2003

Long-Term Effects of Herbicide and Precommercial Thinning Treatments on Species Composition, Stand Structure, and Net Present Value in Spruce-Fir Stands in Maine: The Austin Pond Study

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LONG-TERM EFFECTS OF HERBICIDE AND PRECOMMERCIAL THINNING TREATMENTS ON SPECIES COMPOSITION, STAND STRUCTURE, AND NET PRESENT VALUE IN SPRUCE-FIR STANDS IN MAINE:

THE AUSTIN POND STUDY

By

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B.S. University of Maine, 2000

A THESIS

Submitted in Partial Fulfillment of the

Requirements for the Degree of

Master of Science

(in Forestry)

The Graduate School

The University of Maine

August, 2003

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Thesis Advisor: Dr. Robert G. Wagner

An Abstract of the Thesis Presented
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The long-term effect on the development of spruce-fir stands in Maine from combinations of herbicide (Glyphosate, Triclopyr, 2,4-D, 2,4,5-T, MSMA, Picloram, Water, and Control) and precommercial thinning (PCT and no PCT) treatments was examined 22 years after herbicide application and 13 years after PCT. The study originated in 1977 with the aerial application of herbicide treatments to a 7-year old clearcut of a spruce-fir stand in western Maine. Twenty eight original experimental units 2.64 A (3.3 chains x 8.0 chains) in size were comprised of 14 different combinations of herbicides and application rates each replicated twice. In 1986 (year 16) the original experimental units were split in half (3.3 chains x 4.0 chains) and one half received PCT treatment while the other half was left unthinned resulting in 56 experimental units each 1.32 A in size.

Species and DBH were recorded for all trees at least 4.5 ft tall in each of 4, 0.053 A (27 ft radius) circular sample plots per experimental unit. Treatment effects and interaction effects on overstory variables (density, basal area, total volume, merchantable volume, species composition, quadratic mean diameter, and average height) were tested using a 2-factor (herbicides-12 levels, PCT-2 levels) analysis of variance (ANOVA) model fit to a split-plot design. Tests for differences in overstory variables among treatments were conducted from a series of 19 linear contrasts.

Although there was no influence of herbicide treatment on total stand volume after 29 years, herbicides did reduce hardwood total volume ($p=0.021$). PCT reduced total volume ($p<0.001$) and % hardwood total volume ($p<0.001$). No difference in total volume between the PCT only treatment and the herbicide + PCT treatments was found. Herbicide treatments had no influence on total merchantable volume at year 29. PCT increased total merchantable volume and softwood merchantable volume using the highest merchantability standards ($p<0.001$).

Stand conditions (i.e., species, DBH, and total height) in 1999 for all plots were then projected forward using the NE TWIGS variant of the FVS growth and yield model and financial rotation age determined from maximum net present value (NPV). Internal rates of return (IRR) for investments in herbicide and PCT treatments were calculated at maximum NPV.

Financial rotation age was not affected by herbicide group (p=0.928) or by PCT (p=0.601) and was estimated to be approximately 50 years for all treatments. Herbicide group had no effect (p=0.445) on total stand volume at rotation age. PCT, however reduced (p<0.001) total stand volume at rotation age. Herbicide group had no effect (p=0.225) on maximum NPV, but PCT reduced (p<0.001) maximum NPV. No herbicide or PCT treatment attained a higher maximum NPV (p>0.184) than the untreated Control. There was no interaction between herbicide and PCT treatments (p=0.026). The mean IRR for the herbicide treatments with no thinning was 8.2%. For PCT only the IRR was 6.3%. The mean IRR for plots receiving both herbicide and PCT treatments was 5.8%. Therefore, the rate of return for both herbicide and PCT and combinations of the two treatments would be acceptable to many investors.

ACKNOWLEDGEMENTS

I would like to begin by thanking the Cooperative Forestry Research Unit (CFRU) for funding my thesis program. Thanks are extended to the three members of my thesis committee for their advice and direction in formulating and completing this project Dr. Robert G. Wagner, my advisor, talked me into going to graduate school and provided most of the direction for this work. Dr. Robert S. Seymour taught me most of what I know about silviculture. Dr. William Halteman helped me through the struggles of understanding the statistical analysis in this work. I also want to recognize Dr. David Field and Dr. Mila Alvarez for their help in formulating my economic analysis.

Special thanks go out to all of those who helped collect the data for this project. Ben Herzog and Dave Smith worked very hard the first summer laying out the boundaries of the experimental units and collecting the overstory data. Matt Montgomery not only helped collect understory data in the second summer but taught me most of what I know about shrub and herbaceous vegetation identification. Leah Phillips and my son, Chris, helped me dig soils pits during the third summer.

I am grateful to my fellow graduate students Dawn Opland and Darci Schofield, who shared my trials and tribulations through this entire endeavor, for their support and encouragement. Thanks go out to all other students who listened to my complaints. The support and encouragement of my family, including my son Chris and my daughter Sonya, were instrumental in getting me through this program and for that I will be forever grateful.

Last, but certainly not least, I want to express my utmost gratitude to my wonderful girlfriend and confidant, Leah Phillips. I firmly believe her push down the final stretch was the only thing that got me to the finish line.

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INTRODUCTION

Maine's Spruce-fir Forest

The forest-products industry is the single largest business sector in Maine. The paper industry in particular is very large, even by national standards. Approximately 16,000 people are employed just in production facilities in Maine, and the industry directly generates 24,000 additional jobs. The mills in Maine produce 10,000 tons of paper and 7,000 tons of pulp every day, and Maine is the largest producer of printing and writing papers in the nation. In the production of paper products, Maine is second only to Wisconsin in the nation (Rahman and Wilson 1999).

Approximately 90% of Maine's 19.7 million acres is covered by forests of which 16.9 million acres is classified as commercial timberland available for timber production (Maine Department of Conservation 1998). Timberland ownership in Maine has long been dominated by large pulp and paper companies (Seymour 1992) and Maine currently ranks first among all states in terms of industrially owned timberland.

Much of Maine and the Maritime Provinces are part of the region known as the Acadian Forest Region (Rowe 1972). This region is characterized by shallow, coarse-textured, and acidic soils and by relatively cool, moist summers and cold winters. Annual precipitation averages 32 to 52 inches and is evenly distributed throughout the year (Seymour 1995). Vegetation in this region is characterized as a mixed-species forest marking the transition between broadleaf forests to the south and the boreal forest to the north. The Acadian Forest Region is dominated by conifers, including boreal species such as balsam fir

(*Abies balsamea* (L.) Mill.) and a number of spruces (*Picea* spp. A. Dietr.), and more southern species; e.g., eastern hemlock (*Tsuga canadensis* (L.) Carr.) and pines (*Pinus* spp. L.). Common hardwoods include red maple (*Acer rubrum* L.), paper birch (*Betula papyrifera* Marsh.), and aspen (*Populus* spp. L.) (Brissette *et al.* 1999). Spruce and fir dominate Maine's forests in terms of area comprising 46% of the State's forest landscape. Spruce and fir also rank first and second in growing stock volume comprising 56% of softwood volume and 35% of all volume in the state (Maine Department of Conservation 1998). Maine's forest-products industry is vitally dependent on the spruce-fir resource in its production of pulp and paper as well as for production of dimension lumber. In the year 2000 a total of approximately 724,600,000 (board feet) of spruce-fir sawlogs and 675,000 cords of pulpwood were harvested in Maine (Maine Department of Conservation 2001*a*). It is therefore crucial to Maine's economy to manage this resource to ensure healthy growing stock for the future.

Maine's spruce-fir forest typically arises after the spruce budworm severely defoliates stands and mortality occurs (Anderson 1960, Seymour 1992). Even-aged management of Maine's spruce-fir forests became common following a severe outbreak of spruce budworm (*Choristonuera fumiferana*, Clemens) in the mid 1970s (Seymour 1992) when Maine's entire spruce-fir resource became infested. Prior to this period, from the 1940s to the 1960s, cutting practices were dominated by diameter limit cuttings that removed only the largest diameter trees. During the late 1970s clearcutting became an important harvesting practice in a very short period of time in an attempt to salvage dying stands infested by the spruce budworm. It was not until the outbreak subsided in the early 1980s

that the salvage clearcutting practices also waned (Seymour 1992). While some landowners continued to rely primarily on clearcutting, the number of acres in the state harvested by clearcutting has continuously diminished since that period. In 2001 the area clearcut was 15,077 acres. or less than 3% of the total area harvested (Maine Department of Conservation 2001*b*). Nonetheless, clearcutting remains to be an important tool for silviculturists in Maine and dealing with the problems associated with even-aged management, as with uneven-aged management requires a significant investment in silviculture.

Regeneration in Spruce-fir Stands

Unless an area is to be planted, advance regeneration is crucial to timely stand establishment following clearcut harvesting in the spruce-fir forest type (Seymour 1992). Although not always of the desired species, natural reproduction is prolific in the Acadian Forest (Smith 1991). Seymour (1992) describes an important lesson learned from recent experience in harvesting techniques in terms of timing of overstory removal relative to advance regeneration, and the major effect it can have on future species composition and resulting stand development. Harvesting practices prior to the spruce-budworm outbreak of the 1970s was conducted primarily in mature stands. This allowed the understory reinitiation phase of stand development to occur prior to the stand becoming merchantable for pulpwood and advance regeneration of spruce-fir occupied most if not all of the understory growing space prior to overstory removal. When the overstory was removed, the advance spruce-fir regeneration quickly dominated the new stand. The salvage clearcuts of the 1970s and early 1980s, as well as predicted wood scarcities

throughout the spruce-fir region led to harvests of younger, smaller-diameter stands. These stands had not yet reached the stand reinitiation stage of stand development. Consequently, when the overstory is removed in these young stands much of the growing space is left unoccupied. Although small seedlings of spruce-fir may be present, they rapidly become overtopped by vigorously growing pioneer species (*Rubus* spp., *Betula papyrifera*, *Prunus pensylvanica*, *Populus* spp.). Without vegetation management in these stands dominance of spruce-fir in the overstory is delayed until senescence occurs in the shorter lived pioneer species resulting in longer commercial rotations. Where site quality is high, long-lived tolerant hardwoods may dominate early stand development and eventually kill suppressed advance spruce-fir regeneration resulting in a complete change in forest type.

Vegetation Management

Forest vegetation management has been defined as that part of silviculture directed at manipulating the rate and course of secondary forest succession to achieve a forest of a specific composition, structure, and rate of growth (Wagner 1993). Vegetation management recognizes the importance of suppressing the influence of undesirable species only to the extent that they significantly interfere with desirable species. It also recognizes the inherent value in having the flexibility to choose from a variety of techniques to efficiently manipulate competing vegetation (Walstad and Kuch 1987). It is imperative to understand the influences of competing vegetation on the desired crop species in order to make informed vegetation management decisions. Major programs of conifer release are developing in Maine, Ontario, and the Canadian Maritime Provinces,

where there is widespread visual evidence of competing woody species. These programs, which are designed to maintain the dominance of conifers, are based on the assumption that release will result in substantial increases in survival and growth (Newton 1992b). Data from the Maritime provinces (Baskerville 1961, Richardson 1980, McLean and Morgan 1983, Hynson 1985) suggest any method of release is likely to improve growth of spruce and fir, but there is little evidence on the level of improvement provided by a given degree of vegetation control on particular kinds of sites and, conversely, on how much growth loss results from a given level or type of competition. Newton et al (1992a, 1992b) documented the effects of competing residual hardwood vegetation on spruce-fir crop trees 9 years after herbicide treatment in spruce-fir forests in Maine. This is the only known study quantifying the effects of competing hardwood vegetation on spruce-fir crop trees in the northeastern United States. Studies in other regions have documented the effects of competing vegetation in young conifer stands. Wagner and Radosevich (1991*a*, 1991*b*) describe interspecific competition and other factors influencing the size of Douglas-fir saplings in the Pacific Northwest, as well as predictors of interspecific competition. Wagner and Radosevich also describe a neighborhood approach to quantifying interspecific competition in coastal Oregon forests. Wagner (2000) describes competition and critical-period thresholds in young conifer stands. He describes competition thresholds for forests as the densities of undesirable species where abrupt increase or decrease in the rate-of-change in tree growth or survival occurs. The critical-period threshold is the time period during crop development within which control of undesirable species must occur to prevent loss of yield of crop species. The competition threshold focuses on spatial factors such as vegetation density and size. In contrast,

critical-period thresholds focus on the timing of competitive interactions. Hundreds of studies have been conducted over the last three decades quantifying the effects and mechanisms of vegetative competition in regenerating forest stands. There has, however, been only one controlled study examining critical-period thresholds of North American tree species (Wagner 2000).

Many large landowners in Maine embarked on large-scale vegetation management programs to combat the consequences of harvesting immature stands of spruce-fir (Newton 1992*a*). As a part of the vegetation management programs large landowners rapidly adopted aerial application of herbicides as the preferred method of controlling competing hardwood vegetation (Newton 1992*a*). The scientific basis for these treatments was studies conducted in the Northeastern United States on the efficacy of aerially-applied herbicides to favor eastern white pine (Butler et al 1963, McConkey 1958). There were no studies documenting the effects of herbicide treatments on spruce-fir stand development in the Northeast. McCormack and Newton (1980) published the results of one of the earliest such studies testing the effects of 12 aerially applied herbicide treatments. They found that all herbicides and rates reduced hardwood tree and shrub cover by 50% or more 2 years after treatment and cover greater than 1.5 meters tall was nearly eliminated by treatments with triclopyr amine (Garlon 3A) and glyphosate (Roundup). Newton (1992a, 1992b), in the same study area, 9 years after treatment, reported major differences in height and cover still existed between all treatments and the controls. Newton (1992a, 1992b) acknowledged that this study (The Austin Pond Study)

provided the best opportunity to further document the long-term effects of herbicides on stand development in spruce-fir forests of Maine.

Precommercial Thinning

Another important element of even-aged management is precommercial thinning (PCT). Young spruce-fir stands can be very dense containing over 20,000 stems per acre (Brissette 1999, Seymour 1992). PCT is a method of thinning done early in stand development where cut trees are not utilized (Smith et al. 1997: p. 133). PCT in effect reallocates growing space to selected residual crop trees by removing competing vegetation resulting in increased growth increments of individual crop trees. The hypotheses under which PCT is undertaken are: (1) it provides the opportunity to favor longer-lived conifer species like red spruce and, (2) it decreases the time necessary for individual stems to reach merchantable size. Several studies have documented the effects of PCT on various aspects of tree growth for red spruce and balsam fir and all report increases in diameter growth and crown size with PCT (Barbour et al. 1992, Briggs and Lemin 1994, Burns et al 1996, Brissette et al 1999, Lavigne and Donelly 1989, Ker 1987, Piene 1981, Piene and Anderson 1987). PCT had no effect on the heights of balsam fir trees in some studies (Ker 1987, Piene 1981, Piene and Anderson 1987) which supports the hypothesis that height growth is independent of stand density, but Barbour et al (1992) found that red spruce trees were taller in PCT plots than in plots with no PCT, 15 years after treatment. Brissette (1999), 18 years after PCT, found volume of spruce-fir crop trees to be greater with 2.4m x 2.4m spacing than in the control, but stated if all species were considered, volume in the control was probably higher. In contrast, Ker

(1987), 20 years after PCT, found volume to be greater in PCT plots than in the control, but only with spacing less than 5ft x 5ft. The effects of PCT on wood quality have often been a concern. While Barbour et al (1992) found that the relative density of red spruce wood was not adversely affected by PCT, Shepard and Shottafer (1990) found that the opposite was true for black spruce (*Picea mariana* (Mill.) B.S.P.) a closely related species.

A recent report by the Maine Forest Service (Maine Department of Conservation 1998) cites the importance of PCT and herbicide treatments to the overall future wood supplies in the state. The report identifies one possible scenario of improved forest management activities that achieves a sustainable balance between growth and 100% of current harvest levels by increasing the number of acres under high-yield silvicultural practices to a cumulative total of 9% of Maine's forest land by the year 2015. A recent report by Wagner et al (2003) assessing research priorities for Maine suggests that the principal limitations to projecting changes in wood supply under increasing levels of high-yield management has been a lack of information about how these treatments are likely to alter growth and yield responses in forest stands.

Financial Evaluations of Vegetation Management

While biological evaluations of the need for vegetation management are based on quantitative and qualitative assessments of competition in stands, economic evaluations of the need for vegetative management are derived from comparing expected benefits and costs of controlling competition versus letting the stand develop on its own (Brodie *et al.*

1987). The complexity of forest management, coupled with long rotation periods, accounts for the scarcity of definitive studies that evaluate the ultimate benefits of forest vegetation management in the long run (Walstad and Kuch 1987, Wagner 1993).

Brodie *et al* (1987) describes three approaches to economic analysis of vegetative management at the stand level. The first he calls the "yield-table assumption method". It is the simplest approach since it can be conducted for any species for which yield tables exist. Problems arise when the yield tables are based on data from unmanaged stands. The second method is called the "simulated managed stand comparison method". A computer model of managed stand growth is essential for the application of this method. Managed and unmanaged stands are projected independently and compared. It should only be applied to those situations where accurate data from managed stands exist. The third approach is called the "optimization method". In addition to a managed stand simulator an optimization algorithm, utilizing a wide range of stand treatment alternatives, is used to find the optimal solution through iterative simulations. The three methods all help determine differences in stand attributes. Traditional benefit-cost analysis (Nautiyal et al 2001), sometimes referred to as discounted cash flow analysis (McKenney 2000) is utilized in all three methods to determine three common measures; net present value (NPV), cost/benefit ratio, or internal rate of return (IRR).

Although no known studies utilizing any of these methods have been conducted in the spruce-fir forests of the Northeastern United States, there have been studies conducted in other regions. The 2, 4, 5-T assessment team (U.S. Department of Agriculture 1979),

Stavins et al. (1981), and Green (1983) have all used the yield-table assumption method to conduct economic sensitivity analyses for changes in cost, interest rate, and yield assumptions in vegetation management of Douglas fir stands in the Pacific Northwest. They all found that minor delays or productivity losses due to competition from unwanted vegetation during the regeneration phase result in substantial value losses and justify considerable expenditures for competition release treatments. Four areas in western Oregon and Washington were sampled initially by Roberts (1982) and later by Walstad et al. (1986). Economic analyses of treatments including no treatment, planting, herbicides and commercial thinning were evaluated using the simulated managed stand comparison method. Stand conditions in both treated and untreated stands varied from pure to mixed species stands. In comparisons of all stand conditions, treated stands attained a higher NPV than untreated stands. Brodie et al (1987) utilized an optimization model presented by Valsta and Brodie (1985) to forecast future stand development for loblolly pine plantations planted at different densities and resulting in different percentages of hardwood basal area in the main canopy. They found the reduction of early growth due to hardwood competition caused the optimal rotation in terms of NPV to lengthen and yields to decline.

Growth and Yield Models for Spruce-fir Forests of the Northeastern U.S.

There are three growth and yield functions commonly used in the Northeast to project spruce-fir stand conditions; NE TWIGS, FIBER, and GNY (Randolph et al. 2001). The NE TWIGS growth and yield model (Bush 1995, Hilt and Teck 1987) is a Northeastern variant of the growth and yield function “Prognosis” (Stage 1973) developed as part of

the National Forest Systems (NFS) Timber Management System. Forest Inventory and Analysis (FIA) data from the Northeastern Forest Experiment Station was used to develop the model. FIBER was developed to predict growth interactions among species in the spruce-fir, Northern hardwood, and mixed hardwood-softwood stands in the Northeastern United States (Solomon et al 1987). Nearly 4,000 independent growth plots from northern Maine, New Hampshire, northern New York, Vermont, New Brunswick, and Nova Scotia, were included in the development of FIBER. The GNY model (Nova Scotia Softwood Growth and Yield Model) (Nova Scotia Department of Natural Resources (NSDNR) 1993) simulates the growth of even-aged softwood stands except for Eastern Larch (*Larix laricina* (DuRoi) K. Koch) and jack pine (*Pinus banksiana* Lang.) stands. The GNY model is based on data collected from hundreds of permanent and temporary sample plots measured throughout Nova Scotia over the last quarter century.

FIBER, GNY, and NE TWIGS each have a set of strengths and weaknesses relative to to the objectives of this study. FIBER only grows stems larger than 4.0 in. DBH and accounts for smaller stems through in-growth equations, while NE TWIGS is capable of growing stems 1 inch DBH and larger. GNY is a stand level model and incapable of growing individual trees. This limits its accuracy in mixed species stands. NE TWIGS, on the other hand, is an individual tree growth model suitable for growing mixed species stands (Randolph et al. 2001).

Austin Pond Study

The Austin Pond Study was established in 1977 by the Cooperative Forestry Research Unit at the University of Maine. The original study included 12 aerially sprayed herbicide treatments with water-only and untreated control plots. In 1986, immediately after the Newton et al. study, the original herbicide plots were divided in half and one of the halves was PCT'd to a density of approximately 700 trees per acre.

Study Objectives

This study had two objectives following from the remeasurement of the Austin Pond study in 1999. The first objective (chapter 1) was to quantify and compare the influence of herbicide and PCT treatments on overstory species composition and stand structure 22 years after herbicide application and 13 years after PCT.

The second objective (chapter 2) was to project long-term stand development from current stand conditions and determine financial returns associated with herbicide and PCT treatments in Maine spruce-fir stands.

CHAPTER 1. LONG-TERM EFFECTS OF HERBICIDE AND PRECOMMERCIAL THINNING TREATMENTS ON SPECIES COMPOSITION AND STRUCTURE OF SPRUCE-FIR STANDS IN MAINE

ABSTRACT

The long-term effect on the development of spruce-fir stands in Maine from various combinations of herbicides (glyphosate, triclopyr, 2,4-D, 2,4,5-T, MSMA, and picloram) and precommercial thinning (PCT and no PCT) treatments was examined 22 years after herbicide application and 13 years after PCT. The Austin Pond study originated in 1977 with the aerial application of herbicide treatments to a 7-year old winter clearcut of a predominantly spruce-fir stand in western Maine. Twenty eight original experimental units 2.64 A (3.3 chains x 8.0 chains) in size were comprised of 14 different combinations of herbicides and application rates each replicated twice. In 1986 (year 16) the original experimental units were divided in half (3.3 chains x 4.0 chains) and one half received PCT treatment while the other half was left unthinned resulting in 56 experimental units each 1.32 A in size.

In 1999 (year 29) species and DBH were recorded for all live and standing dead trees within each of four 0.0526 A (27 ft radius) circular samples plots per experimental unit. Within each sample plot, a sub sample was measured for total height and height to the base of live crown. Height to diameter at breast height (DBH) relationships were modeled and used for predicting the heights of those trees not measured directly. Treatment effects and interaction effects on overstory variables (density, basal area, total volume,

merchantable volume, species composition, quadratic mean diameter, and average height) were tested using a 2-factor (herbicides-12 levels, PCT-2 levels) analysis of variance (ANOVA) model fit to a split-plot design. Tests for differences in overstory variables among treatments were conducted from a series of 19 linear contrasts.

To show the effects of merchantability standards on merchantable volumes, stand values, and harvest costs three merchantability classes (low, middle, and high) were developed using different minimum top diameter specifications by species for sawlog and pulpwood products. The low merchantability class utilized the smallest minimum top diameters and thus included the most merchantable volume. The middle and high merchantability used progressively larger minimum top diameters and thus included less merchantable volume.

There was no influence of herbicide treatment on total stand volume after 29 years. Herbicides did, however, reduce hardwood total volume ($p=0.021$). PCT reduced total stand volume ($p<0.001$), reduced % hardwood total volume ($p<0.001$). No difference in total stand volume between the PCT only treatment and the herbicide + PCT treatments was found. Herbicide treatments had no influence on total merchantable volume at year 29, but herbicides did reduce hardwood merchantable volume in the low merchantability class ($p<0.047$). PCT had no effect on total merchantable volume, but did reduce hardwood merchantable volume ($p<0.001$) in all three merchantability classes, and increased softwood merchantable volume ($p=0.026$) in the low merchantability class. Glyphosate at the lowest application rate decreased the value of standing wood while the highest application rate increased the value. Triclopyr increased the financial value of

standing wood at both application rates. The only phenoxy herbicide treatment that increased the value of standing wood was the 2,4-D + 2,4,5-T + MSMA treatment. PCT increased the value of standing wood over that of the Control and in all cases, the value of standing wood in plots receiving PCT treatments was enhanced by a prior herbicide treatment.

The results of this study demonstrate the long-term effectiveness of herbicides in controlling undesirable hardwood vegetation as a result directing stand development towards domination of spruce-fir.

INTRODUCTION

Rahman and Wilson (1999) describe Maine's forest-products industry as the state's single largest business sector. The paper industry in particular is very large, even by national standards. Approximately 16,000 people are employed just in production facilities in Maine, and the industry directly generates 24,000 additional jobs. Maine produces 10,000 tons of paper and 7,000 tons of pulp every day, and Maine is the largest producer of printing and writing papers in the nation. Maine is second only to Wisconsin in the nation in the production of paper products, (Rahman and Wilson 1999).

Approximately 90% of Maine's 19.7 million acres is covered by forests (Maine Department of Conservation 1998). The commercial timberland available for timber production in Maine totals 16.9 million acres. The large pulp and paper companies have long dominated timberland ownership in Maine (nearly 8 million acres) (Seymour 1992)

and Maine currently ranks first among all states in terms of industrially owned timberland.

Much of Maine and the Maritime Provinces are part of the region known as the Acadian Forest Region (Rowe 1972). Shallow, coarse-textured, and acidic soils and relatively cool, moist summers and cold winters characterize this region. Annual precipitation averages 32 to 52 inches and is evenly distributed throughout the year (Seymour 1995). This region marks the transition between broadleaf forests to the south and the boreal forest to the north and vegetation is characterized as a mixed-species type. The Acadian Forest Region is dominated by conifers, including boreal species such as balsam fir (*Abies balsamea* (L.) Mill.) and a number of spruces (*Picea* spp. A. Dietr.), and more southern species; e.g., eastern hemlock (*Tsuga canadensis* (L.) Carr.) and pines (*Pinus* spp. L.). Common hardwoods include red maple (*Acer rubrum* L.), paper birch (*Betula papyrifera* Marsh.), and aspen (*Populus* spp. L.) (Brissette *et al*. 1999). Maine's forests are dominated by spruce and fir in terms of area comprising 46% of the State's forest landscape. Spruce and fir also rank first and second in growing stock volume comprising 60% of softwood volume and 39% of all volume in the state (Seymour 1992). Maine's forest-products industry is vitally dependent on the spruce-fir resource in its production of pulp and paper as well as for production of dimension lumber. A total of approximately 724,600,000 (board feet) of spruce-fir sawlogs and 675,000 cords of pulpwood were harvested in Maine in the year 2000 (Maine Department of Conservation 2001*a*). Management of this resource to ensure healthy growing stock for the future is therefore crucial to Maine's economy.

Successful management of young naturally-regenerated spruce-fir stands in Maine often requires removal or suppression of competing vegetation in the early stages of development to maintain species composition, provide optimal growing conditions for selected crop trees, thus reducing the length of commercial rotations (Seymour 1992). Stands of this type have typically occurred after severe defoliation from the spruce budworm (*Choristonuera fumiferana*, Clemens) and overstory mortality occurs (Newton et al 1992b). Advance regeneration in the understory is released from the canopy reduction following mortality of the overstory. Although much of the future commercial production of spruce-fir in Maine will probably originate from harvested stands or mortality salvage rather than defoliated stands, much of the data available on growth and yield of spruce-fir stands are based on stands of budworm origin and managed stands may develop differently (Newton et al 1992b). Spruce-fir stands of budworm origin often coexist for a period with shrubs and hardwood competitors, and the presence of these competitors affects the growth and early development of the conifers. Understanding the magnitude of the influence of this competition on the growth of softwood regeneration can improve growth and yield projections of managed spruce-fir stands.

Two common silvilcultural techniques for managing these young stands are aerial herbicide applications and precommercial thinning (PCT). A recent report by the Maine Forest Service (Maine Department of Conservation 1998) cites the importance of PCT and herbicide treatments to the overall future wood supplies in the state. The report identifies one possible scenario of improved forest management activities that achieves a

sustainable balance between growth and 100% of current harvest levels by increasing the number of acres under high-yield silvicultural practices to a cumulative total of 9% of Maine's forest land by the year 2015. A report by Wagner et al. (2003) assessing research priorities for Maine suggests that the principal limitations to projecting changes in wood supply under increasing levels of high-yield management has been a lack of information about how PCT and herbicides are likely to alter long-term growth and yield responses in forest stands. Currently, based on state wide averages between 1995 and 2000, approximately 14,052 A/yr undergoes herbicide application and approximately 19,887 A/yr undergo PCT treatments (Wagner et al. 2003).

Much of the research on vegetation management in the northeastern United States to date has reported descriptions of short-term responses of hardwoods to aerial herbicide application and aside from previous progress reports and publications from the Austin Pond Study (McConkey 1958, Butler et al 1963, McCormack and Newton 1980, McCormack 1982, Newton et al 1992a, Newton et al 1992b) there are few studies of sufficient detail to project long-term silvilcultural conditions in the Northeast.

Several studies have documented the effects of PCT on various aspects of tree growth for red spruce and balsam fir and all report increases in diameter growth and crown size with PCT (Piene 1981, Piene and Anderson 1987, Ker 1987, Lavigne and Donelly 1989, Barbour et al 1992, Briggs and Lemin 1994, Burns et al 1996, Brissette et al 1999). PCT had no effect on the heights of balsam fir trees in some studies (Ker 1987, Piene 1981, Piene and Anderson 1987) which supports the hypothesis that height growth is

independent of stand density. In contrast, Barbour et al (1992) found that red spruce trees were taller in PCT plots than in plots with no PCT, 15 years after treatment. Brissette (1999), 18 years after PCT, found overall stand volume to be greater with 2.4m x 2.4m spacing than in the control. Ker (1987) on the other hand, 20 years after PCT, found overall stand volume to be greater than the unthinned control with spacings less than 5ft x 5ft. Barbour *et al* (1992) found that the relative density of red spruce wood was not adversely affected by PCT, Shepard and Shottafer (1990) found that the opposite was true for black spruce (*Picea mariana* (Mill.) B.S.P.) a closely related species.

This investigation was part of the ongoing Austin Pond Study established in 1977 by the Cooperative Forestry Research Unit at the University of Maine. The original study included 12 aerially sprayed herbicide treatments with water-only and untreated control plots. McCormack and Newton (1980) reported, 2 years after treatment (year 9), that all herbicides reduced hardwood and shrub cover by 50% or more. Cover more than 1.5 m tall was nearly eliminated by treatments with triclopyr amine (Garlon 3A), glyphosate (Roundup), or a high rate of 2,4,5-T. The Phenoxy herbicides (2,4-D and 2,4,5-T) led to short-term reductions in birches, maples, aspen, and raspberry, and little change in willows. Newton et al. (1992a) reported that major differences in height and cover still existed between all treatments and the untreated controls, nine years after herbicide application. Newton et al. (1992b) reports development of the naturally regenerated conifers was inversely related to residual hardwood cover and conifer stocking nine years after herbicide treatment and spruce heights and diameters were less affected by hardwood competition than were those of fir. In 1986, immediately after the Newton et

al. study, the original herbicide plots were divided in half and one of the halves was PCT'd to a density of approximately 700 trees per acre. McCormack and Lemin (1998) investigated the early results of the response of individual crop trees to these PCT treatments. They found growth of spruce and fir crop trees, in unthinned plots, was greater with herbicide treatments than with the untreated control and growth was greater on PCT plots than on plots with no PCT.

The objective of this study was to quantify and compare the influence of herbicide and PCT treatments on overstory species composition and stand structure 22 years after herbicide application and 13 years after PCT on the Austin Pond study.

METHODS

Study Area

The Austin Pond study area is located in west-central Maine in Bald Mountain Township (Latitude: 45.20° N, Longitude: 69.70° W) approximately 20 miles northeast of Bingham Village and currently owned by Plum Creek Timber Company. The site is at approximately 1,300 ft elevation on gently sloping outwash with a northeast aspect (Newton 1992a). Soils on the site range from Telos to Chesuncook types and range from a 4 to a low 2 on the Briggs (1994) soil drainage scale. The stand originated in 1970 as a result of a winter clearcut of a predominantly spruce-fir stand approximately 100 acres in size. Regeneration of red spruce, balsam fir, black spruce, and a scattering of white pine were abundant.

In 1977 the original herbicide study was installed by Maxwell McCormack to test the efficacy of current and new herbicides that were available. At the time, conifer regeneration was still abundant but subordinate to deciduous shrubs and hardwoods dominated by aspen, birches, raspberry, pin cherry, sprouting red maple, and willow species (Newton 1992a).

Treatments and Experimental Design

Seven herbicides were tested in various mixtures and rates, making a total of twelve herbicide treatments plus an untreated and water-only control (Table 1.1). Eight of these treatments were dominated by phenoxy herbicides (2,4-D; 2-4-DP; or 2,4,5-T), which were the most commonly used herbicides of the time. Glyphosate (Roundup) and triclopyr (Garlon) were new materials, having just been registered by the U.S. Environmental Protection Agency, and relatively little was understood about their influence in forestry at the time.

The Austin Pond Study includes the earliest applications of glyphosate and triclopyr in North American forests, and may be the oldest surviving set of research plots for these herbicides. A motivation for the original study was the need to evaluate new herbicides at a time when the common treatments of 2,4-D and 2,4,5-T were expected to be no longer available (McCormack and Newton 1980).

Table 1.1: 1977 herbicide treatments compared in Austin Pond Study.

Herbicide Treatment	Treatment plot #'s	Application rate (lbs/A, ae)
Glyphosate (Roundup)	4, 7	1.5
	3, 17	3.0
Triclopyr amine (Garlon 3a)	21, 24	2.0
	1, 16	4.0
2,4,5-T	9, 15	2.0
	8, 18	3.0
Triclopyr amine (Garlon 3a) + 2,4-D	12, 27	2.0 + 2.0
2,4-D + 2,4,5-T	10, 13	1.0 + 1.0
	2, 23	2.0 + 2.0
2,4-D + 2,4,5-T + MSMA	14, 26	1.0 + 1.0 + 0.1
2,4-D + 2,4,5-DP + MSMA	6, 22	1.0 + 1.0 + 0.1
Picloram + 2,4-D (Tordon 101)	11, 20	0.4 + 1.5
Water only	25, 28	NA.
Control (untreated)	5, 19	NA.

Herbicides were applied, in water, by a Bell 47G3 helicopter equipped with D6-46 nozzles on a conventional boom delivering a spray with an approximate median drop size of 400-500 microns. Volume delivered was 4 gal/A in four swaths per plot with a net width of 54.8 ft. Flights were guided by live flaggers on the ground and a spotter flying with the pilot. All treatments were completed during a single morning spray session in early August 1977. There were very few skips in coverage, and effects are analogous to those occurring in continuous coverage in large projects (McCormack and Newton 1980).

Each of the original 14 treatments was replicated twice, resulting in 28 original treatment plots that were 3.3 chains x 8 chains (2.64 A) in size (Figure 1.1). In autumn 1986 following the 9th growing season after herbicide application, each original herbicide treatment plot was divided in half (3.3 chains x 4 chains, 1.32A) with one half receiving

PCT to an operational density of approximately 700 trees/A and one half left unthinned. PCT was conducted by contract crews using motor-manual equipment. Operational guidelines of the landowner, selecting spaced spruce or fir in the most dominant position, were followed and completed before winter (McCormack and Lemin 1998). The resulting experimental design was a randomized, split-plot design containing 56 experimental units including various combinations of herbicide and PCT treatments. During our remeasurement it was necessary to eliminate plots 22 and 28 (Figure 1.1) from this study due to road encroachments and improper thinning densities. We also dropped the replicates of these treatments (plot 6 and 25) (water-only and 2,4-D + 2,4,5-DP + MSMA) to keep a balanced design. Thus, a total of 48 experimental units or treatment plots were available for this study.

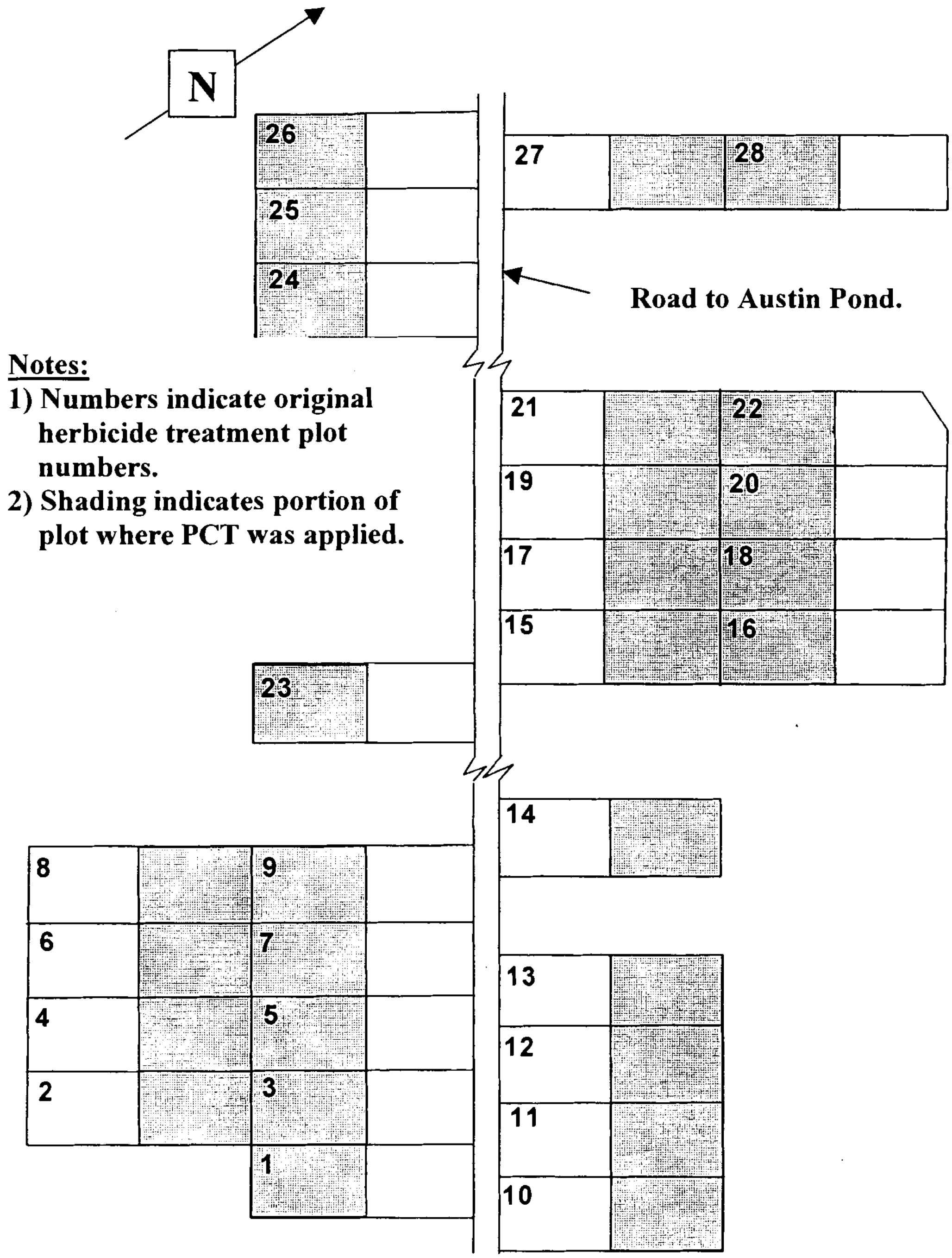


Figure 1.1: The experimental design at the Austin Pond study site.

Variables Measured

Overstory

During the summer of 1999, four permanent circular (27 ft radius) (0.0526 acre) sample plots were located in each treatment plot. The plots were nested near the center of each treatment plot to minimize edge effects (Figure 1.2). The center of each sample plot was marked with rebar and plastic pipe.

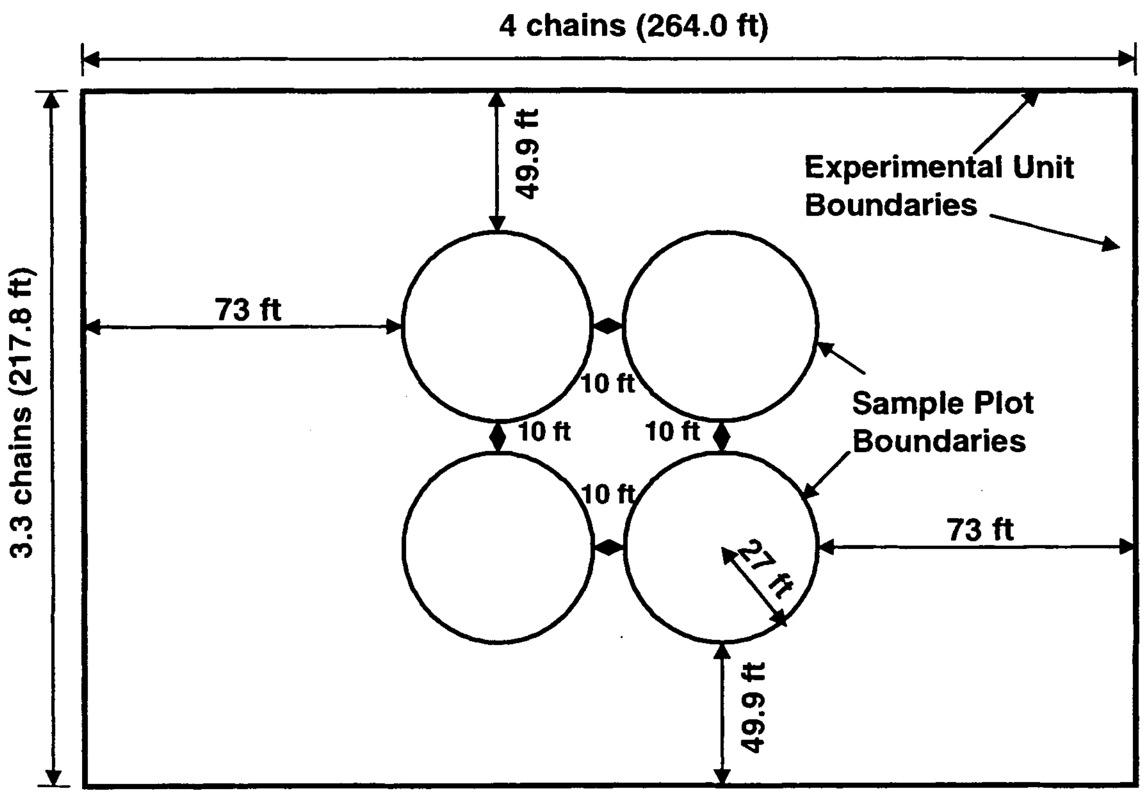


Figure 1.2: Sample plot layout inside each experimental unit (treatment plot).

The species and diameter at breast height (DBH) for all tree stems within each sample plot were measured. Both live and standing dead stems were recorded but tallied separately. DBH was measured to the nearest 0.1 inch with calipers for stems larger than 3.5 inches. For stems 3.5 inches and smaller, DBH was measured with forks calibrated to categorize stems into diameter classes of 0.5, 1, 2, and 3 inches. True azimuth and distance from the plot center were recorded for each stem larger than 3.5 inches DBH. Azimuth was measured with a hand compass to the nearest degree and distance was measured to the nearest 0.1 of a foot using a Haglöf DME (Haglöf, Inc. Lângsele, Sweden), model 20, electronic distance-measuring device .

A subsample of living trees across all DBH classes was selected for each of the dominant tree species in each treatment plot. Total stem height and height to the base of live crown was recorded for each tree. Every effort was made to provide an adequate sample of heights in each treatment plot for regression analysis. Height to the base of live crown was determined by the lowest branch whorl containing at least 75% live branches. Heights were measured to the nearest 0.1 ft using a Haglöf (Haglöf, Inc. Lângsele, Sweden), model vertex II, electronic hypsometer. Increment cores were taken at breast height on 10 dominant balsam fir and 10 red dominant red spruce randomly across the entire site. The average breast height age was 17 years and did not vary by more than 1 year for the entire sample.

Soils

One soil pit was dug in each treatment plot. The pit was located in the center of each plot (between sample plots) and was dug to the depth of hardpan. Six variables were measured to the nearest inch in each pit: depth of the organic layer, depth to mottling, maximum depth of rooting, depth to hardpan, % stoniness of soil removed from the pit, and % surface stoniness. These variables have been associated with forest site productivity in Maine (Briggs and Lemin 1994, Allen 1978). Efforts were made to record the average measurement when measurements varied on different faces of the soil pit.

Dependent Variables

Height

The average height for each of four species (balsam fir, red spruce, quaking aspen, and red maple) was calculated by treatment using the height of all stems attaining a breast height. To determine site index (SI) for each plot and whether the treatments influenced calculation of SI, the average height of the tallest 10% of balsam fir trees larger than 3.5 inches DBH was calculated to determine the average height of dominant trees. This average height was then analyzed using a 2-factor (herbicides = 12 levels, PCT = 2 levels) analysis of variance (ANOVA) fit to a split-plot design. The alpha level for this analysis was 0.05.

Quadratic Mean Diameter

The quadratic mean diameter (QMD) (Curtis and Marshall 2000) of merchantable balsam fir and red spruce stems was calculated for each experimental unit. Treatment effects on QMD were then analyzed using a 2-factor (herbicides = 12 levels, PCT = 2 levels) ANOVA fit to a split-plot design. The alpha level for this analysis was 0.05. In both herbicide and PCT treated plots, balsam fir and red spruce comprised nearly all merchantable volume, therefore analysis of treatment effects on QMD of merchantable stems of other species was deemed inappropriate.

Wood Volume

Total volumes inside bark for each treatment plot were derived using Honer's (1967) volume equations and measured DBH and total stem height. Merchantable volumes also were calculated using Honer's volume equations. Because height to a minimum merchantable top diameter was not measured directly, we calculated this height using a specified minimum top diameter and Honer's "Diameter-Height Ratio Cubic Foot Volume Conversion Coefficients" (Honer 1967, Table 5, pg 18) and solving for "h1" (Height to merchantable limit). This height allowed us to determine the length of merchantable products and to implement merchantable length specifications in the determination of merchantable volumes.

First, we first calculated total stem volume using Honer's total cubic foot volume function statistics (Honer 1967, Table 1, pg 14). We then used the calculated total volume and Honer's "Method 2A" (Honer 1967, Table 4, pg 17) to calculate the merchantable

volume to a specific top diameter for a sawlog. The height to this specified top diameter was then calculated using Honer's "Diameter-Height Ratio Cubic Foot Volume Conversion Coefficients" (Honer 1967, Table 5, pg 18) and solving for "h1" (Height to merchantable limit). We then had the total stem volume, merchantable volume to a specified top diameter, and the height to that specified top diameter. Merchantability standards (Table 1.2) were then applied to determine merchantable volumes by product and by species. Each stem was utilized to maximize the volume in sawlogs and every combination of merchantable lengths was used to consume as much of the merchantable volume as possible. For pulpwood, a minimum length of 12 ft was used with no maximum length. The minimum sawlog length was 8 ft in 2 ft increments to a maximum length of 20 ft allowing 0.5 ft for each sawlog. Once the merchantable length in sawlogs was determined, the volume was again calculated using Honer's "Diameter-Height Ratio Cubic Foot Volume Conversion Coefficients" (Honer 1967, Table 5, pg 18) using the merchantable length and solving for the volume. We then calculated the height to a specified minimum pulpwood top diameter. Using this height minus the height to the top of any merchantable sawlogs, we could determine the length of the remaining stem that could be utilized for pulpwood and its volume.

Three merchantability classes were established using different merchantability standards for softwoods and hardwoods (Table 1.2). Calculations were performed on each record (stem) in the inventory data and merchantable volumes were compiled by treatment for each merchantability class. With over 111,000 records in the data set (207 sample plots) the time necessary to perform these calculations manually for each stem was prohibitive.

Program code was written using SAS software to automate these calculations saving many days of calculation time.

Table 1.2: Merchantability classes and standards used in calculation of merchantable volumes.

Merchantability class	**Species group**	**Pulpwood minimum top diameter (in)**	**Sawlog minimum top diameter (in)**
Low	Softwood	2.0	4.0
	Hardwood	3.0	6.0
Middle			
	Softwood	3.0	5.0
	Hardwood	4.0	8.0
High			
	Softwood	4.0	6.0
	Hardwood	5.0	10.0

Financial Value

All dollar values assigned to the treatments in this study were stumpage values on a per acre basis. Stumpage prices were derived from data published by the Maine Forest Service for Somerset County in the year 2000 (Maine Forest Service 2000*b*). Published prices for various products were assigned to matching products in our calculations (Table 1.3). The prices are reported annually by the Maine Forest Service and are based on landowner reports and then averaged by county.

Table 1.3: Prices by product and species used for this analysis.

Species	Pulpwood $/cord	Sawlogs $/MBF	Studwood $/ton
Aspen/Poplar	10	59	NA
Red maple	9	99	NA
Sugar Maple	9	258	NA
White birch	9	185	NA
Yellow birch	9	175	NA
Other hardwood	9	129	NA
Spruce/fir	34	169	28
White pine	6	125	NA

Analytical Approach

Height and DBH Relationships

To accurately calculate stem volumes, it was necessary to develop regression models to predict height from DBH for all trees that did not have a height measurement. The relationship between tree height and DBH was quantified using regression analysis. A two-step process was used. Linear regression analysis was used first to test whether separate models needed to be developed for each tree species, and between thinned and unthinned treatments within species. Indicator variables were used to test for differences in intercept and slope among the models (Neter et al 1996). Indicators with p-values less than 0.05 were used as the basis for determining that separate models were required. Once these differences were established, the data were then pooled and non-linear regression models developed for each group.

Only five species (balsam fir, red spruce, quaking aspen, red maple, and paper birch) had sufficient sample sizes to develop species-specific models (Table 1.4). Tree species without sufficient sample sizes were grouped with other species of similar silvical characteristics and analyzed as a group. A logarithmic transformation of DBH was required for every species to normalize error terms and provide the best model fit as determined from an analysis of residuals for the linear models. Balsam fir and red maple required only a transformation of DBH, while all other species required a transformation of both height and DBH. Tests of the linear models for balsam fir, red spruce, paper birch, red maple and quaking aspen indicated that different height and DBH models were required for thinned and unthinned plots.

Results from the analysis of the linear models provided the basis for pooling and separating data for development of the best non-linear models. A Chapman-Richards model was used to develop the final height (H) and DBH equations:

[1] $$H = 1.3 + (a * (1 - e\ (-b*DBH))^{c})$$

where a, b, and c are regression coefficients.

In recent studies by Peng et al. (2001) and Huang et al. (1992), the Chapman-Richards model provided the most satisfactory results for modeling tree height and stem diameter relationships. Parameter estimates for the final models are shown in Table 1.5. Examples of the final models are shown for balsam fir in Figure 1.3 and red spruce in Figure 1.4.

Table 1.4: Results of linear regression analysis for the separation of height to DBH models by species and thinning (PCT) treatment.

Species	Total	Sampled	% Sampled	R^2	MSE	p-values Intercept	Slope	Int.+Sl.
Balsam fir	**33,557**	**1,260**	**3.75%**	0.89	9.10	0.00	0.00	0.05
PCT	7,953	725	9.12%	0.92	6.90			
No PCT	25,604	534	2.09%	0.89	8.38			
Paper birch	**4,096**	**73**	**1.78%**	0.77	0.03	0.00	0.34	0.11
PCT	2,128	7	0.33%	0.97	0.01			
No PCT	1,968	65	3.30%	0.71	0.02			
Quaking aspen	**3,032**	**222**	**7.32%**	0.83	0.03	0.00	0.01	0.40
PCT	1,452	63	4.34%	0.71	0.02			
No PCT	1,580	158	10.00%	0.74	0.03			
Red maple	**2,538**	**101**	**3.98%**	0.72	27.76	0.00	0.07	0.33
PCT	1,346	21	1.56%	0.89	20.18			
No PCT	1,192	80	6.71%	0.65	27.18			
Red spruce	**6,290**	**842**	**13.39%**	0.78	0.03	0.00	0.00	0.90
PCT	1,222	428	35.02%	0.90	0.01			
No PCT	5,068	411	8.11%	0.77	0.03			
Sugar maple	60	10	16.67%	0.90	0.00	0.00	0.01	0.63
White pine	73	29	39.73%	0.65	0.02	0.17	0.33	0.62
Brown ash	19	8	42.11%	0.96	0.02	0.04	0.09	0.40
White spruce	51	32	62.75%	0.83	0.02	0.07	0.09	0.93
Black spruce	12	6	50.00%	0.84	0.01	.	.	.
Northern white cedar	95	11	11.58%	0.88	0.02	0.59	0.64	0.93
Gray birch	2,097	30	1.43%	0.78	0.04	0.94	0.54	0.55
TOTAL	**51,920**	**2,624**	**5.05%**					

Table 1.5: Regression parameter estimates for Chapman-Richards models predicting height from DBH by species and thinning treatment.

	Parameter Estimates				
Species or Group	**a**	**b**	**c**	**R^2**	**MSE**
Balsam fir	54.332	0.125	0.843	0.891	9.248
PCT	67.017	0.079	0.804	0.921	6.996
No PCT	63.666	0.107	0.841	0.891	8.714
Paper birch	85.852	0.047	0.554	0.77	19.578
PCT	177.952	0.015	0.641	0.997	1.236
No PCT	74.174	0.055	0.512	0.702	19.354
Quaking aspen	61.293	0.203	0.856	0.789	34.11
PCT	35.951	0.53	1.08	0.712	9.88
No PCT	61.699	0.18	0.736	0.683	41.965
Red maple	53.215	0.204	0.72	0.725	27.561
PCT	54.174	0.19	0.828	0.894	19.66
No PCT	296.507	0.063	0.5	0.659	27.066
Red spruce	27.094	0.368	0.846	0.711	10.018
PCT	34.496	0.155	0.707	0.848	4.874
No PCT	29.344	0.384	0.889	0.718	10.468
Brown ash	78.017	0.196	1.062	0.974	15.296
Grey birch	191.733	0.014	0.615	0.75	30.884
White pine	39.005	0.174	0.69	0.612	14.974
White spruce	38.159	0.144	0.708	0.751	12.663
Yellow birch	47.165	0.491	1.439	0.843	22.089
Black spruce No. white cedar	56.175	0.038	0.52	0.916	6.149
Yellow birch Sugar maple	72.832	0.117	0.716	0.815	19.155
Speckled alder American mt. ash Striped maple Mountain maple Pin cherry Black willow	46.299	0.246	0.841	0.751	18.356

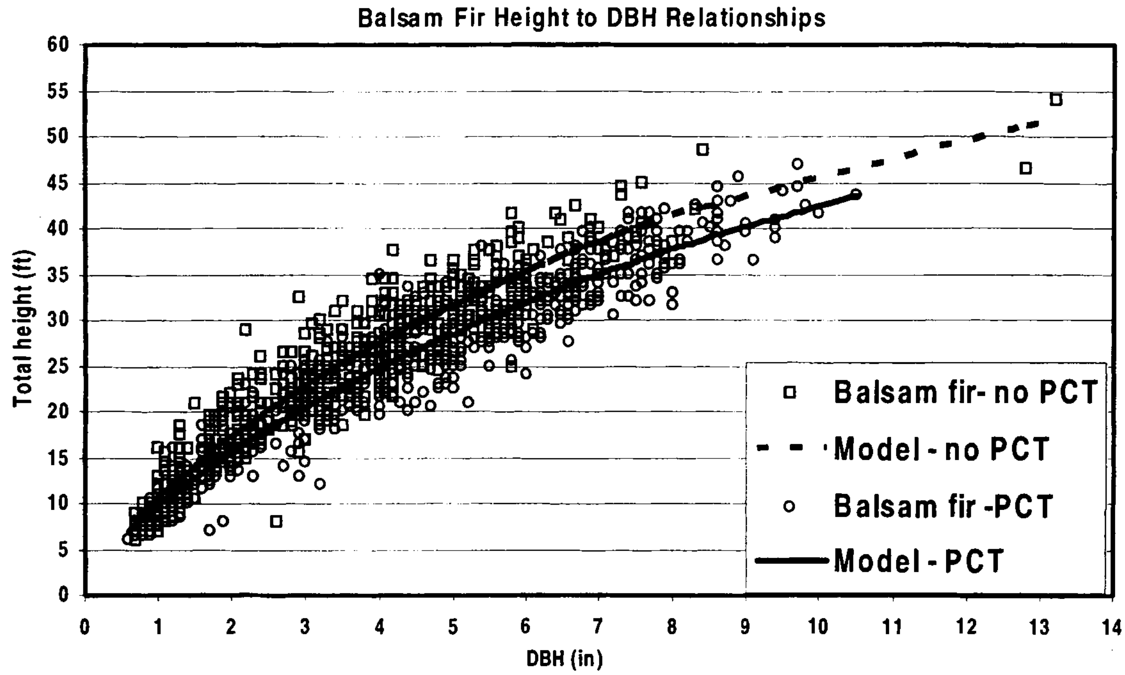


Figure 1.3: Height to DBH relationships for balsam fir depicting the different models for thinned and unthinned plots.

The models clearly show that predicted heights for any DBH are taller in unthinned than thinned plots. Thus, height to diameter ratios was higher in unthinned plots. This pattern was consistent for all five species where a statistical difference was found between the thinning treatments. The slopes of the curves also were steeper for balsam fir than red spruce indicating higher height to diameter ratios for fir than spruce.

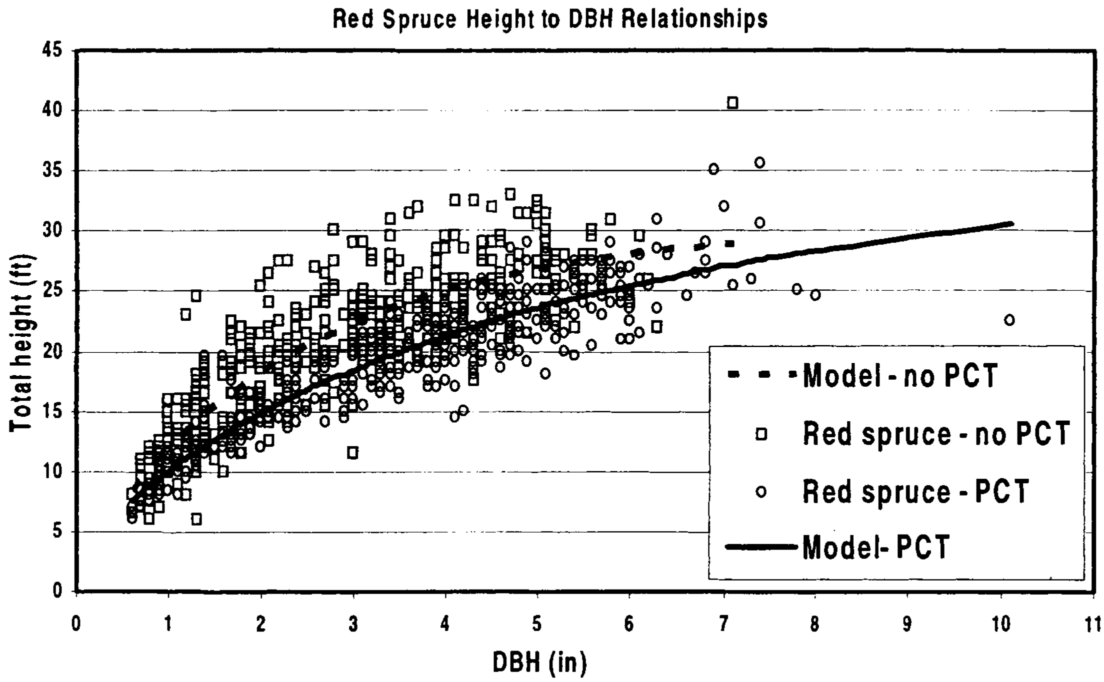


Figure 1.4: Height to DBH relationships for red spruce depicting the different models for thinned and unthinned plots.

Soil and Overstory Relationships

The test whether there was any relation between the soil conditions in each plot, and the composition and structure of the overstory, soils data were used to assess whether any portion of the variation in the overstory variables being examined for treatment differences could be accounted for by variation in soils among plots. Linear regression analysis was used with soil variables as the independent variable and overstory variables (stems/A, basal area/A, total volume/A, merchantable volume/A, QMD, hardwood basal area/A) as the dependent variable. Soil drainage indices (depth to rooting x depth to hard pan, depth to rooting x % profile stoniness, and depth to mottling x depth to hardpan) also were developed using combinations of the soil variables. Several transformations of both

soil and overstory variables were investigated to normalize error terms and improve residual graphs.

No soil variable or soil drainage indices consistently accounted for a significant portion of the variation ($p<0.05$) of any overstory variable (Table 1.6). Although some combinations produced significant relationships, there was no consistent or logical relationship among any of the relationships to develop a convincing case that soil conditions were an important predictor of key overstory conditions. As a result, no compelling case could be made that any of the soils data should be used as a covariate in the analysis of treatment effects on overstory conditions.

Table 1.6: P-values of linear regression models using overstory variables as the dependent variable and soil drainage variables as the independent variable. Shaded cells represent p-values less than 0.05.

	Overstory variables					
Soil drainage variables	**Stems per acre**	**Basal area per acre**	**Total volume per acre**	**Mer-chantable volume per acre**	**Quad-ratic mean diameter**	**Hard-wood basal area per acre**
Depth of organic layer	0.024	0.228	0.413	0.436	0.194	0.010
Maximum depth of rooting	0.715	0.022	0.001	0.544	0.205	0.390
Minimum depth of mottling	0.169	0.578	0.353	0.546	0.029	0.934
Depth to hard pan	0.015	0.459	0.410	0.398	0.004	0.986
% Profile stoniness	0.043	0.016	0.085	0.585	0.803	0.220
% Surface stoniness	0.926	0.581	0.393	0.932	0.454	0.243
Rooting X Hard pan	0.982	0.087	0.002	0.024	0.129	0.563
Rooting X Profile stoniness	0.076	0.005	0.039	0.731	0.833	0.411
Mottling X Hard pan	0.422	0.758	0.645	0.219	0.093	0.954

Treatment Effects on Overstory

A two-factor (herbicides = 12 levels, PCT = 2 levels) analysis of variance (ANOVA) was used to test for treatment effects and interaction effects. The ANOVA model was fit to a completely randomized block, split-plot design. This design required two additional error terms to test for between-plots effects and within-plots effects (Systat manual 2000). The ANOVA model examined was:

Source of Variation	df
Herbicide	11
PCT	1
Herbicides x PCT	11
Plot (Herbicide)	12
PCT x Plot (Herbicide)	12
Error	0

The "Plot (Herbicide)" error term was used to test for herbicide treatment effects (between plots) and the "PCT x Plot (Herbicide)" error term was used to test for PCT treatment effects and interaction effects (within plots).

A series of 19 linear contrasts based on a priori treatment effects of interest were used to test for differences among individual treatments or groups of treatments (Appendix B). The "PCT x Plot (Herbicide)" error term was used for tests of the linear contrasts. The significance level for these tests was determined by dividing the 0.05 alpha level used in the ANOVA model by the number of linear contrasts (0.05/19 = 0.0026). The alpha level

was rounded to 0.003. Overstory variables examined in this analysis included: tree density, height, quadratic mean diameter, basal area, total wood volume, total merchantable wood volume, hardwood basal area, hardwood total volume, % hardwood basal area, % hardwood total volume, softwood basal area, softwood total volume, % softwood basal area, % softwood total volume, and value of standing wood.

RESULTS

Density and Species Composition

Species composition 29 years after harvest (22 years after herbicide treatment and 13 after PCT) was generally dominated by balsam fir in all treatments (Figure 1.5). Balsam fir comprised 70.1% of stem density in the herbicide only plots, 50.3% in the herbicide + PCT plots, 44.6% in the control only plots, and 41.2% in the PCT only plots. The herbicide only treatments were dominated by balsam fir (70.1%) and red spruce (14.6%) which together comprised 84.7% of stem density. Quaking aspen (4.1%) and red maple (2.1%) combined comprised only 6.2% of stem density in the herbicide only treatments. Overstory in the PCT only plots were dominated by balsam fir (41.2%) and red spruce (4.3%) which together comprised 45.5% of total stem density. Quaking aspen (16.8%), red maple (3.2%), and other hardwood trees and shrubs (34.5%), while being mostly confined to the understory, together comprised 54.5% of total stem density in the

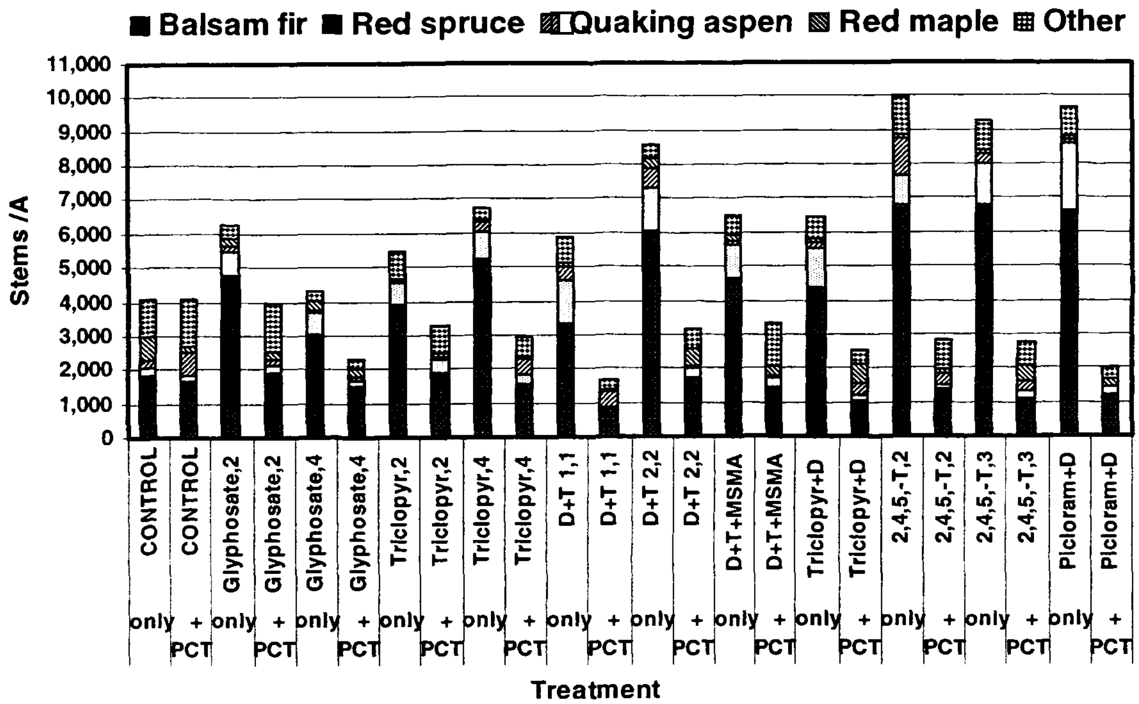


Figure 1.5: Stand density (stems/A) for stems > 0.5 in for all treatments by species.

PCT only plots. The herbicide + PCT plots were dominated by balsam fir (50.3%) and red spruce (8.2%) which together comprised 58.5% of total stem density, while quaking aspen (7.5%), red maple (9.5%), and other trees and shrubs (24.5%) totaled 41.5%. Balsam fir, while almost entirely confined to the understory, also dominated the untreated control, comprising 44.6% of total stem density. Red spruce, a small component of the untreated control and also confined to the understory, comprised 5.3% of stem density. The overstory in the untreated control was dominated by quaking aspen, red maple, and other trees and hardwood shrubs comprising 6.6%, 16.7%, and 26.8% of stem density respectively.

There was wide variation in density of the plots, with most of the difference influenced by the PCT treatment (Figure 1.5) (Appendix A). Results of the ANOVA model indicate herbicide treatments did not influence total stand density (p=0.665). Unthinned plots averaged 6,945 TPA compared with 2,903 TPA for thinned plots (p<0.001). PCT reduced stand density in all treatments with the exception of the Control-only treatment. The plots receiving PCT treatments were originally thinned to a density of approximately 700 TPA and now have on average 2,903 TPA. This difference in stem density is due to sprouting of hardwood trees and shrubs removed during the PCT treatment.

Among individual species, no influence of herbicide treatment was found on stand density (Appendix A): balsam fir (p=0.495), red spruce (p=0.526), quaking aspen (p=0.295) and red maple (p=0.559). PCT reduced density of balsam fir (p<0.001) and red spruce (p<0.001) but not for aspen (p=0.607) and red maple (p=0.499) (Appendix A). There were no significant (p>0.347) treatment interaction effects on stand density for any individual species tested or all species combined. No significant differences (p > 0.013) were found in stand density between any treatment(s) included in the 19 linear contrasts (Appendix B).

Height

The mean total height of all stems >0.5 in DBH for each of the dominant tree species in each treatment is shown in Table 1.7. Herbicide treatments had no effect (p>0.050) on the average height of any of the species (Appendix A) (i.e., balsam fir, red spruce, quaking aspen, and red maple).

Table 1.7: Mean total height (ft) of all stems >0.5 in DBH by treatment for dominant tree species.

Herbicide Treatment	PCT	Balsam fir	Red spruce	Quaking aspen	Red maple
CONTROL	PCT	24.7	18.9	19.5	18.3
CONTROL	No PCT	21.1	15.0	39.6	31.0
Glyphosate (1.5 lbs/A)	PCT	24.8	16.6	19.1	18.9
Glyphosate (1.5 lbs/A)	No PCT	24.5	18.8	28.3	24.3
Glyphosate (3.0 lbs/A)	PCT	27.2	17.7	19.1	18.3
Glyphosate (3.0 lbs/A)	No PCT	27.7	19.4	26.6	26.4
Triclopyr (2.0 lbs/A)	PCT	27.2	19.3	27.0	19.3
Triclopyr (2.0 lbs/A)	No PCT	27.7	18.9	37.3	24.5
Triclopyr 4.0 lbs/A)	PCT	25.7	18.9	19.6	18.3
Triclopyr (4.0 lbs/A)	No PCT	24.6	19.7	35.0	21.3
Triclopyr + 2,4-D	PCT	27.4	15.9	30.9	18.3
Triclopyr + 2,4-D	No PCT	25.5	20.8	30.9	21.3
2,4,5-T (2.0 lbs/A)	PCT	26.1	18.5	19.5	18.3
2,4,5-T (2.0 lbs/A)	No PCT	22.5	18.2	36.6	26.0
2,4,5-T (3.0 lbs/A)	PCT	25.8	22.8	19.7	18.3
2,4,5-T (3.0 lbs/A)	No PCT	24.4	19.6	26.8	21.3
2,4-D +2,4,5-T (1.0+1.0 lbs/A)	PCT	28.6	19.3	22.3	18.3
2,4-D +2,4,5-T (1.0+1.0 lbs/A)	No PCT	25.8	20.1	31.9	22.9
2,4-D +2,4,5-T (2.0+2.0 lbs/A)	PCT	25.5	18.5	19.1	20.2
2,4-D +2,4,5-T (2.0+2.0 lbs/A)	No PCT	22.7	19.8	33.2	23.1
2,4-D + 2,4,5-T + MSMA	PCT	27.2	20.5	19.1	19.7
2,4-D + 2,4,5-T + MSMA	No PCT	27.1	19.7	35.1	24.1
Picloram + 2,4-D	PCT	27.9	17.2	26.5	18.9
Picloram + 2,4-D	No PCT	21.7	17.1	27.7	21.3

PCT had no effect on the average height of red spruce (p=0.703) or quaking aspen (p=0.051) but did significantly (p=0.015) increase average height of balsam fir from 24.6 ft. in the no PCT plots to 26.5 ft. in the PCT plots. PCT also effectively reduced (p<0.001) the average height of red maple from 24.0 ft. in the no PCT plots to 18.8 ft. in the PCT plots.

Neither herbicide treatment nor PCT influenced SI calculation among study plots. The average height of dominant balsam fir was 35.6 ft. and 34.1 ft on PCT and no PCT plots respectively. Increment cores revealed an average breast height age of 17 in 1999, thus 12 years were required on average to achieve breast height. This information was used with average height of balsam fir and Steinman's (unpublished) formula to calculate site index for each treatment plot. Herbicide treatments had no effect on site index (p=0.657). Also, no difference (p=0.112) in site index was found between PCT treatments and non-PCT treatments. The average site index for all plots was 72.1 ft (50-year base).

Quadratic Mean Diameter (QMD)

There were no herbicide effects on QMD of merchantable stems for all species in any of the three merchantability classes (p>0.192) (Appendix A). There were, however, PCT effects on QMD of merchantable stems for all species in the low and middle merchantability classes (p<0.016), but PCT had no effect in the high merchantability class (p=0.876). There were no interaction effects on QMD of merchantable stems for all species (p>0.565). Also, there were no differences in QMD between any of the treatments tested in the 19 linear contrasts (p>0.125) (Appendix B).

There was no influence of herbicide treatment on QMD ($p>0.05$) of merchantable balsam fir trees for any of the three merchantability classes. There were, however, PCT effects on QMD of merchantable balsam fir trees for all three merchantability classes ($p<0.05$). Mean QMD on plots receiving PCT treatments was 5.5, 5.8, and 6.5 in class for the low, middle, and high merchantability classes respectively. Mean QMD on plots receiving no-PCT treatments was 4.4, 4.9, and 5.9 in class for the low, middle, and high merchantability classes, respectively. The difference in mean QMD between plots receiving PCT treatments and plots receiving no-PCT treatment was highly significant ($p<0.001$) for all merchantability classes.

The results of the QMD analysis for red spruce were very similar to those of balsam fir. The mean QMD for merchantable stems of red spruce in plots receiving PCT treatments was 5.0, 5.6, and 6.7 in class for the low, middle, and high merchantability classes, respectively, while the means for those plots receiving no PCT treatment were 4.3, 4.9, and 6.1 in class, respectively. The difference in mean QMD among these treatments was highly significant ($p<0.001$) for the low and middle merchantability classes, but only marginally significant ($p=0.047$) for the high merchantability class.

Except for the control, there were few if any merchantable stems of red maple or quaking aspen in treated plots. Therefore, we did not conduct tests on QMD for these species.

Diameter Distributions

Due to the wide range of variation of individual tree sizes among plots, detecting differences among treatments based on mean diameters of individual trees was difficult. Diameter distributions of selected species, however, more clearly revealed the influence of herbicide and PCT treatments. Figure 1.6 shows the diameter distributions for balsam fir, red spruce, red maple, and aspen for the glyphosate and PCT treatment combinations and the control. Balsam fir has few stems over 4 inches DBH in the untreated controls. Red spruce exhibits a similar pattern to fir. PCT treatments shifted the distribution of fir and spruce diameters to the right.

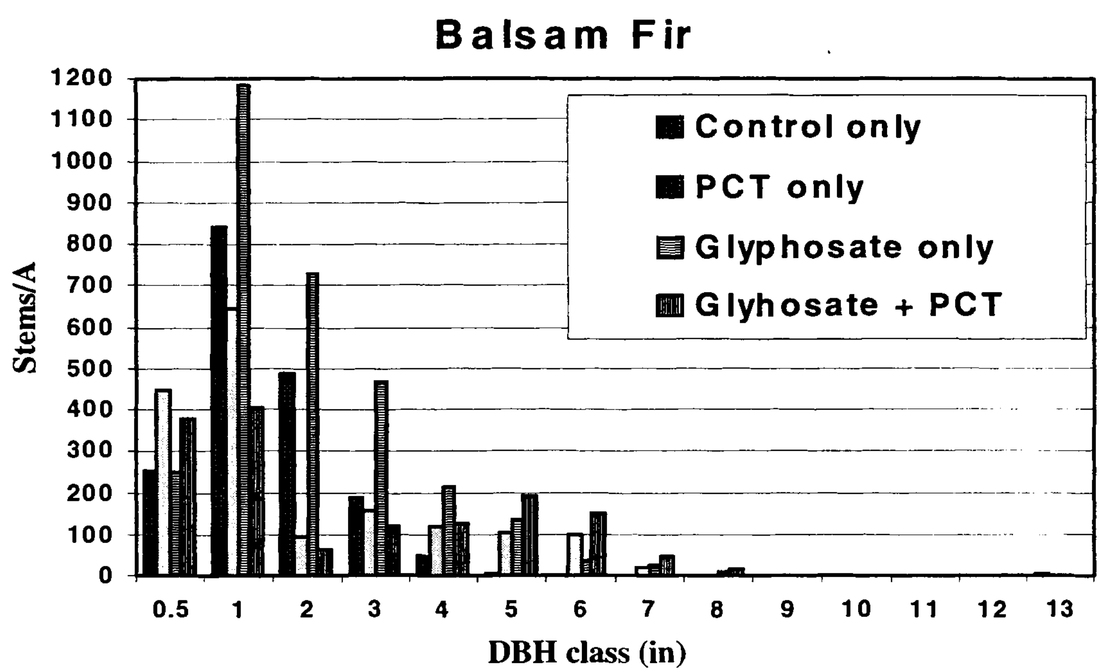
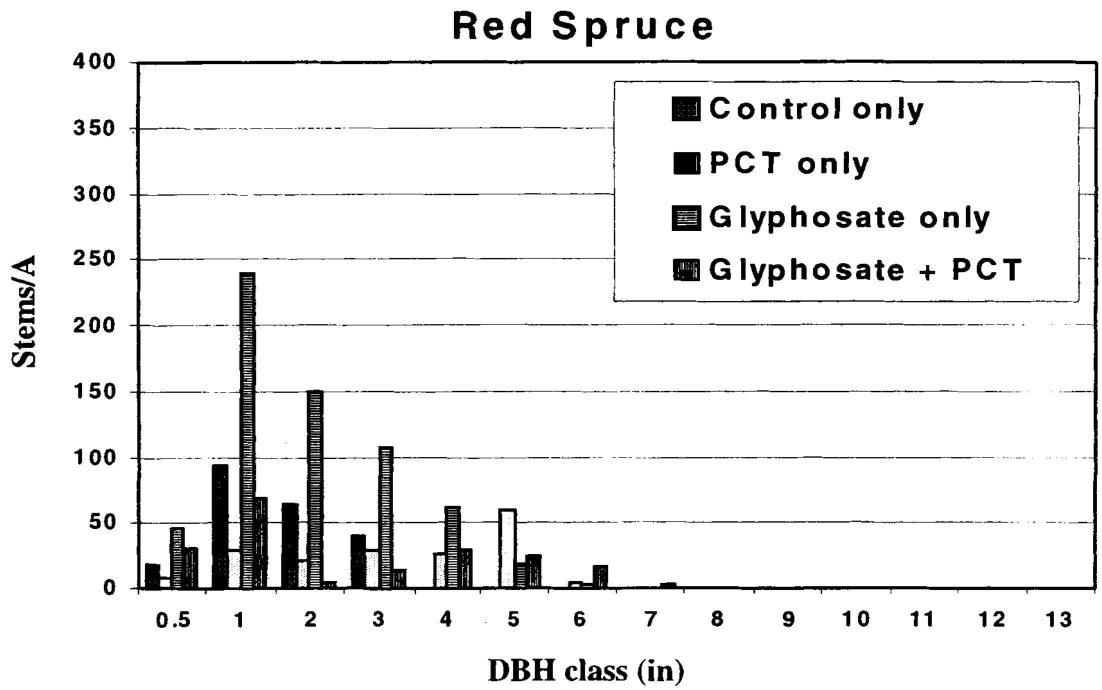


Figure 1.6: Diameter distributions for balsam fir, red spruce, quaking aspen, and red maple for glyphosate herbicide treated and untreated, and PCT and no PCT treatments.



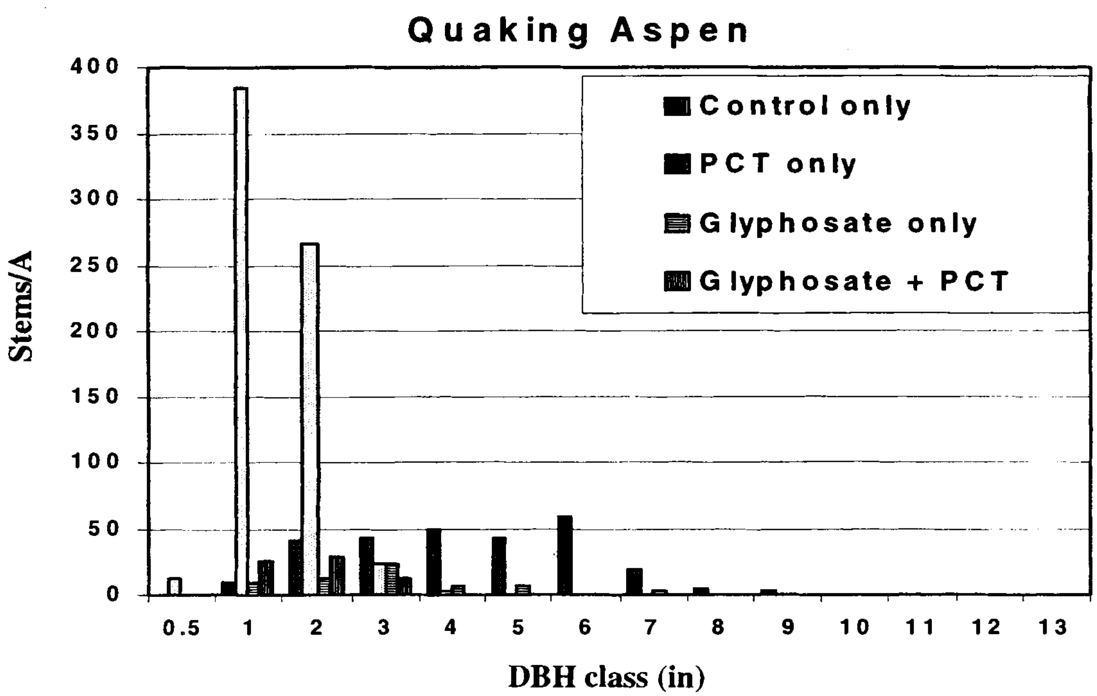


Figure 1.6: Continued.

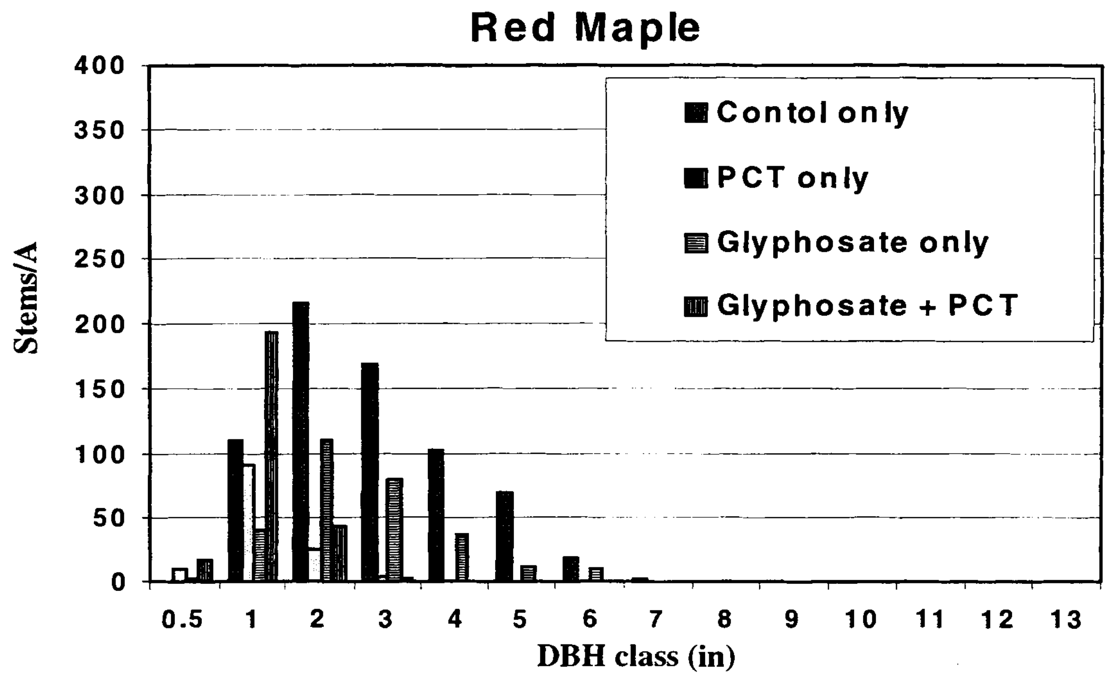


Figure 1.6: Continued.

The influence of PCT on the diameter distribution of hardwood stems was opposite that of conifers. For example, nearly all stems in the 3-inch and larger diameter classes for aspen and maple were in plots with no PCT, and with greater representation among these in the untreated control. The large number of aspen stems in the 2 and 3-inch diameter classes for the Control + PCT treatment were likely not part of the original stand but a result of sprouting after the PCT treatment. For red maple, there were fewer stems in the larger diameter classes for the Glyphosate only treatment than in the Control-no PCT treatment, indicating that glyphosate was relatively effective at suppressing red maple. There was, however, more red maple than quaking aspen in the larger diameter classes in Glyphosate only treatment, suggesting that glyphosate was less effective in controlling

red maple than quaking aspen. PCT effectively reduced red maple, with no stems larger than 3 inches found in either the Control + PCT or the Glyphosate + PCT treatments.

Total Volume

Treatment effects on total volume can be seen in Figure 1.7. Total stand volume among the herbicide only treatments was not different from the Control only treatment 22 years after treatment ($p = 0.117$). However, herbicide only treatments did on average reduce hardwood total volume ($p < 0.001$) and percent hardwood total volume ($p < 0.001$) relative to the Control only. Softwood volume and percent softwood volume on average was higher ($p<0.001$) in the herbicide only treatments than in the Control only. Total volume in the control only treatment was comprised of 77% hardwood while the average for all herbicide only treatments was only 24% hardwood. There was an increase ($p < 0.001$) in softwood total volume from 466 ft^3 /A in the control only treatment to 1,456 ft^3 /A on average among all herbicide only treatments. Total softwood volumes were higher (1,693 ft^3 /A) for the Triclopyr-only treatment ($p < 0.001$) and marginally higher (1,434 ft^3 / A) for the Glyphosate-only treatment ($p = 0.004$) than the Control-only. Total volume in the Triclopyr only and Glyphosate only treatments was comprised of 20% and 19% hardwood, respectively.

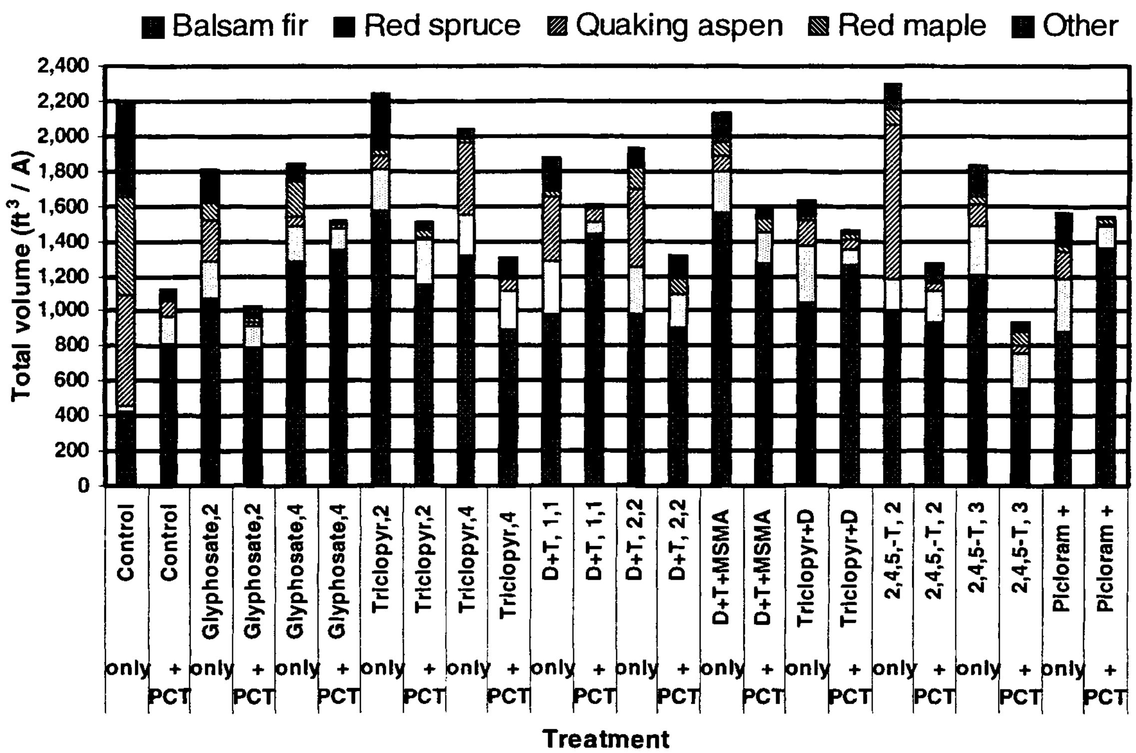


Figure 1.7: Total stand volume for all species by treatment.

PCT reduced total volume ($p < 0.001$) from 2,201 ft^3 /A in the Control only treatment to 1,128 ft^3 /A in the Control + PCT treatment. Hardwood total volume was reduced ($p < 0.001$) from an average of 1,734 ft^3 /A in the Control-only to 155 ft^3 /A in the Control + PCT treatment, and the % hardwood total volume was reduced ($p < 0.001$) from 77% in the Control only treatment to 16% in the Control + PCT treatment. When glyphosate and triclopyr herbicides were used, PCT did not decrease hardwood total volume or % hardwood total volume, and did not increase softwood total volume or % softwood total volume, suggesting that PCT did not substantially alter species composition beyond that caused by prior herbicide treatment.

Herbicide only treatments increased (p=0.003) balsam fir total volume to an average of 1,174.7 ft3/A relative to 422.3 ft^3/A for the Control only. PCT had no effect on the total volume of balsam fir (p=0.536). Total red spruce volume was unaffected by herbicide treatments (p=0.536), but was increased by PCT treatment (p = 0.031). Both herbicides (p=0.027) and PCT (p < 0.001) reduced quaking aspen volume. Red maple volume also was reduced by herbicide only treatments (p <0.001) and PCT only treatments (p<0.001) when compared to the Control only treatment. There also were no significant treatment interaction effects on total volume (p=0.089).

Merchantable Volume

Herbicide treatment alone did not increase (p>0.776) total merchantable volume above the Control only in any of the three merchantability classes tested (Appendix A) (Figures 1.8, 1.9 and 1.10).

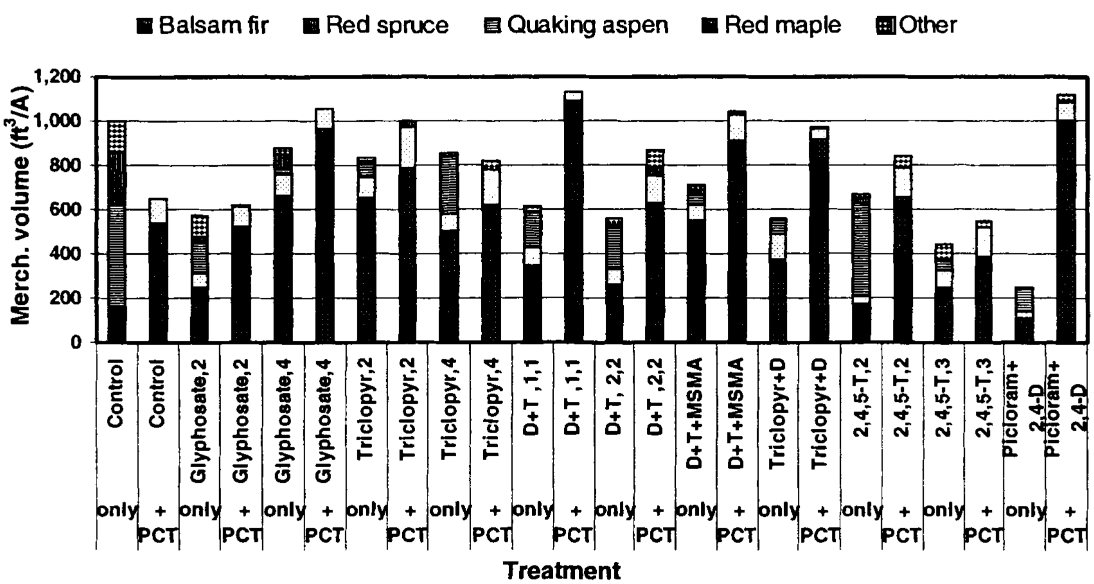


Figure 1.8: Merchantable stem volume (ft^3/A) for all treatments by species using the low merchantability class.

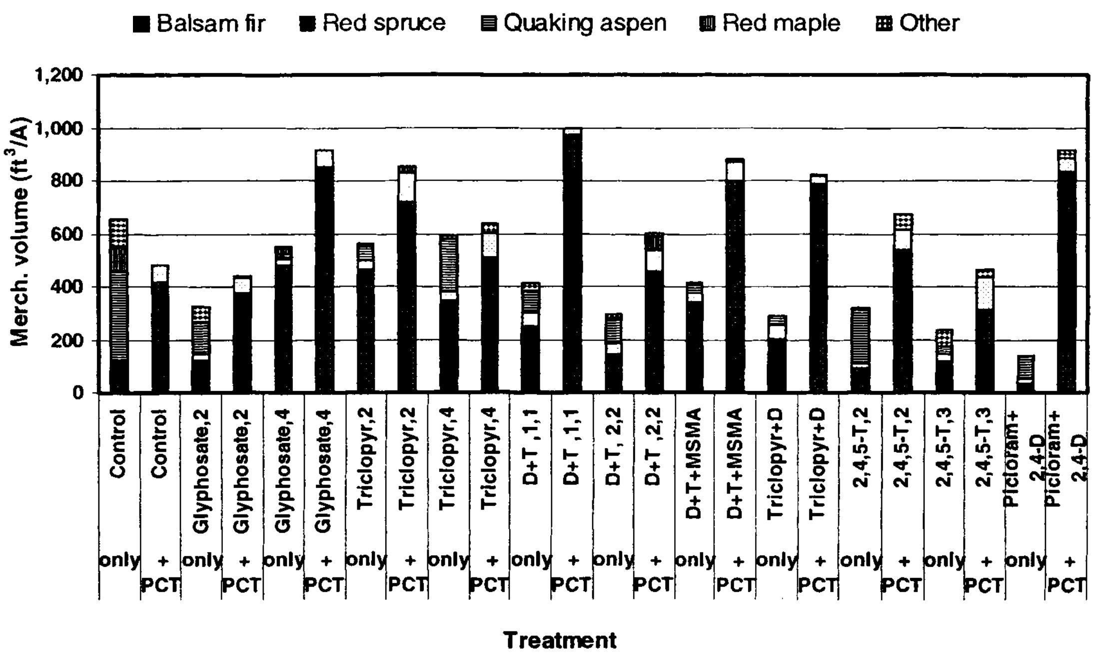


Figure 1.9: Stand merchantable stem volume (ft^3/A) for all treatments by species using the middle merchantability class.

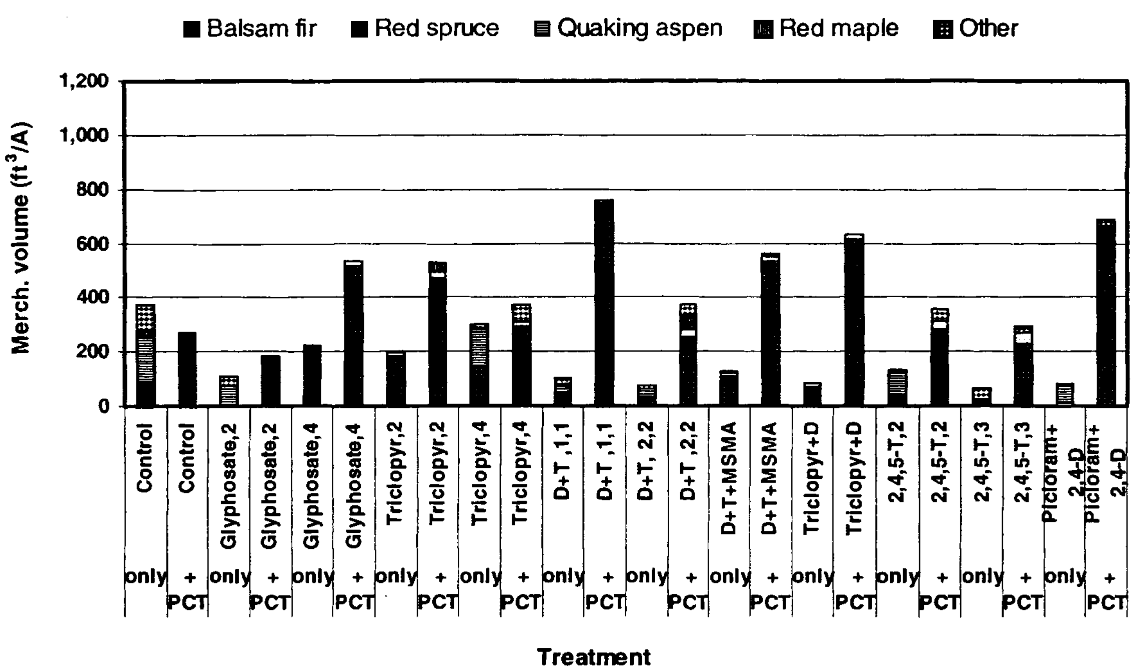


Figure 1.10: Stand merchantable stem volume (ft^3/A) for all treatments by species using the high merchantability class.

Hardwood merchantable volume was reduced by herbicide treatment, but only in the low merchantability class ($p=0.047$).There were no herbicide effects on softwood merchantable volume in any merchantability class ($p>0.244$). Quaking aspen was the only individual species showing a reduced merchantable volume from herbicide, and only in the lowest merchantability class ($p=0.049$).

There was no difference ($p > 0.020$) in total merchantable volume between the Control only treatment (655 ft^3/A, middle merchantability class) and an average of all herbicide only treatments combined (386 ft^3/A, middle merchantability class) in any merchantability class (Appendix B). Hardwood merchantable volume, however, was lower in the herbicide only treatments than the Control-only ($p < 0.001$) in all three merchantability classes. The Control only treatment contained 526 ft^3/A of hardwood merchantable volume (middle merchantability class), or 80% of the total, and the average of all herbicide only treatments combined was 102 ft^3/A (middle merchantability class), or 26% of the total.

Total merchantable volume of the Glyphosate-only treatment was not different than the Control only treatment, but hardwood merchantable volume was substantially reduced ($p < 0.001$) in all merchantability classes. The same was true for Triclopyr-only ($p<0.003$) and the Phenoxy-only treatments ($p<0.001$). The Glyphosate-only treatments had an average of 440 ft^3/A (medium merchantability class) total merchantable volume, of which 85 ft^3/A was hardwood merchantable volume, or 19% of the total. The Triclopyr only

treatment contained 575 ft^3/A (middle merchantability class), of which 127 ft^3/A was in hardwood merchantable volume, or 22% of the total. Totals for the Phenoxy only treatments were 321 ft^3/A total merchantable (middle merchantability class) volume with 101 ft^3/A in hardwood, or 32% of the total. There was no difference in total merchantable volume, hardwood merchantable volume, or softwood merchantable volume in any merchantability class among the Triclopyr only, Glyphosate only, and Phenoxy only treatments ($p>0.362$).

The effects of PCT only on total merchantable volume were significant ($p < 0.001$) only in the highest merchantability class. PCT effects were not significant on hardwood merchantable volume in any merchantability class, but effectively increased softwood merchantable volume in the low ($p=0.026$) and high ($p<0.001$) merchantability classes. In the low merchantability class there was, on average, more merchantable volume in the Control only treatment than in the PCT only treatment. The Control only treatment contained 655 ft^3/A (middle merchantability class) total merchantable volume, of which 526 ft^3/A was in hardwood. The PCT only treatment contained 479 ft^3/A (middle merchantability class) total merchantable volume, none of which was in hardwood. When compared to the Control only treatment, total merchantable volume in the PCT only treatment was not different ($p>0.082$), however, the difference in hardwood merchantable volume was significant ($p < 0.001$).

The Glyphosate + PCT treatment contained 677 ft^3/A total merchantable volume (middle merchantability class) with only 4 ft^3/A in hardwood merchantable volume. Total

merchantable volume for the Glyphosate + PCT was not different from the PCT only (p>0.254) or the Glyphosate only treatment (p>0.104) in any merchantability class. The Triclopyr + PCT treatment contained 746 ft^3/A with 12 ft^3/A in hardwood, and the Phenoxy + PCT contained 727 ft^3/A, with 9 ft^3/A in hardwood. There were no significant differences in either total merchantable volume or hardwood merchantable volume between the Control + PCT, Glyphosate + PCT, Triclopyr + PCT or Phenoxy + PCT treatments (p>0.071).There also were no treatment interaction effects on merchantable volume in any merchantability classes (p>0.089).

Merchantable volume of balsam fir was not effected by herbicide treatments in any merchantability class (p>0.261). PCT only effectively increased balsam fir merchantable volume in all merchantability classes (p<0.002). Similarly, herbicides had no effect on merchantable volume of red spruce (p>0.275). PCT effectively increased merchantable volume in the middle and high merchantability classes (p<0.004). Merchantable volume of quaking aspen was reduced (p<0.049) by herbicide only treatments in only the lowest merchantability class whereas PCT reduced quaking aspen merchantable volume in all three merchantability classes (p<0.001). PCT had no influence on merchantability of red maple in any merchantability class.

Financial Value

Treatment effects on the value of standing wood for the three merchantability standards are shown in Figures 1.11, 1.12 and 1.13. Herbicide effects can be seen when comparing the Control-only treatment to the herbicide-only treatments. Among plots with no PCT

treatment, only the highest rate of Glyphosate, both rates of Triclopyr, and the 2,4-D + 2,4,5-T + MSMA treatments attained a higher stand value than the Control only treatment using the low and middle merchantability classes. Only the highest rates of Glyphosate and Triclopyr attained a higher stand value than the Control only using the highest merchantability standard. Less than half the total value of the Control-only treatment is in softwood while nearly all the value in the herbicide only treatments is in softwood. The Control-only treatment contained more merchantable volume than any other treatment for all three merchantability classes, yet the financial value of the Control only is lower than most of the herbicide only treatments. This difference is indicative of the higher value of spruce and fir, and the reason that herbicide treatments are prescribed in spruce-fir stands.

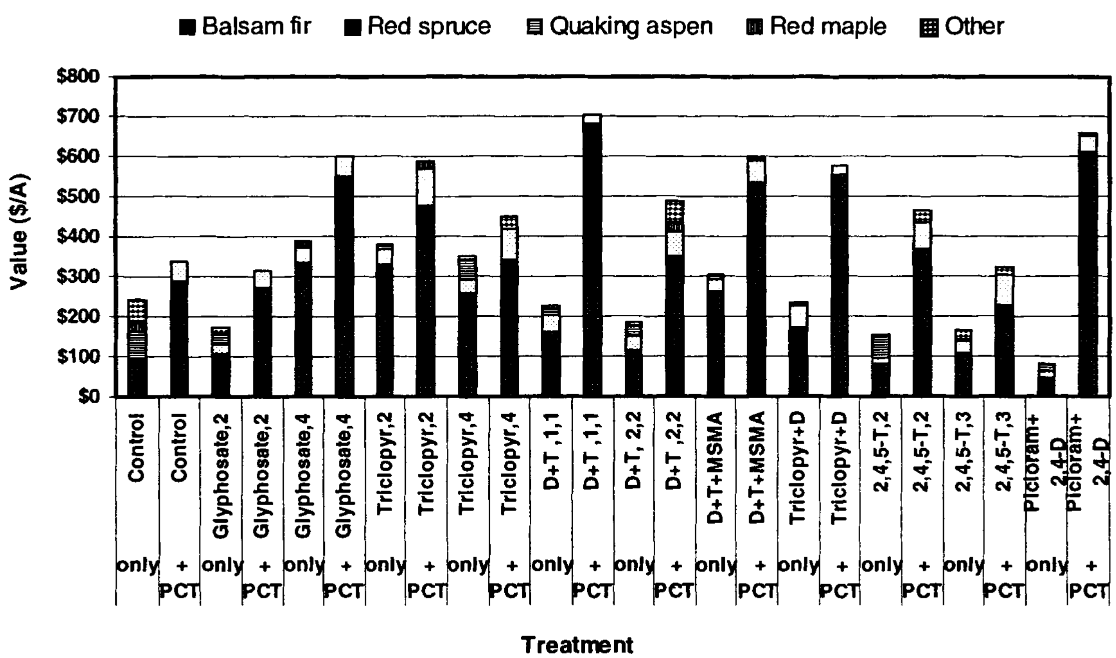


Figure 1.11: Stand value for all treatments by species using the low merchantability class.

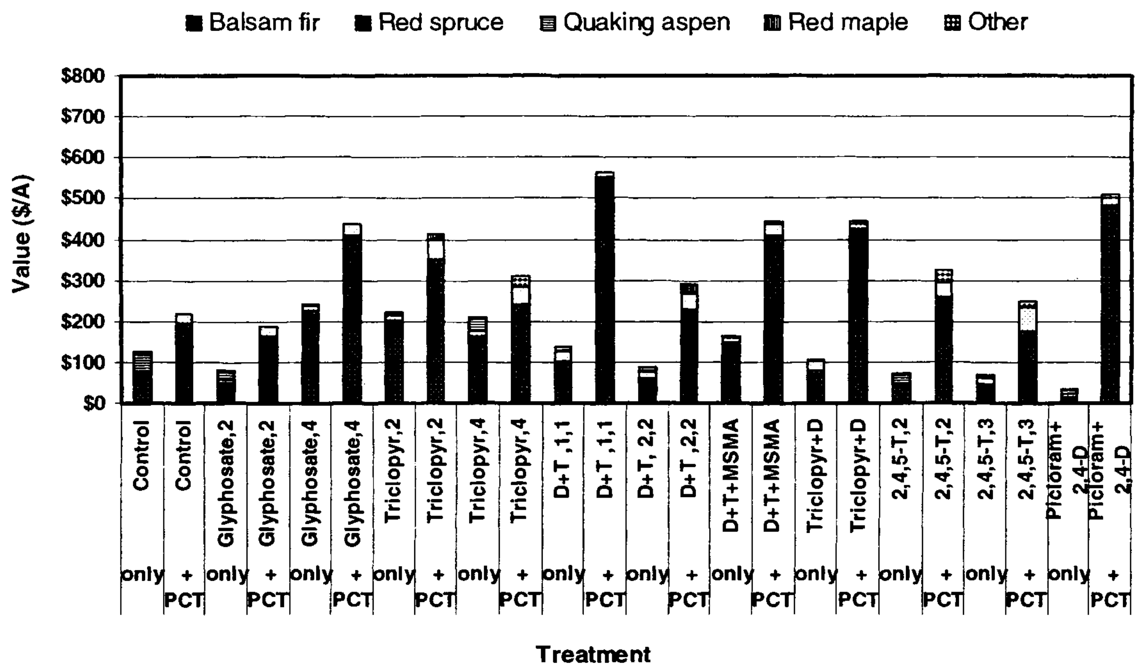


Figure 1.12: Stand value for all treatments by species using the middle merchantability class.

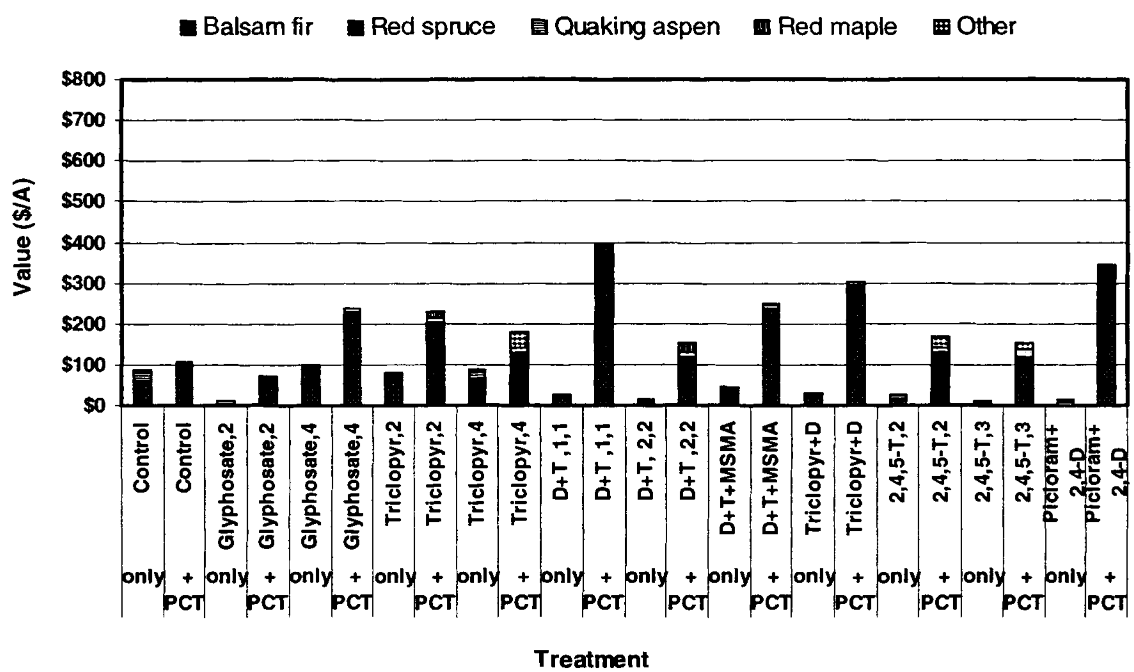


Figure 1.13: Stand value for all treatments by species using the high merchantability class.

Most, if not all, of the value in the Control only treatment is from low-value hardwood pulpwood. Total stand value decreased and the proportion of the total value in hardwood decreased as the merchantability standard was increased for all treatments.

PCT increased the value of standing wood on all three merchantability classes ($p<0.001$). The influence of PCT treatments on the value of standing wood is evident by comparing the Control only treatment to the Control + PCT treatment. The Control + PCT treatment attained a higher ($p<0.001$) total value than the Control only treatment for all merchantability classes, but the difference between the two treatments decreased as the merchantability standard increased. Nearly all of the stand value of the Control + PCT treatment, in all three merchantability classes, was composed of softwood. In contrast, nearly 60% of the total value of the Control only treatment was in hardwood, but this proportion decreased rapidly as merchantability standard increased.

Although we found no statistically significant differences, stand values appeared to be greatly enhanced by PCT treatments after a prior herbicide treatment. In every case, an herbicide treatment that was followed by PCT achieved a higher total stand value in all merchantability classes than the same herbicide treatment without PCT. The increase in value of the herbicide only treatments by PCT was accentuated as the merchantability standard increased. The mean value for all herbicide only treatments was $240.84/A in the low merchantability class, while the mean value for all herbicide + PCT treatments was $523.26/A or an average increase of 117%. For the middle merchantability class, the

mean value of all herbicide only treatments was $124.52/A and the mean value of all herbicide + PCT treatments was $328.52/A representing a 163.8% increase. The average increase in value from herbicide + PCT treatments over that of herbicide only treatments in the high merchantability class was 382.6% with mean values of $203.94/A and $42.26/A respectively. The increase in value of the herbicide only treatments by PCT was greater than the increase in value of the Control only treatment by PCT in all three merchantability classes. The increase in value from PCT in the Control plots was 40.2%, 70.1%, and 23.6% in the low, middle, and high merchantability classes respectively.

DISCUSSION

Results from this study reveal that the influence of herbicide applications and PCT have substantial long-term influences on stand composition, structure, and financial value. These emerging patterns of development were evident shortly after the herbicide treatments. Results reported by McCormack and Newton (1980) and McCormack (1982) revealed that two years after treatment all herbicides and rates of application reduced hardwood cover by 50 % or more and cover taller than 4.9 ft was nearly eliminated by triclopyr, glyphosate, and high rates of 2,4,5-T. By 1986 (9 years after treatment) Newton et al. (1992b) reported that many of the herbicide treatments at Austin Pond were effective to varying degrees in controlling shrubs and hardwood vegetation. Vegetation dynamics established by the herbicide treatments, which were intended to direct stand development toward spruce and fir dominance, have largely met this objective. No intervention, as represented by the Control only, produced stands dominated by intolerant hardwood species with a suppressed understory of scattered conifers.

Based on earlier comparisons, glyphosate and triclopyr were found to be among the two most effective herbicides tested (McCormack and Newton 1980). Two years after herbicide treatments deciduous trees and shrubs comprised from 35% to 38% of all cover in the glyphosate plots, and from 11% to 41% in the triclopyr plots. Of the cover taller than 4.9 ft at this same time, the percentage substantially less in the glyphosate and triclopyr plots ranging from 0% to 10%. In comparison, our results 22 years after herbicide treatments show deciduous trees and shrubs comprise on average 15% of stem density in the herbicide only plots. This result indicates that the early effectiveness of the herbicide treatments was maintained for at least 22 years after treatment. Despite the differences reflected in the stand composition today, we were not able to find any statistical differences in abundance of balsam fir, red spruce, quaking aspen, or red maple, between the phenoxy herbicides (2,4-D and 2,4,5-T) and glyphosate or triclopyr herbicides at any application rate. We also found no difference between the glyphosate and triclopyr treatments. Our inability to find differences between these treatments may be due, in part at least, to the small number of replicates in our study.

The herbicide treatments did not, however, reduce overstocking. Newton et al (1992b) documented the earlier effect of high densities on tree growth in this study. The density of spruce and fir stems nine years after herbicide treatment was about 7,250 stems/A in the glyphosate and triclopyr plots compared to an average of 4,200 stems/A 22 years after herbicide treatment. Although many dead stems can be found in the herbicide-only treatments, indicating a pattern self-thinning, stand density remains high at 29 years.

These high densities and resulting low merchantable volumes in the herbicide-only treatments revealed the continuing negative influence of overstocking on stand development. Overstocking occurs on more than two-thirds of the spruce-fir stands in Maine (Powell and Dickson 1984), thus the need for PCT early in stand development.

The PCT that occurred shortly after the Newton et al. (1992*a*, 1992*b*) studies provided a unique opportunity to examine the combined effects of various combinations of herbicide and PCT. The effects of PCT 13 years post treatment were quite apparent in this study. PCT not only increased spruce and fir composition by reducing interspecific competition from shrubs and hardwoods, but also dramatically reduced intraspecific competition. The result was a 25% increase in QMD of merchantable stems 13 years following PCT. Although there was considerably more merchantable volume in the Control only treatment, the Control + PCT treatment had a 44% higher financial value on average among the three merchantability classes. Most of the merchantable volume in the Control only treatments consisted of low value hardwood pulp, whereas most of the value in the Control + PCT treatment was in spruce-fir pulpwood and a small amount of studwood.

These results are consistent with those of Brissette et al. (1999) who reported more spruce-fir merchantable volume at 2.4 m x 2.4 m spacing plots than in an unspaced control. Brissette et al., however, also indicated that if all tree species were considered, there was probably more merchantable volume in the unthinned control. Results reported by Ker (1987) for 15-year results of PCT also agree. He found that merchantable volume was nearly 50% greater in the unthinned Control than in spacing greater than 7 ft. His

results for spacing of less than 5 ft were dramatically different. There was more volume in the 5 ft spacing than in the unthinned Control. Spacing in this study was approximately 8 ft x 8 ft (700 TPA), somewhat lower than typical PCT spacings today, which range from 900 to 1,200 TPA. Our results combined with those of other studies, suggest that a narrower spacing may have increased overall merchantable volumes. The difference in merchantable volume between these two treatments would be expected to decrease as the stands near rotation age indicating perhaps an even larger difference in value as many more stems in the Control + PCT obtain a size large enough to be merchandised as studwood or sawlogs. The large increases in merchantable volume and financial value of the herbicide + PCT treatments compared with the herbicide-only treatments and PCT only treatments reflects an enhancement of the benefits of herbicide treatments when followed by PCT.

Although we found no statistically significant interactions between herbicide and PCT treatments for any of the dependent variables tested, the positive effects of herbicide application in favoring spruce and fir clearly set up these species to take advantage of PCT. This advantage is reflected with higher merchantable volumes and higher values in nearly all herbicide + PCT treatments than in the PCT only treatments. In year 16, just prior to the PCT treatments, Newton et al. (1992*b*) reported the average height of balsam fir crop trees was more than 3 ft taller (39.5%) and the average height of red spruce crop trees was more than 1 ft taller (11.0%) in the herbicide plots than in the untreated Control plots. In terms of volume, they reported the average volume of balsam fir crop trees was on average 173% greater and the average volume of red spruce crop trees was 35.5%

greater in the herbicide treated plots than in the untreated Control plots. The increased height and volume of balsam fir and red spruce crop trees, as a result of herbicide treatment, placed both species in a better position to respond to PCT. Our results, in year 29, indicated the average height of balsam fir was only 8% taller (2 ft) and the average height of red spruce was slightly less (0.2 ft) in the herbicide + PCT treatments than in the Control + PCT treatment. In terms of volume, balsam fir merchantable stems (middle merchantability class) contained on average 23.5% more volume (0.4 ft^3/stem) in the herbicide + PCT treatments than in the Control + PCT treatment. For red spruce, the average merchantable stem contained 26.7% more volume (0.4 ft^3/stem) in the herbicide + PCT treatments than in the Control + PCT treatments. Also, there were, on average, 24.3% more merchantable stems/A, including both balsam fir and red spruce, in the herbicide + PCT plots compared to the Control + PCT plots (middle merchantability class). The herbicide + PCT plots contained 322.1 merchantable stems/A while the Control + PCT contained 259.2 merchantable stems/A (middle merchantability class). Our results suggest the benefits of increased size resulting from herbicide treatments reported by Newton et al. (1992*b*) enhanced the effects of subsequent PCT treatments as evidenced by increased average volume per merchantable stem and larger densities of merchantable stems , at age 29, in the herbicide + PCT treatments when compared to the Control + PCT treatments.

Our results indicated that herbicide treatments did not increase tree height for any species. PCT, however, did increase the average height of balsam fir. Influences on height in other studies are inconsistent however. Ker (1987) found no difference in total

height of balsam fir trees between PCT and control plots, while others (Brissette 1999, Piene and Anderson 1987, Burns et al 1996) report increased height growth with PCT. Burns et al (1996) concluded PCT increased site index by 30% for black spruce growing on three sites in northern Minnesota.

We found no difference in site index between treatments, but the mean site index for balsam fir (base breast height age 50 years) for all plots was higher (72.1 ft) than expected based on the soils and "off the chart" on site index curves (Steinman unpublished). Our soil drainage data suggests that the Austin Pond site, on average, is a low 3 or high 4 on the Briggs (1994) soil drainage classification system. The higher than expected sited index suggests not only that PCT may increase site index but possibly other management techniques, such as herbicide application, as well. Better data, such as those from this study, are needed for improving site index estimates for managed spruce-fir stands.

CHAPTER 2.

FINANCIAL RETURNS FROM HERBICIDE AND PRECOMMERCIAL THINNING TREATMENTS IN SPRUCE-FIR STANDS OF MAINE

ABSTRACT

Using growth and yield projections of research plots in a long-term study, we determined the net present value (NPV) and internal rate of return (IRR) for investments in herbicide and PCT treatments in young spruce-fir stands. The Forest Vegetation Simulator (FVS)(NE TWIGS variant) was used to project the height and diameter growth of stems in 52 plots in a 3 x 2 factorial design: herbicide treatment (3 levels: glyphosate-triclopyr, phenoxy, and control) and PCT treatment (2 levels: PCT and no PCT), for a simulation period of 100 years using 11, 10-year growth cycles. Total volume and merchantable volume were calculated for each tree species by plot at the end of each growth cycle using the projected diameters and heights of stems and Honer's (1967) volume equations. Values of standing wood were calculated for each plot at the end of every growth cycle using the calculated merchantable volumes and average prices of wood products published by the Maine Forest Service. From these values of standing wood and average cost of herbicide and PCT treatments, we calculated NPV and IRR for each plot at the end of each growth cycle.

Financial rotation age was determined as the age during the simulation when NPV reached a maximum. We then compared all combinations of herbicide and thinning treatments at rotation age for the following dependent variables: maximum NPV, age at

maximum NPV, number of years of positive NPV, IRR, and a flexibility index that integrated the area under the positive portion of the NPV curve over the entire simulation period.

Financial rotation age was not affected by herbicide ($p=0.928$) or PCT ($p=0.601$) treatment, and was estimated to be approximately 50 years for all treatments. Herbicide had no effect ($p=0.445$) on total stand volume at rotation age. PCT, however, reduced ($p<0.001$) total stand volume at rotation age. Herbicide treatments had no effect ($p=0.225$) on maximum NPV, but PCT alone and in combination with herbicides reduced ($p<0.001$) maximum NPV below that of the Control only treatment. There was no interaction between herbicide and PCT treatments ($p=0.026$). Mean IRR for the herbicide treatments alone was 8.2%. For PCT alone the IRR was 6.3%. The mean IRR for plots receiving both herbicide and PCT treatments was 5.8%. Therefore, the rate of return for both herbicide and PCT, and combinations of the two treatments, would be acceptable to many investors. None of the herbicide or PCT treatments attained a higher maximum NPV ($p>0.184$) than the untreated Control plots.

INTRODUCTION

Over the past three decades, Maine forestland owners and professional foresters have been faced with the task of managing young even-aged stands that resulted from large-scale clearcut operations undertaken in the 1970s and 80s. These clearcuts resulted first from the extensive salvage logging of spruce budworm damaged stands and later from a general trend toward even-aged silviculture in the spruce-fir stands of Maine. The stands

that regenerated early in the century had matured by the 1970's when extensive spruce budworm infestations had occurred (Seymour 1992). Many of these stands, at the time of harvest, had sufficient natural regeneration of desirable species (spruce-fir) to comprise a fully stocked stand. Competing hardwood species also were present and if left unmanaged, the overstory of these stands would be rapidly dominated by faster growing pioneer hardwood species. The spruce and fir would be suppressed in the lower canopy for perhaps 100 years until senescence, harvest, or other disturbance removed the hardwood species from the upper canopy, releasing the spruce and fir.

Aerial herbicide application has been used extensively to control competing shrub hardwood tree vegetation in these stands during the first 3 to 10 years of development. Later precommercial thinning (PCT) has been commonly used to reallocate growing space to increase average stem diameter and maintain the crowns of the now dominant spruce-fir stand. Currently, based on state wide averages between 1995 and 2000, approximately 14,052 A/yr undergoes herbicide application and approximately 19,887 A/yr undergo PCT treatments (Wagner et al 2003). A recent report by the Maine Forest Service (Maine Department of Conservation 1998) cites the importance of PCT and herbicide treatments to the overall future wood supplies in the state. The report identifies one possible scenario of improved forest management activities that achieves a sustainable balance between growth and 100% of current harvest levels by increasing the number of acres under high-yield silvicultural practices to a cumulative total of 9% of Maine's forest land by the year 2015. Another report by Wagner et al. (2003) assessing research priorities for Maine suggests that the principal limitations to projecting changes

in wood supply under increasing levels of high-yield management has been a lack of information about how these treatments are likely to alter growth and yield responses in forest stands. The justification for application of herbicide treatments has been the assumption that control of the competing hardwoods can promote early dominance of spruce and fir, increase yields, and shorten rotations. The justification for application of PCT treatments has been the assumption that reallocation of growing space to selected spruce-fir crop trees would promote volume growth of individual stems, shorten financial rotations, improve stem quality, and reduce harvest costs.

Many large landowners have embarked on large-scale programs of using herbicides and PCT with relatively little scientific data to support the long-term effectiveness or economic return on these investments. Newton et al. (1992a) state that the Austin Pond Study is the only study in the Northeastern U.S. providing the opportunity to measure the long-term effects of herbicides on competing hardwood vegetation. Some studies have addressed the short-term effects of herbicide treatments on spruce-fir stand development (McCormack and Newton 1980, Newton et al 1992a, Newton et al 1992b, Lehala 1981), but there are no known studies addressing the long-term effects of these treatments on spruce-fir forests of the Northeast. Similarly, many of the studies examining the effects of PCT in spruce-fir forests in the Northeast (Piene 1981, Piene and Anderson 1987, Baskerville 1961, Brissette et al 1999, Ker 1981, Ker 1987) either explore only the effects on individual crop trees or are not of a sufficient duration to determine the effects of PCT at rotation age.

Even-aged management in spruce-fir stands was not common in Maine prior the 1970s (Seymour 1992) and since stands treated during this period are not yet mature, we have little basis for evaluating the long-term effectiveness or economic returns from herbicide and PCT treatments. This problem is not confined to the northeastern United States, but in fact is a problem in forest types across North America (Wagner 1993). The complexity of forest management, coupled with long rotation periods, accounts for the scarcity of definitive studies that evaluate the ultimate benefits of forest vegetation management in the long run (Walstad and Kuch 1987, Wagner 1993).

Three growth and yield functions are commonly used to project spruce-fir stand conditions in the Northeast; NE TWIGS, FIBER, and GNY (Randolph et al. 2001). The NE TWIGS growth and yield model (Bush 1995, Hilt and Teck 1987) is a Northeastern variant of the growth and yield function "Prognosis" (Stage 1973) developed as part of the National Forest Systems (NFS) Timber Management System. Forest Inventory and Analysis (FIA) data from the Northeastern Forest Experiment Station was used to develop the model. FIBER was developed to predict growth interactions among species in the spruce-fir, Northern hardwood, and mixed hardwood-softwood stands in the Northeastern United States (Solomon et al 1987). Nearly 4,000 independent growth plots from northern Maine, New Hampshire, northern New York, Vermont, New Brunswick, and Nova Scotia, were included in the development of FIBER. The GNY model (Nova Scotia Softwood Growth and Yield Model) (Nova Scotia Department of Natural Resources (NSDNR) 1993) simulates the growth of even-aged softwood stands except for Eastern Larch (*Larix laricina* (DuRoi) K. Koch) and jack pine (*Pinus banksiana*

Lang.) stands. The GNY model is based on data collected from hundreds of permanent and temporary sample plots measured throughout Nova Scotia over the last quarter century.

Economic evaluations of the need for vegetative management are derived from comparing expected benefits and costs of controlling competition versus letting the stand develop on its own (Brodie *et al.* 1987). Brodie et al. (1987) describes three approaches to economic analysis of vegetative management at the stand level. The "yield-table assumption method" is the simplest approach since it can be conducted for any species for which yield tables exist. Problems arise with this method when the yield tables are based on data from unmanaged stands. The second method is called the "simulated managed stand comparison method". A computer model of managed stand growth is essential for the application of this method. Managed and unmanaged stands are projected independently and compared. It should only be applied to those situations where accurate data from managed stands exist. The third approach is called the "optimization method". In addition to a managed stand simulator an optimization algorithm, utilizing a wide range of stand treatment alternatives, is used to find the optimal solution through iterative simulations. The three methods all help determine differences in stand attributes. Traditional benefit-cost analysis (Nautiyal et al 2001), sometimes referred to as discounted cash flow analysis (McKenney 2000) is utilized in all three methods to determine three common measures; net present value (NPV), cost/benefit ratio, or internal rate of return (IRR).

Chapter 1 examined the effects of aerial herbicide application and PCT on species composition and stand structure 22 years after herbicide application and 13 years after PCT at the Austin Pond study site. Both herbicides and PCT were shown to be effective in controlling species composition by promoting dominance of spruce-fir in the overstory young stands. Herbicides and PCT treatments also increased spruce-fir merchantable volume and the financial values of standing wood over that of untreated control plots. The objective of this chapter is: to project long-term stand development following herbicide and PCT treatments beyond 29 years, and to determine rotation-long financial returns associated with herbicide and PCT treatments in spruce-fir stands.

METHODS

Study Site

The Austin Pond study area is located in west-central Maine in Bald Mountain Township (Latitude: 45.20° N, Longitude: 69.70° W) approximately 20 miles northeast of Bingham Village and currently owned by Plum Creek Timber Company. The site is at approximately 1,300 ft elevation on gently sloping outwash with a northeast aspect (Newton 1992a). Soils on the site range from Telos to Chesuncook types and range from a 4 to a low 2 on the Briggs (1994) soil drainage scale. The stand originated in 1970 as a result of a winter clearcut of a predominantly spruce-fir stand approximately 100 acres in size. Regeneration of red spruce, balsam fir, black spruce, and a scattering of white pine were abundant (Chapter 1).

In 1977 the original herbicide study was installed by Maxwell McCormack to test the efficacy of current and new herbicides that were available. At the time, conifer regeneration was still abundant but subordinate to deciduous shrubs and hardwoods dominated by aspen, birches, raspberry, pin cherry, sprouting red maple, and willow species (Newton 1992a).

In autumn following the 9th growing season after herbicide treatment (1986, year 16) each of the original plots was divided in half. One half was thinned to an operational density of approximately 700 trees/A selecting spruce or fir in the most dominant position (McCormack and Lemin 1998).

Experimental Design

The original Austin Pond study (Newton and McCormack 1980) consisted of 28 experimental units, each 2.6 acres (3.3 chains x 8 chains) in size. The initial treatments were applied in August 1977 and included 12 aerially applied herbicide treatments, an aerially applied water treatment, and an untreated control, each with two replicates in a completely randomized design (Chapter 1) (Table 2.1). Herbicides were applied by a Bell 47G3 helicopter equipped with D6-46 nozzles delivering a spray with an approximate median drop size of 400-500 microns. Volume delivered was 37.4 l/ha in four swaths of 16.7 m net coverage. There were very few skips in coverage, and effects are analogous to those occurring in continuous coverage in large projects (Newton et al. 1992a).

Table 2.1: The original herbicide treatments and control at the Austin Pond Study site.

Herbicide treatment	Application rate (kg/ha)	# of replicates
Glyphosate (Roundup)	1.7	2
	3.3	2
Triclopyr amine (Garlon 3A)	2.2	2
	4.4	2
2,4,5-T	2.2	2
	3.3	2
Triclopyr amine + 2,4-D	2.2 + 2.2	2
2,4-D + 2,4,5-T	1.1 +1.1	2
	2.2 +2.2	2
2,4-D + 2,4,5-T +MSMA	1.1 + 1.1 + 0.11	2
2,4-D + 2,4,5-DP +MSMA	1.1 + 1.1 + 0.11	2
Picloram + 2,4-D	0.45 + 1.7	2
Water only	NA	2
Control (untreated)	NA	2

In 1986, one half of each original experimental unit (3.3 chains x 4 chains) received PCT treatments to an operational density of approximately 700 stems/A resulting in a split-plot design with 56 experimental units (1.3 acres in size). The final design, therefore, was a 2 x 14 factorial design with two levels of PCT (PCT and non-PCT) and 14 different herbicide treatments (Chapter 1).

Chapter 1 describes how the original 1977 study plot boundaries were re-established and the boundaries between PCT and no PCT plots were established for this study. Also described in chapter 1 is the sampling approach used for measuring the plots.

Variables Measured

Species and diameter at breast height (DBH) for every stem at least 4.5 ft tall (breast height) were recorded in each sample plot. Both live and dead stems were counted but tallied separately (Chapter 1).

A sub-sample of stems in each sample plot was measured for total height and height to base of live crown to determine height to DBH relationships by species (Chapter 1). Height to DBH relationships were developed using regression analysis and tested for differences between PCT and non-PCT treatments. Separate models were then developed for those species showing differences for the two treatments. These models were then used to predict the heights of trees not measured directly.

Modeling Objectives and Requirements

Our objective for simulating the future growth and yield of the treatment plots was to project the stand volumes and density for each tree species at 10 year cycles over a 100 year simulation. Quadratic mean diameter (QMD) for all stems in each plot was less than 4.0 in, therefore, we needed a model that could project the growth of both large and small stems. In addition, since the plots were generally composed of several tree species, it was important that a model be used that was capable of projecting mixed species stands. Given the length of the simulation period, it also was important that the model be able to account for silvical differences among tree species, particularly the ability to account for the difference in longevity between red spruce and balsam fir.

Growth Models Available

Three growth and yield models are commonly used to predict future stand conditions of spruce-fir forests in Maine: FIBER (Solomon et al 1995), NE TWIGS (Bush 1995) and GNY (NSDNR 1993). FIBER was developed to predict growth interactions among species in the spruce-fir, Northern hardwood, and mixed hardwood-softwood stands in the Northeastern United States (Solomon et al 1987). The model was updated in 1995 to connect the model's growth characteristics to the inclusion of 6 different land classifications or habitats (Solomon et al 1995). Other options include selecting ecological habitat from standing inventory, the use of proportional stocking guides for mixed hardwood-softwood stands, and an expanded list of output options. Nearly 4,000 independent growth plots from northern Maine, New Hampshire, northern New York, Vermont, New Brunswick, and Nova Scotia, were included in the development of FIBER. Plots were measured between 1959 and 1974 at 5-year intervals; the data sets covered a wide range of species composition, sites, management options, and densities. Two data sources included in the development of FIBER were intensively managed (Solomon, 1987).

NE TWIGS is a variant of the growth and yield model "Prognosis" (Stage 1973). Prognosis is an individual-tree, distance-independent growth and yield model which was developed for use in the Inland Empire area of Idaho and Montana. New "variants" of Prognosis result when Stage's Inland Empire model is calibrated for different geographic areas. During the early 1980s, the National Forest Systems (NFS) Timber Management Staff selected Prognosis as the national supported framework for growth and yield

modeling. At that time, much of the Prognosis modular structure and capabilities were incorporated into the national model framework and called the Forest Vegetation Simulator (FVS). Recently, the Northeastern TWIGS (NE TWIGS) model has been adapted into the national framework. Growth and yield equations from the NE-TWIGS model were used (Hilt and Teck 1989). The model is comprised of three growth components: a large-tree model, a small-tree model, and an establishment model. Forest Inventory and Analysis (FIA) data from the Northeastern Forest Experiment Station were used to develop the model. Data from a total of 2,084 sample plots including 1,599 in Maine, 263 in New Hampshire, and 222 in Vermont were used. Data from the Maine plots include more trees because two growth remeasurement intervals were available for most of the Maine plots, one on an 11-year interval and the other on a 12-year interval. The data for the New Hampshire plots include one remeasurement on a 13-year interval and the data from the Vermont plots include one remeasurement on a 12-year interval (Hilt et al 1987).

The GNY model (Nova Scotia Softwood Growth and Yield Model) (NSDNR 1993) simulates the growth of even-aged softwood stands except for Eastern Larch (*Larix laricina* (DuRoi) K. Koch) and jack pine (*Pinus banksiana* Lang.) stands. It is a stand level model therefore individual tree growth is not simulated. At present, one thinning is allowed per simulation and estimates are most accurate up to age 60. Yields projected by GNY are for fully stocked stands only. To project yields from stands that are partially stocked, the estimated % stocking must be multiplied by the simulated basal areas and volumes. This estimation method assumes that the stocked portions of the stand are

growing "normally" and that the understocking is due to "holes" in the stand. The GNY model is based on data collected from hundreds of permanent and temporary sample plots measured throughout Nova Scotia over the last quarter century. These plots are located in plantations, pre-commercial thinnings, commercial thinnings, and shelterwoods of various ages and spacings, as well as in unmanaged stands. They are maintained by the Forest Research Section of the Nova Scotia Department of Natural Resources.

Relative Strengths and Weaknesses of Available Models

Randolph et al. (2001), in their evaluation of FIBER, GNY, and NE TWIGS growth and yield models, describes the relative strengths and weaknesses of each model. FIBER only grows stems larger than 4.0 in. DBH and accounts for smaller stems through in-growth equations, while NE TWIGS is capable of growing stems 1 inch DBH and larger fulfilling one of our model requirements. GNY is a stand level model incapable of growing individual trees, which limits the accuracy in mixed species stands. NE TWIGS, on the other hand, is an individual tree growth model suitable for growing mixed species stands fulfilling another one of our model requirements. Therefore, the NE TWIGS model met our two main model requirements and was therefore chosen as our growth and yield model.

Site Index Selection

Site index is the major mechanism that the NE TWIGS model incorporates to allow for differences in site productivity and provides a means to calibrate the model. To determine what site index (SI) to use for our growth projections, a random sample of age at breast

height measurements was taken using increments cores on dominant balsam fir trees from the study site. The mean age at breast height was 17 years in 1999 when the sample plots were measured. The stand originated as a result of a clearcut in 1970, thus making it 12 years for trees to reach breast height age. SI was calculated using Steinman's (unpublished) formula that uses breast height age as opposed to total age. SI was determined first by calculating the average height of the tallest tree on each of the 207 sample plots and applying Steinman's formula. The result was SI 71.8 ft in 50 years, breast height age.

A second estimate of SI was calculated using the average height of the tallest 10% of trees larger than 4.0 in DBH in each experimental unit. The mean SI from this calculation was 72.1 ft in 50 years.

A third approach was used to corroborate the SI values estimated from the plot data. Using data collected from the Austin Pond plots in 1993 and 1994 by McCormack and Lemin (1998), we used the NE TWIGS model to project volume data for individual treatment plots forward to 1999 so that we could compare these 1999 volume projections with our measured 1999 volumes on the same plots. Data were available for only 20 PCT and 20 non-PCT plots, 2 PCT and 2 non-PCT plots for the following herbicide treatments; Control (untreated), Glyphosate (Roundup) (both application rates), Triclopyr amine (Garlon 3a)(both application rates), 2,4,5-T (both application rates), 2,4-D + 2,4,5-T (both application rates), Triclopyr amine (Garlon 3a) + 2,4-D.

We ran the NE TWIGS model with these data using SI 65, 70, and 75 for each plot and compared projected with observed volumes. There was only a slight difference in the fit among the three SI values (Figure 2.1).

Based on results from the analysis of site trees and from the NE TWIGS projections of previous Austin Pond data, we selected SI 70 as the best value for our model simulations. Therefore, we projected the growth of each treatment plot using NE TWIGS for 100 years using 10-year cycles at SI 70, elevation of 1,300 ft, and an aspect of north 45° east.

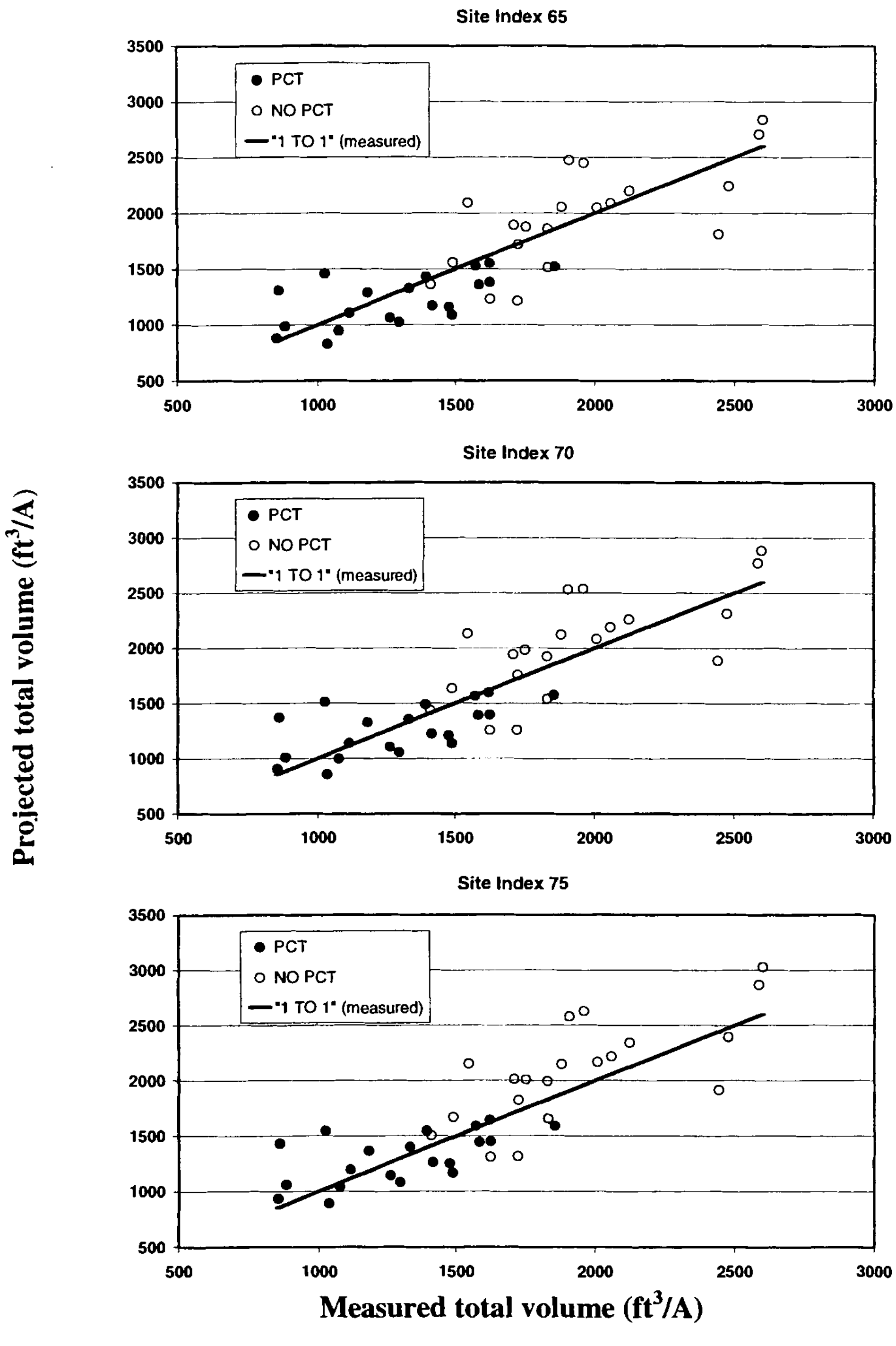


Figure 2.1: Predicted versus measured volumes for study plots in 1999 using values of SI 65, 70, and 75. Predicted volume was derived from NE TWIGS projections using 1993 and 1994 data. Measured volume was derived from 1999 measurements of the same treatment plots.

Wood Volumes, Wood Values, and Merchantability Standards

To include the effects of different merchantability standards on merchantable volumes and financial value in our analysis, we established three merchantability classes using different minimum top diameters for pulpwood and sawlogs for softwoods and hardwoods (Table 2.2).

Table 2.2: Merchantability classes and standards used in the calculation of merchantable volumes.

Merchantability class	Species group	Pulpwood minimum top diameter (inches)	Sawlog minimum top diameter (inches)
Low			
	Softwood	2	4
	Hardwood	3	6
Middle			
	Softwood	3	5
	Hardwood	4	8
High			
	Softwood	4	6
	Hardwood	5	10

For pulpwood, a minimum length of 12 ft was used with no maximum length. The minimum sawlog length was 8 ft in 2 ft increments to a maximum length of 20 ft, allowing for 0.5 ft of trim for each sawlog.

Wood volumes were derived using Honer's (1967) volume equations, measured DBH and either measured total height, if the stem was measured directly, or predicted total

height from the height/DBH regression models that we developed. Honer's volume equations also were utilized indirectly to account for merchantable lengths of various products (e.g., pulpwood, sawlogs, studwood etc.). Because height to a merchantable top diameter was not measured directly, we calculated this height using Honer's "Diameter-Height Ratio Cubic Foot Volume Conversion Coefficients" (Honer 1967, Table 5, pg 18) and solving for "h1" (Height to merchantable limit).

Specifically, we first calculated total stem volume using Honer's total cubic foot volume function statistics (Honer 1967, Table 1, pg 14). We then used the calculated total volume and Honer's "Method 2A" (Honer 1967, Table 4, pg 17) to calculate the merchantable volume to a specific top diameter for a sawlog. The height to this specified top diameter was then calculated as described above. We compared our calculated length to the merchantable length standards to decide if we had a sawlog, how many, and their lengths. The stem was utilized to maximize the volume in sawlogs and every combination of merchantable lengths was used to consume as much of the merchantable volume as possible. Once the merchantable length in sawlogs was calculated, the volume to this length was calculated using the same equation used to calculate merchantable length. This time we used the merchantable length and solved for the volume. We then calculated the height to a specified minimum pulpwood top diameter. Using this height minus the height to the top of any merchantable sawlogs, we were able to determine the length of the remaining stem that could be utilized for pulpwood and its corresponding volume.

These calculations were performed on each record (stem) in the inventory data. With over 50,000 records in the data set (207 sample plots) the time necessary to perform these calculations manually for each stem was prohibitive. Program code was written for SAS software to automate these calculations saving days of calculation time.

All dollar values assigned to the treatments in this study are stumpage values per acre were derived from data published by the Maine Forest Service (Maine Department of Conservation 2001*b*) for Somerset County in the year 2000. The published prices for various products were assigned to matching products in our calculations. Data is published annually by the Maine Forest Service and is based on landowner reports and averaged by county.

Harvest Costs

The harvesting costs were generated with PPHARVST, public domain software available from the US Forest Service (Fight et al. 1999). PPHARVST was developed for use in management planning for ponderosa pine plantations. It allows users to estimate harvesting costs over a wide range of tree sizes and volumes removed. Equipment prices, harvesting productivities, and other assumptions were modified so that the model output very closely approximated the expected cost of harvesting in a Maine softwood forest. The portions of the spreadsheet dealing with NPV were not utilized. We used the following assumptions in the calculations: harvester machine costs = $74.56/hr., forwarder machine costs = $51.88/hr., harvester minimum distance = 15 ft, partial cut trail spacing = 100 ft, slope = 5%, harvester delay fraction = 0.029, forwarder delay

fraction = 0.059, forwarder load weight = 2,200 lbs., skid distance, average one-way = 750 ft, clearcut trail spacing = 50 ft (Randolph et al. 2001).

Analytical Approach

Based on results of the herbicide treatment comparisons described in Chapter 1, the herbicide treatments were grouped for this analysis (Table 2.3). The herbicide treatments were grouped as the Phenoxy group, Glyphosate-Triclopyr group, and the Control group, each having replicates with PCT and without PCT. The Phenoxy group is composed of those treatments containing Phenoxy herbicides alone or in combination with other herbicides.

Wood volumes, wood values, NPV, and IRR were calculated at the end of each 10-year cycle for each treatment plot. Based on these estimates, maximum NPV, age at maximum NPV, number of years of positive NPV, and a Flexibility Index [the integral (calculated numerically) of the function of NPV over the 100-year simulation period] were calculated for each treatment plot. The Flexibility Index can be used as a measure of the magnitude of NPV over the term that it remains positive and can be interpreted as the flexibility a manager might have in deciding when to harvest. Net present value was calculated as the difference between the sum of discounted revenues and the sum of discounted costs (Klemperer 1996). The discounted revenues were calculated as the wood value at the end of the cycle discounted to the year 2000. The sum of the discounted costs was calculated using $50 per acre in 1977 for herbicide application and $200 per acre in 1986 for PCT and then compounding these costs forward to the year 2000.

Table 2.3: The grouping scheme for herbicide treatments used for growth simulations and economic analysis.

Herbicide Treatment	**Application Rate (lbs/A)**	**Group Name**	**Replicates**	
			PCT	**No PCT**
Glyphosate (Roundup)	1.7	Glyphosate-	2	2
	3.3	Glyphosate-	2	2
Triclopyr amine	2.2	Glyphosate-	2	2
	4.4	Glyphosate-	2	2
		Group total	**8**	**8**
2,4,5-T	2.2	Phenoxy	2	2
	3.3	Phenoxy	2	2
Triclopyr amine + 2,4-	2.2 + 2.2	Phenoxy	2	2
2,4-D + 2,4,5-T	1.1 +1.1	Phenoxy	2	2
	2.2 +2.2	Phenoxy	2	2
2,4-D + 2,4,5-T +	1.1 + 1.1 +	Phenoxy	2	2
2,4-D + 2,4,5-DP +	1.1 + 1.1 +	Phenoxy	1	1
Picloram + 2,4-D	0.45 + 1.7	Phenoxy	2	2
		Group total	**15**	**15**
Water only		Control	1	1
Control (untreated)		Control	2	2
		Group total	**3**	**3**
		Grand total	**26**	**26**

A cost of $180 per acre was used for PCT if the plot had received a prior herbicide treatment. For each cycle, NPV was calculated at discount rates of 4%, 6%, 8%, 10% and 12%. IRR was calculated as the discount rate for which NPV was equal to 0 (Klemperer 1996). IRR calculations were not appropriate for the Control plots since no investment was made in these treatments. All economic analyses assumed constant inflation and are real values and rates of return. Our analysis did not account for applicable taxes or overhead costs associated with these stands. All values were in year 2000 U.S. dollars.

A two-factor analysis of variance (ANOVA) was conducted using a completely randomized 3 X 2 factorial design to test for herbicide group (3 levels; Control, Glyphosate-Triclopyr, and Phenoxy) effects and PCT (2 levels; PCT and no-PCT) effects on total volume, maximum NPV, age at maximum NPV, number of years of positive NPV, IRR, and Flexibility Index.

It must be noted that the assumptions of the ANOVA model may be violated due to variance propagation from the growth model and therefore, results of this analysis should be interpreted with this caveat. Mowrer and Frayer (1986) report the results of a study on the propagated variance associated with stand estimates in a forest growth and yield model. The results of the study indicate growth projection estimates may have substantial error components that are not readily apparent from model calibration statistics or bias assessment procedures. Gertner et al (1996) proposes a method for predicting the variance of projections made with a conceptual forest growth model. With this method, it is possible to partition the variance of the projections, approximate error budgets, and

assesses the power of hypotheses tests based on model predictions. These methods were beyond the scope of this study and not incorporated into the analysis.

RESULTS

Effects on Volume Development

The projected effects on total wood volume from the Control, Glyphosate-Triclopyr, and Phenoxy herbicide treatments over the 100-year simulation period are shown in Figure 2.2. The behavior of the Control only group is quite different from the two herbicide treatments. The Control only curve, while beginning very closely to the other treatments, rapidly falls off in the accumulation of total volume and by age 60 there is a substantial difference from the herbicide only treatments. As described in Chapter 1, the control plots were dominated primarily by hardwood species at age 29; while the herbicide treated plots were dominated by fir and spruce. In projecting these stands forward, NE TWIGS predicts that the hardwood-dominated stands of the Control plots will not accumulate as much total volume as the predominantly softwood stands in the herbicide-treated plots.

The influence of PCT on long-term total volume can be clearly seen by comparing Control only to the Control + PCT. The Control only group initially has more total volume and by age 50 still has more total volume, but by age 90 the Control + PCT group has caught up to the Control only and at age 130 has substantially more total volume. The NE TWIGS model may not be properly accounting for the longevity of balsam fir and

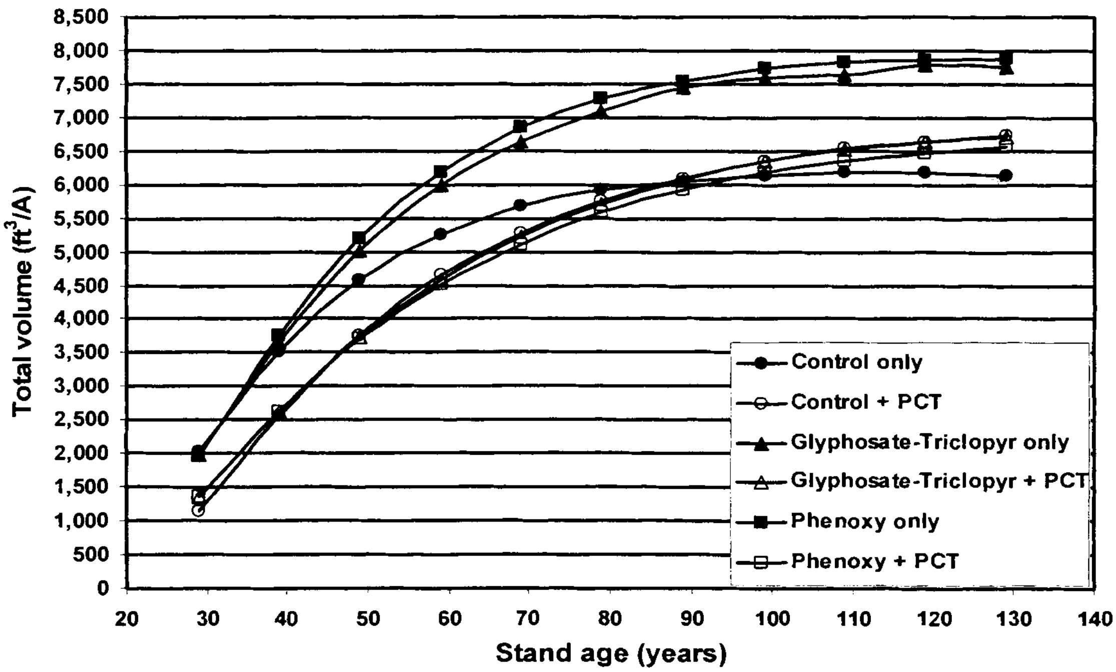


Figure 2.2: Total stand volume versus stand age for six treatments.

this may be why the Control + PCT treatment has more total volume than the Control only treatment at the older ages. There is little difference in total volume over time among the groups receiving PCT treatments including control + PCT, but in all cases treatments receiving PCT have significantly ($p<0.001$) less total volume than treatments that did not receive PCT over the entire simulation period. Results from the NE TWIGS model indicate the PCT plots will never achieve the total volume of the plots with no PCT. This suggests the plots with PCT are under stocked from the relatively low residual density and wide spacing (700 TPA).

Treatment effects on merchantable volume are similar to the effects on total volume (Figure 2.3). Merchantable volume in the Glyphosate-Triclopyr only group and the

Phenoxy only group are similar and there is little difference in the projections between groups receiving PCT treatments.

Again, the Control only group behaves differently than the other treatments groups, but similar to the Control only group for total volume. These effects are consistent for all three merchantability classes. The effects of merchantability standard on merchantable volume are reflected by the lower volumes for the larger standards for all treatments, as would be expected.

PCT effects on merchantable volume can be seen with lower merchantable volumes in the groups receiving PCT than in groups without PCT, but this effect is delayed as the merchantability standard is increased. For example, at age 50, the difference in merchantable volume between the herbicide only groups and the groups receiving PCT decreases from approximately 800 ft^3/A for the low merchantability class to less than 300 ft^3/A for the high merchantability class. At age 50, the difference in merchantable volume between all groups for the highest merchantability standard is relatively small and the influence of PCT is negligible. The amount of merchantable volume at age 50 decreases from approximately 2,800 ft^3/A to 2,300 ft^3/A on the treatment groups receiving PCT as the merchantability standard increases, whereas the amount of merchantable volume for the herbicide only groups decreases from approximately 3,600 ft^3/A to 2,600 ft^3/A. As the merchantability standard increases, the numbers of merchantable stems in the herbicide only groups decrease and the difference in volume between the herbicide only groups and the groups receiving PCT decreases.

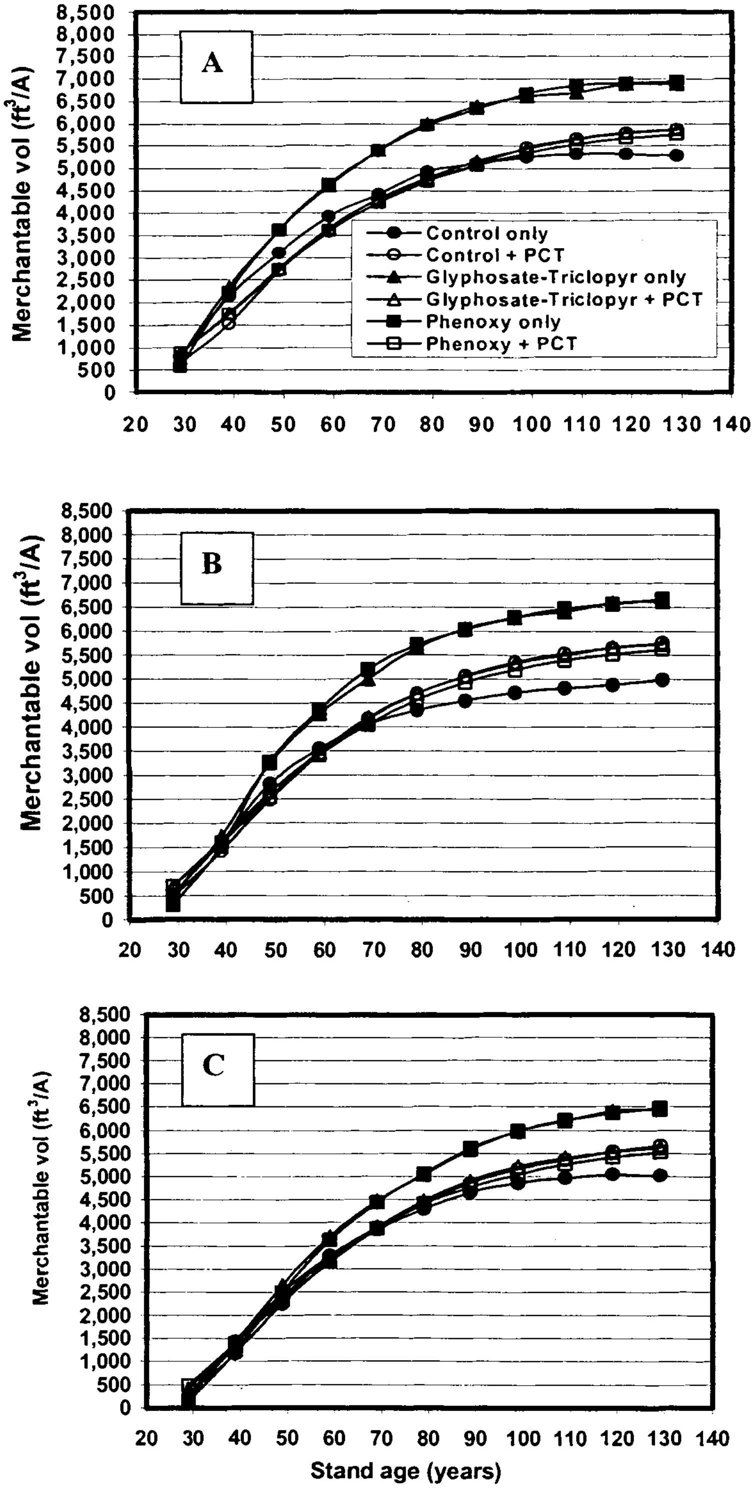


Figure 2.3: Merchantable volume versus stand age for six herbicide and PCT treatments using three merchantability classes. (A) low, (B) middle, (C) high.

Effects on Biological Rotation Age

The biological rotation age of a stand is determined by the maximum mean annual increment (MAI) (Smith 1997). There were no herbicide group effects for biological rotation age (Figure 2.4). The biological rotation length was estimated to be 50 years for the Glyphosate-Triclopyr only, Phenoxy only, and Control only groups, while it was approximately 60 years for each of the three groups receiving PCT. This indicates that PCT lengthened the biological rotation by about 10 years. The points where MAI and periodic annual increment (PAI) cross did not differ greatly between the no-PCT and PCT groups but maximum MAI occurred sooner among the non-PCT groups.

Maximum MAI peaked between 100 and 105 ft^3/A/yr for both the Glyphosate-Triclopyr only and the Phenoxy only groups, while MAI peaks at approximately 95 ft^3/A/yr for the Control only group. There was little difference in maximum MAI between the groups receiving PCT, with all peaking at approximately 80 ft^3/A/yr. The smaller maximum MAI for groups receiving PCT compared to no-PCT groups is indicative of the lower total stand volumes at age 50 in these groups.

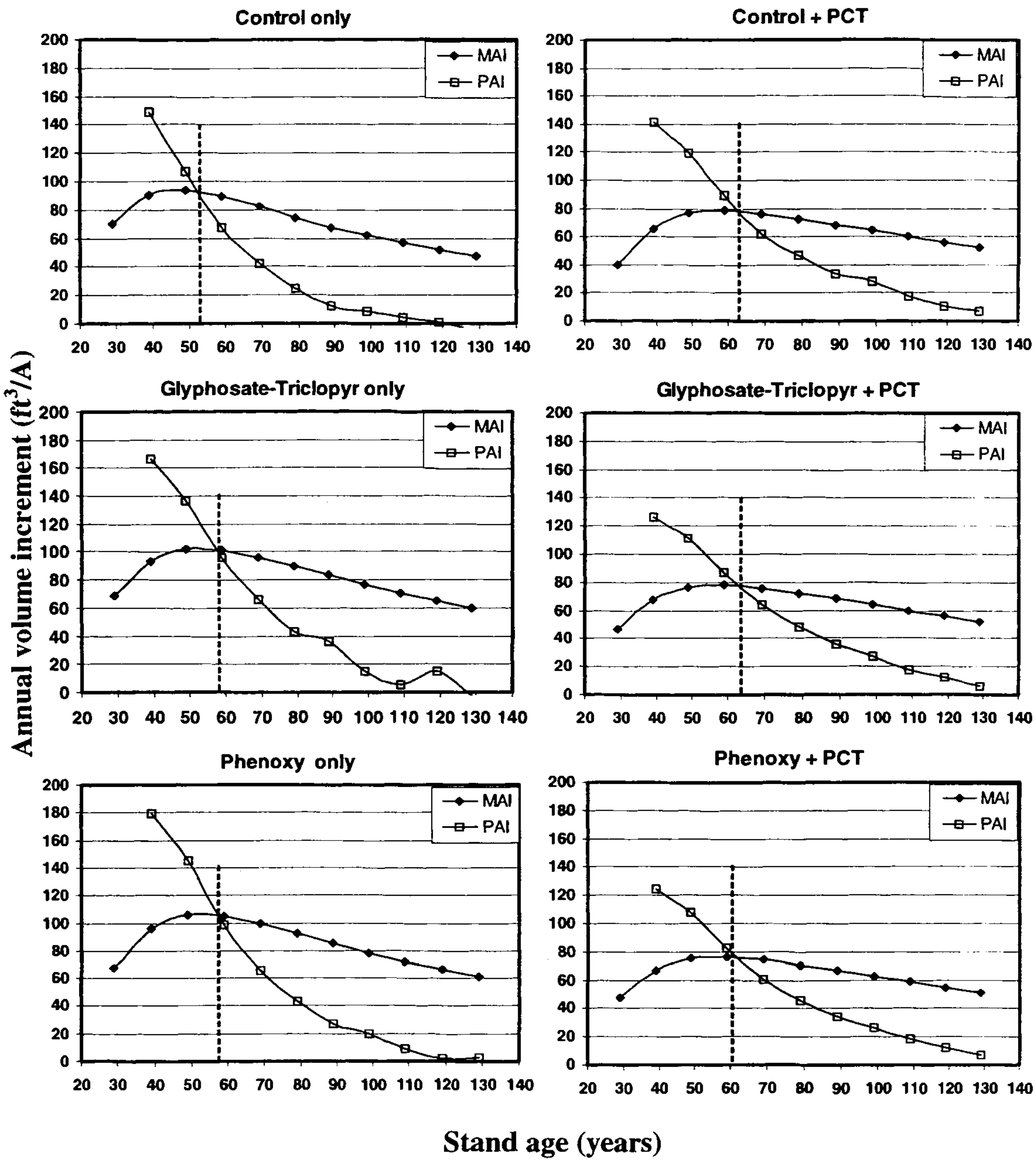


Figure 2.4: Mean annual increment and periodic annual increment versus stand age for six treatments.

Effects on Species Composition

Future tree species composition at age 50 based on total stand volume for the six treatment groups is presented in Table 2.4. Herbicide effects on future species composition are evident by the large difference in softwood volume between the herbicide only groups and the Control only group. Softwoods comprise 77.0% and 66.0% of total stand volume in the Glyphosate-Triclopyr only and Phenoxy only groups, respectively, while softwoods comprise only 32.1% of total stand volume in the Control only group. PCT effects on future species composition are apparent in the difference in softwood volume between the Control only group and the Control + PCT group. Softwoods comprise only 32.1% of total stand volume in the Control only group compared to 83.6% in the Control + PCT group.

The PCT effects do not appear to be enhanced by prior herbicide treatments. The increase in softwood volume from the Control + PCT group to the Glyphosate-Triclopyr + PCT and Phenoxy + PCT groups is only 9.4% and 5.8%, respectively. The softwood volume in the Glyphosate-Triclopyr only group comprises 11% more total stand volume than the Phenoxy only group. This difference is reduced to 3.6 % with the addition of PCT.

Table 2.4: Species composition based on total stand volume at age 50 for six treatments.

Species	No PCT					
	Glyphosate-Triclopyr		Phenoxy		Control	
	volume (ft^3/A)	% of total	volume (ft^3/A)	% of total	volume (ft^3/A)	% of total
Balsam fir	3,064.60	61.0	2,569.44	49.5	1,332.36	29.1
Red spruce	499.64	9.9	576.04	11.1	90.36	2.0
Other softwood	304.71	6.1	283.19	5.5	49.46	1.1
Total softwood	3,868.95	77.0	3,428.66	66.0	1,472.18	32.1
Quaking aspen	850.33	16.9	1,473.64	28.4	1,647.24	36.0
Red maple	111.82	2.2	97.20	1.9	500.62	10.9
Other hardwood	191.50	3.8	191.60	3.7	960.54	21.0
Total hardwood	1,153.64	23.0	1,762.44	34.0	3,108.41	67.9
Total all species	5,022.59	100.0	5,191.10	100.0	4,580.59	100.0

Species	PCT					
	Glyphosate-Triclopyr		Phenoxy		Control	
	volume (ft^3/A)	% of total	volume (ft^3/A)	% of total	volume (ft^3/A)	% of total
Balsam fir	2,938.30	78.8	2,816.42	76.7	2,676.89	71.2
Red spruce	485.90	13.0	403.54	11.0	464.77	12.4
Other softwood	44.27	1.2	61.60	1.7	0.00	0.0
Total softwood	3,468.48	93.0	3,281.56	89.4	3,141.67	83.6
Quaking aspen	106.72	2.9	191.63	5.2	310.79	8.3
Red maple	45.00	1.2	82.51	2.2	36.37	1.0
Other hardwood	107.54	2.9	114.58	3.1	268.27	7.1
Total hardwood	259.26	7.0	388.72	10.6	615.44	16.4
Total all species	3,727.74	100.0	3,670.28	100.0	3,757.11	100.0

Effects of Merchantability Standard

The effects of merchantability standard on sawlog volumes at age 50 were larger than any treatment effect (Figure 2.5), with volumes varying by less than 500 ft^3/A among all six treatment groups while in any single group, the amount of volume decreased by approximately 500 ft^3/A with each increasing merchantability class.

For pulpwood volumes, there appears to be a PCT effect in the low and middle merchantability classes, but only after a prior herbicide treatment. There is little difference in pulpwood volume between the Control only and Control + PCT groups while the difference between the Glyphosate-Triclopyr only and Phenoxy only groups and the Glyphosate-Triclopyr + PCT and Phenoxy + PCT groups is approximately 1,800 ft^3/A. This effect diminishes with increased merchantability standards and in the largest merchantability class, the effect is minimal. The smaller stems in these treatments may be included in pulpwood volumes, but are too small to be used as a sawlogs and as the merchantability class for the pulpwood volume increases, the effect is diminished.

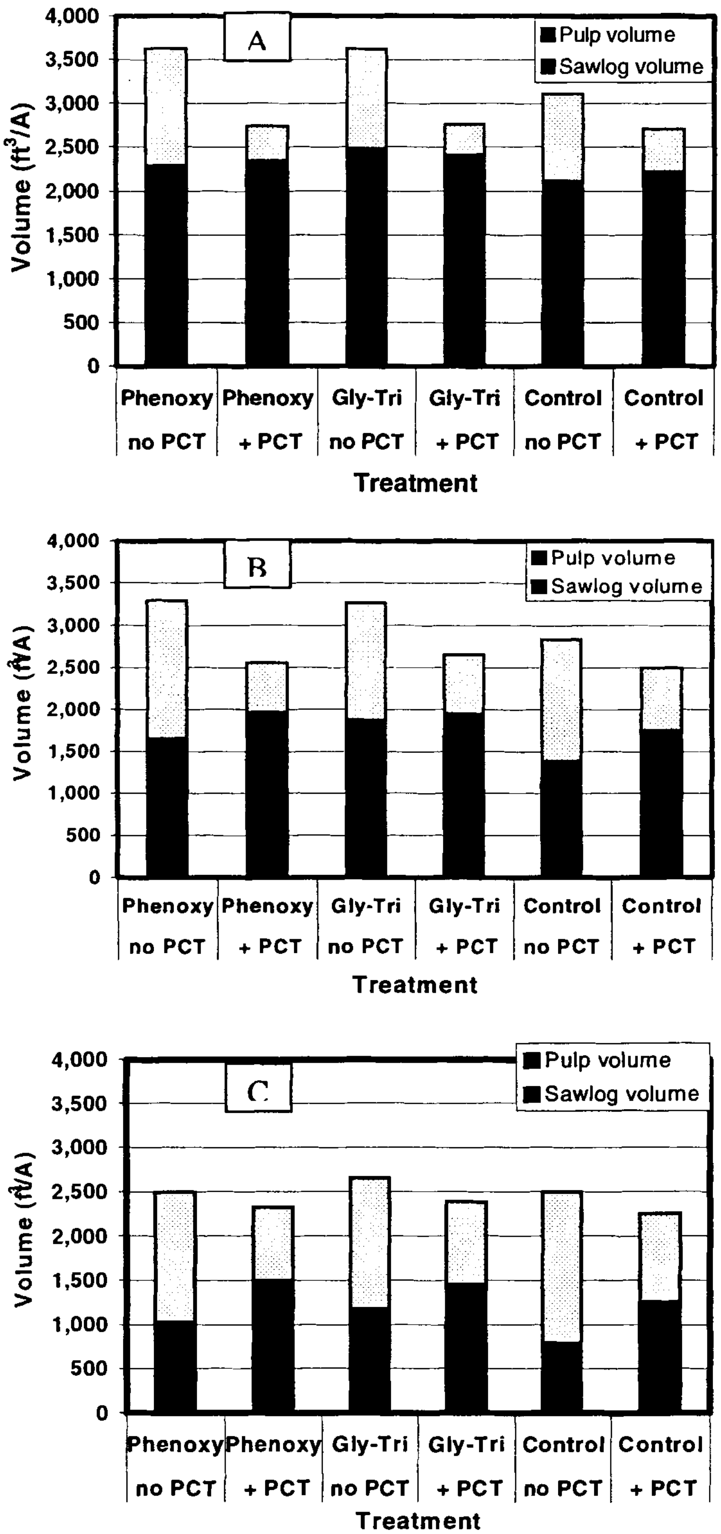


Figure 2.5: Merchantable volume by product and merchantability class. (A) low, (B) middle, (C) high.

Financial Analysis

Maximum NPV

Financial rotation length is defined as point at which NPV is maximized (Smith 1997). Maximum NPV for the six treatment groups occurs, on average at age 50 (Table 2.5, Figure 2.6). The results of a two-factor ANOVA using the middle merchantability class and a discount rate of 4% indicated that herbicide has no influence (p=0.224) on maximum NPV. PCT, however, reduced NPV.

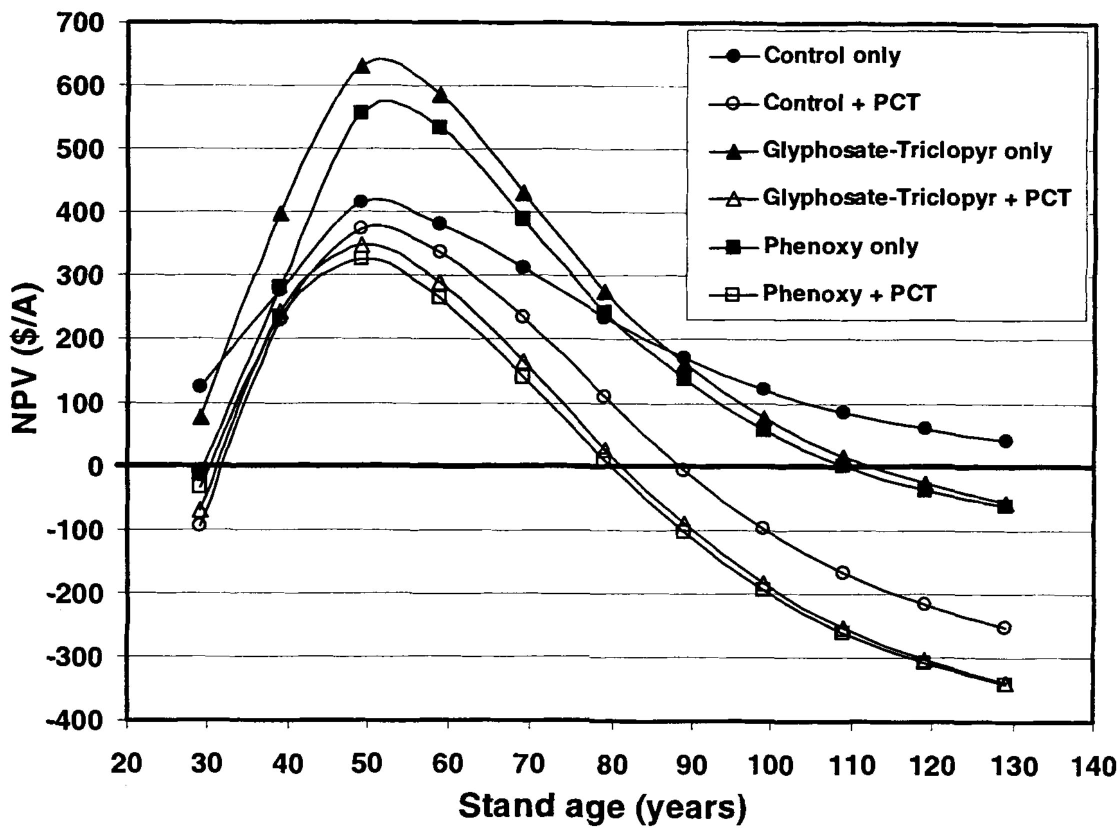


Figure 2.6: NPV in year 2000 dollars using the middle merchantability class and a discount rate of 4% versus stand age for six treatments.

Table 2.5: Means, sample size (N), and standard errors using the middle merchantability class and a 4% discount rate for six treatments.

Treatment	Total stand volume (ft^3/A) @ age 49			Maximum NPV ($/A)			Age @ maximum NPV (financial rotation)		
	N	Mean	Std err	N	Mean	Std err	N	Mean	Std err
Gly-Tri only	8	5,021.6	141.77	8	627.0	36.33	8	50.3	1.26
Gly-Tri + PCT	8	3,727.7	141.77	8	297.0	36.33	8	49.0	1.26
Phenoxy only	15	5,128.2	103.53	15	540.7	26.53	15	49.7	0.92
Phenoxy +	15	3,670.3	103.53	15	291.4	26.53	15	49.0	0.92
Control only	3	4,580.6	231.51	3	413.7	59.32	3	49.0	2.05
Control + PCT	3	3,757.1	231.51	3	359.7	59.32	3	49.0	2.05

Treatment	Number of years of positive NPV			Internal rate of return @ maximum NPV			Flexibility index		
	N	Mean	Std err	N	Mean	Std err	N	Mean	Std err
Gly-Tri only	8	82.5	3.03	8	9.3	0.27	8	2,642.3	153.39
Gly-Tri + PCT	8	41.2	3.03	8	5.9	0.27	8	843.1	153.39
Phenoxy only	15	79.3	2.21	15	8.2	0.19	15	2,141.2	112.02
Phenoxy +	15	41.3	2.21	15	6.0	0.19	15	855.2	112.02
Control only	3	120.0	4.94	NA	NA	NA	3	2,221.2	250.50
Control + PCT	3	53.3	4.94	3	6.4	0.33	3	1,228.7	250.50

(p<0.001) and had significant interaction with herbicide treatment (p=0.024). The group indicating the highest maximum NPV was the Glyphosate -Triclopyr only group at $627.03/A, followed by Phenoxy only group at $540.70 /A, and the Control only group at $413.67/A, followed by all treatments receiving PCT. Clearly, plots receiving PCT treatments have a lower maximum NPV than the Herbicide only and Control only groups. Thus, it appears only the herbicide groups with out PCT achieve a higher maximum NPV than the Control only group.

Financial Rotation Length

Financial rotation length is defined as the stand age at maximum NPV of all costs and revenues at some chosen rate of compound interest (Smith et al. 1997, pg. 436). There were no treatment effects on financial rotation length. Means for all treatments were near age 50 years. There were herbicide group effects ($p<0.001$) on the number of years that NPV remained positive over the 100-year simulation period, but since there were no investments in the Control only group NPV never reaches zero and the mean for this treatment group is 100. PCT treatments reduced ($p<0.001$) the number of years of positive NPV with the mean number of years being 45.3 years for the groups receiving PCT treatments compared to 93.9 years for the no-PCT groups.

Internal Rate of Return

The Control only group was removed form this analysis since no investments were made in this treatment. There was no influence of herbicide treatment on internal rate of return (IRR) (p>0.). PCT reduced IRR ($p<0.001$). The mean IRR for the herbicide only groups was 8.0%, for the Control + PCT (PCT only) group mean IRR was 6.1%, and for the herbicide + PCT groups mean IRR was 5.8%.

Flexibility Index

There were no herbicide group effects on flexibility index but there were PCT effects. Groups receiving PCT treatments had a significantly lower ($p<0.001$) flexibility index than the herbicide only and control only groups. The control only group had the highest

mean flexibility index followed by the Glyphosate-Triclopyr only group and the Phenoxy only group.

Effect of Discount Rate

The effects of discount rate on NPV are shown in Figure 2. 7. As would be expected, higher discount rates reduce NPV and reducing the length of time NPV remains positive. The effects are similar in the Glyphosate-Triclopyr only group and Phenoxy only group but differ from the Control only group. The effects of discount rate on the Control only group reflect no investments made in this treatment and NPV never falls below zero. The flat portion of the curves indicates the period when the value of standing wood has been discounted to a point near zero and NPV is merely the compounded value of the treatments. This point occurs earlier in the rotation as the discount rate is increased. The effect of discount rate, or the distance between NPV curves for the various discount rates, is larger for the Herbicide + PCT groups and the Control + PCT group than the Herbicide only and Control only groups. The larger effect of discount rate for those treatments groups receiving PCT is a reflection of the relatively high cost of PCT.

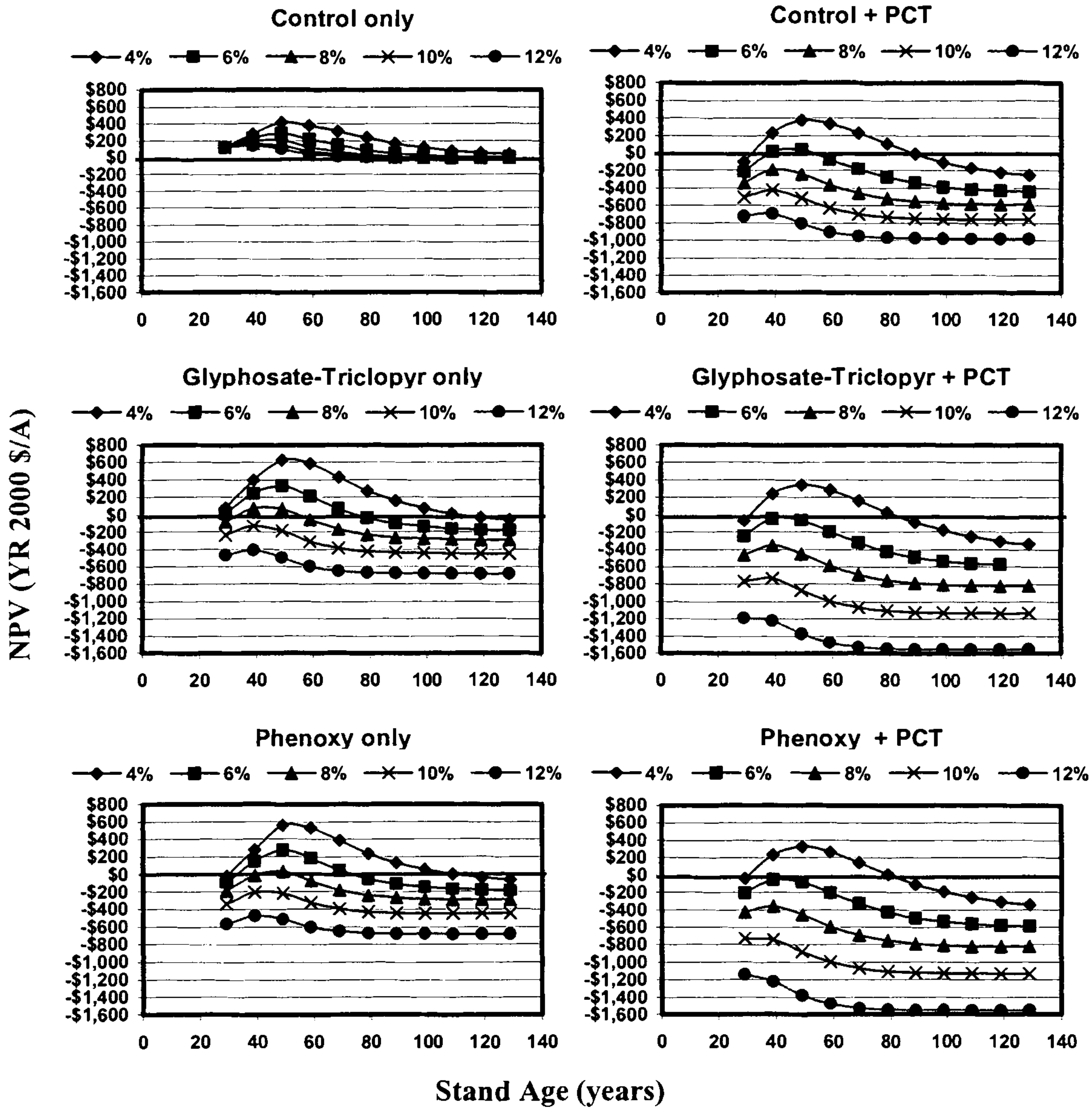


Figure 2.7: NPV year 2000 using the middle merchantability class for six treatments and five discount rates.

Merchantability Standards

The influence of merchantability standards on NPV are shown in Figure 2.8. Higher merchantability standards reduced NPV for all treatments. The maximum difference in NPV between the three merchantability classes occurs at maximum NPV and reaches a minimum at the end of the simulation period. This effect of merchantability class is evident in all treatment groups. The difference in NPV as a result of merchantability class is similar among those treatments with no PCT and similar among those treatments with PCT but differ between the two groups. The magnitude of the difference in NPV is smaller for the treatments with PCT than for the treatments with no PCT.

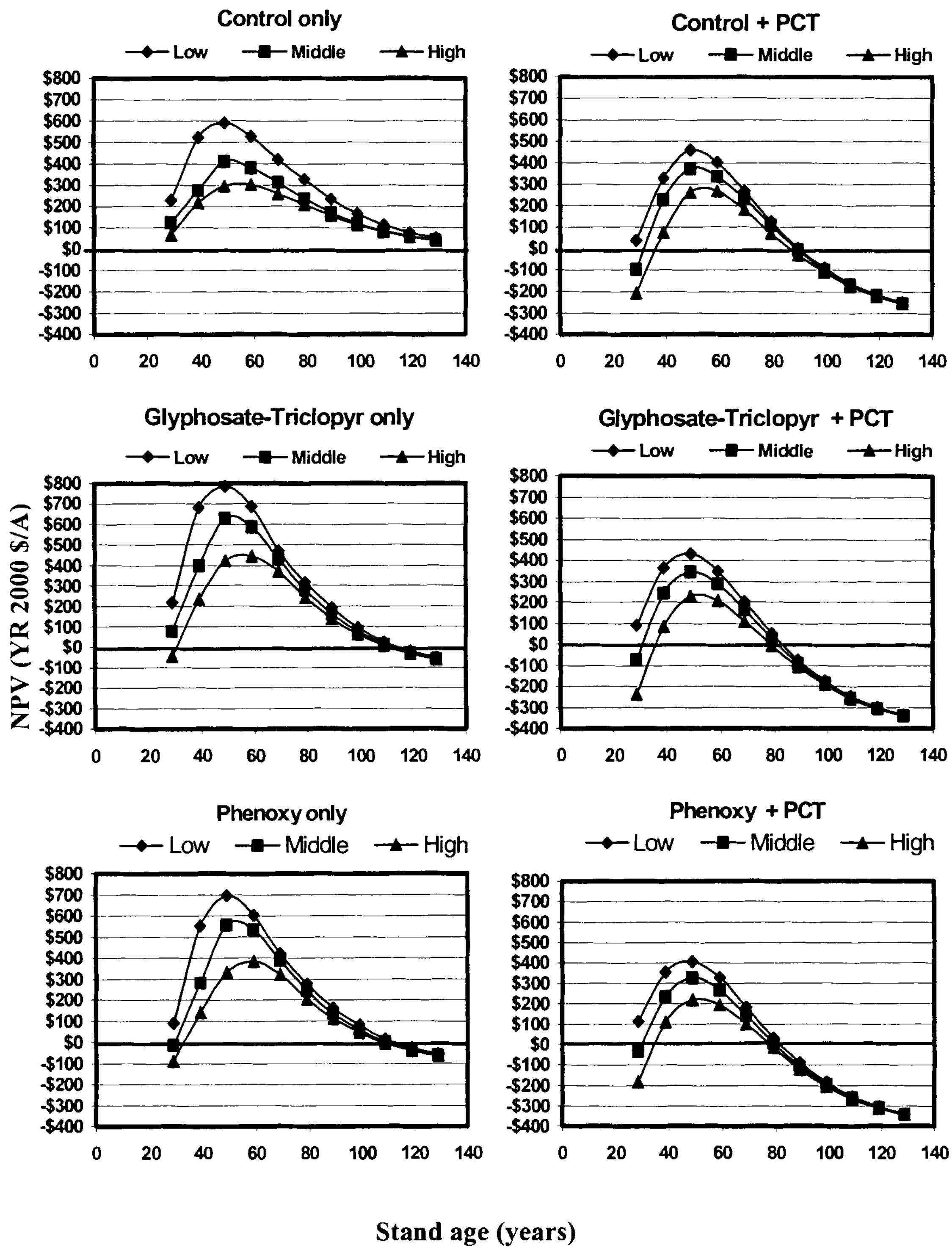


Figure 2.8: NPV in year 2000 dollars using a 4% discount rate for six treatments and three merchantability classes.

Future Harvest Costs

The mean harvest cost at age 50 was calculated for each treatment group for each of the three merchantability classes (Figure 2.9). Since harvest costs are directly related to stem or piece size, merchantability standards have a large effect on harvest cost. The harvest cost associated with the high merchantability class is less than half the cost of the low class for those groups not receiving PCT and is reduced by about a third for the groups receiving PCT. With the largest merchantability class, the costs associated with the Glyphosate-Triclopyr only and the Phenoxy only groups are similar, but both are considerably higher than the control only group. Also, harvest costs associated with groups receiving PCT treatments are lower than those without PCT treatments with the exception of the Control only. As merchantability standards increase, the difference in harvest cost among treatments decrease. Any difference in harvest costs among treatments is small when using a high merchantability class.

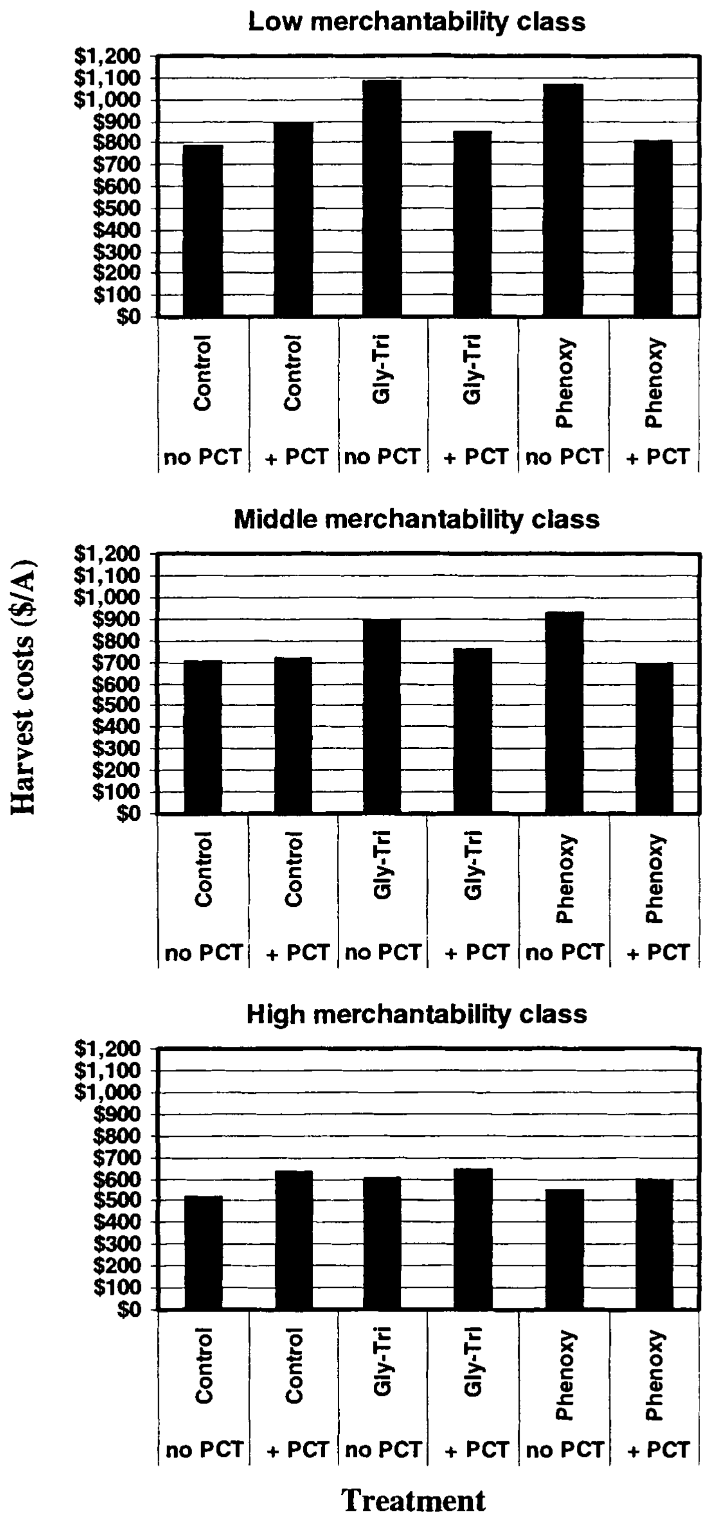


Figure 2.9: Harvest costs per acre at age 50 for six treatments and three merchantability classes.

DISCUSSION

Our results clearly show the effectiveness of herbicide and PCT treatments in determining the long-term species composition of spruce-fir stands. Herbicide treatments alone shifted species composition from predominantly intolerant hardwoods in untreated Control plots to nearly pure softwood (over 70% of total volume) for the Glyphosate-Triclopyr treatments at financial rotation age (50 years). PCT alone was even more effective at controlling species composition, with over 80% of total volume composed of softwood. Herbicide followed by PCT treatments, created pure softwood conditions with over 90% of total volume comprised of softwood for the Glyphosate-Triclopyr treatment.

While both herbicides and PCT were effective in controlling species composition, neither herbicides or PCT increased merchantable volumes above untreated stands. The beneficial effects of these treatments, with respect to merchantable volume, appeared to be almost entirely from shifting species composition from low value hardwood products to much higher value softwood products.

In contrast to the results of Brodie et al (1987), who found that removal of competing vegetation shortened rotation lengths, our results indicated neither herbicide nor PCT reduced financial rotation lengths. In fact, our simulations suggest that PCT treatments reduced merchantable volume at rotation age. This result, however, may be due to the wide spacing (700 trees/A) implemented in these treatments or be an artifact of NE TWIGS. The wide spacing implemented in these PCT treatments may have left growing space unoccupied. Alternatively, the NE TWIGS model may not have increased growth

parameters of individual trees proportionately to the amount of growing space allocated to them in the PCT treatments.

PCT was effective in increasing QMD in the Herbicide + PCT treatments above that in the Herbicide only treatments, resulting in lower estimated harvest costs and increased sawlog to pulpwood ratios. This effect resulting from PCT treatment diminished with increasing merchantability class. In the low and middle merchantability classes, the harvest costs associated with Herbicide + PCT treatments was, on average, 22.1% lower than harvest costs associated with Herbicide only treatments. The difference in harvest costs between these treatments certainly could have implications on their NPV. Although NPV was calculated on the value of standing wood, and prices received for wood products in these calculations did not account for differences in harvest costs, adjustments to the actual stumpage price received for the sale of this wood could be expected according to associated harvest costs. This is due to the effects of harvest costs on the gross profit associated with the sale of this wood to a mill. Equation 3 shows the relationship between anticipated harvest costs and gross profit from the harvest of forest stands.

[3] **Mill price – Trucking costs – Harvest costs – Stumpage price = Gross profit**

If harvest costs are anticipated to be lower because of the larger piece size (QMD) of merchantable stems, a higher stumpage price can be paid without affecting the gross profit of the transaction. Some adjustment upward to the value of standing wood for the

plots receiving PCT treatments may, therefore, be appropriate. An exact adjustment would be difficult to calculate without actual mill delivered prices and trucking costs. This adjustment to the value of standing wood, in turn, would increase the NPV of the plots receiving PCT treatments.

The difference in QMD between Herbicide + PCT and Herbicide only treatments and the Control + PCT and Control only treatments in the high merchantability class was negligible, therefore, the difference in harvest costs between these treatments was also negligible. In fact, the harvest costs associated with the Control + PCT plots was higher than the Control only plots for the low and high merchantability classes. An adjustment to the NPV of the PCT treatments for a comparison between these treatments would not be appropriate.

We have been successful in showing the beneficial effects of herbicides and PCT in controlling species composition and enhancing long-term stand value. However, these treatments require an upfront financial investment. So the most important question is whether the increase in stand value resulting from these treatments exceeds the costs. The results of our financial analysis suggest that herbicide treatments can enhance NPV of stands at rotation age about 40% higher than untreated stands and achieve an IRR of approximately 8%. These results agree with those of Roberts (1982) and later by Walstad et al. (1986) in their study of economic returns of vegetation management in Douglas fir stands in the Pacific Northwest who found that the removal of competing vegetation increased NPV. PCT, on the other hand, did not increase NPV in our analysis above that

of untreated stands. Despite this result, PCT treatments provided a 6% rate of return, a rate above many minimum acceptable rates of return (MAR) used by forest industries in Maine (Field 2002).

We also were able to show the influence that assumptions about future merchantability standards has on NPV estimates. Our results indicate that the benefits of herbicide and PCT treatments are enhanced with a decrease in merchantability standards (i.e., merchandising of smaller diameter stems). Recent trends in forest product utilization indicate decreasing merchantability standards with time so as these standards decrease further, perhaps we could see an increase in the benefits of herbicides and PCT in these types of stands.

All of our results are dependent upon the correctness of the assumptions of the NE TWIGS growth and yield model and the accuracy of the empirical data used to develop it. This model and others were developed from empirical data of unmanaged stands. Clearly, there is a need for long-term studies of managed stands to rotation age to provide data suitable for predicting the growth and yield of these managed stands.

Perhaps the ultimate value of herbicides and PCT are at the forest level where composition shifts and changing the quality of stands can have forest level benefits beyond that provided by the IRR on a particular acre investment analysis. Wagner et al. (2003) describes the benefits of herbicides and PCT in increasing the future wood supply in Maine. They report 25% of Maine spruce-fir forest is in the seedling or sapling stage,

and many hardwood stands are in a young and vigorous condition. Wagner et al. (2003) go on to say, significant opportunities exist for intensifying the management of older stands. More than 27% of Maine merchantable growth eventually ends up decaying on the forest floor, and this proportion has been increasing since the 1950's. Despite this situation, only about 4% of Maine forest (as of 1995) is under intensive or high-yield management. Clearly, the current opportunity is a great for applying intensive silvicultural treatments, including herbicides and PCT, to increase growth of merchantable wood and ultimately increase annual sustainable harvest levels. An extrapolation of our results could perhaps even be used to corroborate the results of Wagner et al. (2003) in the contribution of these treatments to the overall future wood supply in Maine. Additional research on the economic returns of herbicide and PCT treatments to provide a sound basis for investments in these treatments is therefore vital to the economy in Maine. Increased annual sustainable harvest levels will provide an economic boost the forest products industry in Maine and make it more competitive in a global economy.

CHAPTER 3.

MANAGEMENT IMPLICATIONS

The results of this study indicate that the short-term benefits of herbicide and PCT treatments for controlling species composition are maintained through rotation age in Maine spruce-fir stands. The primary influence of both herbicide and PCT treatments was from shifting direction of post-harvest succession to a predominantly spruce-fir overstory rather than a nearly pure hardwood overstory, characteristic of untreated stands. Combined herbicide + PCT treatments created nearly pure spruce-fir stands while untreated controls produced predominantly intolerant hardwood stands through the end of the rotation. Neither herbicides nor PCT increased merchantable volumes over those of untreated stands, but both treatments applied alone increased the value of standing wood. In addition, combined herbicide and PCT treatments increased the value of standing wood, on average, by 177 % above that of herbicide treatments alone.

Our investigation of the return on investments in herbicides treatments revealed an increased NPV in treated stands over those of the untreated stands at rotation age with a return on investment of approximately 8%. Glyphosate and Triclopyr were equally effective and both were as effective as the Phenoxy herbicides. PCT, on the other hand, reduced the NPV below that of untreated stands. PCT also reduced the NPV of previously herbicide treated stands. Although PCT reduced the NPV of stands, the treatment still produced a return on investment of approximately 6%, a rate of return attractive to many investors. We were also able to show that stands receiving PCT

treatments had lower harvest costs than Herbicide only treatments, but this effect of PCT diminishes as merchantability standards increase. If future merchantability standards decrease, lower harvest costs associated with PCT treatments could enhance NPV in PCT plots.

Clearly, herbicide treatments are an attractive alternative for those investors interested in producing stands of spruce-fir while receiving a reasonable return on their investment. For those investors interested in increasing the value of their timberland while maintaining a modest return on investments, PCT, based on our results, could still be an attractive investment.

Our results are dependent on the assumptions of the NE TWIGS growth model which are based on data from unmanaged stands and may underestimate the effects of these treatments. Also, the adverse effects of PCT on NPV shown in our results are based on a residual density of 700 TPA, a density much less than the 1,000 to 1,200 TPA densities commonly used in industry today. Higher densities resulting from narrower PCT spacings may, although not tested in this study, increase merchantable volumes at rotation age to a level equal to or above that of herbicide only treatments. The result could be increased values of standing wood while maintaining a larger quadratic mean diameter (QMD) and lower harvest costs.

The uncertainties included in the financial analysis of this study are indicative of the need for data to rotation age from managed stands. In the introduction to this study we

indicated the importance of maintaining a healthy growing stock of spruce-fir to the economy of Maine and were able to show the benefits of herbicides and PCT treatments in producing predominantly spruce-fir stands. An extrapolation of our results could perhaps even be used to corroborate the results of Wagner et al. (2003) in the contribution of these treatments to the overall future wood supply in Maine. Additional research on the economic returns of herbicide and PCT treatments to provide a sound basis for investments in these treatments is therefore vital to the economy in Maine.

As indicated by Newton et al. (1992a) this on-going study (The Austin Pond Study) provides one of the best opportunities to describe the long-term effects of herbicide and PCT treatments to rotation age. This study area should therefore be preserved, maintained, and studied further to provide data needed for modeling the growth and yield of managed stands.

REFERENCES

Allen, H.L. 1978. Relationship of site index and growth of even-aged spruce-fir stands in northern Maine to site factors. M.S. thesis. University of Maine, Orono.

Anderson, R.E. 1960. Forest and shade tree entomology. Wiley, New York. 428 p.

Barbour, R.J., R.E. Bailey, and J.A. Cook. 1992. Evaluation of relative density, diameter growth, and stem form in a red spruce (*Picea rubens*) stand 15 years after precommercial thinning. Can. J. For. Res. 22: 229-238.

Baskerville, GL. 1961. Response of young fir and spruce to release from shrub competition Can. Dep. For., Ottawa. For. Res. Div. Tech. Note 98. 14 p.

Briggs, R.D. and R. C. Lemin, Jr. 1994. Soil drainage class effects on early response of balsam fir to precommercial thinning. Soil Sci. Soc. Am. J. 58(4): 1231-1239.

Briggs, R.D. 1994. Site classification field guide. Univ. of Maine Agric. Exp. Stn. Misc. Publ. 724 , ISSN 1070-1508.

Brissette, J.C., R.M. Frank, Jr., T.L. Stone, and T.A. Skratt. 1999. Precommercial thinning in a northern conifer stand: 18-year results. Forestry Chronicle 75(6):967-972.

Brodie, J.D., P.J. Kuch, and C. Row. 1987. Economic Analysis of the Silvicultural Effects of Vegetation Management at the Stand and Forest Levels. In: P.J. Kuch and J.D. Walstad, (eds.). Forest Vegetation Management for Conifer Production. Wiley & Sons, Inc. New York. 523 p.

Burns, J., K.H. Puettmann, and D. Perala. 1996. Strip thinning and spacing increases tree growth of young black spruce. North. J. Appl. For. 13(2): 68-72.

Bush, Renate R. 1995. Northeastern TWIGS Variant of the Forest Vegetation Simulator. Available on the US Department of Agriculture, Forest Service website at www.fs.fed.us/fmsc/fvs/fvs_variant_overviews.htm.

Butler, G., N. Hudson, and T.R. Flanagan. 1963. Timber stand improvement by aerial spraying in Vermont, Proc. Northeast. Weed Control Conf. 17: 532-537.

Curtis, R.O. and D.D. Marshall. 2000. Why Quadratic Mean Diameter? Western J. Appl. For. 15(3): 137-139.

Field, D.B., 2002. Financial returns to timber. Univ. of Maine Agric. Exp. Stn. Misc. Publ.429.

Fight, R.D., A. Gicqueau, and B.R. Hartsough. 1999. Harvesting costs for management planning for ponderosa pine plantations. General Technical Report PNW-GTR-467. Portland, OR: USDA, For. Serv., Pacific Northwest Research Station. 8 p.

Gertner, G., P. Parysow, and B. Guan. 1996. Projection Variance Partitioning of a Conceptual Forest Growth Model with Orthogonal Polynomials. Forest Science 42(4): 474-486.

Green, K. 1983. Forests, herbicides and people. A case study of phenoxy herbicides in western Oregon. Council on Economic Priorities. New York, NY. 203 p.

Hilt, D. E. and M. Teck. 1987. Development and implementation of growth and yield models in the Northeast. In: Proceedings of the New England Growth and Yield Workshop. Univ. of Maine Agric. Exp. Stn. Misc. Rep. 325: 31-45.

Honer,T.G., 1967. Standard volume tables and merchantable conversion factors for the commercial tree species of central and eastern Canada. For. Management. Res. & Serv. Int., Ottawa, Ontario, Can., Inf. Rep. FMR-X-5.

Huanng, S.L., S.J. Titus, and S.P. Wiens. 1992. Comparison of nonlinear height-diameter functions for major Alberta tree species. Can. J. For. Res. 22:1297-1304.

Hynson, J.R. 1985. Silvicultural release of seedling and sapling spruce-fir stands. A literature review. Final rep. to Maine For. Serv., Augusta, by the Mahoosuc Corp., Augusta, ME. 78 p.

Ker, M.F. 1987. Effects of spacing on balsam fir: 25-year results from the Green River spacing trials. In: Murray, T.S. and M.D. Cameron, eds.: 58-75.

Klemperer, W.D. 1996. Forest Resource Economics and Finance. McGraw-Hill, Inc., New York. 551 p.

Lavigne, M.B. and J.G. Donelly. 1989. Early results of a spacing trial in a pre-commercially thinned balsam fir stand in western Newfoundland. Forestry Canada, Newfoundland and Labrador Region. Inf. Rep. N-X_269. 23 p.

Lehala, A. 1981. Benefits of herbicide control of unwanted vegetation in the boreal mixedwood forest. In: Proceedings of the Boreal mixedwood symposium. Great Lakes For. Res. Cent. Can. For. Serv., Sault Ste. Marie, Ont. No. O-P-9: 221-223.

Maine Department of Conservation. 1998. Timber supply outlook for Maine 1995-2045 (internet).Augusta, ME: (updated 2002 October 7; cited 2003 May 29). Maine Forest Service Publications. Available from: http://www.state.me.us/doc/mfs/pubs.htm.

Maine Department of Conservation. 2000. Stumpage price report 2000 (internet). Augusta, ME: (updated 2002 October 7; cited 2003 May 29). Maine Forest Service Publications. Available from: http://www.state.me.us/doc/mfs/pubs.htm.

Maine Department of Conservation. 2001*a*.Wood processor report 2001 (internet). Augusta, ME: (updated 2002 October 7; cited 2003 May 29). Maine Forest Service Publications. Available from: http://www.state.me.us/doc/mfs/pubs.htm.

Maine Department of Conservation 2001*b*. Silvicultural activities report 2001 (internet). Augusta, ME: (updated 2002 October 7; cited 2003 May 29). Maine Forest Service Publications. Available from: http://www.state.me.us/doc/mfs/pubs.htm.

McConkey, T.W. 1958. Helicopter spraying with 2,4,5-T to release young white pine. USDA For. Serv. Northeast For. Exp. Stn. Pap. 101. 14 p.

McCormack, M.L. and M. Newton. 1980. Aerial applications of triclopyr, phenoxys, picloram, and glyphosate for conifer release in spruce-fir forests of Maine. Weed Sci. Soc. Am. Abstr. 20: 47-48.

McCormack, M.L. 1982. Silviculture program. In: 1981 annual report of the Coop. Res. Unit, Sch, For. Resour., Univ. Maine, Orono. Misc. Rep. 265: 3-8.

McCormack, M.L. 1985. Vegetation problems and solutions-Northeast. Proc. South. Weed Sci. Soc. 38: 315-326.

McCormack M.L. and R.C. Lemin, Jr. 1998. Crop tree conditions after one herbicide release and precommercial thinning of natural spruce-fir regeneration in northwestern Maine, USA. Third International Conference on Forest Vegetation Management: Popular summaries. Ont. Min. Nat. Resour., Ont. For. Res. Inst., For. Res. Info. Pap. No. 141.

McKenney, D.W. 2000. What's the economics of intensive silviculture? For. Chron. 75(2): 275-281.

McLean, D.L. and M.G. Morgan. 1983. Long-term growth response of young fir and spruce to manual and chemical release from shrub competition. For. Chron. 59:177-183.

Mowrer, H.T. and W.E. Frayer. 1986. Variance propagation in growth and yield projections. Can. J. For. Res. 16: 1196-1200.

Nautiyal, J.C., J.S. Williams, M.R. Innes, L. Gravelines, and A. Ghebremichael. 2001. Financial Evaluation. *In* Wagner, R.G. and S.J. Colombo (eds.). Regenerating the Canadian Forest. Fitzhenry & Whiteside Ltd., Markham, Ontario, Canada.

Neter, J., M.H. Kutner, C.J. Nachtsheim, and W. Wasserman. 1996. Applied Linear Statistical Models. 4th ed. McGraw-Hill, New York. 1408 p.

Newton, M., E.C. Cole, D.E. White, and M.L. McCormack, Jr. 1992a. Young spruce-fir forests released by herbicides. I. Response of hardwoods and shrubs. No. J. Appl. For. 9(4): 126-130.

Newton, M., E.C. Cole, D.E. White, and M.L. McCormack, Jr. 1992b. Young spruce-fir forests released by herbicides. II. Conifer response to residual hardwoods and overstocking. North. J. Appl. For. 9(4): 126-130.

Nova Scotia Department of Natural Resources. 1993. Nova Scotia Softwood Growth and Yield Model – Version 1.0 User Manual. Forest Research Report No. 43. Nova Scotia Department of Natural Resources. 12 p.

Peng C., L. Zhang, and J. Liu. 2001. Developing and Validating Nonlinear Height-Diameter Models for Major Tree Species of Ontario's Boreal Forests. No. J. Appl. For. 18(3): 87-94.

Piene, H. 1981. Early growth responses to operational spacing in young balsam fir stands on the Cape Breton Highlands, Nova Scotia. Can. For. Serv. Maritime Res. Cent., Fredericton. Info. Rep. M-X-125. 29 p.

Piene, H. and W.F.A. Anderson. 1987. Ten –year growth response to spacing in young balsam fir stands, Cape Breton Highlands, Nova Scotia, *In* T.S. Murray and M.D. Cameron (eds.). Precommercial thinning workshop. Pp. 76-85. Canadian Forestry Service, Maritimes Forest Research Centre, Fredericton, NB.

Powell, D.S., and D.R. Dickson. 1984. Forest statistics for Maine, 1971 and 1982. USDA For. Serv. Resour. Bull. NE-81. 194 p.

Rahman, M. and M.J. Wilson. 1999. Maine Portfolio of the Forest Products Industry: A Comparative Analysis of Performance and Prospects. *Maine Business Indicators*, 44: 1.

Randolph, K.C., R.S. Seymour, and R.G. Wagner. 2001. ThinME User's Guide. Cooperative Forestry Research Unit, University of Maine, Orono, ME. 28 p.

Richardson, J. 1980. Release of young spruce and pine from alder competition. Environ. Can. Can. For. Serv. Info. Rep. N.X. 211.

Roberts, C.A. 1982. Cooperative study on the long-term silvicultural benefits of chemical brush control. Interim Report. Corvallis, OR. 13 p. plus tables. (Report on file at the Forest Research Laboratory, College of Forestry, Oregon State University, Corvallis, OR).

Rowe, J.S. 1972. Forest regions of Canada. Canadian Forestry Service, Department of the Environment, Ottawa. Publ. 1300. 172 p.

Seymour, R.S. 1992. The red spruce-balsam fir forest of Maine: Evolution of silvicultural practice in response to stand development patterns and disturbances. Ch.12 (p. 217-244) In: Kelty, M.H., Larson, B.C. and Oliver, C.D., (eds). The Ecology and Silviculture of Mixed-species forests. A festschrift for David M. Smith. Kluwer Publishers, Norwell, MA. 287 p.

Seymour, R.S., 1995. The northeastern region. In: J.W. Barrett, (ed.). Regional silviculture of the United States. 3rd ed. John Wiley & Sons, New York. Pp. 31-79.

Shepard, R.K. and J.E. Shottafer. 1990. Effect of early release on specific gravity and wood yield of black spruce. For. Prod. J. 40(1): 18-20.

Smith, D.M. 1991. Natural regeneration from sprouts and advanced growth, In: C.M. Simpson (ed.). Proceedings of the conference on natural regeneration management. pp.63-66. Forestry Canada, Maritimes Region, Fredericton, NB.

Smith, D.M., B.C. Larson, M.J. Delty, and P.M.S. Ashton. 1997. The practice of silviculture: applied forest ecology, 9th ed. John Wiley & Sons, New York. 537 p.

Solomon, D.S. 1977. The Influence of Stand Density and Structure on Growth of Northern Hardwoods in New England. Res. Pap. NE-362. Upper Darby, PA; U.S. Department of Agriculture, Forest Service, Northeastern Forest Experiment Station. 13 p.

Solomon, D. S., R. Hosmer, and H.T. Haysllett, Jr. 1987. FIBER Handbook: A growth model for spruce-fir and northern hardwood forest types. Modeling forest stand growth in the Northeast. USDA For. Serv., Res. Paper NE-602. 19p.

Solomon, Dale S., David A. Herman, and William B. Leak. 1995. FIBER 3.0: an ecological growth model for northeastern forest types. General Technical Report NE-204. Radnor, PA: U.S. Department of Agriculture, Forest Service, Northeastern Forest Experiment Station. 24 p.

Stage, A.R. 1973. Prognosis Model for Stand Development. Res. Pap. INT-137. U.S. Department of Agriculture. Forest Service. Intermountain Forest and Range Experimental Station. 32 p.

Stavins, R.N., D.L. Galt, and K.L. Eckhouse. 1981. An economic analysis of alternative vegetation management practices in commercial forests of the Pacific Coast region Cooperative Extension and Giannini Foundation of Agricultural Economics, Univ. California, Berkeley, CA. Project Rep. 2. 66 p.

Systat Manual, Systat 10, Statistics I. 2000. SPSS, Inc.

U.S. Department of Agriculture. 1979. The biologic and economic assessment of 2,4,5-T. U.S. Dept. Agr. Tech. Bull. 1671. 445 p.

Wagner, R.G. and S.R. Radosevich. 1991*a*. Neighborhood predictors of interspecific competition in young Douglas-fir plantations. Can. J. For. Res. 21: 821-828.

Wagner, R.G., and S.R. Radosevich. 1991*b*. Interspecific competition and other factors influencing the size of Douglas-fir saplings in the Oregon Coast Range. Can. J. For. Res. 21: 829-835.

Wagner, R.G., 1993. Research directions to advance forest vegetation management in North America. Can. J. For. Res. 23: 2317-2327.

Wagner, R.G. and S.R. Radosevich. 1998. Neighborhood approach for quantifying interspecific competition in coastal Oregon forests. Ecological Applications, 8(3): 779-794.

Wagner, R.G. 2000. Competition and critical-period thresholds for vegetation management decisions in young conifer stands. Forestry Chronicle 76(6):961-968.

Wagner, R.G., E.H. Bowling, and R.S. Seymour. 2003. Assessing silviculture research priorities for Maine using a wood supply analysis. Maine Forest and Agriculture Experiment Station, Technical Bulletin 186. 115 p.

Walstad, J.D., J.D. Brodie, B.G. McGinley, and C.A. Roberts. 1986. Silvicultural value of chemical brush control in the management of Souglas-fir. Western J. Appl. Forestry 1: 69-73.

Walstad, J.D. and Kuch, P.J. (*Eds*). 1987. Forest vegetation management for conifer production. John Wiley and Sons Inc., New York. 523 p.

APPENDIX A. P-VALUES FROM THE RESULTS OF ANOVA MODELS OF TREATMENT EFFECTS AND INTERACTION EFFECTS ON OVERSTORY VARIABLES FOR ALL SPECIES COMBINED AND FOR 4 SELECTED SPECIES.

Table A.1: P-values from the results of ANOVA models of treatment effects and interaction effects on overstory variables for all species combined.

Dependent Variable	Herbicide Effect	PCT Effect	Interaction Effect
Density (stems /A)	0.665	< 0.001	0.205
Basal area (ft^2/A)	0.646	<0.001	0.146
Total volume (ft^3/A)	0.794	<0.001	0.077
Merchantable volume (low) (ft^3/A)	0.825	0.339	0.089
Merchantable volume (mid) (ft^3/A)	0.776	0.132	0.226
Merchantable volume (high) (ft^3/A)	0.896	< 0.001	0.385
Hardwood basal area (ft^2/A)	0.008	< 0.001	0.130
Hardwood total volume (ft^3/A)	0.021	0.251	0.070
Hardwood merchantable volume (low) (ft^3/A)	0.047	0.606	0.052
Hardwood merchantable volume (mid) (ft^3/A)	0.071	0.678	0.073
Hardwood merchantable volume (high) (ft^3/A)	0.231	0.301	0.147
% Hardwood basal area	0.071	0.013	0.347
% Hardwood total volume	0.012	<0.001	0.276
Softwood basal area (ft^2/A)	0.244	<0.001	0.293
Sofwood total volume (ft^3/A)	0.254	0.709	0.342
Softwood merchantable volume (low) (ft^3/A)	0.244	0.026	0.289
Softwood merchantable volume (mid) (ft^3/A)	0.331	0.090	0.548
Softwood merchantable volume (high) (ft^3/A)	0.699	<0.001	0.528
% Softwood basal area	0.025	0.013	0.347
% Softwood total volume	0.012	<0.001	0.276
Quadratic mean diameter (in) (low)	0.875	0.001	0.565
Quadratic mean diameter (in) (mid)	0.845	0.016	0.671
Quadratic mean diameter (in) (high)	0.192	0.876	0.691
Value of standing wood (low) ($/A)	0.595	<0.001	0.446
Value of standing wood (mid) ($/A)	0.580	<0.001	0.566
Value of standing wood (high) ($/A)	0.788	<0.001	0.569

Table A.2: P-values from the results of ANOVA models of treatment effects and interaction effects on overstory variables for balsam fir.

Dependent Variable	Herbicide effect	PCT effect	Interaction effect
Density (stems/A)	0.495	<0.001	0.347
Basal area (ft^2/A)	0.401	0.001	0.112
Total volume (ft^3/A)	0.366	0.536	0.141
Merchantable volume (ft^3/A) (low)	0.261	0.002	0.268
Merchantable volume (ft^3/A) (mid)	0.269	<0.001	0.394
Merchantable volume (ft^3/A) (high)	0.394	<0.001	0.422
QMD (in) (low)	0.902	0.011	0.264
QMD (in) (mid)	0.922	0.017	0.309
QMD (in) (high)	0.005	0.030	<0.001
Average height (ft)	0.214	0.015	0.685

Table A.3: P-values from the results of ANOVA models of treatment effects and interaction effects on overstory variables for red spruce.

Dependent Variable	Herbicide effect	PCT effect	Interaction effect
Density (stems/A)	0.526	<0.001	0.35
Basal area (ft^2/A)	0.623	0.014	0.504
Total volume (ft^3/A)	0.536	0.031	0.518
Merchantable volume (ft^3/A) (low)	0.283	0.666	0.594
Merchantable volume (ft^3/A) (mid)	0.275	0.004	0.476
Merchantable volume (ft^3/A) (high)	0.405	<0.001	0.275
QMD (in) (low)	0.472	<0.001	0.521
QMD (in) (mid)	0.985	0.316	0.815
QMD (in) (high)	0.116	0.530	0.150
Average height (ft)	0.104	0.703	0.330

Table A.4: P-values from the results of ANOVA models of treatment effects and interaction effects on overstory variables for quaking aspen.

Dependent Variable	Herbicide effect	PCT effect	Interaction effect
Density (stems/A)	0.286	0.607	0.472
Basal area (ft^2/A)	0.029	<0.001	0.115
Total volume (ft^3/A)	0.027	<0.001	0.080
Merchantable volume (ft^3/A) (low)	0.049	<0.001	0.067
Merchantable volume (ft^3/A) (mid)	0.104	<0.001	0.110
Merchantable volume (ft^3/A) (high)	0.205	<0.001	0.210
Average height (ft)	0.398	0.051	0.416

Table A.5: P-values from the results of ANOVA models of treatment effects and interaction effects on overstory variables for red maple.

Dependent Variable	Herbicide effect	PCT effect	Interaction effect
Density (stems/A)	0.559	0.499	0.555
Basal Area (ft^2/A)	0.429	0.098	0.244
Total Volume (ft^3/A)	0.427	0.566	0.217
Merchantable Volume (ft^3/A) (Low)	0.512	0.909	0.486
Merchantable Volume (ft^3/A) (Mid)	0.695	0.622	0.391
Merchantable Volume (ft^3/A) (High)	0.585	0.777	0.465
Average Height (ft)	0.390	<0.001	0.152

APPENDIX B: P-VALUES FROM LINEAR CONTRASTS OF OVERSTORY VARIABLES FOR ALL SPECIES COMBINED AND FOR 4 SELECTED SPECIES.

Table B.1: P-values from linear contrast of overstory variables for all species combined.

CONTRAST	Density (stems/A)	Basal area (ft^2/A)	Total volume (ft^3/A)	Merchantable volume (ft^3/A) (low)	Merchantable volume (ft^3/A) (mid)
Herbicide Treated (unthinned) vs. Control (unthinned)	0.038	0.115	0.117	0.020	0.073
Herbicide Treated (thinned) vs. Control (thinned)	0.348	0.465	0.159	0.083	0.085
Glyphosate (unthinned) + Triclopyr (unthinned) vs. Phenoxy treatments (unthinned)	0.013	0.469	0.380	0.014	0.034
Glyphosate (thinned) + Triclopyr (thinned) vs. Phenoxy treatments (thinned)	0.535	0.769	0.623	0.552	0.564
Glyphosate (unthinned) vs.Triclopyr (unthinned)	0.546	0.042	0.062	0.373	0.336
Glyphosate (thinned) vs.Triclopyr (thinned)	0.967	0.384	0.422	0.597	0.615
Glyphosate (unthinned) vs. Control (unthinned)	0.450	0.784	0.071	0.110	0.217
Glyphosate (thinned) vs. Control (thinned)	0.554	0.716	0.453	0.368	0.254
Glyphosate (unthinned) vs. Control (thinned)	0.446	<0.001	0.003	0.649	0.817
Glyphosate (unthinned) vs. Glyphosate (thinned)	0.113	<0.001	0.004	0.392	0.104
Glyphosate (thinned) vs. Control (unthinned)	0.549	0.003	<0.001	0.337	0.897
Control (unthinned) vs Control (thinned)	0.995	0.005	<0.001	0.082	0.374
Triclopyr (unthinned) vs. Control (unthinned)	0.222	0.054	0.766	0.351	0.636
Triclopyr (thinned) vs. Control (thinned)	0.532	0.289	0.172	0.128	0.131
Triclopyr (unthinned) vs. Control (thinned)	0.220	<0.001	<0.001	0.245	0.572
Triclopyr (unthinned) vs.Triclopyr (thinned)	0.035	<0.001	<0.001	0.622	0.227
Triclopyr (thinned) vs. Control (unthinned)	0.528	0.013	<0.001	0.588	0.590
Phenoxy (unthinned) vs Control (unthinned)	0.013	0.094	0.090	0.007	0.032
Phenoxy (thinned) vs Control (thinned)	0.297	0.513	0.141	0.071	0.073

Table B.1: Continued.

CONTRAST	Merchantable volume (ft^3/A) (high)	Hardwood basal area (ft^2/A)	Hardwood total volume (ft^3/A)	Hardwood merchantable volume (ft^3/A) (low)	Hardwood merchantable volume (ft^3/A) (mid)
Herbicide Treated (unthinned) vs. Control (unthinned)	0.130	<0.001	<0.001	<0.001	<0.001
Herbicide Treated (thinned) vs. Control (thinned)	0.176	0.657	0.849	0.921	0.897
Glyphosate (unthinned) + Triclopyr (unthinned) vs. Phenoxy treatments (unthinned)	0.228	0.345	0.464	0.954	0.584
Glyphosate (thinned) + Triclopyr (thinned) vs. Phenoxy treatments (thinned)	0.213	0.832	0.884	0.975	0.980
Glyphosate (unthinned) vs.Triclopyr (unthinned)	0.548	0.826	0.783	0.798	0.521
Glyphosate (thinned) vs.Triclopyr (thinned)	0.520	0.735	0.835	0.896	0.899
Glyphosate (unthinned) vs. Control (unthinned)	0.243	<0.001	<0.001	<0.001	<0.001
Glyphosate (thinned) vs. Control (thinned)	0.609	0.559	0.768	0.983	0.960
Glyphosate (unthinned) vs. Control (thinned)	0.551	0.594	0.278	0.229	0.296
Glyphosate (unthinned) vs. Glyphosate (thinned)	0.188	0.184	0.104	0.153	0.226
Glyphosate (thinned) vs. Control (unthinned)	0.932	<0.001	<0.001	<0.001	<0.001
Control (unthinned) vs Control (thinned)	0.605	<0.001	<0.001	<0.001	<0.001
Triclopyr (unthinned) vs. Control (unthinned)	0.484	<0.001	<0.001	<0.001	<0.001
Triclopyr (thinned) vs. Control (thinned)	0.307	0.756	0.900	0.898	0.878
Triclopyr (unthinned) vs. Control (thinned)	0.915	0.481	0.197	0.165	0.128
Triclopyr (unthinned) vs.Triclopyr (thinned)	0.175	0.223	0.092	0.124	0.096
Triclopyr (thinned) vs. Control (unthinned)	0.658	<0.001	<0.001	<0.001	<0.001
Phenoxy (unthinned) vs Control (unthinned)	0.087	<0.001	<0.001	<0.001	<0.001
Phenoxy (thinned) vs Control (thinned)	0.118	0.695	0.877	0.917	0.895

Table B.1: Continued.

CONTRAST	Hardwood merchantable volume (ft^3/A) (high)	%Hardwood basal area	%Hardwood total volume	Softwood basal area (ft^2/A)	Softwood total volume (ft^3/A)
Herbicide Treated (unthinned) vs. Control (unthinned)	<0.001	<0.001	<0.001	<0.001	<0.001
Herbicide Treated (thinned) vs. Control (thinned)	0.796	0.488	0.539	0.478	0.216
Glyphosate (unthinned) + Triclopyr (unthinned) vs. Phenoxy treatments (unthinned)	0.362	0.730	0.490	0.823	0.227
Glyphosate (thinned) + Triclopyr (thinned) vs. Phenoxy treatments (thinned)	0.918	0.698	0.784	0.757	0.822
Glyphosate (unthinned) vs.Triclopyr (unthinned)	0.355	0.920	0.819	0.276	0.242
Glyphosate (thinned) vs.Triclopyr (thinned)	0.754	0.752	0.713	0.782	0.692
Glyphosate (unthinned) vs. Control (unthinned)	<0.001	<0.001	<0.001	0.003	0.004
Glyphosate (thinned) vs. Control (thinned)	0.953	0.401	0.448	0.552	0.399
Glyphosate (unthinned) vs. Control (thinned)	0.432	0.924	0.723	0.060	0.107
Glyphosate (unthinned) vs. Glyphosate (thinned)	0.375	0.362	0.184	0.098	0.308
Glyphosate (thinned) vs. Control (unthinned)	<0.001	<0.001	<0.001	0.047	0.018
Control (unthinned) vs Control (thinned)	<0.001	0.003	<0.001	0.191	0.130
Triclopyr (unthinned) vs. Control (unthinned)	0.003	<0.001	<0.001	<0.001	<0.001
Triclopyr (thinned) vs. Control (thinned)	0.753	0.555	0.642	0.415	0.302
Triclopyr (unthinned) vs. Control (thinned)	0.136	0.990	0.589	0.011	0.020
Triclopyr (unthinned) vs.Triclopyr (thinned)	0.144	0.481	0.243	0.021	0.251
Triclopyr (thinned) vs. Control (unthinned)	<0.001	<0.001	<0.001	0.031	0.010
Phenoxy (unthinned) vs Control (unthinned)	<0.001	<0.001	<0.001	<0.001	0.002
Phenoxy (thinned) vs Control (thinned)	0.784	0.551	0.599	0.529	0.210

Table B.1: Continued.

CONTRAST	Softwood merchantable volume (ft^3/A) (low)	Softwood merchantable volume (ft^3/A) (mid)	Softwood merchantable volume (ft^3/A) (high)	% Softwood basal area	% Softwood total volume
Herbicide Treated (unthinned) vs. Control (unthinned)	0.051	0.283	0.949	<0.001	<0.001
Herbicide Treated (thinned) vs. Control (thinned)	0.094	0.094	0.182	0.488	0.539
Glyphosate (unthinned) + Triclopyr (unthinned) vs. Phenoxy treatments (unthinned)	0.014	0.054	0.326	0.730	0.490
Glyphosate (thinned) + Triclopyr (thinned) vs. Phenoxy treatments (thinned)	0.567	0.572	0.205	0.698	0.784
Glyphosate (unthinned) vs.Triclopyr (unthinned)	0.475	0.502	0.740	0.920	0.819
Glyphosate (thinned) vs.Triclopyr (thinned)	0.663	0.657	0.565	0.752	0.713
Glyphosate (unthinned) vs. Control (unthinned)	0.028	0.195	0.891	<0.001	<0.001
Glyphosate (thinned) vs. Control (thinned)	0.263	0.262	0.605	0.401	0.448
Glyphosate (unthinned) vs. Control (thinned)	0.673	0.464	0.384	0.924	0.723
Glyphosate (unthinned) vs. Glyphosate (thinned)	0.073	0.036	0.106	0.362	0.184
Glyphosate (thinned) vs. Control (unthinned)	<0.001	0.006	0.143	<0.001	<0.001
Control (unthinned) vs Control (thinned)	0.026	0.090	0.384	0.003	<0.001
Triclopyr (unthinned) vs. Control (unthinned)	0.009	0.077	0.684	<0.001	<0.001
Triclopyr (thinned) vs. Control (thinned)	0.150	0.147	0.331	0.555	0.642
Triclopyr (unthinned) vs. Control (thinned)	0.867	0.851	0.543	0.990	0.589
Triclopyr (unthinned) vs.Triclopyr (thinned)	0.120	0.054	0.069	0.481	0.243
Triclopyr (thinned) vs. Control (unthinned)	<0.001	0.003	0.064	<0.001	<0.001
Phenoxy (unthinned) vs Control (unthinned)	0.159	0.533	0.782	<0.001	<0.001
Phenoxy (thinned) vs Control (thinned)	0.082	0.081	0.122	0.551	0.599

Table B.1: Continued.

CONTRAST	Quadratic mean diameter (in) (low)	Quadratic mean diameter (in) (mid)	Quadratic mean diameter (in) (high)	Value of standing wood ($/A) (low)	Value of standing wood ($/A) (mid)
Herbicide Treated (unthinned) vs. Control (unthinned)	0.134	0.118	0.364	0.997	0.979
Herbicide Treated (thinned) vs. Control (thinned)	0.162	0.211	0.267	0.099	0.125
Glyphosate (unthinned) + Triclopyr (unthinned) vs. Phenoxy treatments (unthinned)	0.721	0.864	0.507	0.061	0.137
Glyphosate (thinned) + Triclopyr (thinned) vs. Phenoxy treatments (thinned)	0.119	0.207	0.234	0.393	0.280
Glyphosate (unthinned) vs.Triclopyr (unthinned)	0.899	0.886	0.392	0.403	0.536
Glyphosate (thinned) vs.Triclopyr (thinned)	0.684	0.650	0.570	0.559	0.645
Glyphosate (unthinned) vs. Control (unthinned)	0.253	0.177	0.508	0.757	0.783
Glyphosate (thinned) vs. Control (thinned)	0.589	0.624	0.735	0.342	0.415
Glyphosate (unthinned) vs. Control (thinned)	0.801	0.986	0.325	0.639	0.612
Glyphosate (unthinned) vs. Glyphosate (thinned)	0.340	0.535	0.421	0.097	0.120
Glyphosate (thinned) vs. Control (unthinned)	0.704	0.379	0.198	0.099	0.126
Control (unthinned) vs Control (thinned)	0.430	0.244	0.165	0.502	0.501
Triclopyr (unthinned) vs. Control (unthinned)	0.216	0.146	0.185	0.326	0.439
Triclopyr (thinned) vs. Control (thinned)	0.389	0.395	0.427	0.164	0.242
Triclopyr (unthinned) vs. Control (thinned)	0.723	0.892	0.768	0.826	1.000
Triclopyr (unthinned) vs.Triclopyr (thinned)	0.150	0.235	0.535	0.150	0.158
Triclopyr (thinned) vs. Control (unthinned)	0.962	0.603	0.393	0.042	0.065
Phenoxy (unthinned) vs Control (unthinned)	0.125	0.134	0.460	0.664	0.759
Phenoxy (thinned) vs Control (thinned)	0.095	0.141	0.185	0.077	0.089

Table B.1: Continued.

CONTRAST	Value of standing wood ($/A) (high)
Herbicide Treated (unthinned) vs. Control (unthinned)	0.587
Herbicide Treated (thinned) vs. Control (thinned)	0.188
Glyphosate (unthinned) + Triclopyr (unthinned) vs. Phenoxy treatments (unthinned)	0.368
Glyphosate (thinned) + Triclopyr (thinned) vs. Phenoxy treatments (thinned)	0.161
Glyphosate (unthinned) vs.Triclopyr (unthinned)	0.720
Glyphosate (thinned) vs.Triclopyr (thinned)	0.605
Glyphosate (unthinned) vs. Control (unthinned)	0.753
Glyphosate (thinned) vs. Control (thinned)	0.636
Glyphosate (unthinned) vs. Control (thinned)	0.600
Glyphosate (unthinned) vs. Glyphosate (thinned)	0.233
Glyphosate (thinned) vs. Control (unthinned)	0.495
Control (unthinned) vs Control (thinned)	0.854
Triclopyr (unthinned) vs. Control (unthinned)	0.983
Triclopyr (thinned) vs. Control (thinned)	0.376
Triclopyr (unthinned) vs. Control (thinned)	0.815
Triclopyr (unthinned) vs.Triclopyr (thinned)	0.181
Triclopyr (thinned) vs. Control (unthinned)	0.278
Phenoxy (unthinned) vs Control (unthinned)	0.470
Phenoxy (thinned) vs Control (thinned)	0.118

Table B.2: P-values from linear contrasts of overstory variables for balsam fir.

CONTRAST	Density (stems/A)	Basal area (ft^2/A)	Total volume (ft^3/A)	Merchantable volume (ft^3/A) (low)	Merchantable volume (ft^3/A) (mid)
Herbicide Treated (unthinned) vs. Control (unthinned)	0.013	<0.001	0.003	0.048	0.309
Herbicide Treated (thinned) vs. Control (thinned)	0.806	0.401	0.217	0.201	0.151
Glyphosate (unthinned) + Triclopyr (unthinned) vs. Phenoxy treatments (unthinned)	0.079	0.384	0.100	0.039	0.055
Glyphosate (thinned) + Triclopyr (thinned) vs. Phenoxy treatments (thinned)	0.497	0.949	0.631	0.542	0.407
Glyphosate (unthinned) vs.Triclopyr (unthinned)	0.544	0.159	0.189	0.342	0.432
Glyphosate (thinned) vs.Triclopyr (thinned)	0.997	0.752	0.799	0.813	0.915
Glyphosate (unthinned) vs. Control (unthinned)	0.138	0.003	0.008	0.045	0.230
Glyphosate (thinned) vs. Control (thinned)	0.991	0.388	0.311	0.315	0.305
Glyphosate (unthinned) vs. Control (thinned)	0.115	0.054	0.158	0.804	0.532
Glyphosate (unthinned) vs. Glyphosate (thinned)	0.061	0.153	0.591	0.350	0.058
Glyphosate (thinned) vs. Control (unthinned)	0.921	0.031	0.018	0.011	0.012
Control (unthinned) vs Control (thinned)	0.924	0.207	0.172	0.112	0.125
Triclopyr (unthinned) vs. Control (unthinned)	0.058	0.012	<0.001	0.010	0.078
Triclopyr (thinned) vs. Control (thinned)	0.988	0.539	0.415	0.411	0.345
Triclopyr (unthinned) vs. Control (thinned)	0.047	0.006	0.021	0.309	0.984
Triclopyr (unthinned) vs.Triclopyr (thinned)	0.020	0.006	0.048	0.801	0.262
Triclopyr (thinned) vs. Control (unthinned)	0.924	0.050	0.027	0.015	0.014
Phenoxy (unthinned) vs Control (unthinned)	0.007	<0.001	0.007	0.123	0.569
Phenoxy (thinned) vs Control (thinned)	0.700	0.419	0.193	0.171	0.119

Table B.2: Continued.

CONTRAST	Merchantable volume (ft^3/A) (high)	QMD (in) (low)	QMD (in) (mid)	QMD (in) (high)	Average height (ft)
Herbicide Treated (unthinned) vs. Control (unthinned)	0.734	0.001	0.001	<0.001	0.044
Herbicide Treated (thinned) vs. Control (thinned)	0.150	0.391	0.401	0.032	0.271
Glyphosate (unthinned) + Triclopyr (unthinned) vs. Phenoxy treatments (unthinned)	0.148	0.620	0.714	0.167	0.088
Glyphosate (thinned) + Triclopyr (thinned) vs. Phenoxy treatments (thinned)	0.250	0.377	0.363	0.014	0.511
Glyphosate (unthinned) vs.Triclopyr (unthinned)	0.611	0.968	0.843	0.257	0.998
Glyphosate (thinned) vs.Triclopyr (thinned)	0.911	0.736	0.784	0.402	0.811
Glyphosate (unthinned) vs. Control (unthinned)	0.568	0.004	0.004	<0.001	0.027
Glyphosate (thinned) vs. Control (thinned)	0.400	0.755	0.754	0.439	0.519
Glyphosate (unthinned) vs. Control (thinned)	0.447	0.649	0.628	0.286	0.482
Glyphosate (unthinned) vs. Glyphosate (thinned)	0.065	0.354	0.336	0.063	0.942
Glyphosate (thinned) vs. Control (unthinned)	0.044	0.015	0.020	<0.001	0.030
Control (unthinned) vs Control (thinned)	0.257	0.019	0.023	<0.001	0.146
Triclopyr (unthinned) vs. Control (unthinned)	0.331	0.004	0.006	<0.001	0.027
Triclopyr (thinned) vs. Control (thinned)	0.353	0.558	0.592	0.161	0.404
Triclopyr (unthinned) vs. Control (thinned)	0.724	0.672	0.745	0.923	0.484
Triclopyr (unthinned) vs.Triclopyr (thinned)	0.130	0.229	0.301	0.077	0.865
Triclopyr (thinned) vs. Control (unthinned)	0.037	0.026	0.030	<0.001	0.021
Phenoxy (unthinned) vs Control (unthinned)	0.992	0.001	0.001	<0.001	0.097
Phenoxy (thinned) vs Control (thinned)	0.104	0.307	0.313	0.012	0.227

Table B.3: P-values from linear contrasts of overstory variables for red spruce.

CONTRAST	Density (stems/A)	Basal area (ft^2/A)	Total volume (ft^3/A)	Merchantable volume (ft^3/A) (low)	Merchantable volume (ft^3/A) (mid)
Herbicide Treated (unthinned) vs. Control (unthinned)	0.019	0.020	0.021	0.059	0.129
Herbicide Treated (thinned) vs. Control (thinned)	0.866	0.950	0.942	0.929	0.865
Glyphosate (unthinned) + Triclopyr (unthinned) vs. Phenoxy treatments (unthinned)	0.011	0.204	0.314	0.986	0.861
Glyphosate (thinned) + Triclopyr (thinned) vs. Phenoxy treatments (thinned)	0.682	0.419	0.413	0.335	0.236
Glyphosate (unthinned) vs.Triclopyr (unthinned)	0.838	0.792	0.758	0.811	0.836
Glyphosate (thinned) vs.Triclopyr (thinned)	0.609	0.182	0.160	0.103	0.061
Glyphosate (unthinned) vs. Control (unthinned)	0.240	0.106	0.096	0.121	0.199
Glyphosate (thinned) vs. Control (thinned)	0.946	0.806	0.790	0.756	0.776
Glyphosate (unthinned) vs. Control (thinned)	0.203	0.528	0.565	0.973	0.358
Glyphosate (unthinned) vs. Glyphosate (thinned)	0.143	0.292	0.311	0.735	0.431
Glyphosate (thinned) vs. Control (unthinned)	0.967	0.414	0.366	0.191	0.066
Control (unthinned) vs Control (thinned)	0.925	0.361	0.315	0.166	0.068
Triclopyr (unthinned) vs. Control (unthinned)	0.185	0.073	0.062	0.086	0.151
Triclopyr (thinned) vs. Control (thinned)	0.627	0.383	0.361	0.282	0.187
Triclopyr (unthinned) vs. Control (thinned)	0.155	0.401	0.412	0.872	0.449
Triclopyr (unthinned) vs.Triclopyr (thinned)	0.236	0.967	0.904	0.262	0.020
Triclopyr (thinned) vs. Control (unthinned)	0.706	0.068	0.052	0.015	0.003
Phenoxy (unthinned) vs Control (unthinned)	0.007	0.013	0.015	0.064	0.146
Phenoxy (thinned) vs Control (thinned)	0.939	0.910	0.915	0.902	0.925

Table B.3: Continued.

CONTRAST	Merchantable volume (ft^3/A) (high)	QMD (in) (low)	QMD (in) (mid)	QMD (in) (high)	Average height (ft)
Herbicide Treated (unthinned) vs. Control (unthinned)	0.243	0.325	0.929	0.287	0.015
Herbicide Treated (thinned) vs. Control (thinned)	0.625	0.325	0.166	0.239	0.883
Glyphosate (unthinned) + Triclopyr (unthinned) vs. Phenoxy treatments (unthinned)	0.857	0.497	0.493	0.868	0.871
Glyphosate (thinned) + Triclopyr (thinned) vs. Phenoxy treatments (thinned)	0.266	0.233	0.748	0.980	0.379
Glyphosate (unthinned) vs.Triclopyr (unthinned)	0.755	0.981	0.577	0.911	0.914
Glyphosate (thinned) vs.Triclopyr (thinned)	0.044	0.851	0.672	0.255	0.201
Glyphosate (unthinned) vs. Control (unthinned)	0.408	0.566	0.979	0.365	0.039
Glyphosate (thinned) vs. Control (thinned)	0.913	0.595	0.209	0.365	0.347
Glyphosate (unthinned) vs. Control (thinned)	0.116	0.182	0.343	0.912	0.910
Glyphosate (unthinned) vs. Glyphosate (thinned)	0.076	0.033	0.031	0.530	0.205
Glyphosate (thinned) vs. Control (unthinned)	0.031	0.021	0.789	0.300	0.244
Control (unthinned) vs Control (thinned)	0.047	0.251	0.890	0.530	0.081
Triclopyr (unthinned) vs. Control (unthinned)	0.286	0.590	0.923	0.658	0.033
Triclopyr (thinned) vs. Control (thinned)	0.110	0.704	0.349	0.141	0.901
Triclopyr (unthinned) vs. Control (thinned)	0.177	0.187	0.685	0.899	0.841
Triclopyr (unthinned) vs.Triclopyr (thinned)	0.002	0.049	0.173	0.707	0.925
Triclopyr (thinned) vs. Control (unthinned)	0.001	0.034	0.819	0.168	0.038
Phenoxy (unthinned) vs Control (unthinned)	0.239	0.778	0.916	0.218	0.016
Phenoxy (thinned) vs Control (thinned)	0.813	0.228	0.157	0.265	0.963

Table B.4: P-values from linear contrasts of overstory variables for quaking aspen.

CONTRAST	Density (stems/A)	Basal area (ft^2/A)	Total volume (ft^3/A)	Merchantable volume (ft^3/A) (low)	Merchantable volume (ft^3/A) (mid)
Herbicide Treated (unthinned) vs. Control (unthinned)	0.902	0.044	0.010	0.003	<0.001
Herbicide Treated (thinned) vs. Control (thinned)	0.057	0.428	0.646	0.970	0.995
Glyphosate (unthinned) + Triclopyr (unthinned) vs. Phenoxy treatments (unthinned)	0.113	0.067	0.117	0.222	0.633
Glyphosate (thinned) + Triclopyr (thinned) vs. Phenoxy treatments (thinned)	0.930	0.884	0.909	0.922	0.986
Glyphosate (unthinned) vs.Triclopyr (unthinned)	0.790	0.473	0.378	0.342	0.296
Glyphosate (thinned) vs.Triclopyr (thinned)	0.535	0.735	0.830	0.959	0.981
Glyphosate (unthinned) vs. Control (unthinned)	0.585	0.014	0.004	0.002	<0.001
Glyphosate (thinned) vs. Control (thinned)	0.059	0.391	0.607	0.933	0.983
Glyphosate (unthinned) vs. Control (thinned)	0.055	0.893	0.694	0.353	0.338
Glyphosate (unthinned) vs. Glyphosate (thinned)	0.957	0.375	0.276	0.222	0.236
Glyphosate (thinned) vs. Control (unthinned)	0.615	0.003	<0.001	<0.001	<0.001
Control (unthinned) vs Control (thinned)	0.200	0.035	0.005	<0.001	<0.001
Triclopyr (unthinned) vs. Control (unthinned)	0.741	0.042	0.017	0.009	0.006
Triclopyr (thinned) vs. Control (thinned)	0.144	0.556	0.733	0.966	0.999
Triclopyr (unthinned) vs. Control (thinned)	0.081	0.648	0.272	0.101	0.083
Triclopyr (unthinned) vs.Triclopyr (thinned)	0.682	0.213	0.091	0.046	0.039
Triclopyr (thinned) vs. Control (unthinned)	0.997	0.006	<0.001	<0.001	<0.001
Phenoxy (unthinned) vs Control (unthinned)	0.634	0.103	0.023	0.006	0.002
Phenoxy (thinned) vs Control (thinned)	0.064	0.457	0.671	0.988	0.998

Table B.4: Continued.

CONTRAST	Merchantable volume (ft^3/A) (high)	Average height (ft)
Herbicide Treated (unthinned) vs. Control (unthinned)	<0.001	0.015
Herbicide Treated (thinned) vs. Control (thinned)	0.993	0.866
Glyphosate (unthinned) + Triclopyr (unthinned) vs. Phenoxy treatments (unthinned)	0.877	0.579
Glyphosate (thinned) + Triclopyr (thinned) vs. Phenoxy treatments (thinned)	0.996	0.950
Glyphosate (unthinned) vs.Triclopyr (unthinned)	0.286	0.087
Glyphosate (thinned) vs.Triclopyr (thinned)	0.986	0.932
Glyphosate (unthinned) vs. Control (unthinned)	0.002	0.011
Glyphosate (thinned) vs. Control (thinned)	0.999	0.914
Glyphosate (unthinned) vs. Control (thinned)	0.351	0.012
Glyphosate (unthinned) vs. Glyphosate (thinned)	0.257	0.004
Glyphosate (thinned) vs. Control (unthinned)	<0.001	<0.001
Control (unthinned) vs Control (thinned)	<0.001	<0.001
Triclopyr (unthinned) vs. Control (unthinned)	0.009	0.163
Triclopyr (thinned) vs. Control (thinned)	0.989	0.918
Triclopyr (unthinned) vs. Control (thinned)	0.084	<0.001
Triclopyr (unthinned) vs.Triclopyr (thinned)	0.041	0.539
Triclopyr (thinned) vs. Control (unthinned)	<0.001	0.400
Phenoxy (unthinned) vs Control (unthinned)	<0.001	0.013
Phenoxy (thinned) vs Control (thinned)	0.992	0.834

Table B.5: P-values from linear contrasts of overstory variables for red maple.

CONTRAST	Density (stems/A)	Basal area (ft^2/A)	Total volume (ft^3/A)	Merchantable volume (ft^3/A) (low)	Merchantable volume (ft^3/A) (mid)
Herbicide Treated (unthinned) vs. Control (unthinned)	0.019	<0.001	0.014	0.022	0.003
Herbicide Treated (thinned) vs. Control (thinned)	0.509	0.751	0.803	0.868	0.709
Glyphosate (unthinned) + Triclopyr (unthinned) vs. Phenoxy treatments (unthinned)	0.979	0.686	0.940	0.885	0.385
Glyphosate (thinned) + Triclopyr (thinned) vs. Phenoxy treatments (thinned)	0.141	0.544	0.701	0.959	0.941
Glyphosate (unthinned) vs.Triclopyr (unthinned)	0.309	0.176	0.875	0.744	0.933
Glyphosate (thinned) vs.Triclopyr (thinned)	0.400	0.916	0.973	0.830	0.713
Glyphosate (unthinned) vs. Control (unthinned)	0.084	0.004	0.003	0.007	0.014
Glyphosate (thinned) vs. Control (thinned)	0.680	0.908	0.941	0.944	0.885
Glyphosate (unthinned) vs. Control (thinned)	0.605	0.246	0.248	0.515	0.644
Glyphosate (unthinned) vs. Glyphosate (thinned)	0.897	0.202	0.188	0.477	0.697
Glyphosate (thinned) vs. Control (unthinned)	0.070	<0.001	<0.001	0.002	0.008
Control (unthinned) vs Control (thinned)	0.058	<0.001	<0.001	0.005	0.014
Triclopyr (unthinned) vs. Control (unthinned)	0.018	<0.001	<0.001	<0.001	0.016
Triclopyr (thinned) vs. Control (thinned)	0.778	0.976	0.919	0.806	0.657
Triclopyr (unthinned) vs. Control (thinned)	0.743	0.964	0.984	0.831	0.617
Triclopyr (unthinned) vs.Triclopyr (thinned)	0.956	0.984	0.996	0.802	0.895
Triclopyr (thinned) vs. Control (unthinned)	0.019	<0.001	<0.001	0.003	0.014
Phenoxy (unthinned) vs Control (unthinned)	0.022	<0.001	<0.001	<0.001	0.003
Phenoxy (thinned) vs Control (thinned)	0.337	0.660	0.745	0.880	0.704

Table B.5: Continued.

CONTRAST	Merchantable volume (ft^3/A) (high)	Average height (ft)
Herbicide Treated (unthinned) vs. Control (unthinned)	0.331	0.043
Herbicide Treated (thinned) vs. Control (thinned)	0.458	0.439
Glyphosate (unthinned) + Triclopyr (unthinned) vs. Phenoxy treatments (unthinned)	0.958	0.428
Glyphosate (thinned) + Triclopyr (thinned) vs. Phenoxy treatments (thinned)	0.850	0.604
Glyphosate (unthinned) vs.Triclopyr (unthinned)	0.942	0.326
Glyphosate (thinned) vs.Triclopyr (thinned)	0.252	0.496
Glyphosate (unthinned) vs. Control (unthinned)	0.119	0.017
Glyphosate (thinned) vs. Control (thinned)	0.825	0.580
Glyphosate (unthinned) vs. Control (thinned)	1.000	0.002
Glyphosate (unthinned) vs. Glyphosate (thinned)	0.787	0.001
Glyphosate (thinned) vs. Control (unthinned)	0.172	<0.001
Control (unthinned) vs Control (thinned)	0.172	<0.001
Triclopyr (unthinned) vs. Control (unthinned)	0.863	0.157
Triclopyr (thinned) vs. Control (thinned)	0.250	0.276
Triclopyr (unthinned) vs. Control (thinned)	0.942	<0.001
Triclopyr (unthinned) vs.Triclopyr (thinned)	0.917	0.002
Triclopyr (thinned) vs. Control (unthinned)	0.646	<0.001
Phenoxy (unthinned) vs Control (unthinned)	0.091	0.065
Phenoxy (thinned) vs Control (thinned)	0.493	0.517

BIOGRAPHY OF THE AUTHOR

Roland Howard Daggett was born in Skowhegan, Maine on February 22nd, 1958. He grew up in Anson, Maine and graduated from Carrabec High School in 1976. Upon graduation from High School, he moved to Bangor, Maine and attended the University of Maine, Orono from 1976 to 1978 and received an Associate of Science Degree in Forest Management Technology.

After receiving his Degree, he began employment performing leak detection on natural gas pipelines in numerous locations in the Southwestern United States. His travels, after a year, ended in Farmington, New Mexico. There, he began a career as a Professional Land Surveyor that lasted for 20 years. During his career as a land surveyor, he worked in the oil and gas industry as an employee for a large natural gas transmission company and as owner and manager of his own land surveying and oil field services business.

The business was sold in 1997. He returned to the Bangor area in 1998 and completed his Bachelor of Science Degree in Forest Management at the University of Maine in the spring of 2000. Immediately upon completion of his Bachelor's Degree, he began graduate studies at the University of Maine. Roland is a candidate for the Master of Science degree in Forestry from The University of Maine in August, 2003.