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Nomenclature:
Barnyardgrass; *Echinochloa crus-galli* (L.) P. Beauv.; Italian ryegrass; *Lolium perenne* L. ssp. *multiflorum* (Lam.) Husnot; hemp sesbania; *Sesbania herbacea* (Mill.) McVaugh; johnsongrass; *Sorghum halepense* (L.) Pers.; Palmer amaranth; *Amaranthus palmeri* (S.) Watson; pitted morningglory; *Ipomoea lacunosa* L.; prickly sida; *Sida spinosa* L.; sicklepod; *Senna obtusifolia* (L.) Irwin & Barneby; velvetleaf; *Abutilon theophrasti* Medik.; soybean; *Glycine max* (L.) Merr.

Keywords:
Harvest weed seed control; kiln; weed seed viability; cultural practices

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Seed destruction of weeds in southern US crops using heat and narrow-windrow burning

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Abstract

Narrow-windrow burning has been a successful form of harvest weed seed control in Australian cropping systems, but little is known about the efficacy of narrow-windrow burning on weed seeds infesting U.S. cropping systems. An experiment was conducted using a high-fire kiln that exposed various grass and broadleaf weed seeds to temperatures of 200, 300, 400, 500, and 600 C for 20, 40, 60, and 80 s to determine the temperature and time needed to kill weed seeds. Weeds evaluated included Italian ryegrass, barnyardgrass, johnsongrass, sicklepod, Palmer amaranth, prickly sida, velvetleaf, pitted morningglory, and hemp sesbania. Two field experiments were also conducted over consecutive growing seasons, with the first experiment aimed at determining the amount of heat produced during burning of narrow windrows of soybean harvest residues (chaff and straw) and the effect of this heat on weed seed mortality. The second field experiment aimed to determine the effect of wind speed on the duration and intensity of burning narrow windrows of soybean harvest residues. Following exposure to the highest temperature and longest duration in the kiln, only sicklepod showed any survival (<1% average); however, in most cases, the seeds were completely destroyed (ash). A heat index of only 22,600 was needed to kill all seeds of Palmer amaranth, barnyardgrass, and Italian ryegrass. In the field, all seeds of the evaluated weed species were completely destroyed by narrow-windrow burning of 1.08 to 1.95 kg m^{-2} of soybean residues. The burn duration of the soybean harvest residues declined as wind speed increased. Findings from the kiln and field experiments show that complete kill is likely for weed seeds concentrated into narrow windrows of burned soybean residues. Given the low cost of implementation of narrow-windrow burning and the seed kill efficacy on various weed species, this strategy may be an attractive option for destroying weed seed.

Introduction

Chemical weed control options have been steadily decreasing over the last two decades because of increasing herbicide resistance in dominant weed species. There is a need to shift weed control programs toward strategies that involve the use of nonchemical approaches in conjunction with current herbicide programs if herbicides are to continue as a sustainable and effective option for growers. Slowing selection for herbicide resistance involves implementing several different techniques, some of which may include tillage, rotating and mixing herbicide sites of action, cover crops, and implementing a weed control technique known as harvest weed seed control (HWSC) (Norsworthy et al. 2012). Harvest weed seed control systems target weed seeds collected during crop harvest with the aim of preventing their input into the soil seedbank (Walsh et al. 2013), thereby reducing selection for herbicide resistance.

Harvest weed seed control strategies are currently being investigated to determine their potential fit for weed management programs in U.S. crop production systems. Harvest weed seed control, more specifically narrow-windrow burning, is a widely adopted practice for destroying rigid ryegrass (*Lolium rigidum* Gaudin) seed and decreasing the soil seedbank when growing wheat (*Triticum aestivum* L.), canola (*Brassica napus* L.), and lupin (*Lupinus angustifolius* L.) in Australia (Walsh et al. 2013). In southern U.S. soybean production systems, there is an opportunity to use narrow-windrow burning of chaff and straw residues in an effort to destroy weed seed that escaped a weed management program and are harvested with the crop (Norsworthy et al. 2016).

Weeds that have escaped chemical control methods and are allowed to continue to grow and produce seed become major contributors to the soil seedbank. Palmer amaranth has been found to retain more than 97% of its total seed production for the growing season at soybean maturity

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(Schwartz et al. 2016). Weed seed that is retained and enters the combine during harvest is normally redistributed across fields, thereby helping to replenish the soil seedbank each year (Shirtliffe and Entz 2005; Walsh and Powles 2007). Seed of weeds, such as Palmer amaranth and common cocklebur (*Xanthium strumarium* L.), collected by the combine during soybean harvest, predominantly exit in the chaff and straw fractions (Green 2019). Capturing and destroying these seed through HWSC practices to prevent seedbank inputs is paramount to the management of these major weed species.

In Australia, HWSC is widely used, with narrow-windrow burning being the most commonly used option (Walsh et al. 2017). This adoption was facilitated by research comparing the efficacy of burning narrow windrows as opposed to burning standing wheat stubble on the seed survival of problematic species such as rigid ryegrass and wild radish (*Raphanus raphanistrum* L.). For the narrow-windrow burns, temperatures at the soil surface were sufficiently high for a long enough duration to destroy the seeds of rigid ryegrass and wild radish; however, burning standing stubble remaining after harvest did not produce the required duration of high temperatures (Walsh and Newman 2007; Walsh et al. 2013). The low cutting height and high amount of biomass that enters the combine during harvest make soybean a favorable candidate to potentially burn and destroy seed from weed escapes in the field.

In southern U.S. crop production systems, two of the most troublesome weeds are Palmer amaranth and barnyardgrass (Riar et al. 2013; Schwartz-Lazaro et al. 2018; WSSA 2017). Palmer amaranth has documented resistance to herbicides that inhibit microtubule assembly, very long chain fatty acid elongase, acetolactate synthase, 5-enolpyruvylshikimate-3-phosphate synthase, photosystem II, 4-hydroxyphenylpyruvate dioxygenase, and protoporphyrinogen oxidase (Brabham et al. 2019; Heap 2019; Varanasi et al. 2018). Barnyardgrass is the most problematic weed of rice (*Oryza sativa* L.), a crop that is routinely grown in rotation with soybean in the southern United States. Additionally, jungle rice (*Echinochloa colona* L.), a close relative of barnyardgrass, has recently evolved resistance to glyphosate in the southern United States, further limiting control options (Nandula et al. 2018). As resistance continues to increase and become more widespread, effective herbicide options decrease. Stewardship of remaining effective herbicide options must be a priority for successful weed management (Norsworthy et al. 2012), requiring growers to diversify weed management tactics. Previous research has shown that narrow-windrow burning can be successful in reducing the population of Palmer amaranth (Norsworthy et al. 2016).

Understanding the efficacy of narrow-windrow burning in soybean requires that multiple weed seeds, ranging from small to large, be evaluated for their response to combinations of burning temperatures and durations. Other notable weeds of concern would be species such as barnyardgrass (small-seeded grass), johnsongrass (large-seeded grass), and pitted morningglory (large-seeded broadleaf). Like Palmer amaranth, barnyardgrass has been shown to be resistant to multiple herbicide sites of action (Heap 2019). Johnsongrass is considered the most troublesome weed in grain sorghum [*Sorghum bicolor* (L.) Moench] and corn (*Zea mays* L.) (SWSS 2012). Johnsongrass has been shown to be resistant to glyphosate in the state of Arkansas (Heap 2019) and can cause substantial yield loss if left untreated in a field. Pitted morningglory is also ranked in the top 10 most troublesome weeds of multiple crops including soybean, corn, and grain sorghum (SWSS 2012, 2013). Pitted morningglory can cause significant yield reduction in soybean (Howe and Oliver 1987; Norsworthy and Oliver 2002), interfere with harvest, and persist for long periods in the soil seedbank (Egley and Chandler 1983).

Harvest weed seed control can be implemented by using various tactics, including narrow-windrow burning, chaff carts, the bale-direct system, or impact mills such as the integrated Harrington Seed Destructor (Walsh et al. 2013). The low cost of implementing narrow-windrow burning makes this strategy an attractive option; however, the efficacy of narrow-windrow burning on various weed seeds that may pass through the combine at harvest is unknown and expected to be different for weed species that differ in size. In previous research by Walsh and Newman (2007), the destruction of rigid ryegrass and wild radish differed with temperature and duration of temperature. The objective of this research was to examine the specific temperature and duration requirements needed to kill the seed of problematic weeds of southern U.S. cropping systems. This research is crucial for estimating the potential efficacy of narrow-windrow burning on weeds common to soybean production systems. Additionally, the efficacy of narrow-windrow burning following soybean grain harvest on Palmer amaranth, barnyardgrass, johnsongrass, and pitted morningglory was evaluated to assess the effectiveness of the tactic in killing seed of these weeds prior to entry into the soil seedbank. It was hypothesized that narrow-windrow burning of soybean harvest residues produced during the harvest of a typical irrigated soybean crop will be successful in destroying seed of major weed species of southern U.S. crops.

Materials and Methods

An experiment was conducted at the Altheimer Laboratory (35.0948 N, 94.1733 W; 384 m elev) located in Fayetteville, AR, to determine the temperature and duration needed to kill the seed of Palmer amaranth, barnyardgrass, johnsongrass, pitted morningglory, hemp sesbania, prickly sida, sicklepod, velvetleaf, and Italian ryegrass. These small- and large-seeded grasses and broadleaves, as well as the weed species with hard seed coats (i.e., pitted morningglory, hemp sesbania, sicklepod, and velvetleaf), were evaluated because they are weeds that frequently occur in southern United States soybean fields.

Viability was initially determined for the seed of each weed species using tetrazolium chloride (Wharton 1955). Once viability was determined, 100 seeds of each species, with the exception of barnyardgrass, were counted into separate packets. For barnyardgrass, samples of 200 seeds were used because of the lower viability of the available seed lot. The seed samples were then emptied into porcelain crucibles measuring 4 cm in height and 5 cm at the top outside diameter (Cole-Parmer, Vernon Hills, IL), placed inside a high-fire kiln (Paragon Industries, L. P. Mesquite, TX), and subjected to 20 combinations of temperature (200, 300, 400, 500, and 600 C) durations (20, 40, 60, 80 s). For the kiln used in this experiment, a burn was considered acceptable if the temperature inside the kiln varied no more than ±10 C of each experimental temperature. Viability of the seeds evaluated prior to burning were accounted for when calculating survival percentage.

The specified temperatures and times for burning seed in this experiment allowed for a calculation of heat index (HI). Heat index is calculated by summing the temperature achieved above ambient for each second duration of heat exposure. The ambient temperature at the time of this experiment was 23.9 C. The experiment was conducted in two runs with two replications per run. After heat treatment, seeds of pitted morningglory, hemp sesbania, sicklepod,

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and velvetleaf were scarified or sliced with a razor blade and placed between two filter papers soaked with a 1% w/v tetrazolium chloride solution for approximately 24 h before checking for germination and staining. Seeds of Palmer amaranth, barnyardgrass, johnsongrass, prickly sida, and Italian ryegrass were soaked between two filter papers soaked with the same tetrazolium chloride solution for approximately 48 h before being sliced to assess staining. A seed was considered viable if the seed had germinated or if 10% of the internal seed structure was stained pink to red. Results for live seed were then converted into a percentage of survivors based on the viability of the unburned controls so that a seed kill rate (mortality) could be determined for each weed species (Equation 1).

$$(\text{Viable seed evaluated} - \text{Surviving seed})/\text{Viable seed evaluated} \times 100 \quad [1]$$

Effectiveness of Narrow-windrow Burning Soybean Harvest Residues on Weed Seed Kill

A field experiment was conducted at the University of Arkansas Northeast Research and Extension Center (35.6720 N, 90.0844 W; 70 m elev) in Keiser, AR, in 2014 and 2015 in a production field of Credenz 4950LL (Bayer CropScience, St. Louis, MO) soybean grown under irrigated conditions to assess the heat intensity and efficacy of killing the seeds of Palmer amaranth, barnyardgrass, johnsongrass, and pitted morningglory. Because the amount of soybean residue will probably affect the heat intensity of burning, narrow windrows with increasing levels of residue were created by harvesting increasingly wider soybean plots (4.8 to 9.6 m) with a Case 2388 combine (Case IH, Mount Pleasant, WI) fitted with a 9.1-m-wide header. This range in plot widths was equivalent to 5 to 10 soybean rows, where one soybean row was added (0.96 m width) for each increase in plot width. The 5 rows harvested represented a low-yielding environment, and the 10 rows represented a normal yield for a typical irrigated, high-yielding soybean, which was approximately 4,700 kg ha^{-1} each year. The length of row was in excess of 10 m for each narrow-windrow burn that was evaluated. After harvest, 1 m of row was collected from each narrow-windrow treatment near the end of the 10-m row. Samples were weighed in the field and were returned to the Altheimer Laboratory in Fayetteville to be dried. Just prior to burning, 100 seeds each of Palmer amaranth, barnyardgrass, johnsongrass, and pitted morningglory were placed beneath the windrow on the soil surface in separate 5-cm-diam aluminum tins to assess weed seed kill of the burn treatments. The temperature at the location of the weed seed was recorded every second throughout the burn using an Omega Engineering Type K thermocouple and data logger (Omega® Engineering Inc., Stamford, CT).

The data logger allowed for a calculation of HI and effective burn time (EBT). Effective burn time is similar to HI but is only the number of seconds that a burn is above a specified temperature. For example, in this experiment, EBT 200 is the designation used for the number of seconds that a burn was above 200 C. Immediately after burning, the weed seed–containing aluminum tins were collected and returned to the Altheimer Laboratory for germination and viability assessments. Seeds that were recovered from the burns were completely ash, with the exception of pitted morningglory. To ensure that no seed was missed in the ash, germination tests were conducted in an incubator set at 40 C with a 16-h day and 8-h night for each weed species for 14 d. In preparation for the germination test, the ash from the tins was placed in Petri dishes lined with filter paper and moistened with a 1% v/v Captan solution (Captan 4 Flowable; Drexel, Memphis, TN) as needed. At the end of the 14-d period, Petri dishes were examined for any germinated or nongerminated seed. For pitted morningglory, seeds were additionally stained using 1% w/v tetrazolium chloride to test for viability.

Effect of Wind Speed on Narrow-windrow Burning

In 2014 and 2015, the impact of wind speed on HI and EBT was assessed using a Stihl BG 55 leaf blower (Stihl Holding AG & Co. KG, Waiblingen, Germany). For this experiment, an anemometer was placed within 10 cm of the windrow, and a leaf blower was positioned to create a predetermined wind speed parallel to the row. An Omega Engineering data logger was placed under the narrow windrow at the time of burning, and temperatures were recorded every 1 s until temperatures peaked. Heat index and EBT calculations were based on the data logger readings in the same manner as described in the previous field experiment.

Statistical Analyses

Data from the kiln experiment averaged across runs were subjected to regression analysis using Equation 2:

$$y = B_0 + B_1x_1 + B_2x_2 + B_3x_1x_2 \quad [2]$$

where y = percent survival, B_0 = intercept, B_1 = temperature (C), B_2 = time (s), and B_3 = the coefficient of the product term for x_1 x x_2. A linear model (Equation 3) was also used to determine the relationship between HI and percent survival:

$$y = B_0 + B_1x_1 \quad [3]$$

where y = percent survival, B_0 = intercept, B_1 = slope estimate for HI.

A determination of lowest HI where no survival was observed was chosen once 0% survival was reached, and no data points after were > 0%.

Data from the field experiment evaluating the influence of soybean biomass (residues) on narrow-windrow burning were fit using Equation 4 with data combined across site-years:

$$y = B_0 + B_1x_1 + B_2x_2 \quad [4]$$

where y = response (HI, EBT 200), B_0 = intercept, B_1 = regression coefficient for soybean residues (kg m^{-2}), and B_2 = regression coefficient for wind speed (m s^{-1}).

Data for the field experiment evaluating the impact of wind speed on narrow-windrow burning were fit to a linear model where y = response (HI and EBT 200), B_0 = intercept, and B_1 = slope estimate for wind speed (m s^{-1}).

For all experiments, data were fit in the FIT MODEL platform in JMP Pro 13 (SAS Institute Inc., Cary, NC).

Results and Discussion

Heat Effects on Weed Seed Survival

Palmer amaranth, barnyardgrass, hemp sesbania, sicklepod, velvetleaf, and Italian ryegrass seed survival were regressed using temperature and duration of exposure as explanatory variables

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Table 1. Parameter estimates and P values from a multiple-regression model[a] for a high-fire kiln experiment conducted on nine species at the Altheimer Laboratory in Fayetteville, AR.

Species	Intercept (B_0)	P value	Temp C (B_1)	P value	Time s (B_2)	P value	Temp × time (B_3)	P value
Palmer amaranth	152 ± 11.2	< 0.0001	−0.3 ± 0.02	< 0.001	−0.4 ± 0.1	0.002	0.002 ± 0.001	0.061
Barnyardgrass	143 ± 8.9	< 0.0001	−0.2 ± 0.02	< 0.001	−0.6 ± 0.1	< 0.001	0.003 ± 0.001	0.001
Johnsongrass	175 ± 9.2	< 0.0001	−0.3 ± 0.02	< 0.001	−0.7 ± 0.1	< 0.001	–	–[b]
Pitted morningglory	193 ± 8.4	< 0.0001	−0.3 ± 0.02	< 0.001	−0.8 ± 0.1	< 0.001	–	–
Prickly sida	188 ± 14.0	< 0.0001	−0.3 ± 0.03	< 0.001	−0.9 ± 0.2	< 0.001	–	–
Italian ryegrass	174 ± 9.7	< 0.0001	−0.3 ± 0.02	< 0.001	−0.6 ± 0.1	< 0.001	0.001 ± 0.001	0.098
Sicklepod	217 ± 9.5	< 0.0001	−0.2 ± 0.02	< 0.001	−1.1 ± 0.1	< 0.001	−0.004 ± 0.001	< 0.001
Velvetleaf	202 ± 10.9	< 0.0001	−0.3 ± 0.02	< 0.001	−1.0 ± 0.1	< 0.001	–	–
Hemp sesbania	182 ± 7.6	< 0.0001	−0.2 ± 0.01	< 0.001	−0.9 ± 0.1	< 0.001	−0.002 ± 0.001	0.002

[a]Model equation: $y = B_0+B_1x_1+B_2x_2+B_3x_1x_2$.
[b]–, No significance.

(Table 1). It is well established that the duration of exposure needed to kill weed seed is lessened as temperature increases to a level typically observed when burning crop residues (Hoyle and McElroy 2012; Thompson et al. 1997; Walsh and Newman 2007; White and Boyd 2016). Likewise, our study found that lengthening the exposure period reduced the temperature needed to achieve mortality of weed seeds evaluated, a result similar to findings in other studies (Egley 1990; Hoyle and McElroy 2012; Walsh and Newman 2007). Seeds of each species tested in this experiment, with the exception of sicklepod, were killed at or before the highest temperature and longest exposure tested, which was 600 C for 80 s (HI = 46,088) (Figures 1 and 2). Using Figure 1, one can estimate the minimum temperature and duration combinations for each weed species necessary to achieve complete mortality, excluding sicklepod. Regardless of species, no seed kill was completely achieved at 200 C for any time tested. These temperature requirements for complete seed kill differ from those for common weeds of turf, where only 5 s at 200 C or 20 s at 150 C was needed to achieve 100% mortality of Virginia buttonweed (*Diodia virginiana* L.), cock's comb killinga (*Kyllinga squamulata* Thonn. ex Vahl), and large crabgrass [*Digitaria sanguinalis* (L.) Scop] (Hoyle and McElroy 2012).

As expected, seed size had some impact on the amount of heat needed to kill each of the nine species. For example, small-seeded species, such as Palmer amaranth and barnyardgrass, showed complete mortality when the seed was exposed to temperatures of 400 C for at least 60 s (HI = 22,566) or 500 C for 40 s (HI = 19,044). However, species with larger seed size and hard seed coats, such as pitted morningglory and sicklepod, required more heat for near or complete seed kill, needing 500 C for 80 s (HI = 38,088) and 600 C for 80 s (HI = 46,088), respectively. Conversely, Egley (1990) found seeds of redroot pigweed, similar in size to Palmer amaranth, and johnsongrass to be more resistant to 70 C exposure for 7 d than prickly sida, spurred anoda [*Anoda cristata* (L.) Schltdl.], and pitted morningglory based on seed viability. We are uncertain why weeds like spurred anoda and pitted morningglory that exhibit physical dormancy as a result of a hard seed coat were more prone to death by heat than the smaller seeded redroot pigweed in Egley's research (1990).

Heat Index and Seed Survival

Heat index was a weak predictor of percent survival in the mid-range of heat indexes tested (Table 2). For velvetleaf as well as the other weeds evaluated, a low HI had little effect on weed seed as expected; however, as HI increased there appeared to be a critical value at which a rapid decline in survival occurred (Figure 3). For instance, velvetleaf survival declined sharply beyond a HI of 15,000.

The survival determined by Walsh and Newman (2007) for rigid ryegrass at the temperatures and exposure durations evaluated was lower than that for Italian ryegrass in our experiment (Figure 1). One reason for the differences in results may lie in the method by which viability was evaluated. Walsh and Newman (2007) classified seed as viable if germination occurred or if the seed remained firm and was not decayed, whereas germination and tetrazolium staining of seed were used in our experiment to test for viability.

Previous research has been conducted to test weed seed viability after being exposed to various temperatures and durations. The seeds of barnyardgrass, tumble pigweed (*Amaranthus albus* L.), annual sowthistle (*Sonchus oleraceus* L.), London rocket (*Sisymbrium irio* L.), common purslane (*Portulaca oleracea* L.), and black nightshade (*Solanum nigrum* L.) were subjected to temperatures ranging from 39 C to 70 C (Dahlquist et al. 2007). As temperature increased for each species, viability decreased, showing that weed seed mortality is attainable by heating. Previous research has also been conducted to determine the efficacy of heat through composting on killing weed seed. According to Wiese et al. (1998), the seeds of pigweed (*Amaranthus hybridus* L. and *Amaranthus palmeri* S. Wats.), barnyardgrass, johnsongrass, kochia [*Bassia scoparia* (L.) A. J. Scott], grain sorghum, and field bindweed (*Convolvulus arvensis* L.) could all be destroyed when the seeds were exposed to temperatures of at least 49 C for 3 d during composting. However, under drier conditions seed survival is much greater, as evidenced by 87% survival of johnsongrass and 100% survival of redroot pigweed following a 7-d exposure to 70 C in a soil having a 1.8% moisture content (Egley 1990).

Effect of Soybean Residue and Wind Speed on Narrow-windrow Burning

For the soybean harvest residue burning experiment, HI values ranged from a low of 20,800 to a high of 659,000 in soybean. These HI values are generally an order of magnitude higher than those reported for wheat (30.6×10^3) in Australia (Walsh and Newman 2007). As expected, the amount of soybean residue present at the time of burning did have an effect on HI and

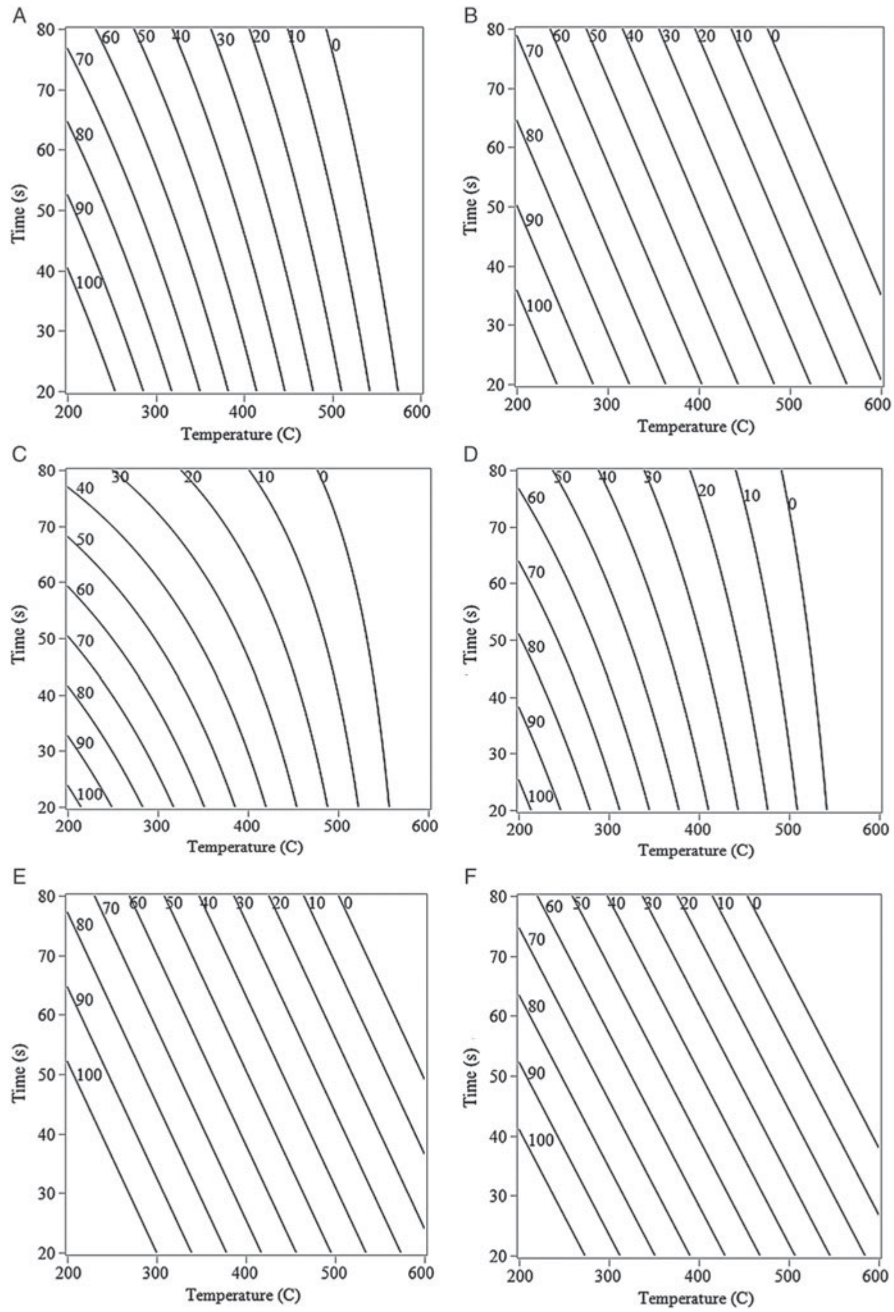

Figure 1. Contour maps for (A) Italian ryegrass, (B) johnsongrass, (C) barnyardgrass, (D) Palmer amaranth, (E) pitted morningglory, and (F) prickly sida survival after exposure to various temperature and heating periods in a high-fire kiln at the Altheimer Laboratory in Fayetteville, AR.

EBT (Table 3). The greater the amount of residue, the greater the HI and EBT. Residue amounts following harvest ranged from 1.95 kg m^{-2} for the 10-row harvested width to 1.78 kg m^{-2}, 1.63 kg m^{-2}, 1.40 kg m^{-2}, 1.26 kg m^{-2}, and 1.08 kg m^{-2} for the 9, 8, 7, 6, and 5-row harvested widths, respectively. At the highest residue amount of 1.95 kg m^{-2}, the EBT 200 was predicted to be 846 s (Table 3), which is considerably longer than the EBT 200 of 264 s for wheat stubble at 2.8 kg m^{-2} in Australia (Walsh and Newman 2007). It is likely that the wheat stubble in the Australian study had lower moisture content than the soybean residue, hence the longer burn of the soybean residue.

In the wind speed experiment, wind speed did have an effect ($P = 0.015$, $P = 0.014$) on HI and EBT 200, respectively (Table 4). As wind speed increased, the HI and EBT 200 decreased rapidly.

Weed Seed Survival in Narrow-windrow Burn

Regardless of the HI and EBT achieved, all seeds of Palmer amaranth, barnyardgrass, johnsongrass, and pitted morningglory were killed when the narrow windrows were burned (data not shown). In fact, the seeds of Palmer amaranth, barnyardgrass, and johnsongrass were burned to ash. Pitted morningglory, as expected, had the

Table 2. Parameter estimates, P values, heat index (HI) where seed death begins, and HI where all seeds are killed from a linear regression model[a] for nine weed species from a high-fire kiln experiment conducted at the Altheimer Laboratory in Fayetteville, AR.

Species	Intercept (B_0)	P value	HI (B_1)	P value	HI (initial kill)[b]	HI (complete kill)[c]
Palmer amaranth	101 ± 4.2	< 0.001***[d]	0.0001 ± 0.0008	0.856	7,040	22,600
Barnyardgrass	100 ± 5.9	0.001***	–[e]	–	3,520	22,600
Johnsongrass	98.5 ± 7.4	< 0.001***	−0.004 ± 0.001	0.766	7,520	30,100
Pitted morningglory	100 ± 5.3	< 0.001***	0.0002 ± 0.0009	0.814	7,520	34,600
Prickly sida	93.3 ± 32.4	0.035***	0.0019 ± 0.007	0.802	5,520	23,000
Italian ryegrass	104 ± 1.0	< 0.001***	–	–	3,520	22,600
Sicklepod	115 ± 6.9	< 0.001***	−0.0003 ± 0.001	0.820	7,520	N/A[f]
Velvetleaf	105 ± 4.3	< 0.001***	0.00007 ± 0.0005	0.894	11,000	23,000
Hemp sesbania	97.5 ± 6.7	< 0.001***	−0.0005 ± 0.001	0.669	7,520	23,000

[a]Model equation: $y = B_0+B_1X_1$.
[b]HI (initial kill), highest HI achieved before seeing a significant decrease in percent survival.
[c]HI (complete kill), lowest HI where survival was zero across all replications.
[d]***, Significant at $\alpha = 0.001$.
[e]–, No P value obtained because of rapid decrease in percent survival from lowest HI tested.
[f]N/A, Zero not reached at the highest HI tested.

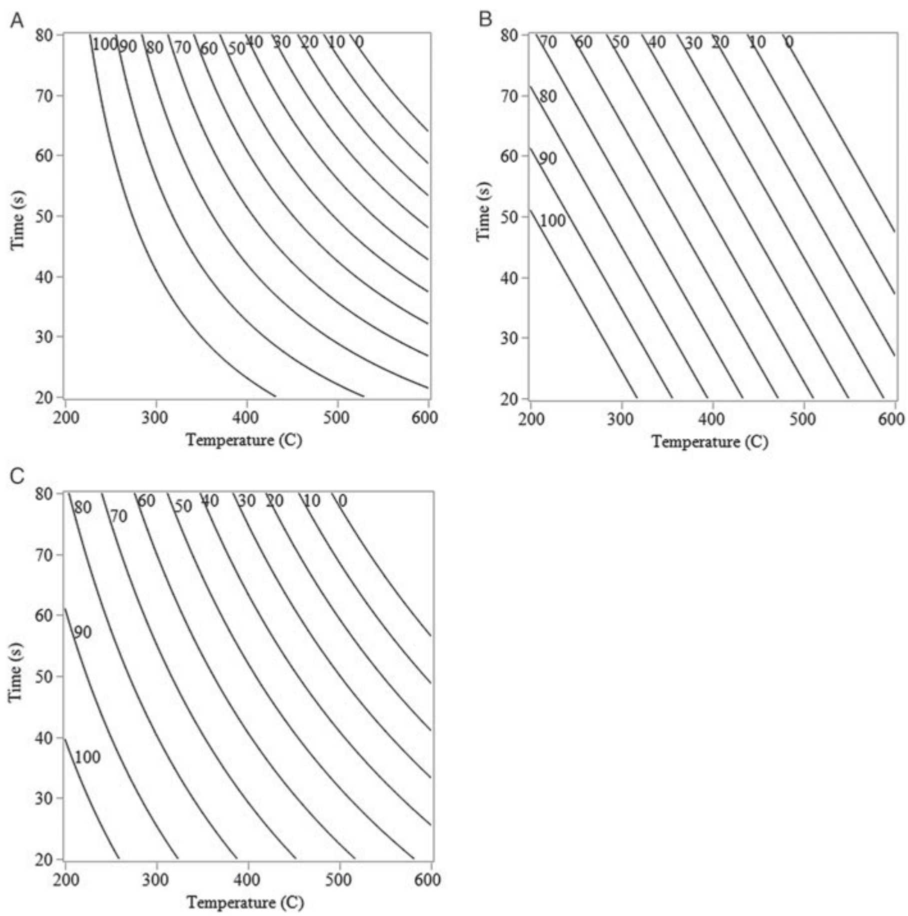

Figure 2. Contour maps for (A) sicklepod, (B) velvetleaf, and (C) hemp sesbania survival after exposure to various temperature and heating periods in a high-fire kiln at the Altheimer Laboratory in Fayetteville, AR.

most resistant seeds and remained intact; however, these seeds were not viable. These data align with those of Walsh and Newman (2007) and Lyon et al. (2016), who reported that a high percentage of wild radish (96%) and Italian and rigid ryegrass (99%) could be killed with narrow-windrow burning in wheat. The duration of temperatures during burning of a typical narrow-windrow soybean plot is shown in Figure 4. The slightly higher weed seed kill rate when burning narrow windrows of soybean than for wheat is attributed to the greater HI for soybean based on the values reported by Walsh and Newman (2007) for wheat.

Practical Implications

Complete control of seeds expelled from the combine is possible through narrow-windrow burning of soybean residues. The

Table 3. Parameter estimates and P values for the regression models[a] for heat index (HI) and effective burn time in seconds above 200 C (EBT 200) from a narrow-windrow burning field experiment conducted in 2014 and 2015 at the Northeast Research and Extension Center in Keiser, AR.

	Parameters	Estimates	P value
HI	Intercept (B_0)	16,300 ± 59,700	0.786[d]
	Slope residue (B_1)	149,000 ± 32,400[b]	< 0.001
	Slope wind speed (B_2)	−21,200 ± 12,600[c]	0.099
EBT 200	Intercept (B_0)	142 ± 175	0.419
	Slope residue (B_1)	434 ± 94.8	< 0.001
	Slope wind speed (B_2)	−60.9 ± 36.7	0.104

[a]Model equation: $y = B_0+B_1x_1+B_2x_2$.
[b]Soybean residue following harvest is expressed in kg m^{-2}.
[c]Wind speed is expressed in m s^{-1}.
[d]P value ≤ 0.05 is significant.

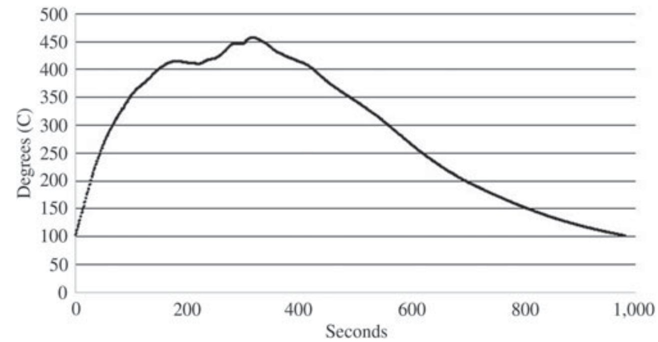

Figure 4. Time and temperatures observed from a typical plot while narrow-windrow burning soybean harvest residues at the Northeast Research and Extension Center in Keiser, AR.

Table 4. Parameter estimates and P values from a nonlinear regression model[a] for heat index (HI) and effective burn time in seconds above 200 C (EBT 200) from narrow-windrow burning experiments where wind speed was created using a leaf blower in 2014 and 2015 at the Northeast Research and Extension Center in Keiser, AR.

	Parameters	Estimates	P value
HI	Intercept (B_0)	36,600 ± 7,400	< 0.001[c]
	Slope wind speed[b] (B_1)	−5,360 ± 2,030	0.015
EBT 200	Intercept (B_0)	106 ± 23.9	< 0.001
	Slope wind speed (B_1)	−17 ± 6.4	0.014

[a]Model equation: $y = B_0+B_1x_1$
[b]Wind speed is expressed as m s^{-1}.
[c]P value ≤ 0.05 is significant.

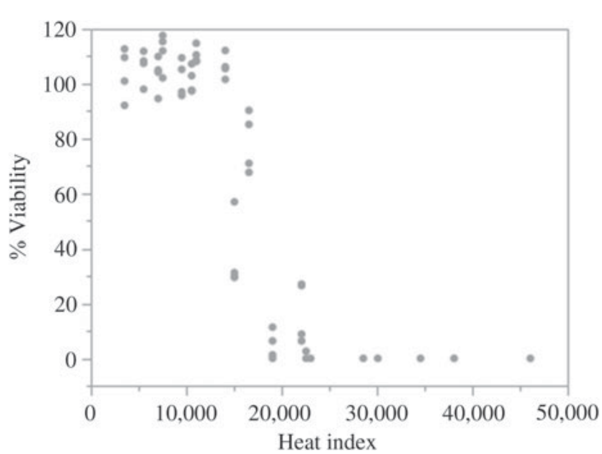

Figure 3. Relationship between heat index and percent viability of velvetleaf as an example of the results from the kiln experiment at the Altheimer Laboratory in Fayetteville, AR.

calculated HI values needed for complete mortality of the nine weed species evaluated in the kiln study was easily achieved in the narrow-windrow burning experiments in the field. In the kiln experiment, seeds of all evaluated species, except sicklepod, were killed at an HI of 34,600 (Table 2). Heat index calculations from narrow-windrow burning experiments showed that values ranged from 20,800 to 659,000, with an average of 242,000 across all burns, regardless of the amount of soybean residue present. If weed seed is taken into the combine at harvest, and subsequently subjected to narrow-windrow burning, the likelihood is high for destruction of all seeds encountered in soybean production systems. Given the validation of weed seed kill in narrow-windrow burning by the results from the kiln experiment, growers may consider utilizing narrow-windrow burning to diminish the return of weed seed to the soil seedbank and thereby reduce selection for herbicide-resistant weeds.

Herbicide-resistant weeds will continue to evolve and decrease the effectiveness of chemical control strategies if herbicide programs are not diversified. Harvest weed seed control, in particular narrow-windrow burning, has been shown to be effective in decreasing the number of weed seed that returns to the soil seedbank in both wheat (Lyon et al. 2016; Walsh and Newman 2007) and soybean. The low cost of setting up a narrow-windrow burning chute (~US $200) and the effectiveness of narrow-windrow burning, as shown here, will make this burning strategy a valuable option, as long as burning continues to be permissible in regions of the United States where farmland predominates.

The positive aspect of this strategy is that even if a farmer is already plagued with herbicide-resistant weeds, narrow-windrow burning will still destroy weed seed that would normally be returned to the soil seedbank and thus, over time, would reduce the number of weeds present in the field. A diminished seedbank, coupled with an effective herbicide program, will help to improve weed control throughout the growing season. However, one limiting factor to narrow-windrow burning is that the amount of weed seed within each narrow windrow is dependent on the seed retention of the weed species present and the ability to get these seed into the combine. For example, previous research on Palmer amaranth and barnyardgrass has shown that each plant retains approximately 97% and 43%, respectively, of the total seed produced when soybean matures (Schwartz et al. 2016; Schwartz-Lazaro et al. 2017). The higher the percentage of seed retention, the more weed seed will enter the combine at harvest and subsequently be placed into the narrow windrow for burning. Proper diversification tactics and effective herbicide programs are essential for the future of herbicides that are currently in use. Growers who are looking to diversify their weed management program may consider implementing narrow-windrow burning to increase diversification of their current weed control program and better target the soil seedbank, two vital components of a successful program (Norsworthy et al. 2012).

Several concerns must be addressed when considering burning as a means of weed seed removal. First, there is always a concern about fire escaping from the narrow windrows, and though this may be an issue in small-grain crops, fire escape is unlikely in soybean fields, because the crop is harvested near the soil surface, leaving few residues available for burning outside of each windrow. Although burning of crop residues is permitted in some regions, this practice continues to be intensively scrutinized near urban areas, and local regulations may sometime prevent its use. Furthermore, windrows concentrate carbon and nutrients, and burning of these windrows would result in loss of these crop residues, as ash is easily windblown. Before narrow-windrow burning is widely recommended as a strategy to aid weed management, several additional questions regarding agronomic management practices will have to be answered through additional research. For instance, would removing residue (via burning) from sloped fields lead to increased erosion on certain soils? Does burning have a positive or negative influence on soil microbial activity? Does burning of residue impose a "non-uniform" pattern on the way soil fertility should be managed the following year? Again, implications of narrow-windrow burning on management of the weed seedbank are obvious, but additional research is needed to fully understand how best to integrate such a strategy into current soybean production systems.

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