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APPLICATION VARIABLES AND THEIR INFLUENCE ON FOREST HERBICIDE EFFICACY AND SELECTIVITY: GAINING UNDERSTANDING AND CONTROL. J.H. Miller, USDA Forest Service, Auburn University, AL 36849.

ABSTRACT

Available research is reviewed on the interactions of application variables, herbicides, and species. Objectives of this review are to gain insights into why variation occurs with herbicide performance, how current knowledge might be applied to enhance efficacy and consistency, and research pathways that should foster integration of application-efficacy models. A historical context is provided on southeastern forestry herbicide applications. Adoptable application technology from agronomy and right-of-way sectors are explored. To enhance consistency and performance, increased rates and optimized timing hold most promise. Optimizing droplet size spectrums and new surfactants also have potential. Multidimensional efficacy functions are needed for the commonly abundant species and often-used tank mixes by rate and timing. Integratable research is the key to advancement.

INTRODUCTION

Herbicides can be viewed as potential energy that is released and directed through the application process. To be effective an herbicide must *reach the* surface of the plant., *be adsorbed* into the plant, and *translocate* to sites of action in adequate concentrations to disrupt critical plant metabolism. Application variables directly influence the first two processes and have been shown to affect translocation to some degree. Thus, understanding these influences is critical for efficient and safe -uses of herbicides.

These physiological pathways are linked to the human challenge of uniformly applying a prescribed rate of herbicide or proportional herbicide mixture, in a specified water volume for sprays, on each land unit in a treatment area. Application occurs as a complex interaction with environment before, during, and after the treatment. Application precision determines whether there is no effect or varying levels of vegetation control up to a herbicide's optimum. The purpose of this paper is to review in a historical context: why we have the variation in outcomes, how we might apply current knowledge of application variables to enhance consistency and optimize herbicide performance, research pathways that would enable integration of application-efficacy models and spawn decision support systems, and some currently adoptable application technology.

In 1996, of Southern forestry herbicides, an estimated 77 percent were applied aerially, mainly as helicopter sprays (7). Ground machines applied 10 percent, backpack sprayers applied less than 1 percent, and the remaining 12 percent was probably by injectors. Because of their importance, this review will focus mainly on aerial applications and spray technology. Other application methods currently used in forestry include granules by helicopter, sprays and granules by ground machine, tree injection, backpack foliar sprays, backpack basal sprays, and manual granule applications. Considerable improvements in both injection and backpack spray applications have been yielded by much recent research in the region. Both operational and research application procedures for these other application methods have been reviewed elsewhere (36, 32)

MSTORY OF SOUTHEASTERN FORESTRY HERBICIDE APPLICATION TECHNOLOGY

After the introduction of 2,4-D in the 1940's, many small companies introduced sprayers into the machinery market. Prior to that time, most spraying was in horticulture, applying fungicides and insecticides. Early sprayers were manufactured by small companies using available components. This situation produced small profit margins. Large machinery manufacturers did not and still do not have R&D efforts in application technology. Aerial application systems for forestry have mainly come from those designed for treating right-of-ways, while ground machine sprayers are still built one at a time. Early equipment development was driven by a boom in registered agricultural herbicides from 25 in 1950, to 75 in 1960 and 120 in 1969 (28).

In forestry, it was the early 1950's that 2,4-D herbicide was first applied using fixed-winged aircraft and also with the newly-developed tree injector. At the same time, rolling drum choppers, brushblades, disk harrows and bedding plows were developed and being rapidly adopted for site preparation in southern forestry. Research and development in the

1960's focused on refining applications of 2,4-D, 2,4,5-T, and silvex with helicopters and mistblowers. The cancellation of 2,4,5-T in 1979 resulted in a surge of new herbicides for forestry that slowed in the late 1980's. During this period the Microfoil boom and its control droplet nozzles were introduced for treating right-of-ways, followed by a gradual adoption by southern forestry. This marked the entry of large-droplet application capabilities in forestry. Conventional hydraulic nozzles on helicopters still applied most forestry herbicides, using a wide spectmm of droplet sizes. These systems still have limited use today.

In the early 1980's, "homemade" sprayers and spreaders were mounted on skidders and bulldozers by both forest industry and consultant applicators. The Omni air-blown spreader was commercially introduced in 1983, with 23 built. During the same period, manual application equipment and methods using backpack foliar directed sprays and basal stem sprays were refined and widely tried. A gradual shift started from mechanical vegetation control to herbicide applications during the 1980's as the treatment cost differentials widened (7). The Raindrop nozzle was first used aerially on helicopter booms to produce a spectmm of large, minimum-drift droplets. This system still remains as an often-used option. The use of herbaceous weed control treatments began to increase, especially on selected State's Conservation Reserve Program lands. Agriculture spray technology, from high-tech (e.g., in-line injection systems with metering) to low-tech, was reconfigured and adopted for forestry needs.

Development in spray technology slowed in the 1990's, as reductions in R&D occurred across the country and industry. Use of backpack applications was scaled back in the early 1990's, as were ground machine applications. A few companies and agencies continued meager efforts in refining application configurations from right-of-way and agronomy. The Thru Valve Boom was introduced as a control droplet application (CDA) system for helicopters and was rapidly adopted by southern applicators. By the mid-1990's, Global Positioning Systems (GPS) were introduced and development started towards their use in treatment documentation as well as helicopter guidance. Drift guard and extended range (low pressure and large droplet) spray tips for ground spraying were introduced. In forestry, the amount of land treated by helicopters in forestry increased as treatment costs remained stable and benefits from treatment response were realized by forest industry.

EFFECTIVE AND SELECTIVE COMPETITION CONTROL - THE DRIVER

Woody and herbaceous competition interferes severely with pine growth and productivity, with their combined antagonism often greater than either component singly (13, 35). Greatly enhanced crop pine growth requires control of most herbaceous competitors during the first two years of plantation establishment and the majority of woody competitors throughout a rotation (24, 35) (Figure 1). At present, multiple applications are required to achieve these low levels of competition because of less than optimum control with a single treatment (35). Also in recent years, it has become evident that forest herbicide applications have both short-term and long-term effects on species diversity, habitat values, and biogeochemical processes (52, 39, 47, 4, 27). Thus, forest vegetation management should be viewed as a broader ecosystem culture, or by a newly coined term, ***ecoculture***.

The term ***ecoculture*** may have use as a term to appropriately expand the actual role performed by vegetation managers. Ecoculture can be defined as: the management of vegetation on the landscape using ecological knowledge to insure sustainability of primary productivity of terrestrial and aquatic systems and diversity in species, genotypes, and habitat. Derivatives of this term would be: Forest Ecoculture = Forest Vegetation Management, Forest Ecoculture Science, and Forest Ecoculturist = Forest Vegetation Management Specialist. These proposed terms are also more concise.

About 20 herbicides are currently labeled for the control of woody and herbaceous competition in southeastern forestry, and fewer new herbicides are being added less frequently. The current herbicides vary greatly in their spectmm of species efficacy, from very narrow to fairly wide (38). Their costs are generally considered high with break-even points for investments unclear. This limits higher rate applications. Without the introduction of more efficacious active ingredients, we are left with seeking improvements in performance through tank mixing, surfactant additions, and advances in application technology. A trial and error approaches appears to be the current path being taken for efficacy optimization due to the complexity of the herbicide-application-species interactions. What is required is renewed efforts in systematic research and development to address this complexity, so that effects can be isolated and understood, and in turn used to advance the technology.

In Southeastern forests there are approximately 200 species of hardwoods, 400 species of shrubs, and more than 2,000 species of herbaceous plants that can potentially compete with tree crops. However, of the commonly abundant ones, less than 80 woody species account for 90 percent of the competition (37). Similarly, less than 100 species of herbaceous plants are found in abundance on most sites. The spectrum of control for even these species using common herbicide mixtures is poorly documented. Surprisingly, species efficacy data are rarely reported in research results. Efficacy and selectivity information is needed not only for intensive vegetation management but also for knowledgeable management of our rich associated flora and its benefits in forest health and long-term productivity and sustainability.

INTERACTIONS OF APPLICATION VARIABLES

There are many interactions among application variables, the environment, and crop and target species. Some of the main elements are shown in figure 2. If developing technology is to aide in enhancing efficacy then an increased understanding of the multiple interactions must be revealed through careful and linkable research.

Interaction of Species with Active Ingredients

Each species of woody and herbaceous plants, and individual populations of species, differ in their uptake, translocation, and detoxification of herbicide active ingredients Green et al. (14) found that red maple (*Acer rubrum*), white oak (*Quercus alba*), yaupon (*Ilex vomitoria*), and loblolly pine (*Pinus taeda*) differed in both absorption and translocation patterns of glyphosate plus a surfactant. They concluded that translocation patterns (e.g., more to roots) were directly related to glyphosate susceptibility and tolerance. D' Anieri et al. (6) found little difference in absorption of glyphosate among red maple, sweetgum (*Liquidambar styraciflua*), and loblolly pine, but identified significant differences in the amounts translocated. These differences explained, in part, the variation in susceptibility observed operationally. Bollig et al. (3) reported that adding an organosilicone surfactant to a spray mixture with triclopyr did not increase translocation in red maple, as had been reported for other plants (48).

Efficacy can be enhanced by increased absorption, but only to a point when translocation becomes limiting (2). Absorption is known to be influenced by formulation, surfactants, droplet size and frequency, coverage, and plant status of moisture stress and physiological activity (18). Thus, if species susceptibility is greatly influenced by internal physiological processes, such as translocation and detoxification, then refinements in application, formulation, or adjuvant additions aimed at increasing absorption may result in only marginal improvements in performance.

Interaction of Application Rate with Active Ingredients and Species

There are five broad-spectrum herbicides currently labeled in forestry. These are imazapyr, glyphosate, triclopyr, hexazinone, and mainly for herbaceous control, sulfometuron. Operationally, four of these active ingredients are commonly applied in tank mixes (less so with hexazinone) to further increase the species control spectrum. Other less commonly added active ingredients are piclomm, dicamba, metsulfuron, and 2,4-D. Species efficacy information on frequently used tank-mix combinations is lacking as they control the common woody and herbaceous species. Only with such information can optimization calculations be made to approach predictable and repeatable levels of control and selectivity (38).

Tank mix sprays are being increasingly used in southern forestry because of the numerous target species on most sites. And because single species are not completely controlled by a single herbicide, even at higher rates. Pitt et al. (43) reported on increasing rates of foliar directed sprays on mixed species in New Brunswick and found that glyphosate formulations were more effective than triclopyr when applied in September, A parabolic rate-control relationship was evident with glyphosate tending towards 100 percent control at the 1X rate, while triclopyr was asymptotic at about 50 percent overall control. Recently collected data for cogongrass (*Imperata cylindrica*) show asymptotic rate-control curves for imazapyr and glyphosate (Figure 3). Both study results suggest that 100 percent control, even of a single species is approachable but not probable, when using increasing rates and only one application for perennial plants. There is a zone of diminishing return where increasing rate controls a smaller and smaller percentage. Still it is well recognized that rate is the most influential determinant of performance.

Active Ingredient Antagonism and Synergism in Tank Mixes

Antagonism and synergism of active ingredients as discussed here is in terms of reduced or increased activity on a species or group of species, not in terms of spray tank incompatibility. Very few investigation have been reported for southeastern forestry. Ezell et al. (8) reported antagonism of sweetgum control occurred when imazapyr was mixed with triclopyr ester and amine, 2,4-D ester and amine, dicamba, and picloram. Only 2,4-DP did not appear to reduce imazapyr efficacy on sweetgum. Miller and Edwards (38) examined the additions of metsulfuron to glyphosate on 14 species of arborescent and nonarborescent woody plants for enhanced control. No antagonism was observed, while synergism was indicated on control of 11 species (see examples Figure 4). Quicke et al. (45) examined pine release sprays in Arkansas and found that adding hexazinone to imazapyr did not improve hardwood control, and no benefits occurred adding metsulfuron to either glyphosate or hexazinone. Horsley (20) found in Pennsylvania that no surfactant or herbicide addition *tested* **increased** *the* control of *striped maple* (*Acer pensylvanicum*) using formulated glyphosate. Additions of one wetting agent and 2,4-D were antagonistic.

Identifying antagonistic tank mixes should be a high priority, since this is the era of tank mix proliferation, Tank mixes offers the most potential for broadening the number of species controlled in intensively managed plantations. However, overall antagonisms may nullify synergistic gains in control of certain species as additional herbicides are addedtoamix.

Thoroughness of Miring

Incomplete mixing of spray solutions has been identified as a problem, especially with large batches for aerial applications (10, 25). Mixing thoroughness of glyphosate has been the main focus . This obviously can be a major source of non-uniformity. Conductivity meters are being used to monitor both mixing homogeneity and to check concentrations of active ingredients within mixing tanks. They also have possible use for detecting critical levels of antagonistic salts. Field-durable conductivity meters are becoming much less costly and offer the most rapid means of assessing a solution's ionic strength which has multiple implications.

Interaction **of Timing and Plant Status with Active Ingredients and Species**

Herbicide activity increases during a period of time, reaches a maximum, and then declines again (Figure 5). Changes in timing appear to be as influential as rate. Miller (30) reported on May, July, and September timings of foliar sprays for imazapyr, glyphosate, triclopyr ester and amine, and 2,4-DP on eight woody species. The timing for maximum control for a woody plant species varied by active ingredient (see examples Figure 6). Even though July was generally the overall most effective time of application, a few specific species would only be marginally controlled at that time. It was evident that timing effects where confounded by herbicide, which causes a timing antagonism that can occur with tank mixes.

Timing of application also interacts with the current year's weather as it effects plant status, most importantly, plant moisture stress. D'Anieri et al. (6) found glyphosate absorption and translocation was influenced by application date, as well as water stress, with the pattern varying among sweetgum, red maple and loblolly pine. Efficacy on sweetgum was a product of both timing and water stress, while timing only was significant with red maple and loblolly pine. Unstressed red maple and sweetgum had very narrow windows of maximum susceptibility in September. This would indicate that to optimize efficacy, precise timing and knowledge of the moisture status would be required.

Rainfastness **and "Dewfastness"**

Growing season applications in mid-summer occur during general periods of isolated thunderstorms and heavy morning dew. Product labels and manufacturer's literature often specify that only hours are needed between application and rainfall to maintain effectiveness. Green et al. (14) found that [^{14}C]glyphosate absorption rates varied greatly among loblolly pine, red maple, yaupon, and white oak, with all but yaupon requiring more than 5 days to absorb greater than 50 percent of maximum absorbed.

Michael et al. (29) reported that 60 to 83 percent of applied imazapyr remained on upper leaf surfaces of common woody species 24 hours after application., while less than 40 percent remained after 48 hours. Blackberry (*Rubus* spp.) was an exception with 59 percent absorption within 1 hour. A rainfall of only 3 mm washed 100 percent of the applied imazapyr *off leaves* of sweetgum and honeysuckle (*Lonicera japonica*). Bollig et al. (3) also reported that only 50 percent of applied triclopyr was absorbed by red maple leaves within 2 hours, while 3 days were required for 78 percent uptake. Michael et al. (29) found similar results with triclopyr ester on sweetgum, with 38 percent absorption within 1 hour and 80 percent uptake within 48 hours.

These findings would indicate that days, not hours, are required for even minimal absorption and that slight rains can wash herbicides from foliage. Much more research is required, especially on the effects of dew, since no research was found on this subject. It would appear that dew would confound the effects of many factors, such as spray volume, droplet size spectrum, surfactant concentrations, and plant moisture status. Hypothetically, dew could enhance foliar absorption through leaf cuticle hydration, even during high moisture stress conditions of mid-summer. The daily rewetting of leaves by dew could stimulate and prolong periods of absorption. However, the dilution effect could be detrimental to specific herbicides, especially for glyphosate which requires high droplet concentrations (26).

Interaction of Droplet Size and Volume with Active Ingredient and Species

Knoche (22) made a literature review of the effect of droplet size and carrier volume on herbicide performance and synthesized over 140 reports from agronomy and forestry. He recognized that droplet size effects are always confounded with droplet frequency at constant herbicide dose and carrier volume. Similarly, carrier volume effects are always confounded with spray concentration and droplet frequency at constant droplet size and herbicide dose. Recognizing these complexities and the absence of appropriate variable controls in certain reviewed studies, in general he found, efficacy increased as droplet size decreased at constant carrier volumes. (Droplet sizes are measured and often expressed as Volume Median Diameter (VMD), which is the diameter (micrometers, μm) where half the spray volume is of larger diameters and half the volume of smaller diameters.) For grasses with predominately vertical structure, decreasing droplet size in the class < 150 μm VMD increased efficacy more consistently than in the droplet size class > 150 μm, or compared to broadleaf plants with a predominantly horizontal structure. Carrier volume effects on herbicide performance were less consistent At low volumes (<100 1 ha^{-1} or IO gal a-‘), performance more frequently decreased as carrier volume decreased, whereas the reverse trend was observed at higher volumes (>400 1 ha^{-1} or 43 gal a”). For glyphosate, efficacy consistently increased as carrier volume decreased, but for other herbicides, performance generally decreased as carrier volume decreased.

Other forestry experiments support these generalizations and provide further specifics on the interactive effects of droplet size and volume applied. Liu and Campbell (26) found that glyphosate concentration was more important than droplet size and number in determining efficacy on trembling aspen (*Populus tremuloides*). Droplet sizes from 177 to 1,589 μm were examined. Prasad and Cadogan (44) applied 150, 350, 450, and 650 μm VMD droplets of formulated glyphosate, triclopyr, and hexazinone to leaves of white birch (*Betula papyrifera*), aspen (*Populus tremufoides*), and red alder (*Alnus rubra*). Smaller droplets caused significant more leaf injury than large droplets, and in the case of glyphosate and triclopyr, more total-plant damage. This last findings is expected since hexazinone is mainly soil active. Usually, droplets less than 450 μm resulted in similar phytotoxicity. Forster et al. (11) reported that increasing droplet size from 650 to 1,OGO μm VMD decreased adhesion on red maple, northern red oak (*Quercus rubra*), and sweetgum leaves.

All nozzles, even control droplet applications systems, produce varying amounts of spray solution in a broad range of droplet diameters. Common VMD's for nozzles used in aerial applications in fores&y vary from 140 to 1,375 μm (Picot et al. 1989). The large droplets (>400 μm) are more apt to fall on to the target swath than small droplets (< 100 μm) that can drift for indefinite distances. Thus, both aerial and ground applications produce a broadened swath of spray deposits-mostly invisible. With better quantification of these behaviors, the interaction of weather variables and droplet spectrum could be used to predict and regulate swath placement and buffer widths. The invisible across-swath spread by wind could be predicted to enhance uniformity.

In more applied research, Hanks and Bryson (15) compared nozzles and adjuvants often used for ground machine spraying of herbaceous plant herbicides in forestry. They found that similar VMD's were produced by TeeJet brass and extended range (XR) nozzles (with VMD's of about 200 μm). However, droplets with twice the VMD were produced by Drift Guard (DG) nozzles at the same pressure. Droplet size was also strongly influenced by adjuvant additions. A drift retardant (Sta-Put) and two wetting agents, Agridex and Induce, increased droplet size VMD, while additions of the commonly used X-77 wetting agent, slightly decreased size. This would indicate that nozzles and drift retardants that produce large droplets may help to prevent drift but their size spectrum may be approaching marginal effectiveness.

Optimum VMD's for maximizing efficacy need to be experimentally determined for herbicides and systems used in both aerial and ground applications in forestry. Also, the actual size spectrum of droplets reaching target canopies in forestry treatments need to be throughly quantified so that development can move for optimization of efficacy and drift prevention.

Interaction of Surfactants and Active Ingredient and Species

Zabkiewicz (48) summarized development and uses of the newer organosilicone surfactants in forestry in New Zealand and reported increased wetting and even increased translocation of glyphosate, metsufuron, and triclopyr. Enhanced control in the field was made clear. Organosilicone surfactant additons caused a larger proportions of applied spray to be taken up rapidly into the stomatal chambers, absorbed efficiently into the leaf cells, and translocated out of the treated foliage.

Bollig et al. (3) found increased absorption of triclopyr in red maple with an organosilicone adjuvant but not increased translocation. Lower leaf surfaces of red maple were more effective in absorption of triclopyr with the organosilicone surf&ant than upper leaf surfaces. An expanded examination of triclopyr (12) found additions of Silwet L-77 organosilicone surfactant increased absorption of the amine formulation to levels comparable to the ester formulation in leaves of red maple, northern red oak, and sweetgum (only the upper leaf surface). The amount of contact leaf damage within 24 hours was also inversely related to the amount of translocation within these species, affirming a long held hypothesis that rapid leafdamage hinders translocation. Additional experiments by the same team (50) confirmed that organosilicone surfactants increased triclopyr absorption from lower leaf surfaces, but the rapid uptake may hinder translocation.

Zedaker and Jackson (51) summarized their research on imazapyr and surfactants and reported: (1) Silwet L-77 provided significantly greater uptake than Cide Kick II, Agri-Dex, Timbersurf 90, LI-700, Sun Wet or Valent X-77 over both leaf surfaces, on red maple and sweetgum; (2) Agri-Dex and X-77 also improved uptake over imazapyr alone, but not consistently across both surfaces and species; (3) uptake in loblolly pine was maximized by LI-700 but no surfactant mix was greater than imazapyr alone; and (4) rainfastness was not affected by surfactants.

This research on the new and promising organosilicone surfactants in forestry indicates that:

a. Organosilicone surfactants, especially Silwet L-77, increase absorption of triclopyr and imazapyr in woody species (young plants in laboratory experiments), mainly by lower leaf surfaces.

b. Translocation does not appear to be generally enhanced.

c. Rainfastness can or cannot be increased.

d Organosilicone and other surfactants vary in their activity by species and leaf surface (lower vs upper).

It is not known, in forest applications, how much herbicide mix is deposited on the lower leaf surfaces where increased absorption has generally been found. This is another piece of information required when determining actual applications deposition of droplets in forestry treatments.

Interaction of Water Quality x Antagonistic Salts x Surfactants

Much research has been focused on glyphosate activity in agronomic crops and weeds as affected by antagonistic salts and surfactants. This work has been done mainly in the northern Mid-west (most recently: 46, 23, 40). Calcium and to a lesser degree, magnesium and iron, have been reported as significant antagonists to glyphosate. Additions of specific surfactants and ammonium sulfate can overcome this antagonism by varying degrees by weed species. In general, as much as 25 percent loss of efficacy can occur when calcium exceeds 300 mg l^{-1}. These results from the Northern Great Plains can have implications for areas in the Southeast that have high levels of calcium chloride in mixing water, such as in some parts of the Lower Coastal Plain and limestone areas of the Ridge and Valley and Cumberland Plateau. There is a need to identify specific locations with prohibitive levels of antagonistic salts where spray water should not be used when applying glyphosate. There is some indicate that antagonistic salts may effect efficacy of imazapyr as well (2 I), which indicates a broader examination of their impacts is needed.

Application Uniformity

Neither single nozzles nor multiple nozzles spaced along a boom produce uniform volume distributions across a swath (31, 33, 42). Uniformity can only be approached with a knowledgeable selection of nozzles, tips for CDA's, and adjustment of nozzle spacing and spray pressure. Within swath distribution of both sprays and granules applied by helicopter are further made non-uniform because of the rotation of the prop (9, 42). Higher volumes of 10 to 20 percent are found on the outer swath edges and there is an inherent skewing to the right side. Within swath uniformity can only be achieved through careful testing and adjustments of nozzles and booms.

Wind turbulence also disrupts uniformity to varying degrees depending on wind and flight speed, wind direction relative to the flight line, and height of release. Wind invariably spreads sprays (and granules) across adjoining swaths, although this is invisible to pilots. Another major source of non-uniformity is the spacing of swaths relative to the speed and direction of the wind Too much swath overlap results in very high-rate streaks and too widely spaced swaths results in skips. Furthermore, accurate on-site weather data along with nozzle-boom characteristics are needed to calculate appropriate swath spacings and buffer sizes (1). Only when these causes of non-uniformities are minimized or eliminated can uniform control be achieved.

Burch et al. (5) using computer simulation predicted that only 65 percent of helicopter applied herbicide would reach the target area using disc-core (conventional) and raindrop nozzles with wind at 8 k hr^{-1} (5 mph) and a 16 m (50 ft) release height. When using the Thru-Valve Boom and TVB 030 nozzles, 85 percent of the mix reached the target area. Thus, 15 to 35 percent of spray mixtures fail to reach target plants during "marginal" wind conditions. Rate adjustments may be needed according to application conditions for predictable control outcomes.

ADOPTABLE APPLICATION TECHNOLOGY

"More than 90 percent of all herbicides are probably applied with sprayers that contain the same four basic components that were available more than 40 years ago-a tank, pressure regulator, pump, and spray nozzles. There have been many proposed alternate methods of applying herbicides, but the conventional hydraulic sprayer continues to be the most acceptable method to apply herbicides" McWhorter and Gebhardt (28) "Introduction to Methods of Applying Herbicides".

Developments in application technology that are being adopted or may have an potential for use in forestry are:
-Hooded sprayers for herbaceous weed control in hardwood and pine plantation establishment (19)
-Air-blast sprayers for mid-story control treatments. Horsley (20) reported that spray distribution in maple crowns with an airblast sprayer was more important for control than the surfactants or other herbicides tested for mixtures with glyphosate.
-Differential Global Positioning System (GPS) for guidance and • &?atment documentation with aerial and ground machine applications (42).
-Low volume oil-water applications as thin invert emulsions (Thinvert) has been introduced for right-of-way spraying and may have use to expand application timing windows and improve efficiency.
-Wipes and "wet blade" machines that apply herbicides when cutting may be applicable to forestry brush control (17).
Other innovative spray systems with some potential for spraying short rotation woody crops and fiber farms, but with development requirements, are: air-assisted electrostatic sprayers, sensor-controlled or weed recognition sprayers, ultra-low volume sprayers, and air-assist sprayers. Carpet roller applicators and wick applicators have been tested in forestry and judged to be impractical (16)

Conceptually, an integrated system would hold potential to increase precision and uniformity of helicopter applications. The components of the system would consist of (1) a real time differential GPS helicopter guidance system, (2) a portable weather station, (3) an easily adjustable aerial boom or system, and (4) an accurate spray application/drift model to specify nozzles, swath spacing, and buffer widths. With real time linkage between the weather station and the GPS guidance system, constant corrections in application could be made for uniformity and to safeguard against drift and buffer trespass.

NEEDED RESEARCH AND DEVELOPMENT

Research is needed to determine the following:
a. A massive effort is required to determine the efficacy of commonly applied herbicide mixtures on the commonly abundant plant species, by rate and timing and subregion (and other application specifics).

b. Within swath droplet deposition patterns by forestry application systems, including the proportion deposited on the top and bottom of leaves.
c. The optimum droplet size spectrum for maximizing control with common herbicides on the commonly species.
d. Improved surfactants for improved wetting and rainfastness.
e. Improved decision support systems for prescribing and applying forest herbicides.
f. The effects of dew on the efficacy of the commonly used tank mixes.

CONCLUSIONS

The numerous interactions of applicationvariables with the multitude of species on forested sites presently yields often unpredictable outcomes. The following factors can assist in minimizing inconsistencies:

1. Careful selection of *the* most *efficacious herbicide and herbicide mixtures* for the spectrum of target species and applications using adequately *high rates* at the *optimum timing* are the most important factors. To be repeatable in this optimization process would require knowledge of all mixtures and their effect on the commonly abundant species at multiple timings. There are about 280 common woody and herbaceous species in the region. The multitude of optimization calculations of potential herbicides for an area could be performed in a decision support system. An expanded version of an existing system, Chemical Expert System for Silviculture (ChESS) (49) would be required with multidimensional efficacy functions.

2. Antagonistic tank mixes should be identified as they influence specific species and overall control.

3. Application uniformity can be increased by adjusting nozzles and booms to minimize within-swathvariation using appropriate monitoring devices, throughly mixing spray solutions, using mixing water that contains no antagonistic salts, and by adding effective surfactants and adjuvants. Conductivity meters can be used to monitor homogeneity of mixing, check concentrations of certain herbicides in solution, and possibly to detect high salt levels in mixing water. Further research and development in surfactant technology may yield higher levels of efficiency by increasing absorption, and possibly translocation and rainfastness.

4. The absence of rainfall within 2 to 3 days of foliar applications appears necessary for optimum absorption. Research is needed on the effects of morning dew on foliar spray applications.

5. To increase efficacy, nozzles should be selected that deliver the smallest droplet size spectrum without resulting in off-site drift and drift into buffer areas.

6. For application of glyphosate, high droplet concentration is required by either decreasing the total spray volume or increasing the rate. Small droplets sizes are usually required when low volumes are applied to achieve adequate coverage.

7. Herbicide effectiveness and safety could be increased using improved application models. Models that integrate current weather conditions and application system variables could assist in optimizing uniformity and safeguarding against off-site drift and buffer trespass.

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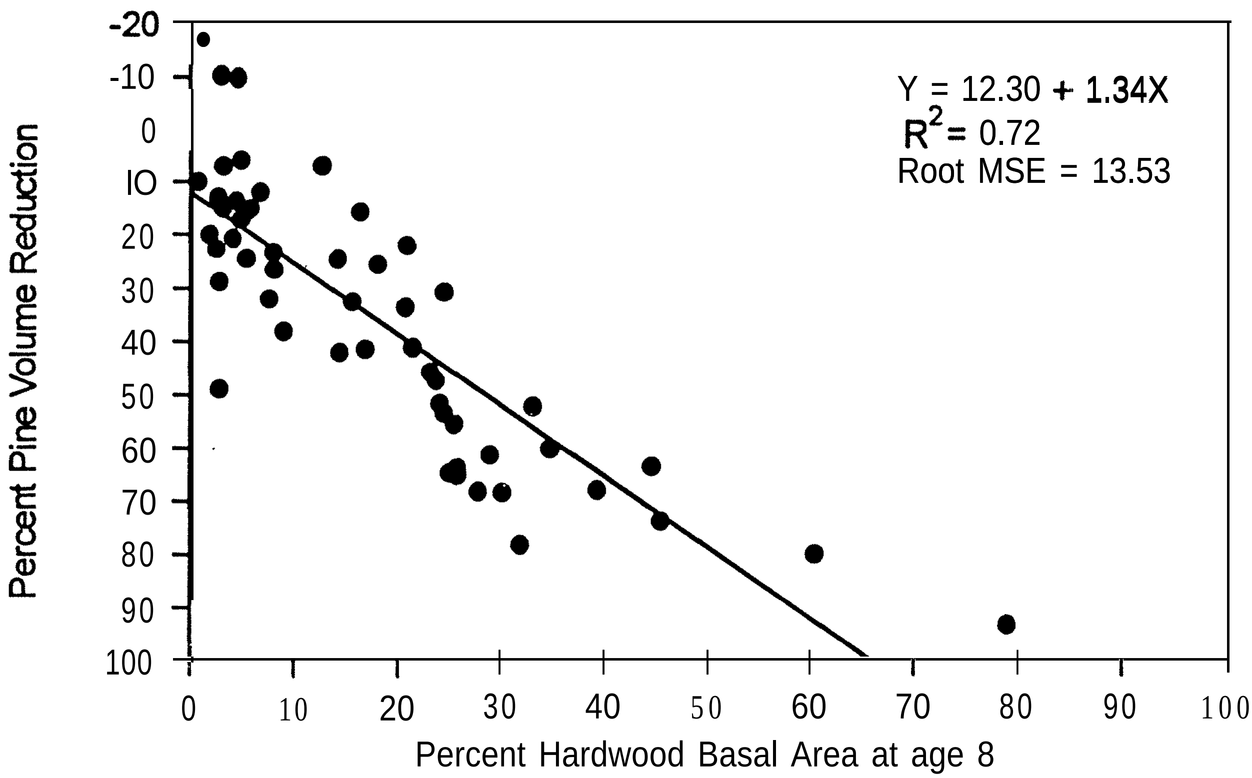

Figure 1. Relationship between hardwood basal area and pine volume at age 8 for the 13 COMP sites located in 7 Southeastern states.

Spray Solution or Granular Product	Application	Plank / *Status*
Active ingredient	Rate	Target species/size
Formulation	X Thorough mixing	X Crop species/size
	Mix Antagonism	Moisture stress
	Timing x Weather	**Physicological Activity**
	Rainfastness	
	Volume and droplet size	
	Adjuvants/surfactants	
	Water quality	
	Uniformity x Weather	

Figure 2. The interactions during application.

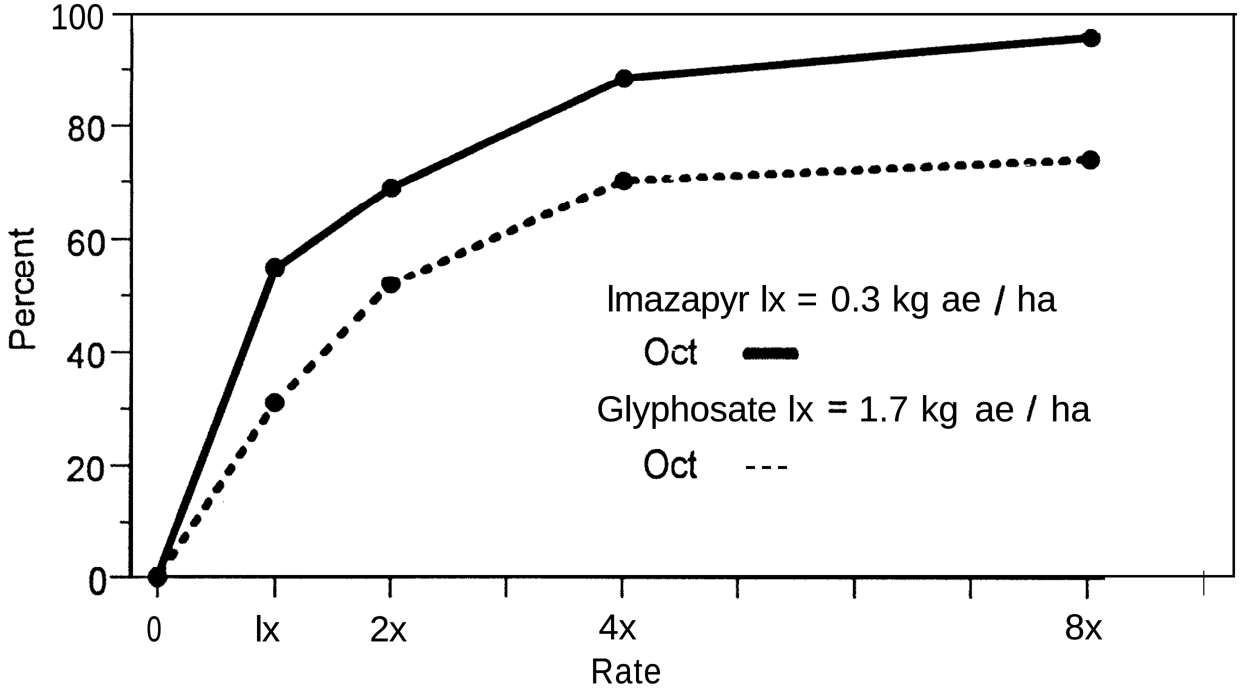

Figure 3. Cogongrass control 12 months after treatment with Imazapyr and Glyphosate in a 20 year old infestation.

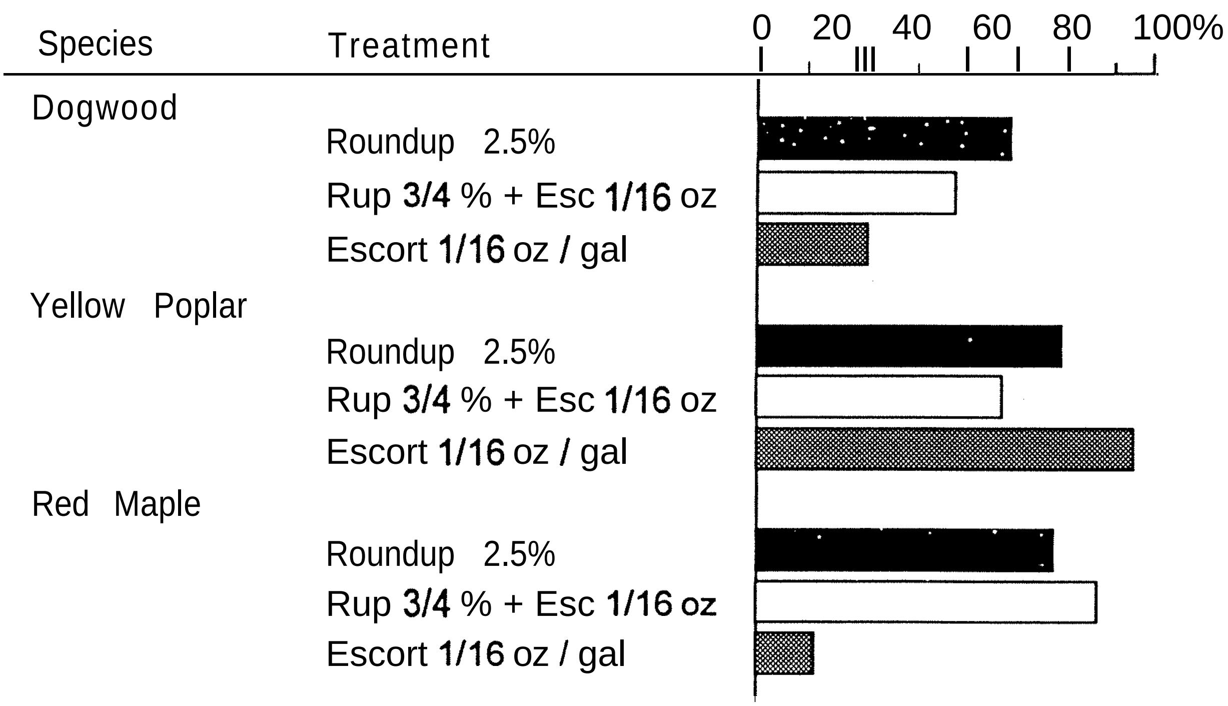

Figure 4. Examples of tank mix additiveness, antagonism, and synerism between glyphosate and metsulfuron when applied as foliar directed sprays.

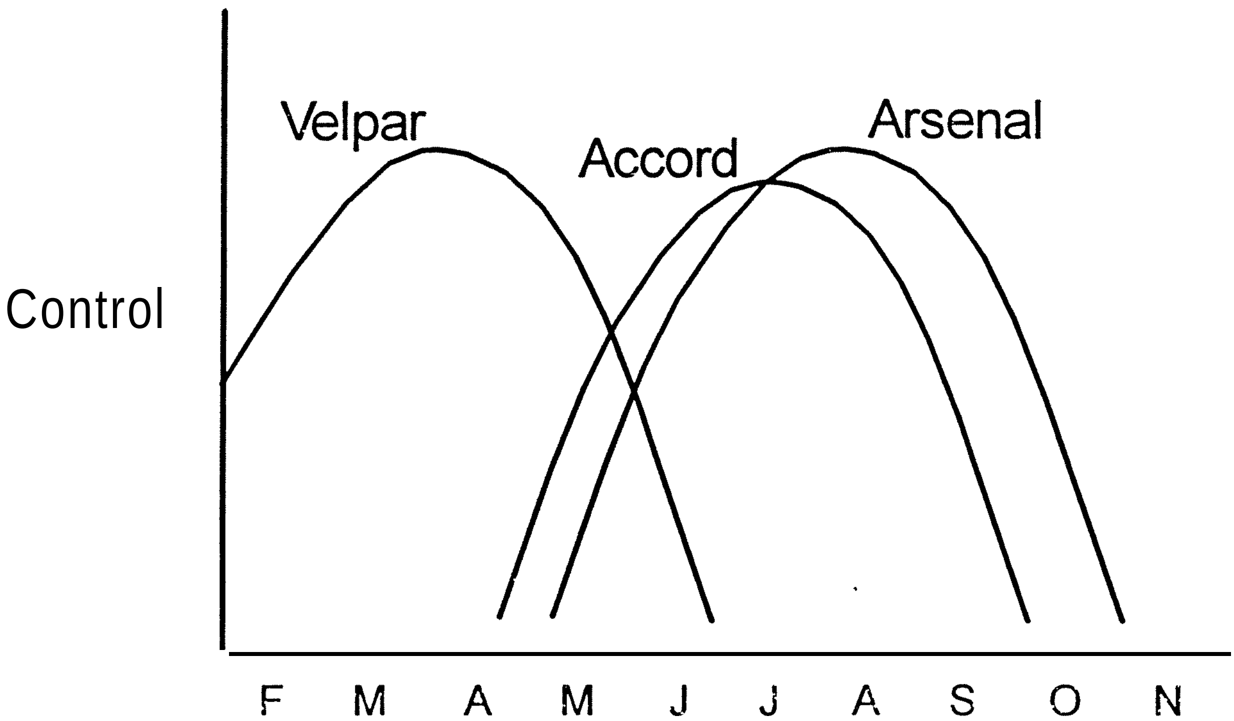

Figure 5. Conceptual relationships between timing and control for three herbicides.

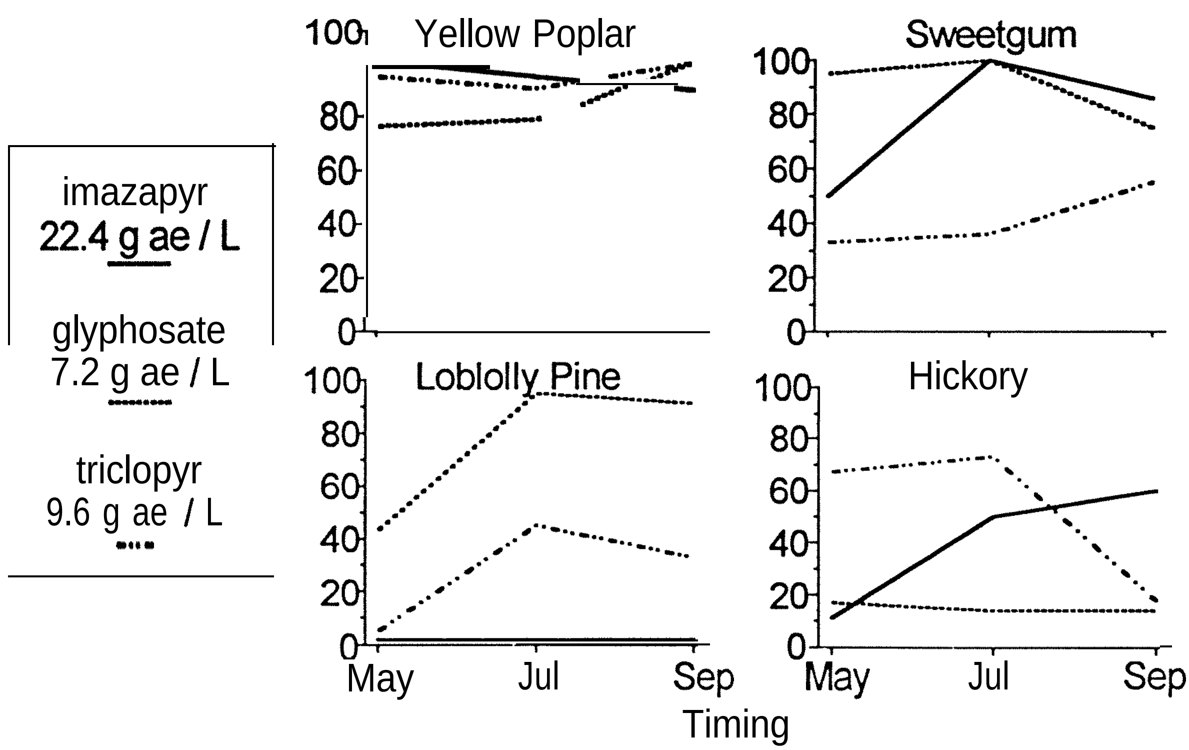

Figure 6. Percent rootstock reduction with foliar sprays applied at three timings.