Weed Control and Tigernut Response to Preemergence Herbicides Applied at Transplanting

Thierry E. Besançon¹, Baylee L. Carr¹, and Albert Ayeni¹

ADDITIONAL INDEX WORDS. *Amaranthus hybridus*, bensulide, *Cyperus esculentus* var. *sativus*, DCPA, *Digitaria sanguinalis*, *Galinsoga quadriradiata*, *Mollugo verticillata*, oxyfluorfen, pendimethalin, S-metolachlor

SUMMARY. Tigernut (*Cyperus esculentus* var. *sativus*) is a type of sedge that is quickly becoming popular as a superfood. As demand for tigernut continues to increase, more information is needed to develop weed management strategies for the crop to maximize tuber yield and quality. However, no herbicide is currently labeled for use with tigernut. Experimental trials were conducted in 2017 and 2018 to assess crop safety and control of economically important weeds with preemergence herbicides for transplanted 'NG3' and 'OG' tigernut. Oxyfluorfen applied alone or mixed with pendimethalin provided excellent control (>85%) of smooth pigweed (*Amaranthus hybridus*), carpetweed (*Mollugo verticillata*), and large crabgrass (*Digitaria sanguinalis*), and it did not cause any tigernut injury, stunting, or yield reduction compared with the weed-free control. However, none of the treatments controlled hairy galinsoga (*Galinsoga quadriradiata*) satisfactorily 2 months after herbicide application. Bensulide alone or associated with oxyfluorfen caused 14% to 25% stunting of tigernut. Bensulide alone only provided short-term control of broadleaf weeds. Increased weed competition and tigernut phytotoxicity associated with bensulide resulted in a 39% reduction in tuber yield compared with oxyfluorfen alone. Finally, S-metolachlor caused up to 78% stunting and a 68% reduction in vegetative tigernut biomass (on average) compared with the weed-free control. Tuber yield was reduced 55% to 97% after S-metolachlor was applied at transplanting. Oxyfluorfen would provide effective weed control up to 8 weeks after treatment in fields where hairy galinsoga is not a weed of concern and fulfill the requirement of a weed-free period without affecting tuber yield of quality.

Tigernut or chufa (*Cyperus esculentus* var. *sativus*) is the cultivated type of yellow nutsedge

(*C. esculentus*) popularly known as a weed in the United States. The plant is a rhizomatous and tuber-producing perennial warm-season sedge cultivated in West African countries, Spain, India, and Pakistan (Malashree et al., 2021). Tigernut is also cultivated to a limited extent in South American countries like Chile and Brazil, and in North American countries, including the United States (Sánchez-Zapata et al., 2012) and

Canada (Elford et al., 2020). In the United States, limited cultivation occurs in Louisiana, Missouri, New Mexico, and Florida, where it is mainly used for feeding turkeys [*Meleagris* sp. (Sánchez-Zapata et al., 2012)].

The origin of tigernut is not clear, but historical records have shown that it was an important food in ancient Egypt, and the dry tubers were found in Egyptian tombs from predynastic times ≈6000 years ago (Defelice, 2002). The tigernut tuber is commercially called a "nut"; that part is eaten raw as snack food or processed into various culinary forms, such as the milk drink known as "horchata de chufa" in Spain (Maduka and Ire, 2018; Martín-Esparza and González-Martínez, 2016; Ogbonna et al., 2013), flour for bakeries and candies (Oladele and Aina, 2007), oil extracted for cooking, and other industrial applications (Adel et al., 2015; Linsen et al., 1988; Oyedele et al., 2015). More recently, innovative technologies have allowed the use of tigernut tubers processed as a spread similar to butter (Bernard et al., 2015) or into tortilla chips (Stevens, 2021). The major nutritional benefits of tigernut are its high energy value (43% carbohydrates), lack of gluten and other allergens, high resistant starch content, healthful fat profile (73% monounsaturated, 18% saturated, and 9% polyunsaturated fatty acids), and high levels of oleic acid, phosphorus, potassium, vitamin C, and vitamin E (Sánchez-Zapata et al., 2012).

Tigernut was a popular food in the tropics in the 1950s and 1960s, but it declined in popularity thereafter. Recently, it has gradually returned to the human diet in different parts of the world and has assumed an increasingly significant role in several cultures as a versatile super food (Malashree et al., 2021). The global tigernut market value was \$153 million in 2020,

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¹Department of Plant Biology, School of Environmental and Biological Sciences, Rutgers, The State University of New Jersey, 59 Dudley Road, New Brunswick, NJ 08901-8525

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T.E.B. is the corresponding author. E-mail: thierry.besancon@rutgers.edu.

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Units

To convert U.S. to SI,
multiply by

U.S. unit

SI unit

To convert SI to U.S.,
multiply by

0.3048

ft

m

3.2808

0.0929

ft²

m²

10.7639

9.3540

gal/acre

L·ha⁻¹

0.1069

2.54

inch(es)

cm

0.3937

25.4

inch(es)

mm

0.0394

1.1209

lb/acre

kg·ha⁻¹

0.8922

28.3495

oz

g

0.0353

70.0532

oz/acre

g·ha⁻¹

0.0143

305.1517

oz/ft²

g·m⁻²

0.0033

6.8948

psi

kPa

0.1450

(°F - 32) ÷ 1.8

°F

°C

(°C × 1.8) + 32

and it is expected to reach \$319 million by 2030 (Transparency Market Research, 2021). Spain leads in the production of tigernut, with more than 1000 acres cultivated annually in the Valencia region. Other small-holder producers include Burkina Faso, Ghana, Mali, Niger, Nigeria, and Senegal, which are all in West Africa (Sánchez-Zapata et al., 2012).

In New Jersey, research conducted at Rutgers University has confirmed that tigernut production is feasible, especially under black plastic mulch, where the plant is exposed to limited weed interference and has access to adequate moisture under natural rain supplemented with irrigation (Satch, 2016). With medium-scale to large-scale production, plastic mulch adds significantly to the production cost for the farmer; therefore, it is essential to identify the herbicide options for weed control when the grower is unable to afford the additional cost for adopting the plastic mulch technology. As a new crop, little information regarding weed interference and management of tigernut in North America is available. Recent studies in Canada showed that a critical weed-free period of 3 weeks resulted in an 844% yield increase compared to the nonweeded control (Elford et al., 2020). However, the reported data pertaining to weed control with tigernut are limited. As demand for tigernut continues to increase in North America and globally, more information is needed to develop weed control packages for optimum weed management of the crop to maximize tuber yield and quality.

This research aimed to evaluate the influence of different preemergence (PRE) herbicides applied at transplanting of two tigernut cultivars on weed control, and to evaluate crop tolerance, yield, and tuber quality.

Materials and methods

Field trials were conducted at the Rutgers Horticultural Farm III in East Brunswick, NJ (lat. 40°27'N, long. 74°25'W), in 2017 and 2018. Because Rutgers Horticultural Farm III was closed for renovation, the 2019 trial was moved to the Rutgers Clifford E. and Melda C. Snyder Research and Extension Farm in Pittstown, NJ (lat. 40°33'N, long. 74°57'W). Based on the soil survey conducted by the U.S.

Department of Agriculture (USDA), Natural Resources Conservation Service (NRCS), the soil type at the East Brunswick location was a Nixon Loam (fine-loamy, mixed, semiactive, mesic Typic Hapludults) with a pH of 6.7 and 3.1% organic matter, whereas the soil type at the Pittstown location was a Quakertown silt loam (fine-loamy, mixed, active, mesic Typic Hapludults) with a pH of 6.3 and 2.4% organic matter (USDA-NRCS, 2021).

'NG3' and 'OG' are the top two of several tigernut selections that have been evaluated by Rutgers University since 2008. Both cultivars are not commercially cultivated yet in the United States. 'NG3' is the code name used for tigernuts obtained from a Nigerian ethnic market in New Jersey, whereas 'OG' was purchased from Organic Gemini Company (Brooklyn, NY), which markets tigernut in the United States. The only visual difference observed between 'NG3' and 'OG' is the average tuber size, with 'NG3' being slightly bigger than 'OG' (Fig. 1). In commercial production, tigernut tubers are planted directly in the field rather than transplanted. During this study, transplants were used to ensure maximum stand establishment. The use of transplants has provided a higher yield than the use of tubers as propagules when both are planted at the same time (A. Ayeni, unpublished data). Tubers of both cultivars were planted in 10-oz plastic containers on 28 Apr. 2017, 30 Apr. 2018, and 24 Apr. 2019. Pots were subsequently maintained in a greenhouse at 75 to 85 °F, with emergence occurring 5 to 7 d after planting. When tigernut seedlings reached the three-leaf stage,

plants were moved to the field and transplanted on disked, raised, black plastic-mulched beds in 2-inch-deep planting holes located within the slit where herbicides were applied beforehand. Plants were spaced 12 inches apart along the row. Based on standard fertilization practices at the Rutgers research farms, fields were fertilized before planting to provide 70 lb/acre of nitrogen (N) in 2017 and 2018, and 60 lb/acre N in 2019. No insecticide or fungicide was applied during the cropping season. The experiment was irrigated with drip irrigation set to deliver 0.3 inches of water weekly.

This study was conducted as a two-factor factorial in a randomized complete block design with three replications. The individual plot size was 3 ft wide × 5 ft long. The main factors included tigernut cultivars and herbicide application. PRE herbicide treatments consisted of 1.43 lb/acre S-metolachlor (Dual Magnum; Syngenta Crop Protection, Greensboro, NC), 0.25 lb/acre oxyfluorfen (Goal-Tender; Corteva Agriscience, Indianapolis, IN) alone or tank-mixed with either 6 lb/acre bensulide (Prefar 4-E; Gowan, Yuma, AZ), 1 lb/acre pendimethalin (Prowl H2O; BASF, Research Triangle Park, NC), or 6 lb/acre dimethyl tetrachloroterephthalate (DCPA) (Dacthal Flowable; AMVAC, Los Angeles, CA). Bensulide at 6 lb/acre, pendimethalin at 1 lb/acre, a weedy control, and a weed-free control weekly hoed throughout the season were also included. Herbicides were applied immediately before transplanting on 22 June 2017, 15 June 2018, and 7 June 2019. Despite being known to cause injury to yellow

Fig. 1. 'NG3' (A) and 'OG' (B) tigernut tubers harvested from a sandy loam soil in 2017 in East Brunswick, NJ.

Fig. 2. Plot layout at tigernut transplanting and before preemergence herbicide application in 2019 in Pittstown, NJ.

nutsedge (Felix and Newberry, 2012; Meyers and Shankle, 2017), *S-metolachlor* was included to evaluate whether injury would still occur with transplanted tigernut plants. Other treatments were selected based on the lack of or poor control of yellow nutsedge (VanGessel, 2020). Before herbicide application, a 1-ft-wide $\times$ 5-ft-long slit was cut out of the black plastic mulch to expose the soil and allow direct contact of the PRE herbicides with the soil (Fig. 2). Herbicides were subsequently sprayed in water with a carbon dioxide (CO_2)-pressurized backpack sprayer equipped with flat-fan nozzles (XR8004VS; TeeJet Technologies, Wheaton, IL) calibrated to deliver 25 gal/acre at 20 psi. Incorporation of herbicides was achieved with rainfall that averaged 2.4 inches in 2017, 1.7 inches in 2018, and 1.6 inches in 2019 over the course of the 10 d that followed herbicide application.

Tigernut tolerance and weed control for the predominant weed species present at each site were assessed visually at 3, 5, and 8 weeks after treatment (WAT). No assessment of carpetweed control was conducted 3 WAT because carpetweed had not yet emerged. Crop injury was rated by scoring the crop canopy for leaf injury (necrosis and chlorosis) and general stunting compared with the untreated weed-free control on a scale of 0% (no injury or growth reduction) to 100% (plant death). Weed control was evaluated on a scale of 0% (no control) to 100% (death of all plants)

based on a composite estimation of weed density reduction, growth inhibition, and foliar injury compared with the weedy control (Frans et al., 1986). Weeds within each plot were counted and aboveground weed and tigernut biomass values were collected before harvest on 16 Oct. 2017, 19 Oct. 2018, and 7 Oct. 2019. Weeds were placed in paper bags, dried at 150 °F for 4 d, and weighed. Tigernut aboveground vegetation was collected on 20 Oct. 2017, 19 Oct. 2018, and 16 Oct. 2019, and dried as described. Tubers were harvested by collecting the soil from the center two plants and sifted through a 0.25-inch wire mesh screen to sort out the tubers during the week that followed the aboveground biomass collection. Yield data consisted of tuber density and total weight. The commercial quality of harvested tubers was visually evaluated by three panelists using a scale of 0 (not commercially acceptable) to 5 (optimal commercial quality) for tuber attractiveness and individual tuber size. Tuber size ranges from extra-small (equivalent to 0) to

extra-large (equivalent to 5) (Fig. 3). Optimal commercial quality refers to the medium to extra-large classifications based on currently available packaging for the U.S. market by Organic Gemini Company and other marketers, and it would include individual tuber size ratings ≥ 3 . Tuber sizes below the medium category are not commercially offered for the snacking market and are instead used as propagules or for flour or oil extraction. Because of the intense weed competition in Pittstown in 2019, the yield was low for all treatments and no visual difference in tuber commercial quality was noted between treatments. Therefore, commercial quality data are only presented for East Brunswick.

All statistical analyses were conducted using the generalized linear mixed model (GLIMMIX) procedure of SAS software (version 9.4; SAS Institute, Cary, NC). Each combination of site and year was considered as a site-year sampled from a population as proposed by Carmer et al. (1989). Site-years, herbicides, tigernut cultivar, and all interactions including these three factors were considered fixed effects, whereas replication (nested within site-year) was designated random in the model. Weedy and weed-free controls were excluded from the three-way analysis of variance (ANOVA) for weed control because values were 0% and 100%, respectively. Because of unequal variance, weed control and crop injury data were converted using the arcsine square root transformation before the ANOVA and back-transformed for presentation purposes (Grafen and Hails, 2002). When main effect interactions were not significant, data were pooled appropriately. Mean comparisons of the fixed effects were performed using Fisher's protected least significant difference test when F values were statistically significant ($P \leq 0.05$).

Fig. 3. 'NG3' tigernut tuber grades: extra-large (XL), large (L), medium-large (M/L), medium (M), small-medium (S/M), small (S), and extra-small (XS). The marketable tuber size ranges from M to XL.

Results and discussion

WEED CONTROL. The two-way interaction of herbicide treatment by site-year was not significant ($P > 0.05$) for weed control. Therefore, corresponding data were pooled across site-years. In the absence of a significant cultivar $\times$ herbicide treatment interaction, weed control ratings were pooled across tigernut cultivars. The weed species rated at the experimental sites were carpetweed (*Mollugo verticillata*) and large crabgrass (*Digitaria sanguinalis*) in East Brunswick in 2017 and 2018, and smooth pigweed (*Amaranthus hybridus*) and hairy galinsoga (*Galinsoga quadriradiata*) in East Brunswick in 2018 and Pittstown in 2019.

Oxyfluorfen provided excellent and lasting control of smooth pigweed that averaged 90% by 8 WAT (Table 1). None of the tank mix partners (bensulide, pendimethalin, DCPA) improved smooth pigweed control compared with oxyfluorfen alone. Previous studies reported that 0.38 lb/acre oxyfluorfen applied at cabbage (*Brassica oleracea* var. *capitata*) transplanting controlled redroot pigweed 90% by 8 WAT (Bhowmik and McGlew, 1986). *S*-metolachlor provided similar smooth pigweed control to oxyfluorfen early during the season, but its efficacy decreased over time, with only 65% control by 8 WAT. Meyers et al. (2010) reported at least 95% palmer amaranth (*Amaranthus palmeri*) control 2 WAT with *S*-metolachlor at 0.71 to 1.16 lb/acre applied at sweetpotato (*Ipomoea batatas*) transplanting, but it decreased to less than 75% by 9 WAT. Smooth

pigweed control with pendimethalin and bensulide was lower compared with that of other herbicide treatments at all rating dates and decreased from 75% by 3 WAT to 32% by 8 WAT (on average).

By 3 WAT, *S*-metolachlor provided greater control of hairy galinsoga (90%) compared with all other treatments except oxyfluorfen plus bensulide (Table 1). However, galinsoga control with bensulide and pendimethalin alone was lower (51% on average) than that when these two herbicides were tank-mixed with oxyfluorfen (79% on average). None of the treatments helped maintain subsequent control of hairy galinsoga, with a maximum of 51% control by 5 WAT with *S*-metolachlor and 20% control by 8 WAT with oxyfluorfen mixed with bensulide or pendimethalin. Previous studies reported more than 95% control of hairy galinsoga by 4 to 8 WAT with an oxyfluorfen rate ranging from 0.21 to 0.54 lb/acre (Hoyt et al., 1996; Reis et al., 2017; Scott et al., 1995). The lack of residual control observed during the present study may be linked to the very high hairy galinsoga density recorded in 2018 and 2019, with an average of 28 plants/ft² by the end of the tigernut growing season. Hairy galinsoga is a fast-growing weed that can produce up to 120,000 seeds/ft² very rapidly, often within 35 to 40 d of plant emergence (Damalas, 2008; Kumar et al., 2009). Therefore, we hypothesized that seeds from mature galinsoga plants growing in weedy neighboring rows or in row middles may have contaminated research plots during the

season and escaped residual control provided by herbicides applied at transplanting. In agreement with previous reports mentioning good control (Sweet, 1986; VanGessel, 2020), *S*-metolachlor efficiently limited the emergence of hairy galinsoga soon after application. The previously stated hypothesis regarding the lack of long-term residual control with oxyfluorfen could also explain the strong reduction of galinsoga control by *S*-metolachlor at 5 and 8 WAT.

All applications that included oxyfluorfen or pendimethalin provided at least 95% carpetweed control by 5 WAT compared with 76% and 15% for *S*-metolachlor and bensulide, respectively (Table 1). By 8 WAT, pendimethalin alone provided 78% control of carpetweed, whereas bensulide and *S*-metolachlor only controlled it 4% and 40%, respectively. A previous study performed in New Jersey similarly reported less than 50% carpetweed control with bensulide at 4 lb/acre (Besançon et al., 2020) and fluctuating control between 23% and 99% by 8 WAT with *S*-metolachlor at 0.4 to 0.6 lb/acre (Norsworthy and Smith, 2005). Oxyfluorfen alone or associated with bensulide, pendimethalin, or DCPA provided 85% to 99% control by 8 WAT. These results are in agreement with those of a previous report of good carpetweed control with oxyfluorfen at 0.37 to 1 lb/acre (Porter, 1991).

Regardless of the PRE herbicide applied before transplanting, large crabgrass was controlled at least 95% by 5 WAT (data not shown). Control remained high by 8 WAT, but

Table 1. Smooth pigweed (AMACH), hairy galinsoga (GASCI), and carpetweed (MOLVE) visual control at 3, 5, and 8 weeks after treatment (WAT) after preemergence herbicides applied before tigernut transplanting in East Brunswick, NJ, in 2017 and 2018, and in Pittstown, NJ, in 2019.

Herbicide	Rate (lb/acre ^z)	Control (%)							
		AMACH			GASCI			MOLVE	
		3 WAT	5 WAT	8 WAT	3 WAT	5 WAT	8 WAT	5 WAT	8 WAT
<i>S</i> -metolachlor	1.43	98 a ^y	86 b	65 b	90 a	51 a	12 ab	76 b	40 d
Bensulide	6	79 b	44 c	37 c	50 c	8 d	0 c	15 c	4 e
Pendimethalin	1	71 c	47 c	27 c	52 c	19 cd	2 bc	95 a	78 c
Oxyfluorfen	0.25	100 a	97 a	90 a	72 b	25 bc	10 a-c	99 a	91 ab
Oxyfluorfen + bensulide	0.25 + 6	99 a	96 a	89 a	80 ab	45 a	20 a	95 a	85 bc
Oxyfluorfen + pendimethalin	0.25 + 1	100 a	95 a	89 a	78 b	43 a	20 a	98 a	93 ab
Oxyfluorfen + DCPA ^x	0.25 + 6	100 a	95 a	92 a	76 b	37 ab	13 a	98 a	99 a

^z1 lb/acre = 1.1209 kg-ha⁻¹.

^yWithin columns, values followed by the same letters are not significantly different at $P \leq 0.05$ using Fisher's protected least significant difference test for multiple means comparisons.

^xDimethyl tetrachloroterephthalate.

without significant differences between treatments, with a minimum of 86% for bensulide and up to 99% with *S*-metolachlor. During a previous study, bensulide at 2 lb/acre, *S*-metolachlor at 0.4 to 0.6 lb/acre, and pendimethalin at 0.38 to 0.77 lb/acre reportedly provided 83% to 100% control of large crabgrass by 8 WAT (Norsworthy and Smith, 2005). Similarly, oxyfluorfen alone at 0.25 to 0.5 lb/acre was shown to control large crabgrass, barnyardgrass (*Echinochloa crus-galli*), and yellow foxtail (*Setaria pumila*) 68% to 98% (Marion et al., 1985).

WEED BIOMASS. The two-way interaction of herbicide treatment $\times$ site-year was significant ($P < 0.0001$) for hairy galinsoga and total weed dry biomass, but not for large crabgrass and smooth pigweed. Further analysis of the interaction indicated that biomass data from East Brunswick in 2017 and 2018 could be pooled because of the lack of significant herbicide treatment $\times$ site-year interaction ($P > 0.05$) for these two site-years.

In East Brunswick, all PRE herbicides applied at transplanting reduced overall weed dry biomass between 53% and 88% (Table 2). Within herbicide treatments, the overall weed biomass was reduced 58% to 75% after oxyfluorfen plus DCPA compared with pendimethalin, *S*-metolachlor, or bensulide alone. In Pittstown, weed biomass was 12-times greater for the untreated control than the average recorded in East Brunswick. Despite greater weed infestation and growth in Pittstown, PRE herbicides applied at transplanting still contributed to reducing the total weed

biomass 40% to 75%. Weed biomass for any of the treatments that included oxyfluorfen was reduced 40% to 58% compared with the least effective herbicide, bensulide.

Hairy galinsoga is a challenging species in many specialty crops because of the limited number of herbicides that will effectively control it (VanGessel, 2020). Hairy galinsoga biomass data confirmed the lack of effectiveness of PRE herbicides previously noted by visual ratings. The hairy galinsoga biomass was similar to that of the untreated control for all herbicide treatments, except for oxyfluorfen plus bensulide in 2019 in Pittstown; the biomass decreased by 54% (on average) compared with that of other herbicide treatments. This may have resulted from slightly better control by 8 WAT, as shown by visual ratings, with 23% control for this treatment compared with less than 10% for other PRE herbicides (data not shown).

All herbicide treatments reduced smooth pigweed biomass 69% to 98% compared with the untreated control. However, oxyfluorfen alone or mixed with other PRE herbicides provided greater biomass reduction, with 97% (on average) biomass reduction compared with the untreated control and compared with bensulide or pendimethalin alone, with 69% and 74% biomass reduction, respectively.

With the exception of pendimethalin (61%), all PRE herbicides applied alone or mixed with oxyfluorfen reduced large crabgrass dry biomass by at least 92% compared with the untreated control (data not shown).

CROP INJURY. The two-way interaction of herbicide treatment $\times$ site-years was significant ($P < 0.0001$) for stunting at 5 and 8 WAT. Further analysis of the interaction indicated that stunting data from East Brunswick in 2018 and Pittstown in 2019 could be pooled because of the lack of significant herbicide treatment $\times$ site-year interaction ($P > 0.05$) for these two site-years. Therefore, stunting data at 5 and 8 WAT were separately analyzed for East Brunswick in 2017, and for the pooling of East Brunswick in 2018 and Pittstown in 2019.

Tigernut necrosis at 3 and 5 WAT was only noted with *S*-metolachlor and did not exceed 3% (data not shown). Higher leaf chlorosis was observed at 3 WAT with *S*-metolachlor (4%) and bensulide alone (8%) or combined with oxyfluorfen (5%) compared with other treatments ($\leq 1\%$). However, by 5 WAT, chlorosis did not exceed 2% regardless of PRE application (data not shown). Higher necrosis ($\leq 4\%$) and chlorosis ($\leq 6\%$) injury were noted at 8 WAT for all herbicide treatments, but they were determined to be the result of damage caused by billbugs (*Sphenophorus* sp.) feeding on tigernut plants (data not shown).

Crop stunting was the most noticeable type of injury observed in response to PRE herbicide application at transplanting (Table 3). *S*-metolachlor caused more stunting (50%) than any other treatments at 3 WAT. *S*-metolachlor was still the most injurious herbicide at 5 WAT at all site-years, causing an average of 70% stunting in

Table 2. Total weed, hairy galinsoga (GASCI), and smooth pigweed (AMACH) biomass at tigernut harvest in response to preemergence herbicides applied before tigernut transplanting in East Brunswick, NJ, in 2017 and 2018 (EB), and in Pittstown, NJ in 2019 (PI).

		Dry biomass (g·m ⁻²) ^z								
		Total				GASCI				
Herbicide	Rate (lb/acre) ^z	EB		PI		EB		PI		AMACH
Untreated		357	a ^y	4,370	a	29	747	a	651	a
S-metolachlor	1.43	168	b	2,176	bc	127	618	a	156	bc
Bensulide	6	118	b	2,633	b	90	719	a	201	b
Pendimethalin	1	100	b	2,190	bc	36	594	a	170	b
Oxyfluorfen	0.25	52	bc	1,528	cd	27	624	a	13	c
Oxyfluorfen + bensulide	0.25 + 6	60	bc	1,574	cd	134	340	b	12	c
Oxyfluorfen + pendimethalin	0.25 + 1	77	bc	1,094	d	78	628	a	30	c
Oxyfluorfen + DCPA ^x	0.25 + 6	42	c	1,534	cd	32	627	a	13	c

^z1 lb/acre = 1.1209 kg·ha⁻¹; 1 g·m⁻² = 0.0033 oz/ft².

^yWithin columns, values followed by the same letters are not significantly different at $P \leq 0.05$ using Fisher's protected least significant difference test for multiple means comparisons.

^xDimethyl tetrachloroterephthalate.

Table 3. Tigernut stunting pooled over cultivars at 3, 5, and 8 weeks after treatment (WAT) as affected by preemergence herbicides applied before transplanting in East Brunswick, NJ, in 2017 (EB17) and 2018 (EB18), and in Pittstown, NJ, in 2019 (PI).

Herbicide	Rate (lb/acre) ^z	Crop stunting (%)							
		3 WAT	5 WAT				8 WAT		
			EB17		EB18 + PI		EB17		EB18 + PI
Weedy	—	0 d ^y	0 d		0 d		0 d		3 c
Weed-free	—	0 d	1 d		0 d		0 d		0 d
S-metolachlor	1.43	50 a	23 a		70 a		13 ab		78 a
Bensulide	6	14 b	16 ab		13 b		21 a		24 b
Pendimethalin	1	2 c	3 cd		1 cd		4 bc		2 cd
Oxyfluorfen	0.25	3 c	0 d		1 cd		2 cd		0 d
Oxyfluorfen + bensulide	0.25 + 6	16 b	8 bc		19 b		20 a		5 c
Oxyfluorfen + pendimethalin	0.25 + 1	1 cd	1 d		1 d		1 cd		1 cd
Oxyfluorfen + DCPA ^x	0.25 + 6	2 c	0 d		3 c		2 cd		5 c

^z1 lb/acre = 1.1209 kg·ha⁻¹.

^yWithin columns, values followed by the same letters are not significantly different at $P \leq 0.05$ using Fisher's protected least significant difference test for multiple means comparisons.

^xDimethyl tetrachloroterephthalate.

East Brunswick in 2018 and in Pittstown in 2019, but only 23% at East Brunswick in 2017. Crop stunting persisted at 8 WAT in East Brunswick in 2018 and in Pittstown in 2019, with 78% injury (on average); however, it declined to 13% in East Brunswick in 2017. These results corroborate those of previous studies that reported excellent control of yellow nutsedge with PRE application of S-metolachlor. For example, Obrigawitch et al. (1980) noted 89% and 75% control of yellow nutsedge 6 and 16 WAT, respectively, with PRE metolachlor applied at 2 lb/acre. Meyers and Shankle (2017) reported 69% yellow nutsedge control (on average) at 15 weeks after transplanting of sweetpotato with PRE S-metolachlor applied at 0.7 or 1.2 lb/acre. However, our data also suggest that S-metolachlor is injurious to established yellow nutsedge naturally emerging from tubers or rhizomes, as described by previous research (Burke et al., 2008; Felix and Newberry, 2012; Loux et al., 2011; Meyers and Shankle, 2017), and will likely cause severe injury to tigernut grown from transplants.

Bensulide was the second most injurious herbicide, with 15% stunting (on average) by 3 WAT when applied alone or mixed with oxyfluorfen. Stunting associated with bensulide persisted at 5 and 8 WAT, ranging from 5% to 24% depending on the site-year, but its rate was lower than that of stunting caused by S-metolachlor in East Brunswick in 2018 and in Pittstown in 2019. Bensulide is not considered as an effective herbicide

for controlling yellow nutsedge (Van Gessel, 2020; Wells and Talbert, 1998). However, Anderson and Dunford (1970) showed that soil-incorporated bensulide at 6 lb/acre caused at least 50% inhibition of root growth of purple nutsedge (*Cyperus rotundus*) up to 33 d after herbicide application. If the number of emerging shoots was unaffected by bensulide application, then they noted that shoot growth was markedly suppressed with bensulide applied at 4 to 8 lb/acre. Therefore, it is possible that bensulide may have similar inhibitory effects on the growth of tigernut roots and rhizomes, which could explain higher crop stunting by 3 and 5 WAT for all bensulide treatments compared with the untreated control.

Pendimethalin alone or mixed with oxyfluorfen, as well as oxyfluorfen alone or mixed with DCPA, resulted in minor stunting by 3 WAT, with $\leq 5\%$ injury observed at any rating time. A similar lack of efficacy of pendimethalin or oxyfluorfen at suppressing yellow nutsedge or purple nutsedge has been reported previous (Akin and Shaw, 2001; Boyd, 2015; Setyowati et al., 1995).

CROP YIELD. The two-way interaction of herbicide treatment $\times$ site-year was significant ($P < 0.02$) for tigernut shoot dry biomass and tuber weight. Further analysis of the interaction indicated that biomass data from East Brunswick in 2017 and 2018 could be pooled because of the lack of significant herbicide treatment $\times$ site-year interaction ($P > 0.05$) for these 2

site-years. Therefore, shoot biomass and tuber weight data were analyzed separately for East Brunswick and Pittstown. Shoot biomass was similar for both tigernut cultivars in New Brunswick and Pittstown (Table 4). However, 'NG3' consistently yielded 12% less and had 15% lower tuber density than 'OG', signaling that 'OG' might be better adapted to New Jersey cropping conditions than 'NG3'.

In East Brunswick, only tigernut plants in plots sprayed with oxyfluorfen tank-mixed with pendimethalin produced a greater amount of shoot biomass than the weedy control. Shoot biomass was reduced 19% (on average) with bensulide and pendimethalin alone compared with the weed-free control, whereas S-metolachlor decreased shoot biomass by 42% and 32% compared with the weed-free and weedy controls, respectively. In Pittstown, higher weed competition caused an 86% decrease of tigernut shoot biomass in the weedy compared with the weed-free control, whereas the reduction was only 15% in East Brunswick. The conjugated effect of weed competition and increased crop injury resulted in 99% shoot biomass decline with S-metolachlor in Pittstown. At this location, only oxyfluorfen alone or combined with pendimethalin resulted in higher shoot biomass (+280%) than the weedy control, but it was still 47% lower than that of the weed-free control.

Weed competition caused tuber yield and density to decrease by 34% and 49%, respectively. Oxyfluorfen alone or mixed with pendimethalin

Table 4. Tigernut shoot dry biomass, tuber yield, and tuber density at harvest as affected by preemergence herbicides applied before transplanting and cultivar in East Brunswick, NJ, in 2017 and 2018 (EB), and in Pittstown, NJ, in 2019 (PI).

Treatment	Rate (lb/acre) ^z	Shoot biomass (g·m ⁻²) ^z				Tuber yield (g·m ⁻²)		Tuber density (no./m ²) ^z	
		EB		PI					
Herbicide									
Weedy	—	202	b ^y	22	d-f	202	cd	138	cd
Weed-free	—	237	a	157	a	305	a	270	a
S-metolachlor	1.43	138	c	2	f	110	e	70	e
Bensulide	6	194	b	13	ef	159	de	108	de
Pendimethalin	1	190	b	57	cd	220	c	190	b
Oxyfluorfen	0.25	209	ab	85	b	289	a	262	a
Oxyfluorfen + bensulide	0.25 + 6	210	ab	50	d	192	cd	133	cd
Oxyfluorfen + pendimethalin	0.25 + 1	223	a	82	bc	282	ab	249	a
Oxyfluorfen + DCPA ^x	0.25 + 6	216	ab	42	de	226	bc	172	bc
Tigernut cultivar									
OG		208		56		229	a	191	a
NG3		195		56		202	b	163	b

^z1 lb/acre = 1.1209 kg·ha⁻¹; 1 g·m⁻² = 0.0033 oz/ft²; 1 tuber/m² = 0.0929 tuber/ft².

^yWithin columns, values followed by the same letters are not significantly different at the $P \leq 0.05$ level using Fisher's protected least significant difference test for multiple means comparisons.

^xDimethyl tetrachloroterephthalate.

were the most productive of all herbicide treatments, with no significant reduction of tuber yield or density in comparison with the weed-free control. Tuber yield and density were similar for the bensulide alone or mixed with oxyfluorfen, pendimethalin alone, and oxyfluorfen mixed with DCPA treatments and the weedy control. However, these treatments reduced tuber yield 26% to 48% and reduced tuber density 30% to 60% compared with the weed-free control, either because of the lack of long-term residual control with PRE application of these herbicides or because of higher injury, as previously shown for bensulide. Reduced shoot biomass with S-metolachlor corresponded to a 46% tuber yield and 49% tuber density reduction compared with the weedy control. These results are similar to those reported by Felix and Newberry (2012), who observed a 56% to 75% decrease of tuber density of yellow nutsedge with S-metolachlor applied preplant incorporated at 1.4 lb/acre and followed by postemergence applications of halosulfuron plus dicamba at 0.5 plus 2.2 oz/acre or 1 plus 4.4 oz/acre.

A visual assessment of harvested tubers in East Brunswick indicated an effect of herbicide treatments on commercial quality (Table 5). A lower tuber quality rating was associated with S-metolachlor (Fig. 4A) and bensulide alone (Fig. 4B) compared with the weed-free control (Fig. 4C). Tubers collected in plots that received

these two treatments showed excessive surface wrinkling and incomplete filling, causing a greater heterogeneity of tuber caliber than observed in the weedy and weed-free controls. None of the tubers harvested in plots sprayed with these two treatments were considered commercially acceptable. The negative effect of bensulide on tuber quality was also noted when this herbicide was tank-mixed with oxyfluorfen with more heterogeneous tuber caliber and more pronounced wrinkling (Fig. 4D) than for the weed-free control. Visual ratings of tuber quality and size for oxyfluorfen alone (Fig. 4E) or mixed with pendimethalin were similar to those of the weed-free control.

Tubers collected in plots sprayed with oxyfluorfen plus DCPA tended to have lower quality and smaller size than those from the weed-free plots and were similar to tubers collected from the weedy control (Fig. 4F).

In conclusion, our findings demonstrate the tolerance of 'NG3' and 'OG' tigernuts to oxyfluorfen at 0.25 lb/acre applied at transplanting alone or mixed with pendimethalin at 1 lb/acre to improve residual control of grass weeds. Excellent control of smooth pigweed, carpetweed, and large crabgrass was noted with these treatments, whereas hairy galinsoga remains a very challenging weed that none of the treatments evaluated in this study was

Table 5. Visual rating pooled over tigernut cultivars of tuber quality and individual size at harvest in response to preemergence herbicides applied before transplanting in 2017 and 2018 in East Brunswick, NJ.

Treatment	Rate (lb/acre) ^z	Visual rating ^y			
		Quality		Size	
Weedy	—	3.5	ab ^x	3.1	bc
Weed-free	—	3.9	a	3.2	a-c
S-metolachlor	1.43	1.8	d	1.9	d
Bensulide	6	2.5	cd	2.5	bc
Pendimethalin	1	3.4	ab	3.1	a-c
Oxyfluorfen	0.25	4.0	a	3.7	ab
Oxyfluorfen + bensulide	0.25 + 6	2.9	bc	2.9	bc
Oxyfluorfen + pendimethalin	0.25 + 1	4.1	a	4.0	a
Oxyfluorfen + DCPA ^w	0.25 + 6	3.3	a-c	3.1	bc

^z1 lb/acre = 1.1209 kg·ha⁻¹.

^yVisual evaluation is based on a rating scale of 0 (not commercially acceptable) to 5 (optimal commercial quality).

^xWithin columns, values followed by the same letters are not significantly different at $P \leq 0.05$ using Fisher's protected least significant difference test for multiple means comparisons.

^wDimethyl tetrachloroterephthalate.

Fig. 4. 'NG3' tigernut tubers harvested in 2018 in East Brunswick, NJ, from individual plots treated at transplanting with 1.43 lb/acre *S*-metolachlor (A), 6 lb/acre bensulide alone (B), or tank-mixed with 0.25 lb/acre oxyfluorfen (D), and with 0.25 lb/acre oxyfluorfen (E). Untreated weed-free (C) and weedy (E) controls are also included for comparison. 1 lb/acre = 1.1209 kg·ha⁻¹.

able to suppress. In the absence of crop injury caused by herbicides, oxyfluorfen alone or tank-mixed with pendimethalin resulted in yields similarly to that of the weed-free control. Bensulide is usually considered as not effective at controlling yellow nutsedge (VanGessel, 2020). However, our results demonstrate that this herbicide used alone or mixed with oxyfluorfen increased crop stunting and reduced tuber yield and quality. Additionally, bensulide control of broadleaf weeds evaluated during this study was weak, which could result in intensified weed competition and further reduction of crop yield. Finally, *S*-metolachlor is not only actively suppresses the emergence of yellow nutsedge seedlings, as demonstrated by previous studies (Felix and Newberry, 2012; Meyers et al., 2010) but also actively prevents the growth and tuber production of transplanted plants, as shown by the high level of stunting injury and low yield during this study. It is also worth mentioning that no emergence of volunteer tigernut was noted during the season after the production year at any of the locations where the study was conducted. This is in agreement with a similar observation by Elford et al. (2020) in Ontario, and

it suggests that development of tigernut production in New Jersey would not lead to the establishment of volunteer weedy tigernut in subsequent crops. However, the most challenging weeds to control with plasticulture-grown tigernut would remain yellow nutsedge and purple nutsedge because the pointed shoot tip of both species allow them to penetrate the polyethylene barrier and directly compete with the crop. No herbicide would selectively control yellow nutsedge or purple nutsedge without severely damaging tigernut, as demonstrated by the use of *S*-metolachlor in this study. Previous research has shown that black plastic mulch can facilitate the propagation of purple nutsedge, with one tuber resulting in the emergence of 3440 shoots within 60 weeks under plastic mulch compared with 1860 shoots in the absence of mulch (Webster, 2005). Conversely, yellow nutsedge propagation tends to be suppressed under plastic mulch, with three-times fewer shoots emerging under plastic mulch 24 weeks after planting than the nonmulched control. Regardless of nutsedge species, effective suppression or selection of fields free of nutsedge infestation before cropping would remain crucial for the

development of tigernut production in the absence of control methods discriminating between wild nutsedge and cultivated tigernut.

Based on the results of these studies, oxyfluorfen alone or mixed with pendimethalin applied at transplanting shows promise as an effective residual herbicide treatment for weed control and good quality tuber yield comparable to the yield in weed free plots. Elford et al. (2020) reported a 2- to 3-week weed-free period for preventing tigernut yield loss. Results of this study show that oxyfluorfen applied PRE would provide effective weed control up to 8 weeks after treatment in fields where hairy galinsoga is not a weed of concern and fulfills the requirement of a weed-free period.

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