AN EVALUATION OF THE EFFICACY OF TREE GROWTH REGULATORS PACLOBUTRAZOL, FLURPRIMIDOL, DIKEGULAC, AND UNICONAZOLE FOR UTILITY LINE CLEARANCE

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Abstract. A multi-year field program was conducted in California and Nevada to determine the efficacy of tree growth regulators (TGRs). At 37 sites, trees were trimmed and treated with paclobutrazol, flurprimidol, dikegulac or uniconazole by trunk injection, tree implants, or bark banding. Tree growth was determined over a period of 1-4 years for 12 common West Coast species. Growth was determined by measuring increase in tree height. At most sites that were not compromised during the study, the TGRs had no detectable effect on growth. Inhibition of growth was observed over 4 years at one site with London plane (*Platanus acerifolia*) trunk-injected with uniconazole, at one site with big leaf maple (*Acer macrophyllum*) trunk-injected with uniconazole, and over 2 years at one site with Chinese elm (*Ulmus parvifolia*) trunk-injected with paclobutrazol or uniconazole. Trunk injections and bark banding of flurprimidol inhibited the growth of blue gum (*Eucalyptus globulus*) over 2 years at one site. There was a lack of consistency in the effects observed; for example, the growth of London plane was inhibited at only one of eight sites. Possible explanations for the low level of effectiveness and lack of consistency include site variability, tree water relations, and hole spacing. Problems were experienced while conducting this large-scale research effort under field conditions. Factors that contributed to a low level of effectiveness and a lack of consistency need to be addressed to improve the cost-effectiveness of the product formulations evaluated.

Each year, Pacific Gas and Electric Company (PG&E) trims or removes about 1 million trees under distribution lines to maintain safe and reliable electric service. Tree trimming is one of the company's largest annual maintenance costs. In the United States, it is estimated that each year 40-50 million trees are trimmed by utilities at a cost of $1.5 billion (18). Such operations generate about 13 million tons of chipped biomass per year (23), and disposal of this material is becoming a concern in certain parts of the country. Tree growth regulators (TGRs), which offer a nonmechanical means of controlling tree growth, have been investigated by researchers and utility arborists since the early 1960s for their potential to reduce costs of trimming and biomass disposal (5, 10). First generation TGRs (e.g., maleic hydrazide, naphthalene acetic acid, and dikegulac) inhibit the terminal bud and affects apical dominance and/or cell division, often producing undesirable phytotoxic effects. In the 1980s, second generation TGRs were introduced (e.g., flurprimidol, paclobutrazol, and uniconazole); these inhibit gibberellin biosynthesis, reducing cell elongation and retarding the growth of trees without the undesirable phytotoxic effects observed with first generation TGRs (7, 9).

From 1964 to the early 1980s, PG&E used the first generation TGRs maleic hydrazide, chlorflurenol, and dikegulac (6). In 1988, PG&E formed the Interutility Vegetation Management Research Consortium with Sierra Pacific Power (SPP) and Southern California Edison Company (SCE) in part to evaluate whether second generation TGRs could be cost-effective and environmentally acceptable in a line maintenance program.

At that time, few evaluations of the performance of paclobutrazol, flurprimidol, and uniconazole in operational tree trimming programs had been reported by utilities (11, 24), although some results were presented at informal meetings organized by the producers of TGRs (e.g., Annual TGR Symposia [1987 and 1988] organized by Chevron

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Chemical and Valent USA Corporation). Most field experience gained with flurprimidol, paclobutrazol, and uniconazole came from utilities in the eastern United States, and thus field data from common species and conditions found in the West were limited. Prior to 1989, most studies of the efficacy of flurprimidol and paclobutrazol applied to trees were short-term, lasting 1 or 2 years (8). Exceptions were Gilliam (12) and Wood (27), who reported that soil applications of TGRs (flurprimidol and paclobutrazol, respectively) inhibited tree growth for 3-4 years, but these studies did not address operational situations or applications likely to be registered in California.

In 1989, the Consortium undertook a comprehensive research program to determine the efficacy under field conditions of flurprimidol, paclobutrazol, and uniconazole applied to common California and Nevada street tree species using new formulations that the manufacturers made available for testing. These formulations included 1) trunk injection for flurprimidol, paclobutrazol, and uniconazole; 2) tree implants of flurprimidol and uniconazole; and 3) a bark-banding formulation of flurprimidol. A secondary goal was to detect any potential dose-response relationship to determine the lowest effective application rate. Though the products tested had little potential for adverse environmental or health impacts (see Material Safety Data Sheets), public concern over chemical applications made the potential for lower application rates attractive along with the possibility of lowered cost per treated tree.

While other researchers (14, 18, 24) used average length of shoots as a measure of tree growth, this study used overall increase in tree height, which was used successfully in a previous study (3). This measure seemed more relevant to line maintenance operations because trimming is required when a single branch grows too close to a conductor rather than when the average growth reaches the conductor. Furthermore, measuring overall tree height eliminates problems of selecting representative shoots from among the hundreds on a single tree (25, 26). Also, the variability in shoot length can make detection of treatment differences difficult, leading some researchers to conclude that it is not the best measure of TGR efficacy (18).

Materials and Methods

Species selected for the study had to be fast growing and common in the utilities' service areas. Twelve species were evaluated: London plane (*Platanus acerifolia*), Chinese elm (*Ulmus parvifolia*), big leaf maple (*Acer macrophyllum*), red gum (*Eucalyptus camaldensis*), blue gum (*E. globulus*), shamel ash (*Fraxinus uhdei*), Modesto ash (*F. velutina*), mulberry (*Morus alba*), Canary Island pine (*Pinus canariensis*), poplar (*Populus* sp.), and Siberian elm (*U. pumila*). Thirty-seven field sites, mostly in urban areas, were selected in California and Nevada by consultation with field personnel from the utilities. Each site had 12 or more trees of the same species and cultivar growing within one or two street blocks. The trees had to be under a distribution line (or in one case, at a substation) and be of similar size (height and trunk diameter), condition, trim type (top trim only), and trim frequency. Trees were randomized to treatment groups and trunk-injected, bark-banded, or implanted with tree implants in 1989, 1990, or 1991. Dikegulac (Atrinal), flurprimidol (Cutless TP, Cutless TI, or basal formulation), paclobutrazol (Clipper 20UL), or uniconazole (Prunit TGR) were used by professional applicators from the respective manufacturer. Dikegulac was applied at three sites to species that were on the product label, because the testing protocol used by Valent USA Corporation (manufacturer of uniconazole) evaluated new products against existing registered products (for which field data are available). Trunk injection sites were established in 1989, 1990, and 1991. Injections were performed using the Arborchem, Davey, or Stallion 75 injector. Injection holes were made 6 or 8 inches apart around the trunk (except with Modesto ash, where spacing was 4 inches) and about 12 inches from the ground using a 7/32-inch drill bit (with the Arborchem injector and a 13/64-inch bit with the Davey injector) at an angle of 45° to the plane of the trunk to intercept the outer sapwood. Hole depths were no greater than 2 1/2 inches. Initial pressures were 50-70 psi. In general, application rates were within the range recommended by the manufacturer (e.g., label rate for flurprimidol is 0.5-1.5 g a.i. per inch dbh, and the application rate for London plane was 0.6-1.5 g a.i. per inch dbh).

In 1989 (for uniconazole) and 1991 (for flurprimidol), tree implants were inserted 12 inches above ground level to a depth of 1-1/4 inch into 3/8-inch-diameter holes (for 1.5-g implants of flurprimidol and 0.15-g implants of uniconazole) and 11/32-inch-diameter holes (for 1.0-g implants of flurprimidol) on a 6-inch spacing around the trunk. With the 1.5-g flurprimidol implants, a second hole was made adjacent to the first and an implant was inserted (to give a final application rate of 1.5 g a.i. per inch dbh). Similar to the 1.0-g flurprimidol implant, a second hole accommodated a second implant (to give an application rate of 1.0 g a.i. per inch dbh). In the absence of this second hole and implant, the application rate was 0.5 g a.i. per inch dbh. Distilled water was sprayed into the hole before insertion of an implant to clean the hole of sawdust and facilitate the dissolving of the implant.

Bark banding was conducted in 1991 using a Birchmeier[R] backpack fitted with a Spraying Systems Company adjustable Cone Jet SS5500Y2 nozzle. The unit was calibrated to deliver 4 ml per second of a formulation of flurprimidol containing 0.25 g a.i. per ml (1 g a.i. applied per second). The solution was applied evenly around the base of the tree from soil level to a height of 15-38 inches for 8-17 seconds, depending on trunk diameter and required dosage.

The trees were roundover trimmed using standard utility line clearance methods within 1 month of TGR treatment. Initial tree height was determined using a clinometer after trimming. Whenever possible, each tree was measured from two directions (recorded for each tree so future measurements would be taken from the same place), and the mean was computed. Control trees were trimmed but not treated with TGR. TGR treatment, trimming, and determination of initial height were accomplished within 3 months, and most were done more quickly.

Tree growth was determined by measuring overall height with a clinometer in September, October, or November following TGR application for up to 4 years. Data for the growth in year 1 were collected at least 12 months after TGR application. Each time the height of a tree was measured, qualitative data were collected on tree health and appearance (fluxing, bark injury, foliage coloration, and size). No further growth data were collected once a site was compromised (e.g., if trees grew rapidly and required trimming for line clearance, or trees were killed in the 1990 freeze). Also, no further data were collected at a site if there was no evidence of growth inhibition by year 2 (i.e., if the mean growth of one or more treatment groups was greater than the control mean, or if control and treatment means were similar). Previous multi-year studies showed that inhibition of growth in trees trunk-injected with second generation TGRs was apparent in year 1 and/or year 2, continuing through years 3 and 4 (11, 3). Thus, trees where no inhibition was seen after 2 years would be unlikely to show inhibition later.

All significance values in the tables presenting results are based on one-way analysis of variance with treatment group or level as the independent factor (30). Ad hoc analyses were performed with Duncan's multiple range test when initial analysis of variance indicated significance at the 5% level. All statistical analyses were performed using SPSS/PC+ (Chicago, IL). Each treatment site was analyzed as a separate experiment.

Results and Discussion

For most species and sites, no tree health or appearance problems were apparent. In the first year after application, fluxing from injection holes was observed with some London plane, and wet, dark stains were seen below the injection sites on all mulberry trees. Bleeding and wet bark have been reported before (11, 3, 13, 16, 29). At all application rates (0.5, 1.0, and 1.5 g a.i. per inch dbh), clumping (stacking of foliage) was observed in shamel ash treated with flurprimidol.

At 22 of the original 37 sites, it was possible to collect data for at least 2 years after TGR application; at 6 of these 22 sites, it was possible to continue data collection for the full 4 years. Results from these sites are presented in Tables 1 and 3, and those sites where there was no significant inhibition of growth are described in

Table 1. Species and sites where dikegulac, paclobutrazol, and uniconazole applied by trunk injection had a significant effect on tree growth after 2 and 4 years.[a]

	Treatment					
	Control	Paclobutrazol	Uniconazole	Uniconazole	Dikegulac	Probability[a]
Site	Growth (Increase in Height)					
16		0.25 g	0.05 g[b]	0.10 g		
Chinese elm	11.3 ± 2.3X	4.3 ± 3.6Y	3.4 ± 0.3Y	3.2 ± 0.7Y		0.001
(*Ulmus parvifolia*)	[4]	[4]	[4]	[4]		
80			0.25 g	0.50 g	0.21 g	
Big leaf maple	8.5 ± 2.2X		4.6 ± 0.2Y	3.3 ± 1.9Y	5.5 ± 2.3X	0.018
(*Acer*	10.1 ± 2.1X		4.4 ± 1.2Y	2.7 ± 2.1Y	7.7 ± 2.4X	0.002
macrophyllum)	[3]		[4]	[4]	[4]	
81		1.00 g	0.50 g	1.00 g		
London plane	5.8 ± 1.2X	3.5 ± 0.7Y	2.2 ± 0.8YZ	1.3 ± 0.8Z		0.001
(*Platanus*	7.4 ± 2.0X	6.1 ± 0.6X	4.7 ± 2.8X	1.8 ± 0.9Y		0.024
acerifolia)	[3]	[3]	[3]	[3]		

[a] Values given are the mean (in feet) ± s.d. for each treatment. Upper mean value is for 2 years growth and lower value is for 4 years. Treatment mean values that are statistically different (p = 0.05), as determined by Duncan's multiple range test, are followed by a different letter (X, Y, Z). Application rate of TGR is given as the number of g active ingredient per inch trunk diameter. Value in square brackets is the number of trees in the treatment group.

[b] This application rate is 50% lower than the recommended label rate.

Table 2. At 15 of the original 37 sites, it was not possible to collect a minimum of 2 years of efficacy data because the sites had been compromised in various ways. Except at site 203, where significant effects were observed in the first year, no further results are presented for these sites. For London plane, significant inhibition of growth (p = 0.05) was observed after 2 years at one site for trees injected with paclobutrazol or uniconazole and after 4 years for trees injected with uniconazole (Table 1). Paclobutrazol had no effect at the six other London plane sites where it was applied, and uniconazole (one site) and flurprimidol (one site) also had no effect (data not shown, see site information in Table 2). Both paclobutrazol and uniconazole, applied by trunk injection, inhibited the growth of Chinese elm over 2 years at one site (Table 1) but not at another site (data not shown, see site information in Table 2), though the same dose rates were used. Uniconazole inhibited the growth of big leaf maple at another site after 2 and 4 years, but dikegulac had no effect (Table 1).

After 4 years, the largest significant inhibition of growth (expressed as a percentage relative to control means) was 76% for London plane (site 81) trunk-injected with uniconazole, and 73% for big leaf maple (site 80) also trunk-injected with uniconazole (percentages calculated from data in Table 1). Similar levels of inhibition were reported in previous 4-year studies (11, 3). In our study, a statistically significant trend suggesting a dose response was seen with London plane (site 81) treated with uniconazole after 4 years (Table 1), but not at any other sites.

At 18 sites (10 species), no significant effect of TGR application was seen after 2 or 4 years (data not shown). The species and sites, as well as the various TGRs applied, are listed in Table 2.

At one blue gum site (203), three methods of applying flurprimidol were evaluated: trunk injection, tree implants, and bark banding. There was significant inhibition of growth for trunk injection and bark banding applications (Table 3). Inhibition ranged up to 56% for 1 g a.i. per inch trunk diameter rate applied by trunk injection and up to 69% for 1.5 g a.i. per inch applied by bark banding. In contrast, at site 108, flurprimidol applied by trunk injection had no effect on the growth of blue gum (data not shown, see site information in Table 2). While the standard

Table 2. Species and treatments for sites where o significant inhibition (p = 0.05) of growth was observed after 2 and 4 years following application by trunk injection of dikegulac, flurprimidol, paclobutrazol, or uniconazole.

Species	Site	Treatment
Red gum (*Eucalyptus camaldensis*)	37[a]	Dikegulac, uniconazole
Blue gum (*Eucalyptus globulus*)	108[b]	Flurprimidol
Shamel ash (*Fraxinus uhdei*)	22[a]	Paclobutrazol
	102[b]	Flurprimidol
	104[b]	Flurprimidol
Modesto ash (*Fraxinus velutina*)	77[a]	Paclobutrazol
Mulberry (*Morus alba*)	44[a,c]	Paclobutrazol
Canary Island pine (*Pinus canariensis*)	112[b,d]	Uniconazole
London plane (*Platanus acerifolia*)	20[a]	Paclobutrazol
	36[b]	Paclobutrazol
	59	Paclobutrazol, uniconazole
	202[a]	Flurprimidol
	959	Paclobutrazol
	1036[b]	Paclobutrazol
	1059	Paclobutrazol
Poplar (*Populus* spp)	87[a,e]	Dikegulac, paclobutrazol, uniconazole
Chinese elm (*Ulmus parviflora*)	28[b,f]	Paclobutrazol, uniconazole
Siberian elm (*Ulmus pumila*)	2[a]	Paclobutrazol, uniconazole

[a] No further data collected after 2 years because there was no evidence of effect; see text for details.
[b] Site compromised before 4-year data could be collected.
[c] Mulberry is not on the label, for paclobutrazol; two treatment rates at this site were within the range for other species on the label, and one treatment was 33% higher than the highest recommended rate.
[d] Application was by tree implant; see text for details. At all other sites, application was by trunk injection.
[e] Poplar is not on the label, for paclobutrazol but is suspected to be sensitive. To avoid overdose, one treatment was 50% less than the lowest recommended rate.
[f] One treatment with uniconazole was 50% below the recommended rate.

deviations for the flurprimidol bark banding treatments were quite large, the large sample numbers (nine trees per treatment group) probably assisted in the detection of a statistically significant difference. Implants of flurprimidol applied to blue gum caused no significant inhibition of growth after 1 year (data not shown) and neither did implants of uniconazole inserted into Canary Island pine after 2 years (Table 3).

Our study found that following treatment with TGRs, significant inhibition of growth was seen in four species at four sites. The growth of London

Table 3. Effect of flurprimidol applied by trunk injection, tree implant, or bark banding on the growth of blue gum (site 203) over 1 year. [a]

Application Method	Treatment	Increase in Height (feet)[b]	Number of Trees
Trunk injection (a.i./inch trunk diameter)	Control	7.0 + 2.8X	13
	Flurprimidol 0.63 g	3.4 + 1.8Y	4
	Flurprimidol 1.00 g	3.5 + 2.3Y	4
	Flurprimidol 1.51 g	4.0 + 1.7Y	4
	Probability	0.023	
Tree implant (a.i./inch trunk diameter)	Control	7.0 + 2.8	13
	Flurprimidol 0.5 g	5.1 + 2.6	4
	Flurprimidol 1.0 g	5.8 + 4.3	4
	Flurprimidol 1.5 g	5.3 + 2.1	4
	Probability	0.585	
Bark banding (a.i./inch trunk diameter)	Control	7.0 + 2.8X	13
	Flurprimidol 0.75 g	3.7 + 2.2Y	9
	Flurprimidol 1.5 g	3.4 + 2.0Y	9
	Probability	0.002	

[a] Data given are for 1 year (trees were trimmed after the first year).

[b] Values given are the mean ± s.d. for each treatment. Mean values marked with a different letter (X or Y) are statistically different ($p = 0.05$) as determined by Duncan's multiple range test. Trunk injection and bark banding significantly inhibited growth, while tree implants had no effect.

plane (at one of eight sites) and Chinese elm (at one of two sites) was inhibited by trunk injections of paclobutrazol and uniconazole, as was big leaf maple trunk injected with uniconazole. Flurprimidol, applied by trunk injection or bark banding, inhibited the growth of blue gum after 1 year. However, at most sites, application of the TGRs caused no statistically significant inhibition of growth. In fact, tree implants of flurprimidol and uniconazole showed no inhibitory effect at either of the sites where they were evaluated. We observed almost no dose response. In contrast, there have been many reports on the successful inhibition of growth of various tree species by paclobutrazol, flurprimidol, and uniconazole, applied by trunk injection, tree implants, or basal drench (1, 2, 3, 7, 9, 11, 12, 14, 18, 20, 21, 22, 24). However, most of these were short-term studies, with few conducted over three or four growing seasons (3, 14, 18, 24). In one long-term study, inhibition of growth of silver maple (*Acer saccharinum*) after injection of flurprimidol and paclobutrazol was reported (14). A recent study in which trees under distribution lines were treated with flurprimidol applied by implant reports that the TGR inhibited the growth of shoots and reduced the amount of biomass removed at trimming of four species (18). Uniconazole applied by trunk injection has been reported to inhibit the growth of a number of tree species over the short- and long-term (2, 3, 21). In our study, we observed no consistency in the effects of dikegulac, a first generation TGR, and the effect of second generation TGRs applied at the same sites.

Wright and Moran (28) report that dikegulac was inhibitory when injected into London plane, although application rates used by these workers were approximately twice those used in our study. These authors suggest that different species may vary in their sensitivity to TGRs, and for a given species there may be cultivar differences, with trees planted in an urban environment being selected for stress tolerance. The growing conditions probably varied between sites in our study, given the geographical distribution of the sites; these may have influenced the responsiveness to the TGRs. Since the aim of the study was to evaluate TGRs under normal operational field conditions, no attempt was made to control for variability between sites. Another reason that detailed site characteristics data were not collected was the conclusion by Consortium members that if site-specific data such as cultivar or soil type or the level of homeowner care were needed to successfully implement a TGR program, it would be too costly to show a financial return.

Another explanation for the low level of effectiveness and lack of consistency could be tree water relations. From 1989 to 1991, rainfall at many sites was substantially below normal. TGRs are thought to be as effective in drought years as in normal years, if rainfall was normal at the time of injection (17). Low rainfall at the time of injection might result in poor distribution at the injection point and/or little translocation away from the injection point immediately after application. Short-term studies of trunk-injected flurprimidol, paclobutrazol, and uniconazole, and a long-term study with the latter, found that most product remains at or close to the site of injection, with only a small percentage being translocated to the upper stem and foliage (2, 20, 21, 22) and thus, distribution at the time of injection may be important for uniformity of response in the tree. In our study, the lack of effect of tree implants of flurprimidol and uniconazole may have been due in part to a shortage of water at the sites. There was evidence that most of the implants in our study failed to dissolve. Redding et al. (18) suggest that implants should dissolve and move from the implant site rapidly to be effective. Low transpiration rates would probably hinder these processes.

The results for London plane could be attributable in part to the hole spacing used for the injections. London plane was not listed on the Clipper (paclobutrazol) information sheet when this study was initiated, suggesting the manufacturer had little or no data on the effectiveness of the product with this species (15). However, ICI recommended a 4-inch spacing between holes for American sycamore (*P. occidentalis*), and the 6-inch spacing used in these studies may have contributed to an apparent lack of effect or a lack of uniformity of effect because of poor distribution within the tree (15). Though London plane is not common as a trial species in TGR studies (28), the congener American sycamore is common (7), but it is not known how the sensitivities of the two species compare with respect to TGRs.

Conclusions

Researchers designing similar large-scale field studies should be aware of the problems we encountered. Conducting field work in the various regions of three utilities over two states proved difficult, with maintenance of the integrity of the sites being the primary problem. It has been suggested that determining tree growth from increase in height does not produce standardized and unbiased field data (4, 19). Problems were encountered at some sites in measuring height using a clinometer. Though we do not believe they affected the study results, we would recommend exploring other methods. We used height poles in preliminary phases of this study, but the fact that a clinometer allows one person to collect data (rather than two) made it attractive. Seiler and McBee (19) propose that tree height, crown width, and live crown length can be estimated manually from photographs of the tree taken from two directions. Image analysis programs (for photographs and video images) could be used to further automate such a technique. The amount of biomass removed at trimming can also be quantified (18), although there is a subjective element in the way a tree is trimmed, and height is the primary trigger for trimming.

The TGRs we evaluated are known to be effective in reducing growth when applied under controlled and uniform conditions in greenhouses, orchards, and tree nurseries. They are used operationally by utilities, particularly in the eastern United States (7). However, under operational conditions for ordinary street trees, the product formulations we evaluated did not perform with high consistency or efficacy in California or Nevada.

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