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Influence of application timing on the impact of glyphosate on giant reed (*Arundo donax* L.)

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ABSTRACT

Experiments were conducted near Davis and Fresno, California, to determine the impact of glyphosate timing on giant reed control. At Davis, giant reed (*Arundo donax* L.) in pots received an application of 1.5% glyphosate solution in September 2006, October 2006, November 2006, April 2007, June 2007, or August 2007. Leaf greenness, number of living and dead stems, and number of newly emerging stems were measured monthly until September 2008. By 1 year after treatment none of the treated container-grown plants at Davis had living stems, regardless of treatment month. For naturally growing giant reed near Fresno, leaf greenness values decline following treatment but recovered in the spring following treatment. Plants treated in September and October had the lowest proportion of living stems m^{-2} one year after treatment. The lowest number of new stems produced for the Fresno study was observed for plants treated in September and October. The combination of greater stem kill and reduced production of new stems indicates that a fall treatment with 1.5% glyphosate resulted in greater kill of giant reed. Differences between the field- and container-grown plants were likely due to smaller plants in the containers, which may be less able to recover from damage due to the reduced rhizome mass.

Key words: herbicide application timing, SPAD.

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INTRODUCTION

Giant reed grows in riparian habitats from northern California to Virginia (Bell 1997). It is an emergent aquatic plant (Cook 1990) that is taller and has more robust stems than

common reed, *Phragmites australis* (Cav.) Trin. (DiTomaso and Healy 2003). Giant reed produces large amounts of biomass (Perdue 1958, Sharma et al. 1998, Spencer et al. 2006), and its presence in some Californian riparian zones has changed control of ecosystem processes from flood- to fire-regulated processes (Rieger and Kreager 1989). In California and Texas giant reed is considered a noxious weed.

Giant reed control can be achieved by mechanical treatments and covering plants with tarps (Lowrey and Watson 2004), treating the plants with herbicides (Finn and Minnesang 1990, Jackson 1994, Bell 1997, Brenton 2002, Spencer et al. 2008), or by combinations of these approaches. Giant reed has been determined a suitable candidate for biological control (Tracy and DeLoach 1999), and one introduced insect has been approved for release (Goolsby and Moran 2009).

Currently, glyphosate is the herbicide most frequently used for giant reed control in California, and it is applied throughout the growing season. Although timing of herbicide application may affect herbicide efficacy (Ross and Lembi 2009), published data provide little guidance in selecting the most appropriate time to apply glyphosate for managing giant reed. Finn and Minnesang (1990) applied a 1.5% glyphosate solution to giant reed in southern California during May, July, and September of 1987 and monitored the plants for 2 years after treatment. They concluded that foliar treatments produced highly variable results with shoot die-back ranging from 10 to 90%, and resprouting ranging from 0 to 100%. These variable results imply possible seasonal differences in glyphosate efficacy; however, the brief article by Finn and Minnesang (1990) did not present data. A report by Jackson (1994) presented a diagram that implied the best time to spray mature stems is from July through the end of October, but no data were presented. An additional study conducted in southern California (Decruyenaere and Holt 2001) concluded that chemical control with phloem-mobile herbicides would be most effective in late summer or early fall, when carbohydrates are transported from leaves to below-ground structures prior to natural leaf senescence. To test the hypothesis proposed by Decruyenaere and Holt (2001), we performed two experiments in California, one at Davis and a second near Fresno, to determine the importance of glyphosate application timing for control of giant reed.

MATERIALS AND METHODS

Outdoor experiments were conducted from 2006 to 2008 in Davis and Fresno, California. In the Davis experiment, giant reed were grown in 20 L pots (25 cm diameter by 30 cm

TABLE 1. INFLUENCE OF GLYPHOSATE APPLICATION TIMING ON THE PROPORTION OF LIVING STEMS AND LEAF CHLOROPHYLL (SPAD) FOR GIANT REED AT DAVIS, CA. VALUES ARE THE MEAN ± ONE STANDARD ERROR. A ZERO VALUE FOR SPAD INDICATES THAT LEAVES HAD SENESCED.

		Month Treatment Applied						
Sample Date	Untreated	Sep 2006	Oct 2006	Nov 2006	Apr 2007	Jun 2007	Jul 2007	Aug 2007
Proportion of Living Stems								
14 Sep 2006	1.00 ± 0.00	1.00 ± 0.00	1.00 ± 0.00	1.00 ± 0.00	1.00 ± 0.00	1.00 ± 0.00	1.00 ± 0.00	1.00 ± 0.00
13 Oct 2006	0.96 ± 0.04	0.57 ± 0.17	1.00 ± 0.00	1.00 ± 0.00	1.00 ± 0.00	1.00 ± 0.00	1.00 ± 0.00	1.00 ± 0.00
15 Nov 2006	0.92 ± 0.04	0.11 ± 0.10	0.64 ± 0.08	0.96 ± 0.04	0.96 ± 0.04	0.98 ± 0.02	0.97 ± 0.03	1.00 ± 0.00
18 Dec 2006	0.92 ± 0.05	0.46 ± 0.08	0.56 ± 0.10	0.96 ± 0.04	0.96 ± 0.04	0.98 ± 0.02	1.00 ± 0.00	1.00 ± 0.00
18 Apr 2007	0.95 ± 0.03	0.63 ± 0.19	0.58 ± 0.07	0.66 ± 0.05	0.96 ± 0.03	0.90 ± 0.03	0.93 ± 0.03	0.98 ± 0.01
20 Jun 2007	0.96 ± 0.03	0	0	0.03 ± 0.02	0.08 ± 0.03	0.91 ± 0.03	0.89 ± 0.01	0.89 ± 0.03
26 Jul 2007	0.92 ± 0.04	0	0	0	0.22 ± 0.11	0.95 ± 0.02	0.92 ± 0.02	0.92 ± 0.03
29 Aug 2007	0.97 ± 0.02	0	0	0	0	0.44 ± 0.03	0.72 ± 0.02	0.92 ± 0.02
27 Sep 2007	0.96 ± 0.02	0	0	0	0	0.54 ± 0.04	0.53 ± 0.12	0.68 ± 0.09
25 Oct 2007	0.99 ± 0.01	0	0	0	0	0.27 ± 0.05	0.19 ± 0.07	0.24 ± 0.05
03 Dec 2007	0.97 ± 0.03	0	0	0	0	0.06 ± 0.03	0	0
31 Mar 2008	0.93 ± 0.04	0	0	0	0	0.21 ± 0.04	0	0
16 Jun 2008	0.90 ± 0.02	0	0	0	0	0	0	0
Leaf Chlorophyll (SPAD)								
14 Sep 2006	25.45 ± 2.02	26.10 ± 1.40	27.47 ± 1.37	28.84 ± 1.05	28.35 ± 1.36	27.68 ± 1.06	27.19 ± 0.44	27.85 ± 1.21
13 Oct 2006	25.59 ± 1.54	7.62 ± 2.61	26.69 ± 0.92	25.25 ± 0.72	25.42 ± 1.59	24.50 ± 1.24	24.76 ± 1.20	24.57 ± 1.77
15 Nov 2006	21.20 ± 1.25	6.34 ± 0.95	8.62 ± 0.55	20.80 ± 0.49	21.25 ± 1.82	19.82 ± 0.59	21.21 ± 1.05	20.73 ± 0.22
18 Dec 2006	18.60 ± 1.61	9.95 ± 0.90	7.46 ± 0.35	13.69 ± 1.05	15.42 ± 1.82	19.29 ± 0.91	19.19 ± 1.04	19.18 ± 2.59
18 Apr 2007	26.19 ± 0.16	9.20 ± 2.77	11.18 ± 0.42	9.67 ± 1.07	25.78 ± 1.84	26.44 ± 0.65	26.72 ± 1.23	26.56 ± 1.68
20 Jun 2007	25.96 ± 0.23	6.19 ± 3.29	8.57 ± 2.85	4.89 ± 2.91	21.71 ± 4.94	26.75 ± 0.57	26.99 ± 1.20	26.29 ± 0.87
26 Jul 2007	29.43 ± 1.06	0	0	0	5.84 ± 0.66	12.84 ± 1.37	26.61 ± 1.51	25.97 ± 0.69
29 Aug 2007	25.02 ± 1.07	0	0	0	4.86 ± 0.37	18.35 ± 2.16	19.69 ± 1.66	24.96 ± 1.02
27 Sep 2007	24.86 ± 0.94	0	0	0	5.54 ± 0.91	13.74 ± 2.40	8.34 ± 1.91	11.14 ± 1.93
25 Oct 2007	23.91 ± 1.40	0	0	0	4.23 ± 0.22	4.75 ± 0.87	4.26 ± 0.38	4.10 ± 0.46
03 Dec 2007	19.60 ± 0.93	0	0	0	1.52 ± 1.42	4.37 ± 0.29	3.91 ± 0.19	4.69 ± 0.60
31 Mar 2008	33.59 ± 0.66	0	0	0	0	0	0	0
16 Jun 2008	25.70 ± 0.96	0	0	0	0	0	0	0

tall) filled with Yolo sandy loam soil obtained from a commercial supplier (Ace Hardware, Davis, California). Rhizome sections were collected from a group of plants growing adjacent to Road 98 in Yolo County (38°38.234'N; 121°51.478'W). The rhizome sections were 98.5 g fresh weight on average (standard deviation = 72.4, N = 33) and were initially planted on 18 May 2006. One day before the first treatment, all plants were measured. The average SPAD value was 27.3 ± 2.6, average height was 0.91 ± 0.14 m, and mean number of stems per plant was 6.8 ± 2.2. Plants were randomly assigned to a treatment month. Herbicide treatment consisted of an application of 1.5% glyphosate solution (active ingredient), applied spray-to-wet (as Aquamaster aquatic herbicide, Monsanto Co., St. Louis, MO), in combination with the surfactant Agridex (Helena Chemical Co., Collierville, TN) at 5.1 mL L^{-1}, and mark-it blue dye (Lawn and Garden Products, Fresno, CA), 7.8 mL L^{-1}). Treatments were made to 4 plants with a backpack sprayer (14.8 L volume; Solo 475 Backpack Sprayer, Newport News, VA) on each of the following dates: 15 September 2006, 16 October 2006, 16 November 2006, 15 April 2007, 15 June 2007, and 15 August 2007. A 1.5% glyphosate was chosen because that concentration is recommended on the label and is frequently the treatment used in giant reed management programs with which we were familiar. Untreated plants served as controls. Plants were monitored until June 2008.

An accompanying experiment was conducted at a site near Fresno (described by Spencer et al. 2008). The procedures were as described above except that naturally occurring mature plants were treated. Plants averaged 130 stems m^{-2}, clump width was on average 3.65 m, stems were 3.9 m tall, and average biomass was 26.8 kg m^{-2} (Spencer et al. 2008). A second difference that there were 3 treated plants (i.e. replications) and plants were treated on 27-28 September and 18 October 2006, and 7 June and 14 August 2007. All treated and control plants were monitored until September 2008.

At monthly intervals, control and treated plants were measured to assess plant health. We used a Minolta 502 SPAD meter (Spectrum Technologies, East Plainfield, IL) to measure leaf chlorophyll content from 10 leaves on each plant

TABLE 2. INFLUENCE OF GLYPHOSATE APPLICATION TIMING ON THE PROPORTION OF LIVING STEMS AND LEAF CHLOROPHYLL (SPAD) FOR GIANT REED AT FRESNO, CA. VALUES ARE THE MEAN ± ONE STANDARD ERROR. A ZERO VALUE FOR SPAD INDICATES THAT LEAVES HAD SENESCED.

		Month Treatment Applied			
Sample Date	Untreated	Sep 2006	Oct 2006	Jun 2007	Aug 2007
Proportion of Living Stems					
03 Aug 06	0.81 ± 0.05	0.84 ± 0.04	0.86 ± 0.03	0.82 ± 0.05	0.77 ± 0.06
02 Nov 06	0.79 ± 0.04	0.70 ± 0.04	0.61 ± 0.09	0.96 ± 0.02	0.64 ± 0.10
01 Dec 06	0.83 ± 0.03	0.70 ± 0.06	0.71 ± 0.07	0.83 ± 0.07	0.70 ± 0.09
08 Mar 07	0.79 ± 0.04	0.72 ± 0.05	0.72 ± 0.06	0.81 ± 0.07	0.71 ± 0.09
11 Apr 07	0.85 ± 0.03	0.67 ± 0.06	0.60 ± 0.08	0.84 ± 0.05	0.78 ± 0.08
10 May 07	0.83 ± 0.04	0.49 ± 0.07	0.67 ± 0.08	0.88 ± 0.04	0.68 ± 0.10
07 Jun 07	0.80 ± 0.04	0.30 ± 0.06	0.69 ± 0.06	0.88 ± 0.06	0.73 ± 0.09
12 Jul 07	0.85 ± 0.03	0.14 ± 0.04	0.51 ± 0.08	0.86 ± 0.07	0.71 ± 0.10
14 Aug 07	0.82 ± 0.04	0.15 ± 0.04	0.33 ± 0.06	0.73 ± 0.08	0.83 ± 0.06
12 Sep 07	0.83 ± 0.03	0.11 ± 0.03	0.36 ± 0.08	0.64 ± 0.07	0.73 ± 0.08
16 Oct 07	0.70 ± 0.08	0.09 ± 0.04	0.27 ± 0.06	0.61 ± 0.07	0.72 ± 0.09
03 Apr 08	0.76 ± 0.07	0.08 ± 0.04	0.25 ± 0.07	0.60 ± 0.07	0.72 ± 0.07
18 Jun 08	0.59 ± 0.10	0.17 ± 0.06	0.19 ± 0.07	0.39 ± 0.08	0.47 ± 0.10
16 Jul 08	0.66 ± 0.07	0.21 ± 0.07	0.29 ± 0.08	0.46 ± 0.08	0.48 ± 0.09
13 Aug 08	0.62 ± 0.09	0.20 ± 0.08	0.30 ± 0.08	0.31 ± 0.08	0.36 ± 0.08
26 Sep 08	0.58 ± 0.09	0.14 ± 0.05	0.29 ± 0.09	0.27 ± 0.08	0.25 ± 0.08
Leaf Chlorophyll (SPAD)					
03 Aug 06	37.98 ± 1.37	38.82 ± 1.80	34.68 ± 2.90	36.24 ± 2.16	30.67 ± 2.14
02 Nov 06	29.68 ± 1.43	18.88 ± 2.09	17.01 ± 1.69	37.92 ± 2.78	23.47 ± 1.96
01 Dec 06	26.17 ± 1.09	22.65 ± 1.99	22.61 ± 2.10	31.74 ± 3.23	23.04 ± 2.50
08 Mar 07	29.86 ± 1.29	23.01 ± 1.56	19.17 ± 1.10	31.67 ± 2.36	24.55 ± 2.19
11 Apr 07	35.88 ± 1.23	26.25 ± 1.96	22.52 ± 1.04	40.30 ± 1.48	38.98 ± 1.04
10 May 07	34.98 ± 0.95	22.21 ± 1.57	20.09 ± 1.60	37.55 ± 1.17	34.15 ± 1.94
07 Jun 07	30.00 ± 1.39	17.90 ± 1.14	17.56 ± 1.92	35.97 ± 2.02	32.30 ± 2.60
12 Jul 07	30.88 ± 1.01	12.53 ± 1.17	12.94 ± 1.39	22.87 ± 2.49	23.33 ± 2.86
14 Aug 07	29.59 ± 1.37	13.59 ± 1.51	18.73 ± 3.38	15.78 ± 2.99	27.67 ± 2.67
12 Sep 07	25.64 ± 1.64	11.46 ± 1.53	13.18 ± 2.12	8.21 ± 1.75	10.26 ± 1.78
16 Oct 07	34.70 ± 1.70	9.97 ± 1.07	20.33 ± 3.59	9.13 ± 0.64	7.08 ± 1.15
03 Apr 08	41.97 ± 1.79	0	37.09 ± 1.55	38.30 ± 0.71	39.14 ± 3.68
18 Jun 08	32.80 ± 1.78	29.25 ± 4.12	26.08 ± 5.10	32.91 ± 4.39	29.64 ± 2.75
16 Jul 08	31.85 ± 2.59	32.33 ± 2.26	40.59 ± 1.49	24.73 ± 2.93	25.98 ± 2.43
13 Aug 8	32.10 ± 2.59	26.69 ± 4.02	37.64 ± 1.64	31.01 ± 2.52	31.59 ± 1.72
26 Sep 08	29.89 ± 2.78	35.18 ± 1.91	33.02 ± 2.72	26.86 ± 3.12	24.93 ± 2.32

Table 3. The influence of glyphosate application timing on chlorophyll (SPAD units), proportion of living stems per m^2, and mean number of new stems produced at 1 year after treatment.

Parameter Measured	Month Treated	Mean
Chlorophyll (SPAD Reading)		
	Control (untreated)	29.6 A[1]
	Aug 2007	31.6 A
	Jun 2007	32.9 A
	Oct 2006	20.3 A
	Sep 2006	11.5 A
Proportion of stems that are alive m^2		
	Control (untreated)	0.73 A
	Jun 2007	0.39 AB
	Aug 2007	0.36 AB
	Oct 2006	0.27 AB
	Sep 2006	0.11 B
Number of New Stems[A]		
	Control (untreated)	9.6 A
	Aug 2007	7.6 A
	Jun 2007	5.4 A
	Sep 2006	0.3 B
	Oct 2006	0.0 B

[1]Tukey's HSD based on transformed values. Untransformed means are presented here.

on each sampling date. SPAD readings, which are strongly correlated with leaf chlorophyll content for giant reed (Spencer et al. 2008), were the mean of 3 readings made at the base, midpoint, and tip of each leaf. For the Fresno field study, randomly placed 20 by 30 cm quadrats were used to measure the number of living and dead stems present within the giant reed clumps. Data from 5 quadrats were collected for each plant on each sampling date. In the absence of leaves, living stems were distinguished from dead stems based on the presence of a green patch adjacent to nodes. The proportion of living stems was calculated by dividing the number of living stems by the total number of stems within each quadrat. (All stems within a pot were counted for the Davis study.) Beginning in spring 2007 the number of newly emerging stems was also counted within each quadrat for the Fresno plants.

The proportion of living stems per quadrat 1 year after treatment, the SPAD reading per leaf 1 year after treatment, and the mean number of newly emerging shoots calculated over the 12 months following treatment were analyzed statistically to detect treatment effects using SAS software (SAS Institute Inc. 2004). The number of newly emerging shoots calculated over the 12 months following treatment (i.e. including counts with zero values) was transformed by adding 1 and taking the natural logarithm. We applied Tukey's HSD procedure to compare treatment means. Tests were considered significant at a probability level <0.05; however, exact probability levels for fixed effect tests are shown in the results.

RESULTS AND DISCUSSION

Chlorophyll values declined significantly ($F_{7, 24} = 708.6$, $P < 0.0001$), for giant reed treated at various times of the year in the outdoor experiment at Davis beginning the month following treatment (Table 1). Chlorophyll values for treated plants did not recover to pretreatment levels. The proportion of living stems displayed a similar significant reduction ($F_{7, 24} = 1913.5$, $P < 0.0001$) except that the decline was not as noticeable immediately following the treatment. However, by 1 year post treatment, none of the treated plants appeared to have any live stems (Table 1). Plant height (data not shown) was unaffected by the treatments ($F_{7, 24} = 1.09$, $P = 0.4$), which was expected because dead giant reed stems may persist for quite some time (DiTomaso and Healy 2003).

Table 4. Influence of glyphosate application timing on the number of new stems m^2 for giant reed at Fresno, CA. Values are the mean ± one standard error.

	Month Treatment Applied				
Sample Date	Untreated	Sep 2006	Oct 2006	Jun 2007	Aug 2007
03 Aug 06	0.0 ± 0.0	0.0 ± 0.0	0.0 ± 0.0	0.0 ± 0.0	0.0 ± 0.0
02 Nov 06	0.0 ± 0.0	0.0 ± 0.0	0.0 ± 0.0	0.0 ± 0.0	0.0 ± 0.0
01 Dec 06	0.0 ± 0.0	0.0 ± 0.0	0.0 ± 0.0	0.0 ± 0.0	0.0 ± 0.0
08 Mar 07	3.3 ± 1.1	0.0 ± 0.0	0.0 ± 0.0	5.6 ± 3.1	5.6 ± 4.5
11 Apr 07	6.4 ± 1.6	2.5 ± 1.8	0.0 ± 0.0	8.9 ± 3.6	8.9 ± 4.8
10 May 07	11.8 ± 2.8	0.0 ± 0.0	0.0 ± 0.0	14.4 ± 5.4	17.8 ± 6.0
07 Jun 07	10.9 ± 2.1	0.0 ± 0.0	0.0 ± 0.0	21.1 ± 6.8	13.3 ± 5.7
12 Jul 07	18.5 ± 3.2	0.0 ± 0.0	0.0 ± 0.0	8.9 ± 4.6	13.3 ± 4.0
14 Aug 07	13.9 ± 2.9	0.0 ± 0.0	0.0 ± 0.0	0.0 ± 0.0	18.9 ± 7.9
12 Sep 07	17.0 ± 3.1	0.0 ± 0.0	0.0 ± 0.0	0.0 ± 0.0	3.3 ± 2.4
16 Oct 07	5.0 ± 2.1	0.0 ± 0.0	0.0 ± 0.0	5.6 ± 3.1	18.9 ± 6.5
03 Apr 08	6.7 ± 3.6	3.3 ± 2.3	7.8 ± 5.8	2.2 ± 2.2	4.4 ± 2.6
18 Jun 08	8.3 ± 3.1	2.5 ± 1.4	11.1 ± 6.8	0.0 ± 0.0	2.2 ± 1.5
16 Jul 08	6.2 ± 2.0	4.2 ± 2.7	14.4 ± 5.6	5.6 ± 3.1	3.3 ± 1.8
13 Aug 08	9.6 ± 2.8	5.0 ± 2.7	41.1 ± 13.4	4.4 ± 2.6	2.2 ± 1.5
26 Sep 08	10.0 ± 2.2	5.0 ± 3.4	31.1 ± 9.9	3.3 ± 2.4	1.1 ± 1.1

Chlorophyll values for giant reed treated at different times of the year near Fresno declined in the month following treatment but then generally recovered (Table 2), with the exception that chlorophyll values for plants treated in September 2006 remained low during 2007. Chlorophyll values for these plants recovered to near control levels in leaves on new shoots produced in 2008. SPAD values 1 year post-treatment compared with values for untreated controls indicated no significant treatment effect (Table 3). In contrast, the proportion of living stems m^{-2} was significantly different ($F_{4,12} = 3.51$, $P = 0.04$) due to timing of the treatment (Table 2). In this case, plants treated in September had the lowest proportion of living stems m^{-2} 1 year after treatment (Table 3). The fact that treated plants produced new stems in the growing seasons following treatment indicated that some rhizomes of the treated plants survived (Table 4). However, timing of treatment significantly affected the number of new shoots produced within the 12 months following treatment ($F_{4, 23} = 13.9$, $P < 0.0001$), with the lowest mean numbers of new stems produced observed for plants originally treated in September or October (Table 4). The combined results for the number of living stems (Table 2) and the subsequent number of new stems produced (Table 4) indicate that September and October treatments with 1.5% glyphosate resulted in greater kill of giant reed than treatments applied in June or August.

The differences between field- and pot-grown experiments are likely due to the smaller pot-grown plants compared to the larger plants treated in the field experiment. Smaller plants are possibly more susceptible to glyphosate due to the reduced rhizome mass available for regrowth following treatment. Giant reed plants in the Davis experiment were about one-fourth the size (average height was 0.91 m) of those at the Fresno site (average height 3.9 m). Giant reed plants included in the Fresno experiment were comparable to giant reed plants in California, Mississippi, and Texas sites that were on average 3.4 m tall (range 1.7 to 5.46 m), had an average of 75 stems m^{-2} (44 to 178 stems m^{-2}), and had biomass values of 17.1 kg m^{-2} (range 3.1 to 40 kg m^{-2}; Spencer et al. 2006).

Results from the naturally growing larger Fresno plants support the hypothesis of Decruyenaere and Holt (2001) that a phloem-mobile herbicide, such as glyphosate, would be most effective in late summer or early fall. The present results also agree with previous research on controlling other perennial weeds. Fall treatments with a systemic herbicide (such as glyphosate) have been shown to be an effective approach (Ross and Lembi 2009). For example, another emergent aquatic plant, cattail (*Typha latifolia*), was most effectively controlled by late summer or fall treatments with glyphosate, when the plants were moving storage products to the rhizomes (Ross and Lembi 1985). Information from this study can be used by land managers to control giant reed by applying glyphosate at the most effective time of year, possibly reducing the need for additional treatments.

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