Forced hot air rotating drum heater: a method for heat treating excavated soil or other media

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Executive Summary

We constructed a rotary soil heating device using an electric cement mixer and portable job-site propane heater and demonstrated that it could heat soil volumes up to about 10 gal to temperatures between 55 and 60 C in less than 30 minutes. Heating efficiency was enhanced by insulating the barrel of the mixer. Injecting water in the form of a mist into the heat stream increased heating efficiency and prevented the soil from drying out excessively. Soil remained hot after being dumped into an insulated vessel, minimizing the amount of time that external heat needed to be applied.

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1. Introduction

A range of heat treatment options are needed to conduct spot treatment of planting sites infested with root-rotting *Phytophthora* species. Heat treatment may also be desired for sites with unknown *Phytophthora* contamination status. Multiple methods are needed because different site conditions (e.g., solar exposure, uncontrolled access by the public, steepness, road access) and timing (winter vs. summer) constrain the type(s) of equipment or methods that can be used.

1.1. *In situ* soil heat treatment

The simplest *in situ* method for heat-treating infested soil is solarization. Long-duration small-area solarization using noncondensing IR greenhouse film was successfully used to heat-treat infested sites at Coyote Ridge (Swiecki and Bernhardt 2015), but sites needed to have nearly unrestricted solar radiation during the peak solar heating season (late spring through early fall) to reach soil temperatures needed to eradicate *Phytophthora*. This technique is also not viable for locations where human or animal activity may puncture or disturb the greenhouse film. Based on field data from Coyote Ridge, adequate heating to eradicate *Phytophthora* with small-area solarization did not extend deeper than a soil depth of about 20-25 cm.

Steam under pressure has been used for heat treating bulk soil. Research into agricultural uses of steam for *in situ* soil disinfestation is ongoing and new equipment is being developed. The Agricultural Soil Steaming Association (https://www.soilsteamingassociation.org/) has been formed recently to speed the commercial development and adoption of soil steaming technologies for agriculture. Surface application of steam under a tarp is highly inefficient and requires very long treatment durations to treat soil to a significant depth. Injecting steam into soil is only marginally more efficient unless the soil is exceptionally porous. Stem injection is also technically difficult if soil is rocky or if woody roots are present. Researchers at UC Davis (Hanson et al 2011) attempted to improve on efficiency of steam heating by agitating the soil with an auger or using rotary tillage while injecting steam. Mixing of the soil while injecting steam greatly increased heating efficiency but required suitably fine-textured soils that are easily tilled and lack large aggregates or rocks. Although steaming equipment developed for preplanting use in easily-tilled agricultural soils is likely to have limited application in wildland settings, it may be possible to adapt some of the technologies for use in wildland infestations.

In a micro pilot-level system, we demonstrated that when a soil auger is used in a cylinder only slightly larger than the auger in diameter, soil is drawn up into the cylinder, where it can be heated using hot air (Swiecki and Bernhardt 2016). In this system, in which soil is not actually heated *in situ* but in an open vessel (the cylinder). Heating occurs above ground in the cylinder into which soil is drawn though the action of the auger. When the auger is removed, the heated soil directly falls back into the hole created by the auger. This heat treatment concept has been investigated by SCVWD, which has developed an operational scale prototype using a soil auger and a cylinder into which heated air is blown. To date, this method is not operational. This system is not likely to work for rocky soils or soils that are difficult to break up by augering. Heat input must be sufficient to offset losses related to heating of the cylinder and auger, as well as heat loss that occurs as air flows out of the cylinder.

1.2. Heating excavated soil

The alternative to *in situ* methods requires that soil from the contaminated site be excavated, heated to the appropriate temperature for an appropriate time period in an external device, and then returned to the excavated site. We have demonstrated that solar ovens can be used for spot heat-treating excavated soil in this way (Swiecki and Bernhardt 2019). This method is viable for use during the peak soil radiation season in locations where solar exposure is not limited and ovens can safely be left unattended for days at a time. Additional treatment options for short-duration heat-treatment of excavated soil would extend possibilities for treatment to areas where solar treatment is not feasible and *in situ* treatment methods are unsuitable or infeasible.

Excavated soil can be heat-treated by placing the soil in a container that can be heated, typically using propane as fuel. The heated container can be static (e.g., asphalt hot boxes), or involve mixing (e.g., using the overall design of an industrial rotary dryer or rotary kiln). In general, static heating will be much slower than heating while mixing, but the equipment for the latter will be more complex. We have previously demonstrated proof of concept for this system by using a forced air propane heater to heat potting media in a modified barrel that was rotated by hand. Due to its greater weight, we were not able to adequately test this nonmotorized system with soil.

For this project, we identified available equipment capable of heat-treating excavated soil after minor modifications. We conducted initial testing to establish parameters for using the equipment to attain target soil temperatures and associated protocols needed for the use of the equipment.

2. Methods

2.1. Equipment

For these trials we used the following equipment:

2.1.1 Propane heater, 30K to 60K BTU output.

We used a Mr. Heater 60 Hero® portable forced-air propane heater as the heat source. This model is equipped with a battery and can be run without an electrical connection. We left the unit plugged into an AC power source for our tests. The unit can be set to two discrete heat settings, nominally 30,000 and 60,000 BTU/hr (527 and 1055 MJ/min). We made several modifications to the heater that are shown in Figure 1. A galvanized reducer (8 inch to 6 inch diameter) and a 6 inch length of ducting (6 inch diameter) was attached to the heater outflow to direct airflow further into the mixer opening and allow more space for the exiting airflow. The reducer should have increased the air velocity but may have reduced airflow somewhat. Even with this ducting, the heater was close enough to the hot air flow exiting the mixer that some softening of the front end of plastic handle was observed. We added a curved piece of galvanized steel in front of the handle to deflect the flow of hot air returning from the rotating drum away from the handle. We also added a port in the 6=inch section of ducting into which a water misting nozzle could be inserted to add moisture to the heated air. A very fine mist was applied through the port so that most, if not all, of the water would be vaporized by the heated air flow, converting it into pressureless steam.

Figure 1. Equipment set up used for heat treatment trials. The Mr. Heater 60 Hero® propane heater (left) has been modified by attaching a reducer and short length of ducting to direct hot air into the mixer while allowing the unit to remain further from the exiting hot air stream. The opening in the top of the ducting is for mist injection (Section 2.1.3). A heat shield has also been added to deflect hot air away from the plastic handle. The heater rests on a drum with a depression in the lid that allows the heater to be tilted. A detachable collar at the opening of the cement mixer (Yardmax® 4 cu. ft. electric cement mixer) allows the mixer to be close to a horizontal position to improve agitation of the soil mass without losing soil out the opening.

2.1.2. Cement mixer

The cement mixer we used was a Yardmax® 4 cu. ft. electric cement mixer. We initially modified the mixer by constricting the opening (Figure 1). This allows the mixer to be used in a more horizontal position, which enhances mixing, without having soil tumble from the opening. The modification involved adding a metal pan around the opening with a hole cut into it and inserting a slightly tapered cylinder (cone frustrum) into the hole. Both of these items, plus metal catches to hold the pieces together, were constructed from a hanging galvanized steel poultry feeder (Little Giant 914273).

To monitor temperature inside of the mixer barrel, we bolted a 6.5 cm length of aluminum T-angle (3.2 mm thickness) to the inside of the barrel near the bottom (Figure 2). Two additional pieces of aluminum were bolted to the upright portion of the T-angle to increase its thickness and extend its length in the direction of the drum rotation. A hole was drilled at an upward ~35° angle along the seam between the two thinner pieces of aluminum that was just large enough to accommodate the 3.5 mm diameter external probe of an Elitech® RC-4 temperature logger. A hole in the mixer drum was drilled in line with the hole in the angle. The probe was inserted through the hole in the drum into the hole in the aluminum angle. The wire from the probe was connected to the logger, which was placed in a plastic enclosure and attached to the outside of the mixer. The logger was set to record temperature at 1-minute intervals. The aluminum angle assembly in the drum protected the probe from damage. Due to the high thermal conductivity of the aluminum angle assembly, measurements by the logger showed very little lag time and provided a fairly responsive measurement of the temperature of the soil in the drum both while it was rotating and when stopped, as long as the angle was covered with soil.

Initial tests were made with only these modifications. For later tests, we added one to two layers of mylar-coated bubble reflective insulation to the portion of the outside of the drum where it would not interfere with the operation of the mixer. Aluminum tape was used to attach the insulation to the drum and to close seams. The insulation was initially applied only to the bottom half of the mixer (below the gear flange) but was later added to the top half of the mixer as well (Figure 2).

Figure 2. Top – Cement mixer with insulation (top) and Elitech® RC-4 temperature logger attached to the bottom of the drum (top right). Insulation on the bottom of the mixer is shown at top left, with attached data logger visible. Top right shows the fully-insulated mixer drum. The external probe of the temperature logger was inserted into a hole drilled into an aluminum angle assembly (bottom) that was bolted to the inside of the drum about 6 mm from the bottom welded seam. The temperature logger was downloaded after each set of tests on a given day was completed.

2.1.3. Mist injector

The mist injector (Figures 3 and 4) was made by attaching a stainless steel misting nozzle (as used for outdoor cooling misting systems) to pipes and adapters that were connected to a hose. A drip irrigation filter between the hose and the pipes leading to the mist nozzle was used to help prevent clogging of the very small nozzle orifice. The output from the mist nozzle was 21.26 ml/min. The water mist was introduced into the hot air stream via a 2 × 2 cm port cut into the ducting attached to the propane heater. The port was 8 cm from the open end of the duct. A venturi effect at the port helped to pull the water mist into the hot air stream. Heat shields made from thin aluminum flexible ducting were later added to protect the mist nozzle from excessive heating (Figure 4). The nozzle was clamped to a stand to support and position it appropriately (Figure 4).

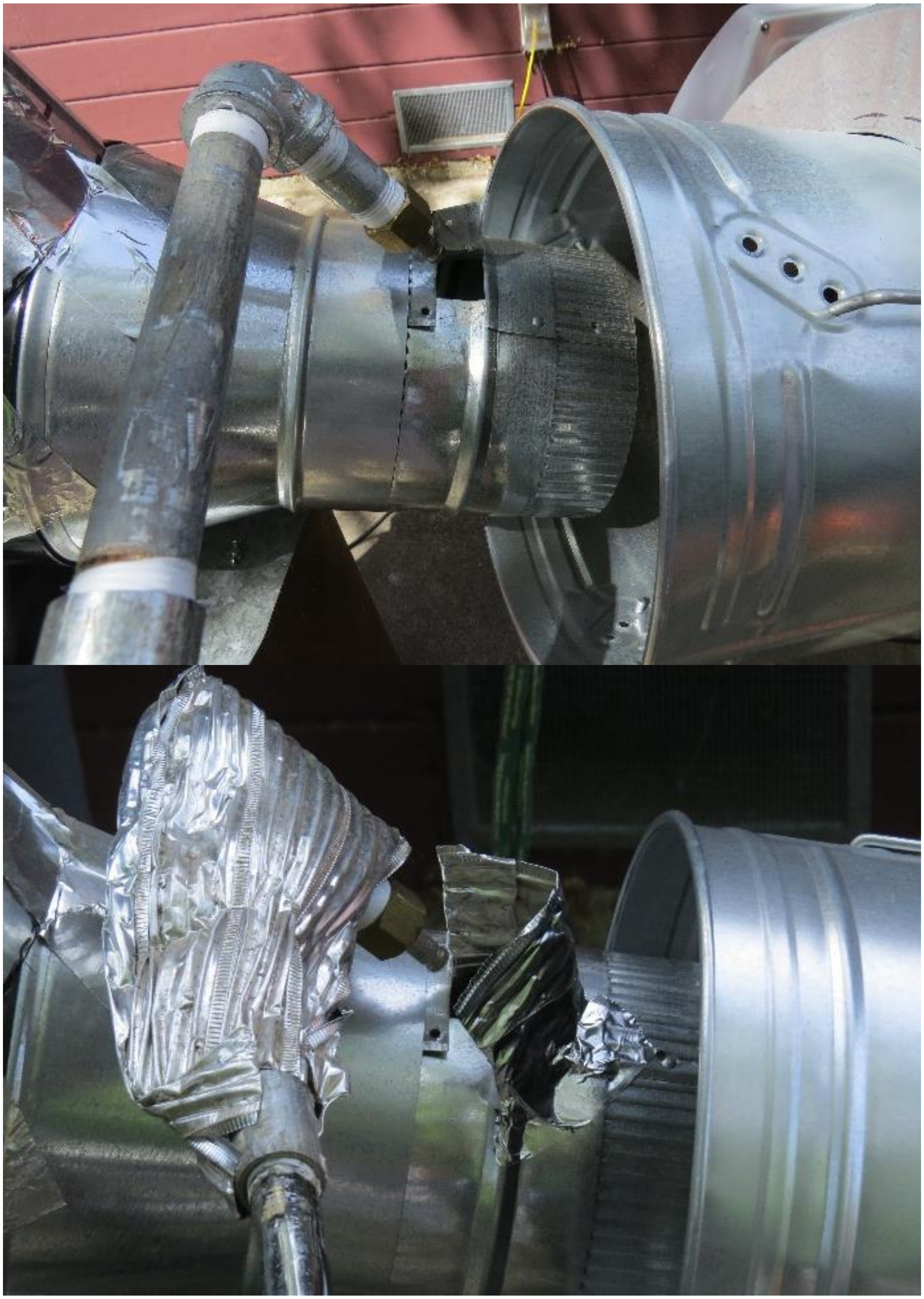


Figure 3. Closeup of mist nozzle setup. Aluminum heat shields were added to prevent heat damage to the mist nozzle from hot air exiting the mixer.

Figure 4. Full equipment setup including mist nozzle suspended by a bike stand. A drip irrigation filter was plumbed into the water supply to help screen out debris that might clog the nozzle. The mist nozzle is covered with an aluminum heat shield. Metal pipe and fittings were needed in the area exposed to the hot air exiting from the mixer. In this image, the mixer drum is only partially covered with insulation. During operation, a handheld IR thermometer (upper left in image) was used to monitor temperature.

2.1.4. Holding vessel for heated soil

Immediately after soil was heated to the target temperature, it was transferred to a holding vessel. The galvanized steel collar had to be removed from the opening of the cement mixer before the soil was dumped into this container. This was done by disengaging the three clips that secured the inner narrow section to the outer collar and then unscrewing three wing nuts and removing the bolts that attached the collar to the mixer drum (Figure 5, top).

After checking the soil temperature with both IR and analog thermometers, the soil was transferred to a large (about 21 gal = 80 L) plastic planting container with a solid bottom. Interior dimensions of the container were 46 cm height, 32.5 cm bottom diameter, and 50.5 cm top diameter. Even for the largest soil batch processed, this container was less than half full. As soon as the soil was transferred to the container, it was moved away from the mixer. The upper surface of the soil was leveled and the external wired temperature probe of a Inkbird® THC-4 temperature logger was inserted into the soil to a depth of about 10 cm at a point 5 cm from the edge of the container. The temperature logger was set to record readings at 3-minute intervals (5-minute intervals in one trial). The top of the container was then covered with a piece of polystyrene foam packing material (minimum 2 cm thick) with an additional piece of 2.5

cm thick foam insulation placed on top (Figure 5). This setup was used for trials 1 - 4. For trials 5 - 9, we also placed the container on a layer of polystyrene foam to minimize heat loss to the underlying concrete pad. For trials 10 - 20, the sides of the container were insulated by wrapping them with 2 layers of convoluted (eggcrate) urethane foam wrapped in a polyethylene tarp. For trials 19 and 20, we also placed foam insulation directly on the soil surface, before adding the polystyrene foam cover (Figure 5).

The process of transferring the soil (removing the galvanized collar, checking temperatures, dumping soil into the container, inserting the temperature logger probe, and covering the container) typically took about 4 minutes.

2.1.5. IR thermometer and soil moisture meter

Because the temperature datalogger could not be accessed while the drum was rotating, a handheld IR thermometer (FLUKE® 62Max, emissivity setting 0.95) was used to periodically check soil temperature during and after the heating process, as well as to measure outer mixer drum temperature during heating. Temperatures were logged into a notebook to track when soil reached above target temperatures in real time. Temperatures read with the IR thermometer during heating were higher than those recorded by the temperature logger probe attached to the drum.

Volumetric soil water content before and after heating was measured using a Vegetronix® VG-METER-200 Soil Moisture Meter. A minimum of 5 readings were taken and averaged to estimate percent volumetric soil water content. For trials 17 - 20, we also collected three 250 ml samples of soil before heating and after cooling. Samples were weighed, oven-dried to a constant mass and reweighed to determine percent gravimetric water content (%GWC) and estimate soil bulk density. This information was used to estimate %GWC for trials in which only %VWC was measured.

2.2. Soil used for testing.

Most tests were run using Capay silty clay loam (as mapped in the Soil Conservation Service Solano Soil Survey) from a suburban garden. This soil forms large stable peds when dry and is very plastic when wet. It was excavated by shovel and large clods (larger than 5 to 6 cm) were broken up before measuring initial soil volume. For two tests, we used Miracle Gro® Potting Mix, a lightweight soilless media consisting mostly of fine organic matter.

2.3. Heating protocol

For each trial run of the heating apparatus, soil volume and water content were measured before the soil was placed into the cement mixer. Most tests were conducted using about 7.5 gal of soil, but soil volumes used in tests ranged from 5 to 10 gallons of soil. For all tests, large clods (>5-6 cm diam) were broken up before measuring soil volume. Starting with trial 8, a hammer was used to break up soil aggregates larger than 2 to 3 cm diam.

Figure 5. Removing soil from mixer. After the target temperature was reached, the collar on the mixer was removed (top). Both IR and analog thermometers (top) were used to check soil temperature before the soil was transferred. At bottom left, heated soil is transferred into a holding vessel (bottom left). In initial tests (trials 1 - 4), this plastic holding vessel was not insulated and was covered with a piece of polystyrene foam. In later tests (trials 5 - 9), the container was also placed on a polystyrene foam base to insulate it from the underlying concrete. In trials 10 - 20, the sides of the vessel were also insulated with a layer of polyurethane foam wrapped in a polyethylene tarp (lower right). In trials 19 and 20, an additional double layer of foam insulation was placed directly on the soil surface inside of the vessel (bottom right).

The protocol for each heating trial was as follows.

1. Excavate soil, break up clods with shovel and hammer.

2. Measure soil volume, add soil to mixer.
3. Rotate soil with mixer, allowing clods to rise to surface. Stop mixer and break up any remaining clods greater than 2 to 3 cm diameter. Repeat several times until all larger clods have been eliminated.
4. Record ambient air temperature and the temperature of the soil in the mixer.
5. Install collar on mixer, align heater duct in collar opening, test mister for clogging.
6. Start propane heater. This heater requires that the electric igniter button remain depressed for 30 second to ensure that the flame remains on.
7. Once heater igniter can be released, start mixer motor, start test timing.
8. Using IR thermometer, periodically record time and temperatures of soil in the mixer and exposed metal portions of the mixer drum.
9. As planned in advance or based on the appearance of dust indicating low soil moisture, move the mister into position over the port in the ducting. Open valve to start misting and record time turned on and off. Turn off and remove mister at least 1 minute before the end of any test.
10. Once target soil temperature or predetermined length of heating run is completed, turn off mixer motor, followed by propane heater (typically within about 15 seconds of each other). Record end time.
11. Use IR thermometer to measure soil surface temperature in the mixer. Insert analog thermometer into soil and record this temperature before dumping soil.
12. Remove collar from mixer.
13. Tilt mixer drum to empty soil into the holding vessel. Place the container on insulation, level soil in container, and insert temperature logger probe into the soil to a depth of about 10 cm at 5 cm from the wall of the container.
14. Place insulating cover on container. For last 2 trials, an additional two layers of polystyrene foam insulation was place on the soil surface directly before the insulating cover was put in place.
15. Monitor temperature shown by the data logger for at least 2 hours or until temperature has dropped below 50 C.
16. Record final water content of the soil and observations about the degree soil aggregation and balling.

We conducted one preliminary test on 30 Jan 2020 using the unmodified mixer and heater. After constructing the collar for the front of the mixer, we conducted 15 heating trials between 21 March and 22 May 2020. One abortive (heater flame blown out) and four complete trials were conducted in May 2021.

During trials 1 and 2 the soil in the drum became too wet and began to stick to the drum. To correct this, we needed to stop the mixer and heater multiple times, scrape off the soil, and restart. Because the heating for those tests occurred in several separate periods with intervening cooling periods, data from those runs are not presented below.

3. Results

We ran a total of 20 trials of the heating apparatus to collect data on its performance. A primary objective of the trials was to adjust various parameters to optimize heating to the degree possible and verify that the apparatus could heat soil to the necessary target temperature. In all but one aborted trial, soil was heated to between 50 and 60 C in about 20 to 30 minutes. By monitoring soil temperature during the heating period and post-heating storage in a holding container, we were able to verify that the duration of the heat treatment was sufficient to kill *Phytophthora*. Some parameters of the 20 trials are listed in Tables 1 and 2.

Table 1. Soil type, volume, and moisture data from 20 heating trials. Blanks indicate that data was missing or could not be calculated. Shading is used to denote trials that differ widely from the others: violet (T1) – heating was stopped and restarted several times; gray (T4) - heater at 60K BTU/h setting; yellow (T9, T10) – potting mix used; green (T14) – smallest soil volume (~5 gal); green (T15) – largest soil volume (~10 gal). Est=estimated.

trial	date	heater BTU/h setting	soil type	insulated drum levels[1]	initial soil volume, L	dry soil mass est, kg	initial % water by mass	kg water added by misting	final est % water by mass	water mass change = post–(pre+mist), kg
T1	3/21/2020	30K	silty clay loam	0	29.9	25.9	14.84%	?		
T2	4/18/2020	30K	silty clay loam	0	28.1	24.3	21.28%	?		
T3	4/18/2020	30K	silty clay loam	0	26.7	23.1	21.53%	0	10.1%	-2.37
T4	4/24/2020	60K	silty clay loam	0	25.1	21.7	16.93%	0.45	12.1%	-1.12
T5	4/25/2020	30K	silty clay loam	0	25.9	22.4	18.42%	?	11.5%	
T6	4/27/2020	30K	silty clay loam	1	28.8	24.9	14.11%	0.30	15.0%	0.59
T7	4/28/2020	30K	silty clay loam	1	28.6	24.8	28.02%	0	10.1%	-4.15
T8	4/29/2020	30K	silty clay loam	1	28.7	24.8	22.17%	0.03	10.1%	-2.73
T9	4/30/2020	30K	potting mix	1	28.7			0.15		
T10	5/1/2020	30K	potting mix	1	28.7			0.21		
T11	5/2/2020	30K	silty clay loam	1	28.7	24.8	15.43%	0.40	9.8%	-1.53
T12	5/5/2020	30K	silty clay loam	1	28.7	24.8	22.04%	0.32	11.7%	-2.48
T13	5/22/2020	30K	silty clay loam	2	28.7	24.8	23.95%	0.40	17.9%	-0.94
T14	5/22/2020	30K	silty clay loam	2	19.1	16.5	23.95%	0.23	11.3%	-2.09
T15	5/22/2020	30K	silty clay loam	2	38.2	33.1	23.95%	0.28	17.0%	-1.40
T16	5/3/2021	30K	silty clay loam	2	28.7	25.0887	16.75%	0		
T17	5/4/2021	30K	silty clay loam	2	28.7	27.93467	13.42%	0.32	10.9%	-0.67
T18	5/4/2021	30K	silty clay loam	2	30.05	25.28207	13.79%	0.21	11.2%	-0.50
T19	5/5/2021	30K	silty clay loam	2	28.7	23.68707	16.65%	0.32	11.9%	-1.06
T20	5/5/2021	30K	silty clay loam	2	28.7	24.5868	18.17%	0.17	14.3%	-0.54

[1] Drum insulation levels: 0 = no added insulation, 1 = partial insulation, mainly lower half of drum, 2 = maximum insulation

Table 2. Temperature data from 20 heating trials. Blanks indicate that data was missing or could not be calculated. Shading is used to denote trials that differ widely from the others: violet (T1) – heating was stopped and restarted several times; gray (T4) - heater at 60K BTU/h setting; yellow (T9, T10) – potting mix used; green (T14) – smallest soil volume (~5 gal); green (T15) – largest soil volume (~10 gal).

trial	insulated drum levels	initial soil T, C	ambient T, C	Final temp C	total heating minutes	Time to 50 C	Time to 57 C	Temp at 3 min, C	calculated % efficiency	deg C gained per minute heated	deg C gained /min/kg dry soil	3 min to 57 C, deg/min/L soil
T1	0	18	20	47.4	42					0.70	0.027	
T2	0	23	20	57.4	25					1.37	0.057	
T3	0	21	21	57.8	23	13	22	27.9	11.5	1.60	0.069	0.050
T4	0	27	30	50.2	25	23		34.6	2.8	0.93	0.043	
T5	0	24	25	58.4	25	13	22	30.4	8.9	1.37	0.061	0.047
T6	1	25.6	29	58.5	20	12	18	33.5	10.4	1.65	0.066	0.045
T7	1	25	28	57.9	20	13	20	32.8	14.9	1.65	0.066	0.042
T8	1	22.2	24	57.6	26	17	25	24.2	10.7	1.36	0.055	0.046
T9	1	22.2	27	51.0	12	13		30.6		2.40		
T10	1	18.3	22	54.1	16	14		22.6		2.23		
T11	1	23.9	23	57.3	26	16	24	29.2	8.4	1.28	0.052	0.040
T12	1	23.9	24	58.5	26	15	23	29.3	10.4	1.33	0.054	0.042
T13	2	17.8	23	59.4	26	17	23	19.7	13.1	1.60	0.065	0.057
T14	2	18.9	24	58.6	17	12	17	24.5	12.7	2.34	0.142	0.100
T15	2	18.9	25	58.7	30	19	26	23.3	14.4	1.33	0.040	0.034
T16	2	28.9	31	35.2	4				10.9	1.58	0.063	
T17	2	19.7	22	55.5	25				9.8	1.43	0.051	
T18	2	30.4	29	56.6	21				8.0	1.25	0.049	
T19	2	24.6	26	60.7	25	14	20	27.5	9.3	1.44	0.061	0.051
T20	2	26.5	31	60.0	25	16	22	26.9	9.4	1.34	0.055	0.048

[1] Drum insulation levels: 0 = no added insulation, 1 = partial insulation, mainly lower half of drum, 2 = maximum insulation

Various parameters that influence heating differed between the trials (Tables 1, 2). Some of these were adjusted by design to assess their effects on heating efficiency. Other parameters varied due to soil and environmental conditions. We used data collected during the trials to assess how various parameters affected performance of the apparatus.

Parameters that affect heating efficiency can be broadly grouped into the two categories: system design parameters and environmental parameters. Trials that examined effect of various parameters are described below by category.

3.1. Effects of system design parameters

System design parameters are features of the heating apparatus and heating protocols that affect the rate at which heat is input, transferred from the hot air stream to the soil, and lost from the system by radiation, convection, and conduction from the heated components. Some of these, such as the dimensions of the mixer, its geometry, and rotation speed were fixed and specific to the equipment used. Switching from a cement mixer to a drum roller, for instance, would allow more options for altering these parameters. Other system design parameters can be adjusted by the user. These include the heater output setting, insulation of the mixer drum and holding container, amount of soil processed at a time, and the addition of water during the heating process.

3.1.1. Heater output setting 30K vs 60K BTU/hr

The Mr. Heater 60 Hero® propane heater has two discrete heat settings, nominally 30,000 and 60,000 BTU/hr (31.65 and 63.30 MJ/hr). We used the 30,000 BTU setting in the first three tests but tested the 60K BTU setting in trial 4 to see if the higher output level would decrease the time required to reach target temperatures. We noted that the heater produced an efficient blue flame at the 30 K BTU setting but produced a longer yellow-orange flame at the 60 K BTU setting, suggesting that combustion was less efficient at this setting. During the 60 K BTU trial, IR measurements indicated slower overall heating of the soil and heater drum, which was confirmed by the temperature logger trace (Figure 6).

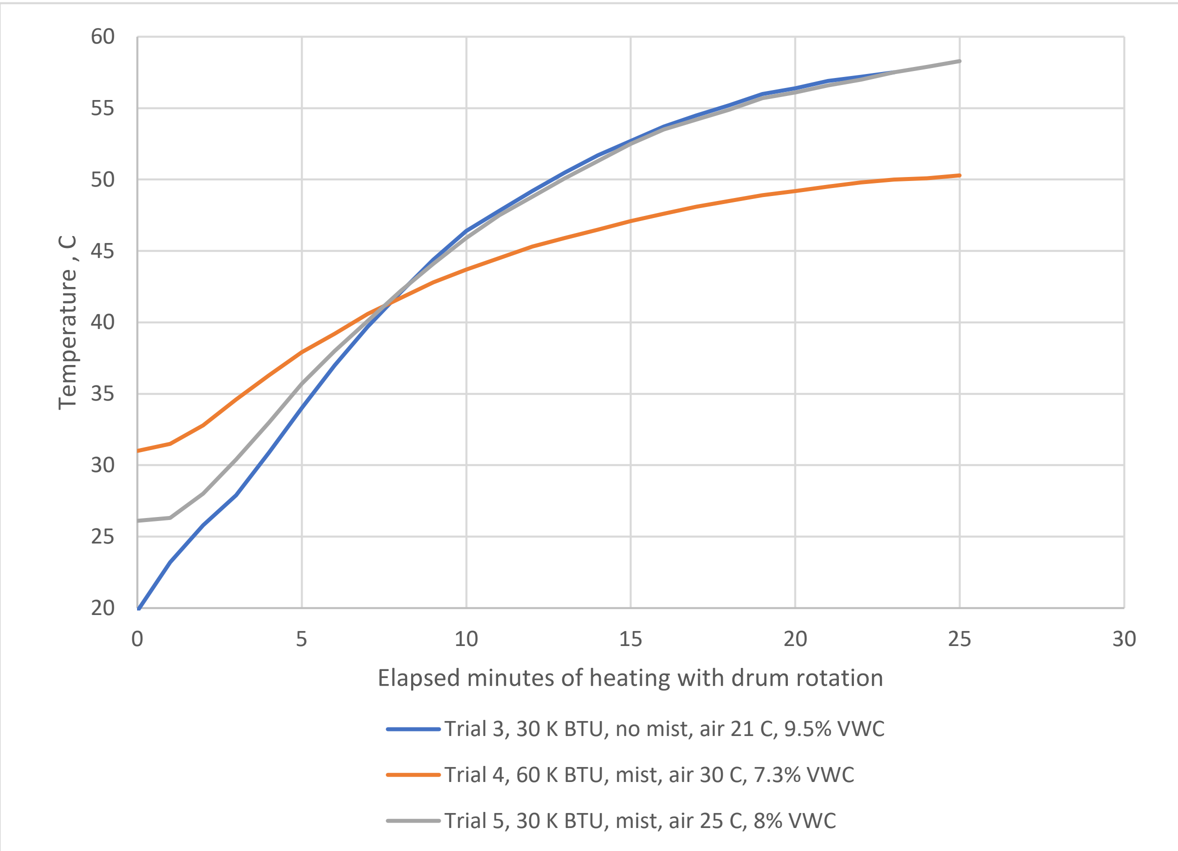


Figure 6. Soil temperatures (1-minute intervals) from the drum temperature logger for heating trials 3 - 5 showing similar test conditions but changing the propane heater setting from 30 K to 60 K BTU output for one test (trial 4). Water was added via the mist nozzle for Trials 4 and 5. Estimated soil volumes were 26.6, 25.1, and 25.9 L for trials 3 - 5, respectively. Temperature data are from the Elitech® RC-4 temperature logger on the back of the mixer drum. VWC = volumetric water content, C = degrees Celsius; both were recorded at the start of each run.

The outcome of this test, slower heating with greater heat input, was counter intuitive. We subsequently checked the temperature of the airstream at the two settings by placing a barbecue thermometer in the port that was made for introducing water mist. At the 30K BTU setting, the thermometer showed 177 C after 2 minutes, whereas at the 60 K BTU, the temperature was only 107 C after 2 minutes. This confirmed that although fuel consumption was higher, the less efficient combustion combined with an increase in airflow (due to the expansion upon combustion of the additional propane) resulted in lower air temperatures, which reduced the rate of soil heating in the mixer. Because the 60 K BTU setting consumed more fuel yet but was clearly less efficient (Figure 6), all further testing was conducted at the 30 K BTU setting, and data from trial 4 were excluded from various analyses of system performance.

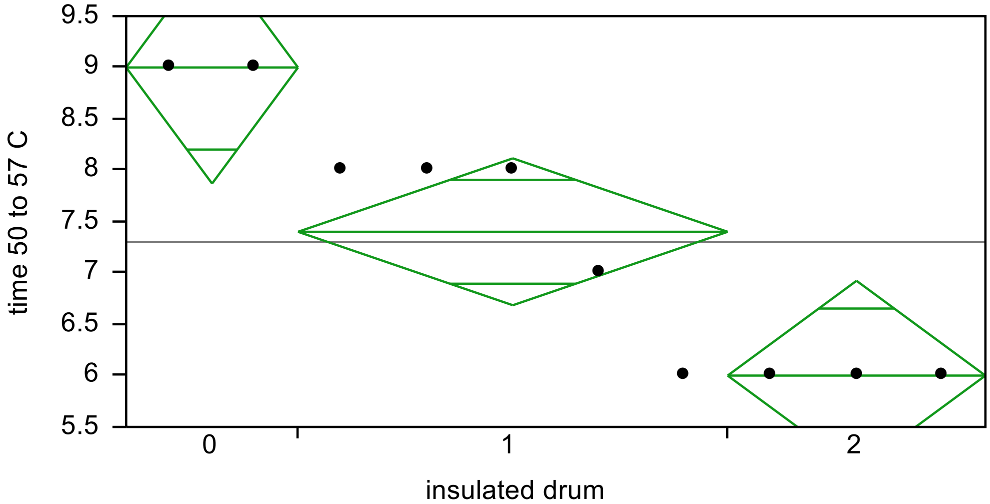
3.1.2. Drum insulation

Intuitively, adding insulation to the drum seems like an obvious way to increase heating efficiency. However, the effect of insulating the drum turned out be more subtle than expected. As seen in Figure 11, a positive effect of drum insulation on heating efficiency is apparent in the rate of soil temperature increase only in the latter phase of heating, as the temperature approaches and exceeds 50 C. When the 10 trials using about 29 L (7.5 gals) of soil are compared, mean amount of time required for soil temperature to increase from 50 to 57 C was significantly affected by the amount of insulation on the drum. The time was longest when the drum was uninsulated, shorter when the lower half of the drum was insulated, and shortest when the drum was insulated to the maximum extent possible (Figure 7). However, if the entire heating period is considered, the rate of heart gain (°C/min) does not show a significant effect of drum insulation.

The modest effect of drum insulation can be explained by considering how heat energy is transferred during the heating process. Heat exchange occurs within the drum as hot air and vaporized water interact with soil particles and the inner surfaces of the mixer drum. Most of the heat energy loss from the system is due to hot air and water vapor exiting the drum before the usable heat can be transferred to the soil. Heat transfer from the drum to the soil predominates while the soil is still relatively cool and the inner drum surfaces are heated. However, as the soil and drum begin to heat well above ambient air temperatures, radiant and convective heat loss from the outer drum surface begins to become more important. Retarding this heat loss via insulation increases heating efficiency as the drum and soil are heated well above ambient.

3.1.3. Amount of soil per batch

Heating efficiency can be affected by the amount of soil heated at once, but the relationship is highly dependent on the physical parameters of the heating system. To look at this factor for our system, we collected a batch of soil from a single spot and mixed it to increase uniformity (see section 3.5 below). Subsets of the soil were then heated sequentially on one day in batches with volumes of approximately 5, 7.5, and 10 gal (19, 29, and 38 L). The largest amount was close to the maximum amount that was practical to use in the mixer. The 7.5 gal batch (Trial 13, T13) was run first, followed by the 5 gal batch (T14) and the 10 gal batch (T15). The water content of all three batches was the same (about 24% GWC) and initial soil temperatures were within 1 C of each other (Table 3). The drum was fully insulated for these tests. Mist was applied during all three tests, but the relative amounts of mist applied varied by batch (Table 3). Expressed as percent of initial water content, the water added by misting was 6%, 7%, and 3% for the 5, 7.5, and 10 gal batches, respectively.



Oneway Anova
Summary of Fit

Rsquare	0.77305
Adj Rsquare	0.708207
Root Mean Square Error	0.676123
Mean of Response	7.3
Observations (or Sum Wgts)	10

Analysis of Variance

Source	DF	Sum of Squares	Mean Square	F Ratio	Prob > F
insulated drum levels	2	10.900000	5.45000	11.9219	0.0056*
Error	7	3.200000	0.45714		
C. Total	9	14.100000			

Means for Oneway Anova

Level	Number	Mean	Std Error	Lower 95%	Upper 95%
0	2	9.00000	0.47809	7.8695	10.131
1	5	7.40000	0.30237	6.6850	8.115
2	3	6.00000	0.39036	5.0769	6.923

Std Error uses a pooled estimate of error variance

Figure 7. Plot of means (top) and analysis of variance table (below) for time (minutes) required for soil in the mixing drum to heat from 50 to 57 C at 3 drum insulation levels. 0 = no insulation, 1 = partial insulation (shown in Figure 5), 2 = full insulation (shown in Figure 1). In the plot, width of diamonds is proportional to sample size, center line is the overall mean, and the upper and lower points of the diamond represent the 95% confidence interval of the mean.

Temperature increase of the soil over time for each batch size measured using the probe fastened to the drum is shown in Figure 8. As expected, the smallest batch size heated the fastest. The time required to reach 57 C was 17, 23, and 26 minutes for the 5, 7.5, and 10 gal batches respectively. However, two 17 minute heat periods (34 minutes total heater time) would have been needed to heat 10 gal of soil in two separate 5 gal batches, compared with the 26 minutes required for a 10 gal batch. Similarly, treating 15 gal of soil would have taken 51 minutes of heating in 5 gal batches but only 46 minutes in two 7.5 gal batches. These time differences do not include the additional time required to load and empty each batch.

Our heating system uses a fairly short mixer drum that limits the amount of time available for convective heat exchange to occur before the heated air is forced out of the mixer drum. Having more soil in the drum presumably increases the opportunities for interaction between soil particles and the air stream, leading to a higher efficiency of energy transfer. Using larger batches also reduces the number of batches needed to treat a given volume of soil. This suggests that to maximize efficiency, the heating unit should be scaled to a size that closely matches the expected batch size, e.g., the volume of soil that would be needed to treat a single infected planting site. As an example, heat treating a DP40 or #1 container planting site with a 20 cm buffer in all directions from the root ball would result in about 20 or 22 gal of excavated soil, respectively.

Table 3. Heating parameters for soil batches for trials 13 - 15. These batches were known to be infested with *P. cactorum* before treatment as discussed in section 3.5 below.

Trial	Soil volume, L	Estimated dry soil mass, kg	Initial water content, kg	Minutes of heating / mist injection	Water added by misting, kg	Mist water as % of initial water	Initial soil T, C	Max. soil T, C	Minutes to reach 57 C
T14	19.1	16.5	4.0	17 / 11	0.23	6%	18.9	58.5	17
T13	28.7	24.8	6.0	26 / 19	0.40	7%	17.8	59.3	23
T15	38.2	33.1	7.9	30 / 13	0.28	3%	18.9	58.5	26

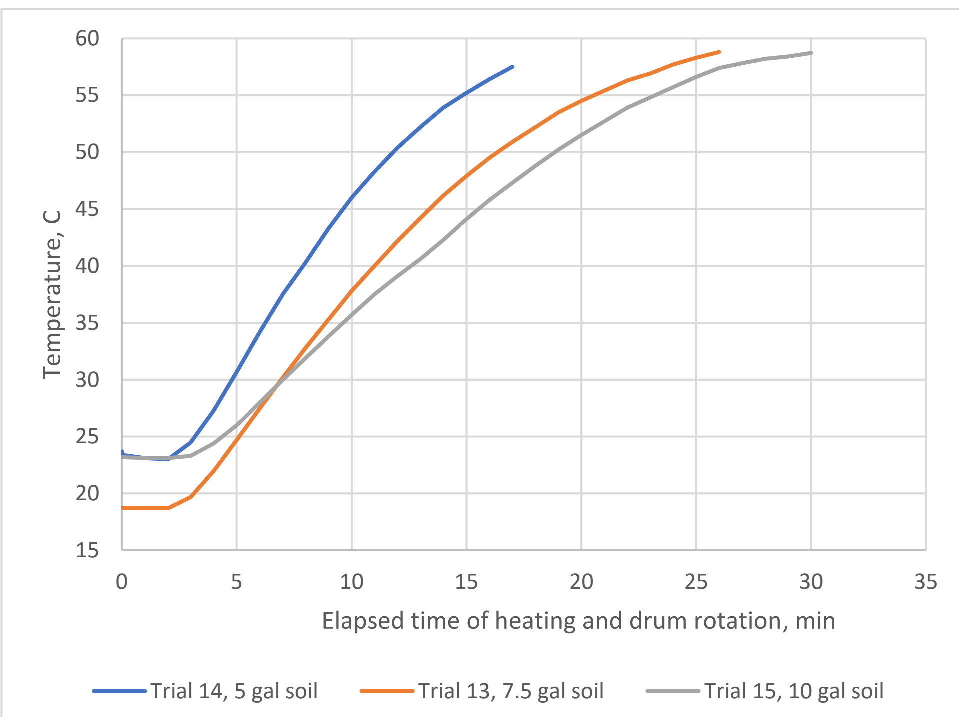


Figure 8. Soil temperatures (1-minute intervals) from the drum temperature logger for heating trials of 3 different soil batch sizes. Soil initial starting temperature was 18-19 C, volumetric water content was 10.7% (about 24% GWC).

3.1.4. Addition of water during heating

The Capay silty clay loam used in all but two trials (potting mix tested in trials 9 and 10) is a fairly heavy soil that can be compressed into stable aggregates when soil moisture is high. In our first preliminary test of the system, the soil was wetter than optimal for tillage and rather sticky. Upon heating and mixing, it formed rounded aggregate balls up to about 4 cm in diameter and also adhered to the back of the mixer. In trial 1, we started with drier soil (part of which had been stored from the preliminary test) and attempted to adjust moisture to a more optimal level by using a fine spray to wet the soil during mixing. Too much water was added by this method and considerable aggregation of the soil occurred (Figure 9, top).

Based on these results, we assumed that soil moisture before heat treatment should be dry enough to be acceptable for tillage. However, water is removed from the soil as water vapor exits the mixer drum during the heating process. We observed that if the soil was too dry, dust began blowing out of the mixer as heating proceeded and the soil dried further from heating. Data from some early trials also suggested that the soil did not heat as quickly if it was very dry. This is likely due to the role that water vapor plays in the transfer of heat energy to the soil.

To adjust and maintain soil moisture during the heating process, we set up a very fine mister (flow rate 21.26 ml/min) to introduce moisture into the hot air stream before it entered the mixer drum. The extremely fine droplets produced by the mister were vaporized into pressureless steam in the hot air stream. This is similar to the way steam is generated in a direct-fired steam generator.

We used the mist nozzle to introduce water during most of the heating trials. Based on observation of mixing soil and the rate of temperature rise, we varied the length of misting to minimize drying of the soil while avoiding excessive soil moisture. In all trials, some rounding of small aggregates occurred due to the tumbling action of the mixer alone. However, at lower moisture levels, fine soil particles did not accrete into large rounded aggregates as was observed in the first trial (Figure 9). In the last few trials, we standardized our procedure to begin misting when IR thermometer readings of the soil in the drum was generally between 55 and 60 C. Temperature readings from the logger were much lower that the IR readings at that point, mostly between 30 and 44 C. Misting was typically stopped at least several minutes before the heater was turned off.

Because levels of various parameters changed over the trials, it is difficult to determine how misting affected heating efficiency. In 10 of 11 comparable trials using approximately 7.5 gal of soil, there was a net loss of water from the soil. The greatest losses occurred in trials with little or no water input via misting (Figure 10). This indicates that misting can be used to offset some or all of the water lost as water vapor during heating. However, not all of the heat energy used to vaporize the mist is transferred to the soil because some is lost in the water vapor that leaves the mixer drum. No significant correlation was detected between the amount of water lost or applied and various heating performance parameters, such as degrees gained per minute of heating. While addition of water to offset water vapor loss is necessary in this system, we were not able to determine an optimum level of water addition, which may vary with soil moisture content, soil type, ambient temperature, and other factors as well as the physical properties of the heating system.

Figure 9. Capay silty clay loam soil after heating and mixing in the cement mixer. Top – In trial 1, the soil was initially quite dry (6% volumetric water content) and water was added during the heating/mixing process using the mist setting of a hose end sprayer. Too much water was added in this first trial and the overly wet soil balled up into large, rounded aggregates as seen in the mixer (left; largest aggregates have accumulated at the surface) and after transfer to the holding vessel (right). Bottom – minimal balling of soil but rounding of small aggregates is seen in heat treated soil from trials 15 (left) and 11 (right).

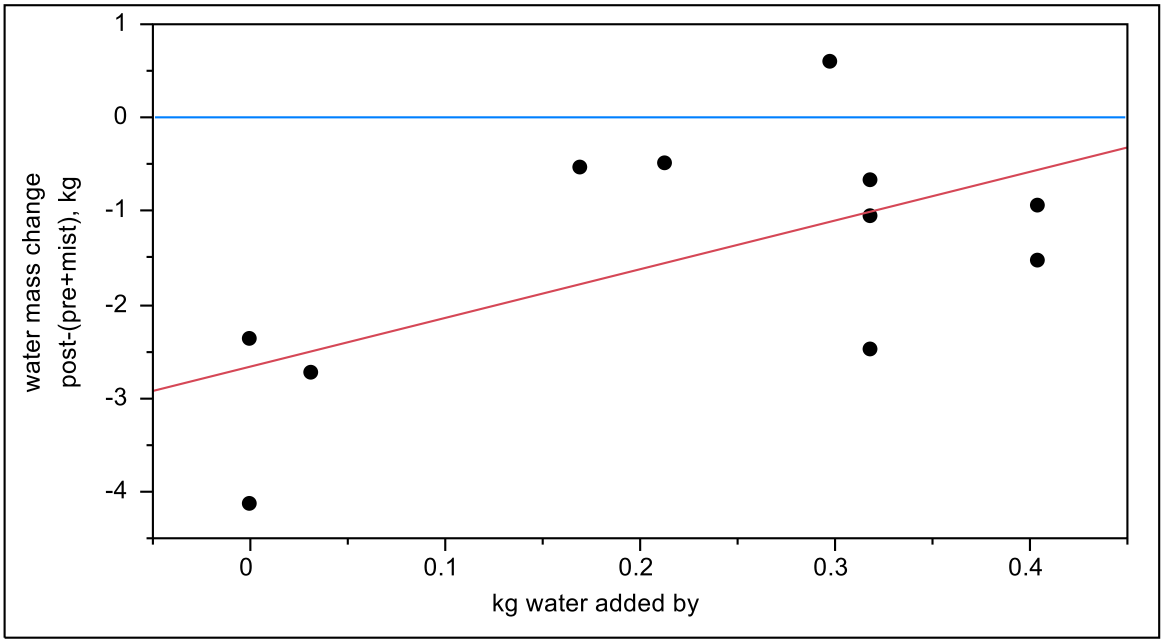


Figure 10. Effect of water input via misting on the estimated change in water mass for 11 heating trials. Water mass change is calculated as the difference between the post-heating soil moisture mass and the combined pre-heating soil moisture mass and water added by misting. Negative numbers indicate a net loss of water from the system.

3.2. Effects of environmental parameters

As used here, environmental parameters include characteristics of the soil and ambient conditions at the time of the treatment. Soil-related factors including soil texture (sand/silt/clay and organic matter percentages), soil structure (degree of aggregation), initial soil temperature, and moisture content have the greatest potential to influence heating efficiency. Of these, soil structure can be modified by mechanically breaking up large aggregates, and soil moisture can be affected either by adding water or letting soil dry before treatment.

The other environmental parameters are ambient air temperature, wind speed, light intensity, and relative humidity at the time of the treatment, which can affect primarily the rate of heat loss from the mixer and holding container. Of these, ambient temperature is likely to have the greatest effect, though the other factors have noticeable effects mainly at high levels. For example, high light intensity can cause surfaces to warm up, high wind velocities can increase convective heat loss, and high humidity may affect rates of water vaporization and condensation. Since environmental parameters vary in the field, it is worthwhile to understand how these factors might affect the time required to reach target temperatures.

3.2.1. Effects of soil temperature and soil water content

Due to the number of factors that varied between different heating trials, there is a considerable amount of confounding between the system design and environmental variables that may influence the rate of heating. Furthermore, the range of values in the data set for these variables is relatively narrow, though representative of field conditions. These factors limit our ability to assess the magnitude of the effects of each of these variables and how they interact. Nonetheless, some comparisons between trials suggest which variables exert the most influence on heating efficiency.

Heating curves for eight comparable trials are plotted in Figure 11. These trials used similar volumes of soil: 6.83 gal for T5, 7.62 for T6 and 7.57 for the remaining trials. As seen in Figure 8, the curves show a short period (about 3 minutes) at the start of the heating period that includes either a lag in heating or a small spike. Some of this may be due to the time required for the temperature probe to equilibrate to the soil temperature. Temperature rise then follows a curve with a gradually decreasing slope, with the rate of temperature rise declining as the soil temperature increases. Overall, the heating curves were similar but show some differences in the slopes of the curves. In addition, starting and ending temperatures for the trials differed, which must be considered when making comparisons.

We created multiple variables to meaningfully describe the factors that might affect heating and the soil heating rate and tested the association between the predictor and outcome variables with regression and general linear models.

The rate of temperature increase was not significantly affected by the starting soil temperature across the range represented (17.8 to 26.5 C), though the coolest soil (T13) showed the steepest overall rate of temperature increase (Figure 11). Ambient air temperatures, which ranged from 23 to 31 C, also did not significantly affect the rate of heating. Although the soil did not heat at a slower rate, cooler soils required longer times to reach target temperatures simply because larger temperature increases were needed.

Because water has a much higher specific heat capacity (4190 J kg^{-1} $°C^{-1}$) than soil minerals (745 J kg^{-1} $°C^{-1}$) or air (1005 J kg^{-1} $°C^{-1}$), we anticipated that water content would have a relatively large effect on the rate of soil heating. However, because soil moisture changed over the heating period due to evaporation and the addition of water via misting and various other factors that affect heating varied between different trials, the relationship between soil moisture and heating was not obvious.

As shown in Figure 12, heating rate was positively correlated with the post-heating soil moisture content across the range of 8.9% to 19.9% GWC. The final moisture level is related to both the initial water content and the amount of water added by misting, and therefore integrates both of these influences to some degree. To obtain a more meaningful heating rate variable, we calculated temperature rise starting 3 minutes after the start of heating to remove the variation that occurs in this initial period. We also used 57 C as the final temperature cut-off, so all trials had a comparable endpoint. Finally, the heating rate for this interval (°C/min) was standardized by the dry mass of the soil batch to account for the small variation in soil batch size in the data set.

From this and other analyses, it appeared that the rate of heating was reduced if the soil was drier for the range of soil moisture levels represented. However, excessive moisture may also reduce the rate of heating. In T6, (black data point in Figure 12, point above blue reference line in Figure 10), water input from misting apparently exceeded the vaporized water loss and the soil heating rate was on the low end of the range. If the soil becomes progressively wetter as it is heated, it will also require progressively more energy to heat due to the net increase in the specific heat capacity.

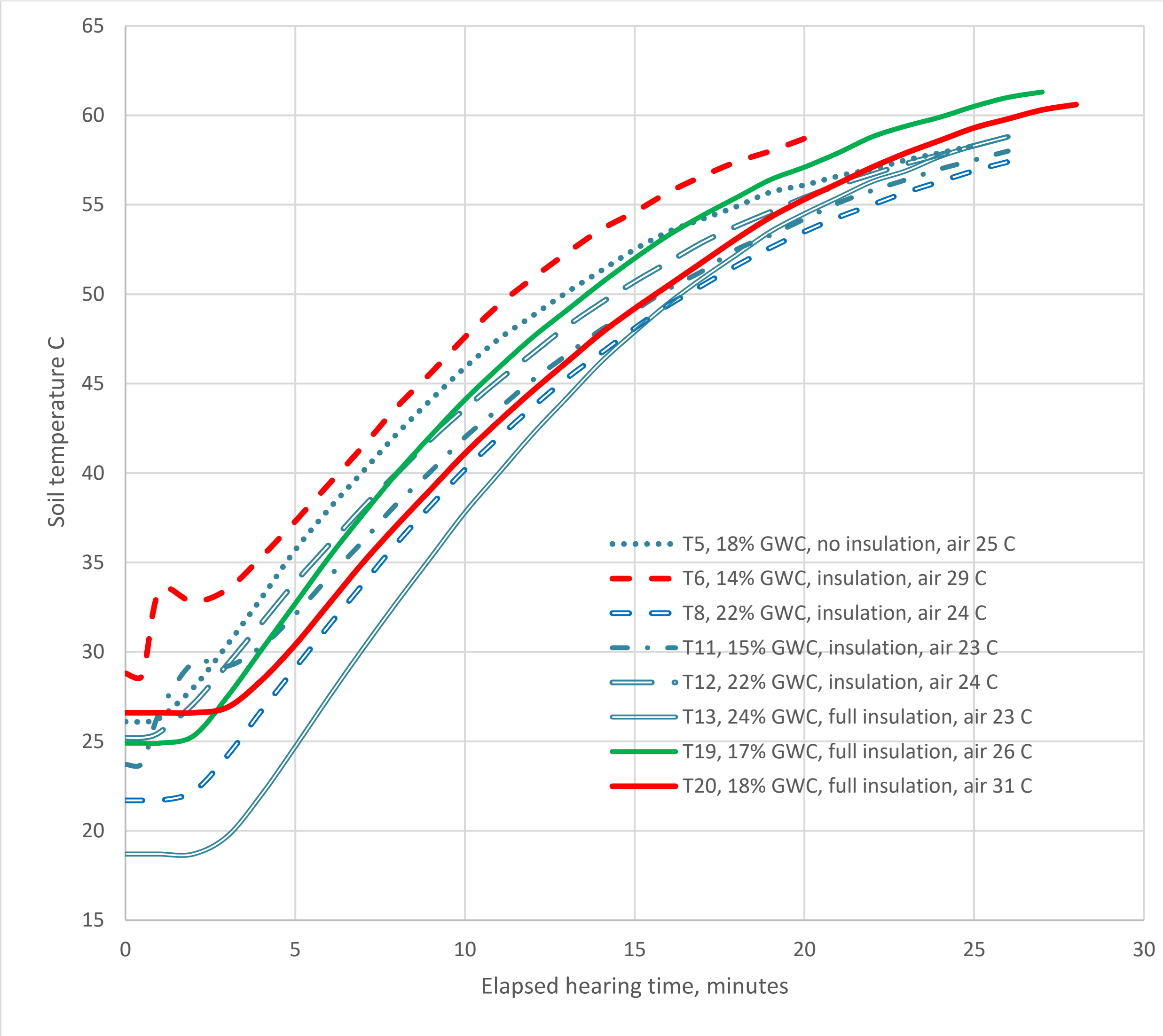


Figure 11. Soil temperatures from drum temperature logger for 8 heating trials using about 7.5 gal soil. The mixer drum was uninsulated in one trial (T5, dotted blue line), insulated on the bottom half for four trials (dashed lines), and fully insulated for three trials (solid lines). Ambient temperature ranged from 23 to 31 C; lines for ambient temperatures from 23-25 C are shown in blue, 26 C is in green, and 29-31 C are in red. Initial estimated percent gravimetric water content (%GWC) is listed in the legend; and the three wettest soils (22-24%GWC) are plotted with open line symbols. Water was added by misting to all samples, but T8 had only a small amount of water added by misting (0.03 kg, compared with 0.17 to 0.40 kg for the others).

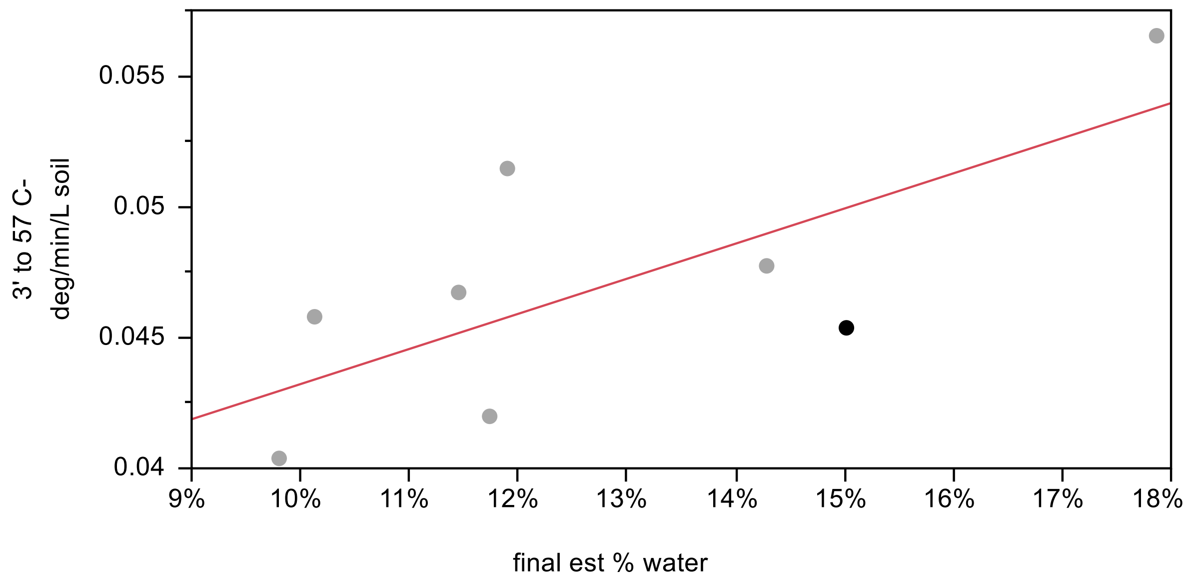


Figure 12. Correlation between heating rate per kg dry soil and estimated final gravimetric water content for the 8 trials shown in Figure 11. Heating rate is calculated as the temperature change from 3 minutes from the start of heating to the time that 57 C was reached, divided by the time required for that temperature increase. Point shown in black is the only trial (T6) that showed a net increase in water content from the initial preheating estimate to the final postheating estimate due to input from misting. Regression line R^2=0.52559, p=0.0418.

3.2.2. Heating an organic potting mix

We did not test other soil types in the heat mixer, but we did conduct two trials using a commercial potting mix (Miracle Gro® Potting Mix) that consists almost entirely of fine organic material. The specific heat of this material is unknown, but soil organic matter typically has a higher specific heat (1926 J kg^{-1} $°C^{-1}$) than soil minerals as well as a higher water holding capacity. The density of the mix is also much lower than mineral soil.

The dry bagged potting mix (7.5 gal volume) was wetted before each trial with 4 L of water and water was added by misting during heating (T9=0.15 kg, T10=0.21 kg). Data were not collected to estimate gravimetric water content, but volumetric water content readings indicated that the water content of the mix increased during heating for both trials. This may be due to the relatively low final temperatures reached (50 and 54 C) compared to the final temperatures in the soil trials (Figure 11).

Heating curves (Figure 13) for these trials show the same overall shape as those for soil (Figure 11). The heating rates to 50 C (excluding the initial 3 minutes) for these trials are compared with rates for 7.5 gal soil trials in Figure 14. Although the heating rate for T9 was near the average for the soil trials, T10 had the highest heating rate for the 3-minute to 50 C range among all the trials. Both initial soil and ambient air temperatures for T10 were the lowest among all the trials and %VWC was much higher than all soil trials, though lower than T9.

These two trials indicated that clay loam soil and the vastly different potting mix showed similar heating characteristics in the mixer, even though the water content of the potting mix was much higher overall. This suggests that this highly organic soil or organic material such as mulches or compost could be heat treated in a device such as this, but that the optimum water content for a given material may need to be determined empirically.

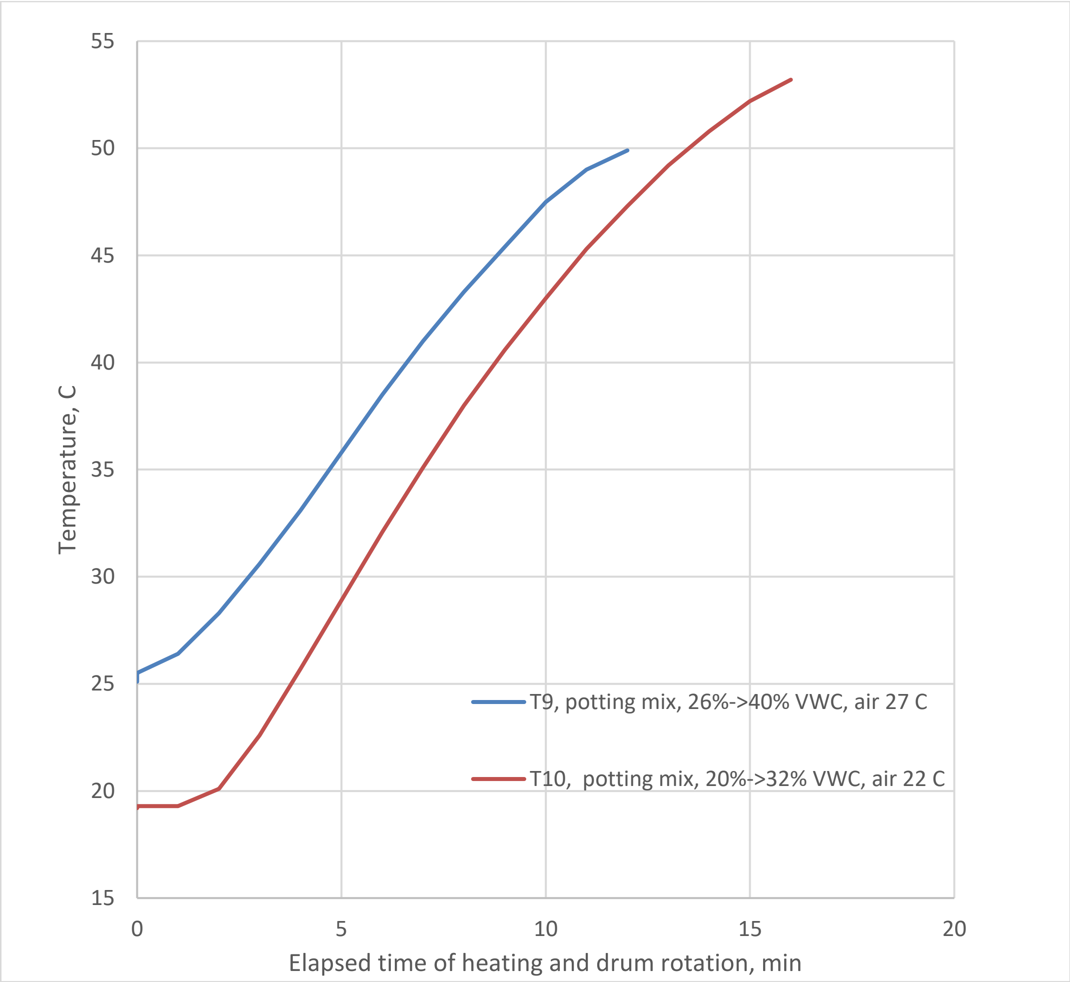


Figure 13. Soil temperatures (1-minute intervals) from the drum temperature logger for two heating trials of Miracle Gro® potting soil (7.5 gal volume). Percent volumetric water content (%VWC) before and after heating and ambient air temperature (C) at the start of each trial are noted.

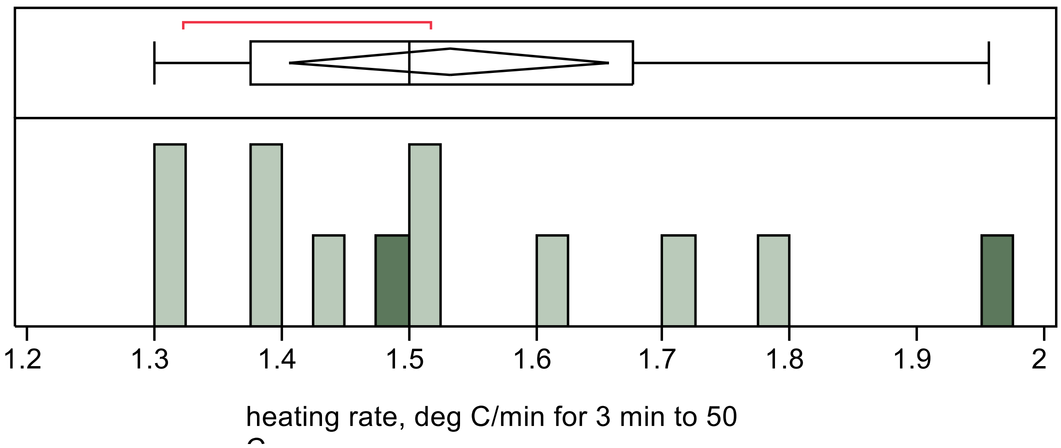


Figure 14. Heating rate to 50 C in trials using 7.5 gal of soil (light green bars) or Miracle Gro® potting mix (dark green bars). Heating rate is calculated as the temperature change from 3 minutes from the start of heating to the time that 50 C was reached, divided by the time required for that temperature increase.

3.3. Overall heating efficiency

Heating efficiency can be evaluated in a fairly basic way by comparing the input energy from the propane heater to the energy associated with the increase in soil temperature. Assuming that the 30K BTU/hr (= 527528 J/min) output rating of the heater is accurate, the input energy is the product of this value and the number of minutes of heating. The energy related to the soil temperature change can be calculated as

$$\Delta E_T = mc_p\Delta T \qquad (1)$$

where ΔE_T=change in energy associated with temperature change, m=soil mass, c_p = specific heat capacity of the soil and associated water, and ΔT=change in soil temperature over the heating period. The specific heat capacity is calculated from the specific heat capacity of the dry soil (c_s), estimated at 745 J/kg at 25 C, the specific heat capacity of water (c_w) = 4190 J/kg, and the percent water content by mass, i.e., the gravimetric water content (%GWC). This was measured directly from soil samples for trials 17-20. For other trials, %GWC was estimated from the soil bulk density (derived from T17-T20 measurements) and the measured volumetric water content. The overall soil/water specific heat capacity is estimated as

$$c_p = \frac{100c_s + wc_w}{100 + w} \qquad (2)$$

Using these equations and data on the temperature gain over time in the various trials, the calculated efficiency of energy transfer from the heater to the soil ranged from 8% to 14.9%, with an overall mean of 10.4% for 13 trials. It is difficult to find comparable heating efficiency data because rotary heating devices are typically used for much different industrial applications. For instance, direct-fired gas rotary dryers are the most closely analogous to our device (e.g., https://feeco.com/direct-vs-indirect-fired-rotary-kilns-dryers/, https://www.sciencedirect.com/topics/agricultural-and-biological-sciences/rotary-dryers), but these are typically used to dry out granular materials rather than to heat them without excessive drying. Nonetheless, the calculated efficiency for our system appears to be within the lower portion of the expected range for such devices, which is consistent with the relatively low temperatures used in our system. Heating efficiency generally increases with temperature.

3.4. Factors affecting soil cooling

Placing the soil immediately after heating into an insulated vessel allowed for additional time above the target temperature without active effort to heat the soil. In the process of transferring the soil into the vessel, its temperature normally dropped by several degrees C (Figures 15, 16). Hence, soil needed to be heated higher than the minimum target temperature to ensure that the soil would start out above the desired threshold temperature during the cooling period.

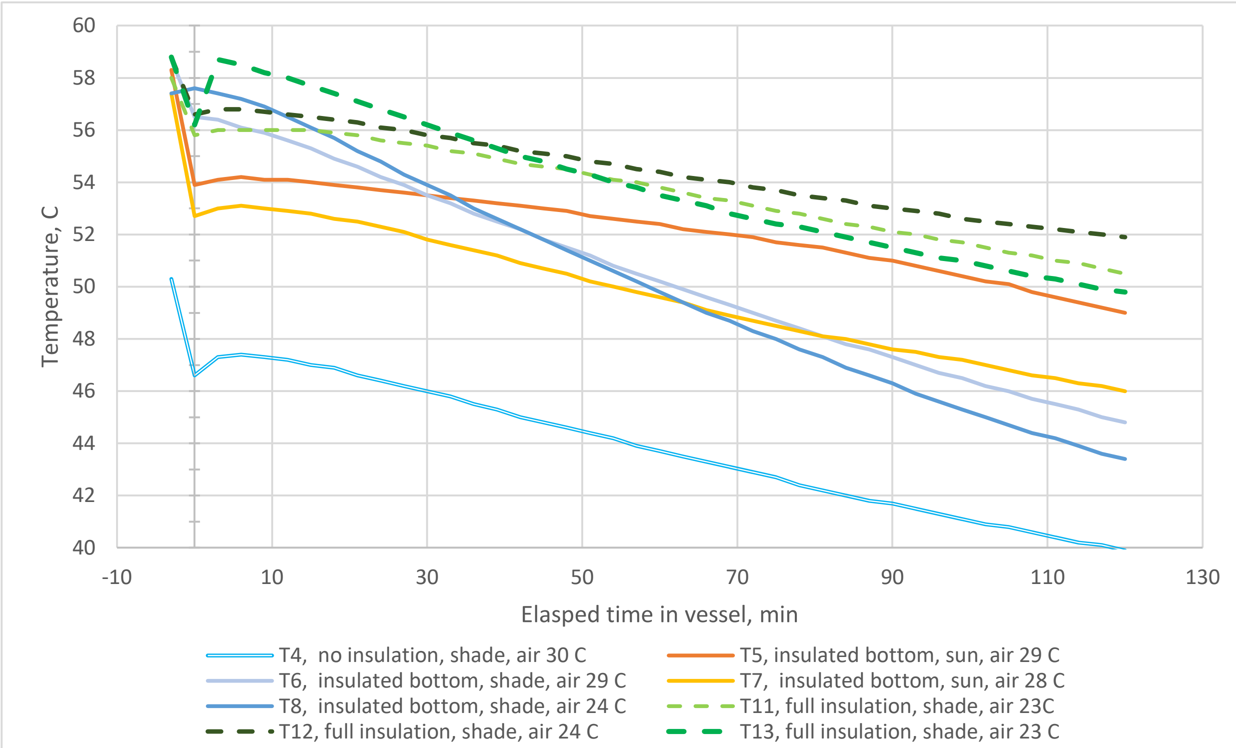
We initially placed heated soil into a noninsulated plastic vessel with a polystyrene foam cover. We later added insulation to the bottom by placing the vessel on a layer of polystyrene foam. Finally, we wrapped the sides of the vessel with two layers of egg crate polyurethane foam that was overwrapped with a polyethylene tarp (Figure 5). Figure 15 shows cooling of soil in the vessel in 8 trials with various levels of insulation and ambient weather conditions changes. As anticipated, the rate of temperature loss was lower as more insulation was added, but higher ambient temperatures and heating of the uninsulated vessel sides also retarded heat loss. Soil in the fully insulated vessel (green lines) maintained the highest temperatures after 120 minutes and had smaller initial drops in temperature (Figure 15).

Soil cooling curves for trials 13-15 (batches of varying volume) and trials 19-20 are shown in Figure 16. The 5-gal batch was placed in a smaller insulated container that was nearly filled to the top. It cooled quickly initially, possibly because more heat loss occurred during transfer, but had a slow rate of cooling thereafter. The largest batch (10 gal), which filled a larger percentage of the insulated vessel, had a slightly slower cooling rate than the 7.5 gal batch. The main difference between these two batches was the amount of air space above the soil in the vessel.

These results suggested that heat retention should be improved by placing insulation directly on the soil surface rather than allowing a large air gap above the soil which resulted because the vessel was normally only about half full. We tested this concept in trials 19 and 20, in which insulation (two 1-inch polystyrene foam insulation layers) was placed directly on the soil surface. The lid on top of the vessel was also used as before. The rate of cooling in trail 20 was the lowest rate observed in all trials, suggesting that this strategy was effective. The similarly insulated soil in trial 19 appeared to cool more rapidly, similar to the rate seen in the 10 gal trial. This may have been a measurement artifact. If the probe wire was pulled when the extra insulation was being put in place, the probe may have been shifted to a more shallow position or closer to the outer wall of the vessel where the temperature drops faster.

Overall cooling rates for the two trials with Miracle Gro potting mix were comparable to equivalent trials using clay loam soil. Average rates of temperature loss between 9 and 120 minutes were 0.44 and 0.43 °C/min for T9 and T10, respectively. However, because the potting mix was heated to lower temperatures than the soil, after the initial temperature drop associated with transfer all post-heating temperatures were below 50 C for T9 and dropped below 50 C within 12 minutes for T10.

These data show that by heating the soil at least 7 C above the minimum target temperature and quickly transferring it to a well-insulated container, the overall heat treatment period can be extended to the necessary duration without any additional input of energy. This strategy could be employed for any method that is used to heat excavated soil to minimize energy costs and minimize the time that the heating unit needs to be used for each treated batch.



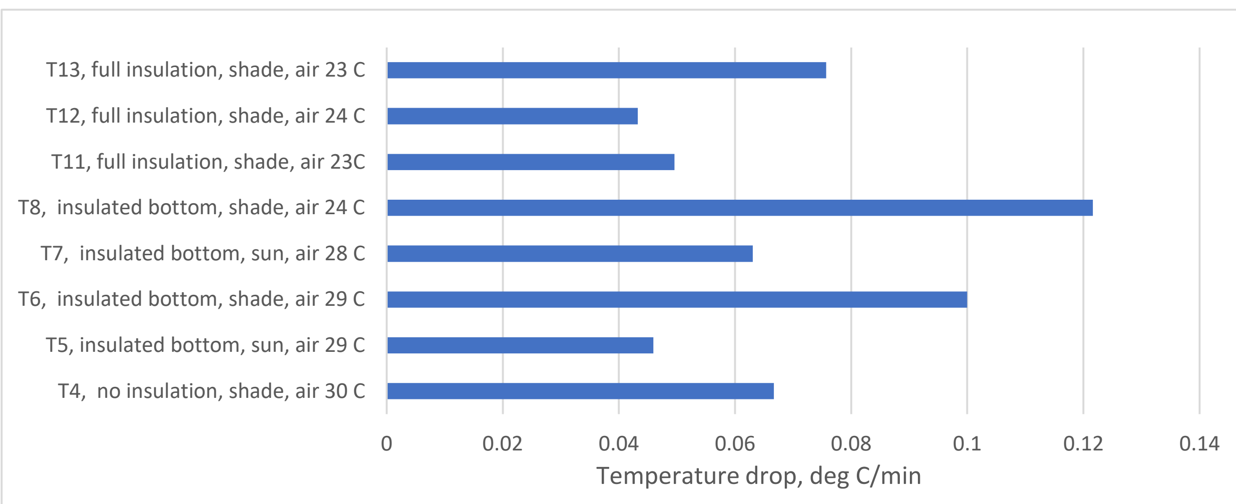
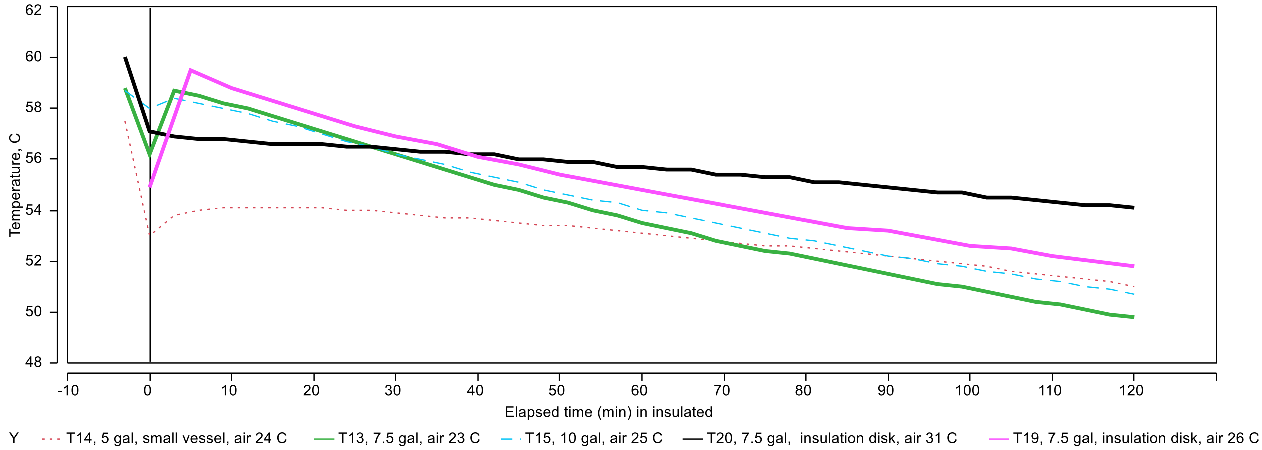


Figure 15. Temperature decline over time (top) and average rate of temperature loss (°C/min) between 9 and 120 minutes (bottom) for the post-heating period in 8 trials with about 7.5 gal soil volume. Initial temperatures (-3 minutes elapsed time) are final temperatures recorded at the end of the heating period in the mixer. The first temperature recorded in the insulated vessel for each batch are shown at 0 elapsed minutes. The holding vessel had no insulation other than the cover in trial 4 (double line), was on a sheet of insulation in trials 5-7 (solid single lines) and had insulated sides in trials 11-13 (dashed lines). The vessel was in the sun for trials 5 and 7 (yellow and orange lines) and in shade for the remaining trials. Ambient air temperature at start of incubation was 28-30 C for trials 4-7 and 23-24 C for the remaining trials.



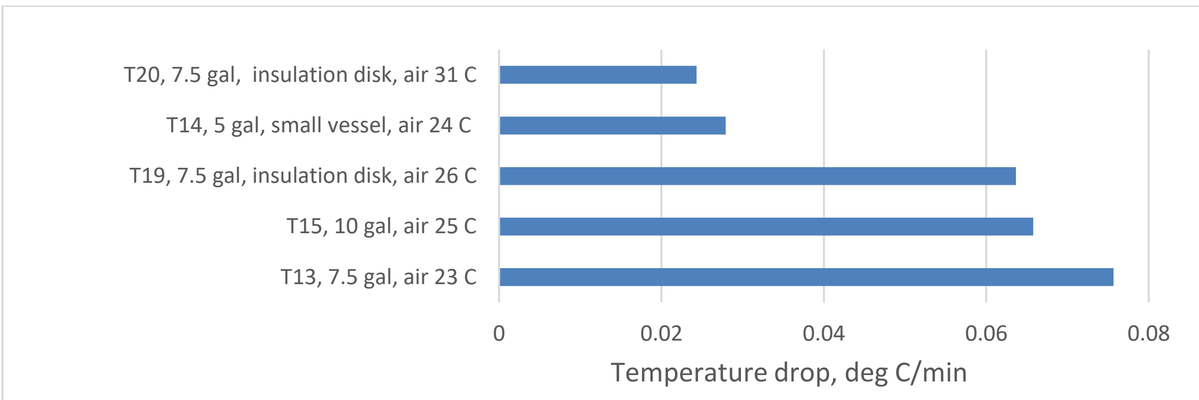


Figure 16. Temperature decline over time (top) and average rate of temperature loss (°C/min) between 9 and 120 minutes (bottom) for the post-heating period in 5 trials. T13 and T15 (10 gal, dashed line) were in the standard, fully insulated vessel. An extra disk of insulation was added directly on the soil surface in T19 and T20. T5 (dotted line) was in a smaller fully-insulated vessel that was nearly completely filled with soil. Initial temperatures (at -3 minutes elapsed time) are the final temperatures recorded at the end of the heating period in the mixer. The first temperature recorded in the insulated vessel for each batch are shown at 0 elapsed minutes.

3.5. Efficacy of heat treatment on soil with natural *Phytophthora* inoculum

For trials 13-15, which compared heating efficiency of different amounts of soil, soil was excavated around the base of a large, nursery-origin toyon (*Heteromeles arbutifolia*) that was mostly dead due to *Phytophthora cactorum* infection. Only a few root suckers of the plant were alive. The soil was excavated to a depth of about 30-40 cm, placed in a wheelbarrow and mixed with a shovel (Figure 17). Two soil samples were removed from the wheelbarrow and baited for *Phytophthora* with green pears, using methods previously described (Swiecki and Bernhardt 2019). *Phytophthora* was detected in both samples, with numerous lesions forming on the pears. Isolations from the pears yielded cultures that closely matched the characteristics of *P. cactorum*, which had previously been confirmed from the root system of this plant by genetic sequencing.

Soil from this mixture was heated in three separate batches as described above in section 3.1.3. The overall heating parameters for the three batches are shown in Table 4 below. After cooling, approximately 1.5 L of heat-treated soil from each batch was collected and baited following the same methods used to bait the untreated soil. No *Phytophthora* lesions developed on pears from any of the heat-treated samples, providing evidence that the heat treatments were sufficient to kill naturally-produced inoculum of *P. cactorum* in soil and roots.

Table 4. Heating parameters for soil batches (trials 13-15) known to be infested with *P. cactorum* before treatment.

					Minutes at 50 C or higher		
Trial	**Soil volume, L**	**Estimated dry soil mass, kg**	**Initial soil T, C**	**Maximum soil T, C**	**During heating**	**Post-heating**	**Total**
T13	28.7	24.8	17.8	59.3	13	116	129
T14	19.1	16.5	18.9	58.5	8	147	155
T15	38.2	33.1	18.9	58.5	14	137	151

Figure 17. Left, soil was collected into a wheelbarrow and mixed to degree possible. Large clods were broken up, root fragments were left in place. Right, soil appearance after heating.

4. Discussion and conclusions

The temperature of static masses of soil tends to change slowly due to low rates of heat conduction between particles. The device we tested overcomes that limitation by mixing the soil so that heat transfer occurs primarily by convection from heated air and water vapor. The overall design of our device is most analogous to a direct-fired rotary dryer, which is quite efficient at transferring heat energy from a gas flame heat source to particulate material that interacts directly with the hot air. However, because our goal was heating rather than drying soil, we introduced mist that was vaporized by the hot air stream to minimize moisture loss from the soil.

The efficiency of this heat transfer process in this type of device can be affected by the way that the hot air stream interacts with the fluidized soil particles in the rotating drum. In these tests, we did not vary these parameters, which were based on the equipment used. Changing the airflow rate and temperature, as well as length and the degree of baffling in the drum could improve heating efficiency by allowing greater time for heat exchange to occur before the air is exhausted. We made a few modifications of our initial system, including addition of moisture via misting and adding insulation to the mixer and holding vessel, that increased the efficiency of the heating process, but it is seems likely that the heating efficiency could be improved further.

Within the moderate range of temperatures in the tests, neither ambient air temperature nor initial soil temperature were related to heating rate, though cooler soils required longer times to reach target temperatures. At substantially lower air and soil temperatures, it is possible that heating rate could be reduced, especially if the temperature of the heated air stream is lower. Ducting or an enclosure that could help recycle warm air back into the heater should largely offset any reduced efficiency that might develop at low air temperatures.

For the silty clay loam soil we used, water content at the end of the heating period was the best single predictor of overall heating efficiency. Efficiency of heating is related to the moisture level of the soil, most likely due to the process of heat transfer via water vapor. Although moderate levels of moisture aid this process, excessive moisture can reduce the rate of heating and can cause undesirable aggregation of soils with high clay content.

Even this simple heating system was able to heat batches of soil to temperatures lethal to *Phytophthora* with less than 30 minutes of heat input. The overall heat treatment period was extended by two hours or more without additional heat input by transferring heated soil into an insulated vessel and holding it there.

5. References

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