Original article

Evaluation of the selectivity of pre-emergence herbicides and their influence on the physiological and agronomic parameters of sweet potato

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Summary

Weed control is one of the greatest problems encountered in the culture of sweet potato because the prostrate growth habit of the plant renders manual weeding arduous and expensive, thus necessitating the use of herbicides. Considering the importance of the tuberous roots of sweet potato as an alternative feedstock for the fuel ethanol industry and the lack of selective herbicides recommended for use with the culture, we aimed to evaluate the effect of different pre-emergence herbicides and their combinations on the physiological and agronomic characteristics of the high ethanol-yielding cultivar Duda. Effects of treatment with herbicides *S*-metolachlor (960 g a.i. ha⁻¹), clomazone (500 g a.i. ha⁻¹), *S*-metolachlor/clomazone mixture (960 and 500 g a.i. ha⁻¹, respectively) and atrazine/*S*-metolachlor mixture (370 and 290 g a.i. ha⁻¹, respectively) were assessed at 14, 21 and 28 days after treatment/planting in pots and at 180 days after treatment/planting in the field. The atrazine/*S*-metolachlor mixture reduced fluorescence quantum yield and chlorophyll content in leaves of sweet potato at the early stages of development, but the plants recovered rapidly thereafter. All herbicides, except for the atrazine/*S*-metolachlor mixture, reduced leaf, root and total dry mass in the first 28 days after treatment/planting in pots, but none of the treatments reduced vine and tuberous root productivity, tuberous root dry mass, starch content and ethanol yield in plants grown in the field. It is concluded that the tested herbicides are selective and could be applied to sweet potato crops without loss of productivity.

Keywords

atrazine, biofuel, clomazone, ethanol, *Ipomoea batatas*, *S*-metolachlor, root productivity, weed control

Significance of this study

What is already known on this subject?

- Weed control in sweet potato cultures is difficult because the prostrate growth habit of the plant renders manual weeding difficult and there is a lack of specific pre-emergence herbicides recommended for use with the culture.

What are the new findings?

- Application of pre-emergence herbicides *S*-metolachlor, clomazone, *S*-metolachlor/clomazone mixture and atrazine/*S*-metolachlor mixture did not reduce vine and tuberous root biomass, productivity, starch content or ethanol yield of field-grown sweet potato cultivar Duda, indicating that these agents are selective and could be applied in a weed management program.

What is the expected impact on horticulture?

- Since roots of sweet potato represent an important potential feedstock for the ethanol industry, knowledge of the activity of these pre-emergence herbicides will maximize their impact in a sustainable weed control program. Moreover, application of a herbicide mixture will not only increase the spectrum of targeted weeds but also facilitate resistance management.

In addition, the roots have considerable potential for the production of fuel ethanol since high yields (more than 40 t ha⁻¹) can be obtained using appropriate cultivars and modern technology (Silveira et al., 2014).

However, one of the major problems encountered in the culture of sweet potato is that of weed infestation, which can result in losses in yield of up to 85% (Seen et al., 2003). An integrated weed management approach, such as mechanical or manual weeding and the use of herbicides, is necessary to control weeds effectively during the early stages of development of sweet potato when competition is high. The mechanical method causes damage to the vines, while manual weeding is arduous, time-consuming and not viable for large crop areas (Harker and O'Donovan, 2013), hence the application of herbicides is unavoidable. However, no selective pre- or post-emergence herbicides are currently registered in Brazil for specific use with sweet potato, mainly because the crop is predominantly produced by family farming and receives rel-

Introduction

Sweet potato [*Ipomoea batatas* (L.) Lam.; Convolvulaceae] is a rustic and drought-tolerant species that is native to Central and South America. The species adapts well to different soils and climates, is easy to cultivate, entails low production costs (Empresa Brasileira de Pesquisa Agropecuária, 2008) and the starch-rich tuberous roots can be employed as raw material in the food, pharmaceutical, cosmetic and bioplastic industries (Cardoso et al., 2005; Silveira et al., 2014).

atively low levels of research investment. In addition, there are a large number of sweet potato genotypes in Brazil, many with potential for fuel ethanol production, each of which may vary with regard to herbicide tolerance (Torquato-Tavares et al., 2017; Santos et al., 2018).

Post-emergence herbicides require activation and careful control of application conditions in order to prevent extensive damage to the crop itself. On the other hand, pre-emergence herbicides may give rise to residual effects that can hamper the growth and yield of the culture, with the degree of impact depending on soil texture and moisture, organic matter content, temperature and solar radiation (Rodrigues and Almeida, 2005; Abdelhafid et al., 2000). For example, Harrison and Dukes (1996) evaluated the effects of the pre-emergence weed killer metribuzin (an inhibitor of photosystem II) on four sweet potato clones and reported that the herbicide caused moderate to severe damage and reduction of yield depending on the level of tolerance/susceptibility of the clone to the herbicide.

Considering the lack of selective herbicides recommended for use with sweet potato, and the importance of this culture as an alternative feedstock for the fuel ethanol industry, we aimed to evaluate the effects of the pre-emergence herbicides *S*-metolachlor, clomazone and atrazine, both alone and in combination, on the physiological and agronomic characteristics of sweet potato plants. Our initial hypothesis was that these pre-emergence herbicides would not reduce the productivity and ethanol yield in sweet potato.

Materials and methods

Plant material and experimental design

Experiments employed the sweet potato cultivar Duda, which was developed for fuel ethanol production by the breeding program at the Universidade Federal do Tocantins (UFT). The cultivar is characterized by a harvesting time of 180 days after planting (DAP), a mean yield of 65.0 t ha⁻¹, a dry matter content of 40.4% and an ethanol yield of up to 161.04 L t⁻¹ of roots (Silveira et al., 2014).

Two separate experiments, each initiated on 3rd May 2017, were carried out in the campus of UFT in Palmas, TO, Brazil (10°10'8"S, 48°19'54"W). Potted plants were used in the evaluation of physiological characteristics and the experiment followed a completely randomized design with five treatments (T1 to T5), three evaluation times (14, 21 and 28 DAP) and four repetitions involving 60 plants in total. The potted plants (each representing a single plot) were grown

in 4.5 L standard plastic pots containing substrate. Field-grown plants were used in the evaluation of agronomic characteristics and the experiment followed a randomized block design with five treatments (T1 to T5), one evaluation time (180 DAP) and four repetitions each. A single experimental plot occupied an area of 2.94 m² and comprised two 2.10 m rows located 70 cm apart with each row containing 7 plants spaced 30 cm one from another. Twenty identical plots, occupying a total area of 58.8 m² and containing 280 plants, were prepared at distances of 70 cm from each other. The doses of herbicides applied in the five treatments were based on manufacturers' recommendation and are presented in Table 1.

Preparation and treatment of experimental plots

The field area was prepared by plowing, harrowing and raising 30 cm planting beds. Cover fertilization was carried out as necessary following preliminary soil analysis (Supplemental Information – Table S1) in accordance with the recommendations of Empresa Brasileira de Pesquisa Agropecuária (1995). Soil substrate for the potted plants was obtained from the experimental field area after fertilizer had been applied. Cuttings of sweet potato vines, approximately 15 to 20 cm in length and containing three to five internodes, were collected from the upper-third portions of healthy and vigorous two-month old plants. The cuttings were transferred to field beds or pots and herbicides were applied immediately after planting using a carbon dioxide pressurized backpack sprayer with the pressure gauge set to dispense a spray volume of 200 L ha⁻¹. Weeding was performed manually on a weekly basis in the control treatments (T1) without herbicide. Prior to irrigation, the field capacity was determined using standard methods. Field-grown plants were irrigated by means of a sprinkler system that delivered 858 mm of water through the entire crop cycle, while potted plants were irrigated using a graduated measuring cylinder to deliver equal amounts of water daily in all repetitions. All plants were exposed to natural climatic conditions.

Evaluation of physiological and agronomic parameters

The physiological parameters analyzed in plotted plants were fluorescence quantum yield, chlorophyll content, phytotoxicity rating and plant dry mass accumulation. Fluorescence quantum yields of fully expanded light-adapted leaves sampled from the middle third of sweet potato vines (marked prior to herbicide application) were determined at 14, 21 and 28 DAP. Measurements were performed on one representative leaf per plot in the morning, between 09:00

TABLE 1. Pre-emergence herbicides used in the treatments of sweet potato (cultivar Duda).

Treatment ^a	Mechanism of action	Doses	
		g a.i. ha ⁻¹	L ha ⁻¹
T1 – Control (no herbicide)	NA	NA	NA
T2 – <i>S</i> -metolachlor	Inhibitor of cell division/elongation	960	1
T3 – clomazone	Inhibitor of carotenoid biosynthesis	500	1
T4 – <i>S</i> -metolachlor and clomazone mixture	Inhibitor of cell division/elongation and carotenoid biosynthesis, respectively	960 + 500	1 + 1
T5 – atrazine ^b and <i>S</i> -metolachlor mixture	Inhibitors of photosystem II and cell division/elongation, respectively	370 + 290	3

a.i.: active ingredient.

NA: not applicable.

^a Suppliers of herbicides in Brazil: atrazine, *S*-metolachlor, atrazine and *S*-metolachlor (Syngenta, São Paulo, SP); clomazone (UPL, Indianópolis, SP).

^b The use of atrazine as a herbicide is not supported in countries of the European Union.

and 12:00 h, using a hand-held FluorPen FP100 fluorometer (Photon Systems Instruments, Drasov, Czech Republic). Fluorescence quantum yield was defined as the ratio of the number of photons emitted by the fluorophore to the number absorbed, and results were expressed as values in the range 0 to 1. Chlorophyll content was determined at 14, 21 and 28 DAP on a representative leaf sample (as described above) using a portable SPAD-502 (Soil-Plant Analyses Development) chlorophyll meter (Konica Minolta Optics, Osaka, Japan), and values were recorded in SPAD units (Swiader and Moore, 2002). Phytotoxicity rating was assessed by visual inspection of the plant (growth and development, leaf color and presence of necrosis) at 14, 21 and 28 DAP. Results were expressed as scores ranging from 0 to 4 where: 0 represents absence of symptoms, 1 indicates mild injuries or reduced growth with quick recovery, 2 represents mild injuries or reduced growth with slow recovery, 3 indicates severe injuries or reduced plant stand with no recovery, and 4 represents plant death (Gazziero, 1995). Accumulation of plant dry mass (g) was determined at 28 DAP for leaves, stems and roots of sample plants. Plant parts were separated, washed and subsequently dried in a forced-air oven at 65°C until constant weight (~72 h). An analytical balance with a precision of 0.0001 g was used to assess the mass of dry matter (Marafon, 2012) and results were expressed in g.

The agronomic parameters analyzed in field-grown plants were masses and productivities of vines and roots, starch content of storage roots, and estimated ethanol yield. The productivities of vines and tuberous roots ($t\ ha^{-1}$) were determined at 180 DAP by harvesting, washing and weighing the vines and roots of 14 plants from each plot ($2.94\ m^2$). Total productivity was estimated by converting the yield per plot into $t\ ha^{-1}$. In order to determine dry mass of tuberous roots (%), eight whole plants were harvested at 180 DAP, the roots and aerial parts were separated, washed, weighed and subsequently dried in a forced-air oven at 65°C until constant weight (~72 h). The starch content (%) of washed and peeled fresh root material was determined at 180 DAP. Prepared roots were sliced using a manual grater, placed on a tray and dried in a forced-air oven at 55°C for 72 h before being ground in a knife mill with a 20 mm sieve mesh to select the smallest particles (Savelli et al., 1995). A model NIR 900 PLS spectrophotometer (FEMTO, São Paulo, SP, Brazil) with FemWin900 software was used to acquire diffuse reflectance spectra at 5 nm intervals in the 1,100–2,500 nm region, and each sample was scanned in triplicate and plotted on a standard curve. The percentage of starch in a wet weight (%WW) basis was determined according to Equation 1 (Ministério da Agricultura, Pecuária e Abastecimento, 2014).

$$\text{Starch (\% WW)} = \frac{(100 \times \text{dry starch}) - (\text{moisture} \times \text{dry starch})}{100} \quad (1)$$

Fuel ethanol yield ($L\ ha^{-1}$) was estimated on the basis of starch content and productivity of storage roots per unit area according to Equation 2 (Silva, 2013).

$$\text{Ethanol yield (L ha}^{-1}\text{)} = (10.349 \times \text{starch \% WW} - 89.349) \text{ root product. ha}^{-1} \quad (2)$$

Statistical analysis

Data relating to all variables were evaluated by analysis of variance (ANOVA) and the *F* test, and the differences between the means were compared using Tukey test at $P < 0.05$. All analyses were performed using Sisvar 5.6 software (Ferreira, 2011).

Results and discussion

Physiological responses of potted plants to pre-emergence herbicides

There were no statistically significant differences in fluorescence quantum yield of sweet potato leaves between controls (T1) and treatments (T2 to T5) at any of the evaluation times, with the exception of treatment T5 (atrazine/*S*-metolachlor mixture). In this case, the fluorescence quantum yield was reduced from the control value of 0.55 to 0.39, representing a reduction of 29% at 14 DAP (Figure 1A; Supplemental Table S2A), but values had reverted to those of the control by 21 DAP. Fluorescence quantum yield is a known indicator of plant stress since it measures the efficiency of photon emission by photosystem II. The reduction of values in plants treated with T5 may have been induced by atrazine through the breakdown of electron transport in photosystem II and the destruction of light-harvesting pigments (chlorophylls and carotenoids) via photo-oxidation reactions in the chloroplast that result in chlorosis followed by necrosis (Oliveira Júnior et al., 2011). The other herbicides tested act via different mechanisms that are not primarily related with photosynthetic reactions, as summarized in Table 1.

Interestingly, in comparison with the control, treatment T5 induced the largest contraction in chlorophyll content from 42.9 to 39.5 SPAD at 14 DAP (Figure 1B; Supplemental Table S2B), although the 8% reduction observed was not statistically significant and levels similar to the control were achieved by 28 DAP. Chlorophyll molecules are vital for photosynthesis and are arranged around the photosystems to capture the light that will convert carbon dioxide and water into chemical energy (Jesus and Marengo, 2008). According to Catunda et al. (2005), the reduction in chlorophyll content indicates a certain degree of injury, and chlorosis is one of the first symptoms to appear. The small reduction in chlorophyll observed in sweet potato plants exposed to T5 was likely induced by the action of atrazine on photosystem II. Treatments T2 to T4 induced no variation in chlorophyll content in leaves of sweet potato since *S*-metolachlor and clomazone act via inhibition of cell division/elongation and carotenoid biosynthesis. Similar results have been reported by Takano et al. (2012) who evaluated the effects of clomazone on common bean (cultivar BRS Pontalon) and found no variation in chlorophyll levels in the leaves of plants 14 and 28 days after emergence.

Concerning phytotoxicity, none of the herbicide treatments caused significant damage to sweet potato plants at any of the evaluation times (Figure 1C; Supplemental Table S2C). Visual inspection of symptoms assists in the diagnosis of herbicide-induced toxicity, but the results cannot be taken alone because some herbicides cause injuries but do not compromise plant yield (Barroso et al., 2012). Brighenti et al. (2000) reported that 20 days after application of the pre-emergence herbicide *S*-metolachlor to sunflower cultivar Morgan M-742, few or no signs of toxicity were observed and crop productivity and oil yield were not affected. In contrast, Harrison and Dukes (1996) assessed visual injury ratings of four sweet potato clones following treatment with metribuzin (an inhibitor of PSII) and reported differential responses in that clone W-262 exhibited metribuzin tolerance similar to the highly tolerant clone Tinian, whereas the commercial cultivar Jewel was intermediate and clone SC 1149-19 presented high sensitivity. According to Takano et al. (2012), clomazone application to common bean cultivars at a dose of $300\ g\ ha^{-1}$ produced moderate plant responses similar to the findings reported herein.

FIGURE 1. Physiological parameters of potted plants treated with different pre-emergence herbicides. Treatments were: T1: control plants (no herbicide); T2: *S*-metolachlor; T3: clomazone; T4: *S*-metolachlor and clomazone mixture, and T5: atrazine and *S*-metolachlor mixture. Evaluation times were performed at 14, 21 and 28 days after planting (DAP). Bars bearing dissimilar lower (upper) case letters indicate statistically significant differences between treatments (evaluation times) according to ANOVA and Tukey test ($P < 0.05$). (See also Supplemental Information, Table S2).

FIGURE 2. Dry matter accumulation of potted plants treated with different pre-emergence herbicides 28 days after planting. Treatments were: T1: control plants (no herbicide); T2: *S*-metolachlor; T3: clomazone; T4: *S*-metolachlor and clomazone mixture, and T5: atrazine and *S*-metolachlor mixture. Bars bearing dissimilar upper case letters indicate statistically significant differences between treatments according to ANOVA and Tukey test ($P < 0.05$). (See also Supplemental Information, Table S3).

The degree of injury caused by pre-emergence herbicides depends on the residual activity, which is influenced by various factors including physical and chemical characteristics of the soil, temperature, humidity and solar radiation (Rodrigues and Almeida, 2005). The sweet potato plants evaluated in the present study exhibited mild to moderate signs (scores 0 to 2) of toxicity in all the treatments, indicating that the tested herbicides or their mixtures could be used as selective herbicides for sweet potato cultivar Duda.

In comparison with the control, treatments T2 to T5 resulted in significant reductions in leaf dry mass (Figure 2A; Supplemental Table S3A), but not the dry mass of stems (Figure 2B; Supplemental Table S3B), at 28 DAP. Root dry mass and total dry mass were reduced significantly by treatments T2, T3 and T4 (Figures 2C and 2D; Supplemental Tables S3C

and S3D), while T5 tended to yield values similar to those of the control. Dry mass accumulation is dependent on several factors including photosynthetic activity, nutrient uptake and allocation of biomass in reproductive and non-reproductive organs. Therefore, this parameter is a valuable indicator of the performance of a culture either under normal or stress conditions (Hole et al., 1983).

The application of pre-emergence herbicides can cause reductions in biomass accumulation at the initial stage of growth and, thereby, hamper productivity. *S*-metolachlor, for example, inhibits the initial growth of plants, reducing cell division in the apical meristem and resulting in reduction of dry matter accumulation (Oliveira Júnior, 2011). On the other hand, clomazone inhibits carotenoid biosynthesis and, since carotenoids and chlorophylls share some common

FIGURE 3. Agronomic parameters of field-grown plants treated with different pre-emergence herbicides at 180 days after planting. Treatments were: T1: control plants (no herbicide); T2: *S*-metolachlor; T3: clomazone; T4: *S*-metolachlor and clomazone mixture, and T5: atrazine and *S*-metolachlor mixture. Bars bearing similar upper case letters indicate no significant differences between treatments according to ANOVA and Tukey test ($P < 0.05$). (See also Supplemental Information, Table S4).

biosynthetic precursors such as geranylgeranyl diphosphate, the levels of synthesis of these pigments are related. Nevertheless, both are essential for the integrity of the photosynthetic apparatus such that clomazone may indirectly reduce carbon allocation in treated plants. It is likely these mechanisms explain the reductions in dry mass content observed following treatments T2, T3 and T4.

Agronomic responses of field-grown plants to pre-emergence herbicides

As shown in Figure 3, there were no differences at 180 DAP between the control and treatments T2 to T5 regarding the productivity of vines and tuberous roots, the dry mass of tuberous roots, starch content or ethanol yield. These findings demonstrate that the herbicides tested, along with their combinations, present great potential for use with sweet potato cultivar Duda at the doses employed.

Vine productivity was similar in all treatments, with a mean yield of 20 t ha⁻¹ (Figure 3A; Supplemental Table S4A). Abreu (2010) reported that vine productivities in plants of cassava cultivar IAC576-70 that had been exposed to clomazone or atrazine were similar to those of the non-treated controls, hence analogous to the results reported herein for sweet potato. The vines of sweet potato are protein- and energy-rich and can be fermented and used as silage for cattle and other ruminants or employed as raw material for second-generation ethanol production (Viana et al., 2001).

Tuberous root dry mass is a particularly important parameter because carbohydrates (mainly starch) that are convertible into fuel ethanol account for around 85% of the root content. According to Silveira et al. (2014), the dry mass of tuberous roots of the sweet potato cultivar Duda is, on average, 40.4% while the values presented herein were greater than 35% (Figure 3B; Supplemental Table S4B), even with application of herbicides.

The productivity of tuberous roots is another important parameter because some herbicides can cause mild injuries and reduce crop yield even when visual symptoms are not apparent, while other agents may cause serious injuries but the plants recover completely (Silva et al., 2003). The present study demonstrated that the productivities of tuberous roots in plants exposed to treatments T2 to T5 were similar to those of the control plants with a mean value of 40 t ha⁻¹ (Figure 3C; Supplemental Table S4C), hence comparable to the results reported by Stephen and Shankle (2017). Similarly, application of clomazone and atrazine did not reduce the productivity of two cassava cultivars (Abreu, 2010), and a mixture of atrazine and *S*-metolachlor has been shown not to reduce the productivity of sweet potato (Korieocha et al., 2011). In Brazil, the average productivity of sweet potato is still rather low (around 14 t ha⁻¹), owing mainly to the lack of knowledge or incorrect use of modern agricultural techniques. Nevertheless, highly productive cultivars are available, including the cultivar Duda, that yield more than 40 t ha⁻¹ (Instituto Brasileiro de Geografia e Estatística, 2016; Silveira et al., 2014) even when exposed to herbicide.

As shown in Figure 3D (Supplemental Table S4D), starch content in tuberous roots was around 20% regardless of the treatment, and such levels were within the range (18.8 to 30.2%) reported by Silveira et al. (2014) for various sweet potato cultivars developed in the state of Tocantins, center west of Brazil, for the specific purpose of ethanol production. Abreu (2010) also reported that starch content in cassava treated with clomazone and other herbicides (PS-II inhibitors) remained similar to that of control plants.

There were no significant differences between the treatments with respect to estimated fuel ethanol production in sweet potato (Figure 3E; Supplemental Table S4E). The ethanol yield of the 'Duda' cultivar was reported by Silveira et al. (2014) to be 10,467 L ha⁻¹, whereas in this study we obtained an average of around 5,000 L ha⁻¹. Ethanol yield in sweet potato is related directly to the productivity of tuberous roots per hectare and to the starch content. Some specially bred sweet potato cultivars have been reported to yield twice as much ethanol as sugar cane, with the extra advantage of allowing two culture cycles per year (Silveira et al., 2014).

Conclusions

Although some minor physiological alterations were observed in potted sweet potato plants exposed to a mixture of atrazine and *S*-metolachlor in the early days of culture (up to 28 DAP), the plants subsequently recovered well. Application of *S*-metolachlor, clomazone, *S*-metolachlor/clomazone mixture and atrazine/*S*-metolachlor mixture did not reduce tuberous root dry mass, vine and tuberous root productivity, starch content or ethanol yield. The evidence presented herein supports our initial hypothesis and indicates these herbicides are selective and could be applied in sweet potato crops without loss of productivity. However, further studies are needed to define the most appropriate dose and time of application of herbicide and possible interactions between herbicide when applied in combination.

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Conflict of interest statement

The authors declare no conflicts of interest.

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SUPPLEMENTAL INFORMATION

SUPPLEMENTAL INFORMATION – TABLE S1. Analysis of soil at a depth between 0–20 cm in the experimental field at the Universidade Federal do Tocantins, Palmas, TO, Brasil.

Variable	Value
pH in water	5.92
P (Mehlich 1 extractant; mg dm ⁻³)	14.54
K (cmolc dm ⁻³)	0.30
Ca (cmolc dm ⁻³)	1.25
Mg (cmolc dm ⁻³)	0.51
Al (cmolc dm ⁻³)	0
H + Al (cmolc dm ⁻³)	0.90
Organic matter (g dm ⁻³)	17.48
Sum of exchangeable bases (cmolc dm ⁻³)	2.06
Cation exchange capacity at pH 7.0 (cmolc dm ⁻³)	2.96
Base saturation (V; %)	69.59
Clay (%)	27.1
Silt (%)	8.3
Sand (%)	64.6

SUPPLEMENTAL INFORMATION – TABLE S2. Analysis of variance (ANOVA) of potted sweet potato plants exposed to pre-emergence herbicides. (Related to Figure 1).

SUPPLEMENTAL TABLE S2A. ANOVA of fluorescence quantum yields.

Sources of variation	Degrees of freedom	Sum of squares	Mean squares	<i>F</i>	<i>P</i>
Herbicides	4	0.05288	0.01322	4.0448*	0.0073
Times	2	0.04185	0.02092	6.4012*	0.0037
Interaction	8	0.09733	0.01217	3.7220*	0.0022
Blocks	3	0.01524	0.00508	1.5543 ns	0.2147
Residuals	42	0.13728	0.00327		
Total	59	0.34458			
Coefficient of variation			9.95		

* Significant at 5% probability; ns: not significant.

SUPPLEMENTAL TABLE S2B. ANOVA of chlorophyll contents.

Sources of variation	Degrees of freedom	Sum of squares	Mean squares	<i>F</i>	<i>P</i>
Herbicides	4	23.42833	5.85708	1.5774 ns	0.1980
Times	2	35.84633	17.92317	4.8271*	0.0129
Interaction	8	83.63867	10.45483	2.8157*	0.0135
Blocks	3	16.83333	5.61111	1.5112 ns	0.2255
Residuals	42	155.94667	3.71302		
Total	59	315.69333			
Coefficient of variation			4.52		

* Significant at 5% probability; ns: not significant.

SUPPLEMENTAL TABLE S2C. ANOVA of phytotoxicity scores.

Sources of variation	Degrees of freedom	Sum of squares	Mean squares	<i>F</i>	<i>P</i>
Herbicides	4	13.06667	3.26667	13.1923*	0.0001
Times	2	10.00000	5.00000	20.1923*	0.0001
Interaction	8	3.33333	0.41667	1.6827 ns	0.1312
Blocks	3	0.85000	0.28333	1.1442 ns	0.3424
Residuals	42	10.40000	0.24762		
Total	59	37.65000			
Coefficient of variation			58.54		

* Significant at 5% probability; ns: not significant.

SUPPLEMENTAL INFORMATION – TABLE S3. Analysis of variance (ANOVA) of potted sweet potato plants exposed to pre-emergence herbicides. (Related to Figure 2).

SUPPLEMENTAL TABLE S3A. ANOVA of leaf dry mass at 28 days after planting.

Sources of variation	Degrees of freedom	Sum of squares	Mean squares	F	P
Blocks	3	1.11909	0.37303	2.9334 ns	0.0767
Herbicides	4	5.78018	1.44505	11.3632*	0.0004
Residuals	12	1.52602	0.12717		
Total	19	8.42530			
Coefficient of variation		25.66			

* Significant at 5% probability; ns: not significant.

SUPPLEMENTAL TABLE S3B. ANOVA of stem dry mass at 28 days after planting.

Sources of variation	Degrees of freedom	Sum of squares	Mean squares	F	P
Blocks	3	0.71874	0.23958	0.9491 ns	0.4478
Herbicides	4	0.93393	0.23348	0.9250 ns	0.4813
Residuals	12	3.02908	0.25242		
Total	19	4.68175			
Coefficient of variation		35.40			

* Significant at 5% probability; ns: not significant.

SUPPLEMENTAL TABLE S3C. ANOVA of root dry mass at 28 days after planting.

Sources of variation	Degrees of freedom	Sum of squares	Mean squares	F	P
Blocks	3	0.68902	0.22967	1.0533 ns	0.4048
Herbicides	4	7.21777	1.80444	8.2752*	0.0018
Residuals	12	2.61665	0.21805		
Total	19	10.52344			
Coefficient of variation		28.77			

* Significant at 5% probability; ns: not significant.

SUPPLEMENTAL TABLE S3D. ANOVA of total dry mass at 28 days after planting.

Sources of variation	Degrees of freedom	Sum of squares	Mean squares	F	P
Blocks	3	3.51705	1.17235	0.8817 ns	0.4780
Herbicides	4	35.93690	8.98422	6.7571*	0.0043
Residuals	12	15.95512	1.32959		
Total	19	55.40906			
Coefficient of variation		26.02			

* Significant at 5% probability; ns: not significant.

SUPPLEMENTAL INFORMATION – TABLE S4. Analysis of variance (ANOVA) of field-grown sweet potato plants exposed to pre-emergence herbicides. (Related to Figure 3).

SUPPLEMENTAL TABLE S4A. ANOVA of productivity of vines.

Sources of variation	Degrees of freedom	Sum of squares	Mean squares	F	P
Blocks	3	133273196.7120	44424398.9040	1.0750 ns	0.3964
Herbicides	4	95379791.52500	23844947.8812	0.5770 ns	0.6849
Residuals	12	495889974.3482	41324164.5290		
Total	19	724542962.5852			
Coefficient of variation		26.37			

* Significant at 5% probability; ns: not significant.

SUPPLEMENTAL TABLE S4B. ANOVA of dry mass of tuberous roots.

Sources of variation	Degrees of freedom	Sum of squares	Mean squares	<i>F</i>	<i>P</i>
Blocks	3	6.65197	2.21732	1.3678 ns	0.2996
Herbicides	4	1.36602	0.34150	0.2107 ns	0.9275
Residuals	12	19.45242	1.62104		
Total	19	27.47040			
Coefficient of variation			3.48		

* Significant at 5% probability; ns: not significant.

SUPPLEMENTAL TABLE S4C. ANOVA of productivity of tuberous roots.

Sources of variation	Degrees of freedom	Sum of squares	Mean squares	<i>F</i>	<i>P</i>
Blocks	3	297123036.5079	99041012.1693	0.8630 ns	0.4867
Herbicides	4	386302389.7393	96575597.4348	0.8415 ns	0.525
Residuals	12	1377161255.726	114763437.977		
Total	19	2060586681.973			
Coefficient of variation			24.03		

* Significant at 5% probability; ns: not significant.

SUPPLEMENTAL TABLE S4D. ANOVA of starch contents.

Sources of variation	Degrees of freedom	Sum of squares	Mean squares	<i>F</i>	<i>P</i>
Blocks	3	33.08425	11.02808	1.3280 ns	0.3111
Herbicides	4	35.41972	8.85493	1.0663 ns	0.415
Residuals	12	99.65245	8.30437		
Total	19	168.15642			
Coefficient of variation			5.39		

* Significant at 5% probability; ns: not significant.

SUPPLEMENTAL TABLE S4E. ANOVA of yields of fuel ethanol.

Sources of variation	Degrees of freedom	Sum of squares	Mean squares	<i>F</i>	<i>P</i>
Blocks	3	4930764.115360	1643588.038453	0.887 ns	0.4757
Herbicides	4	11633049.077950	2908262.269487	1.569 ns	0.2453
Residuals	12	22244827.442690	1853735.620224		
Total	19	38808640.636000			
Coefficient of variation			27.11		

* Significant at 5% probability; ns: not significant.