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Selective herbicides for establishment of *Eucalyptus benthamii* plantations

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Abstract 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 at either pre- or post-weed emergence timing for selective weed control in the establishment of *Eucalyptus benthamii*, a frost-tolerant species showing promise for commercial plantations in the southeastern United States and southern Brazil. Herbicides were applied at two or three rates and compared to a non-treated control and to near-complete weed control obtained with repeated glyphosate directed sprays. Herbicides were most efficacious when applied prior to weed emergence, at 2 weeks after planting 16-week-old containerized eucalyptus seedlings. Pre-emergence imazapic treatments resulted in broad-spectrum and persistent weed control, with 77–82% bare-ground at 60 days after treatment, but both pre- and post-emergence applications of imazapic caused excessive eucalyptus injury at the highest rate tested. Imazapic, sulfometuron, and imazamox were most effective for grass control. Both timings of flumioxazin were effective for forb control at the early assessment. All pre-emergence treatments enhanced stem volume compared to the non-treated control, but post-emergence treatments did not, suggesting the need for early weed control to facilitate *E. benthamii* growth. Pre-emergence applications of medium and high sulfometuron, low imazapic, high imazamox, and high oxyfluorfen rates increased stem volume four-fold to six-fold compared to the non-treated control. Repeated glyphosate directed sprays increased stem volume nearly three-fold compared to the control. These results confirm one early report of flumioxazin effectiveness and identify imazamox and imazapic as new selective herbicides for eucalyptus culture.

Keywords Herbicide tolerance · Herbicide timing · Flumioxazin · Glyphosate · Imazamox · Imazapic · Oxyfluorfen · Sulfometuron-methyl

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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 (Davidson 1993; Rockwood 2012) on more than 17.8 million ha worldwide (Pires et al. 2013). 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 (Dougherty and Wright 2012; Kellison et al. 2013). Studies throughout the world have demonstrated that competition in the first 18 months to 2 years following planting is most impactful on eucalyptus productivity (Adams et al. 2003; Florentine and Fox 2003; Garau et al. 2009). Trees under stress from weed pressure or limited nutrients are more susceptible to cold injury than those without these limitations (Meskimen 1971; Schönau et al. 1981), so controlling competition may also impart greater cold tolerance, an important consideration in temperate climates.

Eucalyptus afforestation efforts by forest industry in the southeastern US have had limited success because of frost intolerance (Meskimen et al. 1987; Kellison et al. 2013), but there is renewed interest in planting cold-tolerant species, hybrids, and genetically-modified cold-hardy planting stock to supply increasing hardwood fiber demand and potential bioenergy markets. Dougherty and Wright (2012) estimated that 5000–10,000 ha of commercial plantations were established annually in the southeastern US and models predict that freeze-tolerant eucalyptus may replace as much as 1.1 million ha of planted and natural pine forests in the region (Wear et al. 2015). *Eucalyptus benthamii* Maiden and Cambage has shown promise for cold hardiness in the Coastal Plain of southeastern US from Louisiana to South Carolina (Stape et al. 2011), and it is the main species considered for eucalyptus plantations in frost-prone regions of southern Brazil (Stahl et al. 2011).

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 (Osiecka and Minogue 2013). 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 that can be sprayed over eucalyptus transplants and provide persistent weed control when applied either prior to weed emergence (pre-emergence) or to actively growing weeds (post-emergence) would advance eucalyptus silviculture.

The non-selective herbicide glyphosate controls a broad weed spectrum, is widely used to prepare sites for planting, and is 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 completely avoid spray contact in operational practice. In their study of the effect of glyphosate spray drift to eucalyptus clones, Tuffi Santos et al. (2007) observed a progression of injury symptoms from leaf chlorosis through to necrosis and plant death, with phytotoxicity positively correlated to increasing application rate. In the absence of herbicides that can be tolerated when applied directly to eucalyptus, multiple applications of glyphosate are needed through the growing season as new weeds emerge in eucalyptus plantations, resulting in a significant management cost (Blazier et al. 2012). There are also concerns regarding the development of resistant weeds when a single herbicide or herbicides with a common mode of action are used in repeated applications, resulting in high selection pressure.

Oxyfluorfen and flumioxazin are selective herbicides that can be applied over newly-planted trees of certain species and growth condition. Oxyfluorfen is effective as a pre- and post-emergence herbicide on small-seeded annual forbs and suppresses annual grasses, but it provides poor control of perennial grasses (Shaner 2014). Oxyfluorfen is widely used in eucalyptus silviculture worldwide, but current product labels restrict applications to "dormant" trees (CDMS 2018), a condition that may not exist in some climates because eucalyptus have naked bud habit and are never truly dormant. Flumioxazin has specific labeling for selective weed control in certain woody ornamentals and deciduous fruit and nut trees, but it is not labeled for eucalyptus culture. Flumioxazin is effective for forb and annual grass control when applied pre-emergence or at a very early stage of weed growth (CDMS 2018), but it has short residual activity because of photodegradation (Shaner 2014). In a recent study in Brazil (Tiburcio et al. 2012) flumioxazin rates ranging from 75 to 125 g active ingredient (a.i.) ha^{-1} were examined for selective weed control in newly planted *Eucalyptus grandis* W. Hill ex Maid. clones. The authors concluded that flumioxazin was non-injurious to eucalyptus at the highest rate tested, but 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 is a soil residual herbicide providing selective weed control with either pre- or post-emergence 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 to dormant trees and it is no longer labeled for this use in the United States (Osiecka and Minogue 2013). Sulfometuron methyl is perhaps most promising among currently used products because it is a long residual herbicide and controls a broad spectrum of annual weeds and some perennial species, but seedling injury is a serious concern where soil pH exceeds 6. This pH-related injury is due to greater soil residual activity of sulfometuron methyl as its degradation by hydrolysis is limited in alkaline conditions (Brown 1990). Blazier et al. (2012) found applications of oxyfluorfen and sulfometuron methyl to reduce competing vegetation and promote *Eucalyptus macarthurii* H. Dean and Maiden seedling height growth better than directed sprays of glyphosate, but they emphasized the need for future research to define sulfometuron methyl rate responses for various vegetation types and soils.

Preliminary experiments at our research center demonstrated the effectiveness of the imidazolinone herbicides imazamox and imazapic for selective weed control in newly established eucalyptus plantations in north Florida, although selectivity differed by herbicide rate, application timing, and *Eucalyptus* species (Osiecka and Minogue 2011). These herbicides have the advantage of being effective both pre- and post-weed emergence, but they provide varying degrees of residual weed control (Shaner 2014).

In this study we examine four promising herbicides (flumioxazin, imazamox, imazapic, and sulfometuron methyl) for selective weed control when applied over newly planted *E. benthamii*, relative to the operational standard herbicide oxyfluorfen, to refine herbicide active ingredient application rate and timing recommendations. We also compare these selective herbicides to near-complete weed control obtained with careful repeated directed sprays of glyphosate. Careful glyphosate directed sprays were intended to provide a high degree of weed control without the negative effects of phytotoxicity, to better examine herbicide selectivity among the new herbicides.

Materials and methods

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°33′N, 84°36′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 (NOAA 2002). The soil is an Orangeburg loamy fine sand (fine-loamy, kaolinitic, thermic Typic Kandiudults) (USDA-NRCS 2018).

Site preparation and plantation establishment

To optimize perennial vegetation control prior to planting, the study site was prepared with high rates of glyphosate, as is the usual practice. In April 2009 5.0 kg acid equivalent (ae) ha^{-1} glyphosate herbicide (Glyfos® X-TRA, Cheminova A/S, P.O. Box 9, Lemving, Denmark) was applied as a broadcast spray. This application was followed by spot application of 2% Glyfos® X-TRA and subsequent harrowing in May. On June 1st a second harrowing provided a bare soil surface to optimize pre-emergence herbicide performance. 16-week-old containerized seedlings of *E. benthamii* Maiden and Cambage were hand planted on June 2nd, 2009 at 2.4 m (between rows) × 1.5 m (between trees within rows) spacing (2777 trees ha^{-1}).

Experimental design

Five herbicides were chosen for their potential to provide selective weed control in *Eucalyptus* plantations and compared at two application timings, pre-weed emergence (PRE) or post-weed emergence (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 rate response has been variable in operational experience. Repeated glyphosate directed sprays and a non-treated 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 16.8 m long and 1.8 m wide, with the narrow dimension centered on tree rows. The 24 treatments were randomized in a complete block design with 4 replications. The study was blocked to account for a small gradient in the depth of the sandy loam surface horizon. Treatment plots were separated by 0.6 m wide non-treated buffers.

Treatment application

Pre-emergence herbicide treatments were applied on June 16th, 2009 and post-emergence herbicide treatments were applied on July 21st, 2009, using a CO_2 pressurized backpack research sprayer providing 130 l ha^{-1} total spray solution. For POST applications, spray solutions of imazamox and imazapic contained 0.25% (v/v) non-ionic surfactant (Induce, Helena Chemical Company, Collierville, TN, 38,017, USA), as directed by the labels

Table 1 Herbicide treatments tested for selective weed control in *Eucalyptus benthamii*, applied over the top of newly-planted seedlings[a], either prior to weed emergence (PRE, 2 weeks after planting) or after weed emergence (POST, 6 weeks after planting), compared to a non-treated control and repeated glyphosate sprays directed to weeds

Treatment	Relative rate	Actual rate[b] (g ha^{-1})	Trade name	Herbicide content
Flumioxazin	Low	290 ai	SureGuard®	51%
Flumioxazin	High	430 ai	SureGuard®	51%
Imazamox	Low	140 ae	Clearcast®	120 g l^{-1}
Imazamox	High	280 ae	Clearcast®	120 g l^{-1}
Imazapic	Low	140 ae	Plateau®	240 g l^{-1}
Imazapic	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%
Non-treated control	–	–	–	–
Repeated directed glyphosate	–	–	4% Accord® XRT	53.6%

[a]Container-grown seedlings were 16 weeks old at planting

[b]Rate of active ingredient (ai) or acid equivalent (ae) applied

(CDMS 2018). 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 were additionally protected with polyethylene shields. All spraying was done during calm conditions in the early morning hours to minimize drift.

Measurements

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), grasses, sedges, and forbs were made by two experienced evaluators working together. Cover was estimated in four 1 by 1 m sampling plots per treatment 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% for values between 10 and 90% cover and to the nearest 1% for 0–10% and 90–100% cover. The dominant weed species, comprising 10% or more of the total cover in sampling plots, were recorded in the non-treated control.

Eucalyptus injury symptoms and growth

Tree injury was assessed at 30, 60, and 90 DAT. Each tree was assigned a symptom severity index of none, slight, moderate, severe, or extreme for each injury symptom, which included: foliar chlorosis, foliar necrosis, defoliation, fasciculation (proliferation of apical or lateral buds), lateral shoot dieback, and leader dieback. The percentage of healthy trees, with no or only minor injury symptoms, was determined for 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 22 weeks after planting on October 29th, 2009. Stem volume index was calculated as $GLD_5^2 \times H$.

Data analysis

The analysis of variance was structured as a one-factor model with 24 treatments. Orthogonal contrast statements were then used to partition treatment effects to perform a factorial-like ANOVA (Milliken and Johnson 1992) to test the significance of herbicide type, herbicide rate, application timing, and the interactions of these factors. Rate, application timing, and their interaction were also tested for each herbicide. For sulfometuron, which was applied at three levels, the rate effect was separated to determine the significance of linear or quadratic rate response. Application timing is known to be important to herbicide selectivity, so additional contrasts were used to perform an analysis of herbicide type and rate effects for PRE and POST timing. Contrast statements were also used to compare the mean across rates for each herbicide type to the non-treated control, to the mean across rates for the oxyfluorfen operational standard, and to the repeated directed glyphosate treatment. Significant findings from analysis of variance (ANOVA), analysis of covariance (ANCOVA), and planned orthogonal contrasts are presented in the text and Tables 2 and 3.

Statistical analyses were performed with SAS/STAT 14.1 software (SAS 2015). The ANOVA or ANCOVA were conducted using mixed models (PROC GLIMMIX), with blocks treated as random effects (Littell et al. 2006). ANOVA was conducted for percent ground cover (bare-ground, grasses, sedges, and forbs), percent tree survival, and percentage of healthy trees, with no or only minor symptoms. ANCOVA was conducted for tree stem volume index, using the initial volume index as a covariate. The arcsin square root transformation was appropriate for analyses of variables expressed as a percentage, and the natural logarithm of $(X+1)$ transformation, where X is the stem volume index value, was used for volume index analyses to meet assumptions of normality and homogeneity of variance. The back-transformed means are reported as recommended by Gomez and Gomez (1984). Approximate standard errors were calculated as described by Jørgensen and Pedersen (1998). The critical level of significance for statistical tests was $\alpha = 0.05$, or as noted in the text and Tables 2 and 3.

Results and discussion

Weed species composition

Several graminoid and forb species were present, but only a few were predominant in weed cover assessments. Grasses were the dominant weed group throughout the study. Most of the grass cover consisted of large crabgrass [*Digitaria sanguinalis* (L.) Scop.] and southern crabgrass [*Digitaria ciliaris* (Retz.) Koel.]. Yellow foxtail (*Setaria glauca* L. P. Beauv) was also present. Sedges were represented mostly by yellow nutsedge (*Cyperus esculentus* L.).

Table 2 Back-transformed LS-mean percent ground cover (standard errors are in parentheses) by vegetation groups 30, 60, and 90 days after treatment (DAT) for herbicides applied over newly-planted *Eucalyptus benthamii* seedlings pre-weed emergence (PRE)

Treatment		Ground cover (%)								
Herbicide	Rate (g ha^{-1})	30 DAT			60 DAT			90 DAT		
		Grass	Sedge	Forb	Grass	Sedge	Forb	Grass	Sedge	Forb
		PRE applications assessed in July			PRE applications assessed in August			PRE applications assessed in September		
Flumioxazin		[CG]		[c]	[cG]	[G]		[G]	[RcgO]	
	Avg.	44 (7)	18 (3)	0 (0)	65 (6)	13 (2)	0 (1)	74 (5)	11 (2)	1 (1)
	290 ai	56 (10)	21 (4)	0 (0)	70 (8)	11 (3)	0 (0)	78 (6)	6 (2)	0 (0)
	430 ai	31 (9)	15 (3)	1 (1)	60 (8)	17 (4)	1 (2)	70 (7)	17 (4)	2 (3)
Imazamox		[rCO]	[ro]		[CGO]	[rCGO]	[CGO]	[CGO]	[rCGO]	[CGO]
	Avg.	7 (4)	22 (3)	6 (6)	25 (5)	19 (3)	26 (6)	37 (5)	14 (2)	31 (6)
	140 ae	15 (7)	29 (4)	12 (4)	35 (8)	14 (3)	29 (9)	42 (7)	9 (3)	37 (10)
	210 ae	2 (2)	15 (3)	3 (2)	16 (6)	25 (4)	22 (8)	31 (7)	20 (4)	25 (9)
Imazapic		[CO]	[CGO]	[c]	[CO]	[G]	[g]	[CO]	[r]	[g]
	Avg.	0 (0)	3 (1)	0 (0)	3 (2)	6 (2)	11 (4)	9 (3)	7 (2)	19 (6)
	140 ae	0 (1)	4 (2)	0 (1)	3 (3)	8 (3)	8 (5)	11 (4)	10 (3)	13 (7)
	280 ae	0 (0)	2 (1)	0 (1)	2 (3)	5 (2)	14 (7)	7 (4)	4 (2)	27 (9)
Oxyfluorfen		[RCG]			[rG]	[G]		[RcG]		[r]
	Avg.	45 (7)	14 (2)	2 (1)	73 (5)	8 (2)	3 (2)	71 (5)	4 (1)	7 (4)
	1120 ai	64 (10)	17 (4)	1 (1)	84 (6)	8 (3)	0 (1)	83 (5)	4 (2)	1 (2)
	2240 ai	27 (9)	13 (3)	3 (2)	60 (8)	8 (3)	9 (6)	58 (7)	5 (2)	16 (7)
Sulfometuron		[CO]	[rcg]	[RcGO]	[rCO]	[cG]	[CGO]	[CO]	[CGO]	[CGO]
	Avg.	0 (1)	11 (2)	19 (3)	4 (2)	17 (2)	47 (5)	5 (2)	12 (2)	52 (6)
	26 ai	0 (1)	15 (3)	34 (7)	15 (6)	20 (4)	35 (9)	6 (3)	14 (3)	54 (10)
	53 ai	0 (1)	12 (3)	16 (5)	2 (2)	13 (3)	60 (9)	9 (4)	8 (3)	64 (9)
	105 ai	0 (0)	5 (2)	11 (4)	1 (1)	18 (4)	46 (9)	2 (2)	16 (3)	37 (10)

Table 2 (continued)

Treatment		Ground cover (%)								
Herbicide	Rate (g ha^{-1})	30 DAT			60 DAT			90 DAT		
		Grass	Sedge	Forb	Grass	Sedge	Forb	Grass	Sedge	Forb
		PRE applications assessed in July			PRE applications assessed in August			PRE applications assessed in September		
Non-treated control		81 (8)	19 (4)	6 (3)	85 (6)	8 (3)	4 (4)	86 (5)	4 (2)	5 (4)
Repeated directed glyphosate		1 (2)	20 (4)	3 (2)	0 (0)	1 (1)	0 (1)	5 (3)	4 (2)	3 (4)

Significance levels for planned tests for the effect of herbicide rate (r = 5%, R = 1%) and the comparison of average cover for each herbicide to the non-treated control (c = 5%, C = 1%), to the average cover of oxyfluorfen rates (o = 5%, O = 1%), and to the repeated glyphosate treatment (g = 5%, G = 1%) are listed in brackets for each herbicide when significant

Table 3 Back-transformed LS-mean percent ground cover (standard errors are in parentheses) by vegetation groups 30, 60, and 90 days after treatment (DAT) for herbicides applied over newly-planted *Eucalyptus benthamii* seedlings post-weed emergence (POST)

Treatment		Ground cover (%)								
Herbicide	Rate (g ha^{-1})	30 DAT			60 DAT			90 DAT		
		Grass	Sedge	Forb	Grass	Sedge	Forb	Grass	Sedge	Forb
		POST applications assessed in August			POST applications assessed in September			POST applications assessed in October		
Flumioxazin		[G]	[Go]	[cO]	[G]	[o]	[o]	[G]		[o]
	Avg.	82 (6)	8 (2)	0 (0)	74 (5)	1 (1)	1 (1)	66 (5)	3 (1)	2 (2)
	290 ai	87 (7)	7 (2)	0 (1)	73 (8)	2 (1)	1 (2)	64 (7)	3 (1)	1 (2)
	430 ai	77 (8)	10 (3)	0 (0)	75 (7)	1 (1)	1 (2)	68 (7)	3 (1)	2 (3)
Imazamox		[G]	[CG]	[G]	[RG]			[RCGO]	[rc]	[g]
	Avg.	66 (7)	20 (3)	8 (3)	67 (6)	7 (2)	8 (4)	40 (5)	5 (1)	19 (6)
	140 ae	76 (8)	17 (4)	10 (4)	83 (6)	6 (2)	9 (5)	57 (7)	2 (1)	20 (8)
	210 ae	54 (10)	24 (4)	7 (3)	47 (9)	8 (2)	7 (5)	24 (6)	9 (3)	19 (8)
Imazapic		[G]	[G]	[g]	[rG]			[RCGO]		[g]
	Avg.	75 (6)	15 (2)	5 (2)	68 (6)	2 (1)	7 (3)	34 (1)	2 (1)	15 (5)
	140 ae	71 (9)	15 (3)	4 (3)	82 (7)	2 (1)	5 (4)	51 (7)	1 (1)	12 (6)
	280 ae	79 (8)	15 (3)	5 (3)	53 (9)	2 (1)	10 (6)	19 (6)	2 (1)	18 (8)
Oxyfluorfen		[G]	[G]	[G]	[G]			[G]		
	Avg.	78 (6)	14 (2)	8 (3)	64 (6)	4 (1)	7 (4)	61 (5)	2 (1)	12 (5)
	1120 ai	72 (9)	14 (3)	8 (4)	66 (8)	4 (2)	10 (6)	57 (7)	2 (1)	17 (7)
	2240 ai	84 (7)	15 (3)	9 (4)	61 (8)	5 (2)	10 (6)	64 (7)	2 (1)	8 (5)
Sulfometuron		[G]	[cG]	[G]	[RG]			[RcGO]		[g]
	Avg.	72 (6)	17 (2)	5 (2)	68 (5)	4 (1)	9 (3)	43 (4)	2 (1)	16 (4)
	26 ai	75 (9)	17 (4)	5 (3)	83 (6)	4 (2)	7 (5)	60 (7)	3 (2)	10 (6)
	53 ai	78 (8)	13 (3)	5 (3)	70 (8)	4 (2)	7 (5)	38 (7)	2 (1)	12 (7)
	105 ai	63 (10)	21 (4)	6 (3)	49 (9)	3 (2)	14 (7)	30 (7)	1 (1)	27 (9)

Table 3 (continued)

Treatment		Ground cover (%)								
Herbicide	Rate (g ha^{-1})	30 DAT			60 DAT			90 DAT		
		Grass	Sedge	Forb	Grass	Sedge	Forb	Grass	Sedge	Forb
		POST applications assessed in August			POST applications assessed in September			POST applications assessed in October		
Non-treated control		85 (8)	9 (3)	5 (3)	77 (7)	4 (2)	6 (4)	63 (7)	1 (1)	12 (6)
Repeated directed glyphosate		0 (0)	1 (1)	0 (0)	4 (3)	4 (2)	4 (4)	0 (1)	2 (1)	2 (3)

Significance levels for planned tests for the effect of herbicide rate (r = 5%, R = 1%) and the comparison of average cover for each herbicide to the non-treated control (c = 5%, C = 1%), to the average cover of oxyfluorfen rates (o = 5%, O = 1%), and to the repeated glyphosate treatment (g = 5%, G = 1%) are listed in brackets for each herbicide when significant

Forb cover was sparse and varied greatly in space and time throughout the study, with the most common species being carpetweed (*Mollugo verticillata* L.) and, beginning in September, hyssop spurge (*Chamaesyce hyssopifolia* L. Small).

Weed control

Bare-ground

Percent bare-ground was significantly affected by herbicide type ($p < 0.001$) and application timing ($p < 0.003$) at all evaluation dates and by herbicide rate ($p = 0.001$) at 30 and 60 DAT (ANOVA not shown). There was an interaction between herbicide type and application timing ($p < 0.025$) at each assessment, which was largely due to differences in herbicide efficacy for grass control with PRE vs. POST timing, as explained below. There was also a significant interaction between application timing and herbicide rate ($p \leq 0.037$). Further treatment comparisons were made separately for PRE and POST applications because efficacy was strongly dependent on application timing.

At 30 DAT bare-ground increased with increasing herbicide rate with all PRE treatments ($p \leq 0.017$), except for both rates of imazapic which had 95–98% bare-ground (Fig. 1). At 60 DAT a positive rate response was observed only for oxyfluorfen ($p = 0.024$), and at 90 DAT only for sulfometuron ($p = 0.021$). Across rates tested for each herbicide, all PRE treatments resulted in greater percent bare-ground than the non-treated control at 30 DAT ($p < 0.001$). At that time, bare-ground was 80% or more for both rates of imazapic and the high rate of imazamox and sulfometuron. At 60 DAT all herbicides had greater bare-ground than the control ($p \leq 0.045$) except for oxyfluorfen, when the average response across rates for each herbicide was compared. At the 90 DAT assessment, only imazapic and sulfometuron treatments had greater bare-ground than the control ($p \leq 0.028$). Across rates, imazapic gave greater bare-ground than the oxyfluorfen standard at all assessments ($p < 0.001$) and imazamox and sulfometuron resulted in greater bare-ground than the standard at 30 and 60 DAT ($p \leq 0.028$). Repeated glyphosate directed sprays gave greater ($p < 0.001$) bare ground than any PRE treatment at 60 and 90 DAT.

Across selective herbicides, POST treatments were not as effective as those applied PRE in providing bare-ground ($p < 0.001$). Among POST treatments, imazamox, imazapic, and sulfometuron resulted in increasing bare-ground with increasing rate at 60 DAT ($p \leq 0.025$), as did imazamox and imazapic at 90 DAT ($p \leq 0.034$) (Fig. 1). Across rates tested for each herbicide, bare-ground with POST treatments did not differ from the non-treated control at 30 or 60 DAT, but at 90 DAT imazapic had greater bare-ground ($p = 0.003$) than the control. At 90 DAT 23% bare-ground was observed in the control, the result of grass senescence. Across rates, at 90 DAT imazamox, imazapic, and sulfometuron had greater ($p < 0.047$) bare-ground than the oxyfluorfen standard. Repeated glyphosate applications gave greater ($p < 0.001$) bare ground than any POST treatment at all assessments.

Grasses

At all evaluation dates percent grass cover was affected by herbicide type ($p < 0.001$), herbicide rate ($p \leq 0.024$), and application timing ($p < 0.001$), and there was an interaction between herbicide type and application timing ($p < 0.001$) (ANOVA not shown). The selective herbicides tested were generally effective when applied PRE, but not when applied POST, so results for the two timings were compared separately.

Fig. 1 Back-transformed LS-mean percent bare-ground 30, 60 and 90 days after treatment (DAT) for herbicides applied at low (L), medium (M) or high (H) rates over newly-planted *Eucalyptus benthamii* seedlings either pre-weed emergence or post-weed emergence ▶

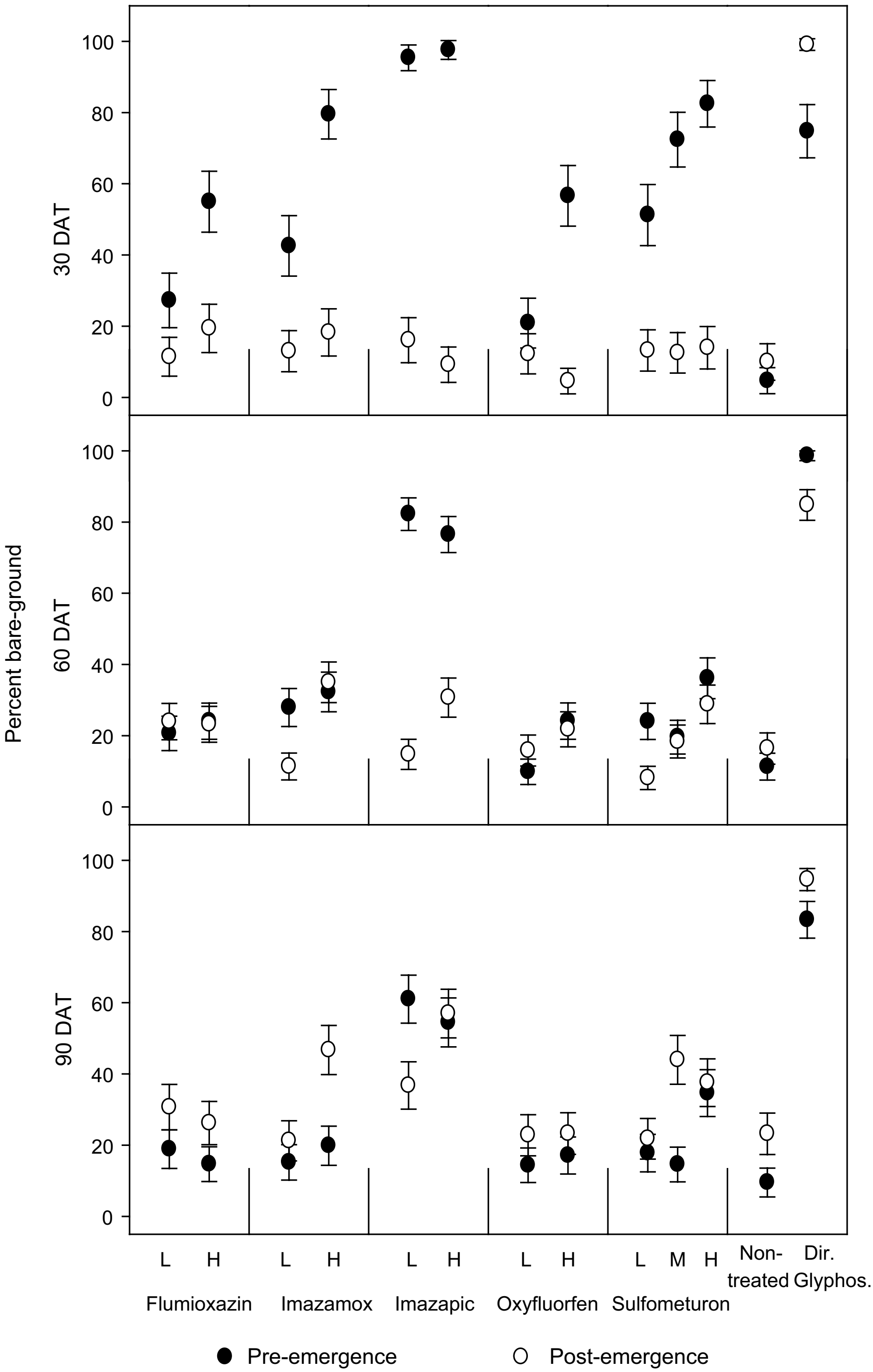
Following PRE treatments, grass cover decreased with increasing oxyfluorfen rate at all assessments ($p \leq 0.025$), as observed for imazamox at 30 DAT ($p = 0.050$) (Table 2). Grass cover decreased linearly with increasing sulfometuron rate at 60 DAT ($p = 0.017$). When averaged across rates for each herbicide, all PRE treatments had less grass cover than the non-treated control at 30 DAT ($p \leq 0.002$), and at 60 DAT all had less grass cover except for oxyfluorfen ($p \leq 0.027$). Imazamox, imazapic, and sulfometuron had less grass cover than the control at 90 DAT ($p < 0.001$). These same herbicides had less grass cover than the oxyfluorfen standard at all assessments ($p < 0.001$). Grass cover with repeated glyphosate was less than that with all selective herbicides ($p < 0.001$), except for imazapic and sulfometuron at all assessment dates, and imazamox at 30 DAT.

Following POST applications, grass cover decreased with increasing rate at 60 and 90 DAT for imazamox ($p \leq 0.002$), imazapic ($p \leq 0.011$), and linearly for sulfometuron ($p \leq 0.005$) (Table 3). Grass cover did not differ among selective POST herbicides at 30 DAT, ranging from 54 to 87% (Table 3). Similar to results for PRE treatments, imazamox, imazapic, and sulfometuron gave the most effective grass control, although grass cover differed from the non-treated control only at 90 DAT. Flumioxazin and oxyfluorfen treatments were not effective for post-emergence grass control at any assessment. As was observed for PRE timing, at 90 DAT imazapic, imazamox, and sulfometuron had less grass cover than the oxyfluorfen standard, across rates ($p \leq 0.007$). Repeated glyphosate directed sprays had less grass cover than any selective PRE herbicide at all assessments ($p < 0.001$).

Sedges

Sedge cover was affected by herbicide type ($p < 0.002$) at all assessments and by application timing ($p < 0.001$) at 60 and 90 DAT (ANOVA not shown). The interaction of herbicide type and application timing was significant at 30 DAT ($p < 0.001$) and 60 DAT ($p = 0.040$), such that efficacy was best considered with respect to application timing. At 30 DAT sedge cover was less than the non-treated control for the average of PRE imazapic ($p < 0.001$) or sulfometuron ($p = 0.031$) rates, but across rates POST imazapic applications did not differ from the control, and POST sulfometuron increased sedge cover relative to the control ($p = 0.043$) (Tables 2 and 3). At 60 DAT selective POST treatments did not differ from the non-treated control, but following PRE treatments sedge cover was greater than the control for imazamox ($p = 0.006$) and sulfometuron ($p = 0.015$), comparing averages across rates. These treatments provided a high degree of bare-ground, which may have fostered sedge seedling establishment.

Sedge cover decreased with increasing rate for PRE applications of sulfometuron ($p = 0.011$, linear) and imazamox ($p = 0.014$) at 30 DAT and imazapic ($p = 0.034$) at 90 DAT, whereas sedge cover increased with increasing rate for imazamox at 60 and 90 DAT ($p < 0.040$) and flumioxazin ($p = 0.005$) at 90 DAT. At 90 DAT sedge cover was greater than the non-treated control for the average rate response to PRE flumioxazin ($p = 0.017$), imazamox ($p = 0.002$), and sulfometuron ($p = 0.003$). Comparing average rate response for selective PRE herbicides to the oxyfluorfen standard, imazapic had less sedge cover than oxyfluorfen at 30 DAT ($p < 0.001$), but imazamox had greater sedge cover at all assessments ($p < 0.043$), and at 90 DAT greater cover was observed for flumioxazin ($p = 0.006$)



Percent bare-ground
30 DAT
60 DAT
90 DAT
0
20
40
60
80
100
L H L H L H L H L M H Non-treated Dir. Glyphos.
Flumioxazin Imazamox Imazapic Oxyfluorfen Sulfometuron
Pre-emergence
Post-emergence

and sulfometuron ($p < 0.001$). At the 30 DAT assessment of PRE treatments there was 20% sedge cover with the directed glyphosate treatment, but this diminished to 1 and 4% cover at 60 and 90 DAT, respectively, with repeated applications. At 30 DAT PRE imazapic ($p < 0.001$) and sulfometuron ($p = 0.014$) had less sedge cover that repeated directed glyphosate sprays, but at 60 DAT repeated glyphosate had less cover ($p < 0.005$) than any selective herbicide, and at 90 DAT sedge cover was greater for the average rate response with flumioxazin ($p = 0.022$), imazamox ($p = 0.002$), and sulfometuron ($p = 0.004$) treatments than with directed glyphosate sprays.

POST applications of the selective herbicides tested were generally not effective for sedge control, and observed sedge cover was low at 60 and 90 DAT assessments for all treatments (Table 3). A herbicide rate response was observed only for imazamox at 90 DAT, when sedge cover increased with increasing rate ($p = 0.013$). At 30 DAT sedge cover was greater with imazamox ($p = 0.007$) and sulfometuron ($p = 0.043$) treatments than in the non-treated control, and all treatments had greater cover than with repeated glyphosate treatment ($p < 0.001$).

Forbs

Forb cover was affected by herbicide type ($p < 0.001$) at all assessments and by application timing ($p \leq 0.014$) at 60 and 90 DAT (ANOVA not shown). There was a significant interaction between herbicide type and application timing ($p < 0.001$) at all assessments, so treatments were compared separately for PRE and POST application timing.

A herbicide rate response was observed only for PRE sulfometuron and oxyfluorfen (Table 2). At 30 DAT forb cover decreased with increasing sulfometuron rate ($p = 0.010$), whereas at 90 DAT forb cover increased with increasing oxyfluorfen rate ($p = 0.040$). When applied PRE, flumioxazin and imazapic rates had 0–1% forb cover at 30 DAT, and the average across rates was less than the 6% cover observed in the non-treated control ($p \leq 0.014$). POST flumioxazin rates had no forb cover at 30 DAT, less than the 5% observed in the control ($p = 0.035$) (Table 3). These were the only cases where forb suppression was observed relative to the non-treated condition, but treatments which provided high levels of grass control tended to be colonized by forbs, particularly at the later assessments. Across rates, PRE sulfometuron increased forb cover relative to the control at all assessments ($p \leq 0.012$), as did PRE imazamox at 60 and 90 DAT ($p \leq 0.007$). Comparing PRE treatments across rates for each herbicide, the oxyfluorfen standard had less forb cover than sulfometuron at all assessments ($p < 0.001$), and less forb cover than imazamox at 60 and 90 DAT ($p \leq 0.002$). POST applications of flumioxazin had less forb cover than oxyfluorfen at all assessments ($p \leq 0.028$). Repeated glyphosate treatment gave less forb cover than PRE applications of sulfometuron at all assessments ($p < 0.001$), or imazamox ($p < 0.001$) and imazapic ($p \leq 0.027$) at 60 and 90 DAT. POST applications of flumioxazin at all assessments, all selective herbicides at 60 DAT, and oxyfluorfen at 90 DAT did not differ from forb cover obtained with repeated glyphosate treatments.

Overall weed control efficacy

All PRE treatments except the low rates of oxyfluorfen and flumioxazin provided effective weed control at the early assessment (Fig. 1). Persistent grass control to 90 DAT was observed for both rates of imazamox and imazapic, and all rates of sulfometuron (Table 2). The high flumioxazin rate controlled grasses to 30 DAT. Those treatments providing effective grass control generally had increased forb and sedge cover relative to the non-treated control. POST treatments were applied when weeds were well-established and cover in the non-treated control averaged 95%. Among selective herbicides, only the high rates of imazapic, imazamox, and medium and high sulfometuron provided effective weed control to 90 DAT, because they were effective for grass control.

Blazier et al. (2012) tested seven herbicides in Louisiana, USA at an early post emergence timing and similar stage of growth in *E. macarthurii*. Their study included 51 and 101 g ha^{-1} oxyfluorfen, much lower than the 1120 and 2240 g 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 5 weeks after treatment they observed 3–8% ground cover with oxyfluorfen treatments and 10–12% 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 annual forbs and one annual grass were predominant. In their study, no differences in ground cover among herbicide treatments and the non-treated control were observed at 10 and 15 weeks after treatment, whereas in our study weed control persisted to 90 DAT for the medium and high (53 and 105 g ha^{-1}) sulfometuron rate.

We found only one other study testing flumioxazin in eucalyptus plantations. In Vicosa, Brazil, Tiburcio et al. (2012) 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 pre-emergence 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 combinations of flumioxazin with other herbicides were more effective than flumioxazin 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.

In the only other known published study regarding the use of imazamox and imazapic for selective weed control in eucalyptus plantations, the same herbicide rates were tested for PRE and POST applications in *Eucalyptus urograndis* clonal plantations at our research center (Minogue and Osiecka 2015). As in the current *E. benthamii* study, PRE applications of these herbicides provided better weed control than POST treatments, although the persistence of weed control at 90 DAT with imazapic (34–37% bare-ground) was not as strong as in the current study (54–61% bare-ground). In the current study a nearly continuous cover of annual grasses developed within 30 days after planting, whereas in the prior study greater forb cover was observed. As in the current study, the previous work in *E. urograndis* demonstrated the effectiveness of imazamox and imazapic for PRE and POST emergence grass control.

Eucalyptus injury symptoms

In general, there was less incidence and severity of herbicide injury symptoms with PRE herbicide timing than POST, and this was particularly true for lateral shoot dieback and leader dieback (data not shown). For most herbicides, seedlings planted 2 weeks prior to PRE application timing had greater herbicide tolerance than for POST applications of the same herbicide and rate 6 weeks after planting. Better tolerance for the younger transplants may be explained by smaller crowns to absorb the foliar spray or inactive growth soon after transplanting, but the relationship between seedling size or stage of growth and herbicide rate tolerance needs to be better elucidated, particularly for sulfometuron.

Fig. 2 Back-transformed LS-mean percentage of healthy *Eucalyptus benthamii* trees, with no or minor ▶ injury symptoms, at 30, 60 and 90 days after treatment (DAT) for herbicides applied at low (L), medium (M) or high (H) rates over newly-planted seedlings, either pre-weed emergence or post-weed emergence. If the values for pre- and post-weed emergence are the same, both are represented by a single point

At all assessments the percentage of healthy trees with no or minor injury symptoms (PHT) was affected by herbicide type ($p<0.001$), herbicide rate ($p\leq0.030$), and application timing ($p<0.001$) and there was an interaction between herbicide type and timing ($p<0.001$) (ANOVA not shown). The extent and severity of injury symptoms was generally less for PRE timing than POST, except for oxyfluorfen which did not cause injury at either timing (Fig. 2).

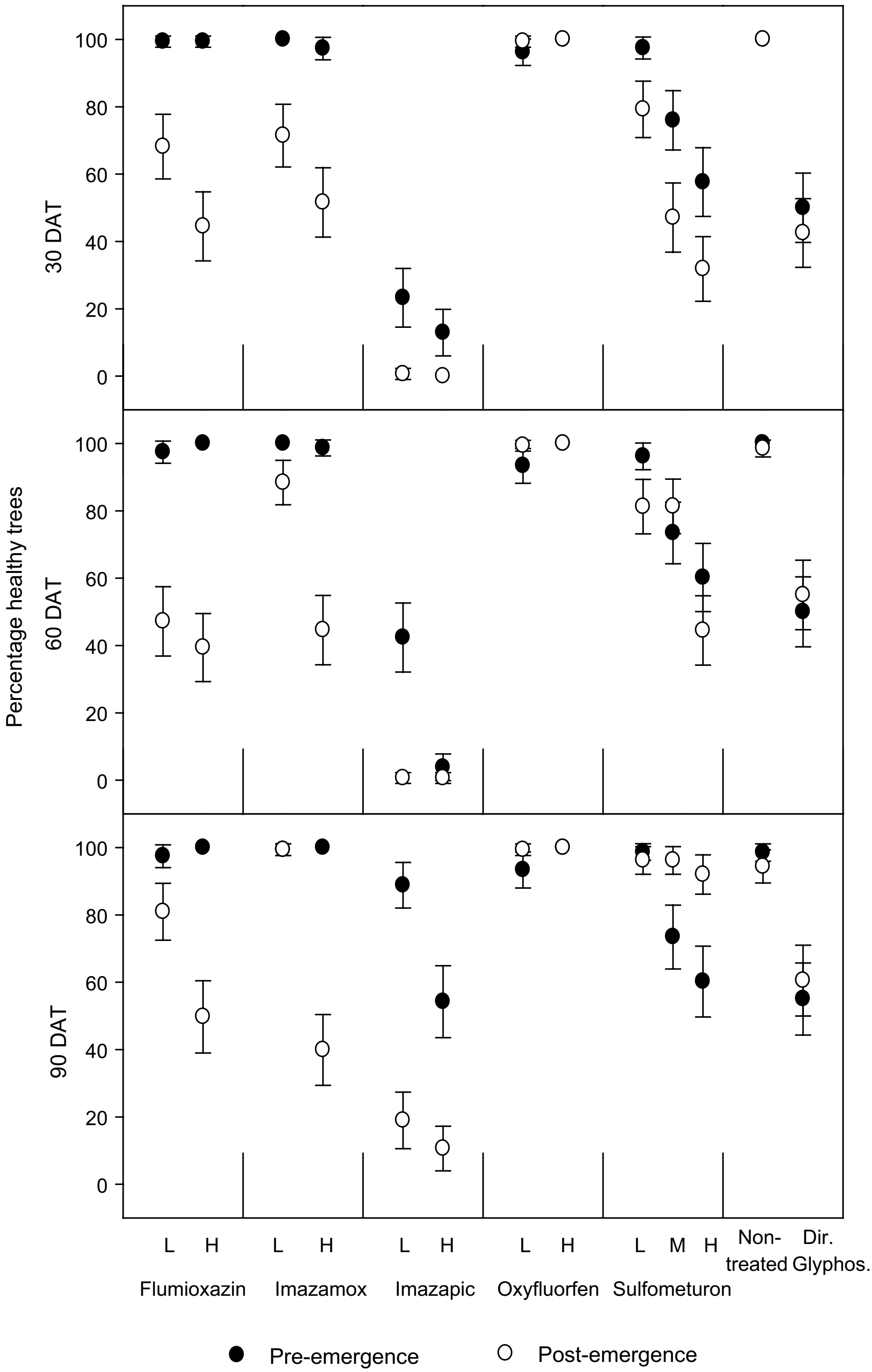
Following PRE applications, PHT decreased with increasing sulfometuron rate linearly at all assessments ($p\leq0.003$), and with increasing imazapic rate at 60 and 90 DAT ($p\leq0.010$). Comparing the mean response across rates for each herbicide, PRE applications of flumioxazin, imazamox, and oxyfluorfen did not reduce PHT relative to the non-treated control; whereas, imazapic and sulfometuron reduced PHT at all assessments ($p\leq0.011$). Repeated glyphosate directed sprays reduced PHT relative to PRE applications of flumioxazin, imazamox, oxyfluorfen ($p<0.001$), and sulfometuron ($p\leq0.023$) at each assessment. Whereas, PRE imazapic reduced PHT compared to directed glyphosate at 30 and 60 DAT ($p\leq0.011$). Flumioxazin and imazamox did not differ from the PRE oxyfluorfen standard in observed PHT, but greater PHT was observed for the standard than imazapic and sulfometuron ($p\leq0.002$) at each assessment, when comparing the average response across rates.

Following POST treatments, PHT declined with increasing sulfometuron rate linearly at 30 and 60 DAT ($p\leq0.005$), but surviving trees recovered from injury completely and rates did not differ at 90 DAT (Fig. 2). Injury following POST imazamox was more delayed, as PHT declined with increasing rate at 60 and 90 DAT ($p<0.001$). Comparing the mean response across rates for each herbicide, PHT for oxyfluorfen treatments did not differ from the control at any assessment, but flumioxazin and imazapic reduced PHT at all assessments ($p\leq0.005$), as did imazamox and sulfometuron at 30 and 60 DAT ($p<0.001$). The PHT for oxyfluorfen treatments at all dates and sulfometuron at 90 DAT was greater than with directed glyphosate sprays ($p\leq0.001$). The PHT for flumioxazin and imazamox treatments did not differ from directed glyphosate, but directed glyphosate sprays had greater PHT than imazapic treatments at all dates ($p<0.001$). At all assessments the oxyfluorfen standard had greater PHT than any other selective herbicide ($p<0.001$), except for sulfometuron at 90 DAT, which had 92–96% healthy trees.

Eucalyptus stem volume index and survival

Stem volume index (*SVI*) was affected by herbicide type ($p=0.007$), herbicide rate ($p=0.041$), and application timing ($p<0.001$), and there was an interaction between herbicide type and timing ($p=0.008$) (ANCOVA not shown). This interaction was largely one of scale, explained by greater differences among herbicides at PRE than POST application timing (Fig. 3). The interaction of herbicide rate and timing was significant ($p=0.018$), with larger differences observed between rates at PRE than POST timing.

Following PRE applications, *SVI* increased with increasing rate of flumioxazin ($p=0.003$), imazamox ($p<0.001$), and linearly with sulfometuron ($p=0.034$), but there was no rate response for oxyfluorfen. The low imazapic rate resulted in greater *SVI* than the



Percentage healthy trees
30 DAT
60 DAT
90 DAT
0
20
40
60
80
100
L H L H L H L H L M H Non-treated Dir. Glyphos.
Flumioxazin
Imazamox
Imazapic
Oxyfluorfen
Sulfometuron
Pre-emergence
Post-emergence

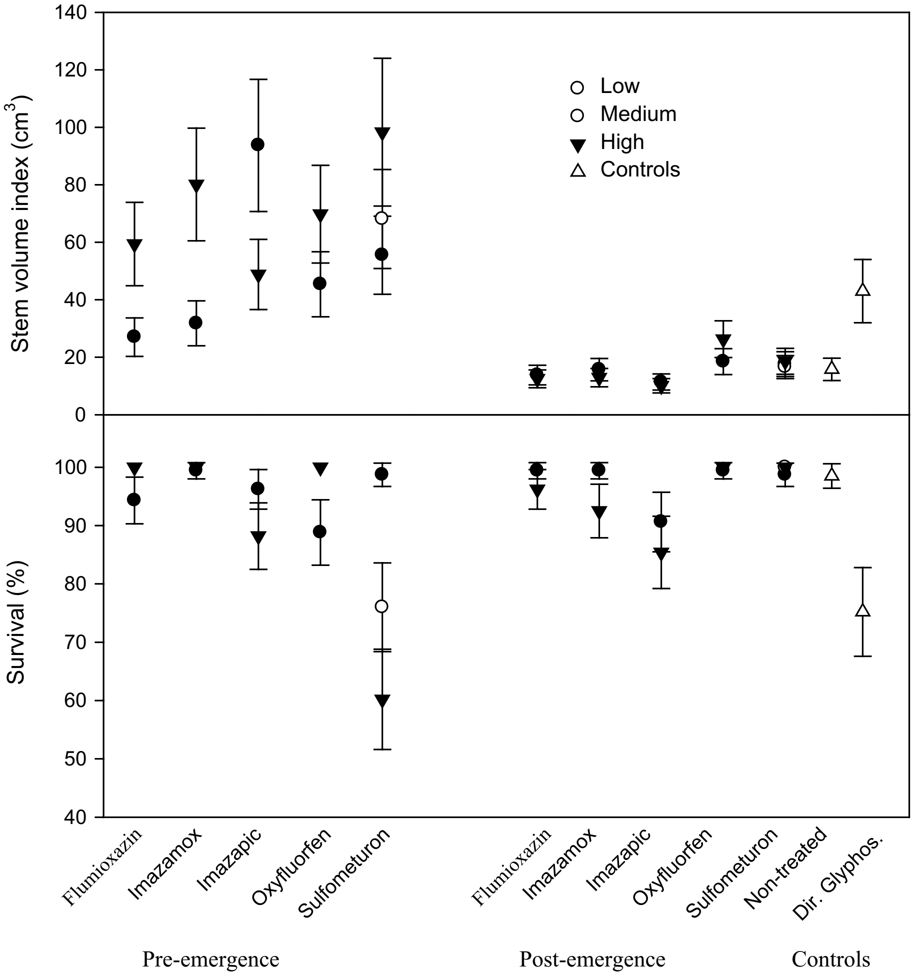


Fig. 3 Back-transformed LS-mean stem volume index (*SVI*) and survival of *Eucalyptus benthamii* trees at the end of the first growing season for pre-emergence or post-emergence applications of various herbicides at low, medium, or high rates. $SVI = GLD_5 \times H$; GLD_5 = outside bark stem diameter 5 cm above ground, H = live stem height

high rate ($p = 0.012$). All selective PRE herbicides had greater ($p < 0.001$) *SVI* (27–98 cm^3) than the non-treated control (16 cm^3). Compared to the control, *SVI* was six-fold to four-fold greater for high sulfometuron, low imazapic, high imazamox, high oxyfluorfen, and medium sulfometuron, in descending order (Fig. 3). Although the largest *SVI* response among these was with high sulfometuron, it had the greatest mortality (40%) (Fig. 3). Comparing the average response across rates for each herbicide, imazapic ($p = 0.046$) and sulfometuron ($p = 0.018$) had greater *SVI* than directed glyphosate. Oxyfluorfen did not differ in *SVI* from other PRE herbicides when the average response across rates was compared.

For POST applied herbicides *SVI* response did not differ by rate. Selective herbicides did not differ from the non-treated control, but repeated directed glyphosate treatment had greater *SVI* (43 cm^3) than the non-treated control (16 cm^3), representing a two-fold increase (Fig. 3). The largest *SVI* value observed among selective POST herbicide treatments was with high oxyfluorfen (26 cm^3) which was not different than directed glyphosate.

Eucalyptus survival was affected by herbicide type ($p=0.006$) but not by herbicide rate or application timing. There was a significant herbicide type by timing interaction ($p=0.013$), explained by greater survival with POST than PRE sulfometuron ($p<0.001$), and no differences between the application timings with other herbicides.

In response to PRE treatment, survival increased with increasing oxyfluorfen rate ($p=0.008$), but decreased linearly with sulfometuron rate increases ($p<0.001$) (Fig. 3). Comparing PRE treatments to the non-treated control, the medium and high sulfometuron rates reduced survival at the end of the first growing season by 23 and 39%, respectively. The 75% survival observed for repeated glyphosate directed spray treatment was significantly less ($p=0.002$) than the 91% average survival for PRE herbicide treatments and significantly less ($p<0.001$) than the 96% average survival for POST herbicide treatments. In response to POST treatment, survival was significantly lower ($p=0.036$) for the average of imazapic rates (88%) than the control (99%).

Our previous study using these herbicide treatments and methods in a plantation established with rooted cuttings of *E. urograndis* (Minogue and Osiecka 2015) demonstrated different tolerance to imazapic applications relative to stage of growth. In that study, the same low and high imazapic rates as used in the current study resulted in 36 and 37% mortality, respectively, when applied PRE, whereas survival was 100% for both imazapic rates applied POST and all other treatments in that study. The difference in imazapic tolerance may be explained by *Eucalyptus* species differences, which have been previously reported (Osiecka and Minogue 2011) or by the difference in seedling versus rooted cutting stock type. The current study also demonstrated greater tolerance to sulfometuron by older transplants. Unlike the reduced survival observed for medium and high sulfometuron treatments applied PRE, POST applications of these rates had 100% survival (Fig. 3).

Near complete weed control

The near-complete weed control treatment, with careful directed glyphosate sprays, was intended to examine eucalyptus growth potential in the absence of competition and with minimal direct negative herbicide effects. Grasses quickly occupied the site after planting, and despite efforts to minimize eucalyptus injury with repeated directed glyphosate sprays, the frequent applications early in the study caused injury. In a similar previous study in *E. urograndis* at our research station this same method resulted in stem volume index more than six-fold greater than the best selective herbicide treatment applied over trees, 2240 g ha^{-1} oxyfluorfen, and more than 60-fold greater stem volume index than the non-treated control (Minogue and Osiecka 2015). The results we are reporting here and those of our previous study in *E. urograndis* demonstrate the impact of competing vegetation on the growth of newly planted eucalyptus, and also the potential for herbicide phytotoxicity to slow tree growth, even with the most selective treatments. In a similar eucalyptus establishment study in Louisiana, Blazier et al. (2012) compared ten herbicide treatments to a non-treated control and directed 5% glyphosate applications made three times during the growing season. Periodic directed glyphosate applications resulted in a 30% reduction in 1-year height growth as compared to the non-treated control, indicating the potential for injury with this approach. However, they also reported that in a subsequent study they compared various sulfometuron rates and non-treated control to the same regime of periodic directed glyphosate applications and observed

220% greater 1-year height growth with directed glyphosate sprays than the non-treated control. Directed glyphosate applications are used operationally in eucalyptus stand establishment worldwide (Tuffi Santos et al. 2007), with less precision than in these research applications. As such, this competition suppression approach is fraught with tree injury potential.

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 directed 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 eucalyptus seedlings may enhance their growth. Repeated applications of selective herbicides could possibly further enhance growth. In general, PRE applications of the herbicides tested were more effective than POST applications and provided weed control during the critical period of tree establishment.

We have shown that flumioxazin is effective for forb control at PRE and POST 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, supporting expansion of product labeling. We have confirmed that sulfometuron is effective for control of annual grasses and sedges in newly planted eucalyptus at PRE timing and have refined selective herbicide rate response relative to transplant age, supporting new product labeling. When applied PRE over seedlings 2 weeks after planting, medium and high sulfometuron reduced survival 24 or 30%, but no mortality occurred when these rates were applied POST over seedlings 6 weeks after planting.

Our study identified two new imidazolinone herbicides for selective weed control in eucalyptus plantings. *Eucalyptus benthamii* showed strong tolerance to PRE-emergent imazamox at rates up to 280 g ae ha^{-1}, with 99–100% of trees showing no or minor injury symptoms at 90 DAT. Persistent annual grass control was obtained with both rates of imazamox applied PRE and with the high rate in POST application. Imazapic caused seedling injury with both rates and 12–15% mortality with PRE or POST applications at the high rate, but rates 140 g ae ha^{-1} (the low rate) and less warrant further testing. Imazapic gave the highest degree of weed control among herbicides compared, even at the low rate, and controlled grasses, sedges, and forbs. At the low rate applied PRE, eucalyptus trees recovered from herbicide symptoms, with 89% showing no or minor injury symptoms at 90 DAT. Eucalyptus stem volume index with PRE imazapic at the low rate was greater than any treatment except the high rate of sulfometuron applied PRE, a treatment that caused 40% mortality. Lower imazapic rates, applications at a more advanced stage of growth, and directed imazapic sprays should be tested for eucalyptus tolerance, as this herbicide also shows promise for selective broad-spectrum weed control with POST applications in established stands.

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