Weed Technology

www.cambridge.org/wet

Narrow-windrow burning to control seeds of Italian ryegrass (*Lolium perenne* ssp. *multiflorum*) in wheat and Palmer amaranth (*Amaranthus palmeri*) in soybean

Research Article

Cite this article: Spoth MP, Haring SC, Everman W, Reberg-Horton C, Greene WC, Flessner ML (2022) Narrow-windrow burning to control seeds of Italian ryegrass (*Lolium perenne* ssp. *multiflorum*) in wheat and Palmer amaranth (*Amaranthus palmeri*) in soybean. Weed Technol. **36**: 716–722. doi: 10.1017/wet.2022.70

Received: 4 April 2022
Revised: 21 August 2022
Accepted: 7 September 2022
First published online: 19 September 2022

Associate Editor:
Michael Walsh, University of Sydney

Nomenclature:
Italian ryegrass, *Lolium perenne* L. ssp *multiflorum* (Lam.) Husnot. LOLMU; Palmer amaranth, *Amaranthus palmeri* S. Watson, AMAPA; soybean; *Glycine max* (L.) Merr.; wheat, *Triticum aestivum* L.

Keywords:
Harvest weed seed control; heat index; effective burn time; thermal weed seed kill; soil seedbank; weed seed viability; weed seed longevity

Author for correspondence:
Michael L. Flessner, 675 Old Glade Rd., Blacksburg, VA 24061. Email: flessner@vt.edu

Matthew P. Spoth[1], Steven C. Haring[1], Wesley Everman[2], Chris Reberg-Horton[2], Wykle C. Greene[1] and Michael L. Flessner[3]

[1]Graduate Research Assistant, School of Plant and Environmental Sciences, Virginia Tech, Blacksburg, VA, USA; [2]Associate Professor, Department of Crop and Soil Sciences, North Carolina State University, Raleigh, NC, USA and [3]Assistant Professor, School of Plant and Environmental Sciences, Virginia Tech, Blacksburg, VA, USA

Abstract

Narrow-windrow burning (NWB) is a form of harvest weed seed control in which crop residues and weed seeds collected by the combine are concentrated into windrows and subsequently burned. The objectives of this study were to determine how NWB will 1) affect seed survival of Italian ryegrass in wheat and Palmer amaranth in soybean and 2) determine whether a relationship exists between NWB heat index (HI; the sum of temperatures above ambient) or effective burn time (EBT; the cumulative number of seconds temperatures exceed 200 C) and the post-NWB seed survival of both species. Average soybean and wheat windrow HI totaled 140,725 ± 14,370 and 66,196 ± 6224 C, and 259 ± 27 and 116 ± 12 s of EBT, respectively. Pre-NWB versus post-NWB germinability testing revealed an estimated seed kill rate of 79.7% for Italian ryegrass, and 86.3% for Palmer amaranth. Non-linear two-parameter exponential regressions between seed kill and HI or EBT indicated NWB at an HI of 146,000 C and 277 s of EBT potentially kills 99% of Palmer amaranth seed. Seventy-six percent of soybean windrow burning events resulted in estimated Palmer amaranth seed kill rates greater than 85%. Predicted Italian ryegrass seed kill was greater than 97% in all but two wheat NWB events; therefore, relationships were not calculated. These results validate the effectiveness of the ability of NWB to reduce seed survival, thereby improving weed management and combating herbicide resistance.

Introduction

Since their introduction, herbicides have been widely adopted to maximize weed control and protect crop yield. Their widespread use led to herbicide-resistant weed populations that now exceed 500 cases and threaten crop production globally (Harker and O'Donovan 2013; Heap 2014, 2022). The overwhelming threat of herbicide resistance (HR) has been a significant driver in producers' search for alternative weed management strategies (Harker and O'Donovan 2013). Solutions intended to slow the development of HR and maintain the productivity of cropping systems have gained attention in scientific and agricultural communities in recent years (Kumar et al. 2013; Norsworthy et al. 2012). Included in this is a renewed focus on weed seedbank dynamics and the increasingly important strategy of targeting weed seeds while they are undispersed on the plant. Preemptive actions can be very successful at limiting problematic weed species such as those that are or have the potential of becoming resistant to herbicides (Walsh and Powles 2007; Walsh et al. 2013). For example, by destroying only 50% of weed seed prior to seedbank deposition, resistance development may be delayed by nearly 10 yr (Somerville et al. 2018).

Harvest weed seed control (HWSC) is an overarching phrase used to describe a variety of technologies and practices designed to capture and concentrate, remove, or destroy weed seeds during crop harvest to limit additions to the weed seedbank (Glasner et al. 2019; Shergill et al. 2020; Walsh et al. 2017a, 2018). HWSC practices have been well established in Australian crop production, where 43% of grain growers routinely had used some form of HWSC as of 2017 (Walsh et al. 2017a). By coupling HWSC with routine harvest processes, Australian growers have been able to reliably, practically, and economically target weed seed to prevent their spread and input into the seedbank in production fields (Walsh and Powles 2014).

The many different systems of HWSC include narrow-windrow burning (NWB), chaff lining, chaff tramlining, chaff carts, bale direct, and seed impact mills (described by Walsh et al. 2013, 2018). The focus of this study is on NWB, in which all crop residue exiting the combine is funneled into a windrow via a chute. Windrows are subsequently ignited, allowed to burn completely, and thus eliminate weed seed viability via thermal kill. Compared to burning entire fields, windrows burn longer at higher temperatures, making it much more effective at killing weed seed (Lyon et al. 2016; Walsh and Newman 2007). Combine modifications are inexpensive and simple to use compared to other HWSC methods, making NWB a popular option for weed seed control (Walsh et al. 2013). In 2017, NWB was the most popular HWSC system in Australia with a 30% adoption rate (Walsh et al. 2017a).

Only a few studies have compared the effects of high temperatures occurring during NWB on weed seed viability (Green et al. 2014; Hoyle and McElroy 2012; Lyon et al. 2016; Norsworthy et al. 2020; Walsh and Newman 2007), but most researchers agree that windrow burning is an effective approach to controlling most weed species. Australian field studies indicate seed kill levels of 99% for both rigid ryegrass (*Lolium rigidum* Gaudin.) and wild radish (*Raphanus raphanistrum* L.) following wheat, canola, and lupin NWB (Walsh and Newman 2007). NWB in Pullman, WA, reduced Italian ryegrass emergence in the following season by 99% (Lyon et al. 2016).

The aggressive growth habit of Italian ryegrass and its prolonged germination from fall until winter wheat canopy closure can pose serious control issues in winter crops of small grains (Bararpour et al. 2017). Additionally, resistance to herbicides from six site-of-action groups has been identified in U.S. populations of Italian ryegrass. Many populations have displayed multiple resistance to Group 1 and Group 2 herbicides (as categorized by the Weed Science Society of America), effectively eliminating all selective postemergence (POST) herbicide options in wheat (Heap 2022). Estimates of harvest seed retention in Italian ryegrass vary among publications. Publications with preliminary data indicate Italian ryegrass retained around 58% of its seed at harvest in the Great Plains region of the United States (Walsh et al. 2018). A more recent study in the Pacific Northwest indicated that seed retention of Italian ryegrass at wheat crop maturity was 40.5% across 6 site-years (San Martín et al. 2021). A close relative, rigid ryegrass, retained 85% of its seed across nine locations of varying weed pressure in Australia at wheat crop harvest (Walsh and Powles 2014).

In Virginia winter wheat fields, HWSC by complete removal of chaff and straw reduced Italian ryegrass tiller density by 30% and 69% in the following season at two locations; however, no differences were observed at a third location (Beam et al. 2019). Similar results were observed by Walsh et al. (2017b), when 1 yr of HWSC including NWB reduced rigid ryegrass populations prior to POST-applied herbicides by 60% on average (reductions ranged from 37% to 90%). Variability in both studies is attributed to differences in initial seedbank densities and Italian ryegrass seed retention and production at harvest. Maity et al. (2022) found that using NWB each year for 4 yr reduced Italian ryegrass soil seedbank size by 78% in Texas, while improving wheat yield. Compared to conventional harvest, NWB reduced Italian ryegrass plant populations during the growing season by 73%, 83%, and 88% in Texas; and by 8%, 55%, and 89% in Arkansas after the second, third, and fourth year of NWB, respectively. In combination with various herbicide treatments, their integrated management program led to large reductions in Italian ryegrass seed survival and annual fecundity (Maity et al. 2022). Problematic status and a lack of regionally specific data in NWB systems makes Italian ryegrass an important candidate for this study.

Palmer amaranth also poses issues to crop production as one of the most economically damaging resistant weed species in corn, soybean, and cotton crops in the United States (Beckie 2006). High fecundity, tolerance to high temperatures and drought, high genetic diversity, and ability to develop HR enables Palmer amaranth to threaten crop yields (Ward et al. 2013; Webster and Nichols 2012). Since the 1993 discovery of acetolactate synthase–resistant Palmer amaranth in Kansas, populations of this weed have evolved multiple resistance mechanisms that confer resistance across eight sites of action (Heap 2022; Horak and Peterson 1995; Ward et al. 2013). Palmer amaranth is, however, a great candidate for HWSC due to its high seed retention at the time of soybean maturity. Multiple studies indicate greater than 95% seed retention at soybean harvest (Schwartz-Lazaro et al. 2017, 2021). Additionally, Palmer amaranth exhibits short longevity in the seedbank, which is important in obtaining relatively quick returns after implementing HWSC (Norsworthy et al. 2008, 2016).

Research examining management of Palmer amaranth with HWSC further indicates the value of HWSC. In combination with herbicide programs, complete field residue removal using a cart or NWB at harvest can reduce Palmer amaranth densities by 37% to 90% in the following year (Norsworthy et al. 2016). NWB was found to be more effective than chaff carts in population reduction (Norsworthy et al. 2016). Beam et al. (2019) observed no differences in Palmer amaranth density between complete residue removal and conventional harvest, which was attributed to overall effective herbicide programs. This study showed promise that there is no yield penalty when implementing HWSC, and it is likely that it will contribute to preventing HR development (Beam et al. 2019). Patterson et al. (2021) reported that NWB alone was 62% more effective at reducing the Palmer amaranth seedbank compared to conventional harvest. In the same study, Palmer amaranth seedbank size increased from 40 to 100 seeds m^{-2} over 3 yr under a POST-only herbicide program. In contrast, the use of NWB in addition to a POST-only herbicide treatment decreased seedbank density from an average of 42 to 18 seeds m^{-2} (Patterson et al. 2021). The problematic status of Palmer amaranth as well as overall success under HWSC in soybean production demands alternative solutions such as NWB, and a determination of the temperature threshold necessary to reduce seed viability.

More research is necessary to understand how effective thermal processes such as NWB are at killing weed seeds at field levels in the United States. Therefore, the objectives of this study were to determine how NWB will 1) affect seed survival of Italian ryegrass in wheat and Palmer amaranth in soybean, and 2) determine whether a relationship exists between the NWB temperature and seed survival of both species. Differences in seed size, dispersal, growth habit, phenology, etc. may play a role in NWB efficacy, which is why these two species were evaluated in separate experiments.

Materials and Methods

Field experiments to evaluate the efficacy of Italian ryegrass and Palmer amaranth control with NWB were established in fields with known infestations of these weed species in soybean and wheat fields in Blackstone, VA (37.082°N, 77.9722°W) and South Hill, VA (36.8322°N, 78.1425°W). Experiments were initiated in fall 2015 and maintained in the same location until fall 2018 for a total of 3 site-years with soybean and 2 site-years with wheat. Each site included multiple HWSC treatments and crop rotations and followed a randomized complete block design with four to five replications per treatment. Herein, we present a subset of data collected from NWB treatments within the experiment. NWB treatment data were collected during (temperature) and after (seed survival) burning of windrows in plots that were 7.5 m × 15 m. Data collection on NWB temperature occurred during wheat NWB for Italian ryegrass and soybean NWB for Palmer amaranth. The sample size (n) is listed in each figure.

In the Italian ryegrass control experiment, winter wheat was grown in a double-crop system with soybean. Winter wheat was planted at 135 kg ha^{-1} with a no-till drill on 20-cm-row spacing. Double-crop soybeans were planted after wheat harvest at 444,600 seeds ha^{-1} with a drill on 35-cm-row spacing. In the Palmer amaranth control experiment, full season soybeans were grown in a no-till system. Soybeans were planted on 76-cm rows at 296,520 seeds ha^{-1}. In both wheat and soybean, all production practices except for herbicide treatments, followed Virginia Cooperative Extension recommendations (Holshouser 2014). The herbicide program mimicked standard grower practices in the area and resulted in uncontrolled weeds at crop harvest due to HR, weed size at application being larger than product label recommendations, or ineffective herbicide selection.

In the Italian ryegrass and Palmer amaranth experiments, plots were harvested with a Gleaner K2 combine (AGCO Corporation, Duluth, GA) with a modified 2.4-m small-grain header or a Wintersteiger Classic combine (Wintersteiger AG, Ried im Innkreis, Austria) with a 1.5-m small-grain header. To effectively mimic an NWB scenario, 0.5-m-wide windrows were formed by replacing the harvester's residue spreader with a chute. The Gleaner combine formed one windrow containing all field residues, per 2.4-m harvest swath, while the Wintersteiger combine was outfitted with chutes that combined three passes of 1.5 m each into a single windrow. Windrows were burned the same day as or the day following harvest. Windrows were ignited at one end with a propane torch, and the fire was allowed to burn along the length of the windrow in each plot until no crop residue remained. Wind speed and direction during burning events was not recorded but was variable. Two temperature loggers (OM-EL-USB-TC-LCD + KQXL-M60U-150; Omega Engineering, Inc., Norwalk, CT) were centered in the width of the windrow at random locations along the 13-m length, and buried in the windrow approximately 1 cm above the soil surface. Loggers recorded temperature once per second from pre-burn until returning to ambient temperature after burning. Temperature data were averaged across the two subsamples for each windrow.

In both weed species experiments, crop residue subsamples and weed seed therein were collected from windrows prior to and after burns were conducted. Welding cloth squares (0.3 by 0.3 m) were placed on the soil surface prior to harvest so that weeds seeds and crop residues covered the square during windrow formation. Welding cloth was chosen as a noncombustible material that minimized heat conduction to weed seeds. Two squares were placed less than 3 m apart from each other, randomly along the 13-m length of the windrow and centered on the width of the windrow in different locations than temperature loggers. One square was collected prior to burning and the other square was collected after burning, creating paired samples. It is important to consider that the precise number of Italian ryegrass or Palmer amaranth seed exposed to NWB is unknown, and no data were collected on the spatial distribution of weeds within plots. Visually, there was an even density across each NWB plot, but quantitative data were not collected to support this, thus introducing some uncertainty in the results of this study. Weed density (per square meter) was collected in each NWB treatment prior to harvest at each site-year. Average weed species density at each site-year was 4.9, 8.3, and 5.0 Palmer amaranth m^{-2} at soybean harvest, and 65.3 or 288 Italian ryegrass m^{-2} at wheat harvest. In soybean, variation of Palmer amaranth density (per square meter) within the field was 8.6%, 18.1%, and 17.0% of the mean (standard error/population mean). In wheat, the same calculation yielded Italian ryegrass density (per square meter) variation to be 8.8% and 9.4% of the mean. Variation across a field is unavoidable; however, the authors believe this variation is low, indicating seeds were likely evenly distributed in the windrow. The assumption is that the number of weed seeds was similar throughout plot windrows due to the visually even weed pressure across plots, low variation within the sampled population across the field, and sample collection within 3 m of each other. Therefore, weed seed collected in pre-NWWB residue samples can be used to estimate the effects of seed post NWB. Since there is some uncertainty in such methodology, reductions in weed seed survival are treated as estimated effects of NWB. To evaluate seed kill, collected residue from each square was spread on top of potting soil in 25-cm by 50-cm trays (one sample per tray). Trays were placed in a greenhouse in Blacksburg, VA (37.231967°N, 80.434754°W), maintained at 15 to 27 C, average relative humidity of 80%, and were watered to maintain adequate moisture for germination. Candidate weed seed emergence was recorded, and seedlings were removed until emergence ceased; typically, a 4-wk period. Trays were then subjected to cold storage for 1 mo at 4.5 C before a second germination period in the greenhouse. The process was repeated for three germination periods, and all emergence was summed across periods for each sample. Seeds that germinated from post-NWB residue samples were considered not killed by NWB, and the difference in emergence between pre-emergence and postemergence were considered killed by NWB.

Two metrics were used to evaluate burning temperature and duration: effective burn time (EBT) and heat index (HI). HI is calculated by summing the temperatures that exceed ambient air temperature during burning at each 1 s duration of heat exposure. Ambient air temperature was calculated using the temperature logger for 3 to 5 min prior to igniting windrows and averaging the temperature across that period. EBT is a measure of how many seconds the burn is above a specified temperature. For this experiment, EBT equals the cumulative number of seconds that the temperature of the burning windrow exceeded 200 C, following the design reported by Norsworthy et al. (2020).

Data were analyzed using JMP Pro 13 software (SAS Institute, Cary, NC) to compare weed population parameters including seed germinability before and after HWSC treatment application, as well as percent survival relationships with HI and EBT. Data were pooled across site-year, and a paired two-tailed t-test ($P < 0.05$) was used for comparisons between pre- versus post-burn or nonlinear two-parameter exponential regression for analysis including HI and EBT. The site-year and blocking factors were treated as random effects to generalize inference across all possible replications in that field (Blouin et al. 2011). To analyze the average temperature across all burn events in both crops, maximum temperature was first determined from each individual temperature recording. Temperature data were then aligned at maximum values and each individual second was averaged across all burns to create a curve that was representative of the average. Using temperature logger data collected from each plot, HI and EBT values were calculated

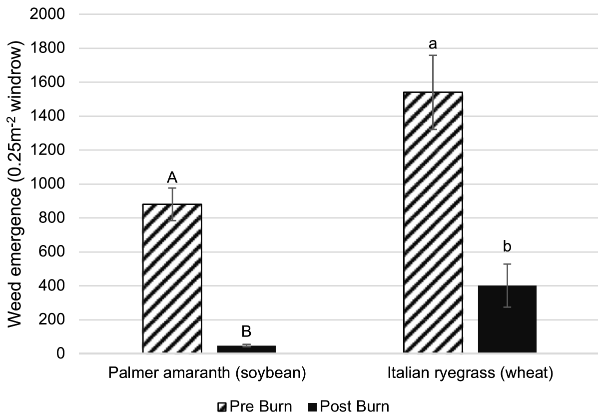

Figure 1. Weed seed germination from windrow samples collected before and after burning of windrows (*n* = 54 soybean, *n* = 27 wheat).

for each burn event and averaged to obtain overall representative values and standard error.

Results and Discussion

Weed Seed Mortality from Narrow-Windrow Burning

In these experimental data, NWB resulted in an estimated reduction (± standard error) in seed survival of 79.7% ± 0.146% in Italian ryegrass, and an 86.3% ± 0.055% in Palmer amaranth survival (as measured by reduced germination; Figure 1). Although the precise number of seed between pre- and post-burn are unknown, the authors of this study are confident in the results, and additionally believe the low standard error of estimated reduction in seed survival further validates this finding. The maximum, minimum, and median estimated reduction in seed survival for Palmer amaranth was 100%, 34.3%, and 98.1%, respectively. In Italian ryegrass, maximum likely reduction was also 100%, however, seed survival was not reduced in 2 of 27 observations. Italian ryegrass median seed kill was estimated to be 98.9%. High median and mean values of approximated reduced seed survival in both weed species indicate that NWB is effective at killing most seeds that enter the windrow. Walsh and Newman (2007) and Lyon et al. (2016) reported that a higher percentage of Italian ryegrass and rigid ryegrass seed (99%) and wild radish seed (96%) could be killed with NWB in wheat. Furthermore, greater biomass accumulation in windrows increased burning temperature and duration, and therein, the mortality of rigid ryegrass and wild radish. It is optimistic that some modeling studies show HWSC may be effective at diminishing weed populations even at seed kill values lower than were observed in this and similar studies (Borger et al. 2021).

Average Windrow Burn Temperature

Average NWB observations in soybean totaled an HI of 140,725 ± 14,370 C, and EBT (>200 C) of 259 ± 27 s (Figure 2). All estimated HI values were in the range of 36,195 and 675,295 C. In similar fashion, Norsworthy et al. (2020) recorded HI during NWB of soybean harvest residues that followed a similar range of 20,800 to 659,000 C, with a higher average of 242,000 C across all burn events. Additionally, Norsworthy et al. (2020) found a greater amount of soybean residue in the windrow increased HI and EBT (>200 C). Soybean residues in that study resulted in windrow biomass levels ranging from 1.08 (4.8-m-wide harvest swath) to 1.95 kg m^{-2} (9.6-m-wide harvest swath), with the average residue in the range being 1.52 kg m^{-2} (Norsworthy et al. 2020). Model predictions indicate the EBT (>200 C) would be 611 s, 988 s, and 802 s for the minimum, maximum, and average amounts, respectively in that study, which are all greater than our calculated EBT value (Norsworthy et al. 2020). Smaller combine headers (2.4 to 4.5 m width) were used to create windrows in this publication, which likely accounts for lower EBT values.

In this study, HI and EBT (>200 C) values observed during wheat NWB totaled 66,196 ± 6224 C and 116 ± 12 s, respectively (Figure 2). Minimum and maximum HI values were 27,780 and 154,376 C, respectively. Walsh and Newman (2007) found elevated temperatures persisted for a marginally longer time (200 s) after the windrow was ignited. In their experiments, NWB of 15,000 kg ha^{-1} wheat stubble produced maximum temperatures of 555.3 C, an HI of 30,600 C, and an EBT (>300 C) of 68 s on average across burns where temperature was recorded. The authors of that study cited considerable variability in recorded temperatures across time both within plot subsamples and treatments. In a study aimed at determining variability in temperature due to wind speed, low wind speed resulted in an HI of 522,000 C, and an EBT of 601 s. Conversely, NWB in high wind speeds decreased HI and EBT to 64,000 C and 89 s, respectively, although the maximum temperature in high wind speed (878 C) was much greater than at the low wind speed (435 C; Walsh and Newman 2007). As hypothesized by Norsworthy et al. (2020), the greater kill percentage of Palmer amaranth compared to Italian ryegrass could be a result of increased HI and EBT values in soybean NWB as opposed to wheat NWB. Our results match and support this hypothesis.

Relationship of Heat Index and Effective Burn Time to Weed Seed Mortality

Examining the relationship between weed seed mortality and temperature metrics, more than 99% of Palmer amaranth seeds would be potentially killed during soybean NWB at an HI of 146,000 C (Figure 3) and an EBT of 277 s (Figure 4). At an HI of 29,000 C and EBT of 47 s, Palmer amaranth estimated seed survival was reduced by 50% via soybean NWB. Both temperature metrics were significant predictors of the resulting seed survival rates, with R^2 values ranging from 0.776 to 0.789.

The relationship between Italian ryegrass seed survival after wheat NWB and HI (Figure 5) or EBT (Figure 6) could not be calculated. Most burn events resulted in a negligible amount of seed survival across all wheat HI and EBT values. One wheat NWB observation when potential survival, HI, and EBT were 100%, 54,136 C, and 116 s, respectively, did not fit the overall data trend. Since both the temperature loggers and seed samples were randomly placed in the window, this sublethal burning event may be due to high amounts of green residue, differences in amount of plant material and wind speed, or increased moisture in the windrow causing the burn to miss weed seed.

In field studies, Norsworthy et al. (2020) reported a minimum HI of 22,600 C was necessary to kill all seeds of Palmer amaranth and Italian ryegrass. Our results estimate less than 50% of Palmer amaranth seed would be killed at this temperature. In the same study, across NWB observations of 1.08 to 1.95 kg m^{-2} of soybean residues, regardless of temperature all weed seeds were reduced to ash. In the study mentioned previously where Italian ryegrass seed survival on the soil surface was reduced to <1%, Lyon et al. (2016)

https://doi.org/10.1017/wet.2022.70 Published online by Cambridge University Press

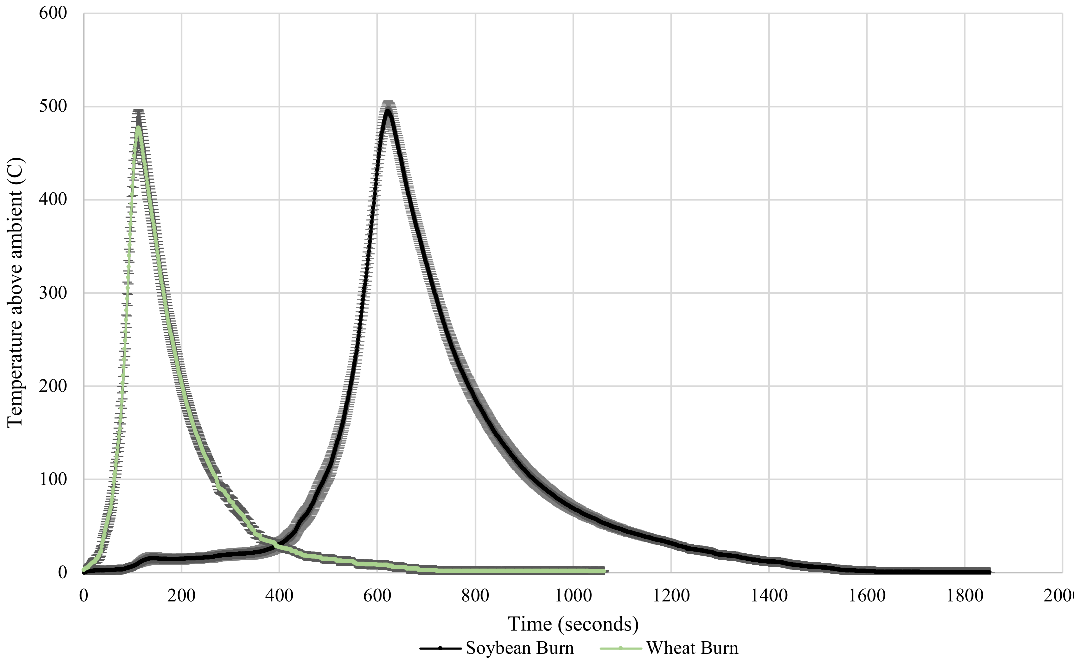

Figure 2. Average temperature (± SE) in narrow-windrow burning of soybean residues between 2016 and 2018 (*n* = 54) and wheat residues in 2016–2017 (*n* = 27) in Virginia.

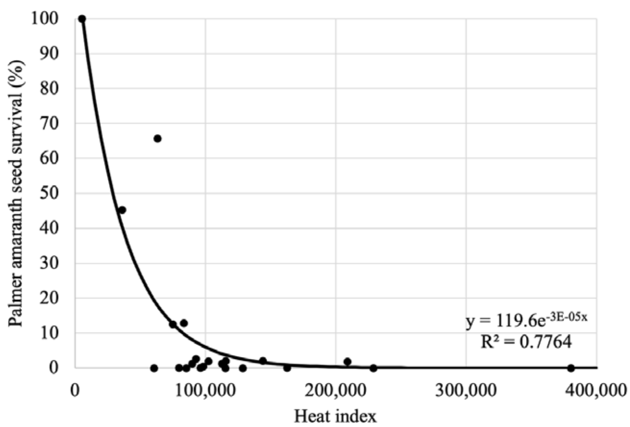

Figure 3. Heat index fitted relationship between the survival (%) of Palmer amaranth subject to soybean narrow-windrow burning (*n* = 22).

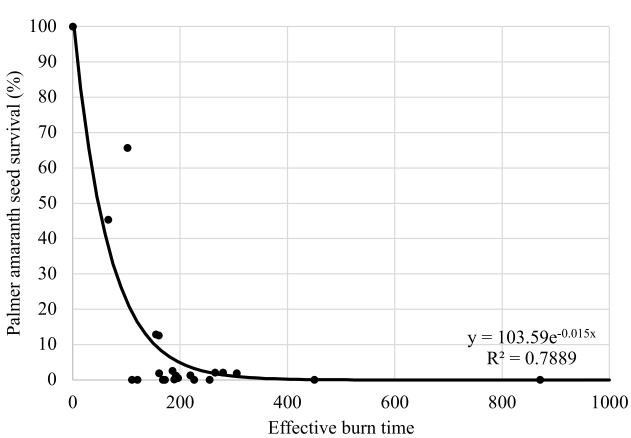

Figure 4. Effective burn time (number of seconds the NWB temperature exceeds 200 C) fitted relationship to the survival (%) of Palmer amaranth seed subject to soybean narrow-windrow burning (*n* = 22).

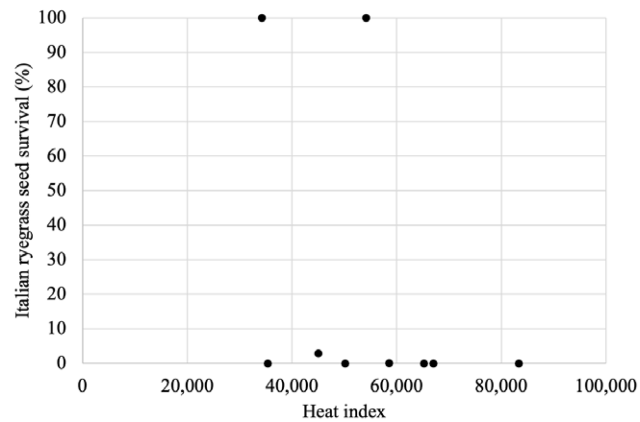

Figure 5. Heat index relationship between the survival (%) of Italian ryegrass seed following wheat narrow-windrow burning (*n* = 9). The fitted relationship is not included due to binary data and limited sample size.

reported sufficient EBT (>200 C) values of 502 and 584 s in 2013 and 2014, respectively. When only standing wheat stubble was burned rather than NWB, EBT (>200 C) decreased to 36 to 37 s, and 48% of Italian ryegrass seed survived (Lyon et al. 2016). Walsh and Newman (2007) found NWB reduced rigid ryegrass emergence over the following season to less than 1% across EBT (>200 C) values of 40 to 160 s. Similarly, low rates of Italian ryegrass survival were observed following wheat NWB in this study across the reported EBT range.

Multiple controlled environment experiments, either in a kiln or with similar methods, have aimed to determine temperature and survival relationships. Hopkins (1936) exposed weed species, including redroot pigweed (*Amaranthus retroflexus* L.), wild oat (*Avena fatua* L.), wild mustard (*Sinapis arvensis* L.), and common lambsquarters (*Chenopodium album* L.) to temperatures ranging from 85 to 105 C for 15 min. This temperature by time duration was lethal to all weed seed. Norsworthy et al. (2020) exposed Italian

https://doi.org/10.1017/wet.2022.70 Published online by Cambridge University Press

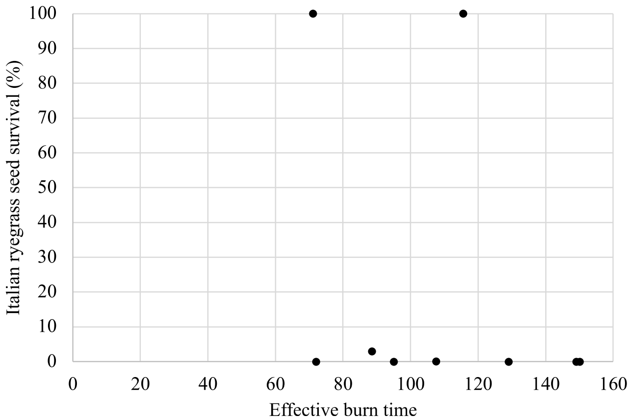

Figure 6. Effective burn time (number of seconds the NWB temperature exceeds 200 C) relationship to the survival (%) of Italian ryegrass seed following wheat narrow-windrow burning ($n = 9$). The fitted relationship is not included due to binary data and limited sample size.

ryegrass and Palmer amaranth seeds to temperatures of 200, 300, 400, 500, and 600 C for 20, 40, 60, and 80 s in a high-fire kiln to determine temperature and time requirements needed to kill seeds. Complete loss of viability was observed at an HI of 34,600 C in both species, however, the temperature must exceed 200 C. There was complete kill of Palmer amaranth seed exposed to 400 C temperature for 60 s (HI = 22,566 C), and 500 C for 40 s (HI = 19,044). A kiln study by Walsh and Newman (2007) found that exposure to a temperature of 400 C for at least 10 s guaranteed the death of rigid ryegrass seeds. As temperature increases, seed viability decreases (Dahlquist et al. 2007). This study agrees, and many of the HI values observed in this research exceeded the critical values tested in both kiln studies, however, complete seed kill was not witnessed in every NWB event.

While the studies are largely in agreement, differences in temperature requirements needed to reduce germinability among studies may be due to various reasons. For example, Norsworthy et al. (2020) cited differences in germinability classification. They used tetrazolium staining of seed, whereas Walsh and Newman (2007) evaluated emergence in the field where NWB was conducted. Our samples were evaluated in a greenhouse setting, which may have optimized germination conditions, leading to potential indications of a reduction in efficacy at lower temperatures. Additionally, initial seed rain into windrows prior to burning is difficult to classify, and higher densities of seed may influence NWB efficacy.

The culmination of this work and similar research indicates that NWB reduces inputs into the soil seedbank; however, questions remain on the long-term sustainability of the practice. Negative consequences include the destruction of crop residues that aid in soil nutrition, water retention and reducing soil erosion, health and safety issues, and unpredictable burn events (Norsworthy et al. 2020; Walsh and Newman 2007). Future research is necessary to evaluate NWB's potential to control other weed species and establish an in situ experiment to observe weed seedbank depletion in the long term. Additional research on large crabgrass (*Digitaria sanguinalis* L.) shows promise, with 50% reductions in viability at lower temperatures of 103 C for 5 s or 99 C for 20 s (Hoyle and McElroy 2012). These results estimate the effectiveness in NWB's ability to prevent weed seedbank deposition from the combine. This study gives insight on the temperature produced in a windrow under field conditions in the mid-Atlantic region, and quantitatively relates those temperatures to germination assays.

In conclusion, NWB offers an opportunity to improve weed management and combat herbicide resistance in the weed species studied.

Acknowledgments. Funding for this work was provided in part by an integrated, collaborative grant from the Colleges of Agriculture and Life Sciences (CALS) at Virginia Tech and North Carolina State University, U.S. Department of Agriculture–Agricultural Research Service Areawide Program award 58-8042-5-054, Virginia Tech CALS Equipment Trust Fund, Virginia Crop Improvement Association, Southern IPM Center, and Virginia Small Grains Board. Additionally, we thank the Virginia Agricultural Experiment Station, and the Hatch Program of the U.S. Department of Agriculture–National Institute of Food and Agriculture for providing funding in part for this research. The authors are grateful to the Callahan family for allowing parts of this research to be conducted on their farm. We are also thankful to others who helped conduct this research including Kara Pittman, Ranjeet Randhawa, Shawn Beam, Lucas Rector, and Kevin Bamber. No conflicts of interest have been declared.

References

Bararpour MT, Norsworthy JK, Burgos NR, Korres NE, Gbur EE (2017) Identification and biological characteristics of ryegrass (*Lolium* spp.) accessions in Arkansas. Weed Sci 65:350–360

Beam SC, Mirsky S, Cahoon C, Haak D, Flessner M (2019) Harvest weed seed control of Italian ryegrass [*Lolium perenne* L. ssp. *multiflorum* (Lam.) Husnot], common ragweed (*Ambrosia artemisiifolia* L.), and Palmer amaranth (*Amaranthus palmeri* S. Watson). Weed Technol 33:627–632

Beckie HJ (2006) Herbicide-resistant weeds: management tactics and practices. Weed Technol 20:793–814

Blouin DC, Webster EP, Bond JA (2011) On the analysis of combined experiments. Weed Technol 25:165–169

Borger CPD, Petersen D, Gill GS (2021) Modelling the long-term impact of harvest weed seed control for species like *Bromus diandrus* and *Hordeum* spp. that shed a portion of seed prior to harvest. Weed Res 61:307–316

Dahlquist RM, Prather TS, Stapleton JJ (2007) Time and temperature requirements for weed seed thermal death. Weed Sci 55:619–625

Glasner C, Vieregge C, Robert J, Fenselau J, Bitarafan Z, Andreasen C (2019) Evaluation of new harvesting methods to reduce weeds on arable fields and collect a new feedstock. Energies 12:1688

Green JK, Norsworthy JK, Scott RC (2014) Narrow-windrow burning of soybean chaff in an effort to decrease the return of weed seed to the soil seedbank. Arkansas Soybean Res Stud 2014

Harker KN, O'Donovan JT (2013) Recent weed control, weed management, and integrated weed management. Weed Technol 27:1–11

Heap I (2014) Global perspective of herbicide-resistant weeds. Pest Manag Sci 70:1306–1315

Heap I (2022) The international survey of herbicide resistant weeds. https://www.weedscience.org. Accessed: September 28, 2022

Hopkins CY (1936) Thermal death point of certain weed seeds. Can J Res 14c:178–183

Holshouser D (2014) Double-Cropping Soybean in Virginia. VCE Pub. CSES – 102NP. Blacksburg: Virginia Coopertive Extension

Horak MJ, Peterson DE (1995) Biotypes of Palmer amaranth (*Amaranthus palmeri*) and common waterhemp (*Amaranthus rudis*) are resistant to imazethapyr and thifensulfuron. Weed Technol 9:192–195

Hoyle JA, McElroy JS (2012) Relationship between temperature and heat duration on large crabgrass (*Digitaria sanguinalis*), Virginia buttonweed (*Diodia virginiana*), and cock's-comb kyllinga (*Kyllinga squamulata*) seed mortality. Weed Technol 26:800–806

Kumar V, Singh S, Chhokar RS, Malik RK, Brainard DC, Ladha JK (2013) Weed management strategies to reduce herbicide use in zero-till rice–wheat cropping systems of the Indo-Gangetic Plains. Weed Technol 27:241–254

https://doi.org/10.1017/wet.2022.70 Published online by Cambridge University Press

Lyon DJ, Huggins DR, Spring JF (2016) Windrow burning eliminates Italian ryegrass (*Lolium perenne* ssp. *multiflorum*) seed viability. Weed Technol 30:279–283

Maity A, Young B, Schwartz-Lazaro LM, Korres N, Walsh MJ, Norsworthy JK, Bagavathiannan M (2022) Seedbank management through an integration of harvest-time and post-harvest tactics for Italian ryegrass (*Lolium perenne* ssp. *multiflorum*) in wheat. Weed Technol 36:187–196

Norsworthy JK, Green JK, Barber T, Roberts TL, Walsh MJ (2020) Seed destruction of weeds in southern US crops using heat and narrow-windrow burning. Weed Technol 34:589–596

Norsworthy JK, Griffith GM, Scott RC, Smith KL, Oliver LR (2008) Confirmation and control of glyphosate-resistant Palmer amaranth (*Amaranthus palmeri*) in Arkansas. Weed Technol 22:108–113

Norsworthy JK, Korres NE, Walsh MJ, Powles SB (2016) Integrating herbicide programs with harvest weed seed control and other fall management practices for the control of glyphosate-resistant Palmer amaranth (*Amaranthus palmeri*). Weed Sci 64:540–550

Norsworthy JK, Ward SM, Shaw DR, Llewellyn RS, Nichols RL, Webster TM, Bradley KW, Frisvold G, Powles SB, Burgos NR, Witt WW, Barrett M (2012) Reducing the risks of herbicide resistance: Best management practices and recommendations. Weed Sci 60(SPI):31–62

Patterson KM, Schwartz-Lazaro LM, LaBiche G, Stephenson DO (2021) Effects of narrow-windrow burning on weed dynamics in soybean in Louisiana. Front Agron 3:1–7

San Martín C, Thorne ME, Gourlie JA, Lyon DJ, Barroso J (2021) Seed retention of grass weeds at wheat harvest in the Pacific Northwest. Weed Sci 69: 238–246

Schwartz-Lazaro LM, Green JK, Norsworthy JK (2017) Seed retention of Palmer amaranth (*Amaranthus palmeri*) and barnyardgrass (*Echinochloa crus-galli*) in soybean. Weed Technol 31:617–622

Schwartz-Lazaro LM, Shergill LS, Evans JA, Bagavathiannan MV, Beam SC, Bish MD, Bond JA, Bradley KW, Curran WS, Davis AS, Everman WJ, Flessner ML, Haring SC, Jordan NR, Korres NE, Lindquist JL, Norsworthy JK, Sanders TL, Steckel LE, Vangessel MJ, Young B, Mirsky SB (2021) Seed-shattering phenology at soybean harvest of economically important weeds in multiple regions of the United States. Part 1: Broadleaf species. Weed Sci 69:95–103

Shergill LS, Schwartz-Lazaro LM, Leon R, Ackroyd VJ, Flessner ML, Bagavathiannan M, Everman W, Norsworthy JK, VanGessel MJ, Mirsky SB (2020) Current outlook and future research needs for harvest weed seed control in North American cropping systems. Pest Manag Sci 76:3887–3895

Somerville GJ, Powles SB, Walsh MJ, Renton M (2018) Modeling the impact of harvest weed seed control on herbicide-resistance evolution. Weed Sci 66:395–403

Walsh M, Newman P (2007) Burning narrow windrows for weed seed destruction. Field Crop Res 104:24–30

Walsh M, Newman P, Powles S (2013) Targeting weed seeds in-crop: A new weed control paradigm for global agriculture. Weed Technol 27:431–436

Walsh M, Ouzman J, Newman P, Powles S, Llewellyn R (2017a) High levels of adoption indicate that harvest weed seed control is now an established weed control practice in Australian cropping. Weed Technol 31:341–347

Walsh MJ, Aves C, Powles SB (2017b) Harvest weed seed control systems are similarly effective on rigid ryegrass. Weed Technol 31:178–183

Walsh MJ, Broster JC, Schwartz-Lazaro LM, Norsworthy JK, Davis AS, Tidemann BD, Beckie HJ, Lyon DJ, Soni N, Neve P, Bagavathiannan MV (2018) Opportunities and challenges for harvest weed seed control in global cropping systems. Pest Manag Sci 74:2235–2245

Walsh MJ, Powles SB (2007) Management strategies for herbicide-resistant weed populations in Australian dryland crop production systems. Weed Technol 21:332–338

Walsh MJ, Powles SB (2014) High seed retention at maturity of annual weeds infesting crop fields highlights the potential for harvest weed seed control. Weed Technol 28:486–493

Ward SM, Webster TM, Steckel LE (2013) Palmer amaranth (*Amaranthus palmeri*): A review. Weed Technol 27:12–27

Webster TM, Nichols RL (2012) Changes in the prevalence of weed species in the major agronomic crops of the Southern United States: 1994/1995 to 2008/2009. Weed Sci 60:145–157