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Purple Nutsedge (*Cyperus rotundus*) Tuber Production and Viability Are Reduced by Imazapic

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Weeds exploit underutilized space, causing economic losses in cropping systems. Weed management tactics alter that underutilized space until the crop can mature and efficiently use that space. One tactic is to reduce the weed propagules (e.g., seeds and tubers) that persist quiescently in the soil, which includes minimizing production and addition of new propagules to the soil. Purple nutsedge is a problematic weed around the globe, persisting between growing seasons as tubers in the soil. Imazapic is a peanut herbicide often used in Georgia for control of purple nutsedge. The objective of the experiment was to evaluate the effect of various rates of imazapic on purple nutsedge tuber production. Single presprouted purple nutsedge tubers were transplanted into outdoor microplots and treated after 6 wk of growth with six rates of imazapic (5 to 140 g ai ha^{-1}) POST. A nontreated control was included. All emerged shoots at the time of application were marked with plastic rings; this allowed for classification of tubers at exhumation as (1) tubers attached to shoots that were emerged at time of application, (2) tubers attached to shoots that emerged after application, and (3) tubers without an aerial shoot during the study. At 7 wk after application, the tubers in the microplots were exhumed, classified, and quantified, and their ability to sprout was evaluated. In the nontreated control, there were 544 total tubers, with a log-logistic regression model describing the declining tuber population with increasing imazapic rate. The rate of imazapic that reduced total tuber population 50% (I_{50}) was 36 g ha^{-1}. In the nontreated control, there were 161 tubers attached to shoots that emerged, as when compared with plots that received an imazapic application that had an $I_{50} = 60$ g ha^{-1}. Viability of purple nutsedge tubers was 44% at 70 g ha^{-1} imazapic, suggesting the action of the herbicide may have rendered the tubers nonviable after new shoots were produced. The final classification of tubers included those that did not have an aerial shoot during the study. These were tubers in which apical dominance suppressed shoot development or were likely the most recent tubers to develop. Of the three classes, the tubers without shoots were the most prevalent in the nontreated control, with 358 tubers and an $I_{50} = 18$ g ha^{-1}. Imazapic controls purple nutsedge foliage but also reduces the number of new tubers produced, and overall tuber viability and is a valuable tool in management of the long-term population density of this weed.
Nomenclature: Imazapic, purple nutsedge, *Cyperus rotundus* L., CYPRO.
Key words: AC 263,222, competition, peanut, perennial weed management.

Purple nutsedge is a nonnative weed of agricultural regions, particularly in the coastal plains of the southern United States, where the soil does not frequently freeze (Bryson and DeFelice 2009). A persistent weed of multiple crops throughout the world (Holm et al. 1977), purple nutsedge is among one of the most difficult to control in vegetable and agronomic crops due to its tolerance of many control practices, including many herbicides (Webster and Nichols 2012). A perennial member of the Cyperaceae family, purple nutsedge primarily reproduces vegetatively via rhizomes and tubers, though it will flower and produce seed. Purple nutsedge tubers are oblong and irregularly shaped, often brown to black in color, and contain multiple axillary buds from which shoots sprout (Bryson and DeFelice 2009). Linked by rhizomes, tuber chains can extend radially from the initial mother plant, with a single tuber expanding to form a 22 m^2 patch in 60 wk (Webster 2005b). During soil preparation prior to crop establishment, these tuber chains are often severed, likely releasing apical dominance and permitting these tubers to germinate. In the absence of competition, purple nutsedge will rapidly produce tubers; a single tuber and shoot developed a plant that produced 378 tubers after 107 d of growth (Webster 2005a). Over a 3 yr period in peanut, purple nutsedge tuber populations increased from 626 to 9,145 tubers m^{-3} in a nontreated control,

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while systems that included imazapic and other acetolactate synthase inhibitors reduced tuber populations to less than 10% of the initial population of the nontreated control (Warren and Coble 1999). Nutsedge tubers are known to be a major contaminant in harvested peanut due to their similar size and can even be identified in harvested peanut when complete control is maintained during the growing season (Johnson and Mullinix 2003). This is due to dormant tubers located in the soil from the previous year's infestations.

A branched-chain amino acid synthesis inhibitor (Group B2), imazapic is registered for weed control in peanut and widely used in Georgia and much of the southeast United States (Senseman 2007). Imazapic was applied to 56% of the U.S. peanut hectares in 2013 (National Agricultural Statistics Service 2013) as a POST application that provides residual weed control. Grichar et al. (2012) indicated that in spite of the high cost associated with imazapic, it provides the greatest net returns due to its ability to control a broad spectrum of weeds. Imazapic controls (>90%) many common weeds in U.S. peanut production, including bristly starbur (*Acanthospermum hispidum* DC), citronmelon [*Citrullus lanatus* (Thunb.) Matsumura & Nakai var. *citroides* (Bailey) Mansf.], coffee senna [*Senna occidentalis* (L.) Link], common cocklebur (*Xanthium strumarium* L.), morningglory species (*Ipomoea* spp.), prickly sida (*Sida spinosa* L.), sicklepod [*Senna obtusifolia* (L.) H. S. Irwin & Barneby], and smallflower morningglory [*Jacquemontia tamnifolia* (L.) Griseb.] (Webster et al. 1997; Wilcut et al. 1996). However, one of its unique attributes is the ability to control purple and yellow nutsedge (*Cyperus esculentus* L.). When applied at the registered use rate (70 to 72 g ha^{-1}), imazapic controlled purple nutsedge ≥95% and yellow nutsedge ≥92% (Grichar and Nester 1997; Grichar et al. 2012; Webster et al. 1997). But variability in yellow and purple nutsedge control for this rate has also been reported, ranging from 39 to 93% in peanut (Dotray and Keeling 1997; Wehtje and Brecke 2004). Imazapic has been shown to reduce carbon assimilation in yellow nutsedge plants by 50% after 2.1 d, similar to halosulfuron but more rapid than glyphosate or MSMA (Ferrell et al. 2004).

Effective weed control programs minimize impact of the weed in the current crop year. However, effective weed management strategies should extend beyond a single season and target reducing the number of propagules added annually that persist in the soil (Gallandt 2006; Mortensen et al. 2000), especially in peanut (Johnson and Mullinix 2003). Imazapic may have the potential to reduce tuber production and cause a decline in purple nutsedge tuber density in the soil propagule bank. However, the effect of imazapic on purple nutsedge tuber production when applied to mature plants is unknown. Therefore, the objective of this study was to quantify the effects of imazapic on tuber production and further evaluate the effects on tubers: (1) attached to shoots emerged at the time of application, (2) attached to shoots that emerged after imazapic application, and (3) without aerial shoots during the study.

Materials and Methods

Purple nutsedge tubers were collected in 2013 and 2014 from a naturalized population in Tift County, GA, using a field cultivator; tuber chains become entangled on the tines of the cultivator and are removed from the machinery after each pass through the field. In 2015 purple nutsedge tubers were collected at the Plant Science Research and Education Unit in Citra, FL, using the previously described procedures. Tubers were then hand separated and classified by size; tubers that were approximately 1.2 cm long and 0.75 cm wide and had a fresh biomass of approximately 1.1 g were used to ensure a uniform tuber size for the study (Wallace et al. 2013). For each experiment, tubers were then planted in pots with steam-sterilized soil and grown in the greenhouse for approximately 3 wk, after which they were transplanted into the experimental units, following the methods of Webster and Grey (2014). Purple nutsedge tubers with a single shoot were transplanted (one per treatment) into outdoor microplots on April 15, 2013, April 3, 2014, and April 8, 2015, at the U.S. Department of Agriculture–Agricultural Research Service Crop Protection and Management Research Unit in Tifton, GA (31.48°N, 83.53°W). Microplots consisted of plastic containers (76 cm diameter, countersunk into the ground to a depth of 76 cm) filled with steam-sterilized Tifton loamy sand (fine-loamy, kaolinitic, thermic, plinthic, Kandiudult) with pH 6.5 and organic matter 0.8%. Soil moisture in microplots was maintained by irrigation as needed via a microjet emitter system. After 6 wk of purple nutsedge growth, imazapic (Cadre 2L; BASF, Research Triangle Park, NC 27709) was applied POST using a CO_2-pressurized backpack sprayer equipped with flat-fan nozzles calibrated to deliver 140 L ha^{-1} at 275 kPa. A nonionic surfactant was included at 0.25% (v/v) for each treatment. Six rates of imazapic (5, 9, 18, 35, 70, and 140 g ai ha^{-1}) were selected on a

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logarithmic dose using a common multiplier of 2 (Seefeldt et al. 1995). A nontreated control was also included. Treatments were arranged as a randomized complete block design, blocked by the number of emerged purple nutsedge shoots at the time of application; there were five replications of each treatment.

Visual evaluation of foliar chlorosis/necrosis occurred at 7 wk after treatment (WAT), using a scale of 0 (no shoot injury) to 100 (complete necrosis). At 7 WAT, digital images of 12.2 megapixels were taken directly over each microplot; images were then analyzed for level of green color using ImageJ software (W. Rasbaud, National Institutes of Health, http://imagej.nih.govij). All of the area outside each round microplot had a black vignette placed around it to allow for accurate estimation of the percent green area in each treatment, which was then expressed as a percentage of the value in the nontreated control.

Individual shoots emerged at the time of imazapic application were marked with 0.3 to 0.5 cm length plastic rings that were slid over leaf blades to the base of each plant to the soil surface (Webster 2005a). The parent tuber was marked at emergence with a plastic ring, and then subsequent shoots were marked in the same fashion prior to imazapic application. Care was taken to ensure that the plastic rings remained in place during the entire growing season. This allowed for the classification of tubers at exhumation as: (1) tubers attached to shoots that were emerged at time of application, (2) tubers attached to shoots that emerged after application, and (3) tubers without an aerial shoot during the study. At 7 WAT, all purple nutsedge plant material from each microplot was exhumed, tubers were sorted according to the previously described classification scheme, and all plant material was then quantified.

Purple nutsedge tubers were then evaluated for viability by placing them between moistened paper towels that were placed in sealable plastic bags that were then placed in plastic bins under greenhouse benches. The average greenhouse day/night temperatures were 32/24 C. Tuber viability was evaluated three times each week over a 90 d period; tubers were scored viable once a 3 mm shoot developed. Tubers that did not sprout during this time and exhibited signs of decay were considered nonviable.

Data were subjected to a mixed-model ANOVA (SAS Institute 2012), with herbicide rate as a fixed factor, while years and the interaction were random factors. The relationships between nutsedge responses and imazapic rate were fit to a log-logistic regression model,

$$y = \left(\frac{d}{1 + \exp\{b[\log(x) - \log(\mathrm{I}_{50})]\}} \right) \qquad [1]$$

where y is purple nutsedge response (i.e., tuber numbers, tuber and shoot biomass, and estimated nutsedge control), d is the upper limit of the regression, x is the rate of imazapic, I_{50} is the rate of imazapic that provides median purple nutsedge response, and b is the slope of the regression at I_{50} (Ritz et al., 2013; Seefeldt et al., 1995). Differences among parameters between regression models were evaluated using a t-test (Glantz and Slinker 2001). An approximate $\mathrm{R}^2_{\mathrm{nonlinear}}$ value (Askew and Wilcut 2001; Jasieniuk et al. 1999) was calculated as:

$$\mathrm{R}^2_{\mathrm{nonlinear}} = 1 - \left(\frac{\text{Residual sum of squares}}{\text{Corrected total sum of squares}} \right) \qquad [2]$$

Results and Discussion

Foliage. Visual ratings of purple nutsedge foliar chlorosis at 7 WAT were regressed on imazapic rate and fit ($\mathrm{R}^2_{\mathrm{nonlinear}} \geq 0.77$, $P < 0.0001$) to a log-logistic regression model (Figure 1). The rate of imazapic needed to cause a 50% response (parameter I_{50}) was estimated at 35 g ha^{-1} (Table 1), while the registered use rate in peanut (70 g ha^{-1}) caused 66% foliar chlorosis (Figure 1). Previous studies have documented >95% control of purple nutsedge late in the season (≥94 d after treatment), but this occurred in the

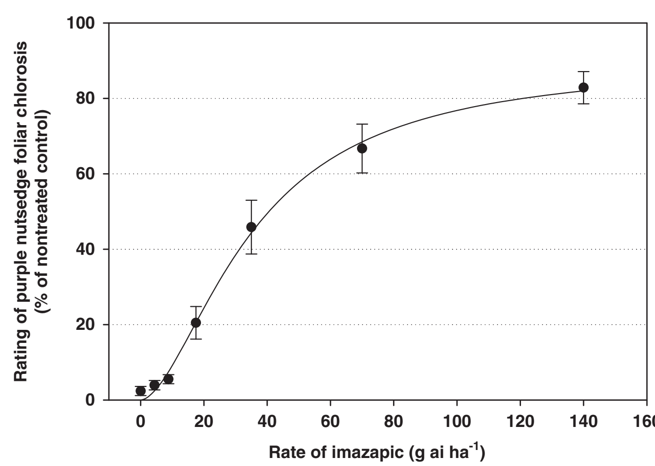

Figure 1. The relationship between rate of imazapic and a visual rating of foliar chlorosis at 7 weeks after imazapic treatment. Each treatment mean is combined over replications and years, with the vertical lines around each treatment mean representing the standard errors. The parameters of the log-logistic regression equation are found in Table 1.

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Table 1. Parameter estimates and their standard errors from the log-logistic regression models[a] relating to purple nutsedge foliar response to rate of imazapic in Figures 1, 2, and 3.

Nutsedge shoot response	I_{50}[b]	SE	*b*[c]	se	*d*[d]	SE	$R^2_{nonlinear}$	P-value
Foliar chlorosis (7 WAT)	35	6.2	−3.9	0.8	90	8.9	0.77	<0.0001
Total biomass of shoots	23	5.0	2.6	0.5	133	9.7	0.52	<0.0001
Foliar area (% of control)	22	3.0	3.2	0.5	94	4.7	0.71	<0.0001

[a] Model: $y=\left(\frac{d}{1+\exp\{b[\log(x)-\log(I_{50})]\}}\right)$, $R^2_{nonlinear}=1-\left(\frac{\text{Residual sum of squares}}{\text{Corrected total sum of squares}}\right)$.

[b] The I_{50} parameter is the rate of imazapic (g ai ha^{-1}, as in Table 2) that imparts a 50% reduction in the measured nutsedge shoot response.

[c] The *b* parameter is the slope of the regression around the I_{50}.

[d] Parameter *d* is the maximum nutsedge shoot response of the regression.

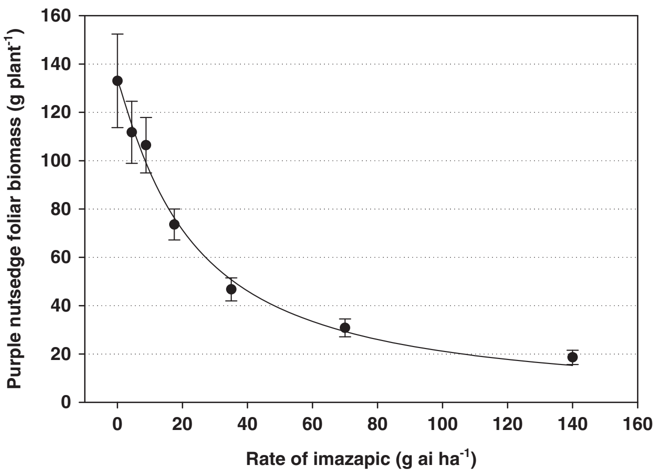

Figure 2. The log-logistic relationship between dry shoot biomass at the conclusion of the season and rate of imazapic. Each treatment mean is combined over replications and years, with the vertical lines around each treatment mean representing the standard errors. The parameters of the regression equation are in Table 1.

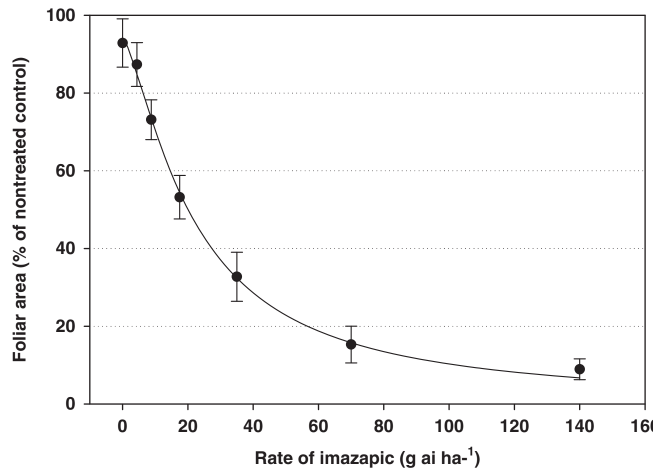

Figure 3. The relationship between rate of imazapic and foliar area (measured by the number of green pixels) expressed as a percent of the nontreated control at 7 weeks after imazapic treatment. Each treatment mean is combined over replications and years, with the vertical lines around each treatment mean representing the standard errors. The parameters of the log-logistic regression equation are in Table 1.

presence of a competitive peanut crop (Grichar and Nester 1997). Purple nutsedge is intolerant of plant competition that limits light interception by the weed and will typically not maintain foliar growth under these conditions (Stoller and Sweet 1987).

Purple nutsedge shoot biomass was reduced by increasing rates of imazapic (Figure 2) and fit to a log-logistic regression model ($R^2_{nonlinear}$ = 0.71, $P < 0.0001$). For each microplot planted with an initial sprouted tuber, total shoot biomass ranged from 19 to 133 g plant^{-1} at the highest rate of imazapic and the nontreated control, respectively. The I_{50} for shoot biomass was 23 g ha^{-1} imazapic, which was not different ($P = 0.13$) from the I_{50} for foliar chlorosis rating. At imazapic rates of 70 g ha^{-1} and 140 g ha^{-1}, shoot biomass was reduced by 70 and 82%, respectively, compared with the nontreated control. Richburg et al. (1994) determined that 71 g ha^{-1} imazapic applied to 15-d-old purple nutsedge plants reduced shoot dry biomass by >89% at 28 d after treatment and shoot regrowth by >93% after an additional 14 d.

A digital assessment of green foliar area was regressed on imazapic rate and fit ($R^2_{nonlinear}$ = 0.71, $P < 0.0001$) to a log-logistic regression (Figure 3). This objective measurement nondestructively assessed both the amount of chlorosis and the overall reduction in shoot growth and ranged from 9 to 97% foliar area relative to the nontreated control at the highest and lowest rates of imazapic, respectively. The estimated I_{50} was 22 g ha^{-1} of imazapic (Table 1), but this value was not different ($P = 0.063$) from the I_{50} for the visual ratings of chlorosis, though the standard error of the digital assessment was half that of the visual ratings. Imazapic at 70 and 140 g ha^{-1} reduced purple nutsedge foliar area to 15 and 9% of the nontreated control, respectively (Figure 3). The ratio of registered use rate to the 50% response ($1\times$:I_{50}) for green foliar area was 3.2. A similar-methodology applied to purple nutsedge response to halosulfuron determined that the $1\times$:I_{50} was 6.5, suggesting a greater foliar response from purple nutsedge to halosulfuron than observed with imazapic at the registered rates (Webster and Grey 2014). Purple nutsedge has been shown to decrease soybean yields by up to 12% with densities of 25 plant m^{-2}, and can reduce yields up to 48% at 200 plants m^{-2} (Das et al. 2014). For that study, the authors determined that the economic threshold for herbicide application for purple nutsedge control was 19 to 22 purple nutsedge plants m^{-2}. A review of the literature indicated that this type of research has not been conducted for peanut.

Tubers. In the nontreated control, there was an average of 544 total tubers (parameter *d*) produced from a single tuber during the 13 wk study (Table 2). This number is comparable to that previously reported for purple nutsedge (530 tubers) using a similar methodology (Webster and Grey 2014). The relationship between total purple nutsedge tuber population and rate of imazapic was described ($R^2_{nonlinear} = 0.47$, $P < 0.0001$) by a log-logistic regression model (Figure 4A). The I_{50} for total tuber population was 36 g ha^{-1} imazapic (Table 2), similar to I_{50} values for foliar chlorosis (P = 0.92) and green area (P = 0.0757). At the registered use rate in peanut (70 g ha^{-1}), there was a 75% reduction in total tuber population, while increasing imazapic rate to 140 g ha^{-1} reduced tuber population density by 85% relative to the nontreated control. Imazapic has been successfully applied with little to no reported injury concerns or reduction in grade and yield of runner-type peanut for more than 20 yr (Dotray et al. 2001; Faircloth and Prostko 2010; Grey et al. 2003; Richburg et al. 1995; Teuton et al. 2004). Peanut producers should follow the recommended 70 g ha^{-1} of imazapic and not reduce the rate to ensure purple nutsedge control that will reduce tuber production and eliminate some foreign material issues during the processing procedure (Whitaker et al. 2008).

The complex nature of vegetative reproduction provides opportunities for herbicides to target tubers at different stages of growth. To evaluate the response of purple nutsedge tubers in different growth stages to imazapic, tubers were separated based on the absence or presence of a foliar shoot that emerged before or after the application of imazapic. In the nontreated control, there were 37 tubers that were attached to foliar shoots at the time of imazapic application; there was no response (P = 0.9575) in tuber numbers in this class to imazapic rates (Figure 4B). These were established tubers, and there is no reason to think there would be any differences in tuber numbers in the short duration of the study. Regression parameter *d*, an estimate of tuber population in the nontreated control, indicated there were 161 tubers attached to shoots that emerged after imazapic application (i.e., late-emerging tubers) (Figure 4C) and 358 tubers that did not have aerial shoots (i.e., shootless tubers) (Figure 4D). Relative to tubers attached to shoots that had emerged before imazapic application, both the late-emerging and shootless tuber classifications likely represent

Table 2. Parameter estimates and their standard errors of the log-logistic regression models[a] that relate purple nutsedge tuber response to rate of imazapic in Figures 4, 5, and 6.

Tuber responses	Tuber class	I_{50}[b]	SE	*b*[c]	SE	*d*[d]	SE	$R^2_{nonlinear}$	P-value
Tuber numbers	Total	36	7.2	3.3	0.8	544	39	0.47	<0.0001
	Emerged shoots at application	—	—	—	—	—	—	—	—
	Late emerging shoots	60	8.0	7.5	2.9	161	9	0.39	<0.0001
	Shootless	18	3.9	3.6	0.9	358	31	0.49	<0.0001
Tuber biomass	Total	19	3.7	2.8	0.5	610	42	0.58	<0.0001
	Emerged shoots at application	—	—	—	—	—	—	—	—
	Late emerging shoots	40	5.4	5.4	1.4	145	8	0.53	<0.0001
	Shootless	10	1.9	3.3	0.7	420	34	0.55	<0.0001
Sprouted tubers (%)	Total	64	6.1	5.0	0.9	87	3	0.65	<0.0001
	Emerged shoots at application	50	5.7	4.2	0.8	92	4	0.65	<0.0001
	Late emerging shoots	75	10.5	4.9	1.4	85	4	0.39	<0.0001
	Shootless	70	11.4	4.0	1.1	85	5	0.39	<0.0001

[a] Model: $y=\left(\frac{d}{1+\exp\{b[\log(x)-\log(I_{50})]\}}\right)$, $R^2_{nonlinear}=1-\left(\frac{\text{Residual sum of squares}}{\text{Corrected total sum of squares}}\right)$

[b] The I_{50} parameter is the rate of imazapic (g ai ha^{-1}) that imparts a 50% reduction in the measured nutsedge shoot response.

[c] The *b* parameter is the slope of the regression around the I_{50}.

[d] Parameter *d* is the maximum nutsedge shoot response of the regression. There was no change in number or biomass of tubers with emerged shoots when imazapic was applied.

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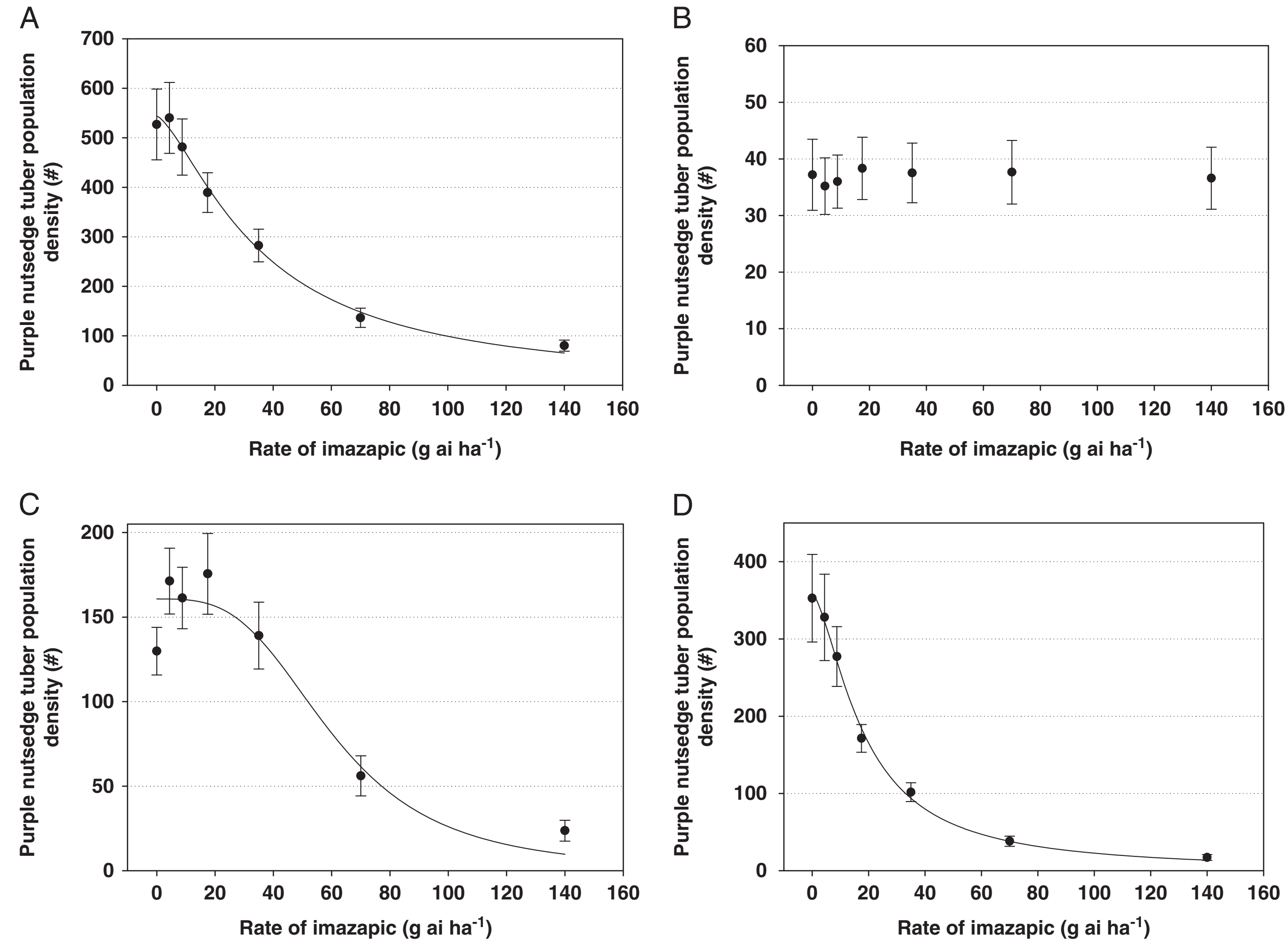

Figure 4. The log-logistic relationship between imazapic rate and total tuber number (A), number of tubers with emerged aerial shoots at the time of imazapic application (B), number of tubers with aerial shoots that emerged following imazapic application (C), and number of tubers without aerial shoots (D). Each treatment mean is combined over replications and years, with the vertical lines around each treatment mean representing the standard errors. The parameters of the regression equation are in Table 2.

younger tubers that were nutrient sinks and potential destinations for imazapic. Population densities for both the late-emerging and shootless tuber classes were fit to log-logistic regression models ($R^2_{nonlinear} = 0.39$ to 0.49, $P < 0.0001$). Late-emerging tuber numbers had an I_{50} of 60 g ha^{-1} imazapic, which was three times greater ($P < 0.0001$) than that for the shootless tuber numbers ($I_{50} = 18$ g ha^{-1}). Differences in tuber population density response to imazapic between late-emerging and shootless tubers were consistent with previous findings with halosulfuron (Webster and Grey 2014).

Total tuber fresh biomass ($I_{50} = 19$ g ha^{-1}) was more sensitive ($P = 0.0429$) to imazapic (Figure 5A) than was total tuber population density ($I_{50} = 36$ g ha^{-1}) (Figure 4A), as indicated by their slopes (3.3 > 2.8) (Table 2). Imazapic rate did not affect ($P > 0.63$) biomass of tubers attached to shoots emerged at application, because they were already established at the time of application, and imazapic prevented development of new tubers (Figure 5B). Biomass of total tubers, late-emerging tubers, and shootless tubers was regressed on imazapic rate and fit to log-logistic models ($R^2_{nonlinear} = 0.53$ to 0.58, $P < 0.0001$) (Figure 5A,C,D). The I_{50} for total tuber biomass (19 g ha^{-1} imazapic) was greater ($P = 0.026$) than that of the biomass of shootless tubers ($I_{50} = 10$ g ha^{-1}) but less ($P = 0.0016$) than that of the biomass of late-emerging tubers ($I_{50} = 40$ g ha^{-1}). In the nontreated control, greater tuber biomass occurred in the shootless tuber class (420 g plant^{-1} or 69%), with late-emerging tubers representing 24% (145 g plant^{-1}), and tubers attached to shoots emerged at application contributed 7% (45 g plant^{-1}).

The sprouting of tubers over a 60 d period in the laboratory following harvest was used to estimate the

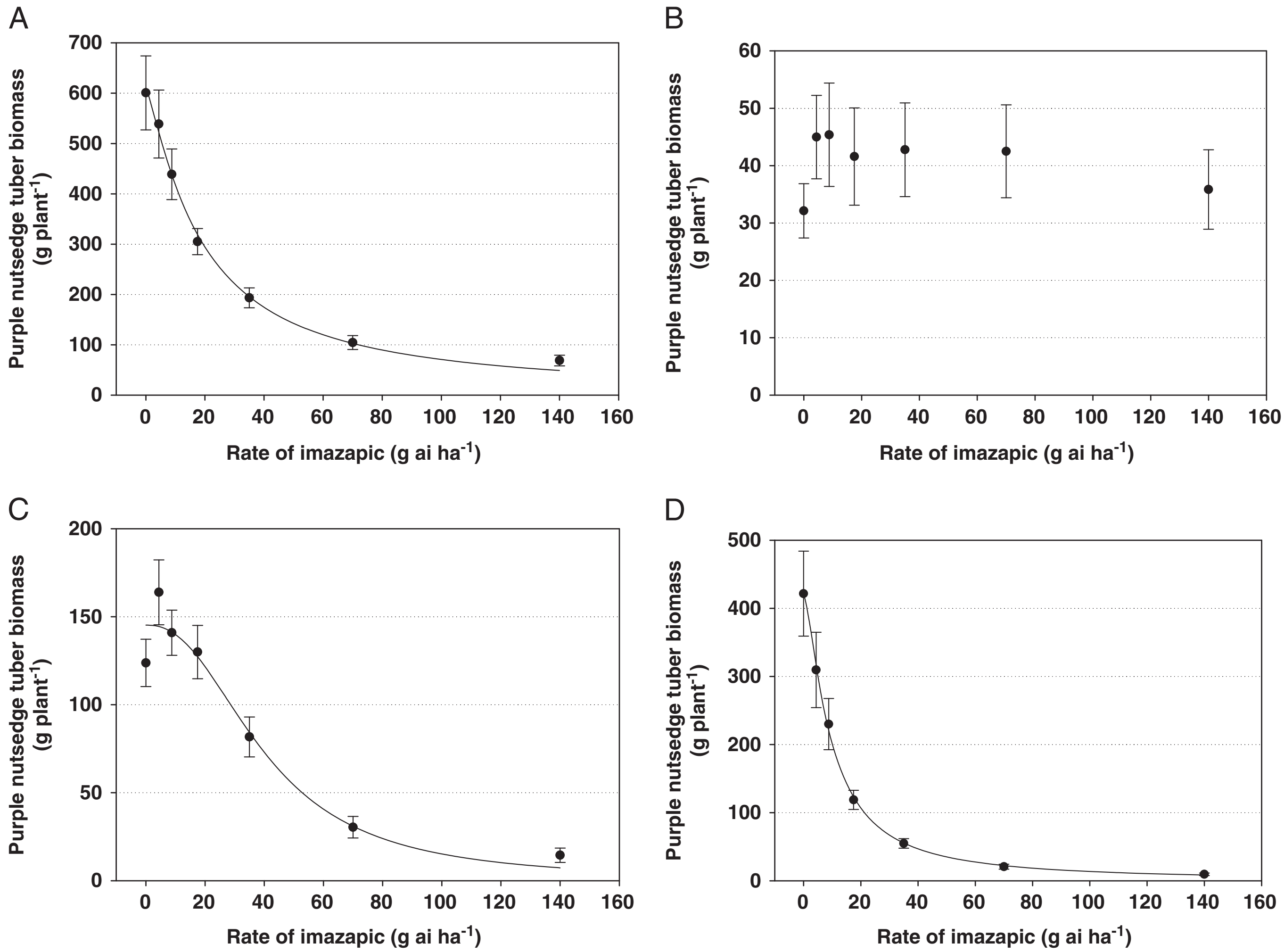

Figure 5. The log-logistic relationship between imazapic rate and total tuber biomass (A), biomass of tubers with aerial shoots at the time of imazapic application (B), biomass of tubers with aerial shoots that emerged following imazapic application (C), and biomass of tubers without aerial shoots (D). Each treatment mean is combined over replications and years, with the vertical lines around each treatment mean representing the standard errors. The parameters of the regression equation are in Table 2.

effect of imazapic on the number of viable tubers (Webster and Grey 2014). Assessment of the maximum total tuber sprouting (parameter *d*) ranged from 85 to 92% across the tuber classes (Table 2). For each tuber class, sprouting ability was regressed on rates of imazapic and fit to log-logistic regression models ($R^2_{nonlinear} = 0.39$ to 0.65, $P < 0.0001$; Figure 6A–D). Purple nutsedge forms chains of tubers, and translocation of imazapic from the foliage to roots and tubers likely occurred. Translocation has been reported for imazapic in johnsongrass [*Sorghum halepense* (L.) Pers.] and sicklepod (Newsom et al. 1993). The I_{50} for viability ranged from 50 to 75 g ha^{-1} imazapic, with only shoots emerged at the time of application ($I_{50} = 0.50$) having lower values ($P = 0.046$) than tubers attached to late-emerging shoots ($I_{50} = 75$ g ha^{-1}); for all other comparisons, there were no detectable differences ($P > 0.1292$). This occurred due to the sensitivity of purple nutsedge to imazapic. While imazapic reduced purple nutsedge tuber viability, the effect was not as strong as previously observed with halosulfuron. With imazapic, the $1\times$:I_{50} ratio for viability among the tuber classes ranged from 0.93 to 1.40, while this ratio with halosulfuron at the vegetable use rate (52 g ha^{-1}) ranged from 2.4 for tubers attached to late-emerging shoots to 6.5 for tubers attached to shoots emerged at the time of application (Webster and Grey 2014).

One of the challenges of purple nutsedge management is the extensive subterranean component of the plant; the visible foliar shoots represent only part of the overall plant biomass. There was a positive linear correlation ($r = 0.86$) between the biomass of all tubers and biomass of emerged shoots; for every 1 g of emerged shoots there were 4.5 g of tuber biomass in the soil (Figure 7), similar to what

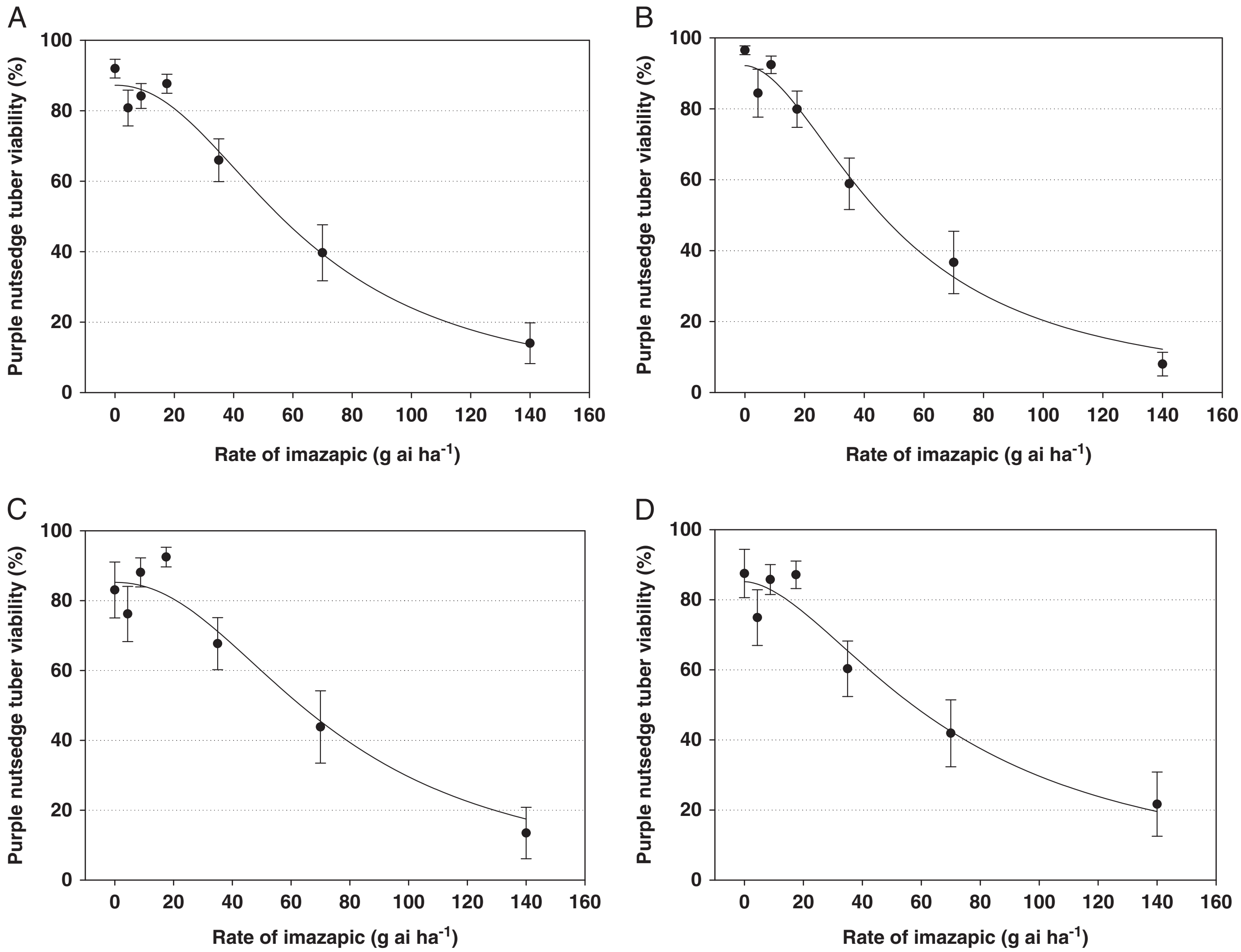

Figure 6. The log-logistic relationship between imazapic rate and viability of all tubers (A), viability of marked tubers (B), viability of tubers with aerial shoots that emerged following imazapic application (C), and viability of tubers without aerial shoots (D). Each treatment mean is combined over replications and years, with the vertical lines around each treatment mean representing the standard errors. The parameters of the regression equation are in Table 2.

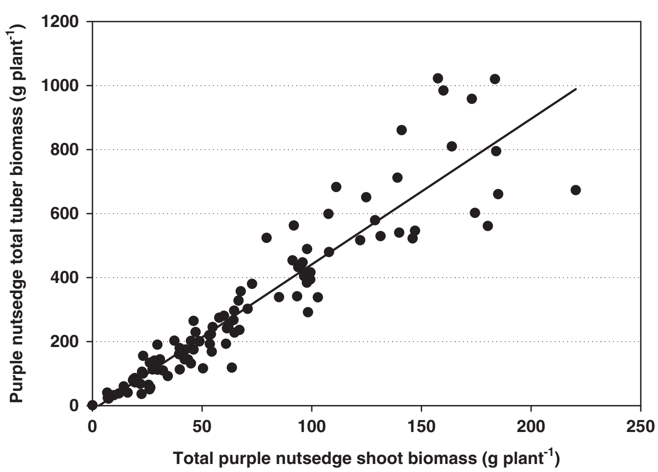

Figure 7. The correlation between the biomass of tubers and the biomass of emerged shoots for all treatments. $y = 4.5x - 13.5$, r = 0.86 ($P \leq 0.001$).

was previously reported (Webster and Grey 2014). In addition, total tuber biomass and total shoot biomass had similar ($P = 0.0429$) I_{50} values ($I_{50} = 19$ and 23 g ha^{-1} imazapic, respectively), a phenomenon that was previously observed with purple nutsedge shoot and tuber response to glyphosate and halosulfuron (Webster and Grey 2014; Webster et al. 2008). Therefore, the foliage of purple nutsedge will provide an accurate estimate of the level of subterranean population (4.5-fold difference), and the impact of the imazapic on foliage will similarly impact the tubers.

Conclusions. Imazapic has been shown to be an important component for reducing the long-term population density of purple nutsedge (Warren and

Coble 1999). We have shown that imazapic reduces growth of purple nutsedge foliage and tuber population density, biomass, and viability. In the nontreated control, there were 161 tubers that were attached to shoots that emerged following imazapic application, while the registered imazapic rate reduced shoot numbers 65%. Without a nontreated control, however, this new shoot emergence may have given the initial impression that the treatment was ineffective, as shoot numbers more than doubled following application of 70 g ha^{-1} imazapic. In addition, imazapic reduced the viability of these tubers to 36% at 70 g ha^{-1}, suggesting the action of the herbicide may have rendered the tubers nonviable after new shoots were produced. Tubers without an aerial shoot during the study were likely those in which shoot development was either suppressed by apical dominance based on their relative position in the tuber chain or were the most recent tubers to develop and lacked sufficient time to develop shoots. Of the three classes, the shootless tubers were the most prevalent in the nontreated control, with 358 tubers. Overall, 70 g ha^{-1} imazapic reduced purple nutsedge shootless tuber production by 89%, with only 42% viability of the tubers produced. Imazapic used in rotation with glyphosate (Webster et al. 2008) or halosulfuron (Webster and Grey 2014) will minimize tuber reproduction, an important component used to reduce the long-term population density of purple nutsedge and similar weeds that are difficult to manage.

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