Comparison of Adjuvants Used in Fall-Release Herbicide Mixtures for Forest Site Preparation

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Tank mixes of the herbicides imazapyr and glyphosate were applied at 3 rates with 3 adjuvants (LI-700®, Nu-Film-IR®, Silwet L-77°) over California hazelnut (Corylus cornuta *Marsh. var.* californica *(A. DC.) Sharp), vine maple* (Acer circina turn *Pursh), and brackenfern* (Pteridium aquilinum (L.) *Kuhn var.* lanuginosum *(Bong.) Fern.). The herbicide 2,4-D was applied at 3 rates with 2 adjuvants (Herbimax®, Nu-Film-IR) over greenleaf manzanita* (Arctostaphylos patula *Greene). Tank mixes of imazapyr and glyphosate with LI-700 or Nu-Film-IR were sprayed at 3 rates over seedlings of Douglas fir* (Pseudotsuga menziesii *(Mirb.) Franco.). The herbicide rate strongly influenced the percentage of foliage injured and percentage of stems killed for all herbicide treatments. The adjuvants evaluated did not influence efficacy of herbicide applications on California hazelnut, vine maple, or brackenfern. Herbimax increased visual foliar damage resulting from 2,4-D application on greenleaf nianzanita. Douglas-fir foliage was damaged by the higher herbicide rates; the damage was greater from Nu-Film-IR than from LI-700.*
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In reforestation settings, herbicides are commonly used to eliminate potential competitors prior to planting conifers or to release established conifers from competition (Walstad and Kuch 1987). Spray adjuvants are often applied in conjunction with foliage-active herbicides to increase herbicide effectiveness (Prasad 1992a, 1992b). Adjuvants enhance efficacy by increasing herbicide assimilation by the target plant through various modes (Harvey 1993). Adjuvants used in our study can be grouped into 3 categories by their modes of action:

1. Surfactants—such as Silwet L-77® (Osi Specialties Inc.) and LI-700® (Loveland Ind.)—increase efficacy by reducing the surface tension of water and allowing it to spread over the leaf more readily, thus increasing the surface area exposed to herbicides. Silwet L-77 is a nonionic organosilicon surfactant that reduces the surface tension of water and relies principally on enhanced stomata! flooding to increase herbicide absorption (Stevens and others 1991). LI-700 is composed of an organic acid in combination with a soybean derivative that increases absorption through enhanced cuticular penetration and stomata! flooding (Harvey 1993).
2. Oil penetrants—including Herbimax® (Loveland Ind.)—are often used when target plants have thick waxy cuticles. The oil solubilizes cuticular waxes and increases penetration of the leaf surface, aiding in the absorption of the herbicide used.
3. Sticking agents—including Nu-Film-IR® (Miller Chemical and Fertilizer Corp.)—prevent loss of herbicide through wash off and sheeting action, thus prolonging the leaf's contact with the herbicide.

The purpose of this study was to compare the efficacy of 3 herbicide applications using several adjuvants. Because adjuvants can injure conifers (Fredrickson 1994), this study also evaluated the phytotoxic effects of the treatments on Douglas-fir *(Pseudotsuga menziesii* (Mirb.) Franco.) seedlings.

Methods

Three experimental trials were performed. Trials 1 and 2 tested the effect the adjuvants had on the efficacy of site preparation weed control. Trial 3 evaluated the potential for the adjuvants tested to increase herbicide phytotoxicity to Douglas-fir when used as fall release treatments.

Trial 1—Vine maple, California hazelnut, and brackenfern response. We tested differences in efficacy as a result of spray adjuvants for 3 common Oregon Coast Range shrub species: vine maple *(Acer circinatum* Pursh), California hazelnut *(Corylus cornuta* Marsh. var. *californica* (A. DC.) Sharp), and brackenfern *(Pteridium aquilinum (L.)* Kuhn var. *lanuginosum* (Bong.) Fern.). All of these species have relatively thin leaf cuticles and are susceptible to late-summer application of imazapyr and glyphosate tank mixes.

A herbicide tank mix was applied at 3 rates using 3 spray adjuvants (table 1) on vine maple, California hazelnut, and brackenfern during September 1995. In addition, a no-herbicide-application control treatment and a treatment at the highest herbicide rate with no surfactant were also applied, for a total of 11 treatment combinations per species. The herbicide tank mix consisted of imazapyr (Arsenal®) and glyphosate (Accord®). From operational experience, the highest rate (0.071 kg ai/ha of imazapyr and 1.41 kg ai/ha of

Table *1-Treatments for weed control trials 7 and 2 and conifer safety trial* 3

	Adjuvant		Trial 1		Trial 2	Trial 3	
Treatment	Name	Dose (LAO'	Imazapyr (kg ai/ha) [b]	Glyphosate (kg ai/ha)	2,4-D (kg ai/ha)	Imazapyr (kg ai/ha)	Glyphosate (kg ai/ha)
Control	No adjuvant	0	0	0	_[c]		
High rate	No adjuvant	0	0.071	1.41	1.48		
	Herbimax®	2.365			1.48		
	LI-700®	0.147	0.071	1.41	—	0.143	2.08
	Nu-Film-IR®	1.034	0.071	1.41	1.48d	0.143	2.08
	Silwet L77®	0.237	0.071	1.41	—		
Moderate rate	No adjuvant	0			0.98		
	Herbimax	2.365			0.98		
	LI-700	0.147	0.036	0.62	—	0.071	1.41
	Nu-Film-IR	1.034	0.036	0.62	0.986	0.071	1.41
	Silwet L77	0.237	0.036	0.62	—		
Low rate	No adjuvant	0			0.48		
	Herbimax	2.365		—	0.48		
	LI-700	0.147	0.018	0.31	—	0.018	0.62
	Nu-Film-I	1.034	0.018	0.31	0.48d	0.018	0.62
	SilOwet L77	0.237	0.018	0.31	—		

N../ha x 9.3527 = gaVa
Ng/ha x 1.1208 = lb/a
Untested treatment combination.
[d] i's/a-Film-IR rate with 2.4-0 over greenleaf manzanita was 0.296 Uha.

glyphosate in a low-volume 95-L/ha spray) applied without surfactant was expected to achieve approximately 75% control of target species. Thus, even at the highest rate, added efficacy due to the surfactants could be recognizable and measurable. Three spray adjuvants were tested: LI-700 at 0.147 L/ha, Nu-Film-IR at 1.034 L/ha, and Silwet L-77 at 0.237 L/ha. To simulate an aerial application, all treatments were applied with a gas-powered boom backpack sprayer.

Five replications of the 11 treatments were applied randomly to 55 hazel clumps. Three replications of the 11 treatments were applied randomly to 33 vine maple clumps and 33 brackenfern areas. In late summer of 1995, before the treatments, the shrub clumps and brackenfern areas were located and flagged in a 2-year-old Douglas-fir clearcut 3.2 km west of Philomath, Oregon. The hazel and vine maple clumps covered areas ranging from 1.4 to 3.2 m^2 (16 to 34 ft^2). Brackenfern areas consisted of 2.4 X 1.5 m (8 x 5 ft) rectangular strips with brackenfern cover of 70°A, or greater. All treatments were applied on September 22, 1995, between 9:00 AM and 12:30 PM. Winds were calm, and air temperature ranged from 18 to 24 °C (64 to 75 °F) during the applications; relative humidity was 65%. The weather remained clear and warm for 2 days following the application, however, the next 3 days it rained, for a cumulative precipitation total of over 5 cm.

Trial 2-Manzanita response. We tested differences in efficacy as a result of spray adjuvants on greenleaf manzanita *(Arctostaphylos Willa* Greene), a thick-cuticled species that is susceptible to late-summer application of 2,4-D. Three rates of the herbicide 2,4-D were applied factorially, with the addition of either no adjuvant, Herbimax (2.365 L/ha), or Nu-Film-IR (0.296 L/ha). A low-volume (95-L/ha) spray was applied at random over 45 greenleaf manzanita clumps, for a total of 9 treatment combinations replicated 5 times (table 1). The high-rate treatment was 1.48 kg ai/ha of 2,4-D. From experience, we expected about 75% control of the manzanita clumps with this rate. In the time between establishment of trial 1 (September 1995) and trial 2 (August 1996), the manufacturer lowered the recommended dosage of Nu-Film-IR from 1.034 L/ha to 0.296 L/ha for low-volume spray applications. Treatments in trial 2 reflect this change.

The greenleaf manzanita clumps were flagged in late summer of 1996 on a 4-year-old Douglas-fir clearcut west of Yoncalla, Oregon. Applications were made on August 12, 1996, between 9:00 AM and 11:30 AM. Winds were calm, temperatures remained below 24 °C (75 °F) and relative humidity was approximately 62%. The weather remained clear and dry for over a week after the application.

Trial 3—Douglas-fir **response.** Two adjuvants were tested for phytotoxic effects on crop Douglas-fir using release herbicide applications. LI-700 and Nu-Film-IR were applied over first-year Douglas-fir seedlings at 2 sites, in combination with each of 3 rates of an imazapyr-glyphosate tank mix, resulting in 6 treatment combinations (table 1). Each treatment was replicated 4 times. These sites were located in the Oregon Coast Range, the first near the town of Eddyville and the second near the town of Falls City. Both had been logged 2 years previously and planted 1 year before treatment. The highest herbicide rate tested was set unusually high to ensure that there would be easily observable damage as a result of the treatment.

The experiment was blocked by the 2 sites (Falls City and Eddyville). Each site consisted of 24 treatment plots in which 4 replications of the 6 herbicide treatments were randomly applied. Each plot consisted of a row of 1-year-old planted Douglas-fir, each row containing 15 seedlings. The treatment applications were applied using a gas-powered boom backpack sprayer on October 16, 1995.

Measurements

Trials 1 and 2. Control efficacy for trial 1 was assessed on May 31, 1996, and on May 15, 1997, for trial 2 (8 and 9 months after the treatment, respectively). Visual estimates of the percentage of clump stems killed and the percentage of foliage showing signs of herbicide injury were made for each California hazelnut, vine maple, and manzanita clump. Because brackenfern has a different growth habit, only a cover value could be estimated visually for this species, and so cover is used as the principal response variable in all analyses for brackenfern control.

Trial 3. Seedling vigor was assessed before treatment, and any seedling that did not appear vigorous at that time was excluded from the reevaluation the following fall. The treated Douglas-fir seedlings were visually assessed for damage on September 25, 1996, 11 months after treatment. The assessment consisted of assigning each seedling a 5-point damage index rating:

1 = No visible herbicide damage to seedling
2 = Slight bottle brushing or needle loss
3 = Moderate bottle brushing or stem dieback
4 = Severe bottle brushing and stem dieback
5 = Seedling mortality

Analysis

Treatment differences for all 3 trials were assessed with ANOVA and means comparisons made using the Waller-Duncan method. In trials 1 and 2, means comparisons for percentage of stems killed, percentage of foliage injured, and brackenfern cover were made. The data were arcsin(sqrtlp])-transformed prior to the analysis to achieve normality and to allow for analysis of percentage or proportionate data; reported results are back-transformed values.

In trial 3, means for each treatment unit (consisting of a row of 15 trees) were generated and subjected to ANOVA blocked by study site. In addition, mean percentages of seedlings exhibiting herbicide damage (a damage index ranking of 2, 3, or 4), and of seedlings killed by the treatments were also evaluated. Residuals were examined for unequal variance and normality, and no transformations were needed.

Results

Herbicide damage increased with herbicide concentration for all the weed species and for conifer seedlings. None of the 3 adjuvants tested resulted in increased efficacy when applied to vine maple, California hazelnut, or brackenfern at the highest herbicide rates (table 2). At the lower rates, control efficacy differed little among adjuvants. In contrast, addition of either Herbimax or Nu-Film-IR to 2,4-D applied to greenleaf manzanita enhanced efficacy at the highest herbicide rate tested, though less so at the lower rates (table 3). Conifer damage varied with adjuvant at the highest herbicide rates, with Nu-Film-IR consistently resulting in greater damage than Li-700 (table 4). At lower herbicide rates, conifer damage did not vary by adjuvant used.

Trial 1. All high-rate treatments resulted in obvious visual signs of herbicide damage on vine maple and California hazelnut clumps, ranging from off-colored foliage to severe leaf deformities and death of stems. No similar deformities were apparent on brackenfern fronds; the only indication of herbicide activity was a reduction in the cover of fronds produced the following spring.

At the high rate, spray adjuvant did not influence the percentage of California hazelnut stems killed or foliage injured, nor did it influence the total cover of brackenfern (table 2). However, the percentage of vine maple stems killed at the high rate with Nu-Film-IR was significantly less than the other treatments.

At the medium rate, no differences in percentage of foliage injured were observed for vine maple or California hazelnut (table 2). However, differences were observed in the percentage of vine maple stems killed; the Nu-Film-IR treatment resulted in a greater percentage of stem kill than LI-700. Similarly, at the medium rate, the Nu-Film-IR treatment reduced brackenfern cover by significantly more than the LI-700 treatment. Silwet L-77 treatments were similar to other adjuvants.

Table 2—*Efficacy of imazapyr–glyphosate tank mixes in combination with spray adjuvants on vine maple* (Acer circinatum *Pursh, California hazelnut* (Corylus cornuta *Marsh. var.* californica *(A. DC.) Sharp), and brackenfern* (Pteridium aquilinum *(L.) Kuhn var.* lanuginosum *(Bong.) Fern.) (trial 1)*[a]

Treatment	Vine maple: Stems killed (%)	Vine maple: Foliage injured (%)	California hazelnut: Stems killed (%)	California hazelnut: Foliage injured (%)	Brackenfern: Cover (%) spring after treatment
Control	0 a	0 a	0 a	0 a	53.0 a
High rate					
No adjuvant	89.0 e	100 e	98.0 e	100 e	6.3 d
LI-700®	94.3 e	100 e	98.8 e	100 e	6.8 d
Nu-Film-IR®	56.4 d	96.8 cde	98.9 e	100 e	6.3 e
Silwet L77®	86.2 e	98.9 de	95.6 de	99.8 de	5.0 d
Medium rate					
LI-700	0.5 ab	72.7 c	77.7 c	79.4 c	36.6 ab
Nu-Film-IR	18.9 c	80.2 cd	73.5 c	90.6 c	15.0 c
Silwet L77	6.7 bc	90.1 cde	83.3 cd	92.3 cd	25.5 bc
Low rate					
LI-700	3.2 ab	31.3 b	6.6 b	9.3 b	25.0 bc
Nu-Film-IR	0.0 a	9.5 ab	13.1 b	18.1 b	42.9 ab
Silwet L77	0.0 a	13.3 ab	18.1 b	18.9 b	29.7 b

[a]Values within a column with the same letter are not significantly ($P \leq 0.05$) different using the Waller-Duncan means comparison test.

Table 3—*Efficacy of 2,4-D treatments in combination with spray adjuvants on greenleaf manzanita* (Arctostaphylos patula *Greene) (trial 2)*[a]

	Stems killed (%)	Foliage injured (%)
High rate		
No adjuvant	25.9 bc	69.3 b
Herbimax®	96.8 a	99.1 a
Nu-Film-IR®	61.4 b	78.4 ab
Medium rate		
No adjuvant	19.6 c	42.5 bc
Herbimax	25.6 bc	76.0 ab
Nu-Film-IR	25.5 bc	37.5 bc
Low rate		
No adjuvant	2.1 c	8.2 c
Herbimax	4.7 c	23.1 c
Nu-Film-IR	3.3 c	10.1 c

[a]Values within a column with the same letter are not significantly ($P \leq 0.05$) different using the Waller-Duncan means comparison test.

Table 4—*Effect of imazapyr–glyphosate treatments in combination with spray adjuvants on seedlings of Douglas-fir* (Pseudotsuga menziesii *(Mirb.) Franco.) (trial 3)*[a]

	MDIR[b]	Seedlings killed (%)	Seedlings damaged (%)
High rate			
LI-700®	1.7 b	8.6 b	31.3 b
Nu-Film-IR®	3.0 a	24.4 a	61.8 a
Medium rate			
LI-700	1.4 bc	7.0 bc	14.1 cd
Nu-Film-IR	1.6 b	7.6 bc	23.6 bc
Low rate			
LI-700	1.0 d	0.0 d	2.3 d
Nu-Film-IR	1.2 cd	2.4 cd	8.7 d

[a]Values within a column with the same letter are not significantly ($P \leq 0.05$) different using the Waller-Duncan means comparison test.
[b]MDIR = mean damage index rating.

Finally, at the low rate, there were no differences in treatment effects in any of the parameters measured.

Trial 2. Control of manzanita using 2,4-D with and without adjuvants was highly variable. Because of this, differences in means that might seem quite large and that may be biologically significant are not necessarily statistically distinct, except with a few exceptions (table 3).

At the highest 2,4-D rate, the percentage of greenleaf manzanita stems killed was greater with Herbimax than with Nu-Film-IR (table 3). Addition of Nu-Film-IR did not increase the percentage of stems killed or foliage injured. In addition, at the highest rate, Herbimax caused greater injury than treatment with no adjuvant added, but results did not differ from those for the Nu-Film-IR treatment. No differences in injury were observed between the Nu-Film-IR treatment and the no-adjuvant treatment. Finally, at the medium and low rates, no significant difference in percentage of stems killed or injured was observed for either of the adjuvants used.

Trial 3. As expected, when the herbicide rate was increased, the conifer damage index rating increased for both adjuvants tested. At the highest rate tested, damage was greater with Nu-Film-IR than with LI-700. Likewise percentage of seedlings damaged or killed was also greater for the Nu-Film-IR treatment than the LI-700 treatment (table 4). At the highest herbicide rate, 61.8% of the seedlings were damaged by the Nu-Film-IR tank mix, in contrast to 31.3% with the LI-700 mix. Similarly, at the highest herbicide rate tested, 24.4% of the seedlings treated were killed when Nu-Film-IR was used, in contrast to 8.6% with LI-700. At the 2 lower herbicide rates, there were no significant differences in seedling damage or mortality between the 2 adjuvants.

Discussion

Efficacy. Findings suggest that under ideal conditions, the use of an adjuvant is unnecessary when applying an imazapyr—glyphosate site preparation spray over leafy deciduous plants with relatively thin cuticles, such as vine maple, California hazelnut, and brackenfern. These species are typically susceptible to both herbicides used (William and others 1996). Under ideal conditions (moderate temperature, moderate humidity, and no rain for 48 hours), adjuvants apparently provided no additional herbicide absorption.

Although thick-cuticled species such as greenleaf manzanita are resistant to late-summer foliar imazapyr and glyphosate treatments (Cole and others 1986; William and others 1996), applications of 2,4-D often result in good control of these species. An oil adjuvant is often added to the mix to increase efficacy. As expected, the oil adjuvant Herbimax probably aided in 2,4-D absorption, resulting in greater control efficacy. The non-oil-based adjuvant Nu-Film-IR did not significantly increase 2,4-D effect, suggesting that on thick-cuticled species it is less effective than Herbimax.

The effectiveness of spray adjuvants varies depending on the species sprayed and the herbicide used (Prasad 1989; Swietlik 1989; Burrill and others 1990; Stevens and others 1991; Fredrickson and Newton 1998). Studies have shown that surfactants such as Silwet L-77 and LI-700 increase herbicide effectiveness (Swietlik 1989; Burrill and others 1990; Stevens and others 1991). This increase may not always be evident at operational rates but may be more obvious at reduced rates (Sweitlik 1989). Because we did not test adjuvants with imazapyr—glyphosate mixes at lower rates against a no-surfactant control, we cannot draw conclusions about added efficacy due to surfactant addition at lower herbicide rates. Nevertheless, at lower herbicide rates, use of all 3 of the adjuvants resulted in similar levels of control across the 3 species tested. This suggests that any benefit that might have occurred did not differ among the 3 adjuvants tested.

Surfactants generally increase the rainfastness of herbicide applications by increasing absorption rate (Stevens and others 1991; Foy 1993; Roggenbuck and others 1993). Having a surfactant in the tank mix may increase efficacy, especially when rain occurs soon after application. The efficacy afforded by the adjuvants we tested could be quite different under moist weather conditions.

Conifer safety. When used in release treatments, both Nu-Film-1R and LI-700 resulted in high levels of conifer damage at the high and medium rates. This suggests that these adjuvants should not be added to imazapyr—glyphosate tank mixes for fall-release treatments. Using adjuvants for release operations is favored by foresters because adjuvants typically aid in the absorption of herbicides (Stevens and others 1991; Roggenbuck and others 1993). Rain is common and unpredictable during the fall when release treatments are applied. Consequently, inclusion of an adjuvant in the mix may make the difference between successful weed control and failure. Thus, foresters often gamble that the benefit in increased weed control derived from adding an adjuvant will make up for any losses resulting from conifer damage. Our results suggest this is a poor gamble.

More work is needed concerning the effect of herbicide applications and conifer growth. Whereas glyphosate can generally be applied in the fall without damaging conifers (Radosevich *and others* 1980), imazapyr can result in intermediate damage (William and others 1996). This difference may be due to both soil and foliage activity of imazapyr. We could not determine whether the observed damage was a result of foliage or soil absorption. In addition, we could not determine if damage was caused by glyphosate, imazapyr, or a combination of both. It is possible that even a no-adjuvant treatment would also have resulted in a moderate amount of conifer damage.

Conclusions

1. The use of the adjuvants under good environmental conditions did not increase efficacy of imazapyr—glyphosate tank mixes for the thin-cuticled deciduous species tested.
2. Addition of an oil adjuvant significantly increased 2,4-D effectiveness for a thick-cuticled species, out-

performing the other adjuvant (a sticking agent).

3. Imazapyr-glyphosate tank mixes used as release sprays should not be mixed with either LI-700 or Nu-Film-IR adjuvants because of the potential for severe damage to Douglas-fir seedlings.

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