Weed Technology

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Soil steaming to disinfect barnyardgrass-infested soil masses

Zahra Bitarafan[1], Wiktoria Kaczmarek-Derda[2], Therese W. Berge[2], Kirsten S. Tørresen[2] and Inger Sundheim Fløistad[3]

[1]Postdoc, Division of Biotechnology and Plant Health, Norwegian Institute of Bioeconomy Research (NIBIO), Ås, Norway; [2]Researcher, Division of Biotechnology and Plant Health, Norwegian Institute of Bioeconomy Research (NIBIO), Ås, Norway and [3]Researcher, Division of Forestry and Forest Resources, Norwegian Institute of Bioeconomy Research (NIBIO), Ås, Norway

Research Article

Cite this article: Bitarafan Z, Kaczmarek-Derda W, Berge TW, Tørresen KS, Fløistad IS (2022) Soil steaming to disinfect barnyardgrass-infested soil masses. Weed Technol. **36**: 177–185. doi: 10.1017/wet.2021.107

Received: 19 August 2021
Revised: 23 November 2021
Accepted: 15 December 2021
First published online: 24 January 2022

Associate Editor:
David Johnson, Corteva Agriscience

Nomenclature:
barnyardgrass; *Echinochloa crus-galli* (L.) P. Beauv.

Keywords:
Invasive species; resource recovery; thermal soil disinfection; weed management

Author for correspondence:
Zahra Bitarafan, Division of Biotechnology and Plant Health, Norwegian Institute of Bioeconomy Research, Høgskoleveien 7, 1433 Ås, Norway. Email: zahra.bitarafan@nibio.no

Abstract

Reusing soil can reduce environmental impacts associated with obtaining natural fresh soil during road construction and analogous activities. However, the movement and reuse of soils can spread numerous plant diseases and pests, including propagules of weeds and invasive alien plant species. To avoid the spread of barnyardgrass in reused soil, its seeds must be killed before that soil is spread to new areas. We investigated the possibility of thermal control of barnyardgrass seeds using a prototype of a stationary soil steaming device. One Polish and four Norwegian seed populations were examined for thermal sensitivity. To mimic a natural range in seed moisture content, dried seeds were moistened for 0, 12, 24, or 48 h before steaming. To find effective soil temperatures and whether exposure duration is important, we tested target soil temperatures in the range 60 to 99 C at an exposure duration of 90 s (Experiment 1) and exposure durations of 30, 90, or 180 s with a target temperature of 99 C (Experiment 2). In a third experiment, we tested exposure durations of 90, 180, and 540 s at 99 C (Experiment 3). Obtaining target temperatures was challenging. For target temperatures of 60, 70, 80, and 99 C, the actual temperatures obtained were 59 to 69, 74 to 76, 77 to 83, and 94 to 99 C, respectively. After steaming treatments, seed germination was followed for 28 d in a greenhouse. Maximum soil temperature affected seed germination, but exposure duration did not. Seed premoistening was of influence but varied among temperatures and populations. The relationships between maximum soil temperature and seed germination were described by a common dose–response function. Seed germination was reduced by 50% when the maximum soil temperature reached 62 to 68 C and 90% at 76 to 86 C. For total weed control, 94 C was required in four populations, whereas 79 C was sufficient in one Norwegian population.

Introduction

Barnyardgrass is one of the world's most noxious weeds (Heap 2014; Michael 2003) and has all of the competitive features and adaptive characteristics that are necessary for survival and competition under a wide range of geographical and climatic conditions (Marambe and Amarsinghe 2002). The success of this weed may be attributed to its production of a large number of small, easily dispersed seeds per plant, possession of seed dormancy, rapid development, ability to flower under a wide range of photoperiods, resistance to herbicides (Maun and Barrett 1986), plasticity in morphology and phenology (Norris 1996), and high morphological and genetic variation (Claerhout et al. 2016; Kaya Altop and Mennan 2011). It is extremely competitive for nutrients, light, water, and other resources available for plant uptake compared to other weed species (Khanh et al. 2007). Unlike most other weeds in northern Europe, barnyardgrass is a C4 plant that is adapted to dry and warm conditions. With increasing temperatures due to climate change, the species may be more favored in the future and spread farther north.

In Norway, barnyardgrass (in Norwegian, *hønsehirse*) is one of the most troublesome weeds in coastal areas of the Oslo Fjord (on both the west and east sides of the inlet) (Figure 1). The species has been a problem there since the 1970s, typically in areas with vegetable and early potato production grown in rotation with cereal crops (VKM 2016). This area is characterized by a mild climate and sandy soils and is the most heavily infested area in Norway. Barnyardgrass has spread in recent years to other cereal cropping areas in Norway with heavier soil types and has been observed up to mid-Norway (VKM 2016) (Figure 1). It is difficult to control because it can escape herbicide sprays and emerge after the allowed time for herbicide treatments. The first occurrence in Norway dates back to before 1900, but it was not a common weed in Norway until the late 1970s (VKM 2016).

Barnyardgrass spreads only by seeds, and its high-capacity seed production allows large populations to establish rapidly (CABI 2015). A density of 10 plants m^{-2} has the ability to produce

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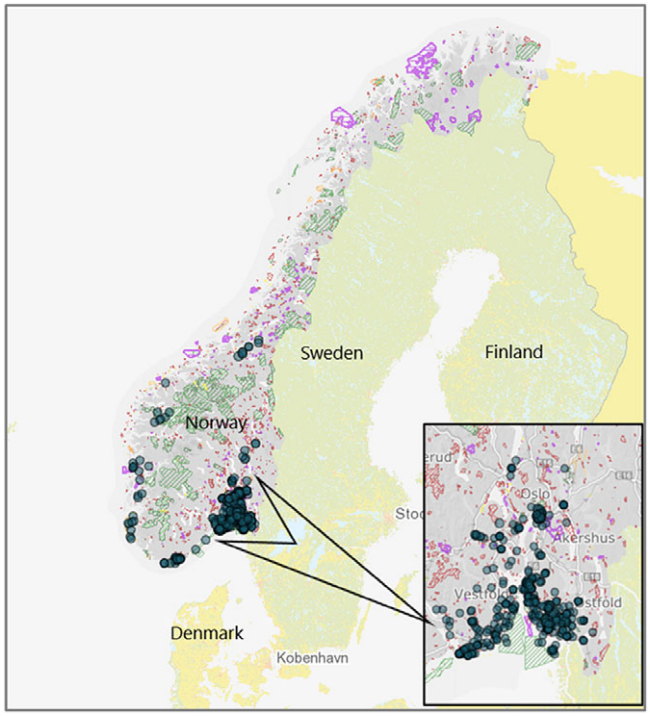


Figure 1. Reported observations of barnyardgrass in Norway (shown by green dots). Coastal areas of the Oslo Fjord (both the west and east sides of the fjord) show the highest infestation in the country (https://www.artsdatabanken.no/).

34,600 seeds m^{-2} (Travlos et al. 2011). Seeds have been reported to lose their viability in soil after 15 yr (Maun and Barrett 1986). In a risk assessment of barnyardgrass in Norway (VKM 2016), relocation of soil, compost soil, seeds for planting, machinery, seeds from places for feeding wild birds, untreated manure, and slaughterhouse waste used as fertilizer are reported as possible pathways for spread. Contaminated soil is a possible if not common way of spreading seeds. For example, barnyardgrass seeds have been found in soils shipped with the ornamental plant *Rosa* sp. from Denmark to Norway (VKM 2016). The Norwegian Nature Diversity Act (entered into force on July 1, 2009) (Norwegian Ministry of Climate and Environment 2009) focuses on relocated soils as an important source of the spread of invasive alien plant species. This pathway is a general pathway for all kinds of weeds, and spread of barnyardgrass by the relocation of soil is documented. Association of this weed with this pathway is considered very likely because the relocation of the soil frequently occurs in infested areas of Norway (VKM 2016). Massive relocation of soil commonly takes place, for example, during road construction. However, the species is not included on the European and Mediterranean Plant Protection Organisation's A1 or A2 list of pests recommended for regulation as quarantine pests (http://www.eppo.int/), and there are no regulations on spreading the species through contaminated soil masses in Norway (VKM 2016).

Soil disinfestation by steaming is now being reconsidered in open-field and greenhouse horticulture for its efficiency in controlling or even eradicating soilborne pathogens, nematodes, and weed seeds while assumedly ensuring low ecological impact (Gay et al. 2010). Steam use for soil disinfestation was envisaged as early as 1888 and was extensively used in the 1960s but was then substituted with cheaper chemical treatments. However, some of the chemical compounds, such as methyl bromide, were phased out because they were included on the list of substances responsible for ozone depletion (Gay et al. 2010). Several machines specifically designed for soil disinfection using steam have been developed (e.g., Gay et al. 2010; Kolberg and Wiles 2002; Peruzzi et al. 2002; Raffaelli et al. 2016), and the method has been tested with positive results for agricultural and horticultural purposes (e.g., Melander and Kristensen 2011; Nishimura et al. 2015; Peruzzi et al. 2012; Van Loenen et al. 2003). A steam treatment breaks the natural thermal equilibrium of soil, forcing a multiphase high-temperature flow through its pores, quickly enhancing soil temperature (Gay et al. 2010) and resulting in seed thermal death. While temperatures equal to or higher than 90 C were suggested by Barker and Craker (1991) to be needed for inhibition of seed germination, temperatures of 50 to 60 C for longer times (3 min with an 8-min resting period) have been suggested by Van Loenen et al. (2003) for 100% seed kill. Thus soil temperature and exposure time are the important interactive factors that influence the efficiency of thermal control (Nishimura et al. 2015).

In the current study, we present the first results of experiments designed to test a prototype stationary soil steaming device to disinfect barnyardgrass-infested soil masses. A larger version of the current prototype is a potential tool for soil disinfection in relocation and reuse processes of soil. Because soil steaming has been shown to be effective on weed seedling emergence in greenhouse and field conditions (e.g., Melander et al. 2002; Melander and Jørgensen 2005; Vidotto et al. 2013), we expect that stationary soil steaming can prevent the spread of barnyardgrass seeds in soil relocation processes. The aim of this study was to estimate the soil temperatures needed to obtain different levels of control of barnyardgrass seeds, that is, parameters of lethal temperature (LT_{50}, LT_{90}). We also tested if the duration of heat exposure and seed moisture content affected the level of seed kill.

Materials and Methods

Three steaming experiments were conducted in July 2020 at Ås, southeastern Norway (59.663°N, 10.790°E) to estimate soil temperature and duration of heat exposure needed to kill seeds of barnyardgrass incorporated in soil masses.

Seed Collection

Mature seeds of barnyardgrass were collected from September to October 2019 from four populations from the east and west sides of Oslofjorden, Norway (East1, East2, West1, and West2). A Polish population sampled in August to September 2019 (Radocza, Poland) was also included. The characteristics of the fields where the populations were sampled are presented in Table 1. At least 20 g of seeds of each population were collected in each field by carefully bending and shaking as many seed-bearing tillers as possible into paper bags. Then pooled seeds were stored under dry conditions at room temperature in paper bags for at least 6 wk, counted (50-seed lots), and transferred into small glass containers with lids and then again stored at room temperature until they were used in the experiments. We estimated the mean 1,000-seed weight for each population by counting and weighing 10 samples of 50 seeds. In June 2020, we checked the germination percentage of the seeds (Table 1).

Experimental Treatment and Data Collection

To find the effective soil temperature to kill seeds and test whether exposure duration is important, we considered target soil

https://doi.org/10.1017/wet.2021.107 Published online by Cambridge University Press

Table 1. Sites, 1,000-seed weights, germination percentage, and field characteristics where seeds from five different populations of barnyardgrass were sampled for the experiments.

Population	Mean 1,000-seed weight	Germination	Field coordinates	Crop in 2019	Precrop in 2018
	g	%			
Poland	2.24	41	49°55′3″N, 19°28′29″E	Spring wheat	Cereals
East1	2.57	79	59°25′27″N, 10°36′37″E	Beets	Cereals
East2	2.34	49	59°22′47″N, 10°40′40″E	Spring barley	Spring wheat
West1	0.97	12	59°14′14″N, 10°17′52″E	Rutabaga	Potato
West2	1.11	4	59°01′20″N, 9°56′04″E	Wheat	Wheat

temperatures of 60, 70, 80, and 99 C with an exposure duration of 90 s (Experiment 1) and three exposure durations of 30, 90, or 180 s following a target soil temperature of 99 C (Experiment 2). Before steaming, seeds were transferred from the glass containers (50 seeds) to polypropylene-fleece bags (9 × 7 cm). To mimic a seed bank with ranges of seed moisture content (as assumed to co-occur in piles of infected soil masses), four pretreatments were included: seeds without premoistening (i.e., dry seeds) and seeds moistened with water for 12, 24, or 48 h at room temperature prior to steaming. Each treatment combination (pretreatment × target soil temperature × exposure duration) had four replicates. Except for two of the populations (West1 and West2), we used 50 seeds per replicate (1 bag × 50 seeds). Owing to relatively poor germination in the germination tests for populations West1 and West2, only 12-h premoistening and 200 seeds per replicate (4 bags × 50 seeds) were used for these populations. For each combination of target soil temperature and exposure duration, all bags (with seeds) in the same replicate were placed at the bottom of a plastic perforated basket container (60 × 40 × 20 cm) and covered with a 7-cm soil layer. Soil was from a local soil reseller. A commercial laboratory characterized it as a loam soil (10% to 25% clay, 25% to 50% silt, <3% organic matter). We estimated the soil to have a moisture content of 40% before being subjected to steaming. This was estimated by drying soil samples for 72 h at 105 C.

Immediately after reaching the target soil temperature and completion of exposure period, all bags containing steamed seeds were taken out of the basket and the warm soil and stored outdoors in shade at an ambient air temperature (~15 C) until transported to the greenhouse (a few hours after steaming). Each bag was opened carefully and placed on the soil surface in 12-cm-diameter pots and covered by a thin layer (2 to 3 mm) of soil. Commercial potting soil was used (Tjerbo torvfabrikk AS, Rakkestad, Norway). It was composed of 80% sphagnum peat, 10% composted bark, and 10% sand (v/v/v), limed and fertilized with NPK (950:40:220 mg L^{-1}) with a pH of 5.5 to 6.5. Pots were placed in a greenhouse (21/16 C and 14/10 h for day/night; RH: 68%) in a randomized design and watered from the bottom with tap water, and thereafter as needed during the experimental period. Seed germination was followed for 28 d, and the number of germinated seeds per pot was counted every 7 d. As controls, nonsteamed seeds subjected to various moistening pretreatments and a soil temperature of 25 C were used. A total of 320 treated pots in Experiment 1 and 160 in Experiment 2, as well as 80 control pots, were evaluated.

In a third experiment, we tested the effects of different steaming durations of 90, 180, and 540 s at 99 C on barnyardgrass seed germination. Four replications of 40 barnyardgrass seeds of populations were placed in polypropylene-fleece bags (9 × 7 cm), moistened for 12 h, and covered by the soil at a 7-cm depth in 60 × 40 × 20 cm plastic perforated basket containers. Steam treatment and seed germination assessment were done in the same way as in Experiments 1 and 2.

Steaming Method

All bags in the same replicate of each combination of target temperature and exposure duration were placed at the bottom of one basket and covered by a 7-cm soil layer. A total of 28 baskets (7 combinations of soil temperatures and exposure durations × 4 replicates), each including 20 bags (3 populations × 4 pretreatments × 1 bag + 2 populations × 1 pretreatment × 4 bags), were used in Experiments 1 and 2. Each basket was placed in the steaming container (190 × 144 × 88 cm, 130 kg, effective steaming area of 120 × 80 cm), and 10 thermocouples were placed in the soil (Figure 2). When the container lid was closed, steam was released from the top with a constant temperature of ~150 C and vacuumed from the bottom of the container. Soil temperature was monitored by means of PT1000 sensors connected to a cRIO-9073 data logger (National Instruments, Austin, TX, USA). A custom-made program was used to record temperature, duration of the period with steam entering the steaming container, and poststeaming exposure duration. Steaming and vacuuming were stopped when at least 5 of the 10 thermocouples had reached the target soil temperature. The basket was removed from the steaming container when the poststeaming exposure duration of either 30, 90, or 180 s was completed. The seed samples were then removed immediately from the basket and the warm soil into a shaded place outdoors.

Postprocessing of Soil Temperature Data

The individual temperature measurement by each of the 10 thermocouples was used to calculate the average soil temperature during steaming for each combination of target soil temperature and poststeaming exposure duration in each replicate. The maximum values of each of the mean soil temperature curves during the steaming process were extracted. Comparison of the target and actual maximum mean soil temperatures showed that it was generally difficult to reach exact target temperatures. Actual maximum mean soil temperature values were 59.3 to 68.5, 73.9 to 75.6, 76.9 to 83, and 94.1 to 99.2 C for the target temperatures of 60, 70, 80, and 99 C, respectively. Examples of mean soil temperature curves are shown in Figure 3. The duration of the target poststeaming exposure was generally obtained. For the planned poststeaming periods 30, 90, and 180 s, actual periods were 29 to 33 s (4 replicate baskets), 87 to 97 s (16 replicate baskets), and 181 to 183 s (4 replicate baskets), respectively.

Statistical Analysis

Data from Experiments 1 and 2 were analyzed with the statistical software SAS version 9.4 (SAS Institute Inc., Cary, NC, USA). The response variable was the proportion of seeds germinated 28 d after steaming. An initial analysis of variance showed that durations of the measured exposure (29 to 183 s) were unimportant. Therefore the data from the two experiments were analyzed together. Using

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Figure 2. Steaming prototype device used in the experiments (left) and basket with soil, seed samples, and thermocouples placed inside the steaming container (right). Photograph by Vinh Hong Le.

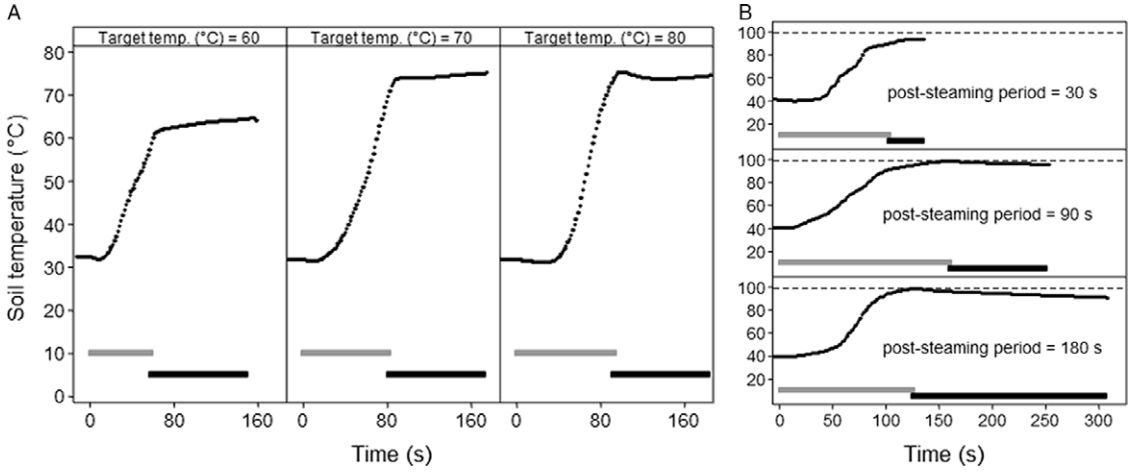


Figure 3. Examples of soil temperature curves in Experiment 1, in which target temperatures were 60, 70, or 80 C and with an exposure duration of 90 s (A), and in Experiment 2, in which the target soil temperature was 99 C (dotted line) with an exposure duration of either 30, 90, or 180 s (B). Each temperature curve is the average of 10 measurements. The gray horizontal bar shows the period with steam entering the steaming container with the seed samples (Figure 2, left). The black horizontal bar indicates the exposure duration, that is, the period after steaming stopped until the basket with the seeds was removed from the container (Figure 2, right).

the NLMIXED procedure, the maximum value of the mean soil temperature curve for each of the 28 experimental units (seven combinations of target soil temperature and exposure duration including nonsteamed controls × four replicates) was used as the independent variable for dose–response modeling using a three-parameter log-logistic dose–response function:

$$p = p_i(t) = \frac{d_{0i}}{1 + \left(\frac{t - t_0}{\alpha_i}\right)^{\beta_i}},\ i = 1, 2, 3, 4, 5 \qquad [1]$$

where p is the probability of a random seed germinating and is a function of maximum soil temperature (t) and population i, where $i = 1$ (Poland), 2 (East1), 3 (East2), 4 (West1), and 5 (West2). Parameters d_{0i}, α_i, and β_i are to be estimated with the data. Parameter d_{0i} is the maximum seed germination in population i at t_0, that is, the nonsteamed control set to 25 C. If t_0 had been zero, the parameter $\alpha_i = \mathrm{LT}_{50}$, that is, the maximum mean soil temperature killing 50% of the seeds from population i. In the current case, the parameter $\alpha_i = \mathrm{LT}_{50}$–$t_0$. Parameter β_i describes the shape, including the steepness, of the function for population i. In the parameter estimations, $t \geq t_0$, $0 < d_{0i} \leq 1$, $\alpha_i > 0$, and $\beta_i > 0$ were assumed.

To estimate LT_{50} and LT_{90} for each population i, the following approach was used. To find the lowest t which for a given proportion q gives $p \leq q \cdot d_{0i}$ (where $0 < q < 1$), the equation $p_i(t) = q \cdot d_{0i}$ was solved with respect to t for each population i. The general solution, $T^{(i)}_{100 \cdot q}$, is given by

$$\mathrm{LT}^{(i)}_{100} = \alpha_i \cdot \left(\frac{1 - q}{q}\right)^{\frac{1}{\beta_i}} + t_0,\ i = 1, 2, 3, 4, 5 \qquad [2]$$

LT_{50} and LT_{90} for each population i can be expressed as $\mathrm{LT}^{(i)}_{100 \cdot q}$, where $q = 0.5$ $[\mathrm{LT}^{(i)}_{50}]$ and $q = 0.9$ $[\mathrm{LT}^{(i)}_{90}]$, respectively. Parameter values for $\mathrm{LT}^{(i)}_{100 \cdot q}$ for $q = 0.5$ and 0.9 were estimated by replacing parameters α_i and β_i in Equation 2 with their respective estimates found from solving Equation 1 (Table 2). Finally, differences in

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Table 2. Parameter estimates from fitting Equation 1 (dose–response model) to data on observed germination of seeds from five barnyardgrass populations in response to maximum mean soil temperature imposed by steaming soil.[a,b,c]

	d_{0i}			α_i			β_i		
Population	Estimate	SE	95% CI	Estimate	SE	95% CI	Estimate	SE	95% CI
Poland	0.75 d	0.018	[0.72, 0.79]	42.06 b	0.841	[40.41, 43.71]	5.89 a	0.339	[5.22, 6.56]
East1	0.84 e	0.014	[0.81, 0.87]	39.81 b	0.520	[38.79, 40.84]	6.86 ab	0.300	[6.27, 7.46]
East2	0.68 c	0.017	[0.65, 0.71]	37.36 a	0.698	[35.98, 38.73]	6.33 a	0.339	[5.66, 6.99]
West1	0.13 a	0.011	[0.11, 0.16]	43.33 b	1.363	[40.65, 46.01]	12.76 b	2.084	[8.67, 16.86]
West2	0.43 b	0.019	[0.39, 0.46]	39.12 ab	1.154	[36.85, 41.39]	6.21 a	0.484	[5.26, 7.16]

[a]Parameter d_{0i} denotes the maximum germination in population i and occurs at t_0, that is, nonsteamed control (set to 25 C). Parameter $\alpha_i = LT_{50}–t_0$, and parameter β_i denotes the shape (slope) of the dose–response curve (Figure 4).
[b]Estimates not sharing the same letter were significantly different (Bonferroni's method, $P \leq 0.05$ divided by the number of hypotheses test = 0.05/10 = 0.005; Supplementary Table S1).
[c]Populations East and West represent populations from east and west sides of the Oslo Fjord, Norway, respectively.

parameter estimates (LT_{50} and LT_{90}) among the five populations were compared using the Bonferroni method (Bonferroni 1936).

To assess whether moistening of the dry seeds before steaming was affecting the seeds' tolerance to high temperature and hence the LT estimates, the three populations in which four levels of moistening were imposed (k) were analyzed individually with the following two-parameter model:

$$p = p_k(t) = \frac{d_0}{1 + \left(\frac{t - t_0}{\alpha_k}\right)^{\beta_k}},\ k = 0,\ 12,\ 24,\ 48 \qquad [3]$$

where $\alpha_j > 0$ and $\beta_j > 0$ are parameters to be estimated, whereas d_0 was fixed to the estimate values found from solving Equation 1 for populations Poland, East1, and East2, that is, 0.75, 0.84, and 0.68, respectively (Table 2). The expression for $LT_{100 \cdot q}$ (Equation 2) was modified correspondingly by replacing α and β with α_k and β_k, respectively. Finally, differences in parameter estimates (LT_{50} and LT_{90}) among the four premoistening levels (k) were compared individually for the three actual populations (Poland, East1, East2) using the Bonferroni method (Bonferroni 1936).

Results and Discussion

In Experiments 1 and 2, the highest germination percentage was observed in controls (25 C), and no germination occurred above 94 C for four of the five populations (Figure 4). For population West1, however, no germination occurred above 79 C. Populations responded differently to the different soil temperatures. The West populations had lower maximum germination (d_{0i}) than the East and Polish populations (Table 2; Figure 4). There was a general viability problem with West populations that can be attributed to the seed collection location and the seed maturity and dormancy at the time of seed collection, as the seeds were collected, stored, and treated in the same way as other populations; the West populations had the lowest seed weight, possibly indicating some seed immaturity (Table 1). In Experiment 3, also, no germination occurred for populations steamed with a target temperature of 99 C at exposure durations of 90, 180, or 540 s.

Increasing steam temperature resulted in decreasing germination ability of all barnyardgrass populations. Seed mortalities of 50% and 90% for all barnyardgrass populations were estimated to temperature ranges of 62 to 68 C and 76 to 86 C, respectively (Table 3). The LT_{90} estimates for Norwegian populations were close to 79.6 C, reported by Vidotto et al. (2013) for seeds of barnyardgrass that were incorporated into loamy-sand soil in tubes and treated in hot-water baths. However, the LT_{90} estimate for the Polish population was higher (86.08 C) compared to their estimate. The generally high heat tolerance of barnyardgrass seeds previously has been attributed to the seed structure, protection of caryopsis by its palea and lemma, sterile floret, the second glume, and partially the first glume (Vidotto et al. 2013).

Thermal weed control technology uses the thermo-method for damaging vital functions of parts of a plant. When heat is provided to a plant part, the temperature of its surface rises. The difference between the temperature of the media and the surface of the plant decreases completely. When the temperature on the surface of the plant rises, the heat's effectiveness depends upon the speed at which the heat spreads in the tissue of the plant, that is, heat conductivity from superficial plant tissues to deeper layers of plant tissues. This process is characterized by the coefficient of heat conductivity of plant tissue. Importantly the coefficient of heat conductivity in living tissues of a plant is low, meaning that heat in living tissues of a plant spreads slowly. The temperature of deeper plant tissues dose not rise quickly, and the temperature that destroys the inner tissues of plants is reached after a delay (Sirvydas et al. 2002). Melander et al. (2002) also showed that steaming the soil before crop sowing has the potential to kill all viable weed seeds in the heated soil volume, where very effective and prolonged weed control can be obtained. A temperature of more than 70 C down to 2.5 cm maintained for 6 to 9 min has been reported to have a complete control effect persisting for several months (Bødker and Noyé 1994). The lethal effect of heating on weed seeds also is known from composting and mulching, where most viable weed seeds lose their germination capacity when the temperature reaches approximately 60 C and persists for a long duration (Davies et al. 1993; Grundy et al. 1998). Melander and Jørgensen (2005) reported weeding effectiveness of more than 90% control within a maximum temperature range of 60 to 80 C; however, the estimations were only made for standardized situations and did not include the influence of important soil factors, such as soil type, soil moisture content, soil structure, and heat duration after steaming (Melander and Kristensen 2011). Temperature and duration of heat exposure are normally inversely related to germination (Melander and Kristensen 2011), although Thomson et al. (1997) and Melander and Jørgensen (2005) suggested the maximum temperature to have greater importance, and rapid chilling is insignificant as long as the target maximum temperature has been achieved. This was also the case in our study.

Steam penetration through the soil, the subsequent rise in soil temperature, and, eventually, the fall in temperature when the steaming has been stopped are expected to vary according to the characteristics of the soil (Dabbene et al. 2003). Texture, porosity, and especially soil moisture are of particular importance (Bristow 2002; Hillel 1980). Water is essential for improving thermal

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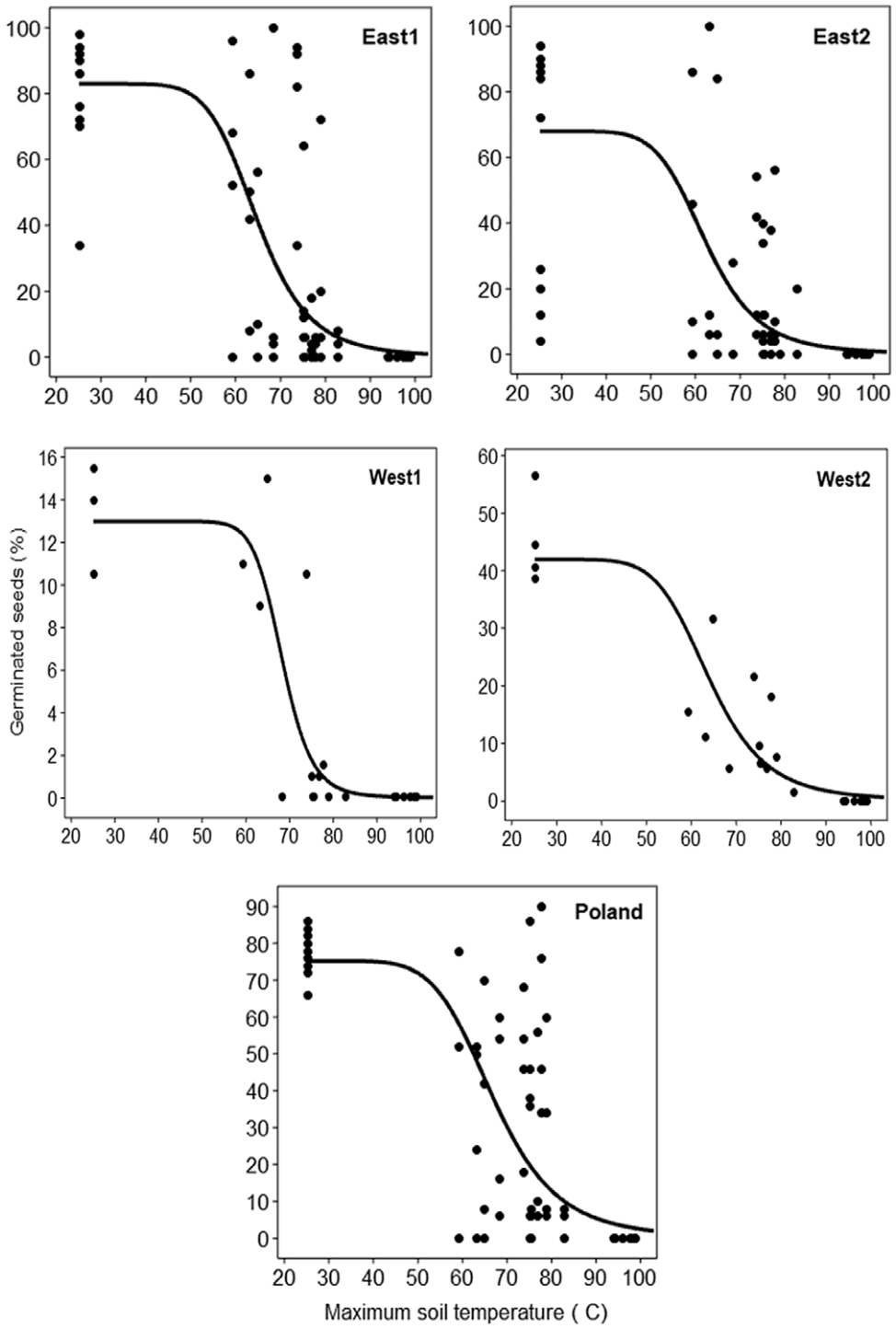


Figure 4. Fitted dose–response curves (black lines) of Equation 1 (using parameter values in Table 2) to the observed seed germination (dots) of five barnyardgrass populations (East1, East2, West1, West2, Poland) as a function of the maximum soil temperature imposed by steaming soil and seeds in a steaming container (Figure 2). Populations East and West represent populations from east and west sides of the Oslo Fjord, Norway, respectively.

conductivity (Nishimura et al. 2015). Soil moisture at levels near field capacity in general is reported to yield high heating efficiency values in relation to steaming disinfection methods (Gay et al. 2010). In our study, the soil was a loam (not too heavy soil), and soil moisture was about 40%; thus we assumed it to be somewhat intermediate regarding heating efficiency. High temperatures in a dry substrate apparently have less effect on seed viability than they do in a moist substrate. Moist soils enhance homogeneous heat distribution (Moonen et al. 2002). The moisture produced from the steam can also promote heat transmission to the core (Melander and Jørgensen 2005).

Moonen et al. (2002) reported that seed size does not seem to play a role, whereas Jakobsen et al. (2019) reported that large seeds are less sensitive to short heat treatment than species with small

https://doi.org/10.1017/wet.2021.107 Published online by Cambridge University Press

Table 3. Parameter estimates for lethal temperatures LT_{50} and LT_{90} estimation (denoting the maximum mean lethal soil temperature required to kill 50% and 90% of barnyardgrass seeds through soil steaming).[a,b]

	LT_{50}			LT_{90}		
Population	Estimate	SE	95% CI	Estimate	SE	95% CI
Poland	67.06 bc	0.841	[65.41, 68.71]	86.08 c	0.744	[84.62, 87.54]
East1	64.81 ab	0.520	[63.79, 65.84]	79.83 b	0.569	[78.71, 80.95]
East2	62.36 a	0.698	[60.98, 63.73]	77.87 ab	0.681	[76.53, 79.21]
West1	68.33 bc	1.363	[65.65, 71.01]	76.46 a	1.013	[74.47, 78.46]
West2	64.12 ab	1.154	[61.85, 66.39]	80.72 b	0.961	[78.83, 82.61]

[a]Parameter estimates not sharing the same letter were significantly different (Bonferroni's method, $P \leq 0.05$ divided by the number of hypotheses test = 0.05/10 = 0.005; Supplementary Table S2).
[b]Populations East and West represent populations from east and west sides of the Oslo Fjord, Norway, respectively.

Table 4. Results of testing whether pretreatment of the seeds (premoistening in water at room temperature for 0, 12, 24, or 48 h before steaming treatment) affected the parameter estimates for lethal temperatures (LT_{50} and LT_{90}) for three barnyardgrass populations: Poland, East1, and East2.[a]

		LT_{50}			LT_{90}		
Population	Pretreatment	Estimate	SE	95% CI	Estimate	SE	95% CI
Poland	0	64.23 b	1.403	[61.44, 67.01]	85.14 ab	1.572	[82.02, 88.26]
	12	71.14 a	1.264	[68.63, 73.65]	89.35 a	1.518	[86.34, 92.37]
	24	63.37 b	1.205	[60.98, 65.76]	81.39 b	1.351	[78.71, 84.08]
	48	70.59 a	0.981	[68.65, 72.54]	86.49 a	1.246	[84.02, 88.96]
East1	0	56.79 c	1.697	[53.42, 60.15]	75.95 b	1.376	[73.22, 78.68]
	12	72.89 a	0.794	[71.32, 74.47]	85.17 a	1.031	[83.13, 87.22]
	24	65.56 b	0.753	[64.07, 67.06]	77.56 b	0.932	[75.71, 79.41]
	48	61.69 c	0.947	[59.81, 63.57]	74.63 b	1.003	[72.64, 76.62]
East2	0	61.77 b	1.614	[58.57, 64.97]	84.11 a	1.756	[80.63, 87.60]
	12	72.59 a	0.546	[71.50, 73.67]	79.75 a	0.723	[78.31, 81.19]
	24	47.54 c	3.633	[40.33, 54.76]	63.31 b	2.478	[58.39, 68.22]
	48	47.25 c	3.782	[39.74, 54.75]	62.28 b	2.614	[57.10, 67.47]

[a]Parameter estimates within the same population not sharing the same letter were significantly different (Bonferroni's method, $P \leq 0.05$ divided by the number of hypotheses test = 0.05/6 = 0.0083; Supplementary Table S3).

seeds, as more energy is spent to heat a large seed than a small seed to break the cell wall and damage the other cell structures. The West1 population had the smallest seeds (low 1,000-seed weight; Table 1), and that could have explained why this population required lower temperatures to kill seeds than the other populations. The sensitivity of seeds probably also depends on the thickness of the seed coat, the structure and morphology of the seed, and the water content of the seeds (Jakobsen et al. 2019; Vidotto et al. 2013). A not fully developed seed coat that could protect the seeds from heat or different levels of dormancy that could render seeds susceptible to lower temperatures could be other possible explanations for the susceptibility of population West1 compared to the other populations. Dry seeds have more tolerance to high temperature, although this was not always the case in our study. Table 4 shows the LT estimates for the three populations in which premoistening of the dry seeds was imposed prior to steaming. In the Polish population, for both LT_{90} and LT_{50}, the highest estimates (i.e., most tolerant to heat) occurred for 12 h and 48 h premoistening, respectively, whereas dry seeds and 24 h premoistening were most sensitive (i.e., smallest estimate). In the East1 population, pretreatment influenced both LT_{50} and LT_{90}, where seeds premoistened for 12 h were the most tolerant (i.e., the highest values). In the East2 population, pretreatment influenced both LT parameters. For LT_{50}, seeds premoistened for 12 h were most tolerant to heat. For LT_{90}, 12-h premoistening and dry seeds were most tolerant to heat (79.7 C and 84.1 C, respectively). Perhaps in some 24- and 48-h premoistened seed samples, the seeds were starting to germinate, which caused them to be especially sensitive to heat. In other cases, seeds may not have started the germination process and thereby were less sensitive.

Soil steaming to kill weed seeds both in the field and greenhouse has been shown by several researchers where, in some cases, an exothermic substance has been added to improve the effect (e.g., Bàrberi et al. 2009; Lenzi et al. 2004; Melander et al. 2002; Melander and Jørgensen 2005; Sirvydas et al. 2002). Lenzi et al. (2004) reported that adding KOH and CaO can be used in association with steam for soil disinfection in vegetable crops without production risks. Depending on the further use of soil, undesired effects of steaming against microarthropods, microorganisms, and the natural soil microflora, in particular, nitrifying bacteria, might be unfavorable (Fenoglio et al. 2006; Roux-Michollet et al. 2008). With prolonged heat exposure, the solubility of metal ions could also lead to plant toxicity (Egli et al. 2006).

Based on many years of barnyardgrass presence and expanded geographical distribution in Norway, the species is considered as established and "naturalized" in specific areas. The risk of further spread could be reduced significantly if relocation of soil from barnyardgrass-infested areas is restricted or if soil is moved only after verification that it is free of propagative material. The current results show that soil steaming can guarantee very good control of barnyardgrass seeds in infested soil masses. Complete seed kill was achieved by steaming soil at 94 C regardless of exposure duration (in the range 29 to 183 s). To reduce energy use of the method, costs, and potential negative impacts of high soil temperature,

https://doi.org/10.1017/wet.2021.107 Published online by Cambridge University Press

future tests should include temperatures in the range 84 to 93 C, because this range was missing in the current study. Further studies are needed to investigate the effect of factors like soil type and soil moisture content on weed seed mortality, as well as whether steaming has any undesirable effects on future uses of soils.

Supplementary material. To view supplementary material for this article, please visit https://doi.org/10.1017/wet.2021.107

Acknowledgments. This work was done as a part of the projects "Innovative Approaches and Technologies to Manage Invasive Alien Species Threatening Biobased Production (BIOIMMIGRANTS)" financed by the Research Council of Norway (Grant no. 194051/F40) and "Controlling *Echinochloa-crus-galli* in Cereals, Potatoes and Vegetables (ECRUSLI)" financed by the Norwegian Research Funding for Agriculture and Food Industry, Bayer AS, Felleskjøpet Agri SA, Norgro AS, Strand Unikorn AS, and the County Governors of Oslo and Akershus, Buskerud, Østfold, Vestfold, and Telemark (Research Council of Norway, Grant no. 267700). We acknowledge Tore Daarstad (Norsk Landbruksrådgiving Viken), Ninni A. Christiansen, and Joachim H. Enghaug (both Norsk Landbruksrådgiving Øst) for collecting the seeds. We thank Henrik Antzée-Hyllseth, Andreas M. Beachell, Marit E. Helgheim, Vinh Hong Le, Marta Bosque Fajardo, and Kjell K. Wærnhus (all NIBIO) for practical help before, during, and after the steaming treatment. We thank Torfinn Torp (NIBIO) for conducting the statistical analyses. We thank Hans K. Westrum, Tobias Glemming, and Cornelis Arnoldussen (all Soil Steam International AS) for providing the stationary soil steaming prototype device and for their collaboration and practical support. No conflicts of interest have been declared. The funders had no role in the design of the research, data collection and analysis, writing the manuscript, or the decision to publish the results.

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