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Research Article

Selective Herbicides for Cultivation of *Eucalyptus urograndis* Clones

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Competition control is essential for successful eucalyptus plantation establishment, yet few selective herbicides have been identified. Five herbicides, flumioxazin, imazamox, imazapic, oxyfluorfen, and sulfometuron methyl, were evaluated for selective weed control in the establishment of genetically modified frost tolerant *Eucalyptus urograndis* clones. Herbicides were applied at two or three rates, either before or after weed emergence, and compared to a nontreated control and to near-complete weed control obtained with glyphosate directed sprays. Applications prior to weed emergence were most effective for weed control and, with the exception of imazapic, all resulted in enhanced eucalyptus growth relative to the nontreated control. Among postemergent treatments, only imazamox enhanced stem volume. Among selective herbicide treatments, preemergent 2240 g ha^{-1} oxyfluorfen produced the best growth response, resulting in stem volume index that was 860% greater than the nontreated control, although only 15% of the volume index obtained with near-complete weed control. Imazapic was the most phytotoxic of all herbicides, resulting in 40% mortality when applied preemergent. Survival was 100% for all other herbicide treatments. This research found the previously nontested herbicides imazamox and imazapic to be effective for selective weed control and refined application rate and timing of five herbicides for use in clonal plantations.

1. Introduction

Because of their adaptability and fast growth rates, *Eucalyptus* species and hybrids have been grown for fiber, fuel, landscaping mulch, essential oils, phytoremediation, and as ornamental trees [1, 2] on more than 17.8 million ha worldwide [3]. Few silvicultural guidelines for eucalyptus plantations in the southern US have been published, but vegetation management during stand establishment and nutrient management are known to be critical to success [4, 5]. In summarizing experience with eucalyptus plantings in this region, Kellison et al. [5] "highly" recommended that plantations be kept free from competition for at least the first two growing seasons. The importance of vegetation management prior to planting eucalyptus is stressed by many authors [6, 7], and studies throughout the world have demonstrated that competition in the first eighteen months to two years following planting is most impactful [8–10] as fast growing eucalyptus trees at typical plantation densities (3 by 3.5 m) quickly close crown canopy, excluding light to the understory, thus limiting the growth of other vegetation. Because trees under stress from weed pressure or limited nutrients are more susceptible to cold injury than those without these limitations [11, 12], controlling competition may also impart greater cold tolerance, an important consideration in temperate climates.

A limited number of herbicides are used in eucalyptus culture worldwide, and even fewer are specifically labeled for eucalyptus plantation silviculture by various regulatory agencies [7]. There are more alternative herbicides for use in site preparation than in established stands, where greater herbicide selectivity is needed. The development of a selective, broad spectrum herbicide, which can be sprayed over eucalyptus transplants and provide persistent weed control when applied either prior to weed emergence (preemergent) or to actively growing weeds (postemergent), would advance eucalyptus silviculture.

The nonselective herbicide glyphosate controls a broad weed spectrum and is widely used to prepare sites for planting and applied after planting using shielded or directed sprays to avoid eucalyptus foliage contact. Because glyphosate does not provide soil residual herbicide activity, applications prior to planting are not injurious to eucalyptus transplants. Conversely, applications after planting often reduce growth rates or cause significant injury or mortality, because it is difficult to eliminate drift in operational practice, even with directed sprays. In their study of the effect of glyphosate spray drift to eucalyptus clones Tuffi Santos et al. [13] observed a progression of injury symptoms from leaf chlorosis through necrosis to plant death, with phytotoxicity positively correlated to increasing application rate. Multiple applications of glyphosate are needed through the growing season as new weeds emerge, resulting in a significant cost [14]. There are also concerns regarding the development of resistant weeds when a single herbicide or herbicides with a common mode of action are used, particularly with repeated applications and high selection pressure.

Oxyfluorfen and flumioxazin are selective herbicides which may be applied over newly planted eucalyptus. Oxyfluorfen is effective as a pre- and early postemergence herbicide on small-seeded annual forbs and it suppresses annual grasses but provides poor control of perennial grasses [15]. Oxyfluorfen is widely used in eucalyptus silviculture, but current product labels restrict applications to "dormant" trees [16], a condition that may not exist in some climates, because eucalyptus have naked bud habit and are never truly dormant. Flumioxazin is effective for forb and annual grass control when applied preemergence or at a very early stage of weed growth [16], but because of photodegradation this herbicide has short residual activity [15]. Flumioxazin is labeled for use in "field grown deciduous trees" [16], but not specifically for eucalyptus plantations. In a recent study in Brazil [17] flumioxazin rates ranging from 75 to 125 g active ingredient (ai) ha^{-1} were examined for selective weed control in newly planted *Eucalyptus grandis* W. Hill ex Maid. clones. The authors concluded that flumioxazin is selective to eucalyptus at the highest rate tested, but that combinations with other herbicides provided better weed control. Research is needed to refine application rate and timing relative to stage of eucalyptus growth and weed development for both oxyfluorfen and flumioxazin.

Sulfometuron methyl (hereafter referred to as sulfometuron) is a soil residual herbicide providing selective weed control with either pre- or postemergence applications in eucalyptus plantations, although best efficacy is obtained when weeds are in an early stage of growth. Specific herbicide labeling for eucalyptus plantations is currently limited [7]. Sulfometuron is perhaps most promising as it is a long residual herbicide and controls a broad spectrum of annual and perennial weeds; however, seedling injury is a serious concern where soil pH exceeds 6. This is explained by greater soil residual activity as degradation by hydrolysis is limited in alkaline conditions [18]. Blazer et al. [14] found applications of oxyfluorfen and sulfometuron to reduce competing vegetation and promote *Eucalyptus macarthurii* H. Dean and Maiden seedling height growth better than directed sprays of glyphosate but emphasized the need for future research to define sulfometuron rate responses for various vegetation types and soils.

Eucalyptus afforestation efforts by forest industry in the southern US have had limited success because of frost intolerance [5, 19], but there is renewed interest in planting cold-tolerant species, hybrids, and genetically modified cold hardy planting stock to meet increasing hardwood fiber demand and to supply potential bioenergy markets. The hybrid *E. urograndis*, a cross between *E. grandis* and *E. urophylla* S.T. Blake, has shown suitability for plantation culture in the southeastern US [5]. Advanced breeding techniques, including genetic modification, are being used to develop cold hardy cultivars, such as Arborgen's (Summerville, South Carolina, USA) "Frost Tolerant Eucalyptus" (FTE) *E. urograndis* clones [20]. Selective herbicides for FTE clones have not been identified.

Preliminary experiments at our research center demonstrated the effectiveness of imazamox and imazapic herbicides for selective weed control in newly established eucalyptus plantations in north Florida, although selectivity differed by herbicide rate, application timing and *Eucalyptus* species [21]. These herbicides have the advantage of being effective both before and after weed emergence but provide varying degrees of residual weed control [15]. This study examines four promising herbicides for selective weed control in eucalyptus, flumioxazin, imazamox, imazapic, and sulfometuron, relative to the widely used oxyfluorfen operational standard, to refine application rate and timing recommendations for selective weed control in two genetically modified frost-tolerant hybrid lines of *Eucalyptus urograndis*.

Eucalyptus growth response to selective herbicide treatments reflects a balance between direct negative effects of the herbicide and the benefits of competition control. To better examine their selectivity, herbicide treatments were compared to two experimental controls, one which was nontreated and one receiving near complete weed control using careful directed sprays of glyphosate. The complete weed control treatment demonstrates the potential for eucalyptus growth in the absence of competition and herbicide phytotoxicity.

2. Materials and Methods

2.1. Site Description. The study site was a fallow agricultural field located at the University of Florida, North Florida Research and Education Center, south of the city of Quincy, in the lower Coastal Plain region of Florida, USA (30°32′N, 84°35′W), at an altitude of approximately 70 m. The local climate is temperate, warm, and wet, with highest temperatures in July (mean temperature 27.1°C, maximum temperature 32.7°C), lowest temperatures in January (mean temperature 10.3°C, minimum temperature 4.0°C), and 1431 mm annual precipitation [22]. The soil is a Dothan- (fine-loamy, kaolinitic, and thermic Plinthic Kandiudults) Fuquay (loamy, kaolinitic, and thermic Arenic Plinthic Kandiudults) complex [23].

2.2. Site Preparation and Plantation Establishment. In October 2008, the study site was prepared for planting by applying 3.4 kg acid equivalent (ae) ha^{-1} glyphosate herbicide (Razor Pro, Nufarm, Burr Ridge, IL, USA) as a broadcast spray and

Table 1: Herbicide treatments tested for selective weed control in *Eucalyptus urograndis* clonal plantation culture near Quincy, Florida, applied over the top of newly planted container-grown cuttings[1], either prior to weed emergence (PRE, two weeks after planting) or after weed emergence (POST, six weeks after planting), compared to a nontreated control and near complete weed control obtained using repeated glyphosate herbicide sprays, carefully directed to weeds while shielding seedlings from spray contact.

Treatment	Relative rate	Actual rate[2] (g ha^{-1})	Trade name	Herbicide content
Flumioxazin	Low	290 ai	SureGuard	51%
Flumioxazin	High	430 ai	SureGuard	51%
Imazamox[3]	Low	140 ae	Clearcast	120 g L^{-1}
Imazamox[3]	High	280 ae	Clearcast	120 g L^{-1}
Imazapic[3]	Low	140 ae	Plateau	240 g L^{-1}
Imazapic[3]	High	210 ae	Plateau	240 g L^{-1}
Oxyfluorfen	Low	1120 ai	GoalTender	480 g L^{-1}
Oxyfluorfen	High	2240 ai	GoalTender	480 g L^{-1}
Sulfometuron methyl	Low	26 ai	Oust XP	75%
Sulfometuron methyl	Medium	53 ai	Oust XP	75%
Sulfometuron methyl	High	105 ai	Oust XP	75%
Nontreated control	—	—	—	—
Complete weed control	—	—	Accord XRT	—

[1]Container grown rooted cuttings were sixteen weeks old at planting.
[2]Rate of active ingredient (ai) or acid equivalent (ae) applied.
[3]A nonionic surfactant was added at 0.25% (v/v) for POST applications of imazamox and imazapic as directed by the herbicide labels.

disking two weeks later. This was followed by a second broadcast spray using 2.2 kg ae ha^{-1} glyphosate (Accord XRT, Dow AgroSciences, Indianapolis, IN, USA) on March 25, 2009, and disking on April 7th to provide a bare soil surface optimum to preemergent herbicide performance. Sixteen-week-old (from cutting) container-grown rooted stem cuttings of two *Eucalyptus urograndis* transgenic clonal lines (Frost Tolerant Eucalyptus (FTE) ArborGen, Summerville, SC, USA) were hand-planted on April 14th, 2009, at 2.4 m (between rows) by 1.5 m (between trees within rows) spacing (2,777 trees ha^{-1}). The two lines were from the same base clone and the same inserted gene set. Each line resulted from an independent transformation event, and, as the location of the insertion is random, the effects can be random. Of the hundreds of lines tested by ArborGen, these two lines provided the best cold tolerance, growth rate and rooting potential (personal communication, William Hammond, ArborGen, February 2012).

2.3. Experimental Design. Five herbicides were chosen for their potential to provide selective weed control in eucalyptus plantations and were compared at two application timings, preemergence of weeds (PRE), or post emergence of weeds (POST) and at two rates, low or high (Table 1). Sulfometuron methyl (hereafter referred to as sulfometuron) was also applied at a third rate, medium, because preliminary testing suggested eucalyptus tolerance to this herbicide [21], but rate response has been variable in operational experience. Repeated glyphosate applications and a nontreated control were used as experimental controls representing two extreme weed control levels: near-complete control and no control, respectively. A total of 24 weed control treatments were tested on ten-tree row treatment plots (whole plots) 16.8 m long and 1.8 m wide, with the narrow dimension centered on tree rows. Herbicide type, herbicide rate, and application timing main effects were tested in a randomized complete block design with four replications. Five rooted stem cuttings of each clone were randomly assigned to half of each whole plot, utilizing a split plot design to test for differences between the genetic lines. Treatment plots were separated by 0.6 m wide nontreated buffers.

2.4. Treatment Application. Preemergent herbicide treatments were applied on April 29, 2009, and POST herbicide treatments were applied on May 30, 2009, using a CO_2 pressurized backpack research sprayer equipped with a four-nozzle boom fitted with 8002 VS flat fan nozzles (Spraying Systems, Wheaton, IL, USA) 46 cm apart, providing a 1.8 m effective swath width. A 4.8 km hr^{-1} ground speed was maintained using a metronome to adjust walking pace. The regulator was set to 172 kPa to produce 1900 mL min^{-1} through all four nozzles on the boom, thus providing 130 L ha^{-1} total spray solution. For POST applications, spray solutions of imazamox and imazapic contained 0.25% (v/v) nonionic surfactant (Induce, Helena Chemical Company, Collierville, TN, USA), as directed by the labels [16]. To maintain near complete weed control, an aqueous solution of 2% glyphosate isopropylamine salt (4% Accord XRT) was applied as needed, as a careful directed spray to avoid contact to eucalyptus foliage using a backpack sprayer equipped with a hooded single flat fan nozzle. During glyphosate applications eucalyptus trees were additionally protected with polyethylene shields. All glyphosate spraying was done during absolute calm conditions in the early morning hours to avoid any drift to eucalyptus foliage.

2.5. Measurements

2.5.1. Weed Control. At 30, 60, and 90 days after treatment (DAT) ocular estimates of percent ground cover for bare ground (area free of live vegetation), forbs (other than vines), grasses, sedges, and vines were made by two experienced evaluators working together. Cover was estimated in four 1 by 1 m sampling plots per treatment plot (two sampling plots per clone split plot) centered between seedlings on the row. The percent ground cover was estimated independently for each group, such that total ground cover may have exceeded 100% where groups had overlapping cover. Percent cover was recorded to the nearest 5 percent for values between 10 and 90% cover and to the nearest 1 percent for 0 to 10% and 90 to 100% cover. The dominant weed species, comprising 10% or more of the total cover in a sampling plot, were recorded in the nontreated control.

2.5.2. Eucalyptus Injury Symptoms and Growth. Eucalyptus injury was assessed at 30, 60, and 90 DAT. Each tree was assigned a symptom severity index (SSI) of 0 to 4 (0 = none, 1 = slight, 2 = moderate, 3 = severe, and 4 = extreme) for each injury symptom, which included foliar chlorosis, foliar necrosis, defoliation, fasciculation (multiple buds at stem apices and branch meristems), lateral shoot dieback, and leader dieback. The percentage of trees with no or only minor symptoms was determined at each assessment date. For this classification, slight symptoms of foliar chlorosis, foliar necrosis, or defoliation were considered minor, whereas any symptoms of fasciculation, lateral shoot dieback, or leader dieback were not regarded as minor. Eucalyptus trees were measured for diameter at 5 cm above ground (GLD_5) to the nearest 0.1 mm and for total live height (H) to the nearest 0.1 cm at planting and at approximately 24 weeks after planting on September 29th, 2009. Stem volume index was calculated as ${GLD_5}^2 \times H$.

2.6. Data Analysis. Statistical analyses were performed with SAS 9.2 software [24]. Analysis of variance (ANOVA) or analysis of covariance (ANCOVA) was conducted using mixed models (Proc Mixed), with blocks treated as random effects [25]. ANOVA was conducted for percent ground cover (bare ground, forbs, grasses, sedges, and vines), percent tree survival, percentage of trees with no or only minor symptoms, and mean severity index for each injury symptom. ANCOVA was conducted for tree stem volume index, using the initial stem volume index as a covariate. The arcsin square root transformation was used for analyses of variables expressed as a percentage and for stem volume index analyses the natural logarithm of $(X + 1)$ transformation, where X is the stem volume index value, was used to meet assumptions of normality and homogeneity of variance. The backtransformed LS-means are reported. The critical level of significance for analysis of variance and LS-mean comparisons was $\alpha = 0.05$. Fisher's protected LSD test was used to compare LS-means. The complete weed control treatment was not included in LS-mean comparisons of percent bare ground or cover for different vegetation groups, as multiple applications were made with the intent to provide near complete weed control and the efficacy of other herbicides was of primary interest.

Two analyses were performed for each dependent variable. The first was a 4-way factorial analysis of a balanced design, excluding the high sulfometuron rate, the nontreated control, and the complete weed control treatment, to evaluate the significance of herbicide type, application timing, herbicide rate, and *E. urograndis* clone (fixed main effects) and their interactions. The second full analysis included all treatments tested. Orthogonal contrasts were used to test for the significance of planned comparisons among these treatments, such as differences among PRE or among POST treatments, or the significance of herbicide rate and application timing effects for individual herbicides.

3. Results and Discussion

3.1. Weed Species Composition. Numerous graminoid and forb species were present, but only a few were predominant. Grasses were the dominant weed group throughout the study. The most common grass species were large crabgrass [*Digitaria sanguinalis* (L.) Scop.], southern crabgrass [*Digitaria ciliaris* (Retz.) Koel.], southern sandspur (*Cenchrus echinatus* L.), and Texas panicum (*Panicum texanum* Buckl.). Sedges were less abundant as a group, with yellow nutsedge (*Cyperus esculentus* L.) being most common. Among forbs, carpetweed (*Mollugo verticillata* L.) was the most prevalent during the first evaluation. Vente conmigo (*Croton glandulosus* L. var. *septentrionalis* Müll. Arg.) became the dominant forb species as the growing season progressed, and common ragweed (*Ambrosia artemisiifolia* L.) cover increased substantially during the study. Vine cover was patchy with smallflower morningglory [*Jacquemontia tamnifolia* (L.) Griseb.] most frequently recorded, and some occurrence of maypop (*Passiflora incarnata* L.).

3.2. Weed Control. The 4-way ANOVA showed no significant *E. urograndis* clone effects for any ground cover variable at any evaluation date (ANOVA not shown). Therefore, weed control responses for the two clones combined are presented and discussed.

3.2.1. Bare Ground. Percent bare ground was significantly affected by herbicide type and application timing at all evaluation dates and by herbicide rate at 30 DAT and 60 DAT. When compared separately for each herbicide, percent bare ground was greater for PRE than POST application timing for all herbicides at 30 DAT and for flumioxazin, imazapic, and sulfometuron at 60 DAT (contrast results not shown). At 90 DAT, PRE oxyfluorfen resulted in less percent bare ground than the POST timing. Application timing had no effect for other herbicides at 90 DAT.

All PRE herbicide treatments resulted in greater percent bare ground than the nontreated control at 30 DAT (Table 2). Bare ground was 80% or more at 30 DAT for all treatments except the low rates of flumioxazin, imazamox, and oxyfluorfen. At 60 DAT high sulfometuron and both imazapic rates resulted 77 to 84% bare ground, compared to 19% for the nontreated control. Percent bare ground continued to decline for all PRE treatments, but at 90 DAT some treatments differed from the nontreated control, including the high flumioxazin rate, both rates of imazapic, medium and high sulfometuron, and the high imazamox rate.

Table 2: Prevalence of bare ground 30, 60, and 90 days after treatment (DAT) for herbicides applied over newly planted *Eucalyptus urograndis* rooted cuttings either prior to weed emergence (PRE) or after weed emergence (POST). Treatments were evaluated at the end of the month indicated for each application timing and periodic assessment.

Treatment		Bare ground cover (%)[1]		
Herbicide	Rate (g ha^{-1})	30 DAT	60 DAT	90 DAT[2]
Applied PRE weed emergence[3]				
		May	June	July
Flumioxazin	290 ai	74 e	41 d	21 b–e
Flumioxazin	430 ai	80 de	48 cd	38 a
Imazamox	140 ae	74 e	38 d	21 b–e
Imazamox	280 ae	80 de	55 cd	29 a–c
Imazapic	140 ae	92 a–c	77 a–c	34 ab
Imazapic	210 ae	94 ab	84 a	37 a
Oxyfluorfen	1120 ai	57 f	13 e	14 de
Oxyfluorfen	2240 ai	89 a–d	45 d	14 de
Sulfometuron	26 ai	84 c–e	51 cd	17 c–e
Sulfometuron	53 ai	86 b–d	64 bc	26 a–d
Sulfometuron	105 ai	95 a	81 a	31 a–c
Nontreated control		33 g	19 e	13 e
Complete weed control		99	97	92
Applied POST weed emergence[3]				
		June	July	August
Flumioxazin	290 ai	25 f–i	30 bc	29
Flumioxazin	430 ai	27 f–h	31 bc	28
Imazamox[4]	140 ae	40 de	34 bc	38
Imazamox[4]	280 ae	57 a–c	44 ab	38
Imazapic[4]	140 ae	53 b–d	43 ab	39
Imazapic[4]	210 ae	70 a	54 a	42
Oxyfluorfen	1120 ai	17 hi	27 bc	23
Oxyfluorfen	2240 ai	22 g–i	27 bc	28
Sulfometuron	26 ai	43 c–e	28 bc	33
Sulfometuron	53 ai	36 ef	26 cd	28
Sulfometuron	105 ai	58 ab	38 a–c	34
Nontreated control		15 i	13 d	21
Complete weed control		98	92	95

[1]LS-means within a column followed by the same letter for PRE or POST applications are not significantly different at $\alpha = 0.05$ using Fisher's protected LSD. Means are for the two *E. urograndis* clones combined, since clone effects were not significant. LS-means for the complete weed control treatment were not included in LSD comparisons, because this treatment was applied repeatedly to provide as close to 100% bare ground as possible and was intended for comparisons of eucalyptus growth response to weed control.
[2]The effect of treatment was not significant for bare ground cover at 90 DAT for POST applications.
[3]PRE weed emergence treatments were applied April 29, 2009; POST weed emergence treatments were applied May 30, 2009. Seedlings were planted April 14, 2009.
[4]A nonionic surfactant was added at 0.25% (v/v) for POST applications of imazamox and imazapic as directed by herbicide labels.

All POST herbicide treatments had greater percent bare ground than the nontreated control at 30 DAT, except both rates of oxyfluorfen and the low flumioxazin rate. At 60 DAT all treatments resulted in greater bare ground than the nontreated control, with the exception of the medium sulfometuron rate. No significant differences among POST treatments were observed at 90 DAT.

3.2.2. Grasses. Percent grass cover was significantly affected by herbicide type and herbicide rate at all evaluation dates and by application timing at 30 and 60 DAT (ANOVA not shown). Comparing the effect of application timing for individual herbicides, percent grass cover was significantly less following PRE application than POST application for all herbicides at 30 DAT and for all herbicides except low oxyfluorfen at 60 DAT. At 90 DAT, PRE oxyfluorfen resulted in greater percent grass cover than POST.

All PRE treatments, except low oxyfluorfen, resulted in significantly less grass cover than the nontreated control at 30 DAT (Table 3). The most effective and longest lasting grass control was achieved with medium and high sulfometuron and with both imazapic rates. Resulting grass cover at

Table 3: Prevalence of ground cover by vegetation groups 30, 60, and 90 days after treatment (DAT) for herbicides applied over newly planted *Eucalyptus urograndis* rooted cuttings either prior to weed emergence (PRE) or after weed emergence (POST). Treatments were evaluated at the end of the month indicated for each application timing and periodic assessment.

Treatment		Ground cover (%)[1]											
Herbicide	Rate ($g\ ha^{-1}$)	30 DAT Grasses	30 DAT Sedges[2]	30 DAT Forbs	30 DAT Vines	60 DAT Grasses	60 DAT Sedges	60 DAT Forbs	60 DAT Vines	90 DAT Grasses	90 DAT Sedges	90 DAT Forbs	90 DAT Vines[2]
Applied PRE weed emergence[3]													
		May				June				July			
Flumioxazin	290 ai	17 c	9	0 a	0 a	52 ef	9 d–f	0 a	0 a	76 e	5 d–e	0 a	0 ab
Flumioxazin	430 ai	14 c	6	0 a	0 a	49 ef	5 a–d	0 a	0 ab	59 c–e	3 b–d	0 a	0 a–c
Imazamox	140 ae	3 ab	6	17 e	0 a	36 c–e	14 f	12 cd	1 a–c	44 bc	8 e	21 cd	2 b–e
Imazamox	210 ae	2 ab	7	12 de	0 a	17 bc	11 ef	19 c–e	0 ab	34 a–c	6 d–e	29 de	0 a–d
Imazapic	140 ae	1 ab	3	3 c	0 a	6 ab	2 ab	13 c–e	0 a	27 ab	1 ab	36 de	0 a
Imazapic	280 ae	0 a	3	3 c	0 a	3 a	2 a	11 c	0 a	20 a	1 a	38 de	0 a
Oxyfluorfen	1120 ai	34 d	6	1 a–c	2 b	75 g	6 a–e	2 ab	3 d	81 e	3 b–d	2 ab	9 fg
Oxyfluorfen	2240 ai	5 b	6	0 ab	0 a	42 d–f	12 ef	1 a	1 b–d	80 e	4 c–e	1 ab	4 d–f
Sulfometuron	26 ai	2 ab	4	10 de	0 a	16 b	8 c–f	24 e	2 cd	47 b–d	5 d–e	30 de	4 e–g
Sulfometuron	53 ai	0 ab	4	9 d	0 a	5 ab	6 b–e	23 de	0 a–c	25 ab	5 d–e	37 de	3 c–f
Sulfometuron	105 ai	0 a	2	2 bc	0 a	3 a	3 a–c	12 c–e	0 a–c	29 ab	4 c–e	32 de	3 c–f
Nontreated control		37 d	7	17 e	8 c	61 fg	7 b–e	9 bc	8 e	72 de	2 a–c	8 bc	10 g
Complete weed control		0	0	0	0	0	1	1	1	1	0	0	6
Applied POST weed emergence[3]													
		June				July				August			
Flumioxazin	290 ai	71 f	4	1 a	3 bc	68 f	2 a	1 a	4 bc	66 de	1 a	2 a	3
Flumioxazin	430 ai	70 f	3	2 a	3 b	66 f	1 a	2 a–c	1 ab	65 de	0 a	2 a	1
Imazamox[4]	140 ae	53 de	4	7 bc	0 a	54 c–f	5 ab	9 b–e	1 a	47 c–e	1 a	12 a–c	1
Imazamox[4]	210 ae	32 bc	7	7 bc	0 a	37 b–d	9 b	9 c–f	2 ab	42 b–d	7 c	10 a–c	2
Imazapic[4]	140 ae	38 b–d	4	7 bc	0 a	35 bc	1 a	20 f–h	0 a	34 bc	0 a	27 c–e	1
Imazapic[4]	280 ae	17 a	6	10 c	0 a	10 a	1 a	34 h	0 a	11 a	1 a	46 e	1
Oxyfluorfen	1120 ai	74 f	6	3 ab	8 de	57 d–f	3 a	3 a–c	11 e	62 de	0 a	7 ab	7
Oxyfluorfen	2240 ai	66 ef	5	3 ab	8 de	61 ef	3 a	2 ab	9 c–e	67 e	1 a	2 a	4
Sulfometuron	26 ai	33 bc	7	12 c	10 e	45 c–e	5 ab	15 d–f	10 de	47 c–e	4 bc	14 a–c	5
Sulfometuron	53 ai	47 cd	5	11 c	5 cd	54 c–f	2 a	19 e–g	6 c–e	51 c–e	1 a	19 b–d	4
Sulfometuron	105 ai	27 ab	4	13 c	3 bc	23 ab	3 a	32 gh	5 cd	21 ab	1 ab	40 de	3
Nontreated control		65 ef	5	10 c	11 e	72 f	2 a	8 b–d	10 de	61 de	1 a	16 bc	6
Complete weed control		0	0	1	0	1	0	0	6	0	0	0	4

[1]LS-means within a column followed by the same letter for PRE or POST applications are not significantly different at $\alpha = 0.05$ using Fisher's protected LSD. Means are for the two *E. urograndis* clones combined, since clone effects were not significant. LS-means for the complete weed control treatment were not included in LSD comparisons, because this treatment was applied repeatedly to provide as close to 100% bare ground as possible and was intended for comparisons of eucalyptus growth response to weed control.
[2]The effect of treatment was not significant for sedge cover at 30 DAT for PRE or POST applications and for vine cover at 90 DAT for POST applications.
[3]PRE weed emergence treatments were applied April 29, 2009. POST weed emergence treatments were applied May 30, 2009. Seedlings were planted April 14, 2009.
[4]A nonionic surfactant was added at 0.25% (v/v) for POST applications of imazapic and imazamox as directed by herbicide label.

the various evaluation dates for these treatments ranged from 0 to 1%, 3 to 6%, and 20 to 29% at 30, 60, and 90 DAT, respectively; compared to 37%, 61%, and 72%, respectively, for the nontreated control. Both rates of imazamox were also effective, with 2 to 3% grass cover at 30 DAT, and significantly less grass cover than the nontreated control at all assessments. Flumioxazin and high oxyfluorfen had less grass cover than the nontreated control at 30 DAT but did not control grasses at later assessments.

Similar to results observed for PRE treatments, among POST treatments high imazapic and high sulfometuron rates provided the longest lasting and greatest degree of grass control, resulting in 82% and 66% reduction in grass cover, respectively, as compared to the nontreated control at 90 DAT. The low imazapic rate was also effective for postemergence control of grasses, with 44% reduction in cover at 90 DAT. Flumioxazin, oxyfluorfen, and the low imazamox rate were not effective for postemergent grass control and did not differ from the nontreated control at any assessment.

3.2.3. Sedges. Sedge cover was not affected by any factor at 30 DAT but was significantly affected by herbicide type and application timing at 60 and 90 DAT. None of the herbicide treatments resulted in less sedge cover than the nontreated control at any evaluation, except for the 60 DAT assessment of PRE imazapic at the high rate (Table 3). Imazapic is widely used to provide selective nutsedge control in peanut [26] and woody and herbaceous landscape plants [27]. Although sedge cover was generally low (0 to 14%), there were cases where PRE applications of imazamox and sulfometuron or POST imazamox had greater sedge cover than the nontreated control, suggesting that sedges may have responded favorably to the control of other vegetation, grasses in particular.

3.2.4. Forbs. When applied PRE, both rates of flumioxazin had no forb cover at any assessment, less than the 8 to 17% cover observed in the nontreated control (Table 3). Flumioxazin treatments applied POST had 1 to 2% forb cover at all assessments, less than the 8 to 16% forb cover in the nontreated control, with the exception of the high rate at 60 DAT. Both rates of oxyfluorfen applied PRE resulted in 2% or less forb cover at each assessment, although not different from the nontreated control with the low rate at 60 DAT and both rates at 90 DAT. Oxyfluorfen applied POST had 3% or less forb cover up to 90 DAT at the high rate and up to 60 DAT at the low rate, although not different from the nontreated control for both rates at 60 DAT or for the low rate at 90 DAT. The only other treatments that resulted in less forb cover than the nontreated control were PRE applied imazapic at both rates and the medium and high sulfometuron rates at 30 DAT. Herbicide treatments which effectively controlled grasses generally had more forb cover. Forb covers greater than the nontreated control were observed at 60 DAT for PRE applications of low and medium sulfometuron and at 90 DAT following all sulfometuron, both imazapic and high imazamox rates. Also, POST applied imazapic and sulfometuron had greater forb cover than the nontreated control at 60 DAT for both imazapic rates and medium and high sulfometuron and at 90 DAT for the high rates of both herbicides.

3.2.5. Vines. All PRE applied herbicides had less vine cover than observed in the nontreated control (8 to 10% cover) at all evaluation dates, except for the low oxyfluorfen and low sulfometuron rates at 90 DAT (Table 3). POST applications of oxyfluorfen and sulfometuron also showed poor vine control, with cover not different from the nontreated control except for the medium and high sulfometuron rates at 30 DAT. Treatment effects for vine cover at 90 DAT were not significant for POST application timing.

3.2.6. Overall Weed Control Efficacy. All PRE treatments provided effective weed control, but persistent control was observed only for high flumioxazin, low and high imazapic, medium and high sulfometuron, and the high imazamox rate. Postemergence treatments were applied when weed cover in the nontreated control averaged 67%. Herbicides providing the best overall postemergence weed control included imazapic, imazamox, and sulfometuron, which all showed a positive herbicide rate response in periodic measures of percent bare ground. These results are consistent with reported effectiveness in controlling established weeds using imazapic and imazamox [28] and sulfometuron efficacy in controlling emerged weeds at an early stage of growth [29]. Postemergence applications of flumioxazin and oxyfluorfen were far less effective in controlling weeds than PRE treatments, which is consistent with label directions that state these herbicides are most effective when applied to bare soil. Unlike results observed for PRE treatments, by the 90 DAT assessment, none of the POST applied herbicides differed from the nontreated control as measured by bare ground.

The herbicides tested are more effective for control of annual plants than perennials [7]. Imazapic and sulfometuron controlled annual grasses with both PRE and POST applications. The high rate of imazapic controlled sedge with PRE application timing, but other herbicides resulting in a high degree of grass control (imazamox, sulfometuron) had greater sedge cover than the nontreated control. Flumioxazin and oxyfluorfen were highly effective for forb control when applied PRE but did not control annual grasses. Climbing vines are damaging in newly established eucalyptus plantations, and some species, particularly morningglory, are not controlled with selective herbicides currently available for use in eucalyptus plantations in the USA. Vine control was best with PRE treatments, although POST treatments were also effective, except for oxyfluorfen and the low sulfometuron rate. Morningglory, which was the predominant vine on this study site and is common on old-field sites in the region, is large-seeded and tends to germinate later than many common agricultural weeds, such that it is often not controlled with herbicides having short residual activity.

Blazer et al. [14] tested seven herbicides at various rates in Louisiana, USA, at an early postemergence application timing and similar stage of eucalyptus growth in *E. macarthurii* and assessed ground cover at 5, 10, and 15 weeks after treatment. Their study included 51 and 101 g ha^{-1} oxyfluorfen, much lower than the 1.1 and 2.2 kg ha^{-1} rates tested in our study. They also tested 27 and 66 g ha^{-1} sulfometuron, similar to the low and medium rates we tested. At five weeks after treatment they observed 3 to 8% ground cover with oxyfluorfen treatments and 10 to 12% ground cover with sulfometuron, which were among their most effective treatments. Our results with sulfometuron are similar, but they observed better efficacy for much lower rates of oxyfluorfen, perhaps because only two susceptible annual forbs and one annual grass were predominant at their study location. In their study, no differences in ground cover among herbicide treatments and the nontreated control were observed at 10 and 15 weeks after treatment, whereas in our study weed control persisted to 90 DAT for all PRE applied herbicides except oxyfluorfen.

We found only one other study testing flumioxazin in eucalyptus plantations. In Vicosa, Brazil, Tiburcio et al. [17] compared flumioxazin alone at 75, 100, and 125 g ha^{-1} and combinations of flumioxazin and isoxaflutole or sulfentrazone to the standard 960 g ha^{-1} oxyfluorfen rate (similar to our low rate) at preemergence timing 20 days after planting *E. grandis* clones. They concluded that the highest flumioxazin rate tested was as effective as the oxyfluorfen standard but that the combinations of flumioxazin with the other herbicides were more effective in controlling weeds than flumioxazin

Table 4: ANOVA/ANCOVA[1] P values for the percentage of *Eucalyptus urograndis* trees showing no or minor injury symptoms at 30, 60, and 90 days after treatment (DAT), for survival and stem volume index (SVI) at the end of the first growing season, and for five herbicides applied at two rates and two application timings over newly planted rooted cuttings of two *E. urograndis* clones.

Factor	Dependent variable: Percentage of trees with no or minor injury symptoms[2] 30 DAT	60 DAT	90 DAT	Survival	SVI[3]
Application timing (AT)[4]	**<0.0001**	0.240	**<0.0001**	**<0.0001**	**<0.0001**
Herbicide (herb)[5]	**<0.0001**	**<0.0001**	**<0.0001**	**<0.0001**	**<0.0001**
Rate[6]	0.080	**0.047**	0.294	0.947	0.364
Clone[7]	0.757	0.736	0.634	0.666	0.781
AT × herb	**<0.0001**	**0.024**	**0.000**	**<0.0001**	**<0.0001**
AT × rate	0.205	0.099	0.073	0.947	0.217
AT × clone	0.426	0.495	0.816	0.666	0.178
Herb × rate	0.592	0.102	0.872	1.000	0.134
Herb × clone	0.743	0.898	0.943	0.944	0.963
Rate × clone	0.620	0.626	0.855	0.482	0.495
AT × herb × rate	0.765	0.069	0.565	1.000	0.386
AT × herb × clone	0.135	0.978	0.391	0.944	0.216
AT × rate × clone	0.514	0.405	0.666	0.482	0.931
Herb × rate × clone	0.818	0.394	0.469	0.738	0.841
AT × herb × rate × clone	0.879	0.802	0.496	0.738	0.495

[1]ANCOVA was conducted for SVI; ANOVA was conducted for the other variables.
[2]Slight foliar chlorosis, slight foliar necrosis, and slight defoliation were considered minor injury symptoms, whereas any observed fasciculation, lateral shoot dieback, and leader dieback were not regarded as minor.
[3]Stem volume index (SVI) = $GLD_5^2 \times H$; GLD_5 = outside bark stem diameter 5 cm above the ground; H = live stem height.
[4]PRE weed emergence or POST weed emergence.
[5]Flumioxazin, imazamox, imazapic, oxyfluorfen, or sulfometuron methyl.
[6]Rate = low or high relative rate.
[7]Two ArborGen proprietary transgenetic FTE (frost tolerant eucalyptus) clones.

alone. In our study weed control with PRE flumioxazin demonstrated a positive rate response to 430 g ha^{-1}, with no concerns regarding eucalyptus phytotoxicity. To our knowledge, no published studies, other than a preliminary research report from our research center [21], have examined imazamox or imazapic applications for selective weed control in eucalyptus plantings.

3.3. Eucalyptus Injury Symptoms and Growth. In the full ANOVA there were no significant differences between the two eucalyptus clones for the various injury symptom severity indices (SSI, ANOVA not shown), percentage of trees with no or minor injury symptoms, tree survival, or stem volume index (Table 4), so treatment means for the two clones combined were compared.

3.3.1. Eucalyptus Injury Symptoms. The most significant phytotoxicity was observed with PRE and POST imazapic, POST imazamox, POST sulfometuron, and PRE sulfometuron at the high rate. With the exception of imazapic, herbicide injury symptoms declined with time as trees recovered. The most pronounced and consequential injury symptoms were fasciculation, leader and lateral shot dieback, and defoliation.

Imazapic caused severe tree injury symptoms at both application rates and timings. When applied PRE, it caused defoliation, fasciculation, and leader dieback (results not shown). Compared to the other herbicide treatments and nontreated control, imazapic resulted in greater severity index for fasciculation at all evaluation times (1.1 to 3.7), and for defoliation and leader dieback at 30 DAT (0.5 to 0.6 and 0.8 to 1.0, resp.), and at 60 DAT (0.5 to 0.6 and 0.8 to 0.9, resp.). At 90 DAT, defoliation was no longer observed for imazapic treatments, but leader dieback was observed for the high rate (SSI 0.3). For PRE sulfometuron at the high rate, elevated severity indices were observed at 30 DAT for defoliation (0.3), fasciculation (0.8), and leader dieback (0.3) compared to SSI 0 for all symptoms for the nontreated control.

Imazapic resulted in the most severe injury symptoms among POST herbicides as well. At 30 DAT, all imazapic-treated trees exhibited extreme lateral shoot dieback (the maximum SSI of 4). This index diminished with time to SSI 0.2 to 0.3 at 90 DAT but was greater than the other POST herbicide treatments and nontreated control (SSI 0) through 90 DAT. POST imazapic also resulted in greater leader dieback index than the nontreated control (SSI 0) at 30 DAT (SSI 1.0, both rates) and at 60 DAT (SSI 0.3, low rate only). Fasciculation SSI at 60 DAT was 2.3 and 1.6 with

Table 5: Percentage of *Eucalyptus urograndis* trees with no or minor injury symptoms at 30, 60, and 90 days after treatment (DAT) for herbicides applied over newly planted rooted cuttings either prior to weed emergence (PRE) or after weed emergence (POST). Treatments were evaluated at the end of the month indicated for each application timing and periodic assessment.

Treatment		Percentage of trees with no or minor injury symptoms[1,2]		
Herbicide	Rate (g ha^{-1})	30 DAT	60 DAT	90 DAT
		Applied PRE weed emergence[3]		
		May	June	July
Flumioxazin	290 ai	100 a	100 a	95 a–c
Flumioxazin	430 ai	100 a	100 a	88 bc
Imazamox	140 ae	97 a	100 a	78 c
Imazamox	280 ae	99 a	100 a	92 a–c
Imazapic	140 ae	0 c	0 b	0 d
Imazapic	210 ae	0 c	0 b	1 d
Oxyfluorfen	1120 ai	100 a	99 a	82 bc
Oxyfluorfen	2240 ai	100 a	99 a	93 a–c
Sulfometuron	26 ai	99 a	99 a	81 bc
Sulfometuron	53 ai	96 a	100 a	99 ab
Sulfometuron	105 ai	53 b	99 a	100 a
Nontreated control		100 a	100 a	96 a–c
Complete weed control		99 a	100 a	99 ab
		Applied POST weed emergence[3]		
		June	July	August
Flumioxazin	290 ai	99 a	99 ab	99 a
Flumioxazin	430 ai	99 a	100 a	100 a
Imazamox[4]	140 ae	6 cd	100 a	100 a
Imazamox[4]	280 ae	0 d	100 a	100 a
Imazapic[4]	140 ae	0 d	0 d	73 b
Imazapic[4]	210 ae	0 d	27 c	56 b
Oxyfluorfen	1120 ai	100 a	100 a	100 a
Oxyfluorfen	2240 ai	99 a	100 a	100 a
Sulfometuron	26 ai	29 b	98 ab	100 a
Sulfometuron	53 ai	10 bc	99 ab	97 a
Sulfometuron	105 ai	8 c	86 b	100 a
Nontreated control		100 a	100 a	100 a
Complete weed control		100 a	100 a	100 a

[1]Slight foliar chlorosis, slight foliar necrosis, and slight defoliation (slight = symptom severity index 1 in a 0–4 scale) were considered minor injury symptoms, whereas any observed fasciculation, lateral shoot dieback, or leader dieback were not regarded as minor.
[2]LS-means within a column followed by the same letter for PRE or POST applications are not significantly different using Fisher's protected LSD at $\alpha = 0.5$. Means are for the two *E. urograndis* clones combined since clone effects were not significant.
[3]PRE weed emergence treatments were applied April 29, 2009; POST weed emergence treatments were applied May 30, 2009. Seedlings were planted April 14, 2009.
[4]A nonionic surfactant at 0.25% (v/v) was added for POST applications of imazapic and imazamox as directed by the herbicide label.

low and high rates of imazapic, respectively, greater than the nontreated control (SSI 0). All rates of POST imazamox and sulfometuron resulted in increased lateral shoot dieback at 30 DAT (SSI 1.8 to 2.9 and 1.3 to 1.9, resp.) as compared to the nontreated control (SSI 0), but trees recovered by 60 DAT (Table 5). Additionally, trees treated with low and medium sulfometuron exhibited some defoliation at 90 DAT (SSI 0.7).

3.3.2. Eucalyptus Condition. Preemergence applications of both the low and high rates of flumioxazin, imazamox, and oxyfluorfen, as well as the low and medium rates of sulfometuron, resulted in negligible phytotoxicity (Table 5). The percentage of trees with no or minor symptoms at 30 and 60 DAT was 96% or greater for these treatments, with no phytotoxicity observed with flumioxazin. At the high sulfometuron rate phytotoxicity was observed at 30 DAT, but by 60 DAT 99% of trees had no or minor injury symptoms. At 90 DAT, the number of trees with no or minor symptoms declined for oxyfluorfen, flumioxazin, and imazamox as some trees exhibited chlorosis and necrosis, probably caused by

Table 6: Survival and stem volume index of *Eucalyptus urograndis* trees at the end of the first growing season for preemergence (PRE) or postemergence (POST) applications of various herbicides, in comparison to a nontreated control and complete weed control obtained with repeated foliar sprays of glyphosate herbicide, directed carefully to weeds.

Treatment	Rate (g ha^{-1})	Survival[1] (%)		Stem volume index[1,2] (cm^3)	
		PRE	POST	PRE	POST
Flumioxazin	290 ai	100 a	100 a	157 bc	46 c–e
Flumioxazin	430 ai	100 a	100 a	226 bc	55 c–e
Imazamox[3]	140 ae	100 a	100 a	200 bc	315 b
Imazamox[3]	280 ae	100 a	100 a	91 cd	116 c
Imazapic[3]	140 ae	64 b	100 a	41 de	55 c–e
Imazapic[3]	210 ae	63 b	100 a	22 e	56 c–e
Oxyfluorfen	1120 ai	100 a	100 a	173 bc	91 cd
Oxyfluorfen	2240 ai	100 a	100 a	403 b	65 c–e
Sulfometuron	26 ai	100 a	100 a	175 bc	47 c–e
Sulfometuron	53 ai	100 a	100 a	276 b	26 e
Sulfometuron	105 ai	100 a	100 a	348 b	65 c–e
Nontreated control		100 a	100 a	42 de	42 de
Complete weed control		100 a	100 a	2665 a	2665 a

[1]LS-means within a column followed by the same letter are not significantly different at $\alpha = 0.05$ using Fisher's protected LSD. Means are for the two *E. urograndis* clones combined since clone effects were not significant.
[2]Stem volume index (SVI) = $GLD_5{}^2 \times H$; GLD_5 = outside bark stem diameter 5 cm above the ground; H = live stem height.
[3]A nonionic surfactant at 0.25% (v/v) was added for POST applications of imazapic and imazamox as directed by the herbicide label.

competition from grasses not controlled by these treatments. Trees in treatments giving better grass control, the medium and high rates of sulfometuron, did not show this decline. Significant injury occurred with PRE applications of imazapic at the rates tested, with essentially all trees showing injury without recovery. At the 90 DAT assessment, only imazapic differed from the nontreated control, with practically no symptom-free trees.

Among POST treatments, flumioxazin and oxyfluorfen resulted in negligible phytotoxicity to eucalyptus trees, with 99 to 100% showing no or minor injury symptoms at all assessments (Table 5). Injury, largely characterized by lateral shoot dieback, increased with increasing sulfometuron rate at 30 DAT. At that assessment 8 to 29% of trees treated with sulfometuron had no or minor symptoms, but nearly all trees recovered by 90 DAT. In general, recovery from initial phytotoxic symptoms was more pronounced following POST applications than for PRE treatments. This was likely due to better resilience of the more established trees in POST treatments, applied one month later than PRE treatments. This effect was most pronounced for POST imazamox, which had 0 to 6% of trees with no or minor injury at 30 DAT, and full recovery to 100% of trees in this condition at 60 and 90 DAT. As observed with PRE applications, imazapic resulted in the greatest and longest lasting phytotoxicity among POST treatments. However, unlike PRE treatment responses, when imazapic was applied POST to more established transplants, 56 to 73% of the trees recovered to show no or minor symptoms at 90 DAT. The greater tolerance observed for more established trees is consistent with a supplemental imazapic product label for use in sweetgum (*Liquidambar styraciflua* L.) fiber farms in the USA [30], which recommends that applications after planting occur when trees have not broken dormancy or at any time after 60 d from full leaf expansion. For POST treatments, nearly all trees had no or minor symptoms at the 90 DAT assessment, except for imazapic.

3.3.3. Eucalyptus Survival and Stem Volume Index. Eucalyptus survival was 100% for all treatments, with exception of PRE imazapic treatments, which resulted in 63 to 64% survival (Table 6). The full ANOVA did not show a significant herbicide rate effect on stem volume index (SVI), but the effects of herbicide type, application timing, and the interaction between herbicide type and timing were significant (Table 4). Contrasts (results not shown) to examine rate effects on SVI for individual herbicides identified a significant rate effect ($P = 0.0105$) for imazamox. The low imazamox rate resulted in 220% (PRE) or 272% (POST) greater stem volume index than the high rate, suggesting that future studies should examine rates less than 280 g ae ha^{-1}. Application timing was significant for flumioxazin, oxyfluorfen, and sulfometuron, with PRE applications resulting in greater SVI than POST treatments for each of these herbicides, regardless of the rate. Stem volume index was not affected by imazapic rate or application timing.

All PRE treatments, except both rates of imazapic and the high imazamox rate, resulted in trees with significantly larger stem volume index than the nontreated control. The high rate of oxyfluorfen gave the greatest stem volume index among PRE treatments, although not significantly different from other treatments except both rates of imazapic and the high imazamox rate. Among POST treatments, both rates of imazamox were the only treatments with greater SVI than the nontreated control. The low rate of imazamox resulted in the largest stem volume index among POST treatments and was significantly greater than all treatments except complete weed control.

The complete weed control treatment provided an opportunity to examine eucalyptus growth potential in the absence of competition and with minimal direct negative herbicide effects. Complete weed control resulted in stem volume index more than sixfold greater than the best herbicide treatment applied over trees, the high rate of oxyfluorfen applied PRE. Complete weed control also resulted in eucalyptus volume index more than sixtyfold greater than the nontreated control, demonstrating the impact of competing vegetation on the growth of young trees. In a similar eucalyptus establishment study in Louisiana, Blazer et al. [14] compared ten herbicide treatments to a nontreated control and directed 5% glyphosate applications made three times during the growing season. Periodic directed glyphosate applications resulted in a 30% reduction in one year height growth as compared to the nontreated control, indicating the potential for injury with this approach. However, in a subsequent study they compared various sulfometuron rates and nontreated control to the same regime of periodic directed glyphosate applications and observed 220% greater one year height growth with directed glyphosate sprays as compared to the nontreated control, perhaps demonstrating the need for careful application to avoid eucalyptus foliage.

4. Summary and Conclusions

Our results confirm sensitivity of newly planted eucalyptus to competing vegetation and underscore the importance of the balance between effective vegetation control and herbicide tolerance. Repeated glyphosate applications can provide effective weed control and enhance eucalyptus growth but are cost-intensive and can result in severe injury or mortality if trees are not adequately protected. This study demonstrated that a single application of one of several selective herbicides over newly planted rooted eucalyptus cuttings may enhance their growth. Repeated applications of selective herbicides could possibly further enhance growth, as suggested by the large growth response to complete weed control. In general, PRE applications of the herbicides tested were more effective than POST applications and also provided weed control during the critical period of tree establishment.

Our results confirm that oxyfluorfen is effective for selective control of forbs in newly established eucalyptus plantings at PRE application timing. We have shown that flumioxazin is also effective for forb control at PRE application timing and that both oxyfluorfen and flumioxazin may be applied at the rates tested for selective weed control in newly planted eucalyptus during active growth. We have confirmed that sulfometuron is most effective for selective control of annual grasses and forbs in newly planted eucalyptus at PRE timing and have refined selective herbicide rate response. Although temporary phytotoxicity was observed using the high sulfometuron rate (105 g ha^{-1}), this treatment was among the best PRE treatments in stem volume index response. Our study identified two new imidazolinone herbicides for selective weed control in eucalyptus plantings. Imazamox showed good selectivity and broad spectrum weed control at both application timings and generally resulted in the best selective weed control among POST treatments. In spite of temporary phytotoxicity, both imazamox rates were the only POST treatments resulting in greater stem volume index than the nontreated control, and the volume response to the low (140 g ae ha^{-1}) imazamox rate was greater than all other POST treatments. Lower imazapic rates, applications at a more advanced stage of growth, and directed sprays should be tested for eucalyptus tolerance, as this herbicide was most efficacious for weed control and shows promise for selective use in established stands.

Conflict of Interests

The authors declare that there is no conflict of interests regarding the publication of this paper.

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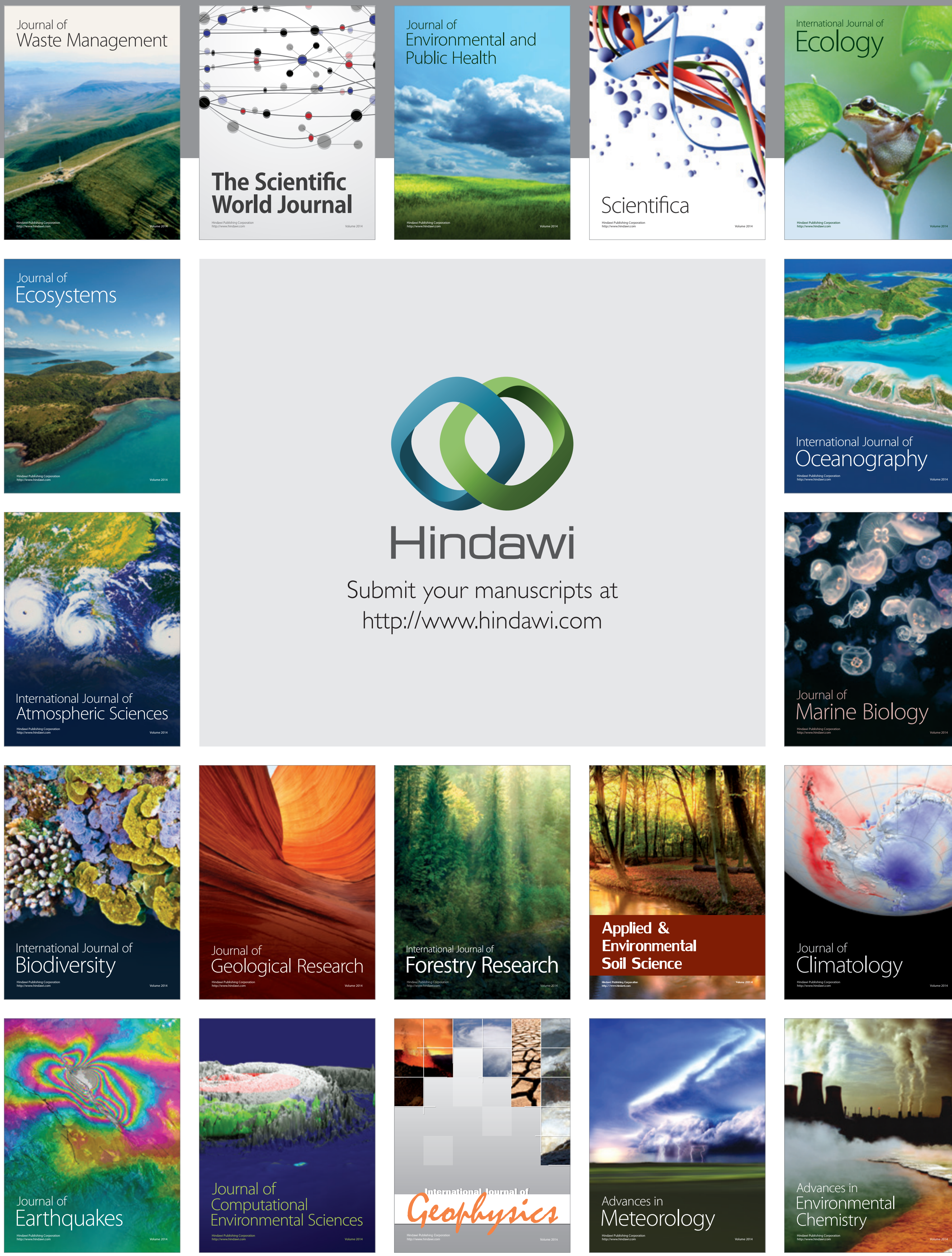
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