

Impact of Soil-applied Steam in Combination with Exothermic Chemicals on Weed and Pathogen Survival

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Abstract. Steam has been used for decades as a nonchemical alternative for soil disinfestation in stationary settings such as greenhouse crop production. However, disinfesting large soil volumes through field-scale steam applications is limited by time, labor, carbon inputs, efficacy, and economic factors. Exothermic substances added to soil before or during steam applications have the potential to improve the control of soilborne pathogens and weed propagules. To test this hypothesis, a 2-year microplot study was conducted to evaluate weed and pathogen suppression with steam in combination with two exothermic substances: quicklime and sodium peroxide. Treatments included a nontreated control, 30-minute steam application, sodium peroxide amendment, sodium peroxide amendment with 30-minute steam application, quicklime amendment, and quicklime amendment with 30-minute steam application. Steam was injected at a depth of 10.2 cm using a stationary SIOUX steam generator and steam-graded spike hoses. *Pythium* propagules per gram of soil were assessed via a wet plating assay. Weed suppression was assessed by evaluating germination rates of artificially introduced weed seeds (vetch, ryegrass, sida) and tubers (yellow nutsedge). *Pythium* propagules (ppg) significantly decreased in comparison with the nontreated control when steam was applied to quicklime-amended soil in both years at the distance of 2.5 cm from steam injection (7.4 ppg in 2021; 0 ppg in 2022) and the 12.5 cm mark from steam injection (41 ppg in 2021; 0 ppg in 2022). Only at the distance of 2.5 cm did steam alone decrease *Pythium* significantly (0 ppg in 2022). The sodium peroxide amendment did not improve *Pythium* suppression at any distance from steam injection. Similarly, weed propagules 2.5 cm from steam emitters were suppressed, and the addition of exothermic substances did not improve propagule suppression. Beyond 12.5 cm, no steam treatment affected weed propagule germination. At a distance of 12.5 cm from emitters, the addition of exothermic substances improved propagule suppression in one of two years, but the results were variable. Reduction in weed propagule emergence was highly correlated with the maximum soil temperature, and clustered distributions suggested that critical threshold temperatures are necessary for adequate suppression.

Crop loss attributable to soilborne pathogens and weeds poses a major problem for specialty crop growers across the United States. For example, black root rot (caused by *Pythium* sp., *Rhizoctonia* sp., *Fusarium* sp., and nematodes) can cause 20% to 40% yield loss in strawberry (Louws and Cline 2019), and *Phytophthora crown rot* (caused by *Phytophthora cactorum*) can cause up to 50% yield loss (Marin et al. 2018). In strawberry and other plasticulture crops, annual weeds can be controlled with plastic mulches or preemergence herbicides. However, even in those systems, weeds emerge in planting

holes, and nutsedges (*Cyperus* sp.) can emerge through the plastic (Bonanno 1996). In other systems, cultivation can spread vegetatively propagated weeds such as hedge bindweed (*Convolvulus sepium*) and alligatorweed (*Alternanthera philoxeroides*) (Neal et al. 2023; University of Florida Institute of Food and Agricultural Science 2023). Consequently, standard practices for controlling soilborne pathogens and weed propagules in strawberry, bulb, vegetable, and cut flower production have historically relied on soil fumigation with methyl bromide (Fennimore and Goodhue 2016; Holmes et al. 2020; Kim et al. 2020; Rainbolt

et al. 2013). However, most agricultural uses of methyl bromide have been phased out.

Typical registered soil fumigants currently in use are 1,3-dichloropropene (1,3-D), chloropicrin, methyl-allylisothiocyanate, allylisothiocyanate, and di-methyl-di-sulfide. However, these have not been found to be as consistently efficacious as methyl bromide against nematodes, soilborne pathogens, and weed propagules (Fennimore and Goodhue 2016; Fennimore et al. 2003; García-Mendez et al. 2008; Rainbolt et al. 2013; Samtani et al. 2010). Furthermore, many of these chemicals are regulated through township caps or local use restrictions in states such as California (California State Legislature 1967). In other areas of the United States, the availability of soil fumigants is affected by supply chain issues or production constraints. Moreover, organic-certified production guidelines prohibit the use of these chemical soil fumigants.

Therefore, a range of nonchemical soil disinfestation alternatives have been studied, such as anaerobic soil disinfestation (Mahalingam et al. 2020; Strauss and Kluepfel 2015), biofumigation (Baysal-Gurel et al. 2018; Lefebvre et al. 2019), soil solarization (Candido et al. 2008; Samtani et al. 2017), and steam application (Guerra et al. 2022; van Loenen et al. 2003). Steam as a soil disinfestation method has been studied for decades and has been proven to be effective at suppressing soilborne pests and pathogens (Katan 2000; Kim et al. 2021; Newhall 1955). Soil temperature, moisture, and heat duration are important factors associated with the efficacy of steam as a soil disinfectant (Gay et al. 2010; Pullman et al. 1981).

Multiple soil steaming application methods have been developed. Stationary steam application is commonly used and efficacious in greenhouse settings, where steam is generated by an external unit connected to hoses that blow steam under a sealed thermoresistant cover (Dabbene et al. 2003; Lu et al. 2010). Additional stationary steam injection methods include buried pipes that eject steam below the soil surface or pipes/hoses that lay on the soil surface and inject steam through attached spikes. Stationary steam application methods can effectively suppress pests (van Loenen et al. 2003; Whitehead et al. 1979), weeds (Bitarafan et al. 2021), and pathogens (Samtani et al. 2012).

Mobile field steam applicators are tractor-pulled or self-propelled machines equipped with a steam generator and injection system. Several field applicator models exist. Some apply steam via shank injectors connected to steam generators (SigmaFire Boiler; Clayton Industries, City of Industry, CA, USA), rototillers (ECOSTAR SC 600; Celli, Forlì, Italy), or steam shields (Egedal, Tørring, Denmark). Despite advancements in mobile steam application, it is still a challenging technology that demands large amounts of fuel (7598 L·ha⁻¹ propane), time (36 h·ha⁻¹), and money (\$19,000 ha⁻¹) (Fennimore and Goodhue 2016; Samtani et al. 2012). Factors that contribute to high inputs include heavy machinery and the time required to reach high soil temperatures throughout a large soil volume (Fennimore and Goodhue 2016).

To increase mobile steam application efficiency, exothermic compounds can be applied to the soil. Exothermic compounds release heat in a reaction with another compound or element (e.g., water). Therefore, the application of exothermic compounds to the soil, in combination with steam, has the potential to reach soil temperatures beyond what steam alone can reach. In addition, it could potentially decrease the time required to reach high soil temperatures. This could lead to more efficient weed and disease control as well as faster steam application times. Previous studies have found that exothermic substances such as quicklime [calcium oxide (CaO) and potassium hydroxide (KOH)] in combination with steam are capable of increasing soil temperature and pathogen suppression *in vitro* (Luvisi and Triolo 2007) or in combination with specific soil steamers (Luvisi et al. 2006; Peruzzi et al. 2000, 2011). Questions remain regarding whether the combination of steam with exothermic substances will lead to better pathogen and weed suppression under general field conditions.

Therefore, we tested the hypothesis that suppression efficacy of soilborne pathogens and weed propagules can be improved by the combination of steam with exothermic compounds under field conditions. We followed the experimental microplot trial setup of Kim et al. (2020). The objectives of the study were to assess weed and pathogen suppression of soilborne *Pythium* sp. using steam combined with quicklime and sodium peroxide (Na₂O₂), evaluate how the distance from steam emitters affected seed germination and pathogen survival with and without the addition of exothermic compounds, and assess the relationships between temperature, pathogens, and weed control.

Materials and Methods

Microplot trials. Research was conducted at the Central Crops Research Station in Clayton, NC, USA. In 2021, the trial was conducted in a field that alternates with annual hill strawberry plasticulture and 'brooks' oat cover crop (lat. 35.668361°N, 78.506261°W). In 2022,

the trial was conducted in a neighboring field with the same recent crop history (lat. 35.668122°N, 78.505150°W). On 1 Jun 2021 and 1 Jun 2022, microplots ($n = 24$) were established in a field with soil type Norfolk loamy sand. Microplots were 1 m wide $\times$ 0.5 m long $\times$ 10.2 cm deep and spaced 3 m apart. The following six treatments were applied in a randomized complete block design (four replicates per treatment) during both years of the trial: nontreated control; 30-min steam (steam); sodium peroxide amendment (SP); sodium peroxide amendment with 30-min steam (SPS); quicklime amendment (QL); and quicklime amendment with 30-min steam (QLS). To evaluate suppression efficacy of steam combined with exothermic substances, pathogen suppression efficacy was evaluated at different distances from the steam injection point (2.5, 12.5, 25, and 38 cm) in each replicate.

Application of steam and exothermic substances. Before steam application, exothermic chemicals were incorporated into the soil at the following rates: 1% (w/w) quicklime (Fisher Scientific, Hampton, NH, USA) and 0.1% (w/w) sodium peroxide (Sigma-Aldrich, Burlington, MA, USA). Low percentages of exothermic chemicals were applied to minimize their impact on soil pH and salt content while still applying enough to have a temperature effect on the soil. The mass of each chemical applied was based on the approximate soil mass of a microplot at a depth of 10.2 cm. Ten soil cores were taken in the field and used to calculate the soil mass of a microplot (152.167 kg) using Eq. [1]:

$$A. \text{ Number of soil cores that fit in one microplot} = \frac{51000 \text{ cm}^3 \text{ microplot volume}}{1768.16 \text{ cm}^3 \text{ soil core volume}} = 28.84 \text{ soil cores}$$

$$B. \text{ Microplot Soil Mass} = 28.84_{\text{soil cores}} \times 5274.08_{\text{g soil core}^{-1}} = 152,157.21 \text{ g}$$

$$C. \text{ Mass of quicklime applied} = 152,157 \text{ g}_{\text{microplot soil mass}} \times 0.01 = 1521.01 \text{ g quicklime}$$

$$D. \text{ Mass of sodium peroxide applied} = 152,157 \text{ g}_{\text{microplot soil mass}} \times 0.001 = 152.10 \text{ g sodium peroxide} \quad [1]$$

The aforementioned equation includes calculations to estimate the mass of a microplot (A and B) and determine the mass required to apply 1% (w/w) of quicklime (C) and 0.1% (w/w) of sodium peroxide (D). Temperature probes were inserted at distance points of 2.5, 12.5, 25, and 38 cm from steam injection to measure soil temperature throughout the steaming process. Type T thermocouple wires were placed adjacent to each seed sachet in front of soil probes at a depth of 10.2 cm to record soil temperatures using a 4-channel thermocouple data logger made by HOBO (Part #UX120-014M; Unset Bourne, MA, USA). Black plastic mulch (Virtual Impermeable Film; TriEst AG Group, Greenville, NC, USA) was used to cover the microplot

area before steam application. Steam was injected using a low-pressure steam generator (Sioux Steam-Flo 25L Boiler; Sioux, Beresford, SD, USA). This generator injected steam into microplots with a depth of 10.2 cm at a pressure of 34 to 48 kPa through the attachment of a steam-grade spike hose (Table 1 and Fig. 1).

Pathogen suppression evaluation. To evaluate soilborne pathogen control, soil was tested for the presence of *Pythium* sp. propagules per gram of soil (ppg) initially found in the soil. Soil samples were taken 24 h after steam application on 2 Jun 2021 and 2 Jun 2022. A soil probe with a 2.5-cm diameter was used to collect four soil cores from each replicate at distance points of 2.5, 12.5, 25, and 38 cm. Each soil core was taken from a depth of 10.2 cm. Soil samples were placed in labeled paper bags, mixed, and left to air dry (at room temperature) for 2 weeks. Dried soil samples were transferred into plastic containers and stored in a refrigerator at 7°C. Soil was analyzed to determine *Pythium* ppg using the plating assay outlined by Klose et al. (2007).

Corn meal agar (17 g L⁻¹; Sigma-Aldrich, St. Louis, MO, USA) was prepared and sterilized at 121°C for 20 min in a SterilMatic Autoclave (Market Forge Industries, Everett, MA, USA). After autoclaving, 1 mL of Tween 20 (Thermo Fisher Scientific, Waltham, MA, USA) was added. This was followed by the addition of prepared antibiotic and antifungal solutions.

Antifungal and antibiotic solutions were added to approximately 50°C corn meal agar at the following concentrations: 0.025 g L⁻¹ Rose Bengal (Fisher Chemical, Fair Lawn, NJ, USA), 250 mg L⁻¹ ampicillin (Fisher BioReagents, Fair Lawn, NJ, USA), 22 mg L⁻¹ benomyl (Sigma-Aldrich; St. Louis, MO, USA), 10 mg L⁻¹ rifampicin solution (Fisher Chemical), and 50 µL of 2.5% aqueous pimarcin stock solution (Sigma-Aldrich). Then, the agar was poured into 100-mm $\times$ 15-mm petri dishes and left in the dark at room temperature for 3 d before plating soil suspension.

Soil suspension (25 mg mL⁻¹) was spread on a plate (replicated 5 $\times$ 3 times) using a sterile cell spreader (VWR International, Radnor, PA, USA). Then, plates were incubated in the dark at room temperature. *Pythium* sp. colonies were counted 48 h and 72 h after plating. Then, the average number of ppg was calculated for each of the three replicates.

Weed germination. The following four bioassay species were selected for the experiment: Italian ryegrass (*Lolium multiflorum*); common vetch (*Vicia sativa*); prickly sida (*Sida spinosa*); and yellow nutsedge (*Cyperus esculentus*). These species are common to the region and were selected to represent a range of propagule sizes, taxa, life cycles, and sensitivities to sterilization methods. Non-coated Italian ryegrass and common vetch seeds were organic USA-certified that were purchased from a local agricultural supply store. Prickly sida seeds (with mericarp) were purchased from Azlin Seed Service (Azlin, MS, USA). Seeds were purchased from commercial

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Table 1. List of six treatments and their abbreviations, chemical quantities, steam pressure, water, and propane used to create microplots. All numbers are averaged across both years of the trial.

Treatment	Abbreviation	Chemical applied		Pressure (kPa) ⁱⁱ	Water use (L·m ⁻²) ⁱⁱⁱ	Propane use (L·m ⁻²) ^{iv}
		% of Soil mass ⁱ	Quantity (g)			
Nontreated control	NTC	—	—	—	—	—
30-min Steam	Steam	—	—	34-48	8.0	1.8
Sodium peroxide	SP	0.1	152.10	n/a	8.0	—
Sodium peroxide + steam	SPS	0.1	152.10	34-48	8.0	1.8
Quicklime	QL	1	1521.01	n/a	8.0	—
Quicklime + steam	QLS	1	1521.01	34-48	8.0	1.8

ⁱ Amount of exothermic chemical applied, as a percentage of the soil mass within the microplot (w/w) and grams of material per microplot (0.25 m²).

ⁱⁱ Kilopascal.

ⁱⁱⁱ Liters of water applied to each microplot averaged over the course of the 2-year trial in the form of steam or water.

^{iv} Liters of propane used to steam each microplot averaged over the course of the 2-year trial.

sources because locally collected seeds have historically had poorer germination than purchased seeds. Yellow nutsedge tubers locally collected for use in the first year of the experiment had very low germination rates. Therefore, for the second year, tubers were purchased from Azlin Seed Service. Nutsedge tubers were sorted by size, and those with a diameter between 5 and 7 mm were used in the test. All propagules were stored dry at 3 °C until use.

Propagules (seeds or tubers) were placed into 100-µm nylon mesh seed sachets (Dulytek Rosin Filter Tube; Dulytek, Seattle, WA, USA), and each species had its own chamber within the nylon mesh (Fig. 2A). Twenty seeds of each seeded species and 10 nutsedge tubers were placed in each seed sachet (Fig. 2A). Seed sachets were placed into a soil probe system as described by Hoffmann and Fennimore (2017). The soil probe system was modified to hold one seed sachet at a depth of 10.2 cm, which is the depth of steam emitters. The soil probes were 30.5 cm long and had a hole with a 5.1-cm diameter centered 20.3 cm from the top. Seed sachets were placed into the 5.1-cm hole and held in place with galvanized hardware cloth secured with eight (four per side) stainless steel self-tapping screws (Fig. 2B). In each microplot, soil probes (treatments: $n = 6$; replicates: $n = 4$; distances: $n = 4$; soil probes: $n = 96$) were driven into place using a rubber mallet at distances of 2.5, 12.5, 25, and 37.5 cm from individual steam emitters (Fig. 2C) for all treatments in a strip plot design. To prevent

interference of lateral thermal movement by the soil probes, the placement of soil probes was staggered with one probe at each distance perpendicular to separate steam injection tines. Then, the temperature probes were installed in front of the soil probes adjacent to each seed sachet at a depth of 10.2 cm.

One day after steam treatments, the soil probes with weed propagules were removed from the ground. The propagules were removed from the sachets and then spread onto the surface of a peat-vermiculite substrate in 10-cm square pots and covered with a minimal amount of the same substrate (Fig. 3). Potting substrate was prepared on-site according to the Cornell Peat-Lite Mix A recipe (Boodley and Sheldrake 1982) consisting of equal parts peatmoss and vermiculite amended with lime and a minimal fertilizer.

Pots were placed in an unheated greenhouse. Ambient air temperature ranged between 18 and 32 °C. Pots were irrigated daily using a fogging nozzle to prevent washing and splashing of the propagules or substrate. Weed emergence was recorded weekly for 2 months and until no new emergence was observed for 2 weeks. Emerged propagules were pulled and discarded after being counted. The percentage of germinated propagules was calculated and used in all data analyses. Nonsprouted propagules in the substrate were not tested for latent viability.

Soil temperature assessment. Soil temperatures were recorded at four distances from the steam injection point (2.5 cm, 12.5 cm,

25 cm, and 38 cm). In the 2021, temperature probes malfunctioned; therefore, no soil temperature data were available that year. In 2022, temperatures were recorded with a HOBO 4-channel thermocouple data logger (part #UX120-014M; Onset, Bourne, MA, USA) with four T-type thermocouple wires. Soil temperatures were recorded for the duration of the steaming event (30 min) and left undisturbed for an additional 15 min after steaming ended. Recorded temperatures were compiled using HOBOWare software (version 3.7.17).

Soil pH. Because quicklime and sodium peroxide affect soil pH, soil samples were taken to analyze pH before and after treatment. Soil was sampled from each distance point within a replicate to create a sample that was representative of the entire microplot. In the first year (2021), 10 g of the mixed soil sample was placed in an open plastic container and air-dried for 1 week. Once samples were dry, they were placed in a 50 mL beaker with 20 mL of deionized water. Then, soil solutions were mixed using a glass stirring rod and left to stand for 10 min. The pH was measured with a PC800 benchtop pH and conductivity meter (Apera Instruments, Columbus, OH, USA). In the second year of the trial, soil samples were sent to the North Carolina Department of Agriculture and Consumer Sciences Agronomic Division for a soil report.

Statistical analysis. All pathogen data were analyzed using RStudio Desktop version 2022.07.02 (RStudio, Boston, MA, USA) with R 3.3.3. Pathogen results were tested for normal distribution (Shapiro-Wilk $\alpha \leq 0.05$) and the number of *Pythium* ppg were log₁₀-transformed before further analyses based on this test. Pathogen suppression was analyzed with an analysis of variance (ANOVA) ($\alpha \leq 0.05$). Tukey's honestly significant difference post hoc test was performed when appropriate ($\alpha \leq 0.05$). Data from each year were analyzed separately ($\alpha \leq 0.05$). Regression analyses were performed between average soil temperature during steam application [$T_{avg}(x)$], maximum soil temperature [$T_{max}(x)$], and *Pythium* ppg (y). An exponential model was chosen because it had the highest r^2 and P values across all analyses compared with linear and logarithmic regression models. Tables and graphs were made using Excel for

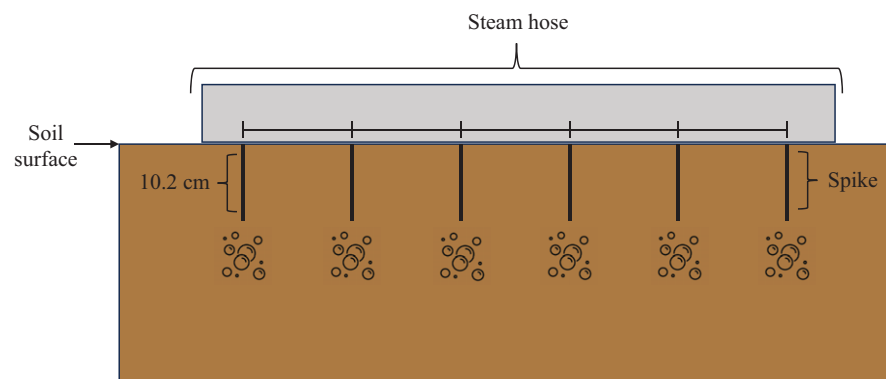


Fig. 1. Steam hose dimensions. Each spike has a length of 10.2 cm; therefore, steam is ejected at a soil depth of 10.2 cm. Each of the spikes is spaced 30 cm apart.

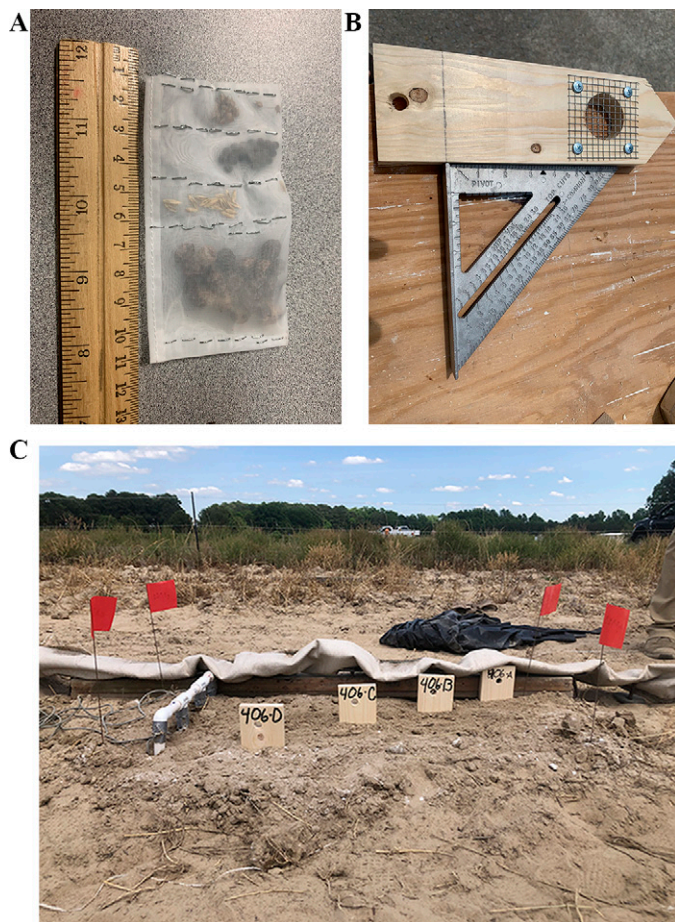


Fig. 2. (A) Seed sachet. (B) Soil probe, galvanized hardware mesh, and stainless screws. (C) Posttreatment view of the microplot after plastic was removed. Soil probes were placed perpendicular to steam emitters in the wooden wedge. Type T thermocouple wires used in 2022 were placed adjacent to seed sachets.

Mac (version 16.69; Microsoft, Redmond, WA, USA) and PowerPoint for Mac (version 16.99.2; Microsoft).

Weed data were subjected to an ANOVA using the general linear model and GLIMMIX procedure in SAS Studio 3.8 (SAS Institute Inc., Cary, NC, USA). Main effects of year, species, and distance from steam emitters and interactions for treatment and replication were all significant ($\alpha \leq 0.05$); therefore, data were analyzed by species and year to investigate the effects of exothermic compounds and distance from emitters. Effects of exothermic compounds on the efficacy of steam treatments were tested using orthogonal contrasts and Dunnett's multiple comparison tests. Regression analyses were performed between percent germination of each species against $T_{\max}$ and T_{avg} using Proc Reg in SAS Studio 3.8 (SAS Institute Inc. Cary, NC, USA). Although linear regression models fit the data well, scatter plots of the data revealed clusters. Ward's hierarchical cluster analysis was conducted using Proc Cluster in SAS Studio 3.8 (SAS Institute Inc. Cary, NC, USA).

Results and Discussion

Pythium sp. suppression with steam and quicklime. The QLS treatment suppressed *Pythium sp.* better than steam alone or QL

treatment. Additionally, QLS treatment significantly reduced *Pythium* ppg at the 2.5 cm mark (7.4 ppg in 2021; 0 ppg in 2022) (Fig. 4) and 12.5 cm mark (41 ppg in 2021; 0 ppg in 2022). Furthermore, QLS treatment reduced *Pythium* ppg at the 25 cm mark in the first year (800 ppg) (Fig. 4). In contrast, steam alone significantly reduced *Pythium* ppg only at the 2.5 cm mark, and only in the second year of the trial (0 ppg) (Fig. 4). The QL treatment significantly reduced *Pythium* ppg only at the 25 cm mark during the first year (600 ppg). The QLS treatment improved *Pythium sp.* suppression compared with steam alone, QL, and steam combined with sodium peroxide.

These findings are in accordance with prior research in which exothermic substances in combination with steam have improved soilborne pathogen control. Potassium hydroxide and steam showed improved suppression of *Rhizoctonia solani* (Triolo et al. 2004) and *Fusarium oxysporum* (Luvisi et al. 2006) compared with steam alone.

However, quicklime has shown variable pathogen control efficacy when combined with steam. *Sclerotinia minor* survival decreased significantly when quicklime and steam were applied in vitro (Luvisi and Triolo 2007), but not in the field (Triolo et al. 2004). The reaction between quicklime and water to form calcium hydroxide $[\text{Ca}(\text{OH})_2]$ is exothermic



Fig. 3. Seed sachets removed from the soil probe and planted into 10.2-cm pots. All four species were monitored for emergence. Plant propagules were not covered with substrate/vermiculite in this image.

($-64.1 \text{ kJ} \cdot \text{mol}^{-1}$) under standard conditions, and soil temperature increases can enhance pathogen suppression. Differences in soil type can affect the rate and distance of temperature increases (Yang et al. 2019) and how resistant the soil is to pH changes. This could potentially explain differences between prior field experiments and this study.

Pythium sp. suppression with steam and sodium peroxide. The SPS treatment did not suppress *Pythium sp.* more effectively than steam alone. However, SPS treatment suppressed *Pythium sp.* more effectively than SP treatment. The SPS treatment suppressed *Pythium sp.* at the 2.5 cm distance point in the first year (0 ppg) (Fig. 5). Similarly, the steam alone treatment had one instance of *Pythium sp.* suppression at the 2.5 cm distance point in the second year (0 ppg) (Fig. 5). The SP treatment did not suppress *Pythium sp.* in either year of the trial. Ultimately, SPS was more effective at pathogen suppression compared with SP, but not compared with steam alone. These results indicate that steam is the primary control agent in the SPS treatment.

The reaction between sodium peroxide and water to form sodium hydroxide (NaOH) and oxygen (O_2) is exothermic ($-278 \text{ kJ} \cdot \text{mol}^{-1}$) under standard conditions. Therefore, we tested the hypothesis that temperature suppression of soil pathogens would improve when steam and sodium peroxide were applied together compared with when the components were applied separately. Our results did not support this hypothesis. To our knowledge, no prior work of soil-applied steam in combination with sodium peroxide has been conducted.

The exothermic reaction between quicklime and water is weak ($-64.1 \text{ kJ} \cdot \text{mol}^{-1}$) compared with sodium peroxide and steam. However, the higher application rate of quicklime (1% w/w)

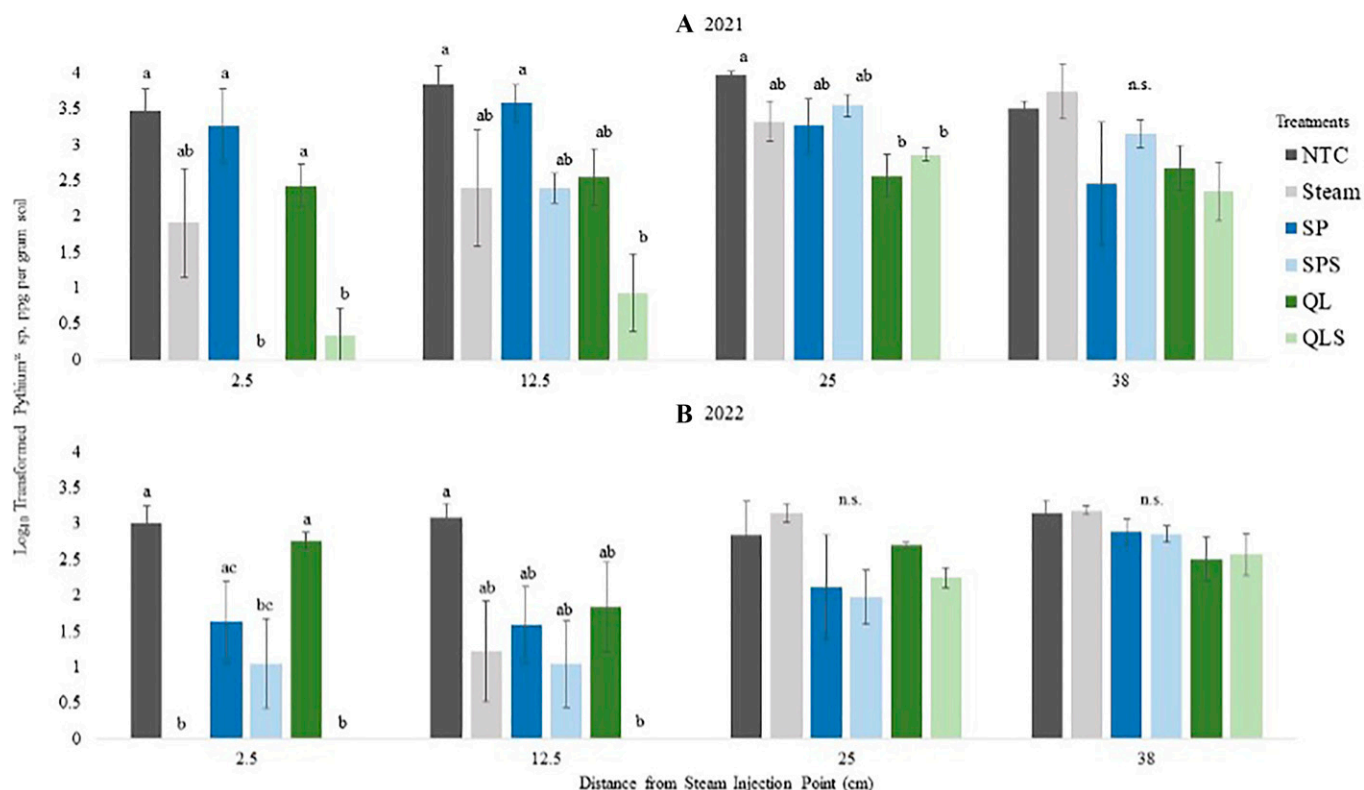


Fig. 4. *Pythium* propagules (ppg) of soil separated by treatment and distance from the steam injection point. Values are the averages of $\log_{10}$ -transformed *Pythium* ppg soil values across four replicates for 2021 (A) and 2022 (B). Different letters indicate significant differences between treatments at the distance point from steam injection according to Tukey's honestly significant difference test ($\alpha \leq 0.05$). Error bars show the standard error of the mean. NTC = nontreated control; QL = quicklime (1% w/w); QLS = quicklime (1% w/w) + 30-min steam application; SP = sodium peroxide (0.1% w/w); SPS = sodium peroxide (0.1% w/w) + 30-min steam application; steam = 30-min steam application.

compared with sodium peroxide (0.1% w/w) could have caused enhanced efficacy in the QLS treatment in regard to temperature and pathogen suppression.

Changes in abiotic factors can also affect pathogen survival. Increases in sodium content have been shown to inhibit microbial growth (Rietz and Haynes 2003). However, microbial

inhibition in response to sodic conditions has been shown to require multiple weeks (Wong et al. 2008). Soil samples were taken only 1 d after treatment application in this study.

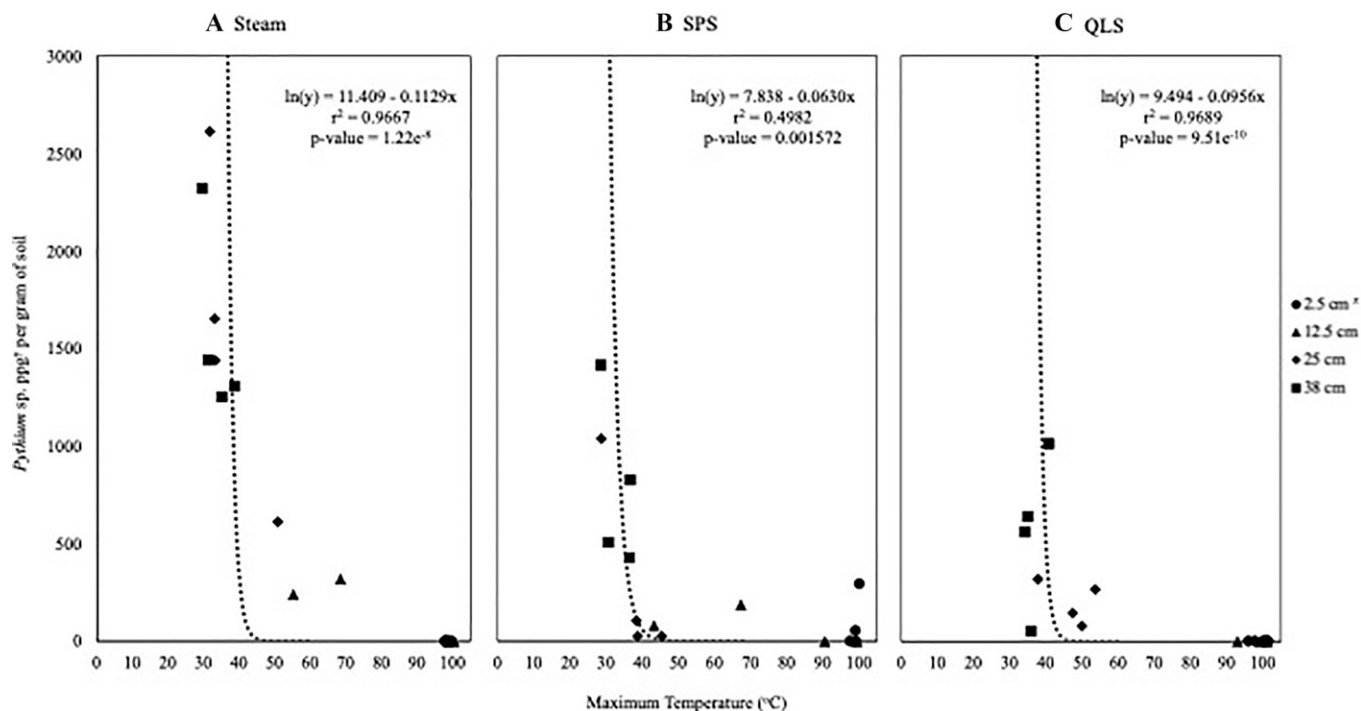


Fig. 5. *Pythium* propagules of soil as impacted by maximum temperatures for (A) steam alone, (B) sodium peroxide + steam (SPS), and (C) quicklime + steam (QLS) treatments in the second year of the trial (2022). The exponential regression curves, regression equations, r^2 values, and P values for each treatment are shown. Circles, triangles, diamonds, and squares designate observation distances from steam injection points of 2.5, 5, 12.5, and 25 cm, respectively. ppg = propagule.

Relationship between maximum soil temperature and *Pythium* sp. suppression. Significant exponential relationships ($\alpha \leq 0.05$) between $T_{\max}$ and *Pythium* ppg were found in all treatments that included steam in the second year of the trial (steam alone, SPS, and QLS). The steam alone and QLS treatments both had r^2 values of 0.97. However, the SPS treatment had a lower r^2 value of 0.50 for the relationship between $T_{\max}$ and *Pythium* ppg (Fig. 5).

Most studies that investigated the effect of short-term high temperatures on pathogen suppression were primarily conducted in vitro. An older study by Byars and Gilbert (1920) found that exposing *Pythium* sp., *Rhizoctonia* sp., and *Heterodera* sp. to 98 °C water in vitro for merely 5 min successfully eradicated the pathogens. This indicates that temperatures above 98 °C for more than 5 min are not necessary to suppress fungal pathogens. Another study found that short exposure (~11 min) to 50 °C in vitro was lethal to *Verticillium dahliae*, *Globodera pallida*, and *Sclerotium cepivorum*, and that short exposure to 60 °C was lethal to *P. ultimum*. (van Loenen et al. 2003).

Various factors can affect field soil temperature, including soil depth (Gelsomino et al. 2010), soil type (Miller et al. 2014), and heat application methods (Huh et al. 2020; Miller et al. 2014). Given the variability of temperature suppression on pathogens, further research of the effects that short high-temperature field applications could have on pathogen survival would help advance heat-based soil disinfestation practices.

Relationship between average soil temperature and *Pythium* sp. suppression. Significant exponential relationships ($\alpha \leq 0.05$) between T_{avg} and *Pythium* ppg were found in all steam treatments in the second year of the trial (steam alone, SPS, and QLS). The steam alone and QLS treatments had exponential r^2 values of 0.86 and 0.81, respectively. Complete *Pythium* suppression (0 ppg) was achieved once T_{avg} reached 58.1 and 57.8 °C in the steam alone and QLS treatments, respectively. In contrast, the SPS treatment had a logarithmic r^2 value of 0.31 and a slightly lower T_{avg} to achieve complete *Pythium* sp. suppression (52.6 °C) (Fig. 6).

Maintenance of high temperatures is understood as an important factor necessary to suppress soilborne pathogens with steam (Pullman et al. 1981), and an average of 65 °C for 30 min can kill most soilborne pathogens (Baker and Roistacher 1957). Thiessen et al. (2020) found that for *Pythium* sp. specifically, 30 min of in vitro incubation at 63 °C effectively suppressed inoculum in Styrofoam float trays. In contrast, in field conditions, temperatures that exceeded 70 °C for more than 30 min showed variable *Pythium* sp. suppression and reduced *Pythium* ppg by 50% to 99.9% (Guerra et al. 2022). Various field conditions can affect fungal pathogen populations other than temperature, including pH (Cruz et al. 2019; Kauraw 1979; Mondal and Hyakumachi 2000; Yang et al. 2022) and soil moisture (Dunn et al. 1985). Therefore, determining an exact average temperature to suppress pathogens is difficult.

Our findings showed that to suppress *Pythium* sp., an average temperature of approximately 56.2 °C for 30 min is beneficial, whether exothermic chemicals are applied or not, under our specific set of field conditions. The QLS treatment reached and exceeded an average temperature of 56.2 °C more often than SPS and steam alone treatments. These findings indicated that the application of quicklime with steam could improve T_{avg} compared with steam alone or SPS. This is supported by prior research in which quicklime (1000 kg·ha⁻¹) with steam as well as potassium hydroxide (1000 kg·ha⁻¹) with steam had significantly higher average temperatures compared with steam alone (Bárberi et al. 2009; Luvisi et al. 2015; Peruzzi et al. 2011).

Soil pH and *Pythium* sp. suppression. The QL and QLS treatments had the greatest effect on soil pH. The initial pH values of the soil in our field study were 5.6 in year 1 and 6.7 in year 2. The QL treatment raised pH to 10.2 in year 1 and 11.7 in year 2. The QLS treatment raised pH to 11.7 in year 1 and 11.1 in year 2. The SP and SPS treatments also raised the soil pH, although less drastically. The SP treatment resulted in pH values of 7.6 and 9.7 in years 1 and 2, respectively. The SPS treatment raised pH to 8.0 and 9.7 in years 1 and 2, respectively. Many of these measurements exceeded the typical pH range recommended for horticultural crops (Table 2).

Quicklime and sodium peroxide can raise soil pH, as we observed in this study after chemical application. Studies have found relationships between pH levels, calcium salt

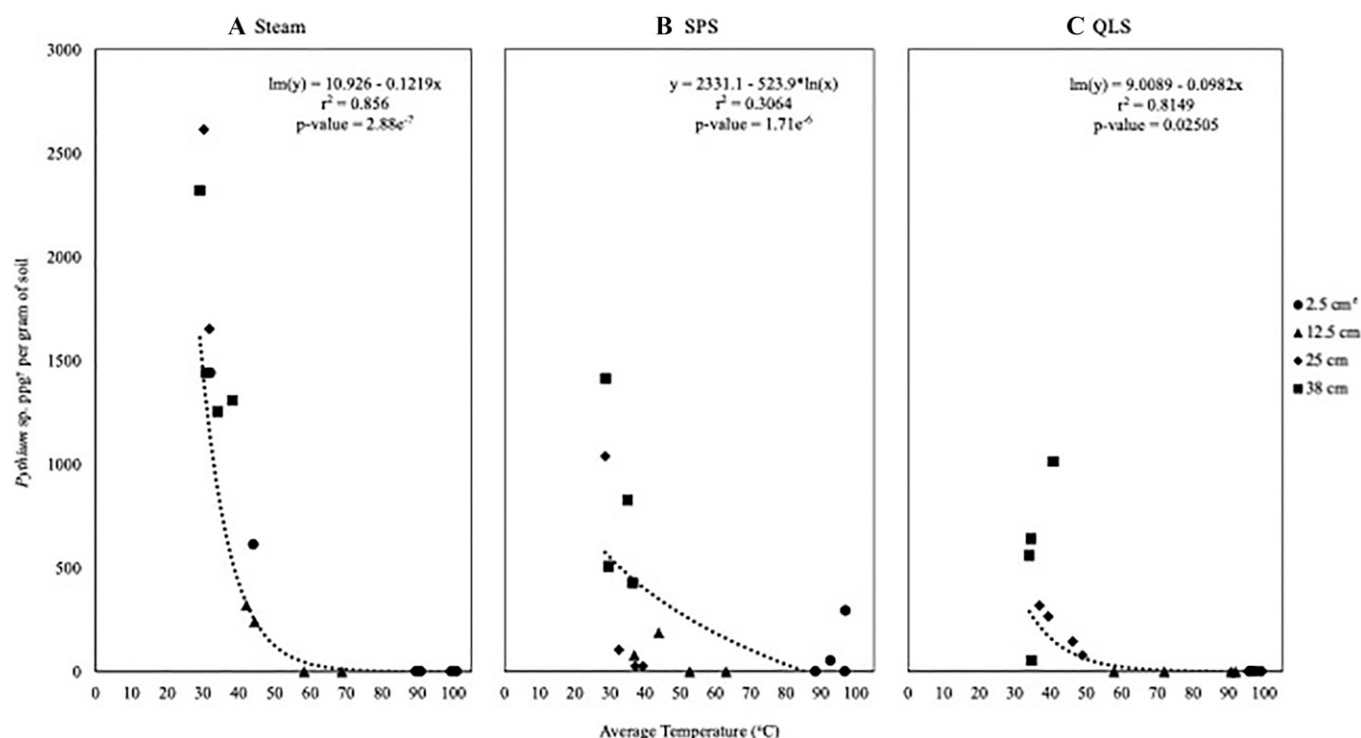


Fig. 6. *Pythium* propagules (ppg) of soil as impacted by average temperatures for (A) steam alone, (B) sodium peroxide + steam (SPS), and (C) quicklime + steam (QLS) treatments in the second year of the trial (2022). The exponential (steam and QLS) and logarithmic (SPS) regression curves, regression equations, r^2 values, and P values for each treatment are shown. Circles, triangles, diamonds, and squares designate observation distances from steam injection points of 2.5, 5, 12.5, and 25 cm, respectively. ppg = propagule.

Table 2. Measurements of pH obtained 1 week after treatment application.

Treatment	Soil pH	
	Year 1	Year 2
Nontreated control	5.6	6.7
Steam	5.5	6.7
Quicklime	10.2	11.7
Sodium peroxide	7.6	9.7
Quicklime + steam	11.7	11.1
Sodium peroxide + steam	8	9.7

levels, and disease resistance. For example, the application of calcium salts can induce disease resistance in the host plant (Corden 1965). In addition, strong alkaline conditions can be detrimental to *Fusarium* sp. growth (Cruz et al. 2019; Yang et al. 2022). Other studies have found that *Pythium* sp. populations decrease when pH is lower than 5.5 and higher than 8.0 (Kauraw 1979; Mondal and Hyakumachi 2000). In our study, the SP, SPS, QL, and QLS treatments raised pH values above 8.0 in at least one of the years of this study. However, QLS treatment showed more thorough *Pythium* sp. suppression compared with the other treatments that increased pH. In addition, the relationship between pH and *Pythium* spp. is weak, with r^2 values of 0.146 and 0.1245 for 2021 and 2022, respectively. This indicated that while pH could play a role in *Pythium* sp. suppression, temperature was the main driver of *Pythium* sp. suppression in this study.

Weed germination. In 2021, nutsedge tuber germination was less than 10% in the nontreated controls; in 2022, vetch germination was poor ($\leq 20\%$). Therefore, only the data of one year are presented for those species. In 2021, temperature thermocouples malfunctioned; therefore, no temperature data are available for 2021.

In the absence of steam, exothermic compounds did not affect weed propagule germination. There were no treatment effects on weed propagule germination at distances of 25 cm or 37.5 cm from the steam emitters. At 2.5 cm from the steam emitter, all steam treatments provided nearly complete suppression control of all species in both years; consequently, the addition of exothermic compounds to steam had no effect on weed germination 2.5 cm from the steam emitter (Table 3).

At 12.5 cm from steam emitters, there were significant differences between steam alone and steam plus exothermic compounds in both years. In 2021, the germination of ryegrass, sida, or vetch seeds placed 12.5 cm from the emitters was not reduced by steam alone (Table 3). In 2022, steam alone reduced germination of ryegrass and sida, but not nutsedge tubers. In 2021, the addition of either exothermic compound improved the suppression of ryegrass, sida, and vetch propagules compared with steam alone (Table 3). There was no significant difference between QLS and SPS treatments ($P > 0.14$ for all species). In contrast, at the 12.5 cm distance in 2022, steam and QLS reduced ryegrass germination compared with the nontreated control, but SPS did not (Table 3). In 2022, sida germination was reduced by all steam treatments, but nutsedge tuber germination was reduced only by QLS, not by steam alone or SPS.

The T_{max} was highly correlated with percent germination, with correlation coefficients of -0.92 , -0.89 , and -0.84 , for ryegrass, sida, and nutsedge, respectively. However, soil temperatures at the 12.5 cm distance from the steam emitters were variable among the four replicates. At that distance from the emitters, soil temperatures for steam-only plots ranged from 57 to 98 °C. For SPS and QLS, soil

temperatures ranged from 51 to 98 °C and 92 to 99 °C, respectively (data not shown).

Ryegrass seed germination was unaffected when the T_{max} was less than 68 °C (Fig. 7A). At ≥ 72 °C, no ryegrass seed germination was observed. This is consistent with the findings of Baker and Roistacher (1957), who reported that T_{max} between 70 and 80 °C for a period of 15 min reduced germination in most weed propagules. This is also consistent with the findings of Vidotto et al. (2013), who reported that short exposures between 68 and 80 °C caused seed mortality in several common weed species. However, the response of sida seeds to increasing T_{max} was separated into three clusters. At T_{max} less than 68 °C, there was little to no change in seed germination. Between 68 and 72 °C, germination was between 35% and 75% (Fig. 7B). No sida seed germination was observed at T_{max} higher than 90 °C. Nutsedge tuber germination percentages also clustered into two groups with centroids of 3.5% germination at T_{max} of 98 and 69% germination at T_{max} of 43 °C (Fig. 7C). There was considerable variation in nutsedge tuber germination within each group, even at T_{max} higher than 90 °C (Fig. 7C). Vidotto et al. (2013) reported that weed seed thermal death points varied with seed size and morphology. Larger weed seeds were less susceptible to lower temperatures than smaller-seeded weeds. Sida seeds are enclosed in a hard persistent mericarp with a length of 2 to 2.5 mm and width of approximately 2 mm (Neal et al. 2023), and the nutsedge tubers used in this study had diameters of approximately 5 to 7 mm. In contrast, Italian ryegrass caryopses are smaller, with a thickness between 0.7 and 1.5 mm (Terrell 2021). The sizes and anatomy of sida seeds and nutsedge tubers likely make these propagules more resilient to

Table 3. Effects of steam with and without exothermic compounds (CaO or Na₂O₂) on weed germination by distance from the emitter, species, and year. No treatment effects were observed at distances greater than 12.5 cm; therefore, data are not presented. In the absence of steam, exothermic compounds did not affect weed propagule germination; therefore, those data are not presented.

Year and treatments	Percent germination by distance from emitter and species ⁱ					
	Distance of 2.5 cm from the emitter			Distance of 12.5 cm from the emitter		
	Vetch	Ryegrass	Sida	Vetch	Ryegrass	Sida
2021						
Nontreated	92	84	53	91	86	64
Steam	0*	0*	0*	70	66	42
+ Na ₂ O ₂	11*	8*	14*	0*	0*	1*
+ CaO	5*	0*	4*	28*	26*	16*
Pooled comparisons ⁱⁱ						
Steam vs. steam + exothermic chemicals	0.266	0.461	0.389	0.008	0.003	0.020
Steam + CaO vs. steam + Na ₂ O ₂	0.453	0.209	0.394	0.193	0.145	0.320
2022						
Nutsedge						
Nontreated	80	94	72	58	82	75
Steam	0	0	0	35	24*	30*
+ Na ₂ O ₂	0	0	0	40	44	35*
+ CaO	0	0	0	12*	0*	3*
Pooled comparisons						
Steam vs. steam + exothermic chemicals	—	—	—	0.611	0.921	0.454
Steam + CaO vs. steam + Na ₂ O ₂	—	—	—	0.177	0.060	0.074

ⁱ Means within a column accompanied by Asterisk (*) were significantly different from the nontreated control based on Dunnett's test with $\alpha = 0.05$.

ⁱⁱ Single degree of freedom contrasts for steam alone vs. pooled data for steam plus exothermic chemical treatments (Na₂O₂ or CaO) and comparisons of steam + CaO vs. steam + Na₂O₂. At the 2.5 cm distance in 2022, all steam treatments had 0% germination; therefore, no single degree of freedom contrasts were performed.

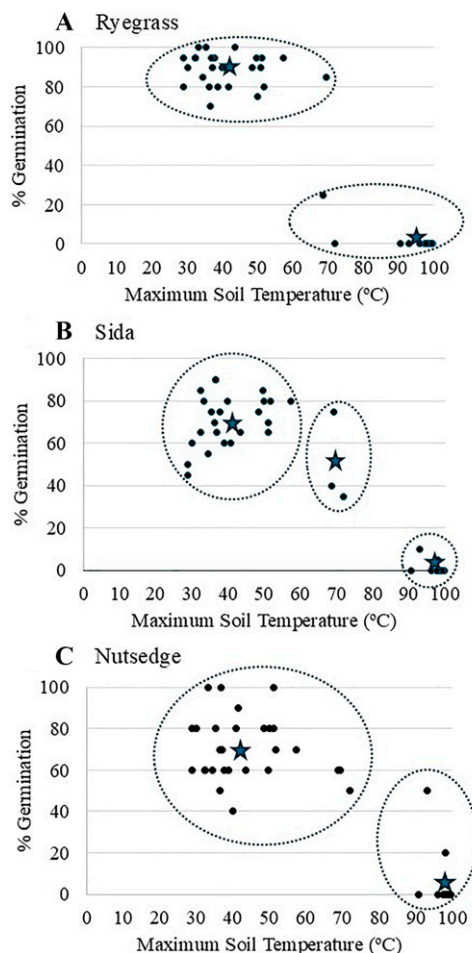


Fig. 7. Percent germination of weed propagules as affected by maximum soil temperature (T_{max}) obtained during steam injection. Data for all steam treatments (steam alone and steam plus exothermic compounds) were combined for these analyses. Scatter plots and clusters are presented by species. Dashed circles are data clusters defined using Ward's hierarchical cluster analysis. *Centroid values for each cluster.

short-duration, high-temperature treatments compared with ryegrass.

Conclusion

The Steam in combination with quicklime (1% w/w) mitigated *Pythium* sp. better than quicklime alone and steam alone. However, the QLS treatment had a variable impact on weed seed germination between treatment years. In 2021, the addition of either exothermic compound reduced weed seed germination compared with steam alone, but not in 2022. Germination of weed propagules and *Pythium* colony growth were highly correlated with maximum soil temperatures, suggesting that critical temperature thresholds for weed and pathogen propagules need to be achieved for successful suppression. Questions regarding how to optimize steam injection in combination with exothermic substances to achieve those thresholds remain unanswered. Additionally, a more thorough understanding of the critical temperatures and duration of exposure to those treatments is necessary. Furthermore, a greater understanding of three-dimensional temperature distribution in soil following steam injections may be necessary to allow refinement of steam emitter and exothermic product placement.

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