Dry Heat and Exposure Time Influence Divine Nightshade and Itchgrass Seed Emergence

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ABSTRACT

In Louisiana, growers remove sugarcane (Saccharum spp. hybrids) residue following green-cane harvesting by prescribed burning. Divine nightshade (Solanum nigrescens (Mart. & Gal) and itchgrass (Rottboellia cochinchinensis (Lour.) Clayton) are problematic weeds in Louisiana sugarcane production. The objective of this study was to determine the effects of dry heat and exposure duration on divine nightshade and itchgrass emergence. Divine nightshade and itchgrass seeds were exposed to three temperature levels (100, 150, and 200°C) for seven exposure timings (0, 5, 10, 20, 40, 80, and 160 s). Exposure to 150 and 200°C for 5 to 20 s reduced divine nightshade emergence 6 to 29%. Divine nightshade emergence was not completely inhibited at 200°C for 160 s. However, itchgrass exposed to 150°C for 40 s or longer or to 200°C for 20 s or longer failed to emerge. Results from this study showed itchgrass seed could be controlled with dry heat, but prescribed burns that produced temperatures below 100°C or temperatures greater than 150°C for short durations may not control all divine nightshade seeds. The aforementioned temperature and exposure duration that allowed divine nightshade to survive introduced the potential for divine nightshade to become more abundant.

Core Ideas

• Itchgrass seed exposed to 150°C dry heat for 40 s or more did not emerge.
• Divine nightshade seed was more tolerant to 150 and 200°C than itchgrass.
• Dry heat was an effective control strategy for surface deposited weed seeds.

itchgrass is a large-seeded C4 annual grass weed often found infesting commercial sugarcane fields throughout the world (Holm et al., 1977). Itchgrass growth during the sugarcane grand growth stage, a period from June through August when water consumption is highest, reduced sucrose yield by 7 and 17% after 30 and 60 d of competition, respectively (Gascho, 1985; Millhollon, 1992). Lencse and Griffin (1991) reported up to 43% reduction in sucrose yield when itchgrass competed season-long with sugarcane. Divine nightshade was identified in a commercial Louisiana sugarcane field in 2010 and since has been identified in additional Parishes where sugarcane is produced (Orgeron et al., 2018). The weed has been observed infesting flowerbeds and landscaping shrubs, which could suggest seed spread was facilitated by birds (Albert Orgeron, personal communication, 2019). Divine nightshade is also found in states adjacent to the Gulf of Mexico, which include Mississippi, Alabama, Florida, Georgia, and South Carolina (USDA, 2018). Hawaii and Puerto Rico are other areas where divine nightshade has become established. Orgeron et al. (2018) reported season-long divine nightshade competition reduced sucrose yield 33% when compared with sucrose yield when divine nightshade was controlled in mid-March with 1120 g ha−1 of triclopyr. The synthetic auxin herbicides 2,4-D, dicamba, or a pre-mix of 2,4-D plus dicamba are typically applied in mid-March to control spotted burclover [Medicago arabica (L.) Huds.], purslane speedwell [Veronica peregrina (L.)], and spiny sowthistle [Sonchus asper (L.) Hill] when sugarcane emerges from winter dormancy (Anonymous, 2019; Griffin and Judice, 2009). Unfortunately, 1120 g ha−1 of dicamba or 2300 plus 800 g ha−1 of 2,4-D plus dicamba applied to 20- to 30-cm tall divine nightshade plants resulted in no more than 35% injury at 22 d after treatment (Orgeron et al., 2018). Investigation of herbicides for itchgrass control in Louisiana sugarcane is well documented (Millhollon 1977, 1986, 1993), but evaluation of nonchemical strategies for itchgrass and divine nightshade management is limited.

Repeated application of the same herbicide site of action to large weed numbers has resulted in the evolution of 255 herbicide-resistant weed species globally (Heap, 2019; Powles and Yu, 2010). Multiple resistance evolution to five herbicide sites of action have been reported in 19 weed species globally (Heap, 2019). No cases of divine nightshade evolving resistance...
to herbicides have been reported; however, few reports of itchgrass evolving resistance to herbicides have been documented globally. Failure to control itchgrass in soybean (Glycine Max (L.)) with fluazifop-P-butyl has been documented in Louisiana, Bolivia, and Costa Rica, and itchgrass resistant to foramsulfuron, iodosulfuron-methyl-sodium, andnicosulfuron was reported in a Venezuelan corn (Zea mays (L.)) field in 2004 (Avila et al., 2007; Castillo-Matamoros et al., 2016; Heap, 2019). Additional weed control strategies that complement herbicides are increasingly necessary because of the limited commercial release of new herbicide sites of action (Duke 2012). Residues from several annual grass species can inhibit establishment of lettuce (Lactuca sativa (L.)), tomato (Solanum lycopersicum (Mill.)), and weeds by forming a physical barrier and by release of allelopathic chemicals (Putnam and DeFrank, 1983; Webber et al., 2017, 2018). Bolfrey-Arkut et al. (2011) reported rice (Oryza sativa (L.)) residue that exceeded 4 Mg ha–1 on the soil surface reduced itchgrass emergence by 50%. A similar study conducted by Richard (1999) showed 79% less morningglory spp. (Ipomoea spp.) emergence from 6.4 Mg ha–1 of post-harvest sugarcane residue retained on the soil surface when compared with emergence from soil with no cover. Other strategies to manage surface-deposited weed seed, particularly in cropping systems plagued by herbicide-resistant weeds, include burning narrow windrows (Walsh and Newman, 2007). Common cocklebur [Xanthium strumarium (L.)], common purslane [Portulaca oleracea (L.)], johnsongrass [Sorghum halepense (L.) Pers.], prickly sida [Sida spinosa (L.)], redroot pigweed [Amaranthus retroflexus (L.)], spurred anoda [Anoda cris-tata (L.) Schldfl.], and velvetleaf [Abutilon theophrasti Medik.] seed exposed to 70°C for prolonged periods in soil have shown reduced germination in the laboratory (Egley, 1990). Dahlquist et al. (2007) reported complete death of black nightshade [(Solanum nigurm (L.))] seed when exposed to 60°C water for 2 h. Walsh and Newman (2007) reported temperatures required to prevent annual ryegrass (Lolium rigidum (Gaudin)) and wild radish (Raphanus raphanistrum (L.)) seed emergence were 400 and 500°C, respectively, for a minimum of 10 s in a kiln experiment.

The majority of sugarcane in Louisiana is green-cane harvested using a chopper harvester. Vegetation is removed from the sugarcane stalk, and the stalks are chopped into 15- to 20-cm-long segments (billets) and loaded into a high-dump wagon. Sugarcane is then transferred to trailers and is hauled to the sugar factory. Post-harvest residue is separated from billets by the chopper harvester and deposited onto the soil surface as cane billets are cut. Removal of post-harvest residue is recommended in winter when sugarcane is dormant by burning or mechanically sweeping residue away from stooks (Viator et al., 2005). The amount of post-harvest residue deposited each year, and the often-reported negative consequences of residue retention on the soil surface, allow for sugarcane growers to at least partially control weed seed using heat. Many studies have shown successful control of problematic weed seeds in numerous cropping systems across the world using heat (Bolfrey-Arkut et al., 2011; Lyon et al., 2016; Walsh et al., 2017; White and Boyd, 2016). Although few studies have investigated the effect of temperature on itchgrass seed mortality (Bolfrey-Arkut et al., 2011), none has reported on divine nightshade. Published research on divine nightshade management in sugarcane is limited, in part, because the broadleaf weed species has only recently become problematic in Louisiana sugarcane (Orgeron et al., 2018). Therefore, the objective of this study was to determine the effects of dry heat and exposure duration on divine nightshade and itchgrass emergence.

**MATERIALS AND METHODS**

**Experimental Design and Seed Preparation**

An experiment was conducted in spring of 2017 and 2018 at the USDA–ARS Sugarcane Research Unit Ardoyne Farm Laboratory in Schriever, LA (29.6372 N; 90.8395 W) to determine the effect of dry heat and exposure time on divine nightshade and itchgrass emergence. Treatments consisted of a two-way complete factorial of temperature with three levels (100, 150, and 200°C) and exposure time with seven levels (0, 5, 10, 20, 40, 80, and 160 s). Treatments were arranged in a randomized complete block design, and each treatment combination (n = 21) was replicated four times. A single divine nightshade fruit and five itchgrass seeds were placed in aluminum weigh dishes and exposed to each combination of constant temperature and exposure time simultaneously. The entire experiment was repeated. Divine nightshade and itchgrass seeds were collected from naturally growing plants in commercial sugarcane production fields near Schriever, LA (29.6372 N; 90.8395 W) when plants reached physiological maturity and were stored in a cooler at 4°C for 3 mo before experimentation. For divine nightshade, physiological maturity was determined when fruits were completely black in color and readily detached from the main cluster when handled. Each fruit typically contained 50 to 100 tan-colored oval seeds (Orgeron et al., 2018). Divine nightshade fruits were weighed prior to experimentation using an analytical balance to reduce seed quantity variation across treatments. The receptacle was removed from the fruit prior to recording weight. Most individual fruits weighed 0.15 to 0.35 g, and care was taken to avoid selecting fruit outside the aforementioned weight range. Divine nightshade seed remained within the fruit capsule to simulate fruit drop in field conditions. Mature itchgrass seeds were collected by placing a large tray below the plant’s inflorescence and gently shaking the stem. Itchgrass seeds were visually inspected for insect damage. Damaged and immature seeds were discarded, and seeds that passed visual inspection were stored in airtight plastic containers at 4°C.

**Dry Heat Treatment**

Constant temperature treatments were achieved using a laboratory oven (Heratherm GP Mechanical Oven; ThermoFisher Scientific, Waltham, MA) set at the desired temperature. The internal oven temperature did not decrease more than 5°C on placing seeds in the oven. After seeds were exposed to the dry heat treatment, seeds were carefully removed from the oven and cooled to room temperature. A new set of seeds were not exposed to the dry heat treatment until the oven temperature reached the desired temperature.

**Weed Seed Planting and Greenhouse Conditions**

Weed seeds were planted into 32-cell polystyrene seedling transplant trays (Peaceful Valley Farm & Garden Supply, Nevada City, CA) immediately after the dry heat treatment and placed in the greenhouse for emergence evaluation. Each seedling cell measured 7.6 cm by 7.6 cm by 7.6 cm and was filled with moistened potting medium (Redi-Earth Plug Mix; Sun-Gro Horticulture, Agawam, MA). Divine nightshade and itchgrass
seeds were planted in separate seedling trays. In each seedling cell, five itchgrass seeds were planted in a star pattern 1 cm below the soil surface using tweezers. Divine nightshade fruits were lanced with a scalpel, and all seed were excised and spread on the potting medium surface using a scalpel. The scalpel was rinsed with water and dried between treatments to ensure seeds were not unintentionally transferred to other cells. Potting medium was moistened by misting the entire seedling tray as necessary using tap water. Seeds were exposed to natural lighting (13–14 h photoperiod) in the greenhouse, and minimum and maximum greenhouse air temperatures were 24 and 35°C, respectively.

**Data Collection and Statistical Analysis**

Emerged divine nightshade and itchgrass seedlings were counted and extracted using tweezers once a week for seven consecutive weeks. Emergence was determined when the hypocotyl extended 0.5 cm above the soil surface for divine nightshade and when the coleoptile was visible for itchgrass. Cumulative emergence data for the 7-wk period are presented. Emergence data were converted to a percent reduction of the nontreated check using Eq. [1], where \( E_n \) is emergence of the nontreated, and \( E_i \) is emergence from the dry heat treatment.

\[
y = \left( \frac{E_n - E_i}{E_n} \right) 100
\]  

Eq. [1]

Data were checked for normality and constant variance using PROC UNIVARIATE in SAS (v. 9.3; SAS Institute, Cary, NC). Emergence reduction data were arcsine square root transformed and analyzed with PROC GLMMIX in SAS, and treatment means were back transformed for presentation. Data were pooled across experimental runs because of a nonsignificant treatment × run effect. Means were separated using Tukey’s HSD at the 0.05 level of significance. Nonlinear regression analysis was performed for each weed species and temperature level using a two-parameter exponential model using SigmaPlot (v. 12.5; Systat Software, San Jose, CA) that regressed emergence reduction against exposure time. Divine nightshade and itchgrass seed exposed to 100°C were modeled using Eq. [2], and seed exposed to 150 and 200°C were modeled using Eq. [3].

\[
y = a \exp(bx)
\]  

Eq. [2]

\[
y = a[1 - \exp(-bx)]
\]  

Eq. [3]

In this model, \( y \) is percent weed emergence reduction, \( a \) is the maximum emergence reduction value, \( b \) is a rate constant that determines the steepness of the curve, and \( x \) is exposure time. Root mean square error (Eq. [4]) and modeling efficiency coefficient (EF) (Eq. [5]) were calculated to test goodness of fit for the logistic model:

\[
\text{RMSE} = \left[ \frac{1}{n} \sum_{i=1}^{n} (P_i - O_i)^2 \right]^{1/2}
\]  

Eq. [4]

\[
\text{EF} = 1 - \frac{\sum_{i=1}^{n} (O_i - P_i)^2}{\sum_{i=1}^{n} (O_i - \bar{O})^2}
\]  

Eq. [5]

where \( P_i \) is the predicted value, \( O_i \) is the observed value, \( n \) is the total number of observations, and \( \bar{O} \) is the mean observation value (Archontoulis and Miguez, 2015; Sarangi et al., 2015). The duration of heat required to reduce weed emergence by 25, 50, and 90% was calculated from regression parameter estimates for divine nightshade and itchgrass exposed to each temperature treatment.

**RESULTS AND DISCUSSION**

Divine nightshade and itchgrass emergence was influenced by the dry heat treatment and exposure time. Divine nightshade and itchgrass emergence reduction was 29 and 100% of the nontreated check, respectively, when exposed to 200°C for 20 s (Table 1). Divine nightshade emergence was not completely inhibited at 200°C for 160 s. However, itchgrass emergence ceased when exposed to 150°C for 40 s or longer or to 200°C for 20 s or longer. Bolfrey-Arku et al. (2011) reported that itchgrass seed exposed to 160°C for 5 min failed to germinate, but 92% of seed germinated when the temperature was reduced to 140°C. Differing results in itchgrass tolerance to heat, especially at temperatures below 140°C, between this study and Bolfrey-Arku et al. (2011) may be due to itchgrass biotype. Millhollen and Burner (1993) categorized itchgrass from 34 countries or territories into five biotypes, based on morphological and phenological characteristics, and reported that Louisiana and Philippine biotypes were not placed in similar categories. In the same study, the Louisiana biotype had 20 2n chromosomes, but the 2n chromosome number was 20 or 60 for Philippine biotypes.

The two-parameter exponential growth model described the relationship between emergence reduction and exposure time for divine nightshade and itchgrass (Table 2; Fig. 1). Emergence reduction data for 150 and 200°C temperature treatments...
Table 2. Regression parameter estimates with standard errors and the goodness of fit RMSE and modeling efficiency coefficient of the two-parameter exponential model used to determine emergence reduction of divine nightshade and itchgrass after exposure to 100, 150, and 200°C for 0, 5, 10, 20, 80, and 160 s.

<table>
<thead>
<tr>
<th>Weed species</th>
<th>Temperature°C</th>
<th>(a) ± SE</th>
<th>(b) ± SE</th>
<th>RMSE§</th>
<th>EF¶</th>
</tr>
</thead>
<tbody>
<tr>
<td>Divine nightshade</td>
<td>100</td>
<td>7.82 ± 2.33</td>
<td>0.016 ± 0.002</td>
<td>20.1</td>
<td>0.79</td>
</tr>
<tr>
<td></td>
<td>150</td>
<td>118.49 ± 14.10</td>
<td>0.015 ± 0.004</td>
<td>21.4</td>
<td>0.87</td>
</tr>
<tr>
<td></td>
<td>200</td>
<td>106.39 ± 6.29</td>
<td>0.030 ± 0.005</td>
<td>18.6</td>
<td>0.92</td>
</tr>
<tr>
<td>Itchgrass</td>
<td>100</td>
<td>9.82 ± 2.53</td>
<td>0.012 ± 0.002</td>
<td>19.4</td>
<td>0.71</td>
</tr>
<tr>
<td></td>
<td>150</td>
<td>106.56 ± 6.48</td>
<td>0.036 ± 0.006</td>
<td>21.3</td>
<td>0.91</td>
</tr>
<tr>
<td></td>
<td>200</td>
<td>105.08 ± 5.04</td>
<td>0.059 ± 0.009</td>
<td>20.4</td>
<td>0.93</td>
</tr>
</tbody>
</table>

† Divine nightshade and itchgrass percent emergence reduction data for 100°C were fitted to the two-parameter exponential growth model \(y = a\exp(bx)\), and data for 150 and 200°C were fitted to the two-parameter exponential rise to maximum model \(y = a[1 - \exp(-bx)]\), where \(y\) is percent weed emergence reduction, \(a\) is the maximum emergence reduction value, \(b\) is a rate constant that determines the steepness of the curve, and \(x\) is exposure time.

‡ Values are mean ± SE.

§ Smaller RMSE values suggest predicted values are closer to observed values, indicating a better model fit.

¶ EF, modeling efficiency coefficient (EF values closer to 1 indicate a better model fit and more accurate estimates).

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Fig. 1. Influence of exposure time on predicted and observed divine nightshade and itchgrass emergence reduction after exposure to 100, 150, and 200°C. Emergence reduction was calculated using the equation \(y = \left(\frac{E_{nt} - E_{int}}{E_{nt}}\right)\times 100\), where \(E_{nt}\) is emergence of the nontreated, and \(E_{int}\) is emergence from the dry heat treatment. Parameter estimates for data fitted to each model are provided in Table 2. Divine nightshade and itchgrass percent emergence reduction data for 100°C were fitted to the two-parameter exponential rise to maximum model \(y = a[1 - \exp(-bx)]\), and data for 150 and 200°C were fitted to the two-parameter exponential model for divine nightshade and itchgrass (Table 2; Fig. 1). Dry heat needed to reduce 50% divine nightshade and itchgrass emergence required 116 and 136 s at 100°C, respectively (Table 3). Doubling the dry heat temperature from 100 to 200°C showed that 21 and 11 s were needed to reduce divine nightshade and itchgrass emergence by 50%, respectively.

The potential for itchgrass to emerge was low after exposure to temperatures of 150°C or higher, particularly when seed were exposed to dry heat for 40 s or longer. The data suggested that itchgrass emergence was reduced from 50 to 90% when seed exposure time increased from 18 to 52 s at 150°C or from 11 to 33 s at 200°C (Table 3). Doyle and Stypa (2004) suggested that 70% weed control may be acceptable for producers who grow crops for silage. However, when the potential for weed seed contamination arises in crops harvested for seed, weed control below 99% may be considered unacceptable (Doyle and Stypa, 2004). Exposure to 150 and 200°C for 5 to 20 s marginally reduced divine nightshade emergence (Table 1). However, short periods of heat exposure have alleviated weed seed dormancy. Herranz et al. (1998) reported that French broom [Genista monspessulana (L.) L.A.S. Johnson], [Cytisus reverchonii (Degen & Hervier) bean], and pitch trefoil [Bituminaria bituminosa (L.) C.H. Stir] seed exposed to 150°C for 60 s increased seed

Table 3. Temperature and duration of heat treatment required to reduce divine nightshade and itchgrass emergence by 25, 50, and 90% for each weed species. Percent emergence reduction values were calculated from the two-parameter exponential model:

<table>
<thead>
<tr>
<th>Weed species</th>
<th>Temperature°C</th>
<th>25%</th>
<th>50%</th>
<th>90%</th>
</tr>
</thead>
<tbody>
<tr>
<td>Divine nightshade</td>
<td>100</td>
<td>73</td>
<td>116</td>
<td>153</td>
</tr>
<tr>
<td></td>
<td>150</td>
<td>16</td>
<td>37</td>
<td>95</td>
</tr>
<tr>
<td></td>
<td>200</td>
<td>9</td>
<td>21</td>
<td>63</td>
</tr>
<tr>
<td>Itchgrass</td>
<td>100</td>
<td>78</td>
<td>136</td>
<td>185</td>
</tr>
<tr>
<td></td>
<td>150</td>
<td>7</td>
<td>18</td>
<td>52</td>
</tr>
<tr>
<td></td>
<td>200</td>
<td>5</td>
<td>11</td>
<td>33</td>
</tr>
</tbody>
</table>

† Divine nightshade and itchgrass percent emergence reduction data for 100°C were fitted to the two-parameter exponential growth model \(y = a\exp(bx)\), and data for 150 and 200°C were fitted to the two-parameter exponential rise to maximum model \(y = a[1 - \exp(-bx)]\), where \(y\) is percent weed emergence reduction, \(a\) is the maximum emergence reduction value, \(b\) is a rate constant that determines the steepness of the curve, and \(x\) is exposure time.
germination by 48 to 62% when compared with nondry heated seeds.

The study showed that itchgrass and divine nightshade seed could be controlled with dry heat, but survival was dependent on the duration of heat exposure for each temperature level. Divine nightshade seed within their fluid-filled fruit were more resilient than itchgrass when exposed to 150 and 200°C for 20 to 40 s. Burning post-harvest sugarcane residue is a common practice in Louisiana in part because post-harvest residue retention has shown to negatively affect ratatou yield in the subsequent season (Viator et al., 2009). In addition to crop yield loss from post-harvest residue retention, residue can intercept soil-applied pre-emergence herbicides and allow weeds to germinate and compete with sugarcane (Carbonari et al., 2016). A report by Ball-Coelho et al. (1993) showed burned post-harvest sugarcane residue could result in a maximum flame temperature of 121 to 288°C. Other researchers reported that burning crop residue was an effective strategy to control surface-deposited wild radish and annual ryegrass seed (Walsh and Newman, 2007).

Weed seed buried within the top 2 cm in coarse-textured soils were potentially more susceptible to heat when compared with fine-textured and muck soils when pre-harvested sugarcane was burned (Sandhu et al., 2013). In Louisiana, sugarcane is produced in a subtropical environment characterized by cool winter temperatures, high rainfall amounts, and ephemeral flooding. Mixing post-harvest sugarcane residue with mud and stagnant water will reduce the potential fuel load and possibly compromise burn temperature and/or burn duration. There is the potential for a weed species to become more abundant because of low thermal temperatures, and data from this study suggested this to be true because no itchgrass emerged when exposed to 150°C for 40 s and 200°C for 20 s, but 51 and 71% of divine nightshade emerged at these same temperatures and exposure durations, respectively. The quantity of post-harvest sugarcane residue deposited on the soil surface may be influenced by crop age and cultivar (Richard, 1999). The quantity of post-harvest residue deposited on the soil surface after green-cane harvesting ranged from 3.76 to 9.2 Mg ha−1 (Richard, 1999; Viator et al., 2006); therefore, future research will determine the effect of burning post-harvest sugarcane residue on itchgrass and divine nightshade emergence in field conditions.

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