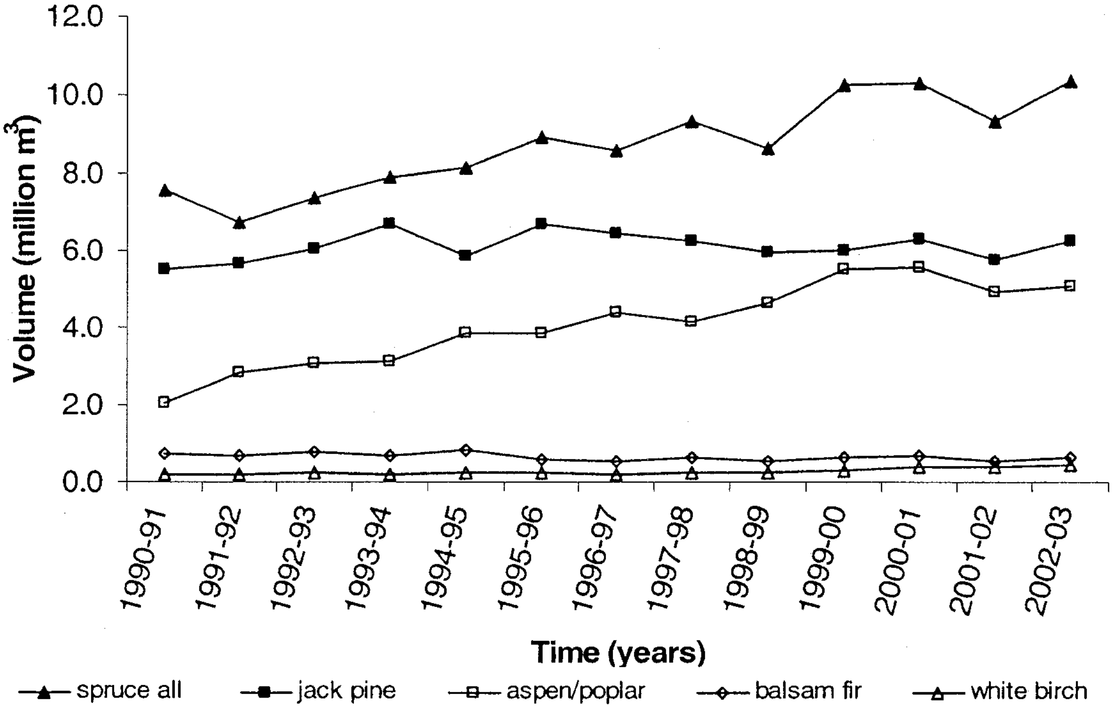

Figure 1.1. Volume of boreal tree species harvested in Ontario from 1990 to 2003. All spruce (*Picea mariana* and *P. glauca*); jack pine (*Pinus banksiana*); aspen/poplar (*Populus tremuloides* and *P. balsamifera*); balsam fir (*Abies balsamea*); white birch (*Betula papyrifera*).
Source: P. Corbett, OMNR Timber Supply Analyst, unpublished data.

1.4 MANAGING VEGETATION IN CONIFER PLANTATIONS

Even though aspen has seen a rise in utilization, selecting for conifer production by vegetation release is still important. Vegetation release is often necessary to reduce the deleterious influence of competing vegetation (which often includes aspen) over planted conifers. A properly applied vegetation release treatment suppresses competing vegetation's influence only to the magnitude that it ceases to considerably impede desirous plant species growth (Walstad and Kuch 1987a, Wagner *et al.* 1999, Wagner *et al.* 2001). Another way of looking at it is to efficiently channel, "limited site resources into usable forest products, rather than into non-commercial plant species (Walstad and Kuch 1987a)."

The sites in this thesis were planted with white (*Picea glauca* [Moench] Voss) and black spruce (*Picea mariana* [Mill] B.S.P.) (moderately shade tolerant), and jack pine (*Pinus banksiana* Lamb.) (shade intolerant) (Farrar 1995). Heavy competition for solar radiation from dense, low growing competing vegetation such as red raspberry (*Rubus idaeus* L. var. *strigosus* [Michx.] Maxim.), blue-joint grass (*Calamagrostis canadensis* [Michx.] Beauv.), fireweed (*Epilobium angustifolium* L.), and other species (Farmer *et al.* 1988, Shropshire *et al.* 2001) can be controlled with vegetation release, thereby increasing planted conifers growth and survival (Nienstaedt and Zasada 1990, Lieffers and Stadt 1994, Groot 1999, Jobidon *et al.* 2003).

Although planted conifers often respond to reductions in competing vegetation with a positive growth response, response may be incrementally low until a treatment response threshold is met. After competing vegetation levels are reduced below the treatment response threshold, a dramatic increase in conifer growth rate can be realised

(Wagner *et al.* 1989, Lepage and Coates 1994). Regardless of the relative shade tolerance of the planted conifer species, increased growth and survival is usually realized when competing vegetation is reduced and available light is thereby increased (Wagner *et al.* 1996).

Vegetation release timing can contribute to increased conifer growth. Although operationally, vegetation release treatments are usually conducted 2 to 5 years after planting in the North American boreal forest (Wood and Von-Althen 1993) – as is the case with the study sites included in this thesis – treatments should usually be carried out as soon after planting as possible. Timely vegetation release treatments improve planted conifer response by ameliorating negative effects of competing vegetation earlier, and reduce the need for repeated future treatments (Wagner 1994, Wagner *et al.* 1996, Wagner *et al.* 1999, Groot 1999, Pitt *et al.* 2000). However, on sites with low levels of competing vegetation, delaying herbicide treatment for several years may still yield positive jack pine growth response (Mallik *et al.* 2002).

Often only one properly-timed release treatment is required to reduce the negative effects of competing vegetation, increasing conifer growth and survival for many years into the future (Sutton 1995, Mallik *et al.* 2002, Cole *et al.* 2003). Although multiple herbicide release applications are operationally unfeasible because they are costly and impractical, experimentally they can reduce competing vegetation at the planting site and provide good growing conditions by increasing light, soil temperatures, moisture and soil nutrient availability (Wood and Von-Althen 1993, Munson *et al.* 1993, Pitt *et al.* 1999, Perie and Munson 2000, Cole *et al.* 2003). Single cutting and herbicide applications, as well as repeated herbicide applications were compared in the studies in this thesis.

1.5 POTENTIAL PROBLEMS WITH CUTTING AND HERBICIDE VEGETATION RELEASE

Vegetation released by cutting treatments may not always improve long-term planted conifer growth. In actuality, it can lead to high levels of competing vegetation in years following treatment if cutting is not properly timed during the season (Lepage and Coates 1994, Pitt *et al.* 2000). Trembling aspen, for example, can be difficult to control and linking the species autecology to cutting method and timing can increase treatment efficacy (Stoeckeler 1947, Sutton 1984, Bell *et al.* 1999).

Bell *et al.* (1999) studied 'treatment windows' for trembling aspen based on cutting height and season. It was determined that trembling aspen cut at 50 cm to 75 cm aboveground in June or July resulted in the greatest stem mortality. Operationally however, cutting trembling aspen and other competing vegetation usually occurs during the autumn after leaf fall, to provide better visibility for forest workers. Cutting competing vegetation at the end of the growing season, after carbohydrates have been stored in the roots (Lambers *et al.* 1998) helps to ensure vigourous vegetative growth the following spring. In addition to improper seasonal timing, improper treatment during stand development -i.e. over many growing seasons - can also negatively affect target conifers. On highly competitive sites, conifers can be severely overtopped and suppressed for years before vegetation release is decided upon by the forest manager.

After release, increased exposure of remaining conifers can lead to thinning shock, reducing growth rate (Lindgren and Sullivan 2001).

Optimal "treatment windows" exist for herbicides as well. According to the Vision ® (glyphosate) product label (Monsanto, Vision Silviculture Herbicide Label, Registration No. 19899 Pest Control Products Act), undesirable competing vegetation may be treated during active growth right up until autumn colour, as long as no major leaf fall has occurred. However, if conifers are to be protected from injury, Vision application must take place outside the period of active growth. Release ® (triclopyr), the other herbicide studied in this thesis, follows a different treatment window (Dow AgroScience, Release Silviculture Herbicide Label, Registration No. 20093 Pest Control Products Act). Triclopyr, is a selective herbicide that is most effective in controlling broadleaf competitors (with minimal effect to conifers and monocots) when applied during active competitor growth, i.e., early to mid-summer (Dow AgroSciences 2002).

In situations where conifers are under physiological stress (i.e. sites with heavy competition), herbicide damage may result. Stressed conifers are susceptible to herbicide injury (Newton *et al.* 1992, Bedford *et al.* 2000) because suppressed conifers harden off later than normal becoming directly damaged by the herbicide. Furthermore, cutting vegetation release treatments on competitive sites can cause drastic changes in site conditions, such as increases in light intensity, which in turn can cause conifer loss by abovementioned thinning shock. Thinning shock is rare within herbicide treatments, since dead standing trees provide some shade and protection. The question to ask is, "How well will a planted conifer in poor condition respond to an improvement in growing conditions (Sutton and Weldon 2003)?" After initial post-treatment losses though, surviving conifers will likely respond well to increased light (Reynolds *et al.* 1997, Reynolds *et al.* 2000), although response to increased light may not be immediate (Mallik *et al.* 2002).

Conifers released from competing vegetation might be more susceptible to frost damage for an eco-physiological reason. Recently released conifers can respond negatively to decreases in atmospheric humidity caused by reductions in competing vegetation cover, making them more susceptible to frost damage. Low near-ground atmospheric humidity and early spring shoot elongation followed by freezing temperatures can damage shoots (Grossnickle 2000). In laboratory growth chambers and field experiments, lower humidity caused earlier seasonal shoot elongation (Marsden *et al.* 1996), which produced early tender shoots susceptible to spring frost. Another study reported that relative humidity near the forest floor was lowest in release treatments where vegetation was highly controlled (herbicide treated plots), was intermediate where vegetation was moderately controlled (brushsaw treated plots), and was highest where no vegetation management release was performed (untreated control plots) (Reynolds *et al.* 2000). Furthermore, some cover (i.e. less efficacious vegetation release, or no release) can increase night time temperature and humidity (Groot 1999), while still providing enough light for planted moderately shade tolerant conifers such as spruce.

1.6 CONSERVING FORESTS THROUGH INTENSIVE FORESTRY AND VEGETATION RELEASE

The Canadian Senate Subcommittee on the Boreal Forest recommends apportioning the boreal forest into three categories of different forest management intensity, in order to balance the competing demands placed on it. Competing demands include, "preserving the resource, maintaining the lifestyle and values of boreal communities, extracting economic wealth, and preserving ecological values (SSBF 1999)." The first category would include intensively managing up to 20% of the boreal forest for the purposes of timber and fibre production (following the Scandinavian model). Increased productivity would make more forests available for ecological preservation, aboriginal use, tourism, and wildlife protection while providing resources for industry. Under the second category, forests would be managed less intensively over an extensive area. Sixty percent of the forest would be apportioned in this category to be enjoyed by a variety of people and communities while allowing forest operations and conserving biodiversity. The forests would maintain relatively natural tree species mixtures and ages. The third category would include protecting 20% of the boreal forest, not allowing forest operations in order to preserve ecological and cultural values (SSBF 1999).

This strategy proposed by the SSFB is gaining support. The Sierra Club of Canada favours the idea of using 20% of Canada's boreal forest for intensive forestry, so that another 20% can be protected from logging. The Sierra club states, "The use of intensive forestry offers an approach to help make these goals politically acceptable and practically achievable (von Mirbach 2001)." Ducks Unlimited Canada supports the strategy as well, believing that, “it is vital to find balance between development and protection while ensuring ecosystem functions are maintained (Ducks Unlimited n.d.).

1.7 THESIS OVERVIEW AND RATIONALE

Intensive forestry, which relies on more intensive silviculture, is likely to increase in Canada (NRCan 2002, NRCan 2003). Since the utilization of herbicides and herbicide alternatives in silviculture is a key component of more intensive forest management, this thesis provides practical and theoretical insight that is directly applicable to current and future forestry practices in Canada. My research, within the framework of the former VMAP program, provides original knowledge and insight that may better equip Ontario foresters in meeting the *diversity* and *economics* objectives of the Crown Forest Sustainability Act.

Chapters 2 and 3 were written as “stand alone” research papers which have been submitted to peer-reviewed journals. Research contained in chapter 2 provides new knowledge relating to tree diversity change. A new and simple method of accounting for diversity change before and after a silviculture disturbance is presented. Chapter 3 addresses vegetation release treatment costs in a cost effectiveness analysis. Estimated treatment costs were calculated per volume of target conifer gross total volume. Chapter 4 is presented as an extension note, targeting practicing foresters; presenting the major findings of chapters 2 and 3 and making generalizations connecting the two papers within the context of Ontario forest management. Leopold was right. The “land organism” is very complex. This thesis strives to describe some of its complexity.

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2.0 PAPER 1:
TREE LEVEL DIVERSITY:
DO TREE-LEVEL MONOCULTURES DEVELOP AFTER CANADIAN BOREAL SILVICULTURE?[4]

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2.1 KEY WORDS

biodiversity, boreal forestry, herbicide alternatives, plantation, rank abundance plots, release treatment, silviculture, vegetation management

2.2 ABSTRACT

Concern about forestry practices creating tree-level monoculture plantations exists. Our study investigates tree diversity responses for six early seral boreal forest plantations in Ontario, Canada, representing three conifer species; black spruce (*Picea mariana* [Mill] B.S.P.), white spruce (*Picea glauca* [Moench] Voss) and jack pine (*Pinus banksiana* Lamb.), 14 release treatments and 94 experimental units. Dominance-diversity curves and Simpson's indices of diversity and evenness indicate tree alpha diversity. We propose a new method for assessing diversity, percentage of theoretical species maximum (%TSM); which is determined by comparing post-disturbance richness (S) with a theoretical species maximum (TSM). Our results support the hypothesis that, "alternative vegetation release treatments generally do not reduce tree-diversity levels (%TSM) relative to untreated plots." The only %TSM ($p \leq 0.05$) comparison that produced a diversity less than control, was repeated annual treatments of Vision herbicide at one of the black spruce study sites. Our results generally support the hypothesis that "tree monocultures do not develop after vegetation release." Only one out of 94 experimental units developed into a tree layer monoculture (Simpson's reciprocal diversity index = 1) This occurred within one of the experimental units planted with black spruce and treated with experimentally intense repeated annual treatments of Vision herbicide - a treatment which is atypical of Canadian forest management.

2.3 INTRODUCTION

Concern about single species, artificially established forests – monoculture plantations – stems from the widely held belief that increases in species diversity provide stability and maintain ecosystem functioning (Boyd *et al.* 1995, Tilman 1996, Bengtsson 1998, Bengtsson *et al.* 2000). Modern forestry in Canada's northern forests often includes clear cutting followed by site preparation, planting and chemical or motor-manual tending (NRCan 2004). This suite of activities is criticized for reducing biodiversity (May 2005) to the point of creating monocultures (Mosquin *et al.* 1995) resulting in potentially unstable and unsustainable forest communities. These are serious allegations that, if true, must be addressed in the context of current ecological knowledge and legislation such as the United Nations World Commission on Environment and Development (Brundtland 1987), the United Nations Convention on Biological Diversity (Environment Canada 1995, SCBD 2005), The Crown Forest Sustainability Act 1994[1] (Anonymous 1994), and the Province of Ontario's Biodiversity Strategy (OMNR 2005).

In order to ensure clarity and consistency, it is prudent to define the terms monoculture and plantation. Sauvageau (1995) defines monoculture as the "cultivation of a single crop or product without using the land for other purposes." Under this definition, a multiple tree species stand harvested entirely for one product, such as pulp fibre, would be considered a monoculture. A second definition provided by this source, "extensive areas of land occupied or dominated by plant species that are closely related genetically," although somewhat better aligned with popular interpretation, is also lacking in clarity. How closely related must species be to qualify under this definition?

A more useful definition is "the growing over a large area of a single crop species or of a single variety of a particular species (Allaby 1998)." We will use Allaby's (1998) qualitative definition of monoculture which can also be defined quantitatively as a Simpson's reciprocal diversity index (SRDI) value equaling 1 (Magurran 1988).

The Food and Agriculture Organization of the United Nations (FAO 2001) defines a forest plantation as, "a forest established by planting and / or seeding in the process of afforestation or reforestation. It consists of introduced species[2] or, in some cases, indigenous species." The FAO definition is appropriate to northern Ontario but must be clarified on two points. First, in *most* cases species planted in northern Ontario *are* indigenous species such as black spruce (*Picea mariana* [Mill] B.S.P.), white spruce (*Picea glauca* [Moench] Voss) and jack pine (*Pinus banksiana* Lamb.) (Farrar 1995). Second, afforestation, defined as "the establishment of a tree crop on an area from which it has always, or for very long, been absent (Sauvageau 1995)," is rare in northern Ontario. Almost all northern Ontario regeneration efforts are by definition, reforestation, which is the successful renewal of a forest crop by planting or direct seeding (Sauvageau 1995), usually conducted within a few years after harvesting.

The Center for International Forest Research (CIFOR 2002), using the FAO definition given above, develops a typology of planted forests based on the nature, purpose and management intensity of planted forests. Under this typology the definition that best describes the six northern Ontario sites in our study is "industrial plantation," defined as "intensively managed forest stands established to provide material for sale locally or outside the immediate region, by planting and / or seeding in the process of afforestation or reforestation. Individual stands or compartments are usually with even age class and regular spacing and consist of one or two indigenous species. Usually either large scale or contributing to one of a few large scale industrial enterprises in the landscape (CIFOR 2002)."

Alternatively, the Forest Stewardship Council (FSC 2003) defines a forest plantation as a "forest area lacking most of the principle characteristics and key elements of native ecosystems, which result from the human activities of either planting, sowing or intensive silvicultural treatments." Although this definition is powerful in that it captures the concerns that are expressed regarding plantations in general, it is not particularly helpful. For example, the specifics of "native ecosystems" are open to interpretation and confusion is therefore inevitable.

One shortcoming of definitions offered by The Center for International Forest Research (CIFOR 2002) and the Forest Stewardship Council (FSC 2003) is the use of the term "intensive." In Canada, the term "intensive" has come to mean something different than what is implied in the abovementioned definitions. According to Dunster and Dunster (1996), intensive silviculture is, "any silvicultural practices designed to accelerate stand development and improve stand value and final yields in stands that are well established. Practices included in the definition vary by jurisdiction. The baseline case is often the historical natural yield of wild, untouched stands." By comparison, the same source defines "basic silviculture" as, "… the practices necessary to establish regeneration of the desired species at specific densities and stocking, free from competing vegetation, and within a certain time limit." For the purposes of this paper, we will use the definition of "industrial plantations" as proposed by CIFOR, with the understanding that most of Canadian silviculture (including the suite of activities in this study) is basic rather than intensive, and that although usually only one species is planted, mixed species stands often develop (Chen and Popadiouk 2002).

The boreal and boreal / Great Lakes – St. Lawrence (GLSL) transition forests of Ontario provide an ideal setting for an investigation into the impacts of silviculture on tree alpha diversity for a number of reasons. First, if Canadian forestry activities are going to create tree-level monocultures anywhere, they could be expected in northern Ontario where natural origin stands commonly have low tree diversity; typical stand compositions in this region include four to eight species (Sims *et al.* 1989, Taylor *et al.* 2000). The latitudinal gradient is also evident here, as natural stands in southern Ontario have approximately twice as many tree species than northwestern Ontario stands (Thompson 2000). Furthermore, tree-level monocultures or near tree-level monocultures can occur naturally on sites without the influence of forestry activities (Rudolph and Laidly 1990, Viereck and Johnston 1990, Thorpe 1992, Johnson *et al.* 2003, Thompson *et al.* 2003).

Second, many of the industrial forest activities linked to creating single species and / or product forests are currently used in the region. For example, for decades regeneration efforts have routinely focused on localized planting of only one native species (usually black spruce, white spruce, or jack pine), followed by herbicide application (NRCan 2004). Thirdly, intensification of forestry activities is anticipated (OFAAB 2002) due to wood supply declines and land use pressures on the provincial landbase (OMNR 2004).

Although tree diversity is "just one of many characteristics" with debatable applicability in the overall assessment of biodiversity change (Erdle and Pollard 2002, Betts *et al.* 2005), trees dominate forest landscapes and hence influence understory vegetation and other biotic communities. Several studies have shown that non-tree layer monocultures rarely develop following typical forest management activities in northern forests (Esseen *et al.* 1997, Archibold *et al.* 2000, Boateng *et al.* 2000, Reich *et al.* 2001, Bell and Newmaster 2002, Rees and Juday 2002, Hunt *et al.* 2003), but few have considered this question from the viewpoint of tree layer diversity exclusively[3].

Our objectives were to (1) quantify early seral tree species diversity and (2) assess whether tree-level monocultures developed ten growing seasons after release treatments, at six northern Ontario conifer-planted study sites. Metrics include dominance-diversity curves, Simpson's indices for diversity and evenness, and a new approach, percentage of theoretical species maximum (%TSM), which compares a pre-disturbance theoretical tree species maximum richness (based on reliable, well-documented historical data), to measured post-disturbance tree richness. We test two hypotheses: first that applying alternative vegetation release treatments after clearcutting, site preparation and planting one conifer species, does not significantly reduce tree-level diversity (%TSM) when compared to untreated control plots (i.e. no vegetation release); and second that tree-level monocultures do not develop after typical boreal silviculture which includes alternative vegetation release treatments.

2.3.1 Study sites

Six study sites (Figure 2.1, Table 2.1) were established between 1990 and 1993 under the Ontario Ministry of Natural Resources (OMNR) Vegetation Management Alternatives Program (VMAP) (Wagner *et al.* 1995) and are found within four unique

North American ecoregions of the Nearctic biogeographical zone (Ricketts *et al.* 1999). Within two to four years of harvest, the study sites were individually planted with three different conifer species (white and black spruce, and jack pine) representing two levels of *relative* shade tolerance (intermediate for spruce and low for pine). After planting, the study sites were released with 14 alternative treatments (Table 2.1).

2.4 METHODS

All sites were sampled ten years after alternative release treatments were applied (Bell *et al.* 1997; Pitt *et al.* 2000; Mallik *et al.* 2002; Pitt *et al.* 2004; FRP 2005). Field data collection methods followed identical procedures, although sampling intensity varied for each study site (Table 2.1), because the study sites were established independently. Randomly laid out sampling transects (10-m by 2-m) were established within each block-treatment area (i.e. 94 experimental units). All tree species stems within sampling areas were identified and tallied. The Sb2 and Sb3 sites likely underestimated the richness and abundance of tree species because individuals under 130-cm (diameter at breast height, DBH) were not recorded *and* these sites were sampled at the lowest intensity (Table 2.2). Tree species richness was portioned and categorized by conifer and hardwood species.

Dominance diversity curves for the trees (Burton *et al.* 1992) (also referred to as rank abundance plots) were produced for each study site, by totaling tree species abundance for each treatment within each study site, across blocks. Relative abundance probabilities were then calculated, ranked and plotted.

Table 2.1. Summary of Study Sites including; planted tree species, location name, terrestrial ecoregion and expected tree richness, pre-disturbance vegetation type and expected localized richness, year of release treatment, experimental design, sampling intensity, treatment package, and number of experimental units.

ID	**Planted Species**	**Name; Location**	**Terrestrial ecoregion** [a]	**Pre-disturbance vegetation type**[b]	**Year of Release**	**Design**	**Sampling intensity (# of 20m^2 transects, m^2/ exp.unit)**	**Treatments** [e,f]	***n***
Sw1	White spruce	Fallingsnow Ecosystem; 48°08' N, 89°49' W	Western Great Lakes Forest	**Block 1 = V-7**[c] Trembling aspen - balsam fir / balsam fir shrub; **Block 2 = V-5**[c] Aspen hardwood; **Block 3 = V-28**[c] Jack pine / low shrub	1993	RCBD; 3 blocks	6, 120	1 rep/block BRU, CON, REL, SIL, VIS	15
Pj1	Jack pine	Bending Lake; 48°57' N, 92°02' W	Western Great Lakes Forest	**V-17**[c] Jack pine mixedwood / shrub rich	1992	RCBD; 4 blocks	6, 120	1 rep/block BRU, CON, CRV, VIS	16
Pj2	"	Domtar-Espanola; 46°47' N, 82°10' W	Eastern Forest/ Boreal Transition	**Block 1 = V-18**[d] Jack pine / black spruce / blueberry **Block 2 = V-17**[d] Jack pine / black spruce / feathermoss **Block 3 = V-17**[d] Jack pine / black spruce / feathermoss	1993	RCBD; 3 blocks	4, 80	1 rep/block BBR, BRR, BRU, CON, CRV, MBV, VIS	21
Sb1	Black spruce	Leether Lake; 50°36' N, 91°45' W	Midwestern Canadian Shield Forests	**V-17**[c] Jack pine mixedwood / shrub rich	1993	CRD	4, 80	3 reps of 4 treatments BRU, CON, CRV, VIS	12
Sb2	"	Nipigon-Hele; 48°59' N, 88°33' W	Central Canadian Shield Forests	**V-4**[c] White birch hardwood and mixedwood	1990	RCBD; 3 blocks	3, 60	1 rep/block CON, CRV, RHV, SGV	12
Sb3	"	Nipigon-Corrigal; 49°02' N, 88°10' W	Central Canadian Shield Forests	**V-14**[c] Balsam fir mixedwood	1990	RCBD; 3 blocks	3, 60	1 rep/block BRV, CON, CRV, EZV, RHV, TLR	18

[a] (Ricketts *et al.* 1999); [b] Based on Forest Resource Inventory (FRI) pre-disturbance stand conditions and unpublished pre-disturbance data; [c] (Sims *et al.* 1989); [d] (Taylor *et al.* 2000); [e] For full descriptions of treatments and sites *cf.* (Bell *et al.* 1997, Pitt *et al.* 2000, Mallik *et al.* 2002, Pitt *et al.* 2004, [FRP] Forest Research Partnership 2005); [f] **BBR**: Basal Bark application of Release (tryclopyr) herbicide with backpack sprayer, **BRR**: Brushsaw cutting with stump herbicide applicator attachment with Release, **BRU**: Brushsaw cutting without herbicide applicator attachment, **BRV**: Brushsaw cutting with stump herbicide applicator attachment with Vision (glyphosate) herbicide, **CON**: Untreated control, **CRV**: Repeated annual treatments of Vision, **EZV**: EZ-Ject injection of Vision into competition basal stem, **MBV**: Backpack mist blower application of Vision, **REL**: Aerial application of Release from a Bell 206 helicopter, **RHV**: Reel and hose application of Vision, **SIL**: Silvana Selective cutting head mounted to a Ford Versatile tractor with parallelogram boom, **SGV**: Spot gun application of Velpar L (hexazinone), **TLR**: Thin-line application of Release, **VIS**: Aerial application of Vision from a Bell 206 helicopter

Of the available diversity indices, Simpson's reciprocal diversity index (SRDI) (Equation 1) was used because of its responsiveness to dominant species (Pielou 1975, Magurran 1988). This was deemed important due to low expected species richness (Sims *et al.* 1989, Taylor *et al.* 2000, Thompson 2000). The value of the index ranges from one (denoting a tree-level monoculture) to greater than five (Magurran 1988, Lande 1996) (indicating the highest values expected for northern Ontario tree diversity). To illustrate, a northern Ontario site with *very* high tree-level diversity might have eight tree species in the following proportions; 30%, 20%, 20%, 10%, 5%, 5%, 5%, 5%. The SRDI value would be 5.26. If species are equally present, the SRDI value would equal the species richness (S).

$SRDI = 1/D = 1/\Sigma p_i^2$ **[Equation 1]**

Where p_i is the proportional abundance of the i^{th} species.

Measures of evenness indicate how species abundance is distributed within a community. Community can be defined as an assemblage of species inhabiting a common environment and interacting with one another. A community with equally abundant tree species will have a high evenness value (i.e. one), whereas, a community with great differences in tree species abundance will have a low evenness value (i.e. approaching zero) (Smith and Wilson 1996). Evenness was calculated with Simpson's evenness index (Equation 2) because it gives precise and unbiased estimates and meets the requirements of an evenness index (Smith and Wilson 1996, Payne *et al.* 2005).

$E_{I/D} = SRDI / S$ **[Equation 2]**

Where SRDI = reciprocal of Simpson's diversity index; and S = species richness

For a community where all species are equally frequent $SRDI$ and S will equal; therefore $E_{I/D}$ will equal one (Lande 1996).

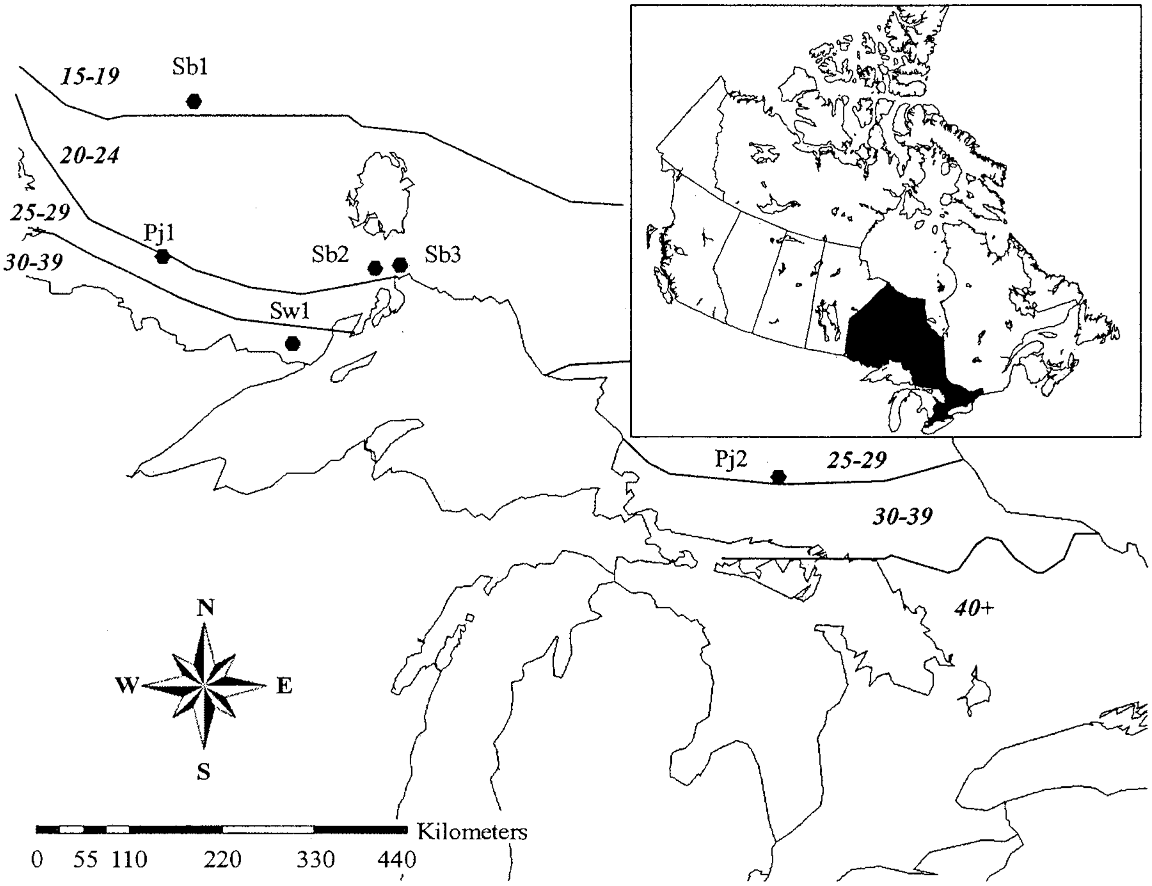
In addition to the abovementioned metrics, we propose a new and simple method, the percent theoretical species maximum (%TSM), for assessing the effects of silviculture by comparing a theoretical maximum pre-disturbance species count, to a measured post-disturbance species count. The theoretical pre-disturbance maximum richness or reference value (White and Walker 1997, Terradas *et al.* 2004) was determined by a checklist approach (Droege *et al.* 1998). Reference values must be carefully documented when applied in this manner because nature is temporally and spatially variable (White and Walker 1997). For this reason, we applied two different theoretical species maximum (TSM) values based on different spatial scales (one local and one regional), to the measured post-disturbance tree richness (total number of tree species per experimental unit) (Boyle 1992).

In the first approach, we classified each site's pre-disturbance vegetation type (Table 2.1) using the standard forest vegetation classification system for northern Ontario (Sims *et al.* 1989, Taylor *et al.* 2000). After the sites were classified to vegetation type (V-Type), we totaled the checklisted trees (as defined by Farrar 1995) in the V-Type description to obtain the local theoretical species maximum (LTSM) which was then used in our calculations of percent local theoretical species maximum

(%LTSM). This LTSM is based on published, accepted spatial and historical data (White and Walker 1997, Landres *et al.* 1999) collected from sites with similar characteristics and is therefore directly applicable to our study.

The second approach is based on range data for individual tree species (Farrar 1995) delineated into geographical regional tree richness values (Figure 2.1; Thompson 2000). We named the high richness value for each delineated region, the regional theoretical species maximum (RTSM) (Table 2.2) and employed this value in our percent regional theoretical species maximum (%RTSM) calculations. For example, the Sw1 site had a maximum tree richness range between 30 to 39 (Figure 2.1). The value we used in the calculation of %RTSM in this instance was 39 tree species (Table 2.2). As with LTSM, the RTSM is based on well-founded and reliable data, however RTSM is at a much broader scale.

The percent local and regional theoretical species maximum (%LTSM, %RTSM) was then calculated by dividing the measured post-disturbance tree richness for each experimental unit by the theoretical species maximum (LTSM and RTSM) for each experimental unit (reference value) and then multiplying by 100% (Equation 3). This approach provides a good method to compare a theoretical maximum to a measured richness. We issue one caveat, however, with this approach; the sampling units within our experimental units are relatively small (60 to 120 m^2 exp. $unit^{-1}$) relative to very large sampling unit used to determine the LTSM (V-Type), and RTSM (species range data). Although not practically feasible, sampling should have been conducted at 100% sampling intensity for each unit, when making a comparison such as this.



Sw1, Site name
20-24, Tree richness (Farrar 1995, Thompson 2000)

Figure 2.1. Location of six early seral post-silviculture disturbance study sites, in northern Ontario, Canada. For site and treatment descriptions, and georeferences of study sites refer to Table 2.1.

$\%LTSM \text{ or } \%RSTM = (S / TSM) \times 100\%$ **[Equation 3]**

Where S = post-disturbance species richness and TSM = either local or regional theoretical species maximum.

Analysis of Variance was run using the SPSS Ver. 11.0.1 General Linear Model (Univariate) function to compare treatments in the underlying experimental designs (RCBD, CRD) for each study site on %LTSM and %RTSM values. Planned comparisons (*a priori*) related all release treatments to the untreated control because it was assumed that control would likely have the greatest relative tree diversity. Diagnostic normal probability plots of model residuals and side-by-side dot plots of residuals were used to verify that the assumptions of normality and homogeneity of variance were met.

Analysis of Variance (ANOVA) was not conducted on Simpson's reciprocal diversity index (SRDI) or Simpson's evenness index (SEI) because diversity indices are based on proportional abundance of species (Magurran 1988) making interpretation difficult (Zar 1984). Furthermore species indices are nonparametric (Magurran 1988) and do not necessarily meet ANOVA assumptions. Indices were used to supplement and provide additional insight into the ranked abundance curves and %TSM values.

2.5 RESULTS

Tree species sampled across all six study sites included: black spruce, white spruce, jack pine, balsam fir (*Abies balsamea* [L.] Mill.), red pine (*Pinus resinosa* Ait.), white pine (*P. strobus* L.), eastern white cedar (*Thuja occidentalis* L.), trembling aspen (*Populus tremuloides* Michx.), balsam poplar (*P. balsamifera* L.), largetooth aspen (*P. grandidentata* Michx.), white birch (*Betula paprifera* Marsh.), sugar maple (*Acer saccharum* Marsh.), red maple (*A. rubrum* L.), black ash (*Fraxinus nigra* Marsh.), and eastern larch (*Larix larcina* [Du Roi] K. Koch).

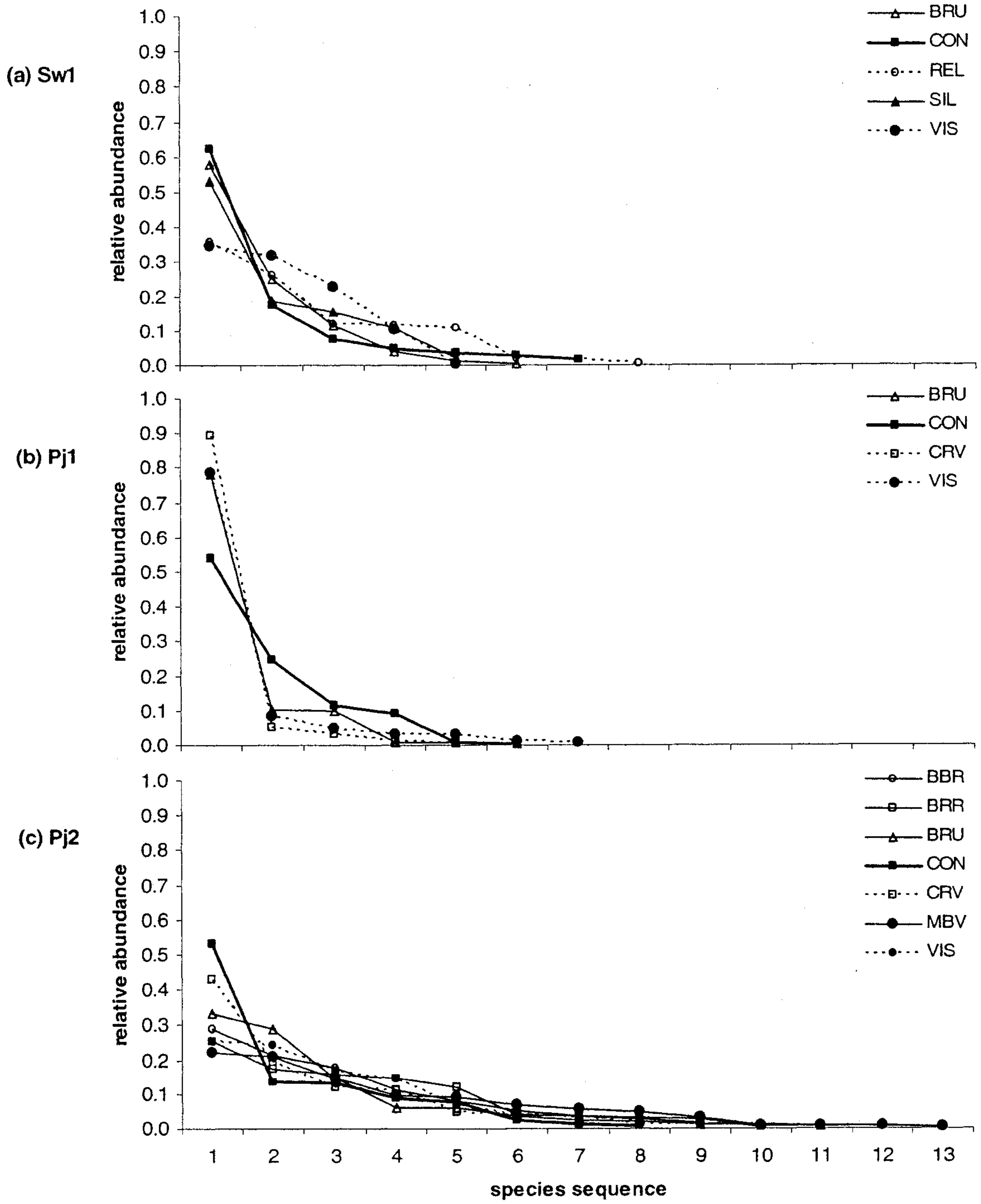
The slope of dominance-diversity curves can suggest diversity and evenness index values (Figure 2.2a-f; Table 2.2). Curves with steep slopes indicate dominance by one or a few species which usually translates into low richness and low evenness (Burton *et al.* 1992). For example, the steep slope of the dominance-diversity curve for the Vision herbicide (VIS) treatment at the Pj1 site (Figure 2.2b) is confirmed by relatively low diversity and evenness (Table 2.2; SRDI = 1.09 to 2.50, SEI = 0.36 to 0.62). As the slope of the dominance-diversity curve becomes more gradual, dominant species become less conspicuous suggesting high diversity and richness (Burton *et al.* 1992). For example, the gradual slope for the Reel Hose Vision (RHV) treatment at the Sb3 site (Figure 2.2f) results in relatively high diversity and evenness (Table 2.2; SRDI = 2.59 to 4.17, SEI = 0.65 to 0.83).

Table 2.2. Study site, treatment, measured tree richness (# of spp., S), number of conifer and hardwood species, Simpson's reciprocal diversity index (SRDI) and Simpson's evenness index (SEI), local theoretical species maximum (LTSM), regional theoretical species maximum (RTSM), percent local theoretical species maximum (%LTSM), percent regional theoretical species maximum (%RTSM), ten years after alternative release treatments in six northern Ontario conifer plantations.

Site	Treatment[a]	# of spp. (S)	# of conifer spp.	# of hardwood spp.	SRDI (1/D)	SEI ($E_{1/D}$)	LTSM[b]	RTSM[c]	%LTSM	%RTSM
Sw1	BRU	3-5	1-3	2	1.67-3.27	0.56-0.65	4-6	39	60-125	8-13
	CON	3-6	1-3	1-3	2.00-2.33	0.39-0.74	4-6	39	75-100	8-15
	REL	6-7	2-4	3-4	2.91-4.80	0.42-0.80	4-6	39	100-175	15-18
	SIL	4-6	2	2	1.92-3.26	0.48-0.65	4-5	39	83-175	10-13
	VIS	3-4	1-2	1-2	1.66-3.10	0.55-0.78	4-6	39	60-75	8-10
Pj1	BRU	2-4	1-2	1-2	1.27-1.78	0.42-0.84	6	29	33-67	7-14
	CON	3-4	1-3	1-3	1.84-3.51	0.52-0.88	6	29	50-67	10-14
	CRV	2-4	2	0-2	1.09-2.89	0.38-0.72	6	29	33-67	7-14
	VIS	2-6	1-4	1-3	1.09-2.50	0.36-0.62	6	29	33-100	7-21
Pj2	BBR	6-7	3-5	2-3	2.62-2.96	0.37-0.44	5-7	29	100-140	21-24
	BRR	6-7	3-5	2-4	1.91-3.99	0.32-0.57	5-7	29	100-140	21-24
	BRU	5-8	4-5	1-3	1.99-4.19	0.40-0.52	5-7	29	100-120	17-28
	CON	4-7	1-4	1-3	1.78-3.25	0.44-0.46	5-7	29	71-140	14-24
	CRV	3-6	2-5	1-2	1.96-3.24	0.46-0.65	5-7	29	60-100	10-21
	MBV	6-11	3-8	3-4	2.91-5.37	0.32-0.52	5-7	29	120-180	21-38
	VIS	5-8	3-5	1-3	1.94-4.74	0.39-0.59	5-7	29	100-114	17-28
Sb1	BRU	3-4	2	1-2	1.70-2.43	0.47-0.81	5	19	60-80	16-21
	CON	3-5	2-3	1	2.28-2.72	0.53-0.76	5	19	60-100	16-26
	CRV	2-3	2	0-1	1.80-2.09	0.60-0.94	5	19	40-60	11-16
	VIS	2-3	2	0-1	1.49-2.24	0.50-0.87	5	19	40-60	11-16
Sb2	CON	2-4	1	1-3	1.41-3.45	0.70-0.86	6	24	33-67	8-17
	CRV	**1**-3	1-2	0-1	**1.00**-1.81	0.60-1.00	6	24	17-50	4-13
	RHV	2-3	2	0-1	1.22-1.98	0.61-0.99	6	24	33-50	8-13
	SGV	2-3	1-2	1	1.60-2.00	0.60-1.00	6	24	33-50	8-13
Sb3	BRV	3-5	1-2	2-3	1.82-2.27	0.36-0.74	8	24	38-63	13-21
	CON	4-5	1-3	2-3	1.72-2.39	0.43-0.52	8	24	50-63	17-21
	CRV	3	2-3	0-1	1.41-2.49	0.47-0.83	8	24	38	13
	EZV	4-6	2-3	2-3	2.51-3.17	0.53-0.63	8	24	50-75	17-25
	RHV	4-5	1-3	2	2.59-4.17	0.65-0.83	8	24	50-63	17-21
	TLR	4	2	2	1.46-2.46	0.37-0.62	8	24	50	17

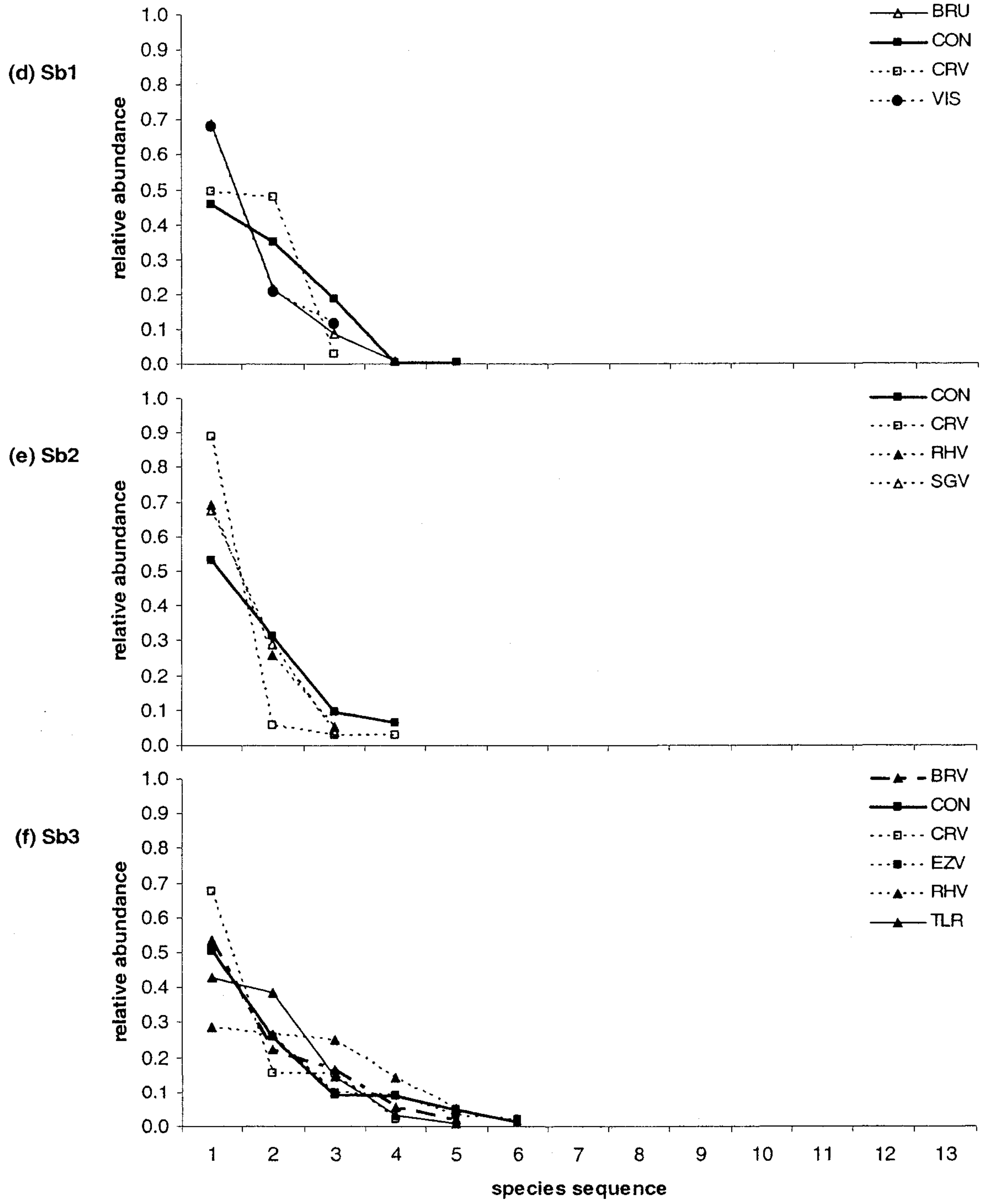
Results are expressed as ranges rather than averages to demonstrate the response variability across blocks within study sites. Tree-level monocultures in **bold.**[a] Refer to Table 2.1 for treatment codes; [b] Based on values from (Sims *et al.* 1989, Taylor *et al.* 2000); [c] Based on maximum values from (Thompson 2000)

Figure 2.2a-c. Dominance diversity curves for one white spruce (Sw1) and two jack pine (Pj1, Pj2) plantations in northern Ontario, ten years after alternative vegetation release treatments



For treatment codes *cf.* Table 2.1.

Figure 2.2 d-f. Dominance diversity curves for three black spruce plantations (Sb1, Sb2, Sb3) in northern Ontario, ten years after alternative vegetation release treatments



For treatment codes *cf.* Table 2.1.

Results for all study sites are presented in Table 2.2 and are expressed as ranges rather than means to demonstrate the response variability across blocks within study sites, and to show where the tree-level monoculture occurred (i.e. the treatment unit with both S and SRDI = 1.00). Of 94 experimental units, one tree-level monoculture was detected in one experimental unit at the Sb2 site in a CRV treatment.

It was expected that generalizations across studies would be difficult due to the wide variety of site factors (i.e. differences in ecoregions, pre-disturbance vegetation types, site histories, harvesting and site preparation methods and planted species), however one obvious trend was observed; both the VIS or CRV resulted in the least tree species diversity (lowest %LTSM and %RTSM) at the majority of the study sites. Furthermore, VIS or CRV selected conifers over hardwoods at most sites as indicated by the number of conifers and number of hardwoods in Table 2.2. Only the Sw1 site had an overall treatment effect ($p \leq 0.05$). Significant *a priori* comparisons ($p \leq 0.05$) of %LTSM and %RTSM included untreated control (CON) vs. Release herbicide (REL) at Sw1; CON vs. mist blower application of Vision (MBV) at Pj2; and CON vs. repeated annual applications of Vision (CRV) at Sb3 (Table 2.3).

Table 2.3. ANOVA results (p-values) for percent local theoretical species maximum (%LTSM), and percent regional theoretical species maximum (%RTSM)

Site	Contrast	%LTSM	%RTSM
Sw1	CON vs. BRU	0.95	0.65
	CON vs. REL	**0.03**	**0.02**
	CON vs. SIL	0.88	1.00
	CON vs. VIS	0.33	0.20
	Overall	**0.05**	**0.03**
	Std. Error	0.17	0.02
Pj1	CON vs. BRU	0.31	0.31
	CON vs. CRV	0.18	0.18
	CON vs. VIS	1.00	1.00
	Overall	0.39	0.39
	Std. Error	0.12	0.12
Pj2	CON vs. BBR	0.26	0.24
	CON vs. BRR	0.26	0.24
	CON vs. BRU	0.47	0.37
	CON vs. CRV	0.45	0.55
	CON vs. MBV	**0.01**	**0.01**
	CON vs. VIS	0.70	0.55
	Overall	0.07	0.06
	Std. Error	0.19	0.04
Sb1	CON vs. BRU	0.35	0.35
	CON vs. CRV	0.17	0.17
	CON vs. VIS	0.35	0.35
	Overall	0.53	0.53
	Std. Error	0.11	0.11
Sb2	CON vs. CRV	0.14	0.14
	CON vs. RHV	0.30	0.30
	CON vs. SGV	0.30	0.30
	Overall	0.46	0.46
	Std. Error	0.10	0.10
Sb3	CON vs. BRV	0.57	0.57
	CON vs. CRV	**0.04**	**0.04**
	CON vs. EZV	0.27	0.27
	CON vs. RHV	1.00	1.00
	CON vs. TLR	0.57	0.57
	Overall	0.09	0.09
	Std. Error	0.07	0.07

Bold values indicate significant p-values

2.6 DISCUSSION

Dominance-diversity curves are useful for graphically presenting community composition. In our study, some generalizations could be inferred by relating curve slope to Simpson's indices (SRDI, SEI). Since these indices are static (Burton 1993), however, their usefulness in temporally dynamic forest systems is limited. In spite of this, Simpson's diversity and evenness indices were included because they; (1) are widely used and accepted, (2) readily allow for comparisons between studies (e.g. Boyd *et al.* 1995; Pitkänen 2000; Roberts and Xhu 2002), and (3) provide a single value which accounts for species richness and abundance indicating relative differences among treatments.

Percentage of LTSM or RTSM, however, implicitly accounts for temporal changes based on a site's pre-disturbance potential, or theoretical species maximum (TSM) and species numbers after a disturbance (S), making it a good comparative tool for investigating changes in plant community diversity on anthropogenically disturbed sites. Regardless of whether LTSM or RTSM was used, the ANOVA produced either identical or very similar results (Table 2.3), suggesting that in the boreal forest, either LTSM or RTSM can be used.

Our first hypothesis states that applying alternative vegetation release treatments after clearcutting, site preparation and planting one conifer species, does not significantly reduce tree-diversity levels (%TSM) when compared to untreated control plots. Only three treatments indicated a significant difference when compared to an untreated control; at Sw1 CON vs. REL, at Pj2 CON vs. MBV and at Sb3 CON vs. CRV (Table 2.3). Of those three comparisons, only one treatment (CRV at Sb3) had a tree-diversity level less than CON (%TSM). Repeated annual treatments of herbicide (CRV) is very intensive, experimental and not is conducted in typical forest management. Alternative treatments - typically used in boreal forest management - will therefore likely produce similar tree-level diversity relative to untreated controll. The increase in tree-level diversity within the two experimental units may be the result of incomplete release treatment coverage (which is typical of spot treatments such as brushsaw) and/or the treatments not killing all the target plants.

2.6.1 The tree monoculture issue

Although we found one tree-level monoculture at the Sb2 site (CRV), previously published results from this site do not match our findings. At the Sb2 site, ten-years after release, Pitt *et al.* (2004) report that less than 11% competing tree cover on repeated annual herbicide application treatments (CRV), however, no tree-level monocultures were reported. This discrepancy between Pitt *et al.* (2004) and our research can be explained by differing field methods. Pitt *et al.* (2004) used 20 crop tree centered sampling sub-plots (4 m^2 each) within each experimental unit, while we used 3, 20 m^2 sampling transects within each experimental unit. Furthermore, we counted tree stems while Pitt *et al.* (2004) used tree cover. It is expected that cover measurements will take up a greater area and can include layering, thus, increasing the likelihood of any one plant being sampled. In effect, the methods reported in Pitt *et al.* (2004) increases the likelihood of sampling more tree species. For example, even if a tree's stem falls outside a plot, its cover (i.e. branches or leaves) may lean into a plot and be recorded.

Tree-level monocultures are of ecological interest, because of the perceived negative ecological effects such as reduced ecosystem functioning. Concerns about clearcutting, planting single species, and spraying prevail in the literature. While this suite of treatments often creates conifer dominated stands (Table 2.2), the only tree-level monoculture detected was on a site intensively treated with annually repeated applications of herbicide (Sb2, CRV), and sampled at the lowest intensity ($60m^2$ $exp.unit.^{-1}$). Species richness counts (S) were used in all calculations and results may have been affected by sampling intensity. Larger sampled areas will likely provide lists with greater species counts (Magurran 1988, Burton *et al.* 1992), therefore, the likelihood of identifying tree-level monocultures will be higher within smaller sampling areas. This small sampling unit may be too small to capture any reasonable amount of natural variation. Furthermore, mathematically rare species can be missed even in large samples (Lande 1996). Our results (especially from sites where sampling intensity was relatively low) therefore provide anecdotal evidence which supports Lande (1996).

The concept, "natural range of variability" (NRV) may help to explain the results. NRV is the range of spatial and temporal variation within an area of land in the absence of human influence (White and Walker 1997, Landres *et al.* 1999). Although we did not explicitly account for or measure NRV, it contributes to the variation between sites and sampling units, and provides insight into our results (i.e. manipulating nature cannot always produce predictable results because of naturally occurring variation).

However, the utilization of small sampling units was sufficient to disprove the tree-level monoculture hypothesis (i.e. tree monocultures develop after typical boreal silviculture) because only one tree-level monoculture was detected within one of the least intensively sampled experimental units (Sb2, CRV). As soon as a second tree species was detected within any given sampling unit, *we could reject the tree-level monoculture hypothesis*. Continuously removing vegetation by annual treatments of Vision may create a monoculture (as was the case with Sb2, CRV), but this will only occur if; (1) there is a single conifer species present, and (2) there is little chance for ingress from other tree species seed.

Within the sampling unit where the tree-level monoculture was detected (Sb2, CRV), non-tree vegetation sampled included; woody shrubs, herbs, grasses, ferns, sedges, mosses, and lichens (unpublished data). Thus, species monocultures (when accounting for non-tree vegetation classes) were not detected in any of the 94 experimental units across northern Ontario. Sites treated with repeated herbicide applications can be similar to afforested plantations, in that these plantations will be dominated by conifer trees. Our results are corroborated with results from a recent study investigating plant diversity on afforested, 50 year old tree plantations, which were formerly abandon agricultural lands. This study, indicates that although there was a reduction in overall plant diversity, no single species monocultures developed (Newmaster *et al.* 2006). Furthermore, the review article by Carnus *et al.* (2006) support our findings as well.

It is not surprising that the intensive herbicide treatment (CRV) produced tree-level monocultures. Pitt *et al.* (2000) suggests that annual herbicide treatments (such as CRV), can produce tree-level monocultures at stand maturity. However, repeated annual treatments of herbicide are very rarely used in Canadian forest operations because of high application costs and single applications of herbicides tend to be sufficient to accomplish the silvicultural objective of maintaining conifer dominated stands. It must also be recognized that conifer dominated tree-level monocultures do develop naturally in northern Ontario forests. Jack pine and black spruce monocultures or near monocultures, for example, can naturally occur on a range of sites without the influence of forestry activities (Rudolph and Laidly 1990, Viereck and Johnston 1990, Thorpe 1992, Johnson *et al.* 2003, Thompson *et al.* 2003).

If mimicking natural disturbances is to be employed in silviculture, forest managers and conservationists should manage individual sites on the landscape for a variety tree diversities, which can legitimately include tree-level monocultures. However, it should *not* be the goal of silviculture to produce tree-level monocultures *on the landscape level* or on sites that historically sustained a greater tree diversity. The latter must be tempered by an understanding of the succesional dynamics of boreal stands that may include near or pure tree-level monocultures as part of a stand's development over time. Furthermore, in order to mimic natural disturbance (i.e. replacing upland conifer dominated stands *with* conifer dominated stands with similar tree species diversity, composition and structure), likely requires the use vegetation release treatments within the silvicultural regime (Pitt *et al.* 2000; Haeussler *et al.* 2004; Pitt *et al.* 2005). Without vegetation release, it is likely that upland sites previously dominated by conifer will be replaced with mixedwoods.

2.7 CONCLUSION

Our first hypothesis stated that applying alternative release treatments after clearcutting, site preparation and planting one conifer species, does not significantly reduce diversity levels (%TSM) relative to untreated control. Our findings generally support hypothesis one. Although tree-level diversity was significantly reduced in one experimental unit (of the 94!), tree-level diversity either remained the same or significantly increased. Furthermore, an overall treatment effect was detected at only one site (Sw1).

Our second hypothesis, stated that tree-layer monocultures do not develop after typical boreal silviculture is applied post-harvest. Our findings support hypothesis two. Only one out of 94 experimental units did develop into a tree-layer monoculture, but this was within an experimental unit that was treated with a repeated annual application of herbicide, which is atypical of boreal forest silviculture. Further, sites with low pre-disturbance tree-diversity may be ideal candidates for small scale intentional tree monocultures on the landscape, in order to emulate a range of natural variability over the whole landscape.

Our study partially, addresses claims that clearcutting followed by site preparation, planting and chemical or motor-manual tending reduces tree-level biodiversity (May 2005) to the point of creating tree-level monocultures (Mosquin *et al.* 1995). We only provide evidence which contradicts Mosquin *et al.*'s (1995) claim that tree-level monocultures develop after silviculture disturbance. A false linkage between reforestation (opposed to afforestation) and monoculture creation exists. Mosquin *et al.* (1995, 72) correctly states that tree plantations established on "lands marginal for agriculture" (afforestation) tend to be monocultures. Indeed, many of Canada's oldest tree plantations *were* established on former agriculture fields (with no trees present, pre-plantation); hence, the straight rowed, single species monocultures. When these plantations were established, it would have been next to impossible to create these monocultures within a forestry context where the tools of the period included; horse with fire plow, stock shipped in from outside the region, and manual weeding by hand - *unless* the planting sites *were* former agriculture fields.

Monocultures do exist, but they are extremely unlikely to develop through typical current Canadian reforestation efforts unless a forest manager can afford multiple herbicide treatments spanning years. Mosquin *et al.* (1995, 72) implies that the practice of "planting single or low numbers of species over large holdings of recently logged public forest lands, coupled with spraying [herbicides] for commercially undesirable species" creates monocultures. This practice *does not* generally create tree-level monocultures in Canada. Applying herbicides can change stand characteristics, however, and influence future development and composition. Without the use of herbicides forest management objectives may not be met. The use of herbicides will likely ensure that harvested conifer-dominated stands are replaced with productive conifer-dominated stands (Wagner *et al.* 2006) with similar pre-harvest tree species diversity.

In order to address May's (2005) claims, we would have needed to relate the tree-level diversity of our study sites' to natural process stands with same age and similar characteristics. Future research should include comparing the silvicultural prescriptions included in this study to natural process stands, to compare how well silviculture treatment prescriptions emulate naturally disturbed early stands (e.g. fire-origin stands).

2.8 NOTES

[1] Crown Forest Sustainability Act [CFSA], 1994. S.O. 1994, CHAPTER 25

[2] Also known as alien species which are introduced via human activities.

[3] We used the Forest Sciences Database, keyword search, searching all fields, limiting search to "Journal Articles" from "09/2005 to 1939." for the basis of this claim. Query 1 = (boreal) = 5038 records; and Query 2 = (boreal) and ((tree biodiversity) or (tree diversity) or (tree species richness)) = 5 records. Of the articles with keyword "boreal" only 0.1% met our "tree diversity" search criteria. Source: Forest Sciences Database. 1997-2005. WebSPIRS. Ovid Technologies. Version 5.1. Build 20050721.

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3.0 PAPER 2:
CUTTING VERSUS HERBICIDES: TENTH-YEAR VOLUME AND RELEASE COST EFFECTIVENESS OF SUB-BOREAL CONIFER PLANTATION[5]

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3.1 KEY WORDS

clearing saws, competition, forest vegetation management, glyphosate, Great Lakes – St. Lawrence Forest, herbicide alternatives, mixedwood, pesticide, release treatment, triclopyr, weed

3.2 ABSTRACT

Few cost effectiveness studies of vegetation management in conifer plantations are reported in the literature. This study provides follow up cost effectiveness analysis from research conducted at the Fallingsnow Ecosystem Project in northwestern Ontario, Canada with the objective of determining the relationship between release treatment costs and planted white spruce (*Picea glauca* [Moench] Voss) stem volume (\$ m^{-3}) ten years post-treatment. Treatment cost estimates for 2003 were calculated by applying 1993 time-study data to estimated 2003 market costs for each treatment component. The most cost effective treatment was the aerial application of herbicide Vision® (\$12.16 m^{-3}), followed by the aerial application of herbicide Release® (\$12.18 m^{-3}), cutting with brushsaw (\$38.38 m^{-3}) and mechanical tending by Silvana Selective (\$42.65 m^{-3}). No cost differences were found between the herbicide treatments ($p = 0.998$) or between the cutting treatments ($p = 0.559$). The herbicide treatments were three-fold more cost effective than the cutting treatments ($p = 0.001$). Since no treatment cost was associated with the control plot, it was not included in the ANOVA. This analysis only considered the planted conifer component of these young stands.

3.3 INTRODUCTION

Economic efficiency is becoming increasingly important in the Canadian forest sector, largely due to tough international competition (NRCan 2002). For example since 1990, Canada has become less competitive in global markets, due to successes in Scandinavian and Southern Hemisphere countries (NRCan 2003). Other countries have shown major gains in forest productivity resulting from more intensive silviculture (including major investments in regeneration, release treatments and other stand tending) (NRCan 2003). This international competition, as well as uncertain local wood supplies, are causing members of the forest industry in Canada to consider broader use of more intensive silviculture (NRCan 2002), both to maintain Canada's international economic competitiveness and to meet global demand for Canadian wood products (NRCan 2002, NRCan 2003).

Long-term economic forest research in Canada is very important (McKenney *et al.* 1997). Although many studies provide economic insight into plantation silviculture (McKenney *et al.* 1992, Richardson 1993, Biblis *et al.* 1998, Holgen *et al.* 2000, George and Brennan 2002, Ahtikoski and Pulkkinen 2003, Huang and Kronrad 2004, Kimberley *et al.* 2004), only one such North American boreal study investigates vegetation release treatment (controlling weed species with herbicide and non-herbicide options) cost effectiveness (Bell *et al.* 1997a). This is corroborated by the review paper by Thompson and Pitt (2003). Of the 1256 scientific publications that directly related to forest vegetation management (NRCan 2004) only 18 publications (1.4%) were related to forest vegetation management treatment economics across all Canadian forest types, with only the abovementioned study in the boreal conifer context.

Work presented here is important due to the dearth of published vegetation management treatment cost data for North American boreal conifer plantations. Furthermore, Pitt *et al.* (1999) emphasize that longer-term growth data are needed for cost and economic analysis of vegetation management options. This study is a follow up cost effectiveness analysis (CEA) to work by Bell *et al.* (1997a) at the Fallingsnow Ecosystem Project. Our objectives were to determine the relationship between release treatment costs and juvenile white spruce stem growth (\$ m^{-3}) (Willcocks *et al.* 1990) in a plantation 10-years after alternative release treatments and to provide baseline economic information to those considering more intensive forest management.

3.4 METHODS

Short- and long-term ecological consequences of alternative conifer release treatments are being evaluated in the Fallingsnow Ecosystem Project, which was established as a randomized complete block design. The research site (48°8-13'N, 89°49-53') is approximately 60 km southwest of Thunder Bay, Ontario, and is located in the transition between the boreal and the Great Lakes-St. Lawrence forests (Rowe 1972). From 1986 to 1988, three 75- to 101-year-old stands, were clear cut. Each stand formed one block that is 20-ha or larger. Within each block, each treatment covers a minimum of 4-ha.

Harvested blocks were planted with 82-cm tall, bareroot white spruce (*Picea glauca* [Moench] Voss) stock (2+2) between 1986 and 1989, with 2- to 2.5-metre spacing. Planting was followed by alternative release treatments in 1993 (Bell *et al.* 1997b), that included: (1) motor-manual cutting by hand-held brushsaws (18-cm above the ground line in mid- to late-October), (2) mechanical cutting by a Ford tractor mounted with a parallelogram boom with a Silvana Selective cutting head attached to the boom (33-cm above ground line in late October to early November), (3) glyphosate herbicide (Vision®) applied at 1.5-kg acid equivalent per hectare (kg-a.e. ha^{-1}) delivered aerially by a Bell 206 helicopter in August and (4) triclopyr herbicide (Release®) applied at 1.9-kg a.e. ha^{-1} delivered aerially by a Bell 206 helicopter in August, and (5) no release treatment (control) (Bell *et al.* 1997a).

3.4.1 Treatment Productivity

Release treatment productive machine hours (PMH) or time that brushsaw, Silvana Selective, or helicopter were working was recorded for each block during detailed time studies (Bell *et al.* 1997a). Only costs associated with treatment and field supervision were included in cost calculations. Costs do not include treatment planning, reconnaissance, layout, monitoring, public meetings, or obtaining pesticide permit applications.

3.4.2 Tree Stem Volume and Density

Sampling of tenth-year growth characteristics (stem diameter, height, density) in early September 2003 were used to calculate tree volume for each treatment area (experimental unit). Six, 10-m x 2-m transects were randomly laid out in each treatment area. Restrictions on randomization included; transects that overlapped, transects that fell within 20 m of roads, and transects that had exposed bedrock or standing water. For each white spruce falling within the sample plot boundaries, diameter at 130 cm above ground (DBH, nearest 0.1 cm, diameter tape) and height (nearest 0.1 m, height poles) were recorded. These two metrics were used to calculate individual-tree gross total volumes (GTV) using Honer's Standard Volume Equation (Eq. 1) (Honer *et al.* 1983).

$$GTV = (0.0043891*D^2(1-0.04365*0.176)^2)/1.440 + 1.3048*342.175/H) \qquad \text{[Eq. 1]}$$

where GTV is gross total volume; D is diameter at breast height measured in centimetres; and H is total height measured in metres.

Tree counts were used to generate an average stem density for each experimental unit and expressed as stems ha^{-1} (sph). Stem densities were multiplied by the average GTV for each experimental unit to generate an estimate of gross volume per hectare (GTV ha^{-1}).

3.4.3 2003 Cost Estimates

Treatment cost estimates for 2003 were calculated by applying 1993 time-study data (Bell *et al.* 1997a) to estimated 2003 market costs for each treatment component. Brushsaw and Silvana Selective treatment costs were estimated based on 2003 cost assumptions (Tables 3.1 and 3.2). Total costs for brushsaw treatments in 1993 were \$173.91 per day; \$21.74 per Scheduled Machine Hour (\$ SMH^{-1}) and \$30.62 per PMH (\$ PMH^{-1}). Total costs for Silvana Selective in 1993 were \$63.07 SMH^{-1} and \$74.20 PMH^{-1} (Bell *et al.* 1997a).

Table 3.1. Actual 1993 and estimated 2003 costs for one brushsaw operator working on a conifer release treatment.

	1993 (Bell et al. 1997)	**2003**
Scheduled hours per day	8	8
Labour rate for operator ($ h^{-1})	$13.70	$25.00
Direct labor cost ($ day^{-1})	$109.61	$200.00
Fringe benefits (%)	20.0%	25.6%
Fringe benefits cost ($ day^{-1})	$21.92	$51.26
Labour cost for operator ($ day^{-1})	$131.53	$251.26
Saw cost (incl. depreciation, gaz blades, files and repairs)	$19.70	$25.00
Other costs (transport and supervision @15% of labour and saw)	$22.68	$41.44
Utilization (%)	71%	71%
Total cost		
per day	***$173.91***	***$317.70***
per productive machine hour	***$30.62***	***$55.93***
per scheduled machine hour	***$21.74***	***$39.71***

Table 3.2. Cost analysis for a cleaning machine used in forestry release operations in 2003

Scheduling	
Hours/day	16
Days/week	5
Weeks/year	25
Scheduled hours/year (SMH)	2000
Estimated life of machine (years)	5
Estimated life of machine (SMH)	10000
Scheduled hours/year (SMH)	2000
Purchase price ($)	$400,000.00
Salvage value ($)	$60,000.00
License ($\$\ \mathrm{year}^{-1}$)	$0.00
Insurance ($\$\ \mathrm{year}^{-1}$)	$8,000.00
Interest rate (%)	8%
Utilization (%)	80%
Estimated life of machine (PMH)	$8,000.00
Lifetime repair cost ($)	$300,000.00
Fuel consumption ($\mathrm{l\ PMH}^{-1}$)	$7.50
Fuel cost ($\$\ \mathrm{l}^{-1}$)	$0.45
Oil & lubrication ($\$\ \mathrm{PMH}^{-1}$)	$0.25
Operator wages ($\$\ \mathrm{SMH}^{-1}$)	$20.00
Fringe benefits (%)	25%
Administration and profit (%)	10%
Fixed costs	
Annual capital cost	$89,955.19
Annual other costs	$8,000.00
Annual total	$97,955.19
Cost per PMH	$61.22
Cost per SMH	$48.98
Variable costs	
Cost per year	$67,250.00
Cost per PMH	$34.53
Cost per SMH	$33.63
Labour costs	
Cost per year	$50,000.00
Cost per PMH	$31.25
Cost per SMH	$25.00
Administration and profit	
Cost per year	$21,520.52
Cost per PMH	$13.45
Cost per SMH	$10.76
Total costs[1]	
Total per year	$236,725.71
Total per PMH	$147.95
Total per SMH	$118.36

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[1] Total costs would likely be higher because supervision and overhead were not accounted for.

Estimated aerial spray treatment costs for 2003 were based on the selling price of Release and the manufacturer's suggested retail price (MSRP) of Vision, using label mixing ratios and actual 1993 application rates. In 2003, the selling price of Release was \$30.00 per litre (\$ L^{-1}) (Darren Dillenbeck, Dow AgroSciences INC, Sault Ste. Marie, ON, *pers. comm.*) and the MSRP of Vision was \$14.50 L^{-1} (Roy Maki, Monsanto Canada INC, Thunder Bay, ON, *pers. comm.*) (Table 3.3).

Table 3.3. Manufacturers' suggested retail price (2003), product concentration, application rate (Bell *et al.* 1997a) and herbicide cost per ha based on application rate.

	MSRP (\$ L^{-1} concentrate)	Product concentrate (kg a.i. L^{-1})	Application rate (kg a.i. ha^{-1})	Cost (\$ ha^{-1})
Release ®	\$30.00	0.480	1.9	\$118.75
Vision ®	\$14.50	0.356	1.5	\$61.10

Many factors influence aerial herbicide application pricing, such as the total size of program in hectares, spray block locations and size, total application volume, and contractor supplied resources. A rotary wing spray program will vary depending upon the abovementioned factors from approximately \$45.00 ha^{-1} to \$70.00 ha^{-1} (Paul Zimmer, Zimmer Air Services INC., Thunder Bay, ON, *pers. comm.*). The estimated aerial spray contract rate used for this study was \$65.00 ha^{-1}, which includes helicopter, pilot, mixer crew, and two block security workers (James Harrison, Greenmantle Forestry INC., *pers. comm.*). Sensitivity analysis was conducted over the range of helicopter rates.

Since no vegetation release treatment cost is associated with the untreated control (i.e. doing nothing; \$0.00 ha^{-1} and a resultant cost effectiveness value of \$0.00 m^{-3}), it was not included in the analysis. If we were to include untreated control in a cost effectiveness analysis, it would suggest that untreated control would always be the most cost effective treatment, even if spruce GTV production was *very* low. Furthermore, untreated control was also not included in the analysis because planting costs are high, necessitating the need to protect the conifer planting investment by vegetation release. For example, in 2003, approximate planting costs for container stock in northwestern Ontario ranged from about \$425 ha^{-1} to \$525 ha^{-1} (based on a planting density of 2500 sph; A. Dorland, Haveman Brothers Forestry Services, Thunder Bay, ON, *per. comm.*).

The treatment cost estimates (\$ ha^{-1}) were then applied to the volume per area measurements (m^3 ha^{-1}) to determine cost effectiveness expressed as treatment cost to planted conifer volume growth (\$ m^{-3}) for each experimental unit (which is the response variable used in the ANOVA).

3.4.4 Analysis of Variance (ANOVA)

Analysis of variance was conducted using SAS® (SAS Institute Inc. 1989) following the linear model (Steel and Torrie 1980):

$$Y_{ij} = \mu + B_i + T_j + \varepsilon_{ij} \qquad \text{[Eq. 2]}$$

$i = 1, 2, 3;\ j = 1, 2, 3, 4$

where Y_{ij} is the measured response from the ith block and the jth treatment; μ is the overall mean; B_i is the random effect of the ith block; T_j is the fixed effect of the jth release treatment; ε_{ij} is the interaction effect of the ith block with the jth release treatment (the error term for testing the fixed treatment effects).

Planned orthogonal contrasts (Wine 1964, Wendorf 2004) were conducted using the SAS® Proc GLM (SAS Institute Inc. 1989). Comparisons included brushsaw vs. Silvana Selective; Release vs. Vision; and herbicide vs. cutting. The untreated control plots were not included in the ANOVA because there is no cost associated with the treatment. Diagnostic normal probability plots of model residuals and side-by-side dot plots of residuals were used to verify that the assumptions of normality and homogeneity of variance were met.

3.5 RESULTS

Averaging across all blocks, the Release treatment produced the greatest white spruce volume, followed by Silvana Selective, Vision, brushsaw and control (no treatments) (Table 3.4). The Vision treatment was most cost effective, followed by Release, brushsaw, and Silvana Selective.

Sensitivity analysis was conducted over the entire range of helicopter contractor rates (\$45.00 ha^{-1} to \$70.00 ha^{-1}). Over this range, aerial spray of herbicide remained the most cost effective relative to other treatments. For example, cost effectiveness for the Release and Vision treatments at the contractor rate of \$45 ha^{-1} were estimated to be \$10.86 m^{-3} and \$10.23 m^{-3} respectively; at the contractor rate of \$65 ha^{-1} (the rate used in this study), they were estimated to be \$12.18 m^{-3} and 12.16 m^{-3} respectively; and at the contractor rate of \$70 ha^{-1}, they were estimated to be \$12.52 m^{-3} and \$12.65 m^{-3}, respectively. The value of \$45 ha^{-1} doesn't capture *all* the associated aerial spray costs (i.e. helicopter, pilot, mixer crew, and two block security workers) because this rate is based on the assumption that some resources are supplied by the forest manager (i.e. block security workers, etc.). The estimated aerial spray contract rate used for this study was \$65.00 ha^{-1}, because this value closely reflects the 2003 rate for contractor provided services.

The ANOVA performed on the cost per volume data (Table 3.5) indicates no difference between a priori hypotheses: Brushsaw and Silvana ($p = 0.559$) and Vision and Release ($p = 0.998$). Since this similarity was detected, the mean for cutting was \$40.52 m^{-3} (standard error 3.46) and the mean for herbicide was \$12.17 (standard error 3.46). Overall, the two herbicide treatments were found to be three-fold more cost effective than the two cutting treatments (least dollars invested to gross total volume produced [\$ m^{-3}]) (Table 3.4). A highly significant difference was detected when the herbicide and cutting treatments were compared ($p = 0.001$).

Table 3.4. White spruce volume, density, release treatment productivity, cost to treatment area ratios, and cost to volume ratios by block and conifer release treatment compared for 1993 and 2003.

	Treatment				
	Brushsaw	**Silvana**	**Release**	**Vision**	**Control**
Block I[1]					
Gross Total Volume (m^3 ha^{-1})	9.24	10.79	11.29	8.06	5.85
Density (sph)	2500	2583	2500	2583	2417
Productive machine hours (h ha^{-1})	10.20	3.73	na	na	na
1993 cost per area ($ ha^{-1})	312.32	276.77	152.51	151.93	na
2003 cost per area ($ ha^{-1})	570.49	551.85	183.75	126.10	na
2003 cost per volume ($ m^{-3})	61.77	51.13	16.27	15.65	na
Block II					
Gross Total Volume (m^3 ha^{-1})	12.80	13.46	23.83	11.56	6.77
Density (sph)	2667	2750	2750	2750	2667
Productive machine hours (h ha^{-1})	6.53	3.85	na	0.01	na
1993 cost per area ($ ha^{-1})	201.48	285.67	152.51	151.93	na
2003 cost per area ($ ha^{-1})	365.22	569.61	183.75	126.10	na
2003 cost per volume ($ m^{-3})	28.53	42.31	7.71	10.91	na
Block III					
Gross Total Volume (m^3 ha^{-1})	6.71	12.21	14.62	12.69	9.30
Density (sph)	2750	2833	2833	2917	2833
Productive machine hours (h ha^{-1})	2.98	2.85	0.01	0.01	na
1993 cost per area ($ ha^{-1})	91.25	211.47	152.51	151.93	na
2003 cost per area ($ ha^{-1})	166.67	421.66	183.75	126.10	na
2003 cost per volume ($ m^{-3})	24.84	34.53	12.57	9.93	na
Average					
Gross Total Volume (m^3 ha^{-1})	9.58	12.16	16.58	10.77	7.31
Density (sph)	2639	2722	2694	2750	2639
Productive machine hours (h ha^{-1})	6.57	3.48	0.01	0.01	na
1993 cost per area ($ ha^{-1})	201.68	257.97	152.51	151.93	na
2003 cost per area ($ ha^{-1})	367.46	514.37	183.75	126.10	na
2003 cost per volume ($ m^{-3})	38.38	42.65	12.18	12.16	na
Standard Error	4.89	4.89	4.89	4.89	na

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[1] Since block one was destroyed (*c.f.* Bell *et al.* 1997a), blocks were renumbered in this study as follows: Block I = Block 2; Block II = Block 3; and Block III = Block 4.

Table 3.5. Analysis of variance results with orthogonal contrasts for cost per volume (\$ m^{-3}) for vegetation release treatments in a white spruce plantation.

Source	df	SS	MS	F-ratio	F-crit (0.05)	F-crit (0.01)	Prob
Constant	1	8329.77	8329.77				
Block	2	590.279	295.139				
Treatment	3	2437.79	812.595	11.322	4.76	9.78	0.007
Vison vs. Release	1	0.0005198	0.0005198	7.24E-06	5.99	13.7	0.998
Brushsaw vs. Silvana	1	27.360587	27.360587	0.381	5.99	13.7	0.559
Herbicide[1] vs. Cutting[2]	1	2410.424	2410.424	33.585	5.99	13.7	0.001
Error (Block*Treatment)	6	430.621	71.7702				
Total	11	3458.69					

[1] Vision and Release
[2] Brushsaw and Silvana Selective

3.6 DISCUSSION

Cost effectiveness analysis and other analyses that attempt to link biological responses to silviculture treatment costs (and other economic indicators) are important but appear infrequently in the literature. Forest companies, however, usually keep detailed records of treatment costs and resultant crop tree response over time. This study provides information that can be used to augment company records and influence future silviculture decision-making.

Admittedly, benefit cost analysis (BCA) is superior (Pearse 1990) to a CEA in that the former compares financial returns (value) on release treatment investment, while the latter only compares release treatment cost effectiveness (dollars invested to spruce volume produced) among treatments with no regard for potential product value. After only ten years of growth post-vegetation release, these stands have virtually no current market value. The stands in this study will likely need to grow for at least another twenty years to reach harvestable volumes, at which time market value for the product may have changed substantially. A BCA was therefore not pursued in this paper because many ecological and economic uncertainties exist until the time when stands will likely be harvested. Consider Pearse's (1990:121) comment;

> "Future costs and revenues associated with forestry projects are often highly uncertain, especially when they are based on predictions spanning several decades. Knowledge about how stands grow and respond to treatments is always limited. Expectations about future harvests can be upset by unpredictable events such as fire and other natural catastrophes. And the technology, product prices, and production costs assumed in making predictions are likely to change in unforeseeable ways."

Aerial herbicide applications were most cost effective mainly due to a very low application cost per hectare and a relatively high volume growth response. The aerial application of Release herbicide produced a high average GTV per hectare (16.58 m^2 ha^{-1}, Table 3.4) because it allowed for some post-treatment competition which encouraged white spruce to shift biomass allocation from branch to stem (Jobidon 2000, Pitt and Bell 2004). The change in allocation may have the secondary benefit of potentially increasing future wood quality. Future sampling will need to assess for wood quality and other indicators that could be indicative of potential products and value. Furthermore, Legare *et al.* (2004) suggests that 5% to 15% aspen (*Populus spp.*) basal area in black spruce (*Picea mariana* [Mill.] BSP) stands could increase economic value per hectare. In and of itself, hardwood fibre has the potential to increase the economic worth of socalled "lower grade" forests as new products and processes (i.e. biofuels, engineered wood products) have been developed, and will likely develop in the future.

Assessment of surviving trembling aspen (*Populus tremuloides* Michx.) in the Release treatment during field data collection showed that some individuals were not killed (Greifenhagen *et al.* 2005). These individuals possess telltale 'crooks' in their stems indicating Release induced rapid cell growth but not death. Reduced efficacy is likely due to application timing. Release herbicide is most effective in controlling broadleaf competitors (with minimal effect to conifers and monocots) when applied during active competitor growth, i.e., early to mid-summer (Dow AgroSciences 2002). The Release treatment may have also been less biologically effective due to relatively low herbicide deposit rates (Thompson *et al.* 1997).

Unlike Release, Vision applied in late summer was very effective in controlling competing vegetation while protecting conifers. Since leaf litter from competing vegetation can enrich the soil, it is possible that good spruce growth rates in Release, can be due to the beneficial effects of some competing vegetation's litter, such as encouraging nutrient cycling, enriching the soil, and reducing soil acidification (Cote and Fyles 1994, Krause 1998, Perie and Munson 2000). The benefits of leaf litter was not realized in the Vision treatment where competition was low relative to Release. These differences in stem volume influenced the CEA. Treatments that were moderately efficacious (*c.f.* Pitt and Bell 2005) in controlling competition (Release and Silvana Selective) produced more spruce stem volume (Table 3.4).

The MSRP for Vision in 2003 was \$14.50 L^{-1}., however, it generally sells for less (Roy Maki, *pers. comm.*). Since Release is sold through agents with set pricing, the product was sold for \$30.00 L^{-1} across Canada in 2003, with no variation in purchase price (Darren Dillenbeck, *per. comm.*). Since Vision can be purchased for less than the MSRP (the price used in this study), Vision treatments can be more cost effective than reported here. Aerial spray costs in typical management operations will likely be lower than the values reported in this study (Table 3.4) because operational sites differ from the small, irregularly shaped treatment blocks and rolling terrain at the Fallingsnow Ecosystem Project. Furthermore, aerial spray cost effectiveness in the study may have been skewed because any aerial application that does not have GPS-assisted guidance (either on-ground or in the air) will compromise application uniformity. As a result, some "green striping" or missed slivers occurred (Bell *et al.* 1997b). Release and Vision treatments had similar cost effectiveness values ($p = 0.998$) which likely had more to do with differences in herbicide purchase prices in 2003 (Table 4) than with growth responses.

Brushsaw and Silvana Selective cutting treatments had similar cost effectiveness values ($p = 0.559$). This can be partially attributed to similar post-treatment responses. In the cut treatments, sprouting and suckering of trembling aspen and other competitive species was evident. Brushsaw and Silvana Selective treatments can be optimized through proper treatment timing and technique. There seems to be an ideal level of aspen (not too high, nor to low) that encourages white spruce production and overall productivity (Man and Lieffers 1999). Cutting competing vegetation in June or July rather than October may provide maximum stem mortality (while still allowing for low levels of competing vegetation) thus reducing the number of post-treatment sprouts and suckers (Bell *et al.* 1999). The ideal balance between the spruce and aspen can lead to increased crop tree volume growth response. Furthermore, the cost of both cutting treatments increased at similar rates from 1993 to 2003 (brushsaw = 82.5%; Silvana

Selective = 99.4%), probably due to commensurate increases in labour and equipment costs. Brushsaw cutting effectiveness is highly dependent on pretreatment stem density; mechanical and herbicide treatment are not affected by this factor. Our CEA is based on average stem density and does not explicitly take this cost factor into account.

Cutting is often seen as a good alternative to herbicides but limitations such as availability of a trained labour force and equipment can exist. Similar cost effectiveness of the two cutting treatments suggests that the Silvana Selective or other mechanical plantation cleaning machines (Ryans and Lirette 2003) may be more suited to geographic areas where worker shortages exist. Forestry field worker shortages have been attributed to poor work conditions including high physical stress, risk of accidents, and seasonal nature of work (Dubeau *et al.* 2003).

Availability of mechanical plantation cleaning machines is another issue. The Silvana Selective is not presently available to Canadian markets and few alternative mechanical plantation cleaning machines exist. The mechanical plantation cleaning machine estimate (Table 3.2) is based on what one might expect to pay to purchase, operate and maintain a machine similar to the Silvana Selective. If market pressures encourage Canadian distributors to supply this equipment, it could become available in the future.

Treatments that provide the greatest cost effectiveness may not necessarily be the most socially acceptable. When managing public forests, the broader social context, such as negative perceptions of aerial herbicide application, must also be considered. Based on surveys, the general public in Ontario deems herbicide use on publicly-owned forests unacceptable (Buse *et al.* 1995, Wagner *et al.* 1998). Furthermore, in the province of Quebec, most pesticides have been banned (Reuters News Service 2002).

Although the general trend in Ontario is to plant densities of around 2500 sph, results from this project suggest that white spruce plantations might benefit from higher initial stocking levels. These densities could be achieved through both conifer and hardwood crop tree species. Higher initial crop tree densities are particularly important if broadcast vegetation management treatments are to be applied. Day and Bell (1988) recommended white spruce crop plans based on established densities of 1900 sph. This estimate, made at a time when empirical data were limited, influenced initial stocking of the Fallingsnow Ecosystem Project.

3.7 FINAL REMARKS

The CEA of conifer release treatments relies on good initial time study data and good treatment cost estimates through time. This study is one of only a few North American CEAs of northern conifer plantation release treatments reported in the literature; therefore, results must be confirmed by other studies. Results from this study can be used to supplement existing industry documentation, but forest managers must continue to maintain detailed costing records to determine cost effectiveness for their own situation. Future research needs include growth and vegetation release cost analysis for other conifer species. Furthermore, cost analysis data gaps exist because broadleaf trees were previously considered undesirable and possessed limited value (i.e. trembling aspen). Future studies and future sampling at Fallingsnow Ecosystem Project should develop field techniques that capture potential stand values (i.e. sampling for quality, not just volume) in order to facilitate a BCA. Field sampling could include destructive sampling to test for wood properties which can be linked to values.

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4.0 CONCLUSIONS:
CAN VEGETATION RELEASE TREATMENTS BE COST EFFECTIVE, WHILE STILL MAINTAINING BIOLOGICALLY DIVERSE BOREAL FORESTS?

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Typical conifer release alternatives in Ontario's boreal and boreal / Great Lakes – St. Lawrence (GLSL) forests include (1) broadcast aerial application of herbicides (usually glyphosate), (2) motor-manual cutting with brush saw and, (3) no treatment (Fig 4.1), with aerial herbicide application of glyphosate being the predominant vegetation control method (Wagner *et al.* 1995). As typically applied, these three treatments sit on a gradient of removal *intensities*, (i.e. incremental reductions in competing vegetation that lead to increased conifer growth), with aerial herbicide application being most intense (efficacious), brush saw being moderately intense and untreated being least intense.

(a) (b) (c)

Figure 4.1. Three typical boreal forest vegetation release treatments. (a) A helicopter equipped with spray booms for aerial application of herbicides (Source: Zimmer Air Services, Inc); (b) A motor-manual cutting treatment with brush saw (Source: Forest Ecosystem Research Network of Sites (FERNS); (c) no treatment (Source: FERNS).

On sites where vegetation treatment is not absolutely essential to maintain conifer stocking and growth, the most *cost effective* treatment would obviously be to leave the plantation untreated. Although this is an inexpensive alternative, its overuse may result in an unacceptable number of stands that do not meet regeneration objectives established under the forest management plan. The next most cost effective treatment (least dollars invested to conifer gross total volume [\$ m^{-3}]) is the aerial application of herbicide, since conifers show good volume response to this relatively low priced treatment (Table 4.1). The least cost effective treatment is the brush saw treatment because it shows relatively poor conifer volume response while being most expensive (Table 4.1). Brush saw efficacy may be increased if proper timing and techniques are employed (Stoeckeler 1947, Bell 1991), although this may increase treatment costs.

Cost effective forest practices which include clear cutting, followed by site preparation, planting, and aerial herbicide or cutting application (NRCan 2004), are employed by the Canadian forest industry. These practices have been criticized for their potential to reduce biodiversity (May 2005) to the point of creating monocultures (Mosquin *et al.* 1995). The vegetation release treatments evaluated in this effort were not appreciably different in terms of ten year post-treatment tree diversity and, in general, produced relatively low tree diversity levels overall (Table 4.1). These results are corroborated with other sources. Low tree diversity is common in northern Ontario, with typical stand compositions in this region ranging from four to eight tree species (Sims *et al.* 1989, Taylor *et al.* 2000). Furthermore, it is not uncommon for tree level monocultures to develop naturally in northern Ontario forests. Jack pine and black spruce monocultures or near monocultures, for example, can naturally occur on a variety of sites without the influence of forestry activities (Rudolph and Laidly 1990, Viereck and Johnston 1990, Thorpe 1992, Johnson *et al.* 2003, Thompson *et al.* 2003).

Table 4.1. Estimated treatment cost, gross total volume, cost effectiveness and tree diversity for juvenile stands released in Ontario's boreal forest

Treatment	**Est. treatment cost[1] ($ ha^{-1})**	**Conifer gross total volume[2]**	**Cost effectiveness[3]**	**Tree diversity[4]**
Aerial herbicide	100.00 to 150.00	High	High	Low
Brush saw	200.00 to 500.00	Moderate	Low	Low
No treatment	0.00	Low	Zero	Low

[1] ranges based on estimates provided by silviculture contractors;
[2] expressed at m^3 of volume per ha (m^3 ha^{-1})
[3] expressed as dollars of vegetation release treatment invested by gross total volume of conifer ($ m^{-3}), high cost effectiveness will have a low $ m^{-3} value, a low cost effectiveness value will have a high $ m^{-3} value;
[4] tree species diversity as measured by SRDI and %TSM, all treatments had similar %TSM responses and were not significantly different from each other.

4.1. IMPLICATIONS FOR THE FORESTER

In deciding which vegetation release treatment to employ (if any), both treatment cost and potential crop tree growth responses must be considered. From a strictly tree species diversity standpoint, responses were very similar across the gradient of removal intensities. Since treatments did very little to change tree species diversity, it might be tempting to disregard diversity in the treatment decision making process. However, it is clear that differing diversity responses are expected when looking at other factors such as structural diversity, or non-tree layer diversity (Esseen *et al.* 1997, Archibold *et al.* 2000, Boateng *et al.* 2000, Reich *et al.* 2001, Bell and Newmaster 2002, Rees and Juday 2002, Hunt *et al.* 2003, Haeussler *et al.* 2004, Pitt and Bell 2005). Furthermore, applying herbicides can change stand characteristics and influence future development and composition. Without the use of herbicides, or other vegetation release treatments, forest management objectives may not be met. The use of herbicides will likely ensure that harvested conifer-dominated stands are replaced with productive conifer-dominated stands (Wagner *et al.* 2006) with similar pre-harvest tree species diversity.

If mimicking natural disturbances is to be employed in silviculture, forest managers should manage for a diversity of varyingly diverse sites on the landscape, which can legitimately include monocultures. However, it should *not* be the goal of silviculture to produce monocultures *at the landscape level* or on sites that can sustain a greater tree diversity.

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