Nursery Soil Fumigation[1]

Dick Karsky[2]

Karsky, D. 1997. Nursery Soil Fumigation. In: Landis, T.D.; Thompson, J.R., tech. coords. National Proceedings, Forest and Conservation Nursery Associations. Gen. Tech. Rep. PNW-GTR-419. Portland, OR: U.S. Department of Agriculture, Forest Service, Pacific Northwest Research Station: 98-108. Available at: http://www.fcnanet.org/proceedings/1997/karsky.pdf

Introduction

Pathogens in the soil affect the growth of young trees at tree nurseries. Cultural practices, such as crop rotation, have been used to reduce the level of pathogens in the seedling beds. In addition, chemicals have commonly been used to sterilize the beds before seed is sown. These practices increase the chances of a successful seedling crop. Fewer treatments are needed to correct diseases that affect the seedlings. The two main chemicals used to sterilize the seedling beds are Basimid and methyl bromide. Methyl bromide, the fumigant of choice, has been found to be environmentally harmful and its use will be banned by the Environmental Protection Agency in the year 2001. Methyl bromide was very effective at controlling microorganisms and killing weed seeds.

The objective of this project is to find an economically and environmentally acceptable method of sterilizing soils. Steam has been used in Europe to prepare the soil for nursery operations. In the 1950's, steam rakes were used in the United States to treat soils. The temperature required for steam treatment to kill certain organisms is listed in Table 1.

Table 1. Temperature required to kill certain organisms (from John Bartok, Jr.).

Temperature (°F)	Pests or weeds affected
115	Water molds (*Pythium* and *Phytophthora*)
120	Nematodes
135	Worms, slugs, centipedes
140	Most plant pathogenic bacteria
160	Soil insects
180	Most weed seeds
215	Few resistant weed seeds and plant viruses

They were abandoned when methyl bromide became available because it could be applied more quickly, was easier to use, and was effective against a wide range of organisms and weeds. During fiscal year 1995, Missoula Technology Development Center (MTDC) built a prototype steam treatment machine to obtain data on its effectiveness and cost of operation.

MTDC Steam Fumigation

Design MTDC has built and tested a portable steam treatment machine with a boiler capacity of 1 million BTU's. The MTDC design consists of a portable steam generator that is pulled through the field at very slow speeds (Figure 1). Initially, a tractor equipped with a creeper gear transmission was used to tow the machine, but the tractor could not go slow enough. The machine was adapted to include a self-powered winch. A deadman (a tractor for instance) is placed down the field and the winch cable is attached to it. The winch pulls the machine over the seedling bed at the slow speeds required. The winch cable passes through a loop mounted on the tongue of the steerable front axle, guiding the front steerable wheels. The steamer can be started up and operated without too much attention. When the steamer reaches the end of a seedling bed, the deadman and the steamer are moved to an adjacent bed.

Figure 1. The steam treatment machine in operation. A winch pulls the machine to the tractor, which acts as a deadman.

The steam from the generator and air from a blower (Figure 2) are mixed to obtain the desired temperature before being injected into the ground. Initially, the blade designed for injecting steam underground was similar to an undercutter blade used for root wrenching or root pruning (Figure 3). A hollow base was added to the bottom of the blade. This created a steam chamber.

Figure 2. The electric blower adds air to regulate the temperature of the steam.

Figure 3. The initial steam injection system used an undercutter blade. Steam was vented from the back of the blade.

Openings at the back edge of this chamber below the blade allowed steam to be injected into the soil. The sides of the blade were constructed out of hollow rectangular tubing. The inside of these tubes were used as conduits for the steam from the blower/steam generator. Some observations on the performance of this blade included:

- In the lifted seedling beds where we operated the machine, the blade had a tendency to push soil well in front of its leading edge. This may have been caused by the blade's blunt edge, by the partially frozen ground during our tests, and by soil that was not consistent in texture.

- Some steam was lost as it came up through openings in the soil, around the ends of the steam injection blade, and near the temperature probe. If the soil had been uniformly tilled, this might not have been a problem. Steam was also lost where the machine's tires passed and compressed the soil. Even after some of the nozzles at the end of the injector blade had been closed off and the treatment width had been narrowed, the problem of steam loss at the ends of the blade was not completely eliminated.

A stainless steel sheet was added over the injector blade surface to try to solve the problem of soil building up in front of the blade's leading edge. This may not be desirable on an operational machine because the stainless steel surface could be worn away quickly. The problem of soil buildup may also have been remedied by using different bed preparation techniques and by reducing the blunt edge of the blade. Instead, a different steam injection system was developed.

A tarp was placed over the soil and above the blade to trap the heated vapor and steam. The tarp was about 10 feet long, long enough to trap the heat and maintain the desired temperature for at least 20 minutes. A temperature probe was built and placed immediately behind the blade to record the temperature at three different levels below the soil surface.

Shank Steam Injection

The undercutter blade was replaced with a series of shanks spaced 6 inches apart in two separate rows. Steam was injected at the back of the base of those shanks (Figure 4). The steam was fed into a manifold and then to hoses connected to the shanks. This configuration of the steam treatment machine was evaluated during the preliminary tests conducted last fall at Forest Service nurseries.

Figure 4. Steam injected behind vertical shanks was distributed more evenly through the seedbed than when steam was injected with the original undercutter injection system.

Sweep Injection
In the spring of 1997 the machine was modified to inject the steam under a series of five 1/4-inch cultivator sweeps. The sweeps were mounted to the shanks and closed at the top. A flat plate was welded to the top of the sweep and a steam injector tube was added. The sweep looks like a triangular plate that is pulled through the soil (Figure 5). The sweeps improved the horizontal distribution of steam through the soil profile.

Figure 5. Sweeps (triangular plates) helped the shanks distribute the steam more evenly than when the vertical shanks were used.

Discussion
Steam is a promising technology that has been around a long time. It could be an economical alternative to methyl bromide fumigation. The success of steam treatment depends on how the steam is applied to the soil. Initially, MTDC started off with an undercutter blade that had a hollow bottom. Steam was injected underneath the soil along the back edge of the blade. The undercutter blade was replaced with a series of shanks that injected the steam into the soil every 6 inches across the standard 4 foot seedbed. The steam was injected to a depth of about 7 inches. The last modification reduced the number of shanks from 13 to 5 and added sweeps to apply the steam underneath the soil. This modification improved the temperature distribution in the soil. Additional modifications to the sweeps have been made to improve the mixing of the hot vapor with the soil, increasing temperature uniformity through out the soil profile.

Two areas of concern have surfaced so far. The main concern is the machine's speed. It takes about an hour to treat a 120-foot long, 4-foot wide nursery bed. Another problem is uniformly distributing steam in the soil. Temperatures monitored in the test plots vary from 105 to 160^{o}F across the width of the seedbed. A pasteurization temperature of 140^{o}F degrees is required to kill most pathogens, nematodes, and some weed seeds. Preliminary monitoring of the pathogens *Fusarium* and *Pythium* in the soil show that steam reduces their numbers greatly, but not as much as methyl bromide.

Test Results for 1996: Using Shanks for Steam Injection
In the fall of 1996 the steam treatment machine with the vertical shanks was taken to Forest Service nurseries at Coeur d'Alene, Placerville, and Medford for testing. These test plots were sampled before and after treatment and again in the spring of 1997 for pathogen levels.

Placerville Nursery (Placerville, CA)
September 19 to 20,1996

Ambient Air Temperature	86°F (9/19/96)	83 °F (9/20/96)
Soil Temperature	74 °F at 2 inches and 68 °F at 4 inches (9/19/96); 58 °F	

(9/20/96)

Three 400-foot long, 5-foot wide beds were treated.

Observations:

- Treated soil temperature varied from 102 to 140 °F.
- Experimental small cultivator sweeps were tried to provided more uniform temperature distribution, but they also created more soil disturbance. The sweeps were positioned too close together. The sweeps had a tendency to pull or drag soil along (these small sweeps were not used in the latest modification.)
- The steamer operated 3 hours between water fills.

Macrophomina (chocolate root rot) is a problem at this nursery.

The vertical soil temperature profile after steam treatment is hown in Table 2, and populations of organisms before and after treatment are given in Table 3.

Table 2. Averages for soil temperature measured in September 1996 and analyzed by Jeff Stone, Oregon State University.

Depth (Inches)	Temperature (°F)
2	140
4	135
6	153
8	75
10	68

Table 3. Numbers of soil organisms in September 1996. Soil samples taken and analyzed by Jeff Stone, Oregon State University.

	Before steam treatment	After steam treatment
Pythium	300	200
Fusarium	1700	720
	Before methyl bromide treatment	After methyl bromide treatment
Pythium	480, 480, 380, 380	10, 0, 6, 0
Fusarium	2900,1800,1880, 1500	340, 140,120,0

Macrophomina Results (Reported by Susan Frankel in April 1997)
Two of the samples were tested for Macrophomina. The Macrophomina level was 2.2 sclerotia per gram before steam treatment at one area. The level was 2.1 sclerotia per gram after steam treatment. Steam was not very effective in reducing Macrophomina.

Methyl bromide fumigation reduced levels of Macrophomina from 2.3 sclerotia to 0 at one area and from 90 sclerotia to 0 at another area.

Coeur d'Alene Nursery (Coeur d'Alene, ID)
September 4 to 5,1996

Ambient Air Temperature	70 °F (9/14/96)	54 °F (9/15/96)
Soil Temperature	67 °F (9/14/96)	58 °F (9/15/96)

Five 100-foot long, 5-foot wide beds were treated.

Observations:

- Treated soil temperature varied from 102 to 140 °F.
- Cultivator sweeps provided more uniform temperature distribution, but also created more soil disturbance. Ssweeps were positioned too close together.
- The steamer operated 3 hours between water fills.
- Pathogens of interest were fusarium and pythium.

Populations of both groups of potential pathogens were reduced by the treatment (Table 4).

Averages for Fusarium were reduced from 408 to 287; those for Pythium from 101 to 25. Dazomet fumigation was more effective, reducing both pathogens to zero.

Table 4. Results of steam treatment on five plots at the coeur Nursery Nursery. Soil samples were taken in September 1996.

	Plot				
	1	2	3	4	5
Fusarium					
(before steam treatment)	749	272	408	204	408
(after steam treatment)	0	68	0	887	478
Pythium					
(before steam treatment)	136	75	95	109	88
(after steam treatment)	7	14	14	61	27

J. Herbert Stone Nursery (Medford, OR)
September 23 to 24, 1996

Ambient Air Temperature	65 °F (9/23/96)
Soil Temperature	59 °F
Vapor Temperature	180 °F

Five 100-foot long, 5-foot wide beds were treated.

Observations:

- Treated soil temperatures ranged from 115 to 155 °F. One-half hour later, the soil temperature was still 102 °F at a depth of 5 inches.
- Soil was prepared by spading under a cover crop 2 weeks before treatment. A lot of organic matter collected on the shanks of the steamer, plugging up the injector shanks. The ground was spaded a second time, improving the bed for steaming. The spading appears to be an excellent method to prepare the soil. The soil at this site had a higher moisture content than at the other test sites. More BTU's were required to heat the moist soil, but the soil appeared to hold the heat better.
- The steamer used 25 gallons of diesel fuel in 4 to 5 hours of operation.

· The electric generator used 2 gallons of gasoline in 4 to 5 hours of operation.

· As an additional experiment, the area around the sprinkler pipelines was steamed to kill the growing vegetation. A tractor operated at its lowest forward speed (about 0.5 mph) pulled the steamer over the vegetation. Figure 6 shows the steamer with the steam chamber in operation.

Figure 6. A steam chamber applies steam directly above vegetation, allowing the steamer to kill weeds.

Results from further testing at J. Herbert Stone Another steam treatment was conducted on October 3, 1997 in Field G, Unit 28, Beds D-F from irrigation riser 0.5 to 4.5 (120 feet). An untreated control plot was located in beds D-F from riser 4.5 to 6 (45 feet). The remainder of the unit was treated with Dazomet on October 11. Samples were taken the day after the steam treatment and all plots were sampled again on December 11. The results are shown in Table 5.

Immediately after treatment, steam appeared to reduce the levels of Fusarium as much as the pesticide Dazomet. Samples were taken this spring before sowing to compare the difference in population levels in areas treated with steam and areas treated with Dazomet. The results were not available for this report.

Table 5. Fusarium and Pythium levels before and after October treatment at Stone Nursery.

	Fusarium levels (parts per gram of soil)		
	October 3 (Before treatment)	October 4 (After treatment)	December 11 (Two months after treatment)
Untreated	—	—	16240
Steam treatment	37080	13200	21467
Dazomet	37080	—	13033

	Pythium levels (parts per gram of soil)		
			December 11

	October 3 (Before treatment)	October 4 (After treatments)	(Two months after treatment)
Untreated	—	—	0
Steam treatment	69	73	77
Dazomet	69	—	0

Test results for 1997 using sweeps for steam injection
Coeur d' Alene Test (June 10 to 11th, 1997)

June 10, 1997		June 11, 1997	
Sunny		Cloudy and light showers	
Air temperature	80 to 83 °F	Air temperature	66 to 74 °F
Soil temperature	72 °F at 2 inches	Soil temperature	62 °F at 2 inches
	68 °F at 8 inches		64 °F at 8 inches
Soil moisture content	13.46%	Soil moisture content	13.72%
Ground Speed	1.5 feet per minute	Ground Speed	1.5 feet per minute
Maximum vapor temperature	200 to 210 °F steam for 190 to 160 °F test plots160 °F steam plus outside air for 130 to 150 °F test plots	Maximum vapor temperature	200 to 210 °F steam for 190 to 160 °F test plots 160 °F plus outside air for 130 to 150 °F test plots
	160 °F Reduced steam flow plus maximum plus maximum outside air for 120 °F test plot		160 °F Reduced steam flow plus maximum flow outside 120 °F test plot

Results

Temperature Uniformity

Figure 7 shows the temperature readings across a horizontal soil profile at depths of 1, 4, and 7 inches. These readings were taken 2 minutes after steam treatment. The temperature at 1 inch and near the surface does not reach the desired 140 °F. Figures 8 and 9 show the same profile 20 and 48 minutes after steam application. Once the soil is heated, it holds that heat for long periods of time. Temperature migration toward the surface from the zone of application did not occur to the extent expected.

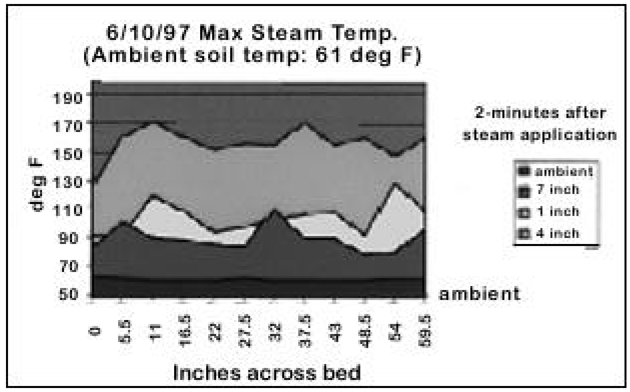

Figure 7. The horizontal temperature profile 2 minutes after steam application (using the sweep injection system).

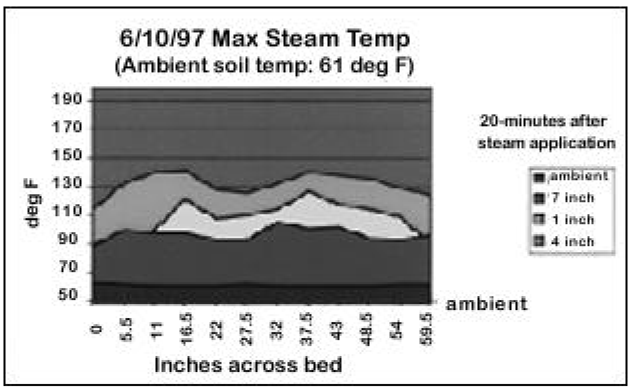

Figure 8. The horizontal temperature profile 20 minutes after steam application (using the sweep injection system).

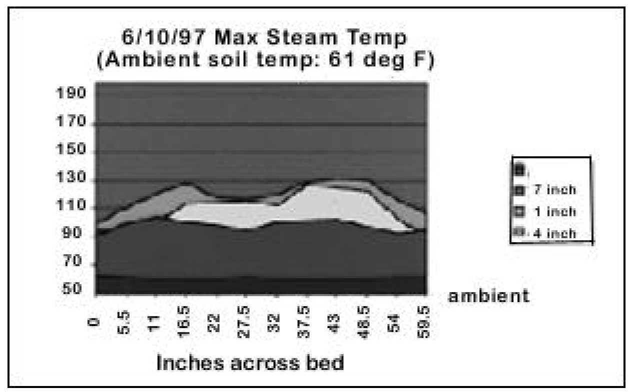

Figure 9. The horizontal temperature profile 48 minutes after steam application (using the sweep injection system).

Figure 10 shows the apparatus used to measure soil temperatures across the seed bed. Figure 11 shows the temperature readings across a vertical profile from the surface to a depth of 8 inches. The time intervals of 2, 20, and 50 minutes after application are shown on the same graph. Figure 12 shows the apparatus used to measure soil temperatures to a depth of 8 inches.

Figure 10. The test apparatus used to measure soil temperatures horizontally acoress the seedbed. The instrument was placed on the soil surface immediately after steam treatment.

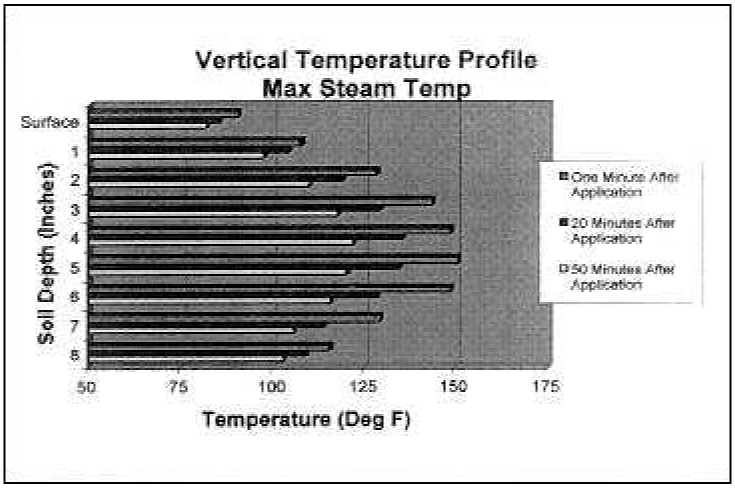

Figure 11. The vertical temperature profile showing soil temperatures at 1-inch intervals (using the sweep injection system).

Figure 12. The thermocouple array used to determine the vertical soil temperature profile. A pit was dug for the instrument immediately after steam treatment.

Treatment Results

Figure 13 compares organism levels in soil samples obtained immediately before steam treatment with levels in samples taken 3 hours after treatment. Organism populations vary throughout the soil. One reason pathogen levels were not reduced or actually increased in some samples may be that the samples were taken from areas that did not reach the desired 140 degrees (see Figure 7). Trichoderma, one of the desirable soil organisms, is an indicator of temperatures desirable soil organisms can tolerate. Figure 13 shows that temperatures of 140 degrees and higher appear to greatly reduce their populations. Soil temperatures are indicated by the numerals in the sample numbers.

Soil Profile Information

Figure 14 shows the organism populations through a vertical profile from the surface to a depth of 7.5 inches. At depths below 6 inches the organism populations are significantly reduced. Figure 15 presents the information graphically.

Figure 13. Microoorganism levels before and after steam treatment for three replications (using the sweep injection system). Soil temperatures are indicated by the digits in the sample numbers.

Coeur d'Alene Nursery Soil Sample Results 6/97

1st Replication

SampleNo.	Fusarium	Pythium	Trichoderma	T/F Ratio
		Before Treatment		
A190B	670	20	4425	6.60
A160B	335	10	3352	10.01
A150B	869	13	5613	6.46
A140B	737	20	4224	5.73
A130B	1075	0	4570	4.25
A120B	601	0	4076	6.78
		After Treatment		
A190A	0	0	0	0.00
A160A	0	0	67	0.00
A150A	335	10	2346	7.00
A140A	0	0	134	0.00
A130A	134	0	1412	10.54
A120A	1403	10	2339	1.67

2nd Replication

SampleNo.	Fusarium	Pythium	Trichoderma	T/F Ratio
		Before Treatment		
B190B	737	30	2414	3.27
B160B	67	10	2479	37.00
B150B	67	0	871	13.00
B140B	268	20	4961	18.51
B130B	67	20	1273	19.00
B120B	67	0	1273	19.00
		After treatment		
B190A	1140	0	3218	2.82
B160A	134	0	134	0.00
B150A	0	0	470	0.00
B140A	67	0	269	4.01
B130A	0	0	67	0.00
B120A	468	0	2740	5.85

3rd Replication

SampleNo.	Fusarium	Pythium	Trichoderma	T/F Ratio
		Before treatment		
C190B	134	10	1608	12.00
C160B	334	0	2138	6.40
C150B	1210	0	1344	1.11
C140B	401	0	2141	5.34
C130B	538	20	2755	5.12
C120B	268	20	1742	6.50
		After treatment		
C190A	0	0	134	0.00
C160A	0	20	201	0.00
C150A	0	0	0	0.00
C140A	67	0	602	8.98
C130A	0	0	1546	0.00
C120A	67	50	2141	31.95

Figure 14. Populations of soil microorganisms at different soil depths before treatment. Few of these microorganisms are found deeper than 6 inches in the soil.

Coeur d'Alene Nursery Soil Profile Sample Results 5/97

1st Replication - Tilled

SampleNo.		Fusarium	Pythium	Trichoderma	T/F Ratio
AP-SUR(5.5)	0'(surface)	870	30	1874	2.15
AP-1.5	1.5'	736	40	1205	1.64
AP-3.0	3.0'	134	10	1336	9.96
AP-4.5	4.5'	134	0	1474	11.00
AP-6.0	6.0'	201	0	1472	7.28
AP-7.5	7.5'	67	0	269	4.01

2nd Replication - Tilled

SampleNo.		Fusarium	Pythium	Trichoderma	T/F Ratio
BP-SUR(5.0)	0'	3360	34	2554	0.76
BP-1.5	1.5'	871	10	1807	2.08
BP-3.0	3.0'	1203	40	2005	1.67
BP4.s	4.5'	941	0	3696	3.93
BP-6.0	6.0'	67	0	2285	31.10
BP-7.5	7.5'	0	0	336	0.00

3rd Replication - Untilled

SampleNo.		Fusarium	Pythium	Trichoderma	T/F Ratio
CP-SUR(5.5)	0'	2613	0	2747	1.05
CP-1.5	1.5'	2078	20	3488	1.68
CP-3.0	3.0'	268	40	2077	7.75
CP-4.5	4.5'	1814	20	3696	2.03
CP-6.0	6.0'	67	0	2138	31.91
CP-7.5	7.5'	0	0	802	0.00

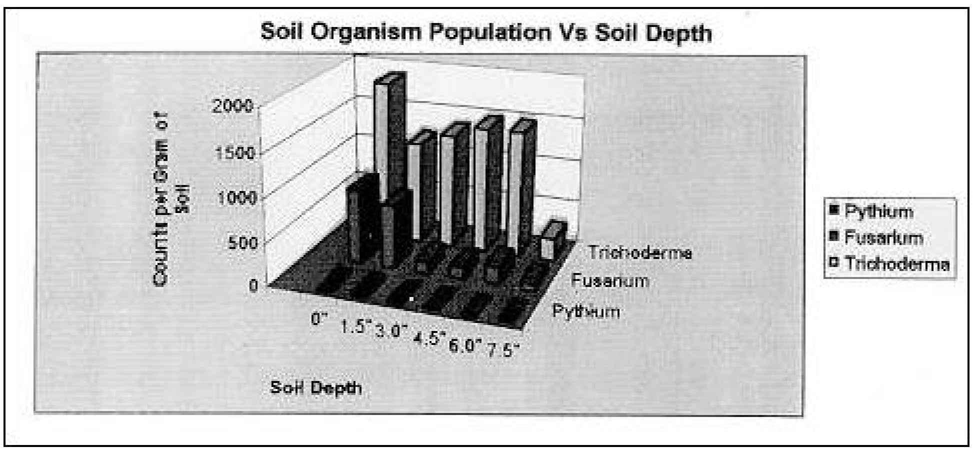

Figure 15. Graphic representation of soil microorganisms found at different soil depths before treatment.

Observations :

- The injector sweeps must be 6 inches or deeper in the soil to prevent excessive steam loss to the surface and for maximum effectiveness in increasing soil temperatures. When the injector sweeps are shallower than 6 inches, steam is lost from the sides, around the shanks. and around the back edge of blade.
- When the injector sweeps are 6 inches deep or deeper, the top 2 inches of soil does not

reach 140 °F for 20 minutes. the temperature needed to kill pathogens.

- It is more efficient to reduce the flow of steam than to increase air flow when reducing vapor temperature.
- Attaching a pulley on the tractor serving as a deadman reduced the winch's line speed by half. With this arrangement, the electric motor operated more efficiently
- The temperature front (the zone where heated soil met unheated soil) did not move much in the soil after the machine had passed. I assume the soil mass kept the temperature front relatively stable.
- Soil temperature was more uniform when the injector sweeps were used than when other systems were used.
- Narrowing the treated path so that the sweeps do not contact the tire path may prevent some steam from being lost out the sides. The tarp should be extended on both sides to help prevent steam loss.
- The PVC pipe used as a spreader bar under the tarp to disperse steam on the surface of the soil was not suitable for high temperatures.
- Two additional design concepts that may improve mixing the steam with the soil more completely are

  1) *Picking up the top 6 inches of soil and moving it through a steam chamber.*

  2) *Agitating the soil while steam is being applied.*

Project Preliminary Observations

- Soil should be heat treated to a depth of 6 inches.
- To reduce the effects on the desirable organisms (*Trichoderma*, etc.) the treatment temperature should be no higher than 140 °F.
- The temperature of all the soil needs to be raised uniformly to the treatment temperature for treatment to be effective.
- Treatment is slow with the prototype experimental machine. A production version would need additional boiler capacity.
- Studies are needed to determine how fast pathogens reinvade the treated area.

Acknowledgments
I wish to acknowledge the personnel at the Forest Service nurseries (Coeur d'Alene Nursery, Coeur d'Alene, ID; J. Herbert Stone Nursery, Medford, OR; Placerville Nursery, Placerville, CA) and the Montana State Nursery, Missoula, MT, for their help in this project. Bob James, Pathologist at the Coeur d'Alene Nursery and his staff analyzed the soil samples and returned the results quickly.

Other Related Work
Robin Rose's Study for the Environmental Protection Agency Robin Rose of the Oregon State University has received a grant from the Environmental Protection Agency to study the different methods of soil sterilization, including steam treatment. He will determine what

effect steam has on weeds and pathogens and their reinvasion after steam treatment. One important item for his experiments is a precise and uniform application of heat.

Test plots will be installed in early September. MTDC will supply the machine for the study.

Jim McDonald's Study at the University of California-Davis

Jim started a study to evaluate using microwaves for soil pasteurization. Recently he has been doing ohmic (resistance) and steam heating of greenhouse soils. He plans to look at the use of longer wavelength radio frequencies for heating, but has not done much work yet.

Aqua Heat

During a phone conversation, Chapman Mayo of AquaHeat, summarized Aqua-Heat's work with hot water to control microorganisms in the soil.

- The special tiller they modified produced uniform temperatures in the soil as the hot water was injected.
- The maximum soil temperature was about 160 °F.
- Treatment depth was about 10 inches. In sandy soil, the temperature gradient would move down below 10 inches after application.
- For weed control, hot water kills the weeds that are easy to kill. Some of the heartier weeds require repeated applications. Speed was critical. Treatment that was too fast produced temperatures that were too low, with poor results.
- No trials were conducted in which crops were raised in treated beds. The nursery where the test plots were installed was closed down after the test.
- The prototype machine was not scaled up, but could be if additional interest is shown.
- Aqua-heat is doing some development that emphasizes combining hot water treatment with friendly, less-toxic chemicals. The company is looking at incorporating a chemical to enhance residue control of Fusarium. Reinvasion of pathogens after treatment was noted after hot water treatment.

---

[1] *Karsky, D. 1997. Nursery Soil Fumigation. In: Landis, T.D.; Thompson, J.R., tech. coords. National Proceedings, Forest and Conservation Nursery Associations. Gen. Tech. Rep. PNW-GTR-419. Portland, OR: U.S. Department of Agriculture, Forest Service, Pacific Northwest Research Station: 98-108.*

[2] *MTDC, USDA Forest Service, Ft. Missoula Bldg. 1, Missoula, MT 59801; Tel: 406/329-3958; Fax: 406/329-3719.*