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Sequential Sulfometuron Methyl Applications in *Eucalyptus benthamii* Plantations

Anna Osiecka and Patrick J. Minogue*

A study was conducted to refine herbicide rates for sequential applications of sulfometuron methyl over newly planted *Eucalyptus benthamii* seedlings in the Coastal Plain of the southeastern United States. Container-grown, 6-wk-old seedlings were planted in July 2011 on a nonbedded agricultural site in Quincy, FL and on a bedded forestry site in Wing, AL. Treatments included a single sulfometuron application at 13, 26, 39, or 52 g ha^{-1}, 2 wk after planting; sequential applications at the same rates, 2 and 8 wk after planting; and a nontreated check. All sulfometuron treatments provided effective control of all vegetation groups at both sites, with the exception of 13 g ha^{-1} for forbs in Quincy. Sparse weed cover in Wing was eliminated by any sulfometuron treatment. In Quincy, two applications provided better weed control than a single one, resulting in more bare ground and less grass and vines. Bare ground increased with increasing sulfometuron rate from 0 to 26 g ha^{-1}. The 26 g ha^{-1} rate resulted in 95 and 88% bare ground 6 and 12 wk after the first application, respectively, compared to 62 and 51%, respectively for the nontreated check. All sulfometuron treatments had a small positive effect on *Eucalyptus* seedling growth at the Quincy site, resulting in greater stem diameter (6.0 to 6.7 mm) than the nontreated check (5.0 mm), despite slight foliar necrosis. At the Wing site, in addition to slight foliar necrosis, sulfometuron decreased final seedling survival, height, and stem diameter (48 to 68%, 77.8 to 81.6 cm, and 8.7 to 9.2 mm, respectively), compared to the nontreated check (99%, 88.3 cm and 11.2 mm, respectively). Two sulfometuron applications at 13 to 26 g ha^{-1} provided selective weed control at both sites, but further refinement is needed for various *Eucalyptus* genotypes, soil, and vegetation types.
Nomenclature: Sulfometuron methyl; camden white gum, Nepean River gum, *Eucalyptus benthamii* Maiden & Cambage.
Key words: Herbicide injury, postplant applications, selective herbicides, sequential applications, weed control.

Se realizó un estudio para refinar las dosis de herbicida para aplicaciones secuenciales de sulfometuron methyl sobre plántulas de *Eucalyptus benthamii* recién plantadas en las planicies de la costa del sureste de los Estados Unidos. Plántulas de 6 semanas de edad, crecidas en contenedores, fueron plantadas en Julio 2011 en un terreno agrícola sin camas de siembra en Quincy, Florida, y en un terreno forestal con camas de siembra en Wing, Alabama. Los tratamientos incluyeron una aplicación sencilla de sulfometuron a 13, 26, 39, ó 52 g ha^{-1}, 2 semanas después de la siembra; aplicaciones secuenciales a las mismas dosis, 2 y 8 semanas después de la siembra; y un testigo sin tratamiento. Todos los tratamientos de sulfometuron brindaron un control efectivo de todos los grupos de vegetación en ambos terrenos, con excepción de 13 g ha^{-1} para el control de especies herbáceas de hoja ancha, en Quincy. En Wing, cualquiera de los tratamientos de sulfometuron eliminó malezas con cobertura escaza. En Quincy, dos aplicaciones brindaron un mejor control de malezas que una sola aplicación, lo que resultó en más suelo desnudo y menos gramíneas y enredaderas. El suelo desnudo aumentó con el incremento de la dosis de sulfometuron de 0 a 26 g ha^{-1}. La dosis de 26 g ha^{-1} resultó en 95 y 88% de suelo desnudo a 6 y 12 semanas después de la primera aplicación, respectivamente, al comparase con 62 y 51%, respectivamente del testigo sin tratamiento. Todos los tratamientos de sulfometuron tuvieron un pequeño efecto positivo en el crecimiento de las plántulas de *Eucalyptus* en Quincy, lo que resultó en un diámetro de tallo mayor (6.0 a 6.7 mm) que el testigo sin tratamiento (5.0 mm), a pesar de que hubo una ligera necrosis foliar. En Wing, además de la ligera necrosis foliar, sulfometuron disminuyó la sobrevivencia final, la altura, y el diámetro de tallo (48 a 68%, 77.8 a 81.6 cm, y 8.7 a 9.2 mm, respectivamente), al compararse con el testigo sin tratamiento (99%, 88.3 cm y 11.2 mm, respectivamente). Dos aplicaciones de sulfometuron a 13 y 26 g ha^{-1} brindaron control de malezas selectivo, pero se necesitan aún más refinamientos para varios genotipos de *Eucalyptus*, y tipos de suelo y vegetación.

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* Senior Biological Scientist and Associate Professor, North Florida Research and Educational Center, University of Florida, 155 Research Road, Quincy, FL 32351. Corresponding author's E-mail: pminogue@ufl.edu

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Eucalyptus is a diverse genus native to Australia, belonging to the *Myrtaceae* family, with the number of currently recognized tree species, depending on author, ranging from 500 to 600 (Florence 2004) to over 800 (Coppen 2005). As new taxa are being described, the number of species classified as *Eucalyptus* continues to grow. Numerous *Eucalyptus* species and hybrids have been grown throughout the world for fiber, fuel, essential oils, phytoremediation, and as ornamental trees. Because of the fast growth rate, which fosters economic gain in a short time period, and also because of a large and varied gene pool, *Eucalyptus* species have been successfully introduced on all continents with the exception of Antarctica (Coppen 2005). By the early 1980s *Eucalyptus grandis* was one of the most commonly used tree species for afforestation in the warmer climates, especially for industrial timber production (Schönau 1984). Currently, *Eucalyptus* is the most widely planted tree in the world, with more than 17.8 million ha worldwide (Pires et al. 2013), including approximately 2 million ha in temperate areas (Neilsen and Ringrose, 2001).

In the southern United States, 5,000 to 10,000 ha per year of commercial *Eucalyptus* plantations are being established, driven by high and constantly growing demand for hardwood fiber, which in 2011 was estimated at more than 92.5 Mg yr^{-1} (Dougherty and Wright 2012). *Eucalyptus* wood applications include pulpwood, landscape mulch, strand board, fiberboard, panels, and saw timber (Rockwood and Peter 2011; Stape et al. 2012). Recently, most interest has been in planting *Eucalyptus* as bioenergy feed stock which can potentially be used for direct electricity generation from wood or from co-firing with coal or other alternative fuel source, for wood pellets, biodiesel, cellulosic ethanol, and torrefaction.

Eucalyptus plantations can play an important role in meeting fast-growing demand for hardwood in southern United States. In Florida *Eucalyptus* species grow faster than any of the native species, but are not invasive according to Rockwood and Peter (2011). Of the species most likely to be cultivated in the southern United States, Gordon et al. (2012) predicted four, including *Eucalyptus benthamii*, to pose low invasion risk, whereas two others were assessed as having high risk. *Eucalyptus* can be grown in the Lower Gulf Coast region of the southern United States, on 6 to 8–yr rotations, and produce 18 to 36 green Mg ha^{-1} yr^{-1}, providing the appropriate silviculture practices are implemented (Dougherty and Wright 2012). Vegetation management is a critical part of *Eucalyptus* culture, because young trees are very sensitive to the adverse effects of plant competition, especially during establishment (Adams et al. 2003; Florentine and Fox 2003; Garau et al. 2008), more so than many other tree species, including pines (Florence 2004).

The economic benefits of vegetation management during establishment have been well demonstrated for many species of fast-growing trees. Weeds can reduce light, water, and nutrient availability to trees, but little research has been done on *Eucalyptus* to interpret the effects of competition between weeds and trees in terms of these processes (Gonçalves et al. 2004).

The short-term impact of vegetation competition on the growth of various *Eucalyptus* species and hybrids has been described by several authors (Adams et al. 2003; Florence 1996; Florentine and Fox 2003) and observed in our earlier studies (Osiecka and Minogue 2011). Adams et al. (2003) investigated the relationship between the timing and duration of weed competition and growth of *Eucalyptus globulus* trees during the first 2 yr of establishment in Tasmania, Australia. After 2 yr, height and diameter of trees under competition was 52 and 40% that of weed-free trees, respectively, but most growth losses occurred during the first year. They concluded that the critical period of weed interference was from planting to age 1.5 yr and effective weed control during this period was necessary to maximize *Eucalyptus* growth potential. Schaller et al. (2003) observed root competition on a fertile site with high rainfall in Costa Rica between young *Eucalyptus deglupta* trees and grasses planted in contour strips, which resulted in up to 40% reduction in both the total number of *Eucalyptus* lateral roots and stem diameter.

The long-term impact of various forms of vegetation control during establishment of *Eucalyptus* has been documented by Little et al. (2003). In their study, the effect of cover crops, chemical, mechanical, and hand-weeding treatments applied during establishing trees of a *Eucalyptus* hybrid (*E. grandis* × *Eucalyptus camaldulensis*) clone was observed within 60 d after planting. By the time of canopy closure, tree performance improved and variability between trees decreased as weed-free area

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increased. Significant differences between treatment means for tree height, volume, and basal area persisted throughout the 7 yr of the trial, despite the absence of competitive vegetation after the first growing season, due to canopy closure. After 7 yr, tree volume in a weed-free control was by 42.5% greater compared to the weedy control. This result points to the significance of effective early vegetation management for *Eucalyptus* productivity, especially when grown on short pulp–wood rotation. Schönau (1984) emphasized that *E. grandis* is very intolerant of weed competition and that reducing this competition in the early life of plantations is one of the main objectives of good site preparation. For optimum growth, plantations should be kept completely weed-free until canopy closure by mechanical means, hand weeding, or by herbicide applications, if justified by cost. Almost two decades later, George and Brennan (2002) compared hand weeding, interrow slashing, cover crops, herbicide applications, and mulching with various materials during establishment of *Eucalyptus dunnii* and *Eucalyptus saligna* plantations in northern New South Wales, Australia. They concluded that herbicides were the most cost-effective weed control option for commercial *Eucalyptus* plantations. Also, according to Gonçalves et al. (2004), chemical weed control may be more effective than mechanical, especially if *Eucalyptus* roots are disturbed by cultivation.

Even though several herbicides have been registered for use in *Eucalyptus* plantations in Florida (Osiecka and Minogue 2013), directed applications of glyphosate are currently most widely used. Because glyphosate is a nonselective herbicide, drift can potentially reduce *Eucalyptus* growth or increase tree mortality. In a study of the glyphosate drift effect on three *Eucalyptus* clones, Santos et al. (2007) observed a progression of injury symptoms from leaf chlorosis through necrosis to plant death. Glyphosate phytotoxicity increased with increasing herbicide rate, with plants exposed to 173 or 346 g ae ha^{-1} displaying severe phytotoxicity symptoms, including reductions in height, stem diameter, and dry mass 50 d after application. Because glyphosate does not provide residual weed control, it requires frequent repeated applications to control weeds fully, resulting in significant costs and increased risk of glyphosate resistance evolving on treated sites (Boerboom and Owen 2006).

In a study comparing 12 herbicide treatments for the release of first-year *Eucalyptus macarthurii* seedlings, over-the-top applications of oxyfluorfen and sulfometuron methyl reduced competing vegetation and promoted tree height growth better than directed glyphosate applications (Blazier et al. 2012). However, sulfometuron methyl rates greater than 79.2 g ha^{-1} damaged first- and second-year *E. macarthurii* seedlings. Herbicide Eucmix® (Macspred, Delacombe, Victoria, Australia), a mixture of terbacil and sulfometuron methyl, has been widely used to control weeds in plantations of *E. globulus*, *Eucalyptus nitens*, and *Eucalyptus regnans* in Australia (Churchill and Beadle 2011).

Eucalyptus benthamii, native to a small area in southeastern Australia (Department of the Environment [DE] 2014), has demonstrated acceptable cold tolerance in the southern United States (Dougherty and Wright 2012; Stape et al. 2012), which was confirmed in earlier studies at the North Florida Research and Education Center (NFREC) in Quincy, FL. It is a promising plantation species in the Gulf Coast Plain and therefore was chosen to test sulfometuron methyl selectivity in this trial.

Previous research at the NFREC has shown that over-the-top applications of sulfometuron methyl can provide broad-spectrum control of forbs and grasses at rates tolerated by newly planted *Eucalyptus* seedlings (Osiecka and Minogue 2011). However, the duration of weed control with these rates is typically only 5 to 8 wk, depending on conditions. The objective of this research was to refine rates and timing of sequential sulfometuron methyl applications for selective weed control in young *Eucalyptus* plantings.

Materials and Methods

Study Sites. Identical studies were established on a fallow agricultural field near Quincy and on a recently harvested forested site near Wing, AL that had been intensively prepared for transplanting using machinery and herbicides. The Quincy site was located in the lower Coastal Plain region at the University of Florida, North Florida Research and Education Center, south of Quincy in Gadsden County (30.53°N, 84.58°W) at an elevation of approximately 70 m above mean sea level. The local climate is temperate, warm, and wet, with highest temperatures in July (mean normal temperature

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27.1 C, maximum normal temperature 32.7 C), lowest temperatures in January (mean normal temperature 10.3 C, minimum normal temperature 4.0 C) and 1,430 mm annual normal precipitation (National Oceanic and Atmospheric Administration [NOAA] 2002b). The soil is a Dothan (fine–loamy, kaolinitic, thermic Plinthic Kandiudults) –Fuquay (loamy, kaolinitic, thermic Arenic Plinthic Kandiudults) complex (U.S. Department of Agriculture, Natural Resources Conservation Service [USDA-NRCS] 2014) with pH of 5.5.

The Wing site previously supported a slash pine (*Pinus elliottii* Engelm.) plantation and was located on forest industry property northeast of Wing in Covington County, in the lower Coastal Plain region of Alabama (31.03°N, 86.57°W) at an elevation of approximately 76 m above mean sea level. The local climate is temperate, warm and wet, with highest temperatures in July (mean normal temperature 27.3 C, maximum normal temperature 33.8 C), lowest temperatures in January (mean normal temperature 9.1 C, minimum normal temperature 2.1 C) and 1,572 mm annual normal precipitation (NOAA 2002a). The soil is a Troup fine sandy loam (loamy, kaolinitic, thermic Grossarenic Kandiudults) (USDA-NRCS 2014) with pH of 5.1.

In the months prior to planting, both locations were treated with nonresidual herbicides, and the Wing site was bedded with the use of a Savannah plow (Savannah Forestry Equipment, LLC, Savannah, GA). At the Quincy site, dimethylamine salt of glyphosate (Accord® XRT II; 479 g acid equivalent (ae) L^{-1}, Dow AgroSciences LLC) was applied in October 2010 as a broadcast spray using 4.4 kg ae ha^{-1} to control agricultural broadleaf and grass weeds. A combination of 11.1 kg ae ha^{-1} glyphosate and 1.1 kg ae ha^{-1} triclopyr butoxyethyl ester (Garlon®4; 479 g ae L^{-1}, Dow AgroSciences LLC) was applied at the Wing site. High herbicide rates were chosen to control previously established woody perennials, including shrubs and arborescent hardwood species, to the greatest extent possible with nonresidual herbicides. Before planting, bedded soil was allowed to settle for an adequate time to ensure a suitable planting condition. At both study sites a second broadcast glyphosate treatment was made approximately 1 wk prior to transplanting with the use of 5.3 kg ae ha^{-1} to control existing vegetation and optimize experimental conditions for evaluation of PRE activity of sulfometuron methyl.

Table 1. Treatments tested for selective weed control when applied over newly planted *Eucalyptus benthamii* seedlings at Quincy, FL and Wing, AL study sites.

Treatment	Sulfometuron methyl rate	Application frequency[a]	Oust® XP rate[b]
	g ha^{-1}		g product ha^{-1}
1	13	1	17
2	13	2	17
3	26	1	35
4	26	2	35
5	39	1	52
6	39	2	52
7	52	1	70
8	52	2	70
9	Nontreated check	0	

[a] 1 = one sulfometuron application 2 wk after planting; 2 = one sufometuron application 2 wk after planting followed by one application 8 wk after planting, at the same sulfometuron rate.

[b] Sulfometuron methyl was applied with the use of Oust® XP, which contains 75% ai.

Experimental Design and Treatments. At each study site, eight sulfometuron methyl treatments and a nontreated control (Table 1) were evaluated in a randomized complete block design with five replications to assess the effect of sulfometuron methyl application rate and application frequency, on weed control, *E. benthamii* herbicide tolerance and seedling growth response.

Treatment plots were 24.4 m long and 1.8 m wide. Sulfometuron methyl treatments were applied in a 1.8-m-wide band centered on the tree row, which followed the long dimension of the plot. Fourteen (Wing site) or 15 (Quincy site) *E. benthamii* seedlings per plot were planted 1.5 m apart in rows 3 m apart. On the bedded site in Wing, tree row spacing varied slightly, but trees were planted on the center of the bed. Container-grown, 6-wk-old seedlings, stored without the containers at approximately 4.4 C for 6 to 9 days prior to planting, were hand planted on July 19, 2011 in Quincy and July 22, 2011 in Wing. Planted seedlings were watered on the day of planting, the operational practice for summer planting.

Sulfometuron methyl (hereafter referred to as sulfometuron) was applied in the form of Oust® XP (75%, E. I. DuPont de Nemours and Company, Wilmington, DE) at four rates and two frequencies

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(once or twice) and compared to a nontreated check. The first sulfometuron applications were made about 2 wk after planting (WAP), when seedlings appeared to be past transplant shock, on August 3, 2011 in Quincy and August 5, 2011 in Wing. Half of the plots treated with each sulfometuron rate received the second application of the same rate 6 wk later (Treatments 2, 4, 6, and 8 in Table 1), on September 9, 2011 in Quincy and September 16, 2011 in Wing.

Sulfometuron treatments were applied with the use of a hand-held CO_2 pressurized backpack research sprayer equipped with a four-nozzle boom fitted with 8002 VS flat-fan nozzles on 46 cm centers, providing a 1.8-m effective swath. A ground speed of 4.8 km h^{-1} was maintained with the use of a metronome. The regulator was set to 172 kPa to produce 2,034 ml min^{-1} through all four nozzles on the boom, thus providing equivalent to 140 L ha^{-1} total spray solution.

Assessments. *Groundcover*. Visual estimates of the area free of live vegetation (percent bare ground), and percent live cover for grasses, sedges, forbs, vines (Quincy site only), *Rubus*, and hardwoods (Wing site only) were made in three 1 by 1–m sampling plots in each treatment plot, centered between seedlings in each row. Percent cover (including bare ground) was recorded to the nearest 1% for cover between 0 and 10% or 90 and 100%, and to the nearest 5% for cover values between 10 and 90%, independently for each component. Where there was a multilayer cover, the sum of all components may have exceeded 100%. Groundcover estimates were made by two experienced evaluators in September at 6 wk after the first sulfometuron application (6WAT1) and in October at 12 wk after the first application (12WAT1). The October assessment was 6 wk after the second sulfometuron application. The dominant species within each vegetation group (10% or greater sampling plot cover) were recorded in the nontreated checks at these same times.

Eucalyptus Seedlings. All live *Eucalyptus* seedlings were measured for stem diameter at 5 cm above ground (GLD_5) and for live stem height at the end of the first growing season in October, 2011, at 12WAT1, approximately 14WAP. Additionally, seedlings in the nontreated checks were measured for initial live height and GLD_5 immediately before the first treatment application (2 WAP). The number of dead seedlings was recorded at the time of the first treatment application, at 6WAT1, and at the final assessment in late October 2011 (12WAT1).

Seedling injury symptoms were assessed at 6WAT1 and 12WAT1. Each seedling was assigned an injury index (0–4) for the following symptoms: foliar chlorosis, foliar necrosis, defoliation, fasciculation, lateral shoot dieback, leader dieback, and mechanical injury (including animal grazing). The injury indices 0, 1, 2, 3, and 4 corresponded to none, slight, moderate, severe, and extreme (near death) injury. Seedlings with mechanical injury index 3 or greater were deleted from analyses of phytotoxicity or growth data.

Data Analyses. Statistical analyses for each study were performed with SAS 9.3 software (SAS 2007). Analysis of variance (ANOVA) was conducted for all variables with the use of mixed models (PROC mixed), with blocks treated as a random effect, to determine the significance of the main effects (sulfometuron rate and application frequency), and their interaction. Percentage data were transformed using the arcsin square root transformation, to normalize variance. The back-transformed least square means (LS-means) have been reported. The critical level of significance for ANOVA and Fisher's protected LSD comparisons of LS-means was $\alpha = 0.05$.

The percent bare ground and groundcover of the various vegetation groups, averaged across the three sampling plots in each treatment plot, were used as dependent variables to test for treatment weed control effectiveness. *Eucalyptus* seedling herbicide tolerance was assessed by comparing mean indices for various injury symptoms, as well as seedling survival, seedling height and stem diameter 5 cm above ground level, at the end of the first growing season in October 2011.

Results and Discussion

Weed Species Composition. *Quincy Site*. Weed cover in the nontreated check consisted mostly of annual grasses and forbs. There were two predominant grass species, southern sandbur (*Cenchrus echinatus* L.) and alexandergrass [*Urochloa plantaginea* (Link.) R.D. Webster] (Table 2), which comprised the majority of the grass cover, and one

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Table 2. Predominant weed species in the nontreated check at the Quincy site 6 and 12 wk after the first sulfometuron application (WAT1).

Scientific name	Synonyms–scientific	Common name	Family	% Groundcover 6WAT1	% Groundcover 12WAT1
Cenchrus echinatus L.		Southern sandbur	*Poaceae*	12	19
Urochloa plantaginea (Link) R.D. Webster	*Brachiaria plantaginea* (Link) Hitchc.	Alexandergrass (plantain signalgrass)	*Poaceae*	6	14
Mollugo verticillata L.		Carpetweed	*Aizoaceae*	15	6
Jacquemontia tamnifolia (L.) Griseb.		Smallflower morningglory	*Convolvulaceae*	0	6

predominant forb species, carpetweed (*Mollugo verticillata* L.), which accounted for a large portion of the forb cover at both assessments. At the 12WAT1 assessment in October, a vine, smallflower morningglory [*Jacquemontia tamnifolia* (L.) Griseb.] reached 10 to 40% groundcover in some plots, averaging 6% for nontreated check. Additionally, 10% or more groundcover was recorded at 12WAT1 in one or two nontreated sampling plots for tropic croton (*Croton glandulosus var. septentrionalis* Muell.-Arg.), mexicantea (*Chenopodium ambrosioides* L.), and corn spurry (*Spergula arvensis* L.). Within 6 wk between the first assessment in September and the second assessment in October, the grass and vine cover in the nontreated plots increased, whereas the forb cover decreased (Table 4).

Wing Site. Average weed cover in the nontreated check in Wing did not exceed 3% at either assessment date and consisted of approximately 1% each of sedges, forbs, and *Rubus* (data not shown). The only species that reached 10% groundcover, in a single nontreated sampling plot, was globe sedge (*Cyperus croceus* Vahl).

Weed Control. *Quincy Site*. Sulfometuron rate had a significant effect on the percent groundcover for bare ground, grasses, forbs, and vines at both assessment dates, 6WAT1 and 12WAT1 (Table 3). At the second assessment date (12WAT1), application frequency also had a significant effect on percent groundcover for bare ground, grasses, and vines. The interaction between sulfometuron rate and application frequency was not significant for any of the groundcover variables. Therefore only the means for the two main effects are presented.

At both assessment dates, percent bare ground showed a positive rate response with increasing sulfometuron rate between 0 and 26 g ha^{-1} (Table 4). Bare ground was 95 and 88% at 6WAT1 and 12WAT1, respectively, following sulfometuron

Table 3. Analysis of variance showing the significance ($P > F$) of sulfometuron rate, application frequency, and the interaction of these factors for percent groundcover for bare ground and different vegetation groups at 6 and 12 wk after the first sulfometuron application (WAT1) over newly planted *Eucalyptus benthamii* seedlings at the Quincy, FL and Wing, AL sites.

Factor	Quincy site: Bare ground	Grasses	Sedges	Forbs	Vines	Wing site: Bare ground	Grasses	Sedges	Forbs	Hardwood
					6WAT1[a]					
Sulfometuron rate	< **0.0001**[b]	< **0.0001**	0.3326	< **0.0001**	**0.0013**	**0.0044**	0.8461	< **0.0001**	**0.0004**	0.1991
					12WAT1[c]					
Sulfometuron rate	< **0.0001**	< **0.0001**	0.5360	**0.0131**	**0.0005**	**0.0219**	0.3574	**0.0033**	**0.0003**	0.2309
Application frequency[d]	< **0.0001**	< **0.0001**	0.0630	0.1157	**0.0109**	0.6677	0.4681	1.0000	0.8608	0.9635
Frequency * Rate	0.0766	0.0647	0.4672	0.6633	0.1993	0.8952	0.7089	1.0000	0.8504	0.7636

[a] Assessed 6 wk after the first sulfometuron application.

[b] Bold $P \leq 0.05$ denotes significant effect.

[c] Assessed 12 wk after the first (6 wk after the second) sulfometuron application.

[d] One or two sulfometuron applications; first application 2 wk after planting; second application 8 wk after planting, at the same sulfometuron rate.

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Table 4. Prevalence of bare ground versus weed infestation at 6 and 12 wk after the first application (WAT1) of various sulfometuron methyl rates over newly planted *Eucalyptus benthamii* seedlings at the Quincy, FL study site averaged over the two application frequencies.[a]

Sulfometuron rate	Bare ground	Grasses	Forbs	Vines	Bare ground	Grasses	Forbs	Vines
g ha^{-1}	% groundcover							
	6WAT1 (assessed September 6, 2011)				12WAT1 (assessed October 19, 2011)			
0	62 c[b]	19 a	17 a	1 a	51 c	33 a	13 a	6 a
13	89 b	2 b	9 b	0 b	77 b	6 b	13 a	1 b
26	95 a	1 bc	3 c	0 b	88 a	3 b	6 b	1 bc
39	96 a	0 c	3 c	0 b	89 a	3 b	6 b	0 c
52	97 a	0 c	2 c	0 b	91 a	2 b	4 b	0 bc

[a] One or two sulfometuron applications; first application 2 wk after planting; second application 8 wk after planting, with the same sulfometuron rate rate. Means are for the rate main effect because interactions between sulfometuron rate and application frequency were not significant for any groundcover variable.

[b] LS-means within a column followed by the same letter are not significantly different according to the Fisher's protected LSD test at $\alpha = 0.05$.

application at 26 g ha^{-1}. Increasing the rate above 26 g ha^{-1} did not result in further increase in percent bare ground.

Sulfometuron provided effective grass control at all rates tested. At 6WAT1, there was no grass following 39 or 52 g ha^{-1} sulfometuron and only 1 to 2% grass cover following 13 or 26 g ha^{-1}, as compared to 19% for the nontreated check (Table 4). All sulfometuron rates resulted in grass cover between 2 and 6% at 12WAT1, lower than the 33% cover in nontreated check plots.

Forb cover at 6WAT1 decreased with increasing sulfometuron rate from 0 to 26 g ha^{-1} and remained unchanged with further rate increase (Table 4). At 12WAT1 the lowest rate, 13 g ha^{-1}, was not effective in controlling forbs, but all higher rates reduced forb cover to less than half that of the nontreated check.

There were few vines in the nontreated check at 6WAT1, and no vines were present in any of the sulfometuron treatments at that assessment (Table 4). Vine cover was between 0 and 1% at 12WAT1 with all sulfometuron treatments, less than the 6% vine cover observed in the nontreated check. The sedge cover was negligible and there was practically no *Rubus* in any treatment, including the nontreated check, at either assessment date (mean cover 0% for both groups).

At the Quincy site, sulfometuron was effective in controlling both grass and broadleaf weed species at half of the minimum rate recommended by the Oust® XP label for release of other hardwood crop species (52 g ha^{-1}) (Anonymous 2013). Sulfometuron performance as a preemergent herbicide was optimized by good control of established perennial and annual weeds with multiple applications of high glyphosate rates prior to study initiation. When evaluated 12WAT1, two consecutive sulfometuron applications resulted in greater percent bare ground, less grass, and less vines than a single treatment, regardless of the sulfometuron rate (Table 5).

Wing Site. Weed cover at the Wing site was extremely sparse at both assessment dates in all treatments, including the nontreated check. This was the result of an effective intensive mechanical

Table 5. Prevalence of bare ground versus weed infestation following one or two sequential applications of sulfometuron methyl over newly planted *Eucalyptus benthamii* seedlings at the Quincy, FL study site, assessed 12 wk after the first application (6 wk after the second application) averaged over the five sulfometuron rates.[a]

Application frequency[b]	Bare ground	Grasses	Forbs	Vines
	% groundcover			
1	72 b[c]	14 a	9 a	2 a
2	88 a	3 b	7 a	0 b

[a] Sulfometuron rates were 0, 13, 26, 39, and 52 g ha^{-1}.

[b] 1 = one sulfometuron application 2 wk after planting; 2 = one sulfomeuron application 2 wk after planting followed by one application 8 wk after planting, with the same sulfometuron rate. Means are for the application frequency main effect because interactions between application frequency and sulfometuron rate were not significant for any groundcover class.

[c] LS-means within a column followed by the same letter are not significantly different according to the Fisher's protected LSD at $\alpha = 0.05$.

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Table 6. Analysis of variance showing the significance (P > F) of sulfometuron rate, application frequency, and the interaction of these factors for *Eucalyptus benthamii* seedling performance following one or two sulfometuron applications at various rates over newly planted seedlings at the Quincy, FL and Wing, AL sites.

	Quincy site				Wing site			
Factor	6WAT1[a] survival	12WAT1[b] survival	12WAT1 height	12WAT1 GLD_5	6WAT1 survival	12WAT1 survival	12WAT1 height	12WAT1 GLD_5
Sulfometuron rate	**0.0066**[c]	**0.0351**	0.5519	**0.0002**	< **0.0001**	< **0.0001**	**0.0172**	**0.0054**
Application frequency[d]	N/A[e]	0.8322	0.8426	0.6183	N/A	0.2377	0.9312	0.8495
Frequency * Rate	N/A	0.7053	0.5442	0.1571	N/A	0.5184	0.8567	0.4124

[a] Six weeks after the first sulfometuron application.

[b] Twelve weeks after the first sulfometuron application, approximately 14 wk after planting seedlings (the end-of-growing-season assessment in late October 2011).

[c] Bold P ≤ 0.05 denotes significant effect.

[d] One or two sulfometuron applications; first application 2 wk after planting; second application 8 wk after planting, with the same sulfometuron rate.

[e] Only one sulfometuron application by 6WAT1.

and chemical site preparation on a recently harvested forested site that likely had small weed seed bank. There were practically no weeds in any plots treated with sulfometuron. Bare ground in the nontreated check was 97% at both assessments, less than the 99 to 100% bare ground recorded for sulfometuron treatments (data not shown). Although statistically significant because of low variation resulting from near-complete control, these differences were too small to be meaningful.

***Eucalyptus* Seedling Injury Symptoms.** *Quincy Site*. Injury symptoms on *Eucalyptus* seedlings treated with sulfometuron were not very pronounced. The only symptoms recorded in numbers sufficient for statistical analyses of injury indices were foliar necrosis, leader dieback, and lateral shoot dieback. There was no significant effect of sulfometuron rate, application frequency or the interaction between these factors on any of the injury indices at either assessment date, except for foliar necrosis at 12WAT1, which was affected by both sulfometuron rate (P = 0.0033) and application frequency (P = 0.0009). At 12WAT1, foliar necrosis index was less for the nontreated check (0.1) than for any other sulfometuron rate (0.4 to 0.6), when averaged over two application frequencies (data not shown). At that assessment, two sulfometuron applications resulted in greater foliar necrosis index than a single application (0.6 and 0.3, respectively), when averaged over all rates (data not shown).

Wing Site. Herbicide injury symptoms on *Eucalyptus* seedlings were also minor at the Wing site. The only symptoms recorded in numbers sufficient for statistical analyses of indices were foliar necrosis and leader dieback. Foliar necrosis index was affected by sulfometuron rate at 6WAT1 (P = 0.045) and was greater for seedlings treated with any sulfometuron rate (0.8 to 0.9) than for the nontreated check (0.4) (data not shown). No other significant effects were observed for any injury symptom. Even though not severe in our study, leaf necrosis can be indicative of herbicide phytotoxicity and can eventually lead to plant death (Santos et al. 2007).

***Eucalyptus* Seedling Growth Response.** *Quincy Site*. Reported survival values following sulfometuron applications are in relation to the number of live seedlings at the time of the first application. Sulfometuron rate affected seedling survival at 6WAT1 (before the second application), as well as seedling survival and stem diameter at the end of the growing season, at 12WAT1 (Table 6). However, sulfometuron rate did not affect tree height. Application frequency and the interaction between rate and frequency were not significant for any of these variables.

The best *Eucalyptus* seedling survival was obtained with 13 g ha^{-1} sulfometuron (Table 7). This rate resulted in greater survival than for 39 or 52 g ha^{-1} or the nontreated check at 6WAT1 and greater than for 39 or 52 g ha^{-1} at the end of the growing season. Increasing sulfometuron rate from 0 to 13 g ha^{-1} resulted in the greatest reduction in weed cover, positively affecting seedling survival. Increasing sulfometuron rate above 26 g ha^{-1} did not improve

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Table 7. *Eucalyptus benthamii* seedling performance at the Quincy, FL and Wing, AL sites following sulfometuron applications at various rates averaged over the two application frequencies.[a]

	Quincy site				Wing site			
Sulfometuron rate	6WAT1[b] Survival	12WAT1[c] Survival	12WAT1 Height	12WAT1 GLD_5	6WAT1 Survival	12WAT1 Survival	12WAT1 Height	12WAT1 GLD_5
g ha^{-1}	%[d]	%[d]	cm	mm	%	%	cm	mm
0	78 bc[e]	77 ab	64.9 a	5.0 b	99 a	99 a	88.3 a	11.2 a
13	94 a	89 a	62.9 a	6.0 a	58 bc	58 b	77.9 b	9.2 b
26	82 ab	77 ab	66.9 a	6.5 a	71 b	68 b	79.2 b	8.9 b
39	72 bc	66 b	61.4 a	6.5 a	64 bc	62 b	81.6 ab	9.5 b
52	64 c	63 b	64.5 a	6.7 a	50 c	48 b	77.8 b	8.7 b

[a] One or two sulfometuron applications; first application 2 wk after planting; second application 8 wk after planting, with the same sulfometuron rate. Means are for the rate main effect because interactions between sulfometuron rate and application frequency were not significant for any seedling growth variable.

[b] Six weeks after the first sulfometuron.

[c] Twelve weeks after the first sulfometuron application, approximately 14 wk after planting seedlings (end-of-growing-season assessment in late October 2011).

[d] Percentage of live seedlings in relation to the number of seedlings alive at the time of the first sulfometuron application.

[e] LS-means within a column followed by the same letter are not significantly different according to the Fisher's protected LSD at $\alpha = 0.05$.

weed control, but apparently reduced *Eucalyptus* seedling survival.

Sulfometuron application at any of the rates tested resulted in greater *Eucalyptus* seedling stem GLD_5 than the non-treated check (Table 7). Reduction in grass and forb competition achieved through sulfometuron treatments was responsible for the enhanced stem diameter growth. Of particular importance was the high efficacy in controlling grasses, which tend to outcompete young trees for water and nutrients, because of high root density, fibrous root architecture, and in some cases the efficiency of C_4 photosynthesis (Coll et al. 2004). On the other hand, there were no differences in seedling height among the treatments (Table 7). Our findings are in agreement with the results of Garau et al. (2009), who observed reduced diameter growth, but no effect on height, with increasing weed cover during the first 3 mo after establishing seedlings of *E. globulus* subsp. *maidenii*. Adams et al. (2003) also reported that competing vegetation caused greater reduction in stem diameter than height of *E. globulus*. According to Florence (2004), weed competition affects *Eucalyptus* stem diameter and crown volume more than its height.

Differences between height and diameter responses have been observed in competition studies of various tree species and could be attributed to differences in resources allocation between apical and cambial growth. Water stress, which can be caused by weed competition, usually reduces cambial growth before height growth (Kozlowski et al. 1991).

Wing Site. Reported survival values are in relation to the number of seedlings that were alive at the time of the first sulfometuron application. We observed a significant effect of sulfometuron rate, but no significant effect of application frequency or interaction between rate and frequency on seedling survival and growth at the Wing site (Table 6). Compared to the nontreated check, sulfometuron application at any rate reduced seedling survival at both the 6WAT1 and the end-of-growing-season evaluation, as well as final GLD_5 (Table 7). Seedling height was also less than in the nontreated check following any sulfometuron rate except for 39 g ha^{-1}.

Decreased seedling survival and growth at Wing, as well as increased leaf necrosis at both sites, following even the lowest sulfometuron rate of 13 g ha^{-1}, indicate high sensitivity of actively growing *E. benthamii* seedlings to sulfometuron applied over-the-top, under certain conditions. This is in agreement with limited information found in the literature. After comparing tolerance of several *Eucalyptus* species to various herbicides in a

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greenhouse study, Campbell and Nicol (1998) concluded that none of the herbicides used was completely safe at rates effective in weed control. Postplanting application of atrazine caused unacceptable mortality in small *Eucalyptus nitens* and *Eucalyptus regnans* seedlings (Florence 2004). All tested rates of granular Eucmix®, containing sulfometuron methyl and terbacil, resulted in substantial reduction in seedling survival of most *Eucalyptus* species. In California field studies comparing phytotoxicity of several herbicides on seven tree species, including one *Eucalyptus*, Lange (1987) observed that red gum (*Eucalyptus camaldulensis*) was one of the most sensitive species tested. The author states that the trees were killed by relatively high rates of four herbicides, including sulfometuron, but provides little details about the applied treatments.

The contrasting sulfometuron effects on the seedlings grown at the two sites in our study underscore the balance between herbicide efficacy and crop phytotoxicity. Sulfometuron had a positive effect on *Eucalyptus* seedlings at the Quincy site, but it negatively affected seedling survival and growth at Wing, reducing both seedling height and stem diameter, as compared to the nontreated check. The difference in seedling response may be attributed to the difference in weed cover between the two study sites. In Quincy, the positive effect of reduced competition may have outweighed the direct negative herbicidal effect on the seedlings. Additionally, weeds absorb part of the applied herbicide, likely resulting in reduced bioavailability to the crop trees. Because of the lack of weeds at the Wing site, a greater amount of sulfometuron may have been available for uptake by *E. benthamii* seedlings, and there was no benefit of vegetation control to offset direct negative effects on seedlings. For sulfometuron, soil pH influences herbicide solubility, and thus plant bioavailability (Shaner 2014), but this would not explain the observed seedling responses in this study, as soil pH values were similar (5.5 and 5.1 for Quincy and Wing, respectively). Semple and Koen (2006) also concluded that over-the-top applications of simazine did not improve survival of newly emerged *Eucalyptus* seedlings because of herbicide phytotoxicity, in spite of prolonged weed suppression. On the other hand, fluazifop-P-butyl applications, which did not damage the seedlings, did not improve survival either, because they were not effective against nongrass vegetation present at the treated sites. When applying a mixture of herbicides, including sulfometuron methyl, to 8-mo-old *E. globulus* at five sites in Western Australia, Fremlin and Misic (1999) observed the greatest growth response on sites with greater initial amounts of weeds.

According to Garau et al. (2008), water stress is the most important abiotic factor limiting survival during *Eucalyptus* plantation establishment. Young plants often experience water stress, referred to as planting shock, immediately after planting in the field. The current operational practice in the southeastern United States is to plant *Eucalyptus* seedlings in summer, when rain is usually abundant, particularly in south Florida. We followed the operational practice, but the hot weather typical for the July planting date may have negatively affected survival and growth of seedlings in our study. Poor seedling survival and growth are common in operational practice with this relatively new crop species in the southeast, prompting our work to develop selective weed control practices in this and other research.

Our research points to herbicide sensitivity of young *Eucalyptus* seedlings, but also shows that over-the-top applications of low sulfometuron rates can be effective for selective weed control in newly established plantations, enhancing young seedling growth. A 13 to 26 g ha^{-1} sulfometuron rate was effective in moderate weed pressure. Two consecutive applications, 6 wk apart, were more effective than a single one. Clearly though, additional research is needed to refine selective rates and optimum application timing for various vegetative and site conditions. According to Oust® XP and Alligare SFM 75 label recommendations for release of hardwood crop species (not including *Eucalyptus* in the case of Oust® XP), over-the-top sulfometuron applications made after trees have broken dormancy may injure or kill them, granted the recommended rates are greater than the ones in our study (Anonymous 2013, 2015). More research is also needed to investigate the interaction of sulfometuron rate and application frequency in various conditions and for different *Eucalyptus* genotypes. Such results could support improved label recommendations for selective weed control in *Eucalyptus*, which are needed because of expanding plantation areas in southern United States and

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globally. The only sulfometuron herbicide currently registered for *Eucalyptus* (except in California) is Alligare SFM 75 (Anonymous 2015; Osiecka and Minogue 2013), which lists *Eucalyptus* for applications made prior to planting and before tree seedlings or transplants break dormancy.

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