Comparison of Chemical and Manual Methods of

Precommercial Thinning Oak Stump-Sprouts

by

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(ABSTRACT)

Precommercial thinning of 12-year-old upland oak stump-sprouts in southwestern Virginia using herbicides and manual felling was compared. Objectives were to quantify and compare residual crop-stem growth and treatment costs between treatments and application methods. 2,4-D and triclopyr were applied to competing stump-sprouts using stem injection and low volume basal spray techniques. Kerosene, the carrier for the ester formulations, was also tested for its efficacy properties. One growing season following treatment, total control (percent affected and dead) of chemically treated sprouts averaged 98 percent. Triclopyr basal spray treatment exhibited the highest mortality to treated sprouts totaling 88.6 percent and kerosene had the lowest mortality occurrence of 7.6 percent. On average, translocation was minimal affecting only 58 percent of the crop-stems with less than 10 percent of the crown exhibiting visual symptoms. Mortality of residual crop-stems did not occur and an average of 36 percent exhibited no visual symptoms. Mean height growth for residual crop-stems was significantly greater for manual thinning over unthinned control. Crop-stem height growth was also significantly greater for the contrasts of manual thinning vs chemical thinning and manual thinning vs basal spray treatments. No significant differences occurred for any growth parameter between unthinned control and chemical treatments nor between injection and basal spray treatments. Results of regression-adjusted volume growth (D^2H) showed that a 2 percent increase in growth over control was realized for the crop-stems following injection treatments versus a 1 percent increase as a result of the basal treatments. The manual thinning treatment was found to exhibit a significantly greater effect on crop-stem growth compared to chemical treatments averaging a 4 percent volume growth increase. Chemical treatment costs ranged from $36.05/ha to $82.23/ha for 2,4-D injection and triclopyr basal spray treatments, respectively. Manual thinning was found to be the most expensive treatment at $105.30/ha. Injection treatments were significantly more productive and the least expensive. Application costs incurred during the present study were representative of costs incurred by forest industry, private, and public agencies in the southern United States. Overall results of this study suggest that chemical precommercial thinning of oak stump-sprouts is a safe, cost effective method of reducing competition and releasing dominant crop-stems.

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Table of Contents

List of Illustrations

List of Tables

Chapter I : Introduction

Vegetation management in North American forestry was not practiced until the early 1900's. At that time undesirable vegetation was removed using fire and mechanical methods. Between 1941 and 1970 there was extensive research conducted on the use of herbicides for vegetation management; however, applications were mostly for agricultural purposes. This research resulted in the discovery of plant growth regulators and the development of organic herbicides which helped to produce major increases in crop yields *(Walstad 1985)*.

About 1945 chemical vegetation management began in forest industry *(Bullock et al. 1988)*. Forest industry's earliest use of chemicals, (primarily 2,4-D), was for site preparation and pine tree release from hardwoods. The rapid expansion in acres of planted pine during the 1970's caused more emphasis to be placed on chemical vegetation management *(Bullock et al. 1988, Nelson et al. 1983)*. By the end of 1980 there were only a few herbicides registered for forestry use. The 1980's were the years of rapid expansion in the development and use of herbicides for forest vegetation management *(Walstad 1985)*. The emphasis was on reducing interspecific competition using herbicides, whereas, intraspecific competition manipulation was performed using manual techniques.

The use of clearcutting in hardwood stands (from which stump sprouts are produced) has historically been the most widely used method of regeneration. This silvicultural system has been used primarily because it is an inexpensive method of reproducing a mixed hardwood stand, as compared to individual tree selection or group selection systems. Also, it has been recommended for many years to be the best method of regeneration for attaining satisfactory hardwood composition and growth *(Roach 1963)*. In the southern Appalachian upland hardwood region, stump sprouting often accounts for one-third or more of the regeneration basal area following clearcutting or fire *(Lamson 1988)*.

Cultural practices in immature hardwood stands rarely yield merchantable products. Stems cut are unmerchantable due to their small size and the high costs of removal, transportation, and processing. Also, when herbicide treatments are used stems are left standing, therefore, there is no immediate revenue. But, regardless of the cultural treatment, the perspective is the same; the treatment costs should be viewed as an investment in an immature stand of timber. The primary goal of these cultural treatments is to provide the landowner with a higher rate of return as a direct result of the early investment *(Miller 1986)*.

Immature hardwood stands increase in value over time due to the increase in tree size and value. The objective of managing these stands is to allow the higher value trees to become the dominant portion of the stand by accelerating the growth of residuals. By favoring high value trees in an early cultural treatment, like precommercial thinning, one would expect an increase in revenue from future harvests. These increased revenues ultimately equate to higher returns on investment when compared to revenues from unthinned hardwood stands.

A majority of the thinning studies in upland hardwoods (including southern Appalachian stands) have been relegated to the more productive sites. The primary reasons are because these highly productive sites are occupied by higher value timber species, the potential for increased crop growth is high, and the cost-benefit ratio of thinning tends to improve as site quality increases *(Zedaker 1986a)*. There is a general lack of research in low to medium quality Appalachian hardwood stands of sprout origin and further investigation of management techniques for these sites is warranted.

Research priorities of these lower quality hardwood stands should include not only growth response after various thinning techniques, but also the economic impacts. Economic analysis of forest vegetation control methods is needed to guide forest managers in management decisions concerning the selection of control techniques *(Kuch 1985)*. Unfortunately, adequate data for estimating costs and benefits only exist for a few vegetative management control options. Without adequate cost-benefit data, future forest management decisions will likely be highly variable and often in error. Before one decides to invest in precommercial treatments of sapling-aged hardwood stands, the following questions need to be addressed *(Miller 1986)*:

1. What is gained by the application of cultural treatments in young stands?
2. What is the financial return on investment of precommercial cultural treatments?
3. Are cultural treatments economical in young hardwood stands?

The objective of precommercial thinning is to control stand density and to redistribute the growth to the more desirable (higher value) stems. Advantages to precommercial thinning are increased diameter growth, improved species composition, and improved tree quality *(Miller 1986)*. There is a negative relationship between the number of sprouts per clump and their individual growth rates, therefore, residual oak stems within clumps should respond to thinning with increased height, diameter, and volume growth *(Stroempl 1984)*. Since the method of reproducing hardwood stands in the Southern Appalachians has historically been clearcutting, resulting in stands where trees of sprout-origin predominate, applying a cultural treatment like precommercial thinning may be a viable alternative.

Lamson (1988) studied manual precommercial thinning of seven- to twelve-year-old upland hardwood stump sprout clumps in West Virginia. The height growth of residual stems was not affected but, diameter growth response was significant and survival increased. Similar results were reported in another study where eight- to twelve-year-old hardwood crop trees of seedling-origin were released from competing trees using glyphosate injected basally *(Wendel and Lamson 1987)*. In addition, the thinned crop-trees exhibited less crown-class retrogression than did the unreleased crop trees. Apparently, whether studies are concerned with the control of interspecific or intraspecific competition in hardwood stands, the results are similar in that there is a positive response in growth of the residual stems when released or thinned.

Miller (1986) performed an economic analysis of precommercial treatments on young Appalachian hardwood stands. He stated that in hardwood stands of 10 to 20 years of age a precommercial thinning could result in a significant increase in diameter growth, but, the response may be short-lived. Thinned trees grow faster than unthinned trees for a maximum period of 10 years, after which, the crop-trees in the thinned stands grow at about the same rate as the unthinned crop-trees. Therefore, the advantage of the precommercial thinning on growth is the slight increase in average diameter of the future crop-trees. In one example by Miller, a 4 percent real rate of return ($356/ha) could be realized at harvest if a diameter increase averaged 2.5 cm with no increase in log grade. This example also assumed that the precommercial thinning was the only thinning performed (@ $74/ha cost) and the 4 percent rate of return was based on a $75 per thousand board feet (Mbf) stumpage price with no *real* increase over a 40 year investment period. The 4 percent real rate of return is equal to a 9 percent annual market rate under a 5 percent annual rate of inflation.

A decisive cost comparison study for manual versus chemical thinning was conducted by *Miller (1984)*. Miller investigated the costs of releasing yellow-poplar (*Liriodendron tulipifera*, L.) and black cherry (*Prunus serotina*, Ehrh.) crop trees (of seedling origin) using manual and chemical methods. The methods used were chainsaw felling, basal stem injection (basal injector), and basal spray to runoff (backpack sprayer). *Miller (1984)* reported that chainsaw felling costs less to apply than the chemical release methods. The per hectare costs ranged from $69-$111 ($28-$45 per acre) for chainsaw, $94-$149 ($38-$60 per acre) for stem injection, and $116-$185 ($47-$75 per acre) for basal spray. The total cost was based on labor, production, and equipment costs. Included in labor costs were application time, time in selecting trees, and time for refilling during herbicide application. Production cost was based on the number of stems treated per man-hour. The production rates were 260 stems per hour, 204 stems per hour, and 309 stems per hour for chainsaw, injection, and basal treatments respectively

One difficulty with these results is that down-time or unproductive time due to equipment failure was not indicated to be included in labor cost. Also, the basal injection method and the basal spray to runoff method are both the least productive methods for that type of application. Using a

Hypo-hatchet® for injection and a banding of the stem (similar to streamlining) with a basal sprayer would have been more productive. *Wiltrout (1976)* reported that 20 percent fewer injections were needed at breast height versus basal height thus resulting in a 65 percent increase in productivity and less chemical used. In regards to basal banding, *Zedaker (1986b)* reported that basal band applications require less time and chemical than the conventional basal spray method to runoff. Therefore, in Miller's study, if down-time labor cost and equipment repair cost were included and, if the chemical treatments were applied more efficiently, the cost of the chemical application may have been more competitive with the chainsaw felling. *Miller (1984)* also stated that a major advantage to chainsaw felling over chemical stem treatment was that all unwanted stems would be eliminated, whereas, chemical thinning would result in missed trees. One would more likely attribute the numbers of trees missed in a thinning operation to the relative experience of the laborers, the size of the crew, inadequate supervision, and the density of the stand being thinned rather than the technique being used.

A more significant factor to consider, over applicator error, is ease of application and safety. Herbicide application techniques and safety precautions can be taught in a relatively short period of time. Individual stem treatments can be applied safely and easily. In contrast, chainsaw felling may require many hours of instruction in technique and safe procedures, depending on the personnel involved. Even with extensive instruction, chainsaw felling is more physically demanding and a more dangerous alternative to the chemical treatment of individual stems *(Walstad and Kuch 1987)*.

Chemical thinning is also not without drawbacks. One such problem is the potential of delayed release affects. If the treated stems are not killed immediately, the time it takes for them to die (possibly 2 or 3 years) may cause a delay in growth response of the crop-tree. Related to the delayed mortality problem is the possibility of secondary causes of sprout mortality associated with herbicide treatment, namely insects and disease, infesting crop-stems. Because the treated stems may not be completely dead, organisms that thrive on living tissue can infect the weakened sprouts and via the root system infect the crop-stem. Infection by these organisms is not a problem with cut sprouts because organisms that infect the remaining stubs are saprophytic not parasitic. Lastly, one other possible drawback is the possibility of translocation of the herbicide into the residual crop-stem via the treated sprouts. All of these potential problems are long-term in nature and need to be researched. Therefore, the need for information concerning manual and chemical thinning of oak stump-sprouts on less than optimal sites, is justified for the following reasons:

1. The general lack of research concerning precommercial thinning of naturally regenerated oak sprouts, whether by chemical or manual methods, on low to medium sites.
2. Precommercial thinning of hardwood sprout-clumps results in increased diameter growth of the residual stems over unthinned, and encourages healthier stems and better growth form.
3. There is a good possibility that chemical thinning has greater benefits than chainsaw felling (eg. lower application costs as a result of increased production rates and, possible decreasing chemical costs over time).
4. Stump sprouts can be treated more safely using stem applied chemicals.

The present study involves manual and chemical thinning of clumps of mixed-oak sprouts with the purpose of releasing a dominant oak sprout within a clump to facilitate increased individual stem growth and development. The goal of this study was to evaluate several methods of thinning that will produce high quality dominant oak trees on low to medium quality sites.

The specific objectives of this study were:

1. To compare the residual stem growth of oak sprouts after thinning via chainsaw felling and chemical thinning (using two herbicides applied by basal bark spray and stem injection methods) for the purpose of releasing a dominant sprout from a common root stock.

2. To compare the treatment costs between thinning methods (manual vs chemical and basal vs injection), using production rates, chemical costs, and labor costs.

Chapter II : Literature Review

Precommercial Thinning of Hardwoods

Clearcutting has been the most widely used method of regeneration in Appalachian upland hardwood stands. Regenerating hardwoods in this manner results in at least one-third of the basal area being of stump-sprout origin *(Lamson 1988)*. Results from a clearcut regeneration study by *Ross and others (1986)* showed that mixed oak regeneration from stump-sprouts accounted for 3.0 to 43.6 percent of stem density in stands ranging from mixed hardwood to mixed oak-pine stands three years after harvest. Natural hardwood regeneration, while usually sufficient to provide a future stand, is most often overstocked. Two years after clearcutting there may be 75,000 or more hardwood stems (of various origin) per hectare. Once the site is fully occupied by these seedlings natural competition is the main factor in stocking reduction. By age 10, there may be 12,000 to 15,000 stems per hectare remaining and by rotation age 600 to 1000 trees per hectare may survive of which many are often unwanted species and poor quality stems of desired species *(Brenneman 1983)*.

Hardwood stands of sprout-origin are generally poorly spaced and the stems exhibit poorer natural pruning. In addition, these stands usually have a mixture of species which vary greatly in potential economic value. Another problem in sprout-origin stands is the probability of heartwood rot infecting the stump-sprouts *(Carvell 1983)*. Therefore, a precommercial thinning and weeding at an early age for the purpose of releasing the more valuable crop stems will likely stimulate growth, ensure survival, and alter species composition in the direction of the desired species *(Carvell 1983, Lamson and Smith 1987).*

Many studies suggest that most hardwood species will respond to release with increased diameter growth. Precommercial thinning of hardwood stands which release crop-trees can promote higher value by concentrating growth on the more valuable stems *(Lamson and Smith 1987).* This principle pertains to hardwoods of both seedling- origin and sprout-origin and to both sapling- and pole-sized stands *(Lamson 1988, Stroempl 1984).* Responses to thinning are influenced by species, site quality, stand age, and the intensity of the thinning. Some tree species respond to thinning better than others which, is influenced by the particular species shade tolerance coupled with the intensity of the thinning. Thinning responses tend to be greater on higher quality sites and also when applied at younger ages (sapling or pole size) when the growth rate is greater. Growth rates are influenced by species, age, crown class, crown vigor, and the amount of open space for crown expansion *(Erdmann 1987, Lamson and Smith 1987)* .

A thinning study on sapling and pole red oak showed that there was an average increase in diameter growth of 5.8 cm over unthinned trees 10 years after treatment *(Hilt 1979). Lamson (1983)* reported that five years after thinning 12-year-old mixed upland hardwoods the average diameter growth was 4.6 cm for thinned stems (3.3 cm for the oaks) and 3.3 cm for the unthinned stems (2.8 cm for the oaks). *Dierauf (1986)* reported an average annual diameter increment of 0.56 cm after 15 years on thinned chestnut, scarlet, and black oaks of pole-size which was twice that of the unthinned trees.

Precommercial Thinning Strategies

The primary objective in precommercial cultural practices is to release the more desirable trees, thereby, redistributing the stand growth onto more valuable stems. In crop-tree release, selection of dominant and codominant trees is accomplished by removing adjacent competitors thereby, stimulating crop-tree growth and ensuring survival *(Lamson and Smith 1987)*. Three reasons exist for applying precommercial treatments:

1. To increase the growth of residual trees for the purpose of shortening the rotation length or to increase diameter at final harvest.
2. To increase potential stand value and encourage the development of high-quality stock by eliminating the poorer quality and undesirable trees.
3. To improve or maintain the species composition.

Lamson (1988) stated there are additional reasons for thinning hardwood sprout clumps other than to increase diameter growth. First, stem quality can be improved by removing sprouts with excessive sweep and low forks. Secondly, there is a reduction in the chances for butt rot developing from dying overtopped sprouts. Thirdly, survival can be increased by reducing the number of high origin sprouts and the potential for stem crown-class retrogression.

Crop-Tree Selection and Release Guidelines

The following guidelines have been recommended field procedures for selecting and releasing crop trees in young hardwood stands *(Lamson 1988, Lamson and Smith 1987, Stroempl 1984)*:

1. Select high-quality, vigorous crop trees of desirable species that occur in dominant and codominant crown positions.
2. Select against trees that are leaning excessively, and against trees with a fork in the butt log.
3. Select crop trees of sprout-origin over seedling-origin trees.
4. When selecting stump sprouts choose sprouts of low origin (below 15 cm) on the uphill side of the stump and when trees are between 5 and 10 cm dbh.
5. Select for one crop stem per clump.

6. Select against leaving more than two crop trees adjacent to each other (different root stocks) when there are an excess of potential crop trees.
7. Release crop trees using the crown-touching method, where any tree in a dominant or codominant position is removed if the crown is in contact with the crown of the crop tree.
8. Release 180 to 250 crop-trees per hectare. Release closer to 250 per hectare when compensating for unexpected mortality and later periodic thinnings.
9. Wait until the stands are 10 to 15 years old depending on site quality, or until the codominants reach 7 to 8 meters in total height.

The rational associated with the crop-tree selection guidelines are as follows:

Selecting codominants and dominants for crop-tree release is preferred because of their vigorous growth habit and well developed crowns. Selecting vigorous crop-trees without disease, deformities, or excessive leaning fulfills the basic objective of precommercial thinning. This basic objective is to redistribute the growth to the stems that will respond the greatest from release in terms of increased diameter growth and log grade *(Lamson and Smith 1987)*. Sprout-origin crop-trees are selected over seedling-origin trees on the basis that sprout-origin trees grow faster and for the potential of decay spreading from a parent stump to the seedling-origin tree *(Johnson and Godman 1983)*. Choosing sprouts of low stump origin over high origin sprouts is recommended to lessen the probability of decay and breaking-off of the sprout from the stump *(Roth and Hepting 1943a and, Roth and Hepting 1943b.)*. Selecting one crop-tree over two reduces direct competition for resources and enhances vigor, which in-turn, reduces the probability of mortality due to infestations of insects and disease. Lastly, when there is an excess of potential crop-trees, leave no more than two adjacent to each other (from different root stocks) for the reason that some good trees must be removed in order to redistribute the growth to the better trees *(Lamson and Smith 1987)*.

The rational associated with the crop-tree release guidelines are as follows:

Releasing crop-trees by the crown-touching method involves removing adjacent competing dominants and codominants that have crowns overlapping or intermeshed with the crowns of the preselected crop-trees. This thinning method is used because the greatest crop-tree response results from the removal of dominants and codominants competing for space and light *(Lamson and Smith 1987)*. Determining the number of crop-trees to release is related to the availability of good crop-trees and the cost involved. Generally, in managed northern hardwood stands it is unnecessary to release more than 180 to 250 crop-trees per hectare because usually about 120 dominant and codominant trees per hectare are present at maturity *(Erdmann 1983)*. Timing of the first thinning is governed by when the potential crop-trees begin to express dominance. *Smith and Lamson (1983)* recommended for Appalachian hardwood stands, to thin first when the codominants have attained approximately 7 to 8 meters in height. Depending on species and site quality, 7 to 8 meters in height corresponds to a stand age of about 10- to 15-years old.

Economics of Precommercial Thinning

Precommercial thinning in immature Appalachian hardwood stands can be a worthwhile investment. The greatest return on investment will undoubtedly come from stands containing high-value species on high quality sites. Research has shown that increases in diameter growth following precommercial thinning are limited and short-lived *(Miller 1986)*. Therefore, for a given growth response, the increase in stand value depends on the future value of crop-trees at final harvest. In addition to increasing diameter growth, early crop tree release can improve species composition, tree quality, and log grade. The improvements in tree and log quality can increase future harvest revenues *(Miller 1986, Schick 1986)* The key to successful cultural treatments of immature stands is to maintain an accelerated increase in value while keeping costs to a minimum *(Lamson and Smith 1987)*. Therefore, managing for high -value products (veneer and sawlog) is needed to justify a precommercial thinning.

In an economic analysis by *Miller (1986)*, it was assumed that one precommercial treatment in Appalachian hardwood stands would result in an increase in diameter of 2.5 cm. Using maximum allowable cost/unit area as a guideline, managers can decide whether a precommercial thinning is justified. In Table 1 maximum allowable costs are given for a range of investment periods and stumpage prices, assuming a 4 percent real rate of return (no allowances for inflation) and a 2.5 cm diameter increase at harvest *(adapted from Miller 1986)*. For example, it would be affordable to spend $225/ha on a precommercial thinning if the average stumpage price was $100/thousand board feet (Mbf) and the investment period was 20 years. Although, if the investment period is 50 years, the maximum allowable cost is only $69/ha.

From the literature reviewed concerning increased diameter growth after thinning, a 2.5 cm increase in diameter at harvest is an estimated average which may be conservative depending on site quality and crop-tree species. *Hilt (1979)* reported a 5.8 cm diameter increase over unthinned trees after 10 years, *Lamson (1983)* reported a 1.3 cm diameter increase after five years and, *Dierauf (1986)* reported a 4.2 cm diameter increase 15 years after thinning. Also, not accounting for an increase in value due to probable increases in log grade *(Lamson 1988)* may result in a conservative estimate of return on investment. This evidence suggests that precommercial thinning can provide competitive rates of return in immature hardwood stands if they are managed for high-value products like veneer and sawtimber.

Table 1. Maximum allowable precommercial thinning cost using a 4 percent real rate of return (Adapted from Miller 1986).

Current stumpage price of future crop trees	Maximum gain in stand volume [2]	Maximum gain in stand value [3]	Maximum allowable [1] precommercial thinning cost by investment period -------------- Years -------------- 20	30	40	50
($/Mbf) [4]	(Mbf/ha)	($/ha)	--------------- ($/ha) ---------------			
50	4.9	245	114	76	52	35
75	4.9	367	168	114	76	52
100	4.9	490	225	153	104	69
125	4.9	612	281	190	128	86
150	4.9	735	338	227	153	104

[1] Maximum investment to earn a 4 percent real rate of return.

[2] Assuming a 2.5 cm diameter increase at final harvest on 148 crop-trees per hectare averaging 40.6 cm dbh and, using the International 1/4-inch rule to estimate volumes.

[3] Values calculated by multiplying column 1 values times corresponding column 2 values.

[4] Mbf = thousand board feet.

Herbicide Use

General Properties of Herbicides

The present study uses herbicides as a tool for thinning oak stump sprouts, therefore, a basic knowledge and understanding of the properties of herbicides is needed for selecting the best herbicide to match the intended silvicultural use. Herbicides are classified primarily by chemical structure and mode of action *(Ashton and Crafts 1981)*. The selectivity and translocation of a herbicide is also determined by these same characteristics. Therefore, in order to properly match the herbicide with the intended silvicultural use, knowledge of the general properties of herbicides is useful.

---- *1. Mode of Entry*

Herbicides enter plants differently depending on the physical properties of the chemical, the type of carrier used in application, the season of application, and the characteristics of the plant *(Hatzois and Penner 1982)*. Pathways into the plant by chemicals are through the leaves, stems, or roots. Biochemical properties of the herbicides determine the metabolic process affected once entry into the plant has occurred *(Ashton and Crafts 1981, Cherry 1976)*.

The degree of penetration through the bark and stem was thought to depend on plant vigor and stage of bark development *(Bukovac 1976)* . *Shiue and others (1958)* found that penetration through the bark using 2,4,5-T was primarily via the lenticles. Also, results indicated that movement of 2,4,5-T was primarily in the xylem. Because of the hydrophobic properties of tree bark, basal applications are generally applied with herbicide ester formulations mixed in oil, thereby, increasing penetration *(Bukovac 1976)*. Sometimes a surfactant like Cidekick® is used to enhance penetration. Studies by *Kline (1986)* and *Hendler and others* showed favorable results for stemkill on various hardwoods following streamline applications of triclopyr plus Cidekick® in diesel fuel. Conversely, when stem injection is used, penetrants are unnecessary because the bark has been bypassed by the injection process *(Bukovac 1976, Hamel 1981, Newton and Knight 1981)*. Therefore, herbicides applied by injection are normally amine formulations of herbicides mixed with water or applied undiluted.

Herbicide trial studies using various carriers applied basally yielded significant results. *Warren (1982)* compared triclopyr basal applications mixed with diesel fuel and water in varying amounts (15 to 100 percent). Results indicated that generally, control increased as the percent of diesel fuel in the mixture increased. Results of a basal application study involving nine herbicides diluted in oil, oil plus water plus surfactant, water plus surfactant, and water alone indicated that mixtures with water were ineffective *(Goodfellow and Mider 1981)*. *Zedaker (1986b)* compared dormant season low volume basal applications of triclopyr plus picloram in Asplundh Oil® and kerosene. Results indicated that mixtures with Asplundh Oil® had higher percent mortality than the kerosene treatments. A possible reason given for these results was that the Asplundh Oil® appeared more viscous and may have resulted in applying more mixture to band the stems.

---- *2. Formulations*

Herbicides are formulated both to improve effectiveness in the field and for ease of application. Formulations that are mixtures of different herbicides are often used in woody plant control because they tend to broaden the spectrum of susceptible species and usually result in a greater reduction of total regrowth *(Chappell and Hipkins 1982)*. Physical properties of herbicides are determined either by the active component of the chemical, or by some reaction product that may alter the chemical's original properties *(Brian 1976)*. Some herbicides are applied as the parent compound, whereas, others are applied usually as salts or esters of the parent compound *(Newton and Knight 1981)*.

Herbicides are formulated for application as *(Klingman and Ashton 1982)*:

1. Solutions of water or oil soluble substances
2. Emulsions
3. Wetable powders (flowables or suspendables)
4. Granules

Water-soluble compounds are used for injection, foliage sprays, and soil application. They do not readily penetrate bark or foliage and are often mixed with a surfactant in foliage applications to increase effectiveness *(Klingman and Ashton 1982)*. Oil-soluble liquids and emulsifiable concentrates are made from acids that have been reacted with alcohols or organic bases to form oil-soluble esters or amines. Oil-solubles and esters are not soluble in water. Oil soluble herbicides are widely used in basal bark applications *(Klingman and Ashton 1982)*. Esters and oil-soluble amines are used for basal spray and foliage applications because of their ability to penetrate bark and waxy leaf surfaces. They are usually more expensive than water-soluble amines and other salts. Oil-soluble amines have little volatility, but most oil-soluble herbicides registered for use in forest management are low-volatile esters *(Klingman and Ashton 1982, Newton and Knight 1981)*. Surfactants such as wetting agents, emulsifiers, and stickers are known to increase total kill when added to some herbicides *(Chappell and Hipkins 1982, McLemore and Cain 1988)*. These additives improve the emulsifying, dispersing, spreading, wetting, or other surface modifying properties of liquids. These enhanced properties allow more quantity of the herbicide to enter the target plant, thereby, increasing efficacy.

---- *3. Mechanisms of Action and Translocation*

The specific biological mode of action is not known for some herbicides, but, for most of the important groups used in forestry, the mechanisms are relatively well understood. Classification of modes of action for herbicides are growth regulators, oxidative phosphorylation inhibitors, chlorophyll inhibitors, photosynthetic inhibitors, protein metabolism inhibitors, and mitotic poisons *(Moreland 1967)*.

Translocation of herbicides within the plant is via the symplastic and apoplastic systems. The symplast is the living portion of the stem, primarily the phloem, and the apoplast is the non-living portion, primarily the xylem *(Ashton and Crafts 1981, Kramer and Kozlowski 1979)*. Some herbicides may be translocated primarily in one of these systems but all herbicides are moved in both the symplast and apoplast to some degree *(Crafts 1967)*. The driving force in translocation of herbicides via the apoplast is transpiration. They travel up the stem via the transpiration stream. Turgor or osmotic pressure in the phloem is the driving force in the transport of herbicides via the symplast which is maintained by a source-sink relationship *(Crafts and Crisp 1971, Hay 1976)*. In other words, the herbicides follow the path of the photosynthates in the phloem which are regulated by the osmotic and turgor pressure of the cells which act as a sink.

---- 4. Methods of Application

Herbicides in forestry are applied by many types of equipment in various fashions. Herbicides are applied by helicopter, backpack sprayer, backpack mist blower, tractor-mounted boom sprayer, tractor-mounted mist blower, and by injection. Some of these machines can be used for many types of applications (broadcast, banded, spot, basal, foliar, etc.) and some are constructed for one application method only *(Cantrell 1985)*.

Basal bark treatment is the application of an oil solution to the basal portions of the stem. The chemical is sometimes applied to the point of runoff and is usually applied around the entire lower portion of the stem (15 to 30 cm up from base). Basal bark applications work best on stems between 2 and 25 cm dbh while the bark is relatively thin *(Bovey 1977, Cantrell 1985, Newton and Knight 1981, Zedaker 1986a)*. Basal and stem treatment utilize the ability of the oil carrier to penetrate bark, thereby, allowing the chemical to enter the vascular system of the tree *(Klingman and Ashton 1982)* . Dosage is controlled by calibrating the basal sprayer.

Low-volume basal herbicide application is increasing in acceptance as an alternative to conventional basal application which wastes chemical by applying to runoff. Low-volume basal treatment uses a 20 to 30 percent herbicide concentration in an oil carrier applied to encircle the lower portion of the stem without runoff. *Melichar and others (1987), and Melichar and Waggoner (1988)*, conducted studies using the low-volume technique applying triclopyr and picloram alone and in combination at various concentrations with kerosene and Arborchem Basal Oil® on many upland hardwood species including oaks, black locust, and red maple. Results showed that at least 85 percent control occurred for each treatment on most species and, that mixtures of triclopyr plus picloram exhibited slightly higher efficacies as compared to triclopyr alone.

Basal applications performed at various times of the year have shown differing results. Growing and dormant season thinline and conventional basal applications trials using triclopyr undiluted and mixed in oil (1:1) both exhibited good control, but, greater control was reported after growing season applications on a variety of hardwood species *(Melichar et al. 1986)*. *Burch and others (1987)* reported better efficacy with the dormant season streamline applications of triclopyr. Possible explanations given for the lower efficacies were interception of the herbicide mix by non-target plants and worker fatigue during the growing season applications. One would expect higher efficacies for growing season applications because there is more movement within the stems due to transpiration and photosynthesis. A study by *Dewey and Appleby (1983)* found that labeled glyphosate applied to tall morningglory (*Ipomoea purpurea*, (L.) Roth) moved to meristematic tissue in similar proportion to labeled assimilates. Therefore, if herbicide movement parallels assimilate translocation, one would expect more herbicide to move to the roots after late summer early fall applications whereas, more herbicide would be expected to move upward after spring applications. Although, movement of herbicide upward in the xylem during the growing season due to transpiration may overshadow any movement in the phloem, as reported by *Yamaguchi and Crafts (1959)*.

Stem injection entails applying the herbicide via a basal injector, a hatchet-type injector, or a hack-and-squirt method performed with an ax and a squirt bottle. Dosage in stem injection is controlled by calibrating the injector and the spacing of the cuts *(Newton and Knight 1981)*. Herbicides formulated for injection are used either diluted with water or undiluted at approximately 1 ml per injection or per cut on hardwoods between 5.0 cm and 30.5 cm dbh *(Cantrell 1985, Zedaker 1986a)*.

Tree injection treatments can be applied at any time of year, but matching the correct herbicide with the season of application may be very important *(Cantrell 1985, Hamel 1981)*. An example of a correct match of a herbicide with the season would be to apply a herbicide that translocates primarily in the symplast late in the growing season when primary movement of starches and carbohydrates are downward to the roots for storage. *Sterrett (1969)* studied stem injections of 2,4-D, picloram, and dicamba applied to various species of oaks across seasons. Results indicated that chestnut oak averaged 64 and 68 percent topkill after growing season and dormant season applications, respectively. In comparison, scarlet oak and white oak exhibited an average topkill of 95 and 97 percent after growing season and dormant season applications, respectively.

When managing immature hardwood stands herbicide selectivity is primarily dependent on placement, therefore, broadcast methods of application would not be feasible. Individual stem treatment including basal spray, stem injection, and stump treatment would be best to use *(Zedaker 1986a)*. Since the present study involves managing immature hardwoods by precommercial thinning of oak stump-sprouts, basal bark spraying and stem injection methods were chosen for the chemical application methods. A disadvantage to stem applications is that they are labor intensive, which results in a major portion of the treatment costs attributed to labor and supervision. Other drawbacks to using stem applied herbicides are the problems with the direction of translocation within the treated stem which may be correlated with season of application and species susceptibility.

---- 5. *Silvicultural Uses*

Herbicides are registered for many silvicultural uses in forestry such as site preparation, pine release, timber stand improvement (TSI), pine and hardwood control *(Cantrell 1985, Nelson et al. 1983)* . Because of the properties of herbicides used in forestry their silvicultural uses are limited for managing hardwood stands. Currently there are no herbicides labeled that are selective enough to eliminate the unwanted hardwoods while leaving the hardwood crop-tree species when applied as a broadcast treatment *(Zedaker 1986a)*. However, basal sprays and stem injection techniques may be used by both forest industry and small private landowners for managing young hardwood stands.

Basal bark applications of various herbicides and formulations to young hardwoods in two studies showed promising results. The results of a study by *McLemore and Cain (1988)*, using several herbicide combinations applied as a basal spray on the lower stem of various hardwood species, reported a 56 percent topkill for 10.2 cm to 17.8 cm trees, and a 77 percent topkill for 2.5 cm to 7.6 cm trees. A report by *Kline and Hern (1985)*, summarizing herbicide studies in the Southeast, showed an average stem kill of 75 percent for chestnut oak and 74 percent for southern red oak when applied basally to the lower stem.

Studies involving stem injection showed even better results than the basal sprays. A study by *McLemore (1986)* using a basal injector and testing 8 chemicals showed 90 percent topkill for various oaks ranging from 2.5 cm to 38.1 cm dbh using undiluted chemical and 63 percent topkill using a 50 percent dilution. Another study by *Peevy (1968)* gave results of an average of 97 percent topkill of various oaks using a Hypo-hatchet® and undiluted chemical. The results of a study by *Kossuth and others (1980)* showed topkill to oaks by 2,4-D and triclopyr injection to average 98 and 100 percent, respectively.

Streamline basal application is a relatively new technique. The method involves applying herbicide mix via a backpack sprayer utilizing various nozzles like Multijet or Conejet nozzle types *(Zedaker 1986b)*. The herbicide mix (20% to 30% concentration in oil) is usually applied from a distance of about 0.5 meters to 2 meters from the stem using enough herbicide mix to wet one side of the stem for 2 to 5 cm dbh trees and both sides of the stem for larger trees *(Hendler et al. 1987)*. Cost analysis on streamlining triclopyr ester in diesel fuel (20% concentration) for releasing pines from hardwood competition was performed in separate studies by *Brewer and others (1987) and Kline (1986)*. Both studies reported average total costs (labor, supervision, and chemical costs) to range from $30 to $100 per hectare ($12 to $41/ac). *Schutzman and Kidd (1987)* reported only chemical costs for a streamlining study to range from $37 to $47 per hectare.

It was decided through a rigorous selection criteria, discussed in the Procedures chapter, that 2,4-D and triclopyr would be used for chemical thinning of the oak sprouts in the present study. Therefore, the remaining literature reviewed emphasizes the characteristics of those herbicides and any research studies involving those herbicides that relate to the present study.

Properties of 2,4-D

2,4-D (2,4-dichlorophenoxyacetic acid) is classified as a phenoxyalkane carboxylic acid (phenoxy) herbicide *(Brian 1976)* . All phenoxy herbicides are known as synthetic growth regulators or auxin-like compounds *(Anderson 1983, Ashton and Crafts 1981, Brian 1976, Crafts 1967, Klingman and Ashton 1982, Kramer and Kozlowski 1979, Newton and Knight 1981)*. 2,4-D has been on the market since 1945 and has been widely used in forestry *(Cartwright 1976)*.

The phenoxys are translocated herbicides that are absorbed through the foliage or bark and moved somewhere to a site of activity. Translocation of the phenoxys is usually to the growing tips, with some deposited in the cambium, roots,and storage tissues *(Ashton and Crafts 1981, Newton and*

Knight 1981, Que Hee and Sutherland 1981, Worthing 1987). The phenoxy herbicides induce several abnormalities in plant growth and structure. They cause dedifferentiation and initiation of cell division in certain mature cells and inhibit cell division in primary meristematic regions *(Cartwright 1976, Kaufman 1955, Hanson and Slife 1969).*

Differential responses of plants to 2,4-D may occur due to different concentrations of the auxin at the cellular level resulting in low levels stimulating growth and high levels inhibiting growth *(Cartwright 1976, Penner and Ashton 1966).* In addition, ethylene production has been shown to be stimulated by application of 2,4-D; however, *Abeles (1968)* concluded that ethylene alone probably does not account for the herbicidal activity since the application of the gas was not responsible for the death of plants tested.

Mechanisms of action of 2,4-D on plants involve primarily two processes, nucleic acid metabolism and cell-wall plasticity *(Hanson and Slife 1969).* Metabolism of 2,4-D in plants is primarily by hydroxylation, decarboxylation, cleavage of the acid side chain, joining of amino acids with the acid side chain, and combining with glucose at the hydroxylated positions *(Mumma and Hamilton 1976).* Low levels of 2,4-D stimulate the production of RNA, protein synthesis, and cell wall enlargement, whereas, high levels act the opposite in that they inhibit these processes *(Robertson and Kirkwood 1970).* These complex reactions are initiated by the depression of the gene regulating the RNAase synthesis. This discovery lead to the conclusion that the RNA and proteins migrate to the stem tissue resulting in disruption of transpiration and translocation which results in assimilate accumulation in the stem and leads to starvation of the roots *(Robertson and Kirkwood 1970).*

Herbicide formulation and environmental factors influence the rate of absorption of 2,4-D through the leaves, roots, and stem. The rate of penetration and translocation of 2,4-D may also play a role in the determination of selectivity in certain species. The degree of response has been correlated with the concentration of the herbicide present in the cells *(Penner and Ashton 1966).* Low concentrations may stimulate a response, whereas, high concentrations of the same herbicide may produce an opposite response. Therefore, a differential response between 2,4-D resistant and susceptible plants may only be a reflection of the different internal concentrations of the herbicide *(Penner and Ashton 1966)*. These differences in internal concentrations of 2,4-D between resistant and susceptible plants may be a direct result of the more rapid rate of detoxification in the resistant plants.

Robertson and Kirkwood (1970) stated that the mechanism controlling herbicide movement to different parts of the plant is influenced by the efficiency of photosynthesis, the growth rate of the plant, and the source-sink relationship. 2,4-D is translocated from the leaves via the phloem to the stem and the roots. The concentration in the stem vascular parenchyma reaches a level which cause the parenchyma to become meristematic. This meristematic activity creates a metabolic sink in the stem which accounts for the altered protein, amino acid, phosphorus, and vitamin content in the stem at the expense of the leaves *(Penner and Ashton 1966, Robertson and Kirkwood 1970)*.

Even though much is known about translocation of 2,4-D from leaves and roots, transportation after penetration through the bark into the stem is not well understood *(Crafts and Crisp 1971, Robertson and Kirkwood 1970)*. There is evidence that stem applied phenoxy herbicides may move from phloem to xylem within the stem and subsequently carried in the transpiration stream to the leaves. *Crafts and Crisp (1971)* concluded that this atypical distribution may result from high concentrations of the herbicide in cells which increases permeability of the phloem.

General uses and formulations of 2,4-D are many and diverse. General herbicidal uses are for control of broadleaf weeds in cereal crops, sugarcane, turf, pastures, and noncrop land. Labeled forestry uses include site preparation and release. Methods of application include cut-surface, foliar spray, and basal bark spray. Basic formulations available for 2,4-D are water soluble amine salts, oil-soluble amine salts, low-volatile esters, invert esters, and acid esters *(Hartley and Kidd 1989, Humburg 1989, Worthing 1987)*. A summary of the specific properties of 2,4-D is included in Appendix A.

Many basal and injection studies using 2,4-D have been performed and their results have been used to determine suggested formulations, rates of application, and application methods for various silvicultural prescriptions. One such study was a brush control study on the grazing lands of Oklahoma where 2,4-D ester applied basally to the stems of post oak and blackjack oak (*Q. marilandica* Muenchh.) *(Elwell 1964)*. The results showed that 2,4-D applied as a 5 percent solution in fuel oil caused a 50 percent stemkill, whereas, 2,4-D applied as a 10 percent solution in fuel oil resulted in a 90 percent stemkill. Basal spray and basal injection applications of 2,4-D ester on scrub oaks (*Quercus* spp.) were compared by *Kirby and others (1967)* on the rangelands of eastern Oklahoma. 2,4-D applied as a 4 percent solution in fuel oil by the basal spray method, gave 31 percent defoliation compared to 100 percent defoliation using a basal injection of 2,4-D as a 10 percent solution in fuel oil.

Peevy (1968, 1972) reported on the use of stem injection of 2,4-D amine (undiluted) for controlling upland hardwoods in the South. Results showed that percent stemkill ranged from 21 percent for red maple to 98 percent for various upland oaks. In another stem injection study 2,4-D was tested along with three other herbicides (triclopyr, picloram, and glyphosate) on mixed southern hardwoods in central Louisiana *(Campbell 1985)*. The herbicides were injected basally at 12.7 cm spacings around 2.5- to 30.5-cm dbh stems at a rate of 1 ml (undiluted) per injection. Results of the 2,4-D injection showed that for all species treated topkill averaged 80 percent, but for the oaks (*Quercus stellata, Q. falcata*), topkill averaged 90 percent. Because of the wide range in stemkill indicated by these two studies, it would appear that the decision to use 2,4-D injected as a diluted or undiluted solution depends on the species to be treated and the management objectives.

Properties of Triclopyr

Triclopyr ([(3,5,6-trichloro-2-pyridinyl)oxy]acetic acid) is a synthetic growth-regulator (auxin type) broad-spectrum translocated herbicide. Since it is an auxin-type herbicide, the effects are similar to 2,4-D, although, triclopyr is regarded as superior in controlling root-sprouting species *(Anderson 1983)*. The metabolic action of triclopyr is not fully understood, but it is thought to be similar to phenoxys. This would indicate that triclopyr absorbs through all tissue, translocates via apoplast and symplast, and accumulates in meristematic tissue *(Humburg 1989, Klingman and Ashton 1982)*. *Gorrell and others (1988)* reported that triclopyr was found to increase in the roots over time following foliar applications to horsenettle (*Solanum carolinense*, L.). Basal applications of triclopyr can be expected to move similarly in the phloem following the movement of photosynthates.

Triclopyr is manufactured by DowElanco and labeled as Garlon 3A® and Garlon 4®, which are liquid formulations. Garlon 3A® (amine formulation) and Garlon 4® (ester formulation) have been on the market since 1980 and have been widely used in forestry applications. Triclopyr is labeled by the EPA for applications including foliar, cut surface, and dormant stem. Average soil persistence for triclopyr is slightly higher than 2,4-D (46 days vs 1 month) *(Hartley and Kidd 1989, Humburg 1989, Kline and Hern 1985, Worthing 1987)*. A summary of the specific properties of triclopyr is included in Appendix A.

Garlon 3A® is labeled for foliar, stump, frill or girdle treatments as well as injection. Garlon 4® is labeled for foliar, basal bark, thinline basal bark, and dormant stem treatments. Both formulations can be used for control of woody plants and broadleaf weeds on rights-of-way, industrial sites, non-crop areas, and in forest site preparation. Both formulations can be applied by high volume or low volume ground equipment, or by helicopter *(Cantrell 1985, Kline and Hern 1985, Newton and Knight 1981)*.

The optimum rate of Garlon 4® suggested in a report by *Kline and Hern (1985)* was determined to be a 10 to 30 percent solution when applied as a low volume basal spray in diesel fuel. Data used in formulating use recommendations came from numerous herbicide test studies in the South applied to various southern hardwood species. This particular recommendation was based on dormant basal applications of triclopyr mixtures with diesel fuel ranging from 2 to 50 percent. Little difference in percent stemkill was found to exist between mix concentrations, therefore, application logistics governed the recommendation. The 2 to 4 percent mixtures were said to be slow in application because of the need to wet the bark to runoff. The high concentrations of triclopyr were suggested to be too viscous for ease of application and resulted in wasted chemical *(Kline and Hern 1985)*. These triclopyr concentration recommendations also agree with results from a herbicide test study conducted on the Crossett Experimental Forest, Arkansas by *McLemore and Cain (1988)*. The results showed that treated mixed hardwoods with triclopyr in a 20 percent solution in diesel fuel exhibited 100 percent topkills.

Streamlining, another method of basal application, has been widely tested for many species in recent years. One such study using streamline applications of triclopyr using a 2 ml dose per stem at 5 to 40 percent concentrations resulted in a percent crown reduction of 17 to 70 percent, respectively *(Yeiser and Boyd 1989)*. Another streamlining application study using a 20 percent concentration of triclopyr ester in diesel fuel (5 ml dose/stem) resulted in an 80 percent or greater control for all species tested *(Schutzman and Kidd 1987)*.

Directed foliar sprays and thinline basal treatments were performed in another study in Alabama with six different herbicides including triclopyr *(Miller 1988)*. The thinline treatments tested triclopyr alone using concentrations ranging from 10 to 50 percent and applied to 27 tree species less than 15 cm inches dbh. Some of the species included post oak, southern red oak, hickory (*Carya* spp.), blackgum (*Nyssa sylvatica*, Marsh) and black cherry. Results showed that all species tested had a 70 to 80 percent height growth reduction after two growing seasons. Also, for most species, control was found to increase with application rate. The 30 percent triclopyr solution in diesel fuel resulted in a 75 percent height growth reduction for most of the hardwood species treated.

A stem injection study involving triclopyr and picloram in diluted and undiluted solutions applied to 10.2- to 55.9-cm dbh tanoak (*Lithocarpus densiflorus*, (Hook. & Arn.) Rehd.) and black oak in Douglas-fir (*Pseudotsuga menziesii*, (Mirb.) Franco) and coast redwood (*Sequoia sempervirens*, (D.Don) Endl.) stands was reported by *Warren (1980)*. Results showed that triclopyr applied either diluted (1:1) or undiluted controlled an average of 94 percent of the stems with no observable effects on the conifers. *Campbell (1985)* conducted a stem injection study on mixed southern hardwoods (including post oak and southern red oak) using triclopyr as well as other herbicides (picloram, 2,4-D, and others) in central Louisiana. The herbicides were injected basally at 12.7 cm spacings around 2.5- to 30.5-cm dbh stems at a rate of 1 ml (undiluted) per injection. Triclopyr performed the best with an average of 93 percent topkill for all species and for the oaks alone. Therefore, to meet the objectives of the present study, an application of triclopyr to oak stems would appear to be an appropriate choice.

Properties of Kerosene

Kerosene is a colorless, light oil (hydrocarbon mixture) with a density less than water. Usually, kerosene is fractionally distilled from petroleum but, can also be obtained from coal and oil shale. Presently, the primary uses of kerosene are as a carrier for pesticides and as a fuel component in jet engines *(Levey and Greenhall 1983)*.

Several fractions of petroleum have been found to be carcinogenic to animals. Most fuel oil fractions, including kerosene and diesel fuel, are either not considered carcinogenic or only marginally *(Bingham et al. 1980)* In one particular study on petroleum distillates, kerosene was shown to adversely effect the kidneys of mice following chronic dermal applications *(Easley et al. 1982)*.

Kerosene is the recommended carrier for ester formulations of both 2,4-D and triclopyr. Kerosene has a low viscosity and surface tension which allows entry through the bark more readily than heavier oils. Kerosene is somewhat phytotoxic but is not normally used in weed control because it is highly refined, which results in a high volatility and because kerosene has been found to be environmentally toxic *(Klingman and Ashton 1982)*.

It is believed that oils move primarily through the intercellular spaces and may move in any direction, either up, down, radially, or tangentially *(Minshall and Helson 1949)*. Since kerosene can readily enter the bark and has a relatively low phytotoxic effect, the smaller diameter treated stems may exhibit significant effects. Therefore, kerosene applied basally to hardwood stems may prove to be sufficiently phytotoxic for the objectives of the present study.

Chapter III : Procedures

Study Area Description

The study was conducted in the Ridge and Valley physiographic region of Virginia which is characterized by a series of northeast to southwest tending ridges separated by wide valleys. Significant acreage occurs in the low to medium site index range, (10 to 20 meters for upland oaks, base age 50, *Olson 1959*), where poorer quality upland hardwoods dominate. On southeastern exposures at midslope, mixtures of chestnut oak (*Quercus prinus*, L.) and scarlet oak (*Q. coccinea*, Muenchh.) dominate with some black oak (*Q. velutina*, Lam.) mixed in. The drier south-southwest slopes have increasing numbers of pines while the oaks decrease in number *(Blount et al. 1986, Ross et al. 1986)*. The present study was restricted to sites where chestnut oak and scarlet oak dominate as naturally regenerated sprout-clumps.

Chestnut oak is a vigorous sprouter which, in some areas, constitutes 75 percent of all reproduction *(Core 1971)*. Chestnut oak dominates on the broader sideslopes where it exhibits faster growth and greater number of sprouts per stump *(Ross et al. 1986)*. Scarlet oak is also a vigorous sprouter and, in combination with black oak, dominates on the more protected slopes and coves *(Ross et al. 1986)*. Even though black oak generally exhibits faster growth than both chestnut and scarlet oaks, *(Trimble 1960)*, and sprouts prolifically from small stumps, it cannot survive under a dense canopy. Therefore, black oak generally does not dominate when growing in competition with high densities of chestnut and scarlet oak *(Core 1971, Ross et al. 1986)*.

The study site was located midslope on the southeastern face of Potts Mountain on the New Castle Ranger District of the Jefferson National Forest, Craig County, Virginia. In 1979 a series of small clearcuts (whole-tree harvested) were installed as part of a natural regeneration study. The clearcut area was comprised of four distinct vegetation types which were mixed pine, mixed oak-pine, mixed oak, and mixed hardwood with a site index range of 10 to 22 meters (base age 50 for upland oaks), *(Blount et al. 1986).* Study site elevations range from 770 meters to 800 meters and the slope ranges from 20 to 65 percent. Soil parent materials are nutrient poor shales and sandstones which usually result in coarse-textured, shallow, and strongly leached soils. Soil classification is Typic Hapludult; clayey-skeletal, mixed, mesic with no known soil series *(Morin 1978).* Annual precipitation averages 96.5 cm and is mostly even in distribution. The sample stands for this study are characterized as the mixed-oak forest type with chestnut oak and scarlet oak being the dominant oaks in the overstory. The site index averaged 20 meters (base age 50 for upland oaks) with a range of 19 to 22 meters. A map of the study area is depicted in Figure 1.

A sample survey performed prior to treatment indicated that the oak stumps with living sprouts averaged about 490 per hectare with about 245 per hectare had two or more sprouts per stump. The average diameter at breast height of the dominant oak sprout on rootstocks with two or more sprouts was 7.6 cm. Competing sprouts of those rootstocks averaged 4 stems per stump and 5.0 cm in diameter at breast height.

Also, during the sample survey, associated species composition was noted. Associated overstory hardwood species were red maple, sourwood (*Oxydendrum arboreum*, (L.) DC.), black locust (*Robinia pseudoacacia*, L.), and blackgum (*Nyssa sylvatica*, Marsh.). Associated understory woody species were sassafras (*Sassafras albidum*, (Nutt.) Nees), American chestnut (*Castanea dentata*, (Marsh.) Borkh.), blackgum, mountain laurel (*Kalmia latifolia*, L.), and wild azalea (*Rhododendron nudiflorum*, (L.) Torrey). Other associated vegetation included blueberries (*Vaccinium stamineum, L., V. vacillans*, Torrey), blackberry (*Rubus hispidus*, L.), greenbriar (*Smilax glauca, Walt., S. rotundifolia*, L.), and summer grape (*Vitis aestivalis*, Michx.).

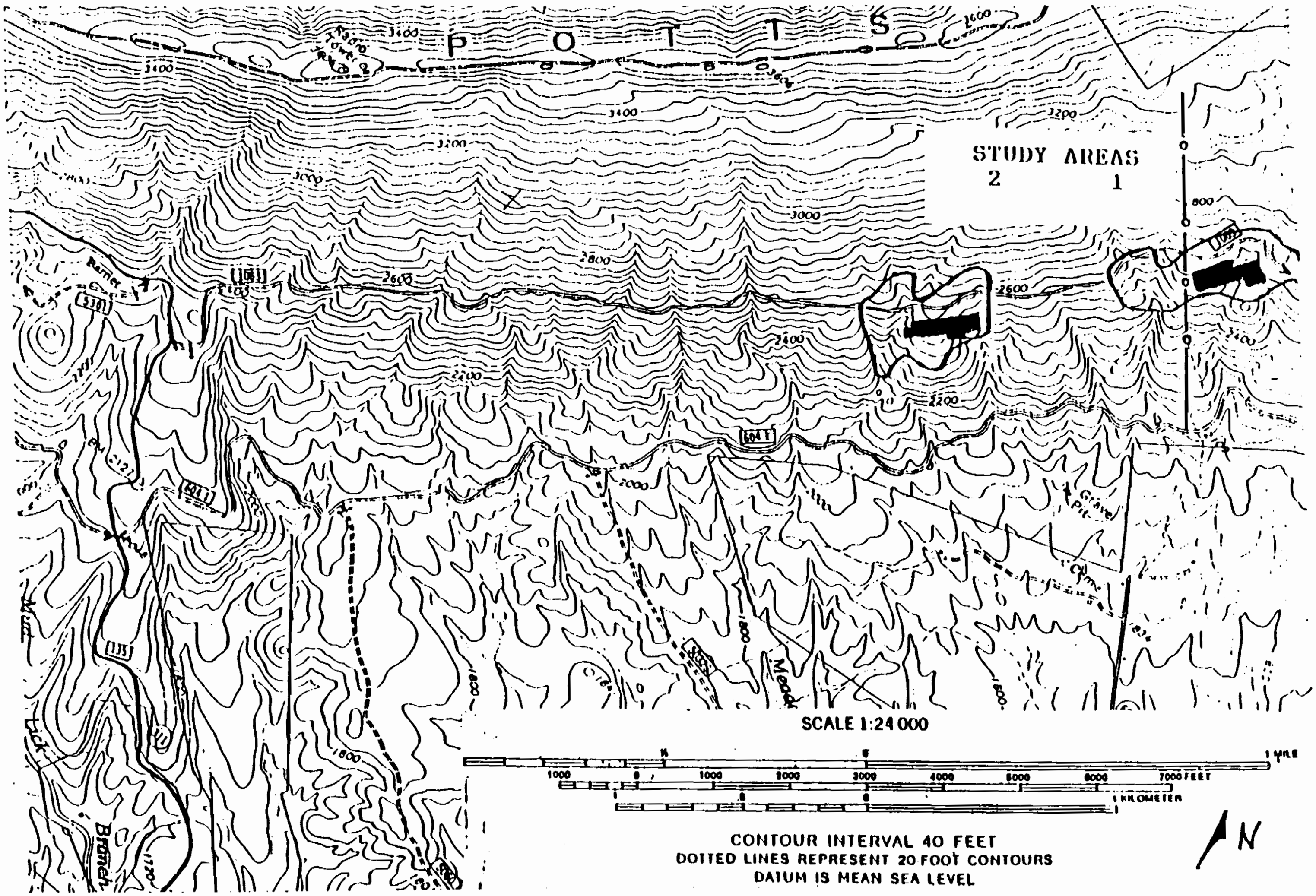

Figure 1. Study area locations on Potts Mountain: Located on the Jefferson National Forest, in Craig County, Virginia.

Table 2. Vegetation summary from fixed plots on the southeast face of Potts Mountain, Craig County, Virginia.

	Total Stems		Basal Area [1]		Avg. Ht.		Avg.Dia.	
Site Index [2]	1986	1991	1986	1991	1986	1991	1986	1991
(m)	(#/ha)		(m^2/ha)		(m)		(cm)	
			TREE STRATUM					
≤15	118	762	0.22	2.31	5.4	6.2	4.3	5.3
19	625	2,636	1.00	6.99	5.6	6.4	4.8	5.6
22	2,401	5,255	3.60	14.93	6.0	7.8	4.8	5.8
			SHRUB STRATUM					
≤15	16,613	12,777	6.83	7.36	1.6	2.2	1.9	2.3
19	49,500	10,841	15.05	6.27	2.2	2.9	2.3	2.5
22	15,837	2,281	8.25	1.54	2.9	3.8	2.6	2.8

[1] Basal area measured at 15 cm above stem origin for the shrub stratum and 1.37 m above stem origin for the tree stratum.

[2] Site index (metric equivalent of base age 50 for upland oaks, Olson 1959). Site index ≤15 stands are mixed oak-pine, site index 19 stands are mixed oak, and site index 22 stands are mixed hardwood.

The data in Table 2 show the effects of site quality on average stem densities, basal areas, total heights, and stem diameters for both the tree and shrub strata as surveyed 7 and 12 years after clearcutting. One notes that the rate of movement from a stand of shrubs to a stand of trees differs significantly by site index. In 1986 the tree (>5.0 m) densities in the SI 22 stands (mixed hardwood) were at the level that the SI 19 stands (mixed oak) were in 1991. Also, the shrub (>1.0 m and ≤ 5.0 m) densities were at a comparable level in 1986 (SI 22) as they were in 1991 for the SI 19 stands. The SI 15 stands (mixed oak-pine) are developing at the slowest rate with only 762 tree stems/ha as compared to 2636 tree stems/ha and 5255 tree stems/ha present in SI 19 and SI 22 stands, respectively, for 1991. The average total heights and diameters for trees and shrubs between site indices exhibited significant differences for both 1986 and 1991 surveys. Also, the average tree and shrub growth between survey years were influenced by both site quality and stem densities. Tree and shrub strata average total height growth increased as site index increased, whereas, average diameter growth were influenced by both stem density and site quality.

Experimental Plot Design

Plots were installed on two homogeneous sites which were reflected in the site quality, uniformity of topographic features, and overstory oak regeneration densities on each site. Study plots were installed on backslopes of spurridges off the midslope position of Potts Mountain with an east to southeast aspect. Site index was estimated at each plot location utilizing the forest site quality index (FSQI) and a site index equation from *Wathen (1977)* (Appendix B). A total of 35 plots were installed in close proximity to the whole-tree harvest study plots installed in 1977. Individual treatment combinations were randomly assigned to individual plots using five replications of seven treatments in a completely randomized design. Each replication included two herbicides applied two ways (basally and by injection), one carrier (kerosene) applied basally, a manual release (chainsaw felled), and a control (Table 3). Sample plots were square and 0.09 ha in size (30m x 30m) with a total sampling area of 3.15 ha for the five replications (Figure 2). Study plots were

Table 3. Treatment allocations assigned to study plots located on Potts Mountain Craig County, Virginia.

Herbicide / Method	Trmt #	Plot #
2,4-D / Injection	1	1, 5, 11, 16, 19
2,4-D / Basal Spray	2	3, 6, 15, 26, 31
Triclopyr / Injection	3	7, 8, 17, 21, 24
Triclopyr / Basal Spray	4	12, 20, 27, 29, 33
Kerosene / Basal Spray	5	4, 10, 14, 32, 35
Manual / Chainsaw	6	9, 18, 23, 25, 34
Control	7	2, 13, 22, 28, 30

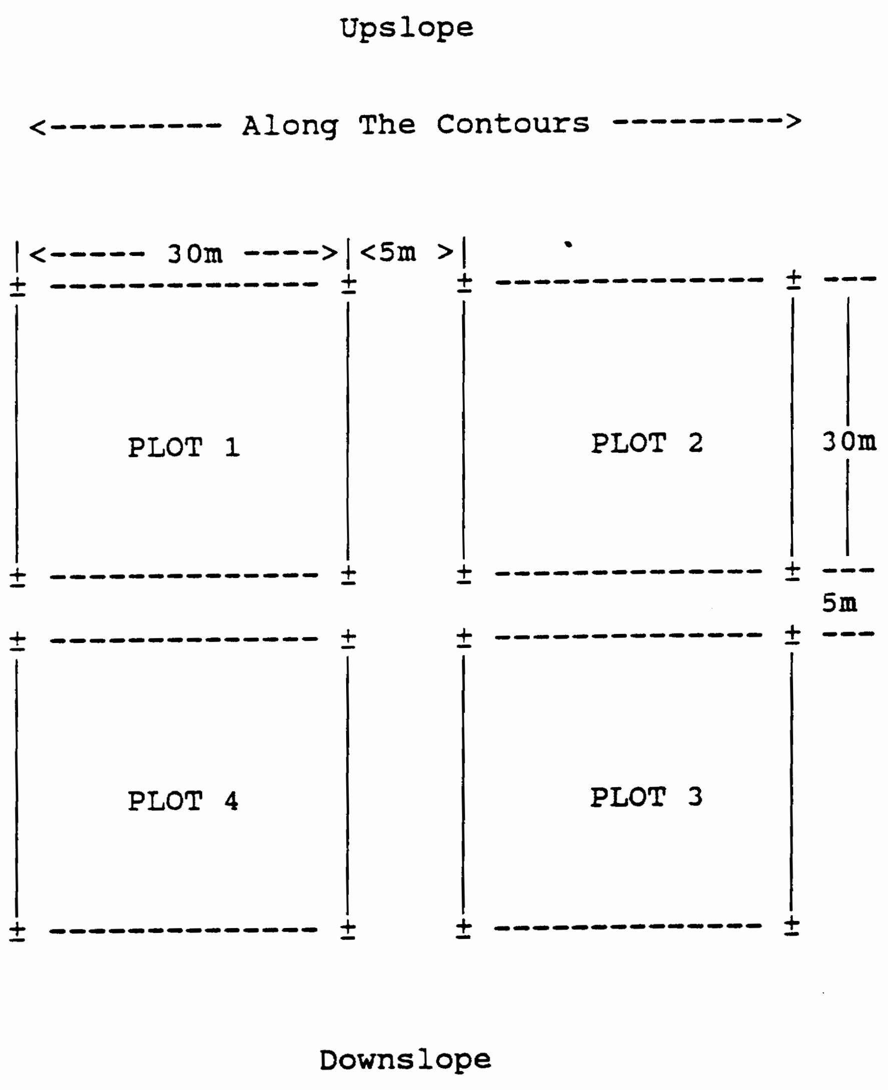

Figure 2. A typical study plot layout: The map illustrates plot size, slope position, and configuration. Study plots similar to these are located on Potts Mountain in the Jefferson National Forest, Craig County, Virginia.

installed with five meter buffers separating each plot. Plot corners were permanently marked, tagged, and numbered. The detailed procedures used for plot establishment are identical to the procedures established by *Smith and Torbert (1990)*.

Oak Clump and Sprout Selection Criteria

Oak clumps and their respective dominant sprouts were selected after initial plot boundaries were established. Each plot had contained 20 oak clumps that were randomly selected for treatment. Each oak clump must have had at least two dominant or codominant sprouts to be selected. The 20 oak clumps were based on the maximum number of crop-trees that would be in the stand at the time of harvest, (180 to 250/ha), assuming a sawtimber product objective. Since the objective of the thinning was to select the highest quality sprout from each root-stock, the following criteria was used in selection process *(Stroempl 1984, Lamson 1988)*:

1. Sprouts were chosen that were the dominant (tallest, straightest, and largest diameter) sprout in each stump-clump.
2. Defective sprouts that had major defects such as a major fork below 1 log (5.2 meters), large stem cankers or heavy insect damage were selected against.
3. Sprouts with a 'V-Type' connection with another sprout or were high on the stump were selected against.
4. Sprouts that had a 'U-Type' connection with another sprout or separated from the other sprouts were selected.
5. Sprouts that were located low on the stump (below 15 cm) and were not leaning excessively were selected.

Chemical Selection Process

The herbicide selection process was a very important part of this study. The matching of the study objectives with the proper herbicide and application method was critical in order to accomplish the desired effects. The management objectives for the present study were; 1. to release the dominant oak sprout in a selected sprout-clump by basally applying herbicide to the stems of the competing sprouts, thereby, eliminating competition for light and nutrients and, 2. to use a herbicide that would minimize the translocation into the crop-tree.

Herbicides labeled for forestry use that may be useful in managing young hardwood stands similar to those present on the study site are included below *(Zedaker 1986a)*. These herbicides come in various formulations that govern their method of application and subsequently their silvicultural uses.

1. 2,4-D
2. 2,4-DP (dichlorprop)
3. dicamba
4. fosamine
5. glyphosate
6. hexazinone
7. MSMA
8. picloram
9. triclopyr

Selection criteria were established to ensure that the selection process would result in matching the proper herbicides with the objectives of the present study and meet any ownership constraints. The following selection criteria were used to determine which herbicides were best suited for the study:

1. Herbicides must be registered for specific forestry applications, namely injection and basal bark methods.
2. Herbicides must be manufactured in both amine and ester formulations so that they are both water and oil soluble.
3. Herbicides must not be formulated with other herbicides so as not to confound the results.
4. Use herbicides that do not translocate readily to the root system (via symplast) when applied to the stem.
5. Herbicides must be able to be applied at any time of year without significantly affecting their effectiveness or selectivity.
6. Herbicides must be selective against oaks and are effective on other hardwood species also.
7. Herbicides must have high LD_{50} values and short to medium persistence.
8. Herbicides must be relatively inexpensive.
9. Herbicides must be permitted for use on the Jefferson National Forest.

The herbicide selection process was made quite simple because most herbicides did not meet the first three guidelines. Even if a herbicide met the first eight guidelines, it would have to meet the last one for final approval, which governs the herbicides permitted for forestry use on National Forests (Table 4).

The first herbicides to be deleted from the list of nine suggested by *Zedaker (1986a)* were fosamine, glyphosate, hexazinone, and MSMA because they were not labeled for both injection and basal application. Dicamba, 2,4-DP, and picloram were deleted because their ester formulation were mixed with 2,4-D and triclopyr *(Hartley and Kidd 1989, Humburg 1989, Worthing 1987)*. The remaining herbicides were 2,4-D and triclopyr. All criteria were met and subsequently were chosen as the herbicides for study. The specific chemical formulations and application rates used in the present study are provided in Appendix C.

Kerosene was chosen as the carrier because it was recommended on the labels of both the selected herbicides. The herbicide carrier was tested to determine whether or not the carrier has sufficient

Table 4. Herbicides permitted for forestry use on National Forests.

Cut Surface Application (Amine Formulations)	Basal Application (Ester Formulations)
1. 2,4-D	1. 2,4-D
2. dicamba	2. 2,4-DP
3. triclopyr	3. triclopyr
4. glyphosate	
5. imazapyr	
6. picloram	

Adapted from U.S.D.A. Forest Service (1989).

phytotoxic effects on the oaks to warrant the possibility of using it alone. Therefore, the decision was made to treat it like a herbicide and to apply it in the same manor as the basally applied herbicides in the study.

Treatment Procedures and Data Collection

Data Collection

After the oak clumps and crop stems (released sprouts) were identified, each clump of sprouts was distinguished by species and the sprout to be released was numbered, and tagged. Details of tagging procedures can be found in the Forest Component User Manual by *Smith and Torbert (1990).* To facilitate ease in future measurements, the relative position of each selected oak clump was mapped within a 5 by 5 meter grid and the x,y coordinates were recorded on the data sheets (Figure 3).

Initial measurements on the selected crop-trees were total height (nearest 0.10m), stem diameter (nearest 0.25cm at 1.37m above ground), and relative crown position in the stand (dominant or codominant). Remeasurements performed 12 months after treatment included total heights and diameters. The specific details of stem measurement procedures can be found in the Forest Component User Manual by *Smith and Torbert (1990).*

Initial measurements taken for the treated oak sprouts were stem diameter (nearest 0.25cm at 1.37m above ground), relative crown position, and any occurrence of insect, disease, or animal damage. Treatment sprouts were measured in a clockwise direction from the dominant sprout for identification purposes in future measurements. Six to twelve weeks following treatment photographs were taken along with brief descriptions of the visual symptoms to document the initial effects of the chemical treatments. Specific objective data were not collected because the treatment applications

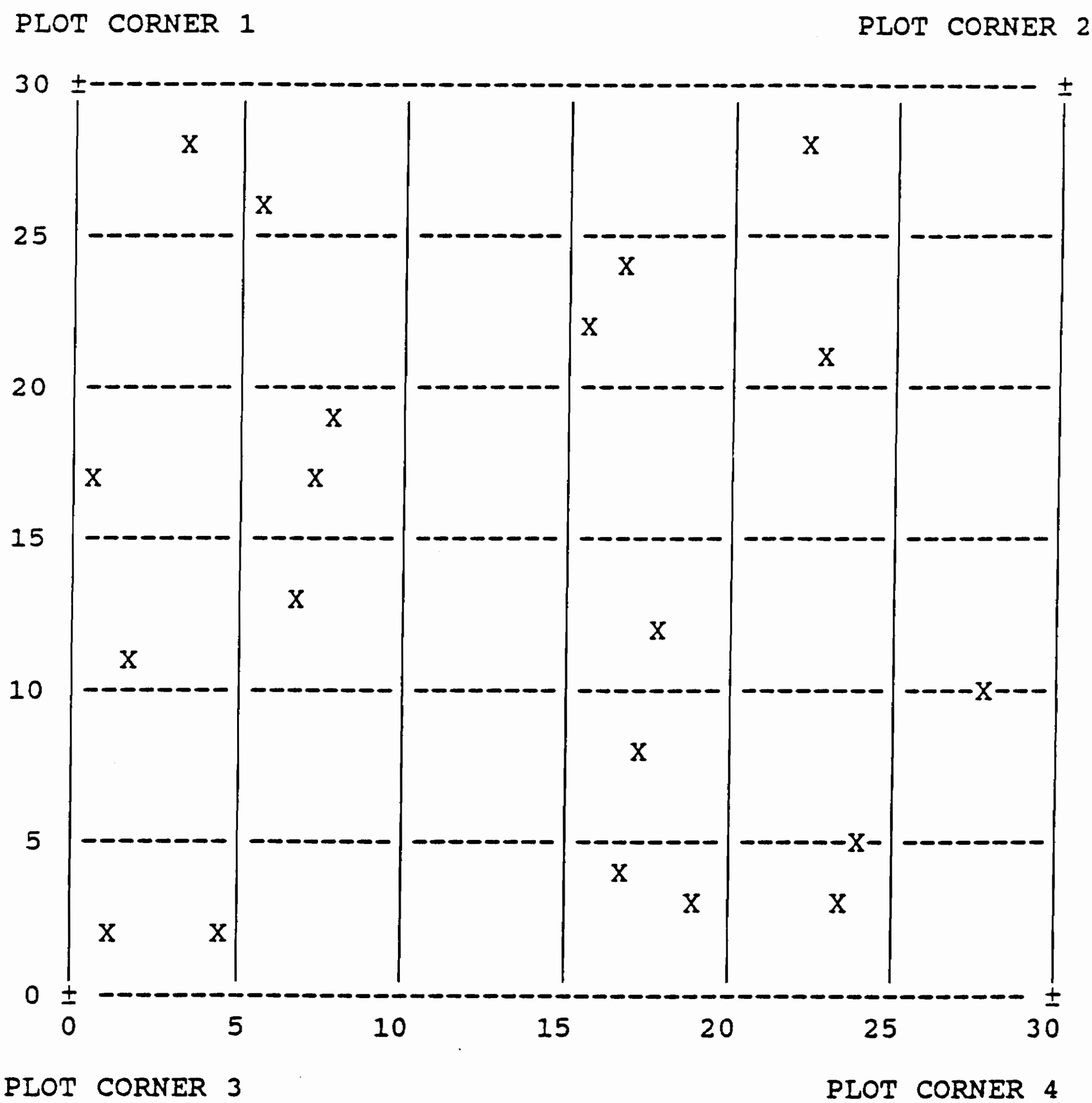

Figure 3. Sample plot layout: A study plot example with a 5 by 5 meter grid and oak-clump relative positions (X). Study plots similar to the above are located on Potts Mtn. in the Jefferson National Forest, Craig County, Virginia.

occurred near the end of the growing season (late July 1990), and it was assumed that the effects would not be fully apparent until the end of the next growing season (1991). A more objective assessment of the treatments was performed 1 year after treatment when the number of unaffected, affected, and dead were recorded. Also, the number of treated sprouts having new basal sprouts were recorded and any crop-stem translocation effects were assessed.

Treatment Procedures

The thinning procedure was to treat all competing sprouts on a given stump thereby releasing one dominant crop stem. Any hardwood stem in the overstory with the crown in direct contact with the chosen crop-stem was treated. Also, any sprout clump of maple or sourwood in a dominant or codominant position, near an oak clump, and that had three or more sprouts was treated. These procedures were used to mimic an actual precommercial thinning where some undesirable species were controlled.

Since the cost of thinning was to be analyzed, two-person crews were used so that production time could be recorded, but, a wage rate for only one person was used in the cost analysis. One crew member applied the treatment while the other crew member timed the event. This procedure assured that all selected oak clumps were treated in each plot, and tallied, by one-inch diameter class, the additional competing trees that were treated. Therefore, each replication or plot was separately timed excluding down-time. The amount of chemical used for each treatment was determined after all five replications were completed by subtracting the remaining herbicide mix from what was originally placed in the container.

The chemical thinning was performed by basal spray using a prototype backpack sprayer equipped with a wand delivering a metered amount through an adjustable solid cone tip, and by injection with a Hypo-hatchet®. Care in application was observed so that the sprouts designated for treatment were the only sprouts treated. Also, when the basal spray was applied, care was taken to apply the chemical above breast height so that no runoff occurred at the point of sprout origin. This procedure was followed to minimize the amount of chemical reaching the roots and potential contamination of adjacent stems.

Injections with the Hypo-hatchet® were applied at approximately breast height (1.37 m above base of stem) with one injection per 2.5 cm of diameter at breast height. Each injection on a stem penetrated the inner bark at about a 45° angle depositing an average of 1.5 ml (approx. 0.09 mg a.i. per cm dbh) of a 50 percent solution in water of 2,4-D and triclopyr amines. Basal bark treatment involved each sprout being sprayed to encircle the stem with an average of 5.2 ml per 2.5 cm (approx. 0.09 mg a.i. per cm dbh) of diameter using an 8 percent mixture of 2,4-D and triclopyr esters with kerosene applied at least 1.37 m above the base of stem attachment. The doses reported reflect the actual average amount applied per unit area. The 5 ml dosage was obtained by field trials which were designed to determine the amount of kerosene needed to sufficiently wet the bark of a 2.54 cm diameter oak stem at breast height without running down the stem to the point of origin on the stump.

The manual thinning of sprout clumps was performed using a chainsaw. The sprouts to be treated in each clump were cut as low as possible with the chainsaw taking care not to injure the crop stem. As in the chemical treatments, trees directly competing outside the clumps were treated along with sourwood and maple sprouts encountered when moving from one oak sprout-clump to another.

Data Analysis

One-way analysis of variance was employed to determine whether the treatment means for a given parameter were significantly different from zero at the 0.05 probability level. Parameters investigated were treatment costs, production rates, and stand growth by treatment. If a significance (prob $> F$) was detected at ≤ 0.10 level then a follow-up analysis was performed to determine which treatment means were significantly different. When balanced data were analyzed, Duncan's Multiple Range Test was employed at the alpha level of 0.10. Also, if any grouping of the data resulted in an unbalanced analysis then Tukey's Studentized Range Test (HSD) was employed at the alpha level of 0.10. Pre-planned treatment contrasts were also analyzed to determine if differences in growth response between treatments and thinning methods were significant at the 0.05 probability level (Table 5).

Treatment Cost and Production Rate Analysis

One of the primary objectives of the present study was to compare treatment costs in order to determine which was the most productive and least expensive method. Amount of chemical applied, number of stems treated, and amount of circumference treated were calculated per plot and averaged by treatment. Amount of chemical used was combined with number of stems and circumference treated to obtain amount of chemical applied per unit (ml/stem and ml/cm of circumference). Chemical costs by treatment were then calculated using 1990 local retail prices, obtained from Dow Elanco and a local retailer, (Table 6), and multiplied by the average amount of chemical applied per unit of stem circumference and per treated stem. Application time was calculated per plot and averaged by treatment and thinning technique (injection, basal spray, and manual cut). Production rates were calculated by combining application time with numbers of treated stems and circumference on a plot basis and averaged by treatment and thinning technique to obtain units of cm/hr and stems/hr. Application costs were then computed by dividing labor costs ($/hr) by the average production rates by thinning technique. Labor costs for treatment applications were based on an estimated 1990 wage rate of $7.50 per hour. Total treatment costs (per hectare) were then calculated by summing previously calculated application costs and chemical costs and multiplying by the number of stems/hectare or circumference/hectare averaged across all treatments. Using these procedures total treatment costs were calculated by specific treatment and thinning method (injection, basal spray, and manual cut).

Table 5. Treatment contrast descriptions.

Contrasts	Contrast Description
C1	Control vs Manual
C2	Control vs Chemical
C3	Control vs Injection
C4	Control vs Basal Spray
C5	Manual vs Chemical
C6	Injection vs Basal Spray
C7	Manual vs Injection
C8	Manual vs Basal Spray
C9	Kerosene vs Herbicide

Table 6. Local retail prices (summer 1990) and actual costs incurred for herbicides, fuel, and oil.

Chemical	Retail Price	Incurred Cost [1]
	($/liter)	($/ha)
2,4-D Amine	2.64	6.45
2,4-D Ester	3.96	16.44
Triclopyr Amine (Garlon 3A®)	14.07	15.76
Triclopyr Ester (Garlon 4®)	18.18	54.04
Kerosene	0.29	7.58
Gasoline	0.31	9.00

[1] Incurred costs are based on application rates and chemical formulation. Kerosene cost is included for the 2,4-D ester and triclopyr ester applications. Chainsaw oil, and bar lubricant, is included the gasoline cost for the manual thinning application.

General Equation Used For Computing Treatment Costs

Application Cost (by thinning method as \$/cir or \$/stem) =

Labor Rate (\$/hr) ÷ Avg. Production Rate (cm/hr or stems/hr)

Chemical Cost (by treatment as \$/cir or \$/stem) =

Chemical Application (ml/cm or ml/stem) X Retail Chemical Cost (\$/ml)

Total Treatment Cost (\$/ha) =

Application Cost + Chemical Cost) X Overall Avg. Treated Density (cm/ha or stems/ha)

NOTE: When more than one chemical was applied in a treatment (e.g basal sprays) the chemical costs were calculated for each chemical (e.g. herbicide vs kerosene) separately and then summed. An estimated additional cost of \$5.75/ha (for chainsaw oil and bar lubricant) was added to the calculated cost of manual thinning for the present study.

In order to relate the present study cost analysis with actual professional forestry operations, a comparison was made with Southwide averages from forest industry, private and public agencies. This comparison included data from 70 questionnaire respondents in 12 southern states covering over 162,000 hectares from a survey conducted by *Watson et al. (1987)*. The direct comparisons were made possible by using the average application costs (labor & equipment) for chemical injection and basal spray methods that were reported for 1986 in the Southwide study. These application costs were then added to the chemical costs from the present study. This method adjusted the 1986 Southwide averages for the more accurate chemical costs of the present.

Adjusted Southwide Average Equation

Adjusted Total Treatment Cost (by thinning method as \$/ha) =

{ Reported Total Cost (\$/ha) X Reported Appl. Cost (%) } +

{ Avg. Chem. Cost (\$/cm or \$/stem) X Overall Avg. Prod. (cm/ha or stems/ha) }

Growth Analysis

Change in stem size 12 months after treatment was analyzed by calculating the mean growth for each plot and averaging by treatment. The growth parameters compared were diameter growth, height growth, basal area growth, and volume growth (D^2H). Nine pre-planned contrasts (Table 5) were also analyzed for the same growth parameters, where significance (prob. > F) was calculated.

Another statistical analysis performed on residual crop-stem growth response was based on a study by *Knowe and others (1990)* where ratio and regression estimators of hardwood growth after treatment were compared for estimating efficacy of herbicide treatments. Conclusions from *Knowe and others (1990)* were that a regression approach is more flexible than a ratio approach since any deviations from a straight-line relationship between pre- and post-treatment sizes may be accounted for by using multiple regressions, linear transformations, or weighted regressions to compensate for heterogeneity of variance.

Zedaker and Lewis (1983) stated that efficacy should be based on some measure of crown dimensions to reduce subjectivity and minimize variances. Difficulty exists in accurately measuring crown dimensions in the dense stands under study as prescribed by *Zedaker and Lewis (1983)*. Because of this difficulty, the dimension to represent growth was chosen to be a volume index based on the product of stem diameter and stem height (D^2H), called stem size.

The regression estimator used in the analysis was based on linear regression procedures and was a function of the mean observed pre- and post-treatment crop-stem sizes on untreated plots and the observed pre-treatment size of an individual crop-stem. The regression estimator (Hlr) adjusted the mean post-treatment crop-stem size (μH1) on untreated plots by how much the observed pre-treatment (H0) size of an individual crop-stem was above or below the average pre-treatment crop-stem size (μH0) on untreated plots *(adapted from Knowe et al. 1990).* Therefore, in the present study the regression estimator did not have to meet the assumption that all plots have equal means and distributions of crop-stem sizes because the post-treatment estimate was based on growth relative to the control not to the pre-treatment crop-stem sizes on treated plots.

The following equations were adapted from the study by *Knowe and others (1990).*

$$\mathbf{Hlr} = \mu\mathbf{H1} + \beta\,(\mathbf{H0} - \mu\mathbf{H0})$$

Where;

Hlr	Expected post-treatment stem size (D^2H) of an individual crop stem based on a regression estimator.
β	Slope of the regression estimate.
μ**H1**	Mean post-treatment crop stem size (D^2H) on untreated plots after one growing season.
μ**H0**	Mean pre-treatment crop stem size (D^2H) on untreated plots.
H0	Observed pre-treatment stem size (D^2H) of an individual crop stem on any plot.

The influence of treatment on crop-stem growth using the regression- adjusted estimator used was expressed as percent increase in stem size (D^2H).

$$\mathbf{Glr} = [\,(\mathbf{H1} - \mathbf{Hlr}) \div \mathbf{Hlr}\,] \times 100$$

Where;

Glr The expression of percent crop-stem growth (D^2H) as a result of the treatment based on the regression estimate.

H1 Observed post-treatment stem size (D^2H) of an individual crop- stem on any plot after one growing season.

Hlr Previously described.

Residual Chemical and Cutting Effects

Herbicide application effects on treated oak stump sprouts and the subsequent crop-stem translocation were analyzed. During the first remeasurement of the residual crop stems an assessment of chemical treatment effects on the oak stump-sprouts was performed. Since the focus of this study is to quantify the treatment effects on the crop stems, a detailed assessment on treated sprouts was not done. Instead, within each treated oak clump stem counts of affected, dead, and new sprouts were recorded. New sprouts were primarily growing from the base of dead sprouts. But in some instances, new sprouts were growing from the base of severely affected sprouts.

One objective of the present study is to compare crop stem growth differences after thinning using chemical applications. A major factor affecting residual stem growth after chemical have been applied to surrounding sprouts is translocation of the chemicals into the residual crop stem. The results of the growth analysis implies crop-stem translocation but, to directly estimate translocation a visual assessment was performed. Translocation assessment was based on a visual estimation of percent crown damage. Crown damage was defined as foliage discoloration, deformation, and loss.

Four translocation categories were used:

Trans0 No visible symptoms apparent.

Trans1 Less than 10 percent crown damage.

Trans2 Between 10 and 50 percent crown damage.

Trans3 50 percent or more crown damage.

Chapter IV : Results and Discussion

Pre-treatment Stand Conditions

No statistically significant differences, (alpha = 0.05), between treatments for pre-treatment crop-stem size parameters occurred (Table 7). This was exhibited by the p-values resulting from a one-way analysis of variance performed on mean crop-stem dbh, total height, basal area, and site index for all treatments. A difference in treatment means could only be detected at the 4 to 11 percent confidence level, (1 - p-value), for dbh, total height, and basal area. Crop stem diameters averaged 7.7cm across all treatments, and ranged from 7.5 cm to 8.0 cm for treatment means. Total heights averaged 8.3 m with a mean range of 8.1 m to 8.6 m by treatment. The basal areas also show a narrow mean range of 1.32 m^2/ha to 1.50 m^2/ha and an overall mean of 1.40 m^2/ha. The narrow range in mean values and overall nonsignificant differences between treatments indicates a fairly uniform site quality and tree density across treatments. Mean site index by treatment ranged from 20.7 to 21.9 (metric equivalent of base 50, *Wathen 1977*) and averaged 21.4 across treatments. Even though a difference in treatment means for site index was detected at the 88 percent confidence level, the study sites were assumed to be uniform.

Generally, sprout stems to be thinned within the oak clumps exhibited significant differences (before treatment at alpha = 0.10) between injection and basal spray treatments for stem diameters (Table 8). Stem diameters of these treated oaks averaged 5.0 cm across treatments and ranged from 4.7 cm to 5.3 cm. The average stem diameter for the treated oak sprouts was significantly less than the corresponding average crop-stem diameter of 7.7cm (Table 7). This difference in stem diameter shows that dominance has occurred for at least one oak stem in a sprout-clump. Significant dif-

Table 7. Pre-treatment summary for oak crop-stems; on Potts Mountain, Craig County, Virginia.

Trmt/Method	DBH	Total Height	Basal Area	Site Index
	(cm)	(m)	(m^2/ha)	(base 50)
2,4-D / Injection	7.5	8.3	1.32	21.3
2,4-D / Basal Spray	8.0	8.6	1.50	21.5
Triclopyr / Injection	7.8	8.3	1.39	20.7
Triclopyr / Basal Spray	7.8	8.2	1.43	21.5
Kerosene / Basal Spray	7.7	8.1	1.39	21.9
Manual / Chainsaw	7.7	8.1	1.36	21.1
Control	7.8	8.4	1.42	21.7
Overall Mean	7.7	8.3	1.40	21.4
P-value	0.96	0.89	0.94	0.22

NOTE: Values are the mean of five replications for each treatment. P-values were obtained from a one-way analysis of variance.

Table 8. Pre-treatment summary for all thinned stems; on Potts Mountain, Craig County, Virginia.

	---------- Oak-Clumps [1] ----------			---- Other Competing Spp. [2]----		
Trmt/Method	DBH	Density	Basal Area	DBH	Density	Basal Area
	(cm)	(#/ha)	(m^2/ha)	(cm)	(#/ha)	(m^2/ha)
2,4-D / Injection	5.2 ab	535	1.64	4.9	267 abc	0.67 ab
2,4-D / Basal	5.3 a	511	1.74	5.8	351 ab	1.24 a
Triclopyr / Injection	4.7 c	653	1.63	6.1	200 c	0.67 ab
Triclopyr / Basal	4.9 bc	615	1.74	5.0	509 a	1.31 a
Kerosene / Basal	5.1 abc	584	1.76	5.3	258 abc	0.69 ab
Manual / Chainsaw	4.8 bc	542	1.44	6.5	42 c	0.08 b
Overall Mean	5.0	573	1.66	5.6	271	0.78
P-values	< 0.06	0.26	0.82	0.18	< 0.09	< 0.07

NOTE: Values are the mean of five replications for each treatment. Values within a column followed by the same letter are not statistically significant at the 0.10 probability level using Duncan's Multiple Range Test.

[1] Includes only treated oaks within the selected sprout-clumps.

[2] Includes only competing stems (dominants or codominants) outside of the selected oak sprout-clumps. Species include oaks, red maple, sourwood, and black locust.

ferences between treatment means for treated stem densities and basal areas within oak clumps were not detected. This is apparent from the high p-values of 0.26 and 0.82 resulting from an analysis of variance for mean stem densities and basal areas, respectively. Stem densities for treated oak sprouts averaged 574/ha which corresponds to approximately 3 sprouts per clump. The range of mean stem densities by treatment was 511/ha to 653/ha which corresponds to 2.3 and 2.9 sprouts per clump, respectively. These high average stem densities imply a need for thinning since a maximum of 250 dominant and codominant crop-stems per hectare normally occur at maturity. Basal areas averaged 1.66m^2/ha across treatments and also had a narrow range of 1.44m^2/ha to 1.76m^2/ha (Table 8).

Competing stems outside the selected oak clumps were highly variable in number and distribution (Table 8). These competing stems were mainly clumps of other oaks, sourwood, red maple, and black locust. No significant difference ($p = 0.82$) was detected between treatment mean stem diameters. Stem diameters averaged 5.6cm across treatments as compared to the 5.0cm mean for the oak-clump treated sprouts. The mean range of stem diameters was also larger for the perimeter competing sprouts, being from 4.9cm to 6.5cm. The corresponding average basal areas for the perimeter competing sprouts differed significantly (alpha = 0.10) between treatments for all but the injection and the kerosene treatments. Stem density values also showed a significant difference (alpha = 0.10) between means of most treatments. Stem densities averaged 271/ha across all treatments but, had a wide range of means between 42/ha (manual thinning) and 509/ha for the triclopyr basal treatment. These density differences were due to the random occurrence of large versus smaller competing sprout-clumps with less sprouts per clump in close proximity to the preselected oak clumps. The variability of stem densities indicate that the distribution of dominant and codominant sprouts may have been clumped. This distribution pattern would indicate a need for a precommercial thinning to redistribute the crop species more evenly and, therefore, enhance growth *(Lamson and Smith 1987)*.

Chemical Application Effects: Treated Oak Sprouts

A visual check of the chemical treatment effects was performed 6 and 12 weeks after treatment, with the 12 week check occurring during leaf fall. A sampling intensity of approximately five percent was used. This check was purely subjective, with the purpose of documenting the extent of the chemical treatment effects by descriptions and photographs. After 12 months another assessment was performed sampling all treated stems within the oak clumps.

Preliminary Results (6-12 weeks after treatment)

Both 2,4-D and triclopyr injection treatments exhibited browning to complete crown dieback of the 5 to 8 cm dbh classes of treated stems. The larger diameter class showed slight crown damage. There was exudation from the injection cuts in the bark. The smallest diameter stems (2 to 3 cm) showed marginal effects, but exhibited complete browning of the crown. After 12 weeks larger splits were evident on the bark of the treated stems.

Leaf curl and browning occurred but was highly variable 6 weeks after 2,4-D basal treatment. Greater effects occurred on smaller diameter stems (< 10 cm dbh) with some bark eruptions evident on the stems. Larger bark eruptions were noted 12 weeks after treatment. Six weeks after triclopyr basal treatment effects on both small and large diameter stems were evident. Brown spotting to total browning of foliage occurred along with small bark eruptions. These effects were more evident on smaller diameter stems. After 12 weeks, large eruptions were evident on the bark. Kerosene treated stems exhibited no visual symptoms after 6 weeks, but, brown spotting on the bark was apparent on some stems after 12 weeks. These results agree with a study by *Miller (1990)* where streamline basal applications of triclopyr were used. Miller noted that during the first growing season defoliation was gradual. Also, Miller correlated stem size with the resulting degree of control.

Treatment Results After 12 Months

Treated sprouts within the oak clumps were assessed after 12 months as either affected or dead as a result of the chemical treatment. Both 2,4-D treatments and the triclopyr basal treatment are statistically different from triclopyr injection and kerosene basal treatments for percent sprouts affected (Table 9). The triclopyr basal treatment shows statistically better control where 88.6 percent mortality occurred and an additional 11.4 percent exhibited some degree of control. These triclopyr (basal spray) results surpass the results reported by *Miller (1990)* where the treated oaks exhibited a 55 percent kill on average. The differences in study results may be attributed to species susceptibility to the herbicides used because different species of oak were treated than in the present study. The next highest mortality value was 28.7 percent resulting from the 2,4-D basal treatment in addition to 69.3 percent exhibiting some degree of control. The 2,4-D injection, triclopyr and kerosene basal spray treatments were significantly different from the other treatments for percent mortality, with the basal treatments exhibiting the greatest occurrence of mortality.

The results of the 2,4-D and triclopyr injection treatments along with the kerosene basal spray treatment showed no significance between treatments for percent affected or dead (Table 9). The 2,4-D and triclopyr injection treatments exhibited similar results in percent affected (88.6, 82.0) and percent dead (11.4, 15.6), respectively. Whereas, the kerosene application exhibited similar results for percent affected (85.1) but, had a lower mortality rate of 7.6 percent. The results of a study by *Kossuth and others (1980)* reported topkill to oaks by 2,4-D and triclopyr injection to average 98 and 100 percent, respectively. *Campbell (1985)* reported similar results. Once more, the oak species treated were different form the present study. A comparison a oak species susceptibility was evident in a study conducted by *Sterrett (1969)* where oaks were injected with 2,4-D across all seasons. The results indicated that for summer treatments only 43 percent of the chestnut oak exhibited topkill, whereas, scarlet and white oaks exhibited 100 percent topkill.

Table 9. Summary of treatment effects after 12 months for thinned oak sprouts; on Potts Mountain, Craig County, Virginia.

Trmt/Method	Total No. Trmt.Sprouts	Percent [1] Affected	Percent Dead	Total Percent Re-sprouts
2,4-D / Injection	243	88.6 a	11.4 c	3.3 b
2,4-D / Basal Spray	232	69.3 b	28.7 b	5.5 b
Triclopyr / Injection	294	82.0 ab	15.6 bc	2.2 b
Triclopyr / Basal Spray	277	11.4 c	88.6 a	8.4 b
Kerosene / Basal Spray	263	85.1 ab	7.6 c	1.5 b
Manual / Chainsaw	244	N/A	N/A	74.4 a
Overall Mean [2]	259	67.3	30.4	4.2
P-value	0.26	< 0.01	< 0.01	< 0.01

NOTE: Values followed by the same letter within a column are not significant (alpha = 0.05) using Duncan's Multiple Range Test.

[1] Total number of treated sprouts with visual symptoms (not dead) divided by total number of treated sprouts. Performed on a plot basis and averaged by treatment.

[2] Overall mean for the total percent re-sprouts reflects the five chemical treatments.

An important result of the chemical versus manual treatments is the effects on resprouting (Table 9). The chemically treated stems exhibited significantly lower resprouting over the manual treatment, (1.5 % - 8.4 % vs 74.4 %). Lower rates of resprouting using chemical application (especially stem injection) is a clear advantage over manual thinning by providing a longer release period from competition and potential greater crop-stem growth *(Wendel and Lamson 1987)*. Resprouting occurred less on stems treated by injection (approx. 2.7 %) over basal spray applications which exhibited an average resprouting of 5.1 percent. Although these differences in resprouting are not statistically significant, they can be correlated with percent mortality associated with treatment, therefore may be of biological significance. Kerosene basal treatment had the lowest resprouting occurrence (1.5 %) and also the lowest mortality rate of 7.6 percent. These resprouting results indicate that the method of chemical application (injection vs. basal spray) is correlated better with the apparent efficacy than specific chemicals used. Also, the results indicate a need for additional research in factoring-out application methods and various rates of chemical application.

All chemical treatments showed some degree of efficacy, which is apparent from summing the percent affected and dead values for each treatment (Table 9). Even though all treatments show symptoms of chemical control, the triclopyr basal treatment exhibited the greatest control. The results of the chemical treatments in the present study after 12 months are still preliminary. The injuries to the stems caused by chemical application provide entry points for insects and disease. It was noted that on chemically treated stems insects were devouring foliage that remained after treatment. Continued deterioration of the treated stems will most likely occur during the next few years. *Miller (1990)* noted an increase in mortality of treated stems from 4 to 35 percent three years after treatment, presumably caused by insect and disease infestations.

Chemical Application Effects: Crop Stems

Translocation Into Crop Stems

The results of the residual crop-stem visual translocation assessment were encouraging (Table 10). On average, translocation into crop-stems was minimal, affecting less than 10 percent of the crown on 58 percent of total residuals. The 2,4-D injection and triclopyr basal spray treatments had the highest translocation effects (68 %, 92 %) on the crop-stems, although they are significantly different from each other. These results are correlated with the greatest total affected and dead treated sprouts for the same treatments in Table 9. Moderate translocation (Trans2) averaged 5 percent of the crop stems, except for the triclopyr basal spray treatment where 12 percent of the crop stems exhibited moderate translocation effects. The one stem rated as Trans3 (2,4-D basal) exhibited approximately 50 percent of the branches devoid of foliage and the remaining foliage deformed and/or discolored. This particular crop-stem appeared to have been subjected to over-spray of 2,4-D onto the stem in error. The severity of translocation effects on crop-stems appeared to be correlated with the method of application except for the triclopyr basal treatment. Crop-stem translocation for triclopyr basal spray treatment was significantly different from the other treatments. The triclopyr basal treatment appeared to be translocated more easily than the other treatments with 80 and 12 percent of the crop stems in the Trans1 and Trans2 categories, respectively. From these results it appears that the high occurrence of treated stem mortality associated with the triclopyr basal spray treatment (88.6 %; Table 9) was positively correlated with the high crop-stem translocation occurrence (92 %; Table 10). Therefore, dilute solutions of herbicide mix would be safer to apply, allowing sufficient control and, at the same time, causing minimal translocation effects. The best herbicide treatment based on the lowest crop-stem translocation (visual assessment) would be either 2,4-D basal or the kerosene basal treatments.

Table 10. Crop-stem translocation effects by chemical treatment; on Potts Mountain, Craig County, Virginia.

Trmt/Method	Trans0	Trans1	Trans2	Trans3	Total Trans.
	----------	----------	(%)	----------	----------
2,4-D / Injection	32 ab	63 ab	5	0	68 ab
2,4-D / Basal Spray	49 a	45 b	5	1	51 b
Triclopyr / Injection	42 a	54 b	4	0	59 b
Triclopyr / Basal Spray	8 b	80 a	12	0	92 a
Kerosene / Basal Spray	50 a	45 b	5	0	50 b
Overall Mean	36	57	6	0	64
P-values	< 0.01	< 0.01	0.17	0.43	< 0.01

NOTE: Trans0 = no visual symptoms, Trans1 = < 10% crown damage, Trans 2 = 10% to 50% crown damage, Trans3 = > = 50% crown damage. Column values followed by the same letter are not significant (alpha = 0.05) using Duncan's Multiple Range Test.

Growth Analysis

Growth of young trees is affected by the availability of soil moisture, soil nutrients, light, site quality, and general vigor of the tree. If one can hold these factors constant then evaluation of herbicide treatment effects on growth is made simple. In the present study an attempt was made to hold site quality constant and the remaining factors were assumed to be constant.

Results indicate that treatment mean differences are not significant (alpha = 0.05) for diameter growth (p = 0.95), height growth (p = 0.30), basal area growth (p = 0.98), or volume (D^2H) growth (p = 0.98), (Table 11). Average diameter growth was 0.87 cm for the herbicide treatments, 0.91 cm for the manual thinning, and 0.81 cm for the control. The manual thinning treatment was also greater in both height growth (0.75 m) and volume growth (0.0186 m^3). The 2,4-D and triclopyr basal treatments exhibited the least height growth of all treatments, averaging 0.59 m and 0.60 m, respectively. Chemical treatments averaged 0.62 m in height growth while the control averaged 0.58 m. Basal area growth on a per stem basis averaged 0.0014 m^2 and volume growth averaged 0.0178 m^3 per crop-stem.

The significance of the manual treatment growth increase over the chemical treatment growth is due to the immediate response from complete removal of competition and the chemical effects, via translocation, on the crop-stems. *Wendel and Lamson (1987)* recognized the probable growth response from complete removal of competition in their thinning study. *Sonderman (1987)* reported 3.5 cm in diameter growth for 18-year-old oaks over an 8-year period after manual thinning as compared to a 2.0 cm diameter growth for the control. This diameter growth equates to a 75 percent increase over the control. On an annual basis the reported diameter increases averaged 0.44 cm/yr and 0.25 cm/yr for manual and control treatments, respectively. For comparison, the present study exhibits a 12 percent increase in diameter growth for the manual treatment over the control. This smaller difference in growth of manual over control compared to Sonderman's study is probably due to the fact that these results are for the first growing season, whereas, Sonderman's were

Table 11. Oak crop-stem growth summary 12 months after treatment; on Potts Mountain, Craig County, Virginia.

Trmt/Method	Diameter Growth	Height Growth	Basal Area Growth	Volume (D^2H) Growth
	(cm)	(m)	(m^2)	(m^3)
2,4-D / Injection	0.86	0.62	0.0014	0.0165
2,4-D / Basal Spray	0.87	0.59	0.0015	0.0185
Triclopyr / Injection	0.88	0.65	0.0015	0.0184
Triclopyr / Basal Spray	0.87	0.60	0.0015	0.0178
Kerosene / Basal Spray	0.85	0.65	0.0014	0.0175
Manual / Chainsaw	0.91	0.75	0.0015	0.0186
Control	0.81	0.58	0.0014	0.0173
Overall Mean	0.86	0.63	0.0015	0.0178
P-value	0.95	0.30	0.98	0.98

NOTE: Values are the mean of five replications. P-values obtained from a one-way analysis of variance.

averaged over an 8-year period. Sonderman also reported that the general quality and vigor of the oaks were lower than the faster growing competing species both before and after thinning. *Lamson (1983)* reported a 20 percent increase in diameter growth of manual over control after 5 years for red oak. One would expect that the oaks in the present study will increase in growth over time for the reason that they are clearly dominating the site and, also, if one assumes the results of Lamson's and Sonderman's studies are normal.

Statistical significance was computed for the nine pre-planned contrasts (Table 5) concerning diameter growth, total height growth, basal area growth, and volume (D^2H) growth. Growth response resulting from treatment was found to be insignificant (alpha = 0.05) for six of the nine contrasts. The three contrasts exhibiting significance were control vs manual thinning ($p = 0.0291$), manual thinning vs chemical ($p = 0.0328$), and manual thinning vs basal spray ($p = 0.0191$). These significance levels were for height growth only, because all other growth parameters proved insignificant. These results agree with the height growth analysis calculated by treatment for manual thinning and control, although, only significant at the 0.30 probability level (Table 11). Also, diameter growth, basal area growth and volume growth were highly insignificant which agreed with the insignificance of the growth parameters for the nine pre-planned contrasts (Table 11). The similarity between results of these two analyses was possible because diameter growth differences between treatments were found to be insignificant and, because diameter is heavily weighted in basal area and volume estimations. Overall, the results indicate that after 12 months the crop-stems have responded better to the manual treatment than the chemical treatments and, that the crop-stems exhibited a better response to thinning than to the control.

In order to analyze correctly the effects of the chemical thinning on the crop-stems using a regression-adjusted growth index (D^2H), the control data was analyzed first. Post-treatment D^2H was plotted against pre-treatment D^2H and regressed for the control data to determine whether transformations of the data were needed. *Knowe et al. (1990)* suggested this approach to determine whether a ratio or regression estimator was more appropriate for the data. The resulting scatter plot and T-test for significance of the intercept equalling zero indicated that the regression line did not pass through the origin and that the variance was homogeneous. Since these assumptions were met by the data, no transformations were performed. Therefore, the resulting slope estimate (beta = 1.277161) along with pre- and post-treatment control means (D^2H) obtained from the regression were used in the post-treatment regression estimator for treated sprout-clumps.

$$\mathbf{H1r = 0.0739 + 1.2772 \times (H0 - 0.0565)}$$

$$\text{Prob.} > F = 0.0001; \; R^2 = 0.98$$

NOTE: Refer to the Data Analysis section in Chapter III for the details on the variable definitions.

In a study by *Knowe and others (1990)* the regression- adjusted estimator approach was used on the treated stems to analyzed efficacy or the effect on treated stem growth. The present study was concerned with analyzing the effects of treatment on the growth of the selected oak crop-stems. The resulting mean percent growth (Glr) estimates indicated a positive response to treatment based on volume (D^2H) increase over control (Table 12). The injection treatment resulted in an average of 2 percent increase over the control in crop-stem volume. This volume increase over the control was significant at the $p=0.0516$ level for the triclopyr injection treatment and the $p=0.0668$ level for the 2,4-D injection treatment. The basal spray treatment resulted in an average of < 1 percent increase in crop-stem volume over the control. This increase over the control was significant at the $p=0.1407$, $p=0.2033$, $p=0.2963$ levels for the kerosene, triclopyr basal spray, and 2,4-D basal spray treatments, respectively. The reason for the lower growth response of crop-stems following the triclopyr basal spray treatment may be due to the high translocation occurrence (92 %) cancelling some of the thinning effects. The reason for the low growth responses after the kerosene and 2,4-D basal spray treatments are not readily apparent at this time, but, may be due in part to chemical translocation into the crop-stems. The manual thinning treatment was included for comparison to the chemical treatments. A more significant effect on crop-stem volume growth resulted from the manual thinning treatment, where a 4 percent increase over the control was noted

(Table 12). The p-value (p = 0.0001) also indicated a high degree of significance for volume growth over the control.

Since the relationship between the control values for volume are used to estimate post-treatment stem volume on treated plots, contrasts involving the control could not be analyzed for significance (Table 13). The contrasts involving the manual thinning treatment showed a significance level less than 0.05 for the mean volume increase (Glr) values. The manual thinning vs chemical thinning and manual thinning vs basal spray contrasts exhibited a significant difference for Glr at the confidence level (1 - p-value) of 82 and 84 percent, respectively. These significance values for contrasts agree with the nonsignificance (alpha = 0.05) of mean Glr values between manual thinning and other treatments (Tables 12 and 13). But, the p-values for Glr contrasts do not agree with the volume D^2H change analysis, where, the p-values ranged from 0.62 to 0.90 for the same contrasts. These discrepancies between Glr and volume change would indicate that pre-treatment mean crop-stem differences between treatments were large enough to influence growth. These pre-treatment crop-stem differences may have been caused by the variability of competing sprout densities on an individual sprout- clump basis. Similar results were noted by *Knowe and others (1990)* when comparing analyses based on change with regression- adjusted estimators. Because of these discrepancies in results between analyses, regression-adjusted volume growth estimators may be more appropriate over simple volume change for future analysis of the present study.

Treatment Production Rate and Cost Comparisons

Production rate comparisons were summarized on circumference per hour, stem per hour, and hectares per hour bases (Table 14 on page 70 PAGE = NO.). Treatment costs were summarized on both circumference per hour and stem per hour bases (Table 15). Treatment cost and production rate comparisons based on circumference per hour should be weighted more heavily because it was a better indicator of actual amount treated. Differences in costs between production

Table 12. Crop-stem growth increase (Glr) over control based on regression-adjusted volume; on Potts Mountain, Craig County, Virginia

Trmt/Method	Mean Percent Glr [1]	Prob > Control [2]
2,4-D / Injection	2.01	0.0668
2,4-D / Basal spray	0.59	0.2963
Triclopyr / Injection	2.00	0.0516
Triclopyr / Basal spray	0.89	0.2033
Kerosene / Basal spray	0.91	0.1407
Manual / Chainsaw	4.32	< 0.0001

[1] Results from a one-way analysis of variance indicated no significant difference (alpha = 0.05) between treatment mean Glr values.

[2] P-values indicate significance of the mean Glr different from the control, where the control = 0.

Table 13. Significance of crop-stem growth (Glr) for treatment contrasts; on Potts Mountain, Craig County, Virginia.

Contrast	(Prob > F)
Manual vs Chemical	0.1784
Manual vs Injection	0.3545
Manual vs Basal Spray	0.1570
Injection vs Basal Spray	0.5147
Kerosene vs Herbicide	0.8394

bases (circumference versus stems per hour) within a treatment were most likely caused by the variance in individual stem circumference versus number of stems treated. Therefore, the larger the difference in cost between production rates for a treatment, the larger the variance in treated stem circumference.

The injection method of chemical treatment was significantly more productive (3232 cm/hr, 208 stems/hr) than the basal spray method (2295 cm/hr, 144 stems/hr) or the manual cutting method (1015 cm/hr, 65 stems/hr) (Table 14). The injection method averaged 29 percent and 68 percent higher productivity over basal spray and manual cutting methods, respectively, based on circumference treated per hour. Production rates based on stems per hour resulted in injection treatments over basal and manual treatments by 31 and 69 percent, respectively. The average injection production rate of 208 stems per hour compares well with the average injection rate of 223 stems per hour reported by *Campbell (1985)*. The injection production rate for the present study averaged 0.25 ha/hr (4.0 hr/ha) which includes time in locating each pre-selected oak sprout-clump. Average sprouts treated per crop-stem was 3.7. *Miller (1984)* reported a production time of 0.08 ha/hr (13.1 hr/ha) for injection, but the average number of sprouts treated per crop-tree was 13.5. Consequently, they treated 3.6 times more stems at about a 3.1 times slower production rate than the present study. If one considers the differential between the treated sprouts per crop-tree, the production time compares well for both studies.

Basal spray applications averaged 2295 cm/hr or 144 stems/hr (Table 14). Considering labor time (location and application), the average production time for the basal spray treatment was 0.15 ha/hr (6.8 hr/ha), or 42 sec/stem. Application time reported for basal spray by *Zedaker (1986a)* averaged about 5 sec. per stem. Zedaker noted that productivity rates were dependent on the stem densities present, stem size variability, and length of stem to be treated. The application time reported by Zedaker was based on stem densities of ≤2500 per hectare (1000/ac), whereas, the total stem densities of the present study averaged > 12,000 per hectare (4800/ac). The high stem densities in addition to clump location time accounts for the difference in average application times between the present study and Zedaker's report.

Table 14. Summaries of production rates by application method; on Potts Mountain, Craig County, Virginia.

Trmt / Method	Circ. Per Hr	Stems Per Hr	Area Per Hr
	(cm/hr)	(#/hr)	(ha/hr)
Injection	3232 a	208 a	0.25 a
Basal Spray	2295 b	144 b	0.15 b
Manual	1017 c	65 c	0.10 b
P-value	< 0.0001	< 0.0001	< 0.0001

NOTE: Values within a column followed by the same letter are not statistically significant at the 0.05 probability level using Tukey's (HSD) Test. P-values obtained from a one-way analysis of variance.

Table 15. Average treatment costs incurred on Potts Mountain, Craig County, Virginia and adjusted Southwide averages.

Trmt / Method	Present Study Circ/Hr	Present Study Stems/Hr	South Avg. [1] Unknown Basis
	$/ha		
2,4-D / Injection	36.05	31.35	N/A
Triclopyr / Injection	64.14	64.00	N/A
Average Injection	50.10	50.50	49.74
2,4-D / Basal Spray	56.32	49.41	N/A
Triclopyr / Basal Spray	82.23	80.34	N/A
Kerosene / Basal Spray	49.39	45.51	N/A
Average Basal Spray	62.65	58.45	65.69
Manual / Chainsaw	105.30	92.35	129.53

[1] Southwide average values were obtained from Watson and others (1987) where the reported values were adjusted (except manual cut) by replacing the reported 1986 chemical costs with 1990 chemical costs from the present study.

The differences between treatment costs are a direct result of the differences in production rates and herbicide cost for the respective chemical treatments (Table 15). The higher cost of manual thinning ($105.30/ha) is based entirely on the lower production rates, (1015 cm/hr or 65 stems/hr). The low production rates for the manual cut treatment was caused by three factors: 1) The high stand density of > 12,000/ha; 2) Sprouts were not left standing after felling but, were brought to the ground with extra care not to damage another nearby crop-stem. and; 3) Thinning sprout-clumps is more tedious than thinning seedling-origin stems because of the close proximity of cut stems to crop-stems.

Miller (1984) reported a felling production rate of 260 stems per hour, which resulted in a total cost of $83.00/ha ($33.60/ac). The thinning criteria used for competing stems in Miller's study was similar to the criteria used in the present study. Although, Miller's study had three important differences from the present study: 1) The average stand density was about 6700 stems/ha; 2) A majority of the treated stems were of seedling-origin which are much easier to fell and; 3) It was unclear whether the labor cost of locating and marking trees was included in the total costs. Therefore, the cost of manual thinning cannot be compared directly to the present study.

The average treatment cost for the basal spray method ($62.65/ha) was 20 percent higher than the average cost of injection ($50.10/ha), (Table 15). The average cost of manual thinning ($105.30/ha) was 40 and 52 percent higher than the basal spray and injection methods, respectively. The most economical treatment combining application method and chemical appears to be 2,4-D injection at $36.05/ha. The average treatment costs by application method compare favorably with the adjusted Southwide averages (Table 15). The Southwide averages were about 5 and 19 percent higher than the present study for basal spray and manual methods, respectively. The present study's average cost of injection ($50.10/ha) compares very well with the Southwide average ($49.74/ha) resulting in only a one percent difference. These results in comparing with the adjusted Southwide averages indicate that the application costs incurred during the present study are representative of actual application costs incurred by forest industry, private, and public agencies in the southern United States.

Chapter V : Summary and Conclusions

After one growing season it appears from the results that the majority of translocation into the residual crop-stems via the treated sprouts was slight. Low levels of translocation symptoms were evident on 50 to 90 percent of the crop-stem sprouts depending on the herbicide and application method. Mortality of crop-stems did not occur and only one instance of severe translocation symptoms were evident, which was due to an over-spray of 2,4-D. Control of the treated oak sprouts averaged 98 percent across all treatments. The treatment exhibiting the greatest control on treated stems was 2,4-D injection and triclopyr basal spray. Triclopyr basal spray treatment also exhibited the highest mortality on treated stems totaling 88.6 percent. The kerosene treatment resulted in the lowest mortality and resprouting occurrence in addition to the lowest crop-stem translocation rating. Even though kerosene exhibited phytotoxic effects it is not recommended for use alone as a precommercial thinning tool since the within-clump efficacy was highly variable and crop-stem translocation was directly proportional to within-clump efficacy.

Significant differences in re-sprouting of chemically treated and manual thinned sprouts occurred. Approximately 75 percent of the mechanically thinned stems re-sprouted, whereas, on average only 5 percent of the chemically treated stems have re-sprouted. Twelve months is too soon to make any predictions as to the effects of the resprouting on residual crop-stem growth. Although, one could conclude that the continued survival of the new sprouts will effect future resource availability to the crop-stems.

The analysis of variance and mean separation tests on crop-stem growth resulted in no significant differences between paired treatments for mean diameter, basal area, and volume growth at the 0.05 probability level. Although, mean height growth was significantly different between the manual thinning treatment and other treatments. An analysis of pre-planned treatment contrasts resulted in a significance between control versus manual thinning, manual thinning versus chemical, and manual thinning versus basal spray for mean height growth. These results indicate that only the manual thinning treatment has exhibited a significant growth response from the residual crop-stems after one growing season.

Significant differences in treatments resulted after using regression- adjusted growth estimators based on untreated pre- and post-treatment volume growth (D^2H). The mean growth increase of the residual crop-stems over the control was slight ranging from less than 1 percent for the basal spray to 2 percent for the injection treatments. The manual thinning treatment increased volume growth 4 percent over the control. Therefore, results from the regression-adjusted analysis were similar to the crop-stem growth results based on change, in that, the manual thinning treatment exhibited the greatest growth response after one growing season.

Production rates and treatment costs were both lower for the present study as compared to other related studies in the literature. The injection treatments exhibited the highest productivity, with basal spraying being next highest, and manual thinning being the least productive. Treatment costs ranged from \$36.05 per hectare for 2,4-D injection to \$105.30 per hectare for manual thinning. One cost that was not factored into total treatment costs was the labor cost of selecting and marking sprout-clumps and residual crop-stems prior to treatment. An estimated additional \$20.00/ha might be added to total treatment costs to account for sprout-clump and crop-stem selection time if the selection and thinning could not be done concurrently.

Average Southwide treatment costs for chemical injection, basal spray, and manual thinning compared favorably with the average treatment costs for the present study. Basal spray and manual thinning costs for the present study averaged 5 and 19 percent lower, respectively, than the Southwide cost averages. Chemical injection cost for the present study was 1 percent higher than the Southwide average. These results indicate that the application costs incurred during the present study compare favorably with the average application costs incurred for similar operations conducted by forest industry, private and public agencies throughout the southern United States.

At this point in time, chemical precommercial thinning of oak stump- sprouts appears to be a viable alternative to manual thinning. Chemical thinning can be performed safely and, if dilute solutions are applied, minimum damage to the residual crop-stems can be expected. A competitive cost advantage can exist for chemical thinning over manual thinning if care is taken in selecting the herbicide and method of application. Future remeasurements of the residual crop-stems will show whether there are any significant growth advantages of chemical application techniques versus manual thinning.

The present study should be regarded as an initial study in reference to the application of herbicides as a precommercial thinning tool for oak stump-sprouts. Additional research is needed to factor out the effects of various chemical application rates and application methods along with experimenting with other crop species.

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Appendix A. Properties of 2,4-D and Triclopyr

---- 2,4 - D ----

Referenced from Hartley and Kidd 1989, Humburg 1989, and Worthing 1987.

- Common Name: 2,4-D (BSI,ISO,WSSA).
- Chemical Name(s): (2,4-dichlorophenoxy)acetic acid.
- Trade name(s): DACAMINE 4D, EMULASAMINE E-3, and many more commercial formulations.
- Manufacturer(s): Fermenda and Rhone-Poulenc Ag Company.
- Chemical Family: Phenoxy.
- Molecular formula: $C_8H_6Cl_2O_3$
- Solubility: Soluble in water and in most organic solvents. Some formulations are soluble in oil and insoluble in water.
- Other Formulations: Amine salt, oil soluble amine salt, inorganic salt, high volatile ester, low volatile ester, invert ester, acid ester.
- Soil Behavior: Adsorption ratio 1:95 in black acid soils. Salts of 2,4-D are leached in sandy soils. Microbial breakdown in warm, moist soil. Rate of breakdown depending on soil characteristics, temperature, moisture, and organic matter. Oil soluble amines very low volatility. Average persistence 1 to 4 weeks.
- Mode of Action: Plants absorb salt forms of 2,4-D most readily. Translocation is influenced by growth status of plant. Both xylem and phloem movement and accumulation occurs at the meristematic regions of shoots and roots. Causes abnormal growth response and affects respiration, food reserves, and cell division.

- Principal Use: 2,4-D is a systemic herbicide widely used for control of broadleaf weeds in cereal crops and other crops.
- Application: Spray application is usually post-emergence, by air or ground equipment. Usual carriers are water,diesel,or oil. Application rates range from 3 to 4 lbs/acre.
- Toxicological Properties: Acute toxicity (oral LD_{50}) of the various formulations are in the range of 300 to 1000 mg/kg for rats, guinea pigs, and rabbits.

---- TRICLOPYR ----

Referenced from Hartley and Kidd 1989, Humburg 1989, and Worthing 1987.

- Common Name(s): Triclopyr (BSI,ISO,ANSI,WSSA).
- Chemical Name(s): [3,5,6-trichloro-2-pyridinyl)oxy]acetic acid.
- Trade Name(s): GARLON 3A, GARLON 4, GRAZON ET, TURFLON Amine, and TURFLON Ester.
- Manufacturer(s): Dow Chemical Co.
- Chemical Family: Pyridine, organochlorine.
- Molecular Formula: $C_7H_4Cl_3NO_3$
- Solubility: Soluble in water and most organic solvents.
- Other Formulations: Triclopyr + 2,4-D (as esters), triclopyr + picloram (as amine salts), triclopyr + 3,6-dichloropicolinic acid.
- Soil Behavior: Fairly rapid degradation by microbial activity, with an average half-life of 46 days, depending on soil and climatic conditions.
- Mode of Action: Selective systemic herbicide, absorbed by foliage and roots, with translocation throughout the plant and accumulating in the meristematic tissue. Acts as an auxin-like substance.
- Principle Use: Control of woody plants and many broad-leaved weeds. Used in grassland, uncultivated areas, pine forests, and rice plantations.
- Application: Ground or aerial foliage spray, basal, tree injection, and postemergence in turf. Application rates range from 0.25 to 9lbs/acre. Usual carrier is water for foliage spray and fuel oil for basal application.
- Toxicological Properties: Acute oral LD_{50} is 713 mg/kg for rats, 550 mg/kg for rabbits, and 310 mg/kg for guinea pigs.

Appendix B. Site Index determination.

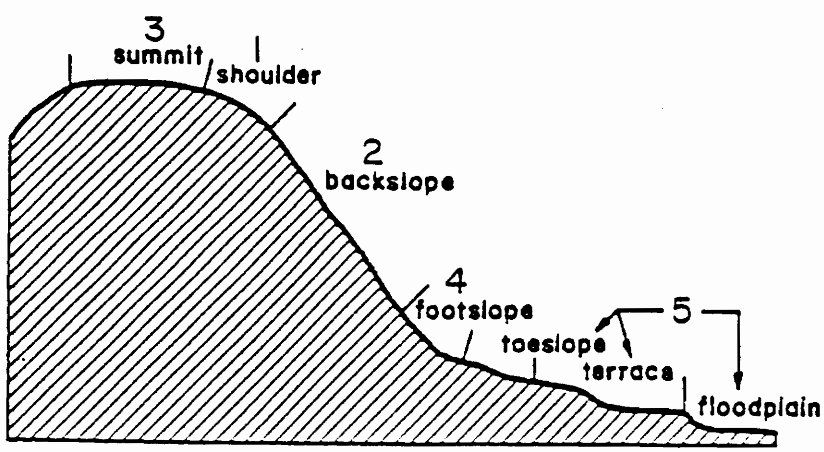
Relative productivity ranking of aspect, slope position, and slope percent used for determination of the Forest Site Quality Index (FSQI). The sum of the ranks for aspect, slope position, and slope percent is the FSQI. The higher sums represent higher site quality. By inserting an FSQI value into the site index equation, a site index value in feet (base age 50) for upland oaks is obtained *(Wathen 1977)*.

SI = 35.033 + 3.301 (FSQI)

Example: an aspect ranking of 5 (81-145 degees), a slope ranking of 3 (30-44%), and a slope position ranking of 2 (backslope) sums to 10.

Therefore: SI = 35.033 + (3.301 x 10) = 68.0 ; metric equivalent = 20.7

Aspect Ranking	Azimuth Range (Degrees)	Slope (Percent)	Ranking
1	196-260	3-14	5
2	166-195, 261-280	15-29	4
3	146-165, 281-340	30-44	3
4	0-20, 341-360	45-59	2
5	81-145	> 60	1
6	21-80		



Appendix C. Chemical formulations and application rates.

Injection: Applied at 1 ml per 2.54 cm dbh diluted in water. (1 ml of chemical solution per 2.54 cm dbh is a recommended dosage from the label).

Garlon 3A	44.4% a.i. per gal.of Triclopyr (triethylamine salt) or 31.8% a.e. (0.35 kg/l or 3.0 lbs/gal) of Triclopyr. Mixed as a 1:1 solution in water. (0.23 mg a.i. per 2.54 cm dbh).
2,4-D Amine	46.8% a.i. per gal of 2,4-D (dimethylamine salt) or 38.9% a.e. (0.44kg/l or 3.8 lbs/gal) of 2,4-D. Mixed as a 1:1 solution in water. (0.23 mg a.i. per 2.54 cm dbh).

Basal Spray: Applied at 5 ml per 2.54 cm DBH diluted in kerosene.

Garlon 4	61.6% a.i. per gal of Triclopyr (butoxyethyl ester) or 44.3% a.e. (0.47kg/l or 4.0 lbs/gal.) of Triclopyr. Mixed as a 1:13 solution in kerosene. (0.23 mg a.i. per 2.54 cm dbh).
2,4-D Ester	62.5% a.i. per gal of 2,4-D (octyl ester) or 43.7% a.e. (0.44 kg/l or 3.8 lbs/gal.) of 2,4-D. Mixed as a 1:13 solution in kerosene. (0.23 mg a.i. per 2.54 cm dbh).
Kerosene	5 ml of kerosene applied undiluted per 2.54 cm dbh.

Vita

of

Henry David Stein

PERSONAL

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Military Service:	U.S. Army, Active Duty (1973-74), Rank: E4 U.S. Army, Inactive Reserve (1974-79)

EDUCATION

M.S. - 1991	Virginia Polytechnic Institute & State University, Blacksburg, VA. Major: Forestry
B.S. - 1989	North Carolina State University, Raleigh, NC. Major: Forestry Graduated with Honors
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PROFESSIONAL ORGANIZATIONS

Society of American Foresters (SAF), National and Chapter.
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