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Weed Control and Radish (*Raphanus sativus*) Response to *S*-metolachlor on Organic Soils

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***Abstract*. Field experiments were conducted to determine weed control and radish (*Raphanus sativus*) response to *S*-metolachlor on organic soil in the Everglades Agricultural Area (EAA) using a dose–response bioassay. *S*-metolachlor was applied preemergence at 0.35, 0.7, 1.4, 2.8, 5.6, and 11.2 kg·ha^{-1}. The rate of *S*-metolachlor required to provide 90% weed control (ED$_{90}$) and result in 5% and 10% radish injury were determined by fitting a three-parameter log-logistic model. The ED$_{90}$ values for common lambsquarters, spiny amaranth, and fall panicum control were 2.7, 1.6, and 1.2 kg·ha^{-1} of *S*-metolachlor, respectively, at 14 days after treatment (DAT). At 28 DAT, the ED$_{90}$ values were 3.8, 1.9, and 1.5 kg·ha^{-1} of *S*-metolachlor, respectively. Injury on radish increased as *S*-metolachlor rates increased with maximum injury of 24% and 19% at 14 and 28 DAT, respectively. *S*-metolachlor at 2.1 and 3.1 kg·ha^{-1} at 14 DAT and 2.6 and 3.7 kg·ha^{-1} at 28 DAT would result in 5% and 10% radish injury, respectively. Radish yield decreased with increasing rates of *S*-metolachlor. At the proposed *S*-metolachlor use rate of 1.4 kg·ha^{-1} for root crops, radish yield was 80% of the weed-free yield probably resulting from competition from common lambsquarters, which was controlled 74%. These results show that preemergence *S*-metolachlor would provide effective control of spiny amaranth and fall panicum in radish on organic soils of the EAA at the proposed use rate for root crops while about three times the proposed use rate would be required to provide effective common lambsquarters control. This implies that infestation of common lambsquarters on radish fields on organic soils will not be effectively controlled by *S*-metolachlor at the proposed use rate resulting in yield reduction.**

Radish, a member of the Brassicaceae family is an important cool-season crop grown in rotation with sugarcane (*Saccharum* spp. hybrids), leafy vegetables, and rice (*Oryza sativa* L.) in the EAA of south Florida. The EAA is dominated by organic soils (Histosols) that were formed under flooded conditions, which precluded decomposition of organic matter, allowing those materials to form organic soils with up to 85% or more organic matter (Snyder, 1994; Wright and Hanlon, 2009). About 3200 ha of radish valued at $3 million are planted annually in the EAA (Chris Miller, personal communication).

Radish has a relatively short growth period and is primarily planted in the EAA from October to April. 'Red silk' is the predominant variety of radish cultivated in the EAA because of its high adaptability to organic soils (Miller et al., 2014). This variety is an open pollinated, globe, red, medium top size with excellent flesh quality, and matures in 26 to 30 d (Miller et al., 2014). Weed competition can limit radish production despite its relative short growth period. For instance, Santos et al. (1998) reported complete radish crop failure as a result of season-long competition from 100 to 200 purple nutsedge (*Cyperus rotundus* L.) plants/m^2 over a 30-d growing season. In the organic soils of the EAA, negative effects of weed interference on radish are due to lack of registered effective preemergence or postemergence herbicides for broad-spectrum weed control. Many soil-applied preemergence herbicides are prone to adsorption and metabolism by soil microorganisms in these organic soils because of their high cation exchange capacity, large soil microbial populations, and relatively high soil moisture and temperature (Schueneman and Sanchez, 1994; Shea, 1989). Binding and degradation of soil-applied herbicides on these organic soils due to adsorption and metabolism combine to reduce their efficacy, resulting in poor weed control (Schueneman and Sanchez, 1994). Also, mechanical weed control by cultivation is not an option for radish grown on these organic soils because of concerns of disturbance of the crop's rooting system.

Radish is a Group 1B vegetable along with carrot (*Daucus carota* L.) and garden beet (*Beta vulgaris* L.) (Legal Information Institute, 2010). Recently, *S*-metolachlor was registered for preemergence weed control in root and tuber vegetable crops Group 1B under Special Local Needs 24 (c) registration through the Third Party Registrations, Inc., a subsidiary of the Florida Fruit and Vegetable Association (Florida Fruit & Vegetable Association, 2015). *S*-metolachlor is a preemergence chloroacetanilide herbicide for broadleaf weed and grass control thought to inhibit the very long-chain fatty acid synthesis (Böger et al., 2000; Shaner, 2014). This herbicide more readily adsorbs to organic matter and is primarily absorbed by emerging shoots of susceptible grasses just above the seed and in broadleaf weeds through the root and shoot (Shaner, 2014). *S*-metolachlor is an 88:12 mixture of the *S*- and *R*-isomers, respectively; however, it is the *S*-isomer that provides 95% of the herbicidal activity (Moser et al., 1982; Muller et al., 2001; O'Connell et al., 1998). Also, *S*-metolachlor is more active at the site of action in susceptible plants and allows for lower use rates than the racemic (50:50) mixture of *S*- and *R*-isomers of metolachlor (Shaner, 2014). The lower use rate of *S*-metolachlor compared with the racemic mixture of metolachlor on an active ingredient basis has provided growers with the opportunity to reduce herbicide load applied to the environment while still maintaining biological performance (O'Connell et al., 1998; Shaner, 2014). For example, *S*-metolachlor provided the same efficacy on major grass weeds and tolerance to different corn (*Zea mays* L.) varieties at 65% use rate of racemic metolachlor (O'Connell et al., 1998). Thus, radish growers in the EAA have an opportunity to use *S*-metolachlor at lower rates compared with the racemic metolachlor in the environmentally sensitive EAA for weed management. But, the residual activity of soil-applied *S*-metolachlor should be long enough on organic soils to prevent deleterious effects of weed interference for an extended period until radish achieves a competitive advantage. Currently, there is limited information on the efficacy and level of crop safety of *S*-metolachlor on radish grown on organic soils of the EAA. Therefore, this study was conducted to determine the efficacy of soil-applied preemergence *S*-metolachlor on weed control and radish tolerance on organic soils of the EAA using a dose–response bioassay.

Materials and Methods

Field studies were conducted at the Everglades Research and Education Center in Belle Glade, FL, between 2013 and 2015. The soil type was Dania Muck (Euic, hyperthermic, shallow Lithic Haplosaprists) with a pH of 7.3% and 78% organic matter. Fields were chisel plowed, followed by disking with a harrow before pressing into 0.9 m wide beds. Fertilizer 11–37–0 was applied at 561 kg·ha^{-1} at bedding. Two rows of 'Red silk' radish were directly seeded on each bed at a spacing of 0.3 m between rows and 2.5 cm between plants on 11 Dec. 2013, 14 Feb. 2014, and 22 Jan. 2015 at a seeding rate of 864,000 seeds/ha using a Stanhay planter (Stanhay 870, Stanhay Webb Ltd, Grantham, UK).

The experiment was arranged in a randomized complete block design with three replications in 2014 and four replications in 2013 and 2015. Treatments consisted of six rates of *S*-metolachlor (Dual II Magnum, Syngenta Crop Protection, LLC, Greensboro, NC) applied preemergence immediately after planting at 0.35, 0.7, 1.4, 2.8, 5.6, and

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11.2 kg·ha^{-1} (equivalent to the 0.25×, 0.5×, 1×, 2×, 4×, and 8× the recommended use rate for root and tuber crops). Untreated and weed-free controls were included for comparison. Plots were kept weed free by hand removal and hoeing at weekly intervals throughout the season. Experimental plots were 1.8 m (two beds) wide by 7.6 m long. The herbicide treatments were applied using a CO_2-pressurized sprayer calibrated to deliver 187 L·ha^{-1} of total volume at 276 kPa using Teejet® XR11002VS nozzle tips (Spraying Systems Co., Wheaton, IL). Experimental plots were overhead irrigated to supply 13 mm of water to incorporate the herbicide immediately following treatment application.

Visual estimation of radish injury and weed control were made using a scale of 0% to 100%, with 0% being no crop injury or weed control and 100% being crop death or complete weed control at 14 and 28 DAT. Prevalent weed species were common lambsquarters (*Chenopodium album* L.), spiny amaranth (*Amaranthus spinosus* L.), and fall panicum (*Panicum dichotomiflorum* Michx.) at densities of 161, 75, and 22 plants/m^2, respectively, averaged over 3 years. Radish was harvested by hand from both beds to determine root yield at 28 d after planting. The relative yield of radish was calculated as a percentage of weed-free yields.

Weed control, radish injury, and radish relative yield data were subjected to analysis of variance (ANOVA) using the lme function of the R program (R version 3.1.1; R Foundation for Statistical Computing, Vienna, Austria) to evaluate treatment main effects as well as interactions at $P \leq 0.05$. Data were combined across years when no significant year-by-treatment interaction occurred. Nonlinear regression analysis was then performed on weed control and radish injury data using the drc package (Ritz and Streibig, 2005) of the R program. A three-parameter log-logistic model (Eq. [1]) similar to that proposed by Seefeldt et al. (1995) was fitted to weed control data for each species and radish injury data, but with the lower limit constrained to 0:

$$Y = d/1 + \exp(b(\log(x) - \log(e))) \quad [1]$$

where Y is the response (% weed control or radish injury), x is the S-metolachlor rate in kg·ha^{-1}, b is the slope of the curve at the inflection point, d is the upper limit of the fitted curve, and e is the inflection point of the fitted curve. This model is biologically significant because no weed control or crop injury will be observed when no herbicide is applied. A lack-of-fit test at the 95% level comparing the regression model (Eq. [1]) to ANOVA was conducted to determine whether the regression model was an appropriate fit to the data (Ritz and Streibig, 2005). The fitted weed control model was used to estimate ED_{90} values (effective rate of S-metolachlor required to provide 90% weed control) for each weed species at 14 and 28 DAT. The relative differences of ED_{90} values at 14 and 28 DAT for each weed species were compared. The rates required to result in 5% and 10% injury were calculated from the fitted model for radish injury. The relationship between the relative

Table 1. Parameter estimates (SE in parenthesis) for the three-parameter log-logistic model (Eq. [1]) for weed control on organic soil in response to preemergence S-metolachlor application and the rate required to provide 90% control (ED_{90}).

Weed species	Timing (DAT)	Parameter estimates^z b	d	e	Lack-of-fit test^y (P value)	ED_{90} (kg·ha^{-1})
Common Lambsquarters	14	–1.16 (0.14)	101.76 (2.87)	0.47 (0.04)	0.5108	2.70 (0.65)
	28	–1.15 (0.13)	99.75 (3.00)	0.56 (0.04)	0.6428	3.82 (1.00)
Spiny amaranth	14	–1.96 (0.14)	98.97 (1.24)	0.50 (0.02)	0.5736	1.62 (0.15)
	28	–1.87 (0.14)	98.33 (1.36)	0.52 (0.02)	0.5830	1.82 (0.20)
Fall panicum	14	–2.41 (0.21)	99.98 (1.37)	0.47 (0.02)	0.9999	1.17 (0.10)
	28	–2.37 (0.23)	98.39 (1.68)	0.54 (0.02)	0.9977	1.46 (0.16)

DAT = days after treatment.

^{z}Parameters: b is the slope of the curve at the inflection point, d is the upper limit of the curve, and e is the inflection point of the fitted curve.

^{y}A lack-of-fit test at the 95% level comparing the log-logistic model to analysis of variance conducted to determine whether the model was an appropriate fit to data.

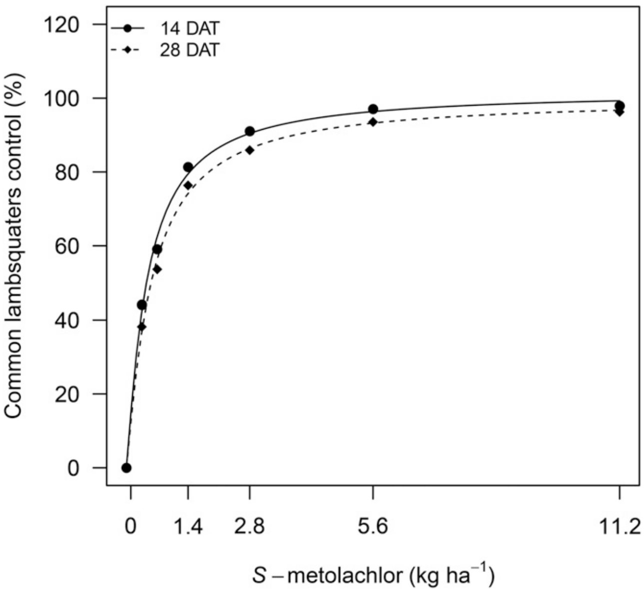

Fig. 1. Common lambsquarters control at 14 and 28 days after treatment (DAT) in response to S-metolachlor applied preemergence on organic soil. Parameter estimates and SE of the fitted curves, as described in Eq. [1], are provided in Table 1.

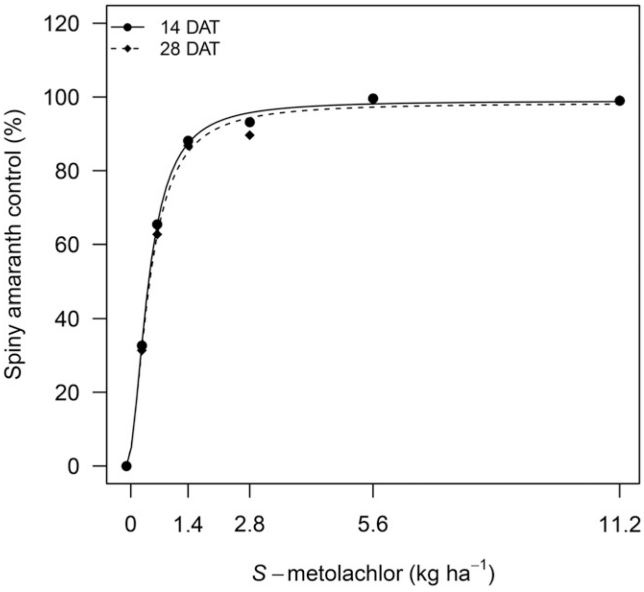

Fig. 2. Spiny amaranth control at 14 and 28 days after treatment (DAT) in response to S-metolachlor applied preemergence on organic soil. Parameter estimates and SE of the fitted curves, as described in Eq. [1], are provided in Table 1.

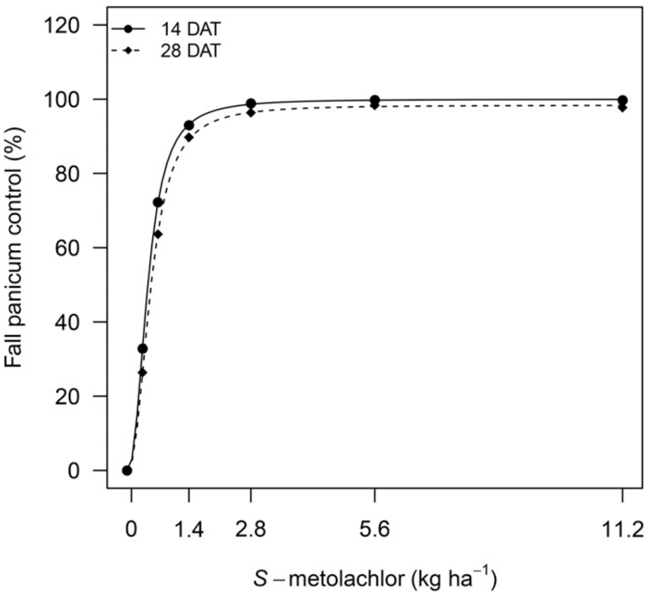

Fig. 3. Fall panicum control at 14 and 28 days after treatment (DAT) in response to *S*-metolachlor applied preemergence on organic soil. Parameter estimates and SE of the fitted curves, as described in Eq. [1], are provided in Table 1.

Table 2. Parameter estimates (SE in parenthesis) for the three-parameter log-logistic model (Eq. [1]) for radish injury on organic soil in response to preemergence *S*-metolachlor application and the rate required to result in 5% and 10% injury presented as I_5 and I_{10}, respectively.

Radish	Parameter estimates[z]			Lack-of-fit test[y]	I_5	I_{10}
injury (DAT)	*b*	*d*	*e*	(*P* value)	(kg·ha⁻¹)	
14	–2.48 (0.18)	24.13 (0.71)	3.58 (0.14)	0.6999	2.08 (0.07)	3.12 (0.11)
28	–3.29 (0.38)	18.62 (0.67)	3.32 (0.17)	0.9995	2.64 (0.11)	3.74 (0.19)

DAT = days after treatment.

[z] Parameters: *b* is the slope of the curve at the inflection point, *d* is the upper limit of the curve, and *e* is the inflection point of the fitted curve.

[y] A lack-of-fit test at the 95% level comparing the log-logistic model to analysis of variance conducted to determine whether the model was an appropriate fit to data.

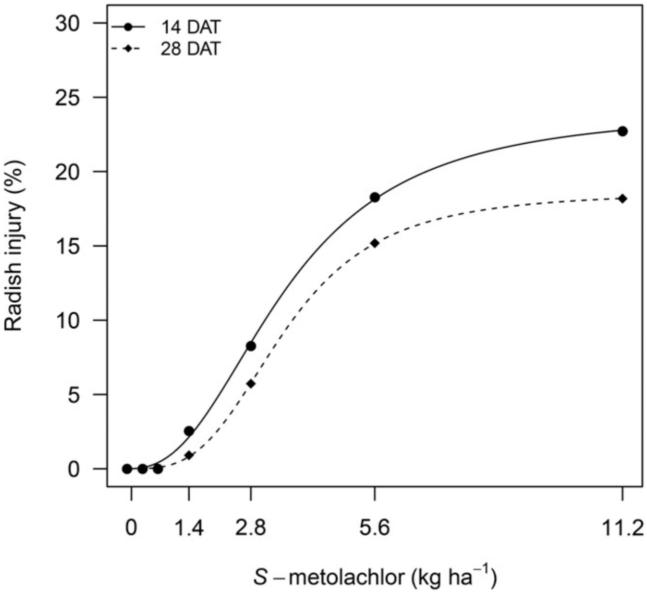

Fig. 4. Radish injury at 14 and 28 days after treatment (DAT) in response to *S*-metolachlor applied preemergence on organic soil. Parameter estimates and SE of the fitted curves, as described in Eq. [1], are provided in Table 2.

root yield of radish and *S*-metolachlor rate was determined using a linear model:

$$Y = a + bx \qquad [2]$$

where Y is the relative yield of radish (% of the weed-free yield), x is the *S*-metolachlor rate in kg·ha⁻¹, a is the intercept, and b is the slope of the fitted line. The linear model (Eq. [2]) was fitted using the lm function of the R program.

Results and Discussion

Weed control data at 14 and 28 DAT were analyzed separately for each weed species. There was no significant year-by-treatment interaction for control of each weed species at 14 and 28 DAT ($P > 0.05$); therefore, data were combined for analysis for each weed species over years. The lack-of-fit test was not significant for the fitted model (Eq. [1]) for control of all weed species at 14 and 28 DAT (Table 1; Figs. 1–3), indicating that the model was appropriate to describe the functional relationship between weed control and *S*-metolachlor rate (Nielsen et al., 2004; Ritz and Streibig, 2005). Estimates of model parameters for weed control are presented in Table 1.

The negative slope of the inflection point indicated that control of all weed species increased as *S*-metolachlor rate increased (Table 1; Figs. 1–3). The model predicted that *S*-metolachlor would provide a maximum of ≥98% control of all weed species by 28 DAT based on the rates used in this study. At 1.4 kg·ha⁻¹ of *S*-metolachlor, which is the rate proposed for use in root crops, common lambsquarters, spiny amaranth, and fall panicum were controlled 79%, 87%, and 93% at 14 DAT and 74%, 85%, and 89% at 28 DAT, respectively. The rate of *S*-metolachlor required to provide 90% control (ED_{90}) of common lambsquarters, spiny amaranth, and fall panicum was 2.7, 1.6, and 1.2 kg·ha⁻¹, respectively, at 14 DAT. At 28 DAT, the ED_{90} values were 3.8, 1.9, and 1.5 kg·ha⁻¹ of *S*-metolachlor, respectively. The relative difference of the ED_{90} values at 14 and 28 DAT for each weed species was not significant. Although there were no significant differences between ED_{90} values at 14 and 28 DAT, higher rates of *S*-metolachlor were required to provide season-long control of all weed species in radish. Based on these results, the proposed use rate of *S*-metolachlor for root crops will provide nearly 90% control of fall panicum and spiny amaranth in radish on organic soils of the EAA while about three times the use rate will be required to provide similar control of common lambsquarters at 28 DAT. Higher rates of *S*-metolachlor have been reported to improve common lambsquarters control in other crops on mineral soils with low organic matter content (Fennimore et al., 2001; Richardson et al., 2004). However, *S*-metolachlor at 1.07 kg·ha⁻¹ has been reported to provide complete control of *Amaranthus* species in soils with up to 3% organic matter (Peachey et al., 2012). A similar rate of *S*-metolachlor would provide an estimated 78% control of spiny amaranth in our study at

28 DAT. The lower level of spiny amaranth control in our study compared with control of similar *Amaranthus* species in the report by Peachey et al. (2012) could probably be attributed to the ability of the herbicide to readily adsorb to organic soils compared with soils with low organic matter (Shaner, 2014). Dusky (1986) reported that the racemic metolachlor at 1.68 and 3.36 kg·ha^{-1} provided an average of 75% and 86% control, respectively, of broadleaf weeds including common lambsquarters and spiny amaranth on radish on organic soil in the EAA at 28 DAT. We estimated from the fitted model (Eq. [1]) for broadleaf weeds (common lambsquarters and spiny amaranth) in the present study that *S*-metolachlor at 1.68 and 3.36 kg·ha^{-1} would provide an average of 83% and 92% control, respectively, of these species at 28 DAT, indicating that *S*-metolachlor would provide better weed control on the organic soils of the EAA compared with the racemic metolachlor.

Injury from *S*-metolachlor on radish resulted in stunting of the plants. Radish injury data at 14 and 28 DAT were analyzed separately. Radish injury data at 14 DAT were combined over years for analysis because of lack of significant year-by-treatment interaction ($P > 0.05$). Similarly, injury data at 28 DAT were combined for analysis because of lack of significant year-by-treatment interaction. The regression model (Eq. [1]) was appropriate to describe the functional relationship between radish injury and *S*-metolachlor rate because the lack-of-fit test was not significant for the fitted model at 14 and 28 DAT (Table 2; Fig. 4). Estimates of model parameters for radish injury are presented in Table 2. Injury on radish at 14 and 28 DAT increased as *S*-metolachlor rates increased based on negative slopes of the inflection point (Table 2; Fig. 4). The model predicted maximum radish injury of 24% and 19% at 14 and 28 DAT, respectively. The rate of *S*-metolachlor that would result in 5% and 10% radish injury was estimated to be 2.1 and 3.1 kg·ha^{-1}, respectively, at 14 DAT, and 2.6 and 3.7 kg·ha^{-1}, respectively, at 28 DAT. Application of *S*-metolachlor at the proposed use rate of 1.4 kg·ha^{-1} would result in an estimated 2% and 1% radish injury at 14 and 28 DAT, respectively, indicating an acceptable level of crop safety.

There was no treatment-by-year interaction for relative yield of radish; therefore, data were pooled over years for analysis. The linear relationship between relative yield of radish and *S*-metolachlor rate was significant ($P < 0.001$). The negative slope of the fitted linear model (Table 3) indicated that the relative yield of radish decreased as the rate of *S*-metolachlor increased (Fig. 5). Based on the fitted linear model, *S*-metolachlor at the proposed use rate of 1.4 kg·ha^{-1} would result in an estimated 80% relative yield of radish. The lower relative yield of radish (80% of the weed-free yield) at the proposed use rate was not attributed to *S*-metolachlor injury (<2%), but probably to competition from the high density of common lambsquarters (161 plants/m^2) as a result of reduced control (74%) at harvest. In addition, although the higher rates of *S*-metolachlor (>2.8 kg·ha^{-1}) resulted in acceptable control of all weed species, injury at these rates was high enough to result in significant radish yield reduction because the crop was probably not able to compensate for the initial growth reduction as a result of its short growth cycle.

These results show that preemergence *S*-metolachlor provided effective control of spiny amaranth and fall panicum in radish on organic soils of the EAA at the proposed use rate of 1.4 kg·ha^{-1} for root crops. However, about three times the proposed use rate would be required to provide effective common lambsquarters control on these organic soils. In addition, there was significant radish yield reduction at higher *S*-metolachlor rates required to provide effective control of common lambsquarters. This implies that heavy infestation of common lambsquarters on radish fields on organic soils of the EAA will not be adequately controlled by *S*-metolachlor at the proposed use rate resulting in yield reduction.

Table 3. Parameter estimates and SE for the linear model (Eq. [2]) describing the relative yield of radish on organic soil in response to preemergence *S*-metolachlor application.[z]

Parameter[y]	Parameter estimate	SE	*t* value	Pr (>|t|)
a	86.29	3.12	27.70	<0.0001
b	–4.71	0.62	–7.65	<0.0001

[z] $R^2 = 0.54$ for the fitted regression line.

[y] Parameters: *a* is the intercept and *b* is the slope of the fitted line.

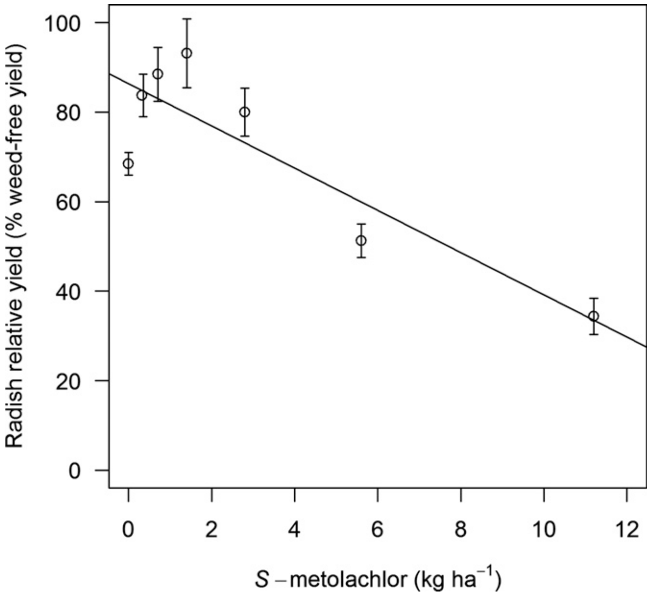

Fig. 5. Radish relative yield (% weed-free yield) in response to *S*-metolachlor applied preemergence on organic soil. Parameter estimates and SE of the fitted line, as described in Eq. [2], are provided in Table 3. Error bars represent SE of the mean.

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