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Effect of Dry Heat, Direct Flame, and Straw Burning on Seed Germination of Weed Species Found in Lowbush Blueberry Fields

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Experiments were conducted to determine the effects of dry heat, direct flame, and straw burning on germination of several weed species from lowbush blueberry fields. Dry heat experiments were designed as factorial arrangements of temperature (100, 200, and 300 C in experiment 1 and room temperature, 100, 200, and 300 C in experiment 2) and exposure time (0, 5, 10, 20, 40, and 80 s in experiment 1 and 2, 5, 10, and 20 s in experiment 2) to determine the exposure time required to reduce germination for each temperature. Susceptibility to dry heat varied across species tested, but germination of spreading dogbane, meadow salsify, fireweed, and hair fescue seeds collected from lowbush blueberry fields in Nova Scotia, Canada generally declined exponentially as a function of duration of heat exposure at the temperatures tested. Germination decreased more rapidly at higher temperatures in all species, although the duration of heat exposure required to reduce germination by 50 and 90% varied across temperatures and species. Exposure of seeds to direct flame rapidly reduced germination, with less than 1 s of exposure required to reduce seed germination of witchgrass, spreading dogbane, and meadow salsify by > 90%. Straw burning did not consistently reduce germination of hair fescue or winter bentgrass, indicating that a surface burn occurring above weed seeds may not be consistently effective at reducing seed viability. These results provide important estimates of the temperature and exposure times required to reduce viability of weed seeds in lowbush blueberry fields and suggest that thermal technologies that expose weed seeds to direct flame will be the most consistent in reducing seed viability.

Nomenclature: Fireweed, *Chamerion angustifolium* (L.) Holub CHAAN; hair fescue, *Festuca filiformis* Pourret FESTE; meadow salsify, *Tragopogon pratensis* L. TROPR; spreading dogbane, *Apocynum androsaemifolium* L. APCAN; winter bentgrass, *Agrostis hyemalis* (Walt.); witchgrass, *Panicum capillaire* L. PANCA; lowbush blueberry, *Vaccinium angustifolium* Ait.

Key words: Exposure time, lethal duration, perennial crops.

Experimentos fueron realizados para determinar los efectos de calor seco, llama directa, y la quema de paja sobre la germinación de varias especies de malezas en campos de arándano de arbusto bajo. Los experimentos con calor seco fueron diseñados como arreglos factoriales de temperatura (100, 200, y 300 C en el experimento 1, y temperatura ambiente, 100, 200, y 300 C en el experimento 2) y de duración de exposición (0, 5, 10, 20, 40, y 80 s en experimento 1, y 2, 5, 10, y 20 s en experimento 2), para determinar el tiempo de exposición requerido para reducir la germinación en cada temperatura. La susceptibilidad al calor seco varió entre las especies evaluadas, pero la germinación de semillas de *Apocynum androsaemifolium*, *Tragopogon pratensis*, *Chamerion angustifolium*, y *Festuca filiformis* colectadas en campos de arándano de arbusto bajo en Nova Scotia, Canada, generalmente declinó exponencialmente en función de la duración de la exposición al calor a las temperaturas evaluadas. La germinación disminuyó más rápidamente a temperaturas más altas en todas las especies, aunque la duración de la exposición al calor requerida para reducir la germinación en 50 y 90% varió entre las temperaturas y las especies. La exposición directa de semillas a llamas rápidamente redujo la germinación, con menos de 1 s de exposición requerida para reducir en >90% la germinación de las semillas de *Panicum capillare*, *A. androsaemifolium*, y *T. pratensis*. La quema de paja no redujo consistentemente la germinación de *F. filiformis* o de *Agrostis hyemalis*, indicando que una quema superficial sobre las semillas de malezas no sería consistentemente efectiva para reducir la viabilidad de las semillas. Estos resultados brindan estimados importantes de la temperatura y los tiempos de exposición requeridos para reducir la viabilidad de las semillas de malezas en campos de arándano de arbusto bajo y sugiere que las tecnologías termales que exponen directamente las malezas de semillas a llamas serán las más consistentes para reducir la viabilidad de las semillas.

The lowbush blueberry is a rhizomatous perennial berry species. Commercial fields are developed from native stands and managed primarily on a 2-yr cycle in which fields are pruned by flail mowing or burning in the first year and harvested in the second

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year (AAFC 2005; Jensen and Yarborough 2004). Pruning by flail mowing is most common because of reduced production costs (Yarborough 2004), but many growers periodically prune by burning because of the potential role of fire in field sanitation (Lambert 1990). Pruning by burning controls some weeds (Penney et al. 2008), but no research has been conducted to determine the specific effect of heat on weed seed germination in lowbush blueberry.

Exposure of seeds to heat can stimulate or inhibit seed germination (Egley 1990; Herranz et al. 1998), with the response depending upon the temperature, exposure time, and heat source (Paula and Pausas 2008; Sweet et al. 2008). Large interspecific variation in sensitivity to temperature and exposure time is common (Gashaw and Michelsen 2002; González-Rabanal and Casal 1995), resulting in variable response among species to heat treatments (Egley 1990). The weed flora of lowbush blueberry fields is extremely diverse, with more than 100 weed species commonly found in this production system (McCully et al. 1991). Perennial weeds dominate this flora, but the number of weed species that rely predominantly on seed for establishment and spread is increasing (Jensen and Yarborough 2004). Lowbush blueberry fields are not tilled, suggesting that the majority of weed seeds deposited remain near the soil surface (Cardina et al. 2002; Yenish et al. 1992). Heat sources, such as fire, can reduce germination and emergence of weed seeds at the soil surface (Vermeire and Rinella 2009; Young et al. 1990), and there is interest from the blueberry industry to revisit the use of thermal technologies for pruning, field sanitation, and weed control.

Several thermal technologies are available to lowbush blueberry growers for pruning fields, ranging from simple free burns, the application of plant material (e.g., straw) to fuel a burn, or the use of burners fueled by oil or liquid propane (DeGomez 1988). Depending on burning method, seeds in lowbush blueberry fields are exposed to dry heat at the soil surface or to direct flame during the burn. Direct exposure to flame causes greater reductions in seed germination than dry heat (Sweet et al. 2008), but this is not always possible at the soil surface. Dry heat at the soil surface can reduce germination, but is highly dependent upon the temperature achieved during the burn and the length of exposure (Young et al. 1990). Use of plant material, such as straw, to fuel a burn can be effective, but reductions in seed germination are dependent upon the amount of material applied to fuel the burn (Kyser et al. 2008; Vermeire and Rinella 2009). The objectives of this research were therefore to determine: (1) the effect of dry heat temperature and exposure time on seed germination of weed species common to commercial lowbush blueberry fields, (2) the effect of direct flame exposure on seed germination, and (3) the effect of straw application rate on seed germination after a straw-fueled surface burn.

Materials and Methods

Seed Material. Seeds used in all experiments were collected from commercial lowbush blueberry fields throughout Nova Scotia. Seeds were collected at physiological maturity of all weed species. Seeds were brought back to the lab, placed in paper envelopes, and stored at 4 C until use. No seeds were stored for more than 6 mo before use.

Experiment 1—Effect of Seed Exposure to Dry Heat on Germination. Two experiments were conducted to determine the effect of duration of dry heat exposure on germination of weed seeds. The first experiment was designed as a 3 by 6 factorial arrangement of temperature (100, 200, and 300 C) and exposure time (0, 5, 10, 20, 40, and 80 s). Seeds of spreading dogbane, meadow salsify, fireweed, and hair fescue were used in this experiment. The second experiment was designed as a 4 by 4 factorial arrangement of temperature (room temperature, 100, 200, and 300 C) and exposure time (2, 5, 10, and 20 s). Seeds of winter bentgrass, witchgrass, and Canada bluegrass (*Poa compressa*) were used in this experiment. Temperature treatments in each experiment were achieved using a laboratory box furnace (Model 51894, Lindberg Manufacturing, Watertown, WI). Thirty seeds of each species were exposed to each combination of temperature and exposure time in aluminum weigh dishes, and each treatment combination was replicated four times. Exposed seeds were then placed in petri dishes lined with two pieces of Whatman No. 1 9-cm-diam filter paper (Whatman Ltd., GE Healthcare Companies). Filter paper was moistened with 5 ml of distilled water just before placing seeds in each dish. Petri dishes were then sealed for the remaining duration of the

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experiment with Parafilm™ and placed in a controlled-environment chamber (Model CMP5090, Conviron Controlled Environments Limited, Winnipeg, MB, Canada) maintained at 25/10 C (day/night) with a 12-h photoperiod. The number of germinated seeds was counted in each dish 28 d after placement in the chamber, and each experiment was repeated once.

Experiment 2—Effect of Seed Exposure to Direct Flame on Germination. An experiment was conducted to determine the effect of exposure time to direct flame on germination and consisted of exposing seeds of witchgrass, spreading dogbane, and meadow salsify to direct flame from a bunsen burner for 0, 1, 2, and 4 s. Seeds were clasped by metal tweezers and held in the upper portion of the flame for each respective exposure time. Mean temperature of the upper portion of the flame, as measured with a Hobo U12 thermocouple data logger (Model U12-014, Onset Computer Corporation), was 497 C ± 35 C (mean ± SE). Twenty seeds of each species were exposed to each exposure time and each treatment was replicated four times. Exposed seeds were then placed in petri dishes lined with two pieces of Whatman No. 1 9-cm-diam filter paper (Whatman). Filter paper was moistened with 5 ml of distilled water just before placing seeds in each dish. Petri dishes were then sealed for the duration of the experiment with Parafilm and placed in a controlled-environment chamber (Model CMP5090, Conviron Controlled Environments) maintained at 25/10 C (day/night) with a 12-h photoperiod. The number of germinated seeds was counted in each dish 28 d after placement in the chamber, and the experiment was repeated once.

Experiment 3—Effect of Seed Exposure to Straw Burning on Germination. An experiment was conducted to determine the effect of straw burning on germination of seeds of hair fescue and winter bentgrass. Seeds were subject to burning treatments by placing 30 seeds on top of sand in a 7-cm-diam circular aluminum weigh dish that was then placed in the center of a 1,525 cm^3 square aluminum tray filled with the same soil. The weigh dish was placed in a hole in the center of the square tray so that seeds of each weed species lay flush with the soil surface within the larger tray. This technique was used to ensure that we could locate the seeds within the necessary surface area required for spreading and burning the straw. Experimental treatments for each species were: (1) no straw (nontreated control), (2) 50% straw cover (490 kg straw ha^{-1}), and (3) 100% straw cover (980 kg straw ha^{-1}), with 100% straw cover being the rate required to completely cover the soil surface. The experiment was designed as a completely randomized design. The straw was chopped barley straw obtained from a local dairy farm. The weight of straw required for the 100% straw cover was determined before initiation of the experiment, and the straw rate required for each treatment was weighed immediately before application of the experimental treatments. The appropriate straw rate for each treatment was spread evenly over the soil surface and ignited with a handheld butane lighter. Straw was consistently ignited on the same side of the large aluminum dish for consistency in the direction of the burn in each replication of each treatment. The burn was timed until debris was no longer smoldering, and a visual estimate of the proportion of straw burned was made. Seeds of each species were collected by carefully removing the small aluminum weigh dish from the larger tray and emptying the contents of the dish into a paper bag. Collected seeds were then mixed with a 1 : 1 Pro-mix:topsoil mixture, placed into 10-cm–diam plastic pots, and germinated in the greenhouse. Germinated seeds were counted in each pot 19 d after planting.

Statistical Analysis. Germination percentage data in the dry heat and direct flame experiments were plotted as a function of exposure time to assess the effect of each combination of temperature and exposure time on germination. Where appropriate, nonlinear exponential decay models developed in SigmaPlot (SigmaPlot Version 12, Systat Software Inc., 501 Canal Boulevard, Point Richmond, CA 94804-2028) were used to estimate the LD_{50} and LD_{90} exposure time for direct flame and each dry heat temperature and species combination. ANOVA (PROC MIXED, SAS Version 9.2, SAS Institute, Cary, NC) was used to determine the effect of straw application rate on germination of hair fescue and winter bentgrass. Treatment effects were considered significant at $P = 0.05$, and means were separated by Tukey's multiple means comparison.

Results and Discussion

Germination of spreading dogbane, meadow salsify, fireweed, and hair fescue seeds collected

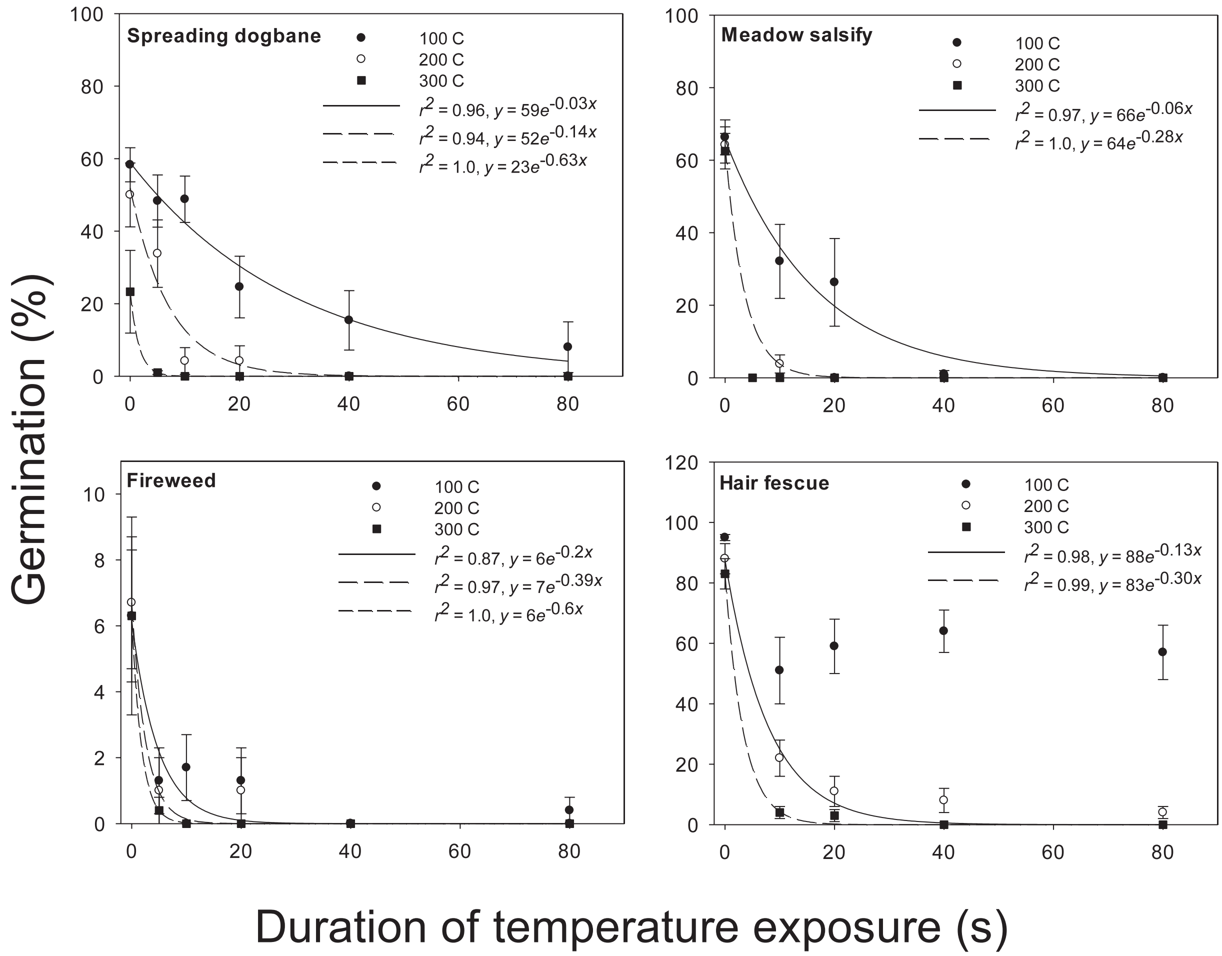

Figure 1. Effect of duration of exposure to 100, 200, and 300 C on germination of spreading dogbane, meadow salsify, fireweed, and hair fescue seeds collected from lowbush blueberry fields in Nova Scotia, Canada.

from lowbush blueberry fields in Nova Scotia, Canada generally declined exponentially as a function of duration of heat exposure at the temperatures tested (Figure 1). Germination decreased more rapidly at higher temperatures in all species, although the duration of heat exposure required to reduce germination by 50 and 90% varied across temperatures and species (Table 1). Seeds of fireweed were most susceptible to heat in this experiment (Figure 1), as less than 20 s at all temperatures tested reduced germination by > 90% (Table 1). Reasons for the low germination rate of fireweed are unclear as seeds of this species generally lack dormancy and therefore readily germinate (Jobidon 1986; Myerscough and Whitehead 1966). Dormancy status and germination rates of fresh fireweed seeds collected from lowbush blueberry fields, however, have not been determined.

Exposure to 100 C did not reliably reduce germination in hair fescue (Figure 1), but durations of 38 to 69 s at this temperature reduced germination of meadow salsify and spreading dogbane by 90%, respectively (Table 1). In contrast, exposure to 200 and 300 C gave rapid and consistent reductions in seed germination across all species tested (Figure 1). Exposure to 100 C may therefore be effective in reducing germination of seeds of some species, but only after prolonged exposure. Results were similar in the second dry heat experiment conducted with winter bentgrass, witchgrass, and Canada bluegrass, where exposure to 200 and 300 C was generally more effective at reducing germination than 100 C (Figure 2). Surface temperatures exceed 300 C during burning under field conditions, but only for 1 to 2 s (N. Boyd, unpublished data). It is therefore unclear if

Table 1. Predicted lethal durations of heat exposure for 50% (LD_{50}) and 90% (LD_{90}) reduction in seed germination of four weed species after exposure to 100, 200, and 300 C for 0, 5, 10, 20, 40, and 80 s.

Weed species	Temperature	LD_{50}	LD_{90}
	C	s	s
Spreading dogbane	100	21	69
	200	5	17
	300	1	4
Meadow salsify	100	11	38
	200	3	8
	300	—[a]	—
Fireweed	100	3	11
	200	2	6
	300	1	4
Hair fescue	100	—	—
	200	5	18
	300	2	8

[a] Estimates could not be determined from experimental data because of complete (meadow salsify) and no (hair fescue) inhibition of seed germination.

sufficient durations of high temperature are achieved to reduce seed germination under field conditions. In contrast to seeds of other species, seeds of witchgrass were quite sensitive to 100 C and had reduced germination after 5 s of exposure to this temperature (Figure 2). Severe infestations of this species produce a large abundance of plant material that would fuel a burn (Anonymous 2012). Given the sensitivity of seeds of this species to heat, burning would likely be quite effective in managing the seed bank of this species in lowbush blueberry fields.

Exposure of seeds to direct flame rapidly reduced germination (Figure 3), with > 90% reduction in germination after 1 s of exposure. Similar results were also reported for seeds of ripgut brome (*Bromus diandrus* Roth) when exposed to direct flame (Sweet et al. 2008). Collectively, results of these experiments indicate interspecific variation in weed seed response to dry heat in lowbush blueberry fields, similar to results reported in other plant communities (Egley 1990; Gashaw and Michelsen 2002). Exposure of seeds to direct flame, however, provides more consistent reduction in germination, and thermal technologies that expose weed seeds to direct flame will likely provide greater interspecific reductions in weed seed germination. Results of the direct flame exposure experiment also suggest that

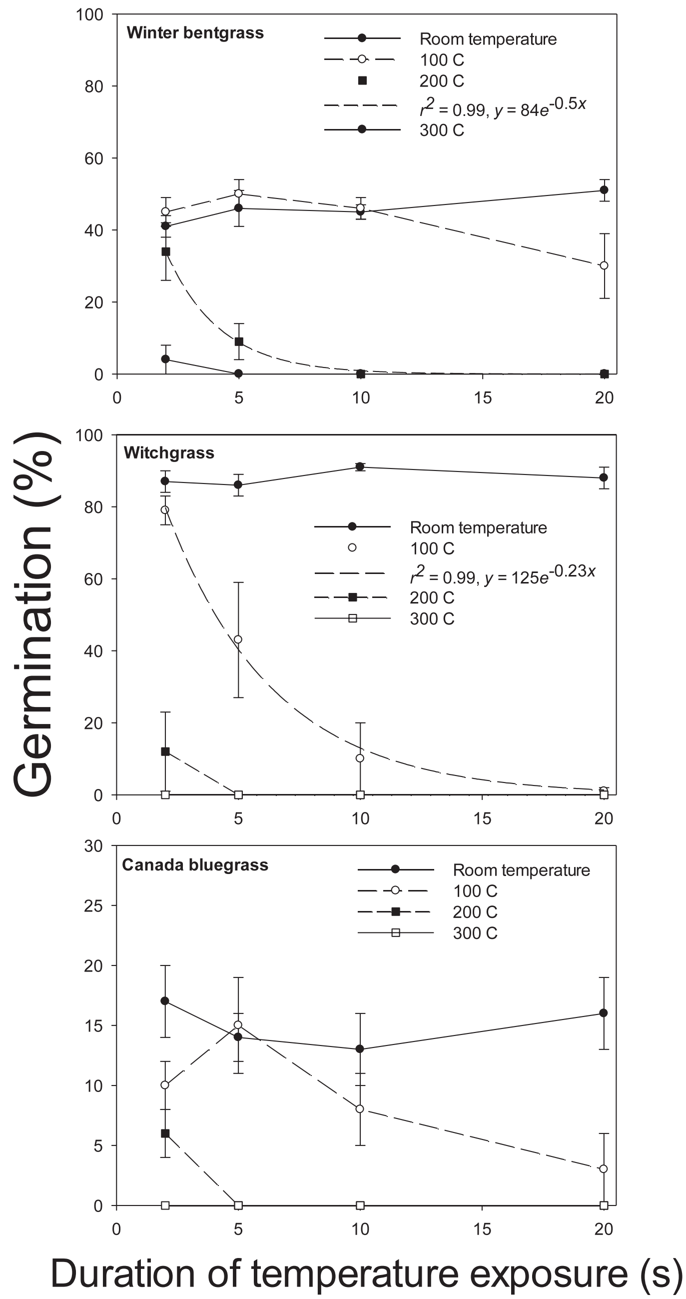

Figure 2. Effect of duration of exposure to room temperature, 100, 200, and 300 C on germination of winter bentgrass, witchgrass, and Canada bluegrass seeds collected from lowbush blueberry fields in Nova Scotia, Canada.

burning while seeds are still suspended in the plant canopy may be more effective at reducing seed viability than exposing seeds to a surface burn. This approach is recommended when using burning to control invasive plant species (DiTomaso et al. 2006), as seeds retained in the canopy are exposed

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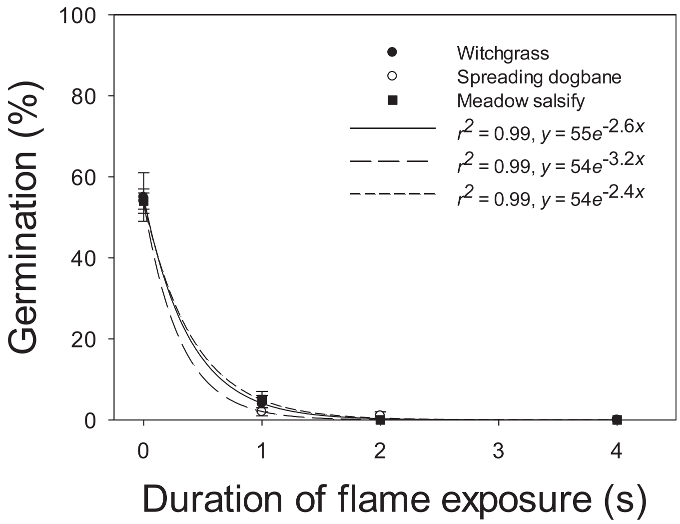

Figure 3. Effect of duration of direct flame exposure on germination of witchgrass, spreading dogbane, and meadow salsify seeds collected from lowbush blueberields in Nova Scotia, Canada.

to the high temperatures of direct flame (McKell et al. 1962). This may not be possible without crop sacrifice in lowbush blueberry, but could prevent the establishment of a weed seed bank during the initial establishment phase of a new weed species.

There was a significant experimental run-by-treatment interaction ($P \leq 0.0487$) in both straw-burning experiments, and data are therefore presented separately for each experimental run for each species. Straw burning did not consistently reduce germination of hair fescue or winter bentgrass at either of the straw rates used (Table 2). The shorter burn duration and smaller proportion of straw burned in the 490 kg ha^{-1} treatment may explain the variability in response in this treatment, but these parameters were consistently higher in the 980 kg ha^{-1} treatment (Table 2). Direct exposure to flame was much more effective than straw burning (Figure 3), indicating that a surface burn occurring above weed seeds, as occurs during straw burning, may not be consistently effective at reducing seed germination. Burning technologies that utilize downward-directed flame, such as oil or propane-based burners, may therefore be more effective at reducing weed seed germination under field conditions. For example, Smith and Hilton (1971) found similar surface temperatures associated with straw burning and use of a kerosene flame thrower when pruning lowbush blueberry fields, but found deeper heat penetration from the flamethrower. Deeper heat penetration can be detrimental to blueberry plants (Duchesne and Wetzel 2004), but could be used in extreme cases to help deplete seed banks of persistent weed species. A limitation in this experiment was that seeds were not exposed to fire while contained in the typical surface organic layer found in lowbush blueberry fields (Penney et al. 1997). This material can provide additional fuel for a fire, and even low-intensity fires are thought to reduce viability of seeds

Table 2. Effect of straw burning on hair fescue and winter bentgrass seed germination.[a]

Weed species	Experimental run	Straw rate	Straw burned	Burn duration	Germination
		kg ha^{-1}	%	s	%
Hair fescue	1	0	N/A[b]	N/A	87 ± 6 a
		490	—[c]	—	64 ± 12 a
		980	—	—	83 ± 3 a
	2	0	—	—	14 ± 4 a
		490	66 ± 5	84 ± 3	9 ± 5 a
		980	98 ± 2	256 ± 21	2 ± 1 b
Winter bentgrass	1	0	N/A	N/A	75 ± 10 a
		490	75 ± 2	167 ± 11	8 ± 3 b
		980	93 ± 5	302 ± 12	1 ± 1 c
	2	0	—	—	51 ± 14 a
		490	74 ± 1	176 ± 14	61 ± 6 a
		980	90 ± 4	304 ± 51	43 ± 14 a

[a] Means followed by the same letter are not significantly different according to a Tukey's multiple means at $P < 0.05$.
[b] Not applicable.
[c] Data not collected.

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contained in such layers (Moore and Wein 1977). Future experiments should therefore attempt to quantify the effect of burning on seed germination under conditions that reflect those typically found at the soil surface in a lowbush blueberry field. We also acknowledge that the straw application rate of 980 kg ha^{-1} used in our study is somewhat low relative to rates reported elsewhere. For example, Smith and Hilton (1971) used 4,500 kg ha^{-1} for burning a wild blueberry stand in northeastern Ontario and Penney et al. (1997, 2008) used 21,000 kg ha^{-1} to burn wild blueberry stands in Newfoundland. Recommendations regarding straw application rates for burning are variable, but higher application rates will likely provide hotter burns of longer duration. Our experimental design imposed a limitation on the amount of straw that could be used because of our requirement to recover seeds exposed to burning. This approach could be modified, however, to enable evaluation of the effect of burning with higher straw application rates on weed seed germination.

In conclusion, seeds of weed species collected from lowbush blueberry fields varied in their susceptibility to temperatures near 100 C, but generally had consistent reductions in germination at temperatures greater than 200 C. Exposure of seeds to direct flame gave the most consistent reductions in germination across species. These results provide important estimates of the temperature and exposure times required to reduce viability of weed seeds in lowbush blueberry fields and suggest that thermal technologies that expose weed seeds to direct flame will be the most consistent in reducing seed germination. Burning should therefore be considered an important tool for managing seed banks of some weed species in this production system.

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