A Technique for Treating Contaminated Soil with Steam for Eradication of *Phytophthora*

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Abstract

During a series of large riparian restoration projects in the San Francisco Bay Area, Phytophthoras on infected planting stock were inadvertently introduced into a number of sites. There are many planting basins at some of these sites where hosts from a nursery that had a high rate of *Phytophthora* positives were planted (**Figure 1**). These basins are scheduled for treatment once a potential mitigation approach to kill any introduced Phytophthoras is decided upon. Steaming has been shown to be an effective mitigation treatment to eliminate Phytophthoras from infested soil. In nursery and landscape sites where *P. ramorum* has been detected, steaming soils to reach a temperature of 50 °C at 30 cm for 30 minutes is an accepted USDA APHIS mitigation treatment. In this project, two steaming techniques were tested. In addition, thermal cover materials for retaining heat in steamed soil were compared. Testing was done at a restoration site in California (CA) and at WSU Puyallup (WSUP).

At the CA site, a 24" diameter steam auger was attached to a hydraulic-powered shaft that passed through a transfer case welded to an excavator bucket. Steam was delivered to the auger via a 2-inch diameter hose that connected a steam generator to the transfer case. Steam was introduced through the auger during soil mixing. In another set of trials the soil was first augured to 24" depth, then a 1.5” diameter injector was used to introduce steam at the bottom of the hole. Temperatures were measured at several depths along the edges of the holes during and after steaming. Testing in a similar soil type at WSUP under several moisture conditions was done using the injector and temperature sensors mounted on a grid inside the hole. The temperature at each point on the grid was measured during and after steaming.

Several thermal cover materials were tested at Puyallup. A thermal cover used after steaming will retain heat in the soil after 10 minutes of steaming when sufficient heat has accumulated. There was little difference between the steamed, uncovered plots and plots with some type of thermal cover after 5 minutes of steaming. After 10 minutes, the differences between thermal cover treatments were significant at all depths. The materials that prevented the most heat loss from the soil were an insulated metal drain pan, rubber floor mats, and denim insulation.

Preliminary results from auger and injector field tests in CA were not conclusive due to saturated soil conditions. Although a steam auger was not tested at Puyallup, the results with the steam injector indicate that the results of at least the steam injector tests at the CA site would have likely been acceptable if they had been done under dryer soil conditions. In the silt loam soil at WSUP, the conditions for killing *P. ramorum* (50 °C for 15 minutes) and *P. pini*, which has a heat resistant spore stage (50 °C for 40 minutes) were reached over most of the soil volume when soil at field capacity was steamed for 5 or 10 minutes.

Figure 1. Restoration sites at Adobe Gulch Grassland in March 2018

Data collected during the steaming at both sites (**Figure 2**) indicated that there is little risk of a negative impact to organisms in the bulk soils adjacent to augured and steamed planting basins unless the soil has larger channels for the steam to move outside of the soil in the augured hole.

The San Francisco Garter Snake (*Thamnophis sirtalis tetrataenia*)

This snake was placed on the state and federal endangered species lists in 1967. Its preferred habitat is riparian areas and wetlands, where it preys on amphibians including the endangered California red legged frog (*Rana draytonii*). Suitable habitat has declined severely due to urban development, agricultural land use, and changes in hydrology. San Francisco garter snakes are popular pets in Europe, where it is possible that there are more of them as pets than there are in the wild in California.

http://www.californiaherps.com/snakes/pages/t.s.tetrataenia.html

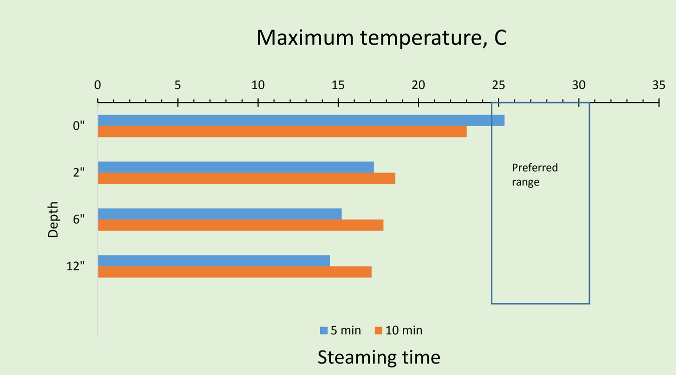

Figure 2. Maximum temperatures at four depths in undisturbed soil 30 cm (12") from the edges of the holes of augered-soil during steaming for 5 or 10 minutes at WSU Puyallup. The preferred temperature range for garter snakes is shown in the blue rectangle.

1. Pilot test at Adobe Gulch Grassland (AGG)

During March, pilot steaming trials were conducted at the Adobe Gulch Grassland (AGG) restoration site. This site is being planted to restore habitat for several endangered species including the San Francisco garter snake and the California red legged frog.

For the steaming tests, five planting basins were selected that had no *Phytophthora* positives. The soil type at the site was a 115 Los Gatos loam with 30-75% slopes. During the 10 days prior to testing the area received 1.81” of rain. An additional 1.12” of rain fell during the test. This resulted in saturated soil conditions with standing water in some areas at the start of each steaming trial.

A Sioux SF-11 steam generator was used to provide steam to a 24” diameter auger that had been modified to deliver steam to the trailing edge of the auger blades. Participants in the pilot tests initially met at the Millbrae yard to go over the operation of the steam generator (**Figure 3**). At the AGG site, the auger was attached to a hydraulic-powered shaft that passed through a transfer case welded to an excavator bucket. Steam was delivered to the auger via a 2-inch diameter steam hose that connected the steamer to the transfer case. Results and details of the trials are in **Table 1 and Figure 4**. Trials 1-3 used steam introduced through the auger while mixing the soil (**Figure 5**). In trials 4-5 the soil was augured with a 24” diameter auger, then a 1.5” diameter injector was used to introduce steam into the bottom of the hole with the loose soil (**Figure 6**). It was decided to auger to the depth of 24” or to clay soil. This is the depth of the Bt horizon, which was composed of a very gravelly clay loam. The soil at this depth was a light tan color, in contrast to the upper layers. Bedrock is located at depths of 26-36” in this soil type at this site.

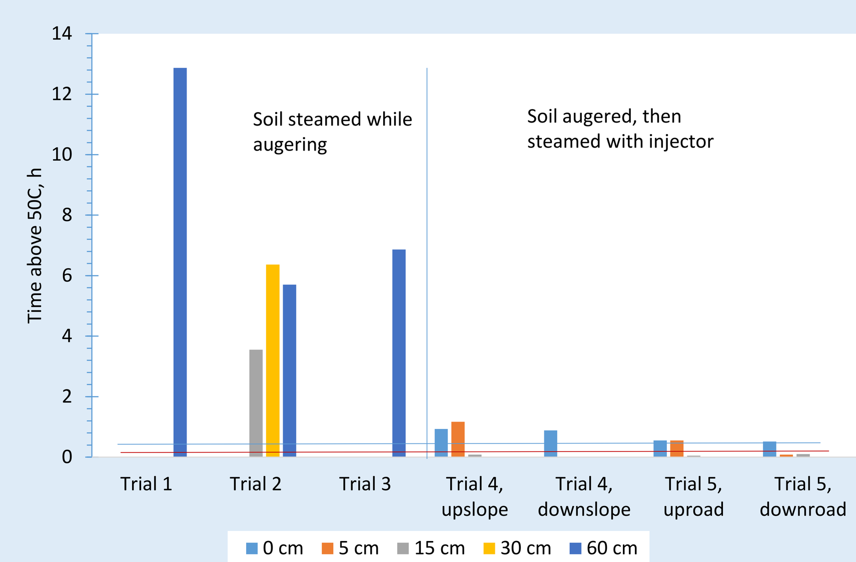

Figure 4. Results of steaming trials at AGG using the steam auger (trials 1-3) and injector (trials 4-5). The amount of time that the soil temperatures were above 50C was determined for each trial at five depths. Red line indicates 15 minutes, recommended time above 50C to kill *P. ramorum*. Blue line, 40 minutes, the time recommended to kill *P. pini*, which has a more heat resistant spore stage. (See **Table 1** for a description of the steaming conditions)

Figure 3. Training and test run of the Sioux SF-11 steamer at the Millbrae yard, 3/20/18.

Table 1. Steaming trials done at Adobe Gulch Grassland in March 2018. Trial 4: upslope (US) and downslope (DS) edges of the hole. Trial 5: up-road (UR) and down-road (DR) edges of hole along the slope, perpendicular to the orientation in Trial 4.

	Time				Time above 50C at various depths (hr)				
Trial	Steaming (min)	Temperature data collection (hr)	Steam supply	Cover	0 cm	5 cm	15 cm	30 cm	60 cm
Trial 1	9	25	Auger	Yes	0.00	0.00	0.00	0.00	12.87
Trial 2	7	24	Auger	Yes	0.00	0.00	3.55	6.37	5.70
Trial 3	7	23	Auger	No	0.00	0.00	0.00	0.00	6.87
Trial 4 (US)	11	1.4	Probe	Yes	0.93	1.17	0.08	0.00	0.00
Trial 4 (DS)	11	1.4	Probe	Yes	0.88	0.00	0.00	0.00	0.00
Trial 5 (UR)	11	0.7	Probe	No	0.55	0.55	0.05	0.00	0.00
Trial 5 (DR)	11	0.7	Probe	No	0.52	0.08	0.10	0.00	0.00

Figure 5. A) Steam auger attached to excavator, and **B, C)** soil being steamed during mixing with the auger at sites 1-3. **D)** A tarp was used to prevent heat loss from the soil after steaming. The tarp was folded and placed over the steamed basin after temperature sensors were inserted into the soil. Cooling was measured for 24h after steaming.

Figure 6. Trial 4 & 5 sites were located in a bank along a road. **A)** Soil was augered to a depth of 24" and then **B)** an injector was placed in the center of the hole filled with augered soil. **C)** A cover was used to retain heat during steaming. Directions for temperature sensor placement varied by trial. In Trial 4, the temperature sensors were place in a line perpendicular to the road on the “up slope” and “down slope” edges of the hole, while in Trial 5 the sensors were place on a line parallel to the road on the down (left) or up road edges of the hole after the soil at each site had been augered.

2. Thermal covers for heat retention on steamed sites

Materials for insulating the soil surface to improve heat retention after steaming were evaluated in June 2017. The average soil moisture on all plots during the experiment was 15%, and the average daily temperature range was 9.9 - 21.8 °C (49.8 – 71.2 °F).

Holes were dug in Puyallup fine sandy loam soil approximately 30" deep and 24" in diameter using an auger mounted on a tractor. Temperature sensors were placed in each hole at depths of 5, 15, and 30 cm, and on the soil surface. These were attached to dataloggers that measured the temperature once per minute. The 1.5“ diameter injector attached to 60' of 2" steam hose was used in each hole as in the grid tests described above. After the injector and temperature sensors were installed, the soil was replaced in the hole and compacted around the injector to minimize leakage of steam. A sample was taken to measure soil moisture from the unsteamed plots. There were three replicate plots of each thermal cover/steaming time treatment. The SF-20 steamer was used to apply steam with the valve open 1 turn (14%) for 5 or 10 minutes or until all sensors reached 50°C, whichever came first. Immediately after steaming, the thermal cover was placed on the plot and the edges covered with soil (**Figure 7**). The cover and temperature sensors were left in place and cooling was measured for 24 hrs following steaming.

The soils maintained the 50°C target temperature for 30 minutes after both 5 minutes and 10 minutes of steaming, for all the thermal cover treatments including the treatment of steam + no covering material. This suggests that it may not be necessary to use a thermal cover after steaming for at least 5 minutes. Further tests should be done, including shorter steaming times and adding a cover to retain heat. Ambient temperatures may also play a role in cooling at the soil surface. The soils stayed above 50°C after 10 minutes of steaming for almost 10x longer in some cases (**Table 2**). There were more significant differences among treatments after 10 minutes of steaming, with the denim insulation retaining heat for the longest, followed by floor mats and insulated drain pan, then the radiant barrier. Under both steaming times the upper layers of soil (0 cm and 5 cm) were at the target temperature for less time than the 30 cm depth.

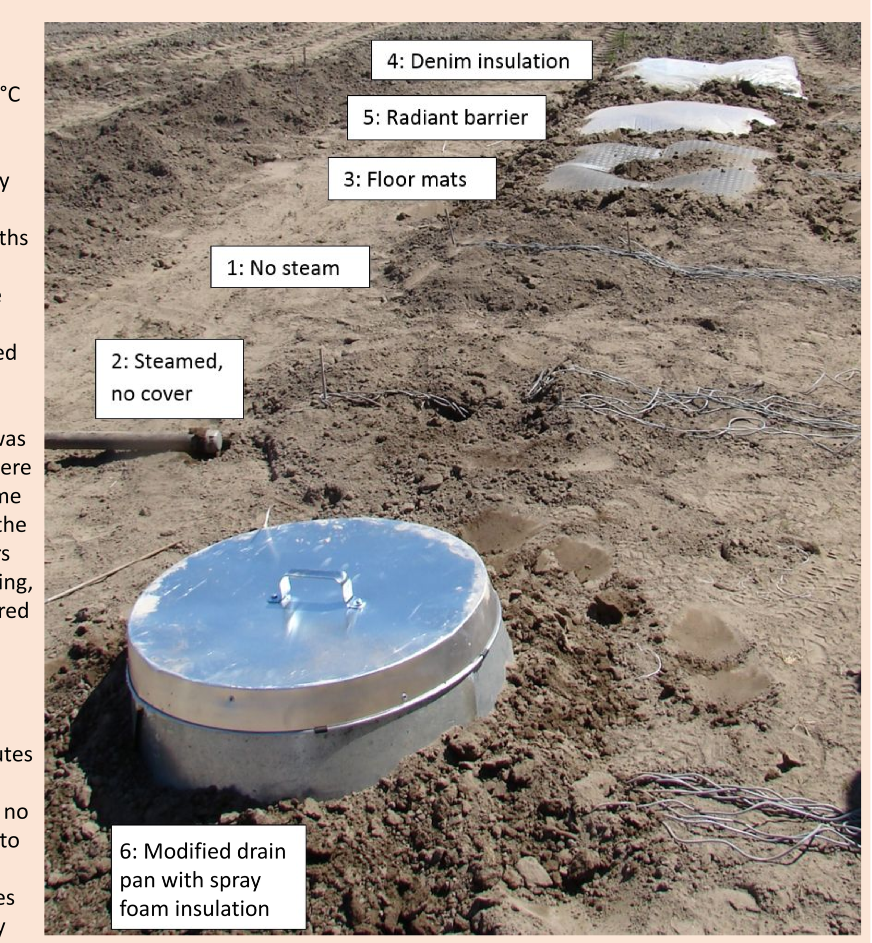

Figure 7. Thermal cover treatments placed on the soil surface immediately after steaming. Temperature was measured for 24h following steaming.

Table 2. Time above 50°C, minutes, for soils steamed for 5 minute and 10 minute intervals and then covered with various materials for heat retention. Heat retention was measured over a 24 hr period after steaming. Red cells = soil above 50°C > 30 minutes, the conditions for killing *P. ramorum* inoculum.

	No steam	Steamed, no cover	Denim insulation	Insulated drain pan	Floor mats	Radiant barrier
5 minutes of steaming						
0 cm	0	0	96	53	46	4
5 cm	0	11	1	70	6	0
15 cm	0	58	6	221	119	109
30 cm	0	256	296	553	488	362
10 minutes of steaming						
0 cm	0	79	1154	728	686	521
5 cm	0	190	1126	748	758	577
15 cm	0	521	1174	958	988	827
30 cm	0	804	1189	1104	1159	1086

3. Grid tests at WSU Puyallup

Given the problems in heating the saturated soils at the AGG site, a series of tests steaming soil at lower moisture conditions were conducted at WSU Puyallup in April-May 2018. These tests were done in Kitsap silt loam, which has similar properties to the Los Gatos loam at the AGG site.

A Sioux SF-20 steam generator was used in these trials. The SF-20 generates 680 lbs of steam per hour at full capacity compared to the 370 lbs/hr generated by the SF-11 unit. Holes were dug in the Kitsap silt loam soil approximately 36" deep” using a 24" diameter auger. After removal of the soil in the hole, a sensor grid constructed by placing 60 temperature sensors on a 24” by 48” piece of expanded metal wire mesh at 4" spacing was placed in the hole (**Figure 8**). The area covered by the sensors on the grid was 24" wide by 36" tall. The temperature sensors were attached to dataloggers that recorded the temperature once every 10 seconds. A steam injector for delivering steam into the soil was fabricated from 30" black iron 1.5" diameter pipe, with 16 3/8" holes drilled 24" from the steam input end (**Figure 6B, below**). The bottom of the pipe was capped. The injector which was attached to the steamer with 60' of 2" steam hose was placed at the center of the grid with the end 24" below the soil surface and 6" from the bottom of the hole. The top row of sensors measured temperatures 4" above the soil surface. Two sets of additional sensors at 0, 5, 15, and 30 cm depth were installed 30 cm (1 ft) from the outside edge on opposite sides of the hole to measure the rate of horizontal heat transfer through undisturbed soil during steaming.

After the injector and temperature sensor grid were installed, the soil was replaced in the hole and compacted around the injector to minimize leakage of steam. In addition to steaming five holes filled with unaltered soil, ten gallons of water was applied evenly across the soil surface after soil was replaced in a set of five holes. The water was allowed to infiltrate for approximately 15 minutes before steam was applied through the injector. A soil sample was taken from the top 4” (10 cm) to measure the soil moisture status before steaming in both the holes with unaltered (FC, field capacity) and watered saturated (SAT) soil. A summary of the grid tests is given in **Table 3**.

The SF-20 steamer was used to apply steam with the valve open 1 turn (14%, 355 lbs steam/hr) for 5 or 10 minute intervals. The temperature sensors were left in place and the cooling of the soil was measured for 24 hrs following steaming. The holes were not covered after steaming. Data was collected on the time to reach 50°C (**Figure 9**), maximum temperature (**Figure 10**), and the amount of time above 50°C (**Figure 11**) for each location on the sensor grid.

Figure 8. A) WSU’s SF-20 steamer, steam injector, and grid during steaming in Kitsap silt loam soil at WSU Puyallup. **B)** Temperature sensor grid and **C)** dataloggers for the soil heating tests at WSU Puyallup.

Table 3. Grid tests at WSU Puyallup in April-May 2018. All holes were augured to a depth of 36", with the sensor grid depth 24". Values for heating time, time above 50C, and maximum temperature are the average of all sensors on the grid. Treatments: FC = Field capacity, no water added; SAT = saturated, 10 gallons of water added to soil surface 15 minutes before steaming. Soil moisture was measured on samples collected in the top 4" (10cm) of soil.

Date	Test	Treatment	Time steamed, minutes	Soil moisture, %	Heating time to 50C, minutes	Time above 50C, minutes	Maximum temperature, C
23-Apr	1	FC	5	21%	3.98	166.96	71.67
24-Apr	2	FC	10	19%	3.75	74.46	97.59
25-Apr	3	FC	5	25%	2.86	295.86	78.70
26-Apr	4	FC	10	23%	3.74	217.44	99.20
30-Apr	5	FC	5	24%	2.56	352.89	65.48
1-May	6	FC	10	23%	4.64	327.62	99.37
3-May	8	SAT	5	27%	3.10	5.53	39.75
7-May	9	SAT	10	31%	5.46	73.57	78.38
29-May	12	SAT	5	25%	4.50	104.77	50.93
30-May	13	SAT	10	28%	5.64	144.80	84.83
31-May	14	SAT	5	29%	4.40	3.27	43.84

Time, minutes: 0, 2, 4, 6, 8, 10

Depth, inches	4"	8"	12"
4"	6.10	9.01	7.25
0"	7.50	5.36	5.88
-4"	3.63	3.65	3.89
-8"	2.19	2.42	2.19
-12"	1.14	1.81	1.75
-16"	0.39	1.58	1.17
-20"	0.18	1.04	0.58
-24"	0.39	1.28	0.58
-28"	5.67	3.75	4.68
-32"	6.25	7.01	7.21

Figure 9. Time (minutes) for soil to heat to 50°C during steaming for Kitsap silt loam soil at field capacity (18-25% moisture) at distances of 4, 8, and 12 inches from the steam source (red tip at the end of the gray injector) and depths of 4" above and between 0 - 32" below the soil surface. Average values are shown for sensors that reached 50°C during 5 or 10 minutes of steaming. Steam was applied 24" beneath the soil surface.

Temp, °C: 0, 20, 40, 60, 80, 100

Depth (in.)	A: 5 minutes of steaming 4"	8"	12"	B: 10 minutes of steaming 4"	8"	12"
4"	59	42	33	84	79	65
0"	41	63	65	96	98	99
-4"	89	90	87	100	99	100
-8"	100	100	100	101	100	100
-12"	100	94	91	100	92	100
-16"	100	94	91	100	89	93
-20"	98	100	100	99	100	100
-24"	100	95	100	100	99	94
-28"	70	75	77	54	70	77
-32"	64	62	54	42	43	51

Figure 10. Maximum soil temperatures (°C) during soil steaming grid tests at WSU Puyallup. Soil was at field capacity (18-25% moisture). Temperatures were measured at horizontal distances of 4, 8, and 12 inches from the steam source (red tip at the end of the gray injector) and depths from 4" above to 32" below the soil surface. Soils were steamed for 5 minutes (**A**) or 10 minutes (**B**). Average values are shown for maximum temperature at each sample point during the 5 or 10 minutes of steaming. Steam was applied 24" beneath the soil surface.

Time, minutes: 0, 50, 100, 200, 400, 800, 1000

Depth (in.)	A: 5 minutes of steaming 4"	8"	12"	B: 10 minutes of steaming 4"	8"	12"
4"	7	0	0	17	3	2
0"	0	58	83	27	49	34
-4"	372	280	156	465	366	246
-8"	600	439	224	615	659	390
-12"	683	540	239	817	698	484
-16"	717	557	255	831	692	498
-20"	603	499	248	703	606	577
-24"	428	335	135	522	495	448
-28"	63	74	30	52	142	160
-32"	51	22	24	30	25	86

Figure 11. Time that soil was above 50°C (minutes) during soil steaming grid tests at WSU Puyallup. The target time for *P. ramorum* is 15 minutes and for species with more resistant spore stages such as *P. pini*, 40 minutes. Soil was at field capacity (18-25% moisture). Temperatures were measured at horizontal distances of 4, 8, and 12 inches from the steam source (red tip at the end of the gray injector) and depths from 4" above to 32" below the soil surface. Soils were steamed for 5 minutes (**A**) or 10 minutes (**B**). Average values are shown for sensors that reached 50°C. Steam was applied 24" beneath the soil surface.

Recommendations for steaming

- Since steaming was less than optimal under high soil moisture at the AGG site, we recommend that steaming treatments be done when soil is at field capacity, not at high soil moisture levels during the rainy season.
- The injector method heated the surface layers of the soil better than using the steam auger, and also is more practical than the auger from a logistics standpoint.
- For best results, the soil should be augured to a depth of 24" and then steamed using the injector for at least 5 minutes.
- A thermal cover placed over the treated site after steaming will reduce cooling of the soil surface and prolong the duration of time the soil stays at temperatures sufficient to kill Phytophthoras.
- If steamed sites are to be replanted, considerations should be given to amending the steamed soil with organic matter to improve structure before replanting. Mixing a *Trichoderma* soil additive may improve plant growth and protection from soilborne diseases that may colonize later.

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