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# ALTERNATIVES TO CHEMICAL FUMIGATION IN BAREROOT FOREST NURSERIES: EFFECTS ON PATHOGEN LEVELS AND SEEDLING DENSITY, MORTALITY AND QUALITY[1]

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## ABSTRACT

Our objectives were to develop cultural approaches aimed at reducing populations of soil-borne pathogenic fungi in forest nurseries to reduce or replace conventional chemical soil fumigation. One three-year cycle of this study has been completed in seven nurseries in Oregon, California, and Idaho. A second cycle of experiments has been initiated in six nurseries. In the first cycle, non-chemical, cultural methods, including bare fallow, organic soil amendments, seed cover, and time of sowing were compared with methyl bromide (MC-33) or dazomet soil fumigation in reducing preplant pathogen populations. Bare fallow, with or without periodic tilling, was equivalent to chemical fumigation treatments in reducing preplant levels of *Fusarium oxysporum*. Seedling density and mortality varied among several treatments, but at all nurseries combinations of soil amendments and bare fallowing yielded seedling densities and mortalities equivalent or superior to chemically treated plots. Two-year old seedlings were on average larger and had better developed root systems from fumigated plots in some nurseries. In several nurseries, seedlings from non-fumigated bare fallow plots were equivalent in height and root collar diameter to fumigated treatments. Bare fallowing and other management alternatives may help nurseries control seedling disease problems without or with reduced use of soil fumigants.


## INTRODUCTION

Many forest tree nurseries use chemical biocides for soil fumigation treatment prior to sowing. Methyl bromide (67%) with chloropicrin (33%) (MC-33) is one of the most commonly used fumigants, and is generally considered the best for controlling soil-borne diseases, insects, weeds, and nematodes and achieving a uniform, vigorous crop of high-quality conifer seedlings. Dazomet is also used, and its granular form is considered more safe to handle than gaseous methyl bromide mixtures (Landis and Campbell 1991). Because methyl bromide has a high potential to deplete stratospheric ozone, production and importation in the United States will be prohibited after January 1, 2001 (Anonymous 1995; World Meteorological Organization 1995). Since 1994, methyl bromide production in the U.S. has been restricted to 1991 levels. Reliance on any chemical biocide to maintain production is inherently risky over the long term. Such chemicals are likely to become restricted in use due to human or environmental health hazards.

In addition to the health hazards of chemical biocides, fumigation drastically disrupts soil biology, destroying beneficial and detrimental organisms alike (Munnecke and Van Gurdy 1979). Among the first microorganisms to recolonize fumigated soil, either from residual survivors in roots and debris, from blowing dust or from soil fragments on equipment, may be opportunistic pathogens (Vaartaja 1979). Populations of some beneficial microorganisms, including those antagonistic to pathogens, develop slowly, while populations of many opportunistic pathogenic fungi can increase rapidly under favorable conditions (Marx et al. 1989; Stone and Hansen 1994). Opportunistic pathogens such as *Fusarium oxysporum* Schlecht. are relatively common in agricultural soils but infrequent or absent in forest soils (Schisler and Linderman 1984). Absence of *Fusarium* in forest soils may be attributable to microbial antagonists in forest soil communities (Schisler and Linderman 1984). Fumigation can result in a need for continued fumigation due to elimination of beneficial microbial antagonists.

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The cultural cycle employed by many bareroot nurseries, especially those in the Pacific Northwest of the U.S., includes a 2-year production of the main seedling crop followed by a season of cover cropping. The cover crop is usually incorporated as a green soil amendment in late summer. This input of rich organic matter can cause sharp increases in populations of soil fungi such as *F. oxysporum*, which have the capability to grow saprobically and survive at high levels in soil over the winter through formation of chlamydospores (Stone and Hansen 1994). High populations of *F. oxysporum* can be associated with severe disease losses (Stone and Hansen 1994). Many nurseries in the Pacific Northwest correct this problem by fumigating soils in late summer or fall after incorporating cover crops.

Although fumigation may eliminate a number of pest problems simultaneously, alternatives can be developed to address the specific needs at individual nurseries based on their histories of pest problems and cultural practices. Long term reductions in dependence on chemical fumigation relies on development of cultural alternatives that favor microbial antagonists of pathogens and promote diverse soil microbial communities.

A technology development project funded by the USDA Forest Service (Forest Health Protection) entitled "Alternatives to Chemical Fumigation in Bareroot Forest Nurseries" concentrated on management of soil-borne seedling diseases. The goal was to enable nurseries to produce comparable seedling crops without or with reduced use of chemical soil fumigation. Specific objectives were to produce seedling crops having seedbed densities and seedling quality equivalent to those grown with conventional fumigation.

## MATERIALS AND METHODS

Study sites included five USDA Forest Service nurseries: Coeur d'Alene Nusery in Coeur d'Alene, ID; Lucky Peak Nursery near Boise, ID; Placerville Nursery near Placerville, CA; Bend Pine Nursery in Bend, OR; and J. Herbert Stone Nursery near Medford, OR. Treatments employed varied among nurseries according to individual nursery pest problems and management concerns. Presow soil treatments included cover cropping, fallowing, fumigation, and incorporation of soil amendments. Mulch treatments covered seed after sowing. Chemical fumigants used for comprison were those conventional ly used at each nursery. Conifer species tested represented a major crop species produced at each nursery. A single seedlot was sown into all treatment plots within a nursery, except as noted. All study plots were established in spring 1993, prior to soil treatments.

*Measurement of seedling density and mortality*:

For the first growing season, seedling densities (seedlings/m$^2$) were recorded approximately three weeks after emergence, at mid-season and at the end of the first growing season (1-0). Three fixed plots 0.15m x 1.22m, oriented across beds were established in each treatment replicate plot for each nursery. Total numbers of live seedlings, seedlings killed by disease (post-emergence damping-off and root disease), and seedlings killed by other causes were recorded for each fixed plot for each measurement period. Cumulative percent mortality from disease during the first growing season beginning with the emergence count and ending with the last first-season count (1-0) was used for statistical analyses. Final density was taken at the end of the second growing season (2-0) for three randomly located plots as described above in each replicate plot.

*Measurement of seedling quality*:

Seedling shoot length and root collar diameter were recorded for a sample of 50-100 seedlings from each replicate plot in each nursery at the end of both the first and second growing seasons. Measurements were made using the Machine Vision seedling inspection system, a line scanning digitizer image analysis developed by the University of Oklahoma, using the software provided by the manufacturer. Use of the Machine Vision system was kindly provided by the USDA Forest Service J. Herbert Stone Nursery, where it is routinely used for grading seedlings.

*Soil sampling*:

Soil samples were collected for determination of *Fusarium* spp. and *Pythium* spp. levels at three times for each nursery: spring 1993 at the time plots were established after incorporation of soil amendments, fall 1993 at approximately 3 weeks following fumigation treatments, and in spring 1994 immediately prior to sowing. Soil samples were collected in polyethylene bags, transported to the laboratory in coolers, stored at 4°C, and processed within 48 hours of collection. Soil samples were paseed through a 0.6cm screen and 10g (fresh wt) added to flasks containing 10ml of 0.1% water agar. These samples were mixed and serially diluted (1:10, 1:100) in 0.1% water agar for plating. A portion of each soil sample was oven-dried for determination of water content and conversion of propagule counts to a dry weight basis.

Four plates of each sample, 0.5ml diluted soil on each plate, were prepared on a selective medium. Komada's medium (Komada 1975), modified with an amendment of 1g/l LiCl for suppression of *Trichoderma* spp. (Wildman 1991) was used for enumeration of *F. oxysporum*. Dilution plates of Komada's medium were incubated under fluorescent light and read after 6 days. The average number of colonies on four plates multiplied by the dilution factor and soil water conversion factor yielded colony-forming units per gram of oven-dried soil (CFU).

*Statistical analyses*:

Statistical analyses were carried out using SYSTAT (SYSTAT 1992) or SAS software (SAS 1992). ANOVA tests with Tukey's or Scheffe's multiple comparison procedures were used for comparisons of seedling quality factors among treatments at each nursery. Seedling density and mortality data were logit transformed (Sabin and Stafford 1990) and analyzed using ANOVA. Mean CFU for each replicate plot were analyzed using the Kruskal-Wallis procedure and the Mann-Whitney U statistic for comparisons between treatments.

*Study sites*:

*Bend Pine Nursery*:

The entire study block at this nursery received 200 cu yd/A aged sawdust with 300 lb/A of 34-0-0 nitrogen. Treatments included 3 bare fallow and 2 with pea cover crops sown in May, 1993. One bare fallow treatment had tilling at 3-week intervals, and the other two had no tilling. One bare fallow without tilling treatments had a mulch of pine needles (pine mulch) collected locally the previous fall and applied after sowing to cover seed. The treatment representing standard nursery practice was fumigation with MC-33 in September, 1993, at approximately 392kg/ha, after incorporation of the pea cover crop. The same cover crop treatment without fumigation provided a comparison. Seedbeds were formed and ponderosa pine (*Pinus ponderosa* Laws.) sown in late April, 1994. The study area was a block 122m x 15m, divided into 32 plots. Five replicates of each of five treatments were randomly assigned to plots, leaving seven unused plots.

*J. Herbert Stone Nursery*:

All treatments included bare fallow, four with tilling at 3-week intervals, and one without tilling. Sawdust was incorporated as a soil amendment in May, 1993 for four treatments. Supplemental nitrogen was included with the sawdust in three treatments (SD+N). In the fourth sawdust treatment, extra nitrogen was provided only after seedling emergence (SD delayed N). The treatment representing standard nursery practice was sawdust with nitrogen, periodic tilling, and fumigation with dazomet in September, 1993, at approximately 392kg/ha. Seedbeds were formed with Douglas-fir (*Pseudotsuga menziesii* Franco) and ponderosa pine sown in late April, 1994. The study area was 213m x 17m, divided into 27 plots. Five replicates of each of 5 treatments were randomly assigned to plots, leaving two unused plots. Each plot consisted of one bed of ponderosa pine and one of Douglas-fir.

*Coeur d'Alene Nursery*:

All treatments included bare fallow with tilling. Fields were kept weed free by periodic tilling for 1 year prior to sowing. Two soil organic amendment treatments were incorporated in late June, 1993. These were composted bark chips (bark compost) and sewage sludge, a composted mixture of sludge with wood waste (results not discussed in this paper). The "pine mulch" treatment was a layer of pine needles (collected locally the previous fall) applied after sowing to cover seed. The fumigation treatment was dazomet applied at approximately 392kg/ha, water sealed and rolled in late September, 1993. Seedbeds were formed and Douglas-fir (*P. menziesii* var. *glauca* [Beissn.] Franco) sown in early May, 1994. The study area was 122m x 7m, divided into 32 plots. Five replicates of five treatments were randomly assigned to plots, with seven plots unused.

*Lucky Peak Nursery*:

All treatments were kept bare fallow for 1 year before sowing, four without tilling and one with tilling at 1-month intervals between mid-June and late September 1993. Two soil amendments were incorporated in early June, 1993. These were mushroom compost (m compost), waste composted material used in the commercial production of mushrooms, and commercial sawdust containing supplemental nitrogen (SD+N). The standard nursery fumigation treatment was MC-33 applied at approximately 392kg/ha in September. Two study areas were established in different fields, each 106m x 9m. Each study area was divided into 35 plots; five treatments randomly assigned to the plots, leaving 10 plots unused. One study area was sown with a single seedlot of ponderosa pine and the other with three different seedlings of lodgepole pine (*Pinus contor-*

*ta* Dougl.). The seedbeds were formed and sown in late May, 1994.

*Placerville Nursery*:

All treatments began with bare fallow and tilling every few weeks, followed by an over-winter soil covering of rice straw, sawdust, pine needles, dry hydromulch, or nothing (bare soil). Shasta red fir (*Abies magnifica* A. Murr. var. *shastensis* Lemm.) seed was sown in March (early) or mid-April (late), and covered with soil, hydromulch, or sawdust. The nursery had no fumigation treatment. The study site was made up of 4 blocks, each 64m x 3m; each block was divided into seven plots, with seven treatments randomly assigned within each block.

## RESULTS

*Bend Pine Nursery*:

At the Bend Pine Nursery, mean seedling bed density was equivalent among the fumigated and three bare fallow treatments, and mean seedling mortality was not significantly different ($P=0.05$) among these four treatments (Table 1). Methyl bromide fumigation reduced preplant *Fusarium* populations, but not to below detectable limits. Mean presow *Fusarium* levels for the three bare fallow treatments were not statistically different from the fumigated treatment. Presow *Fusarium* populations were much greater in the pea cover crop without fumigation, and seedling mortality was correspondingly much greater (Table 1).

Seedling quality was similarly comparable for the three bare fallow and fumigation treatments; mean 2-0 ponderosa pine seedling shoot height was significantly greater in the fumigation treatment and similar in all other treatments. All treatments resulted in seedlings with mean heights well within the acceptable standards of 10-40cm for 2-0 ponderosa pine (Table 1). Mean root collar diameter measurements for all treatments were also well above the minimum acceptable 4mm. Seedlings from the bare fallow treatments had similar mean calipers; those from the methyl bromide fumigation were significantly larger. Mean caliper of seedlings from pea cover crop without fumigation was much greater, the result of very low bed densities (one-third that of the other treatments), with the same amount of seed and fertilizer as the other treatments. Cost of seed and fertilizer for seedlings grown under this regime would be three times that of seedlings grown under the other treatments.

*J. Herbert Stone Nursery*:

At J. Herbert Stone Nursery, dazomet fumigation reduced presow *Fusarium* levels, but not to below detectable levels. *Fusarium* populations were significantly greater only in the one treatment without tilling, which had excessive weed growth. The weeds were mainly *Portulaca oleraca* L. that resulted in increased *Fusarium* populations in much the same way as a cover crop. Although mean bed densities for this treatment were lower than other treatments for both ponderosa pine and Douglas-fir, these effects were significant at $P<0.05$ only for Douglas-fir and only between the no till treatment and the tilling with sawdust and delayed N fertilization (Table 2). Mortality was relatively low for this treatment in ponderosa pine (Table 3); however this may reflect the difficulty of detecting seedlings emerging in plots with dense weed cover. Although mean seedling mortality for Douglas-fir was not significantly different among treatments (Table 2), mortality may have been underestimated in the no till treatment due to weed cover.

Ponderosa pine seedlings averaged somewhat smaller for the no till treatment (root collar diameter different at $P<0.06$), but still within acceptable limits for all treatments (Table 3). Mean Douglas-fir seedling height was within acceptable limits for wet site 2-0 Douglas-fir, 20-50cm, except in the no till treatment. Differences among treatments were statistically significant only between the no till treatment and dazomet fumigation and tilling without sawdust treatment. Mean Douglas-fir caliper was well above the acceptable minimum of 4mm for all treatments (Table 2). Smaller, less vigorous seedlings in the no till treatment as compared to other treatments was probably related to the weed infestation and may reflect combined competition with weeds and injurious but non-lethal root colonization by *Fusarium* or other pathogens.

Table 1. Effects of selected soil treatments on ponderosa pine seedling density, morphology, mortality and *Fusarium* populations aat the Bend Pine Nursery, Oregon.[1]

| Treatment[2] | Density[2] | Diameter (mm) | Height (mm) | Mortality[4] | Initial Fusarium[5] | Pre-sow Fusarium[5] |
|---|---|---|---|---|---|---|
| Peas, MC-33 | 226a | 6.8b | 25.4a | 5.5a | 31948 | 170a |
| Fallow, till | 237a | 6.2a | 19.1b | 11.4a | 9583 | 618a |
| Fallow | 226a | 6.1a | 20.4b | 9.3a | 2333594 | 948a |
| Pine mulch | 226a | 5.8 | 15.9b | na | 4530 | 219a |
| Peas, No fum. | 75b | 8.5 | 19.6 | 39.1b | 4088 | 3711b |

[1] Within each column, means followed by the same letter are not significantly different (P=0.05) using Tukey's multiple comparison procedure

[2] Sawdust with nitrogen was incorporated into all plots at the beginning of treatment.

[3] Number of 2-0 seedlings/m².

[4] Percent of seedlings killed by disease during the first growing season.

[5] CFU per gram dry weight of soil

[6] Pine needle mulch prevented accurate emergence counts.

Table 2. Effects of selected soil treatments on Douglas-fir seedling density, morphology, mortality and *Fusarium* populations at the J. Herbert Stone Nursery, Medford, OR[1]

| Treatment[2] | Density[2] | Diameter (mm) | Height (mm) | Mortality[4] | Initial Fusarium[5] | Pre-sow Fusarium[5] |
|---|---|---|---|---|---|---|
| Till, S+N, Fum. | 210ab | 7.4ab | 29.2a | 9.9 | 1157 | 135a |
| Fallow, S+N | 182ab | 6.5a | 21.8ab | 13.1 | 506 | 2194a |
| No till, S+N | 160a | 6.6ab | 17.8b | 15.7 | 1193 | 3469b |
| Till, no S | 206ab | 8.0b | 29.6a | 11.7 | 415 | 1106a |
| Till, S+del.N | 256b | 6.9ab | 27.4ab | 9.8 | 516 | 808a |

[1] Within each column, means followed by the same letter are not significantly different (P=0.05) using Tukey's multiple comparison procedure.

[2] All treatments were bare fallow; fumigation was with dazomet; treatment 5 had delayed application of nitrogen.

[3] Number of 2-0 seedlings/m².

[4] Percent of seedlings killed by disease during the first growing season.

[5] CFU per gram dry weight of soil.

Table 3. Effects of selected soil treatments on ponderosa pine seedling density, morphology, mortality and *Fusarium* populations at the J. Herbert Stone Nursery, Medford, OR[1]

| Treatment[2] | Density[3] | Diameter (mm) | Height (mm) | Mortality[4] | Initial Fusarium[5] | Pre-sow Fusarium[5] |
|---|---|---|---|---|---|---|
| Till, SD+N, Fum. | 214 | 8.5 | 31.5a | 9.1 | 1157 | 135a |
| Till, SD+N | 230 | 8.8 | 31.0a | 2.7 | 506 | 2194a |
| No till, SD+N | 180 | 7.8 | 22.6b | 3.3 | 1193 | 3469b |
| Till, no S | 225 | 8.8 | 31.7a | 6.5 | 415 | 1106a |
| Till, S+del.N | 250 | 8.1 | 29.8a | 6.0 | 516 | 808a |

[1] Within each column, means followed by the same letter are not significantly different (P=0.05) using Tukey's multiple comparison procedure.
[2] All treatments were bare fallow; fumigation was with dazomet; treatment 5 had delayed application of nitrogen.
[3] Number of 2-0 seedlings/m².
[4] Percent of seedlings killed by disease during the first growing season.
[5] CFU per gram dry weight of soil.

*Coeur d'Alene Nursery*:

At Coeur d'Alene Nursery, dazomet fumigation reduced *Fusarium* populations but not to below detectable levels. Mean presow *Fusarium* levels were significantly greater in the sewage sludge compost treatment than for the fumigation, sawdust compost and no amendment treatments, but not significantly different from the pine mulch treatment. Mean seedbed densities were not significantly different among the different treatments, despite high first-year mortality in all treatments (Table 4).

For dry-site 2-0 Douglas-fir, the minimum acceptable seedling height is 15 cm and 5 mm caliper; average seedling dimensions from all treatments were within these parameters. Mean seedling height differed significantly only between seedlings grown in the dazomet fumigation treatment and sawdust compost treatment. Mean caliper did not differ significantly among treatments (Table 4).

*Lucky Peak Nursery*:

At Lucky Peak Nursery, methyl bromide fumigation reduced *Fusarium* levels compared to the other treatments, but not to below detectable levels. Both study sites had comparatively low initial *Fusarium*; levels in the mushroom compost treatment increased slightly in the ponderosa pine field, and somewhat more in the lodgepole pine field (Tables 5 and 6). Mean seedling mortality for ponderosa pine was lowest in the methyl bromide fumigated treatment and highest in the bare fallow without tilling or soil amendment, but the only significant differences among treatment means were between fumigated and bare fallow without tilling. Mean seedling mortality in the sawdust plus N amendment was comparable to that for the methyl bromide fumigation. Mean seedling density was lowest for the bare fallow without tilling; however, this difference was significant only at the $P<0.1$ level (Table 5).

Mean ponderosa pine seedling heights were well within acceptable limits of 10-40cm for 2-0 stock for all treatments. Mean heights were similar in the bare fallow alone and fumigation treatments, and these were significantly greater than either soil amendment treatment. Mean caliper was well above the minimum 4mm for all treatments, and showed a similar pattern to height with respect to treatment effects (Table 5). Although seedlings in the bare fallow alone treatment had larger mean caliper and height compared to other treatments, these seedlings also had lower mean bed densities and the greater size may reflect lower densities.

Table 4. Effects of selected soil treatments on Douglas-fir seedling density, morphology, mortality and *Fusarium* populations at the Coeur d'Alene Nursery, ID[1]

| Treatment[2] | Density[3] | Diameter (mm) | Height (mm) | Mortality[4] | Initial Fusarium[5] | Pre-sow Fusarium[5] |
|---|---|---|---|---|---|---|
| Dazomet | 315 | 6.0 | 24.1a | 64.0 | 350 | 73a |
| Sawdust comp. | 297 | 5.0 | 16.1b | 61.9 | 333 | 217a |
| Bare fallow | 285 | 6.0 | 20.0a | 53.2 | 266 | 172a |
| Pine mulch | 290 | 6.0 | 20.0a | na[6] | 577 | 1329ab |
| Sludge comp. | 296 | na[7] | na[7] | 53.6 | 679 | 2180b |

[1] Within each column, means followed by the same letter are not significantly different (P=0.05) using Tukey's multiple comparison procedure.

[2] All treatments included bare fallow with tilling; sawdust and sludge organic amendments were composted prior to incorporation.

[3] Number of 2-0 seedlings/$m^2$.

[4] Percent of seedlings emerged that were no longer present in plots at the end of the first growing season; not all mortality likely due to disease.

[5] CFU per gram dry weight of soil.

[6] Pine needle mulch prevented accurate emergence counts.

[7] Data not available.

Table 5. Effects of selected soil treatments on ponderosa pine seedling density, morphology, mortality and *Fusarium* populations at the Lucky Peak Nursery, Boise,ID[1]

| Treatment[2] | Density[3] | Diameter (mm) | Height (mm) | Mortality[4] | Initial Fusarium[5] | Pre-sow Fusarium[5] |
|---|---|---|---|---|---|---|
| Fallow, till | 229 | 6.5b | 25.4b | 13.9ab | 448 | 496 |
| Fallow | 191 | 7.0b | 27.0b | 17.1b | 81 | 241 |
| Fallow, comp. | 205 | 6.0a | 20.5a | 11.3ab | 123 | 227 |
| Fallow, sawdust | 249 | 6.0b | 22.5a | 7.9ab | 310 | 214 |
| Fallow, MC-33 | 229 | 6.6b | 27.1b | 3.7a | 96 | 80 |

[1] Within each column, means followed by the same letter are not significantly different (P=0.05) using Tukey's multiple comparison procedure.

[2] Sawdust with nitrogen was incorporated in all plots at the beginning of treatment.

[3] Number of 2-0 seedlings/$m^2$.

[4] Percent of seedlings killed by disease during the first growing season.

[5] CFU per gram dry weight of soil.

Table 6. Effects of selected soil treatments on lodgepole pine seedling density, morphology, mortality and *Fusarium* populations at the Lucky Peak Nursery, Boise, ID[1]

| Treatment[2] | Density[3] | Diameter (mm) | Height (mm) | Mortality[4] | Initial Fusarium[5] | Pre-sow Fusarium[5] |
|---|---|---|---|---|---|---|
| Fallow, till | 182a | 4.7 | 15.8ab | 18.3ab | 189 | 456 |
| Fallow | 220a | 4.5 | 16.4ab | 16.0ab | 468 | 510 |
| Fallow, comp. | 150a | 4.4 | 13.4b | 29.7b | 28 | 655 |
| Fallow, sawdust | 178a | 4.6 | 15.9ab | 21.0ab | 151 | 1020 |
| Fallow, MC-33 | 217b | 4.8 | 18.9ab | 11.0a | 84 | 108 |

[1] Within each column, means followed by the same letter are not significantly different (P=0.05) using Tukey's multiple comparison procedure

[2] Sawdust with nitrogen was incorporated in all plots at the beginning of treatment

[3] Number of 1-0 seedlings/m²

[4] Percent of seedlings killed by disease in the first growing season.

[5] CFU per gram dry weight of soil

Seedling mortality for lodgepole pine was significantly greater in the mushroom compost treatment compared to the fumigation treatment. These two means were significantly different at $P<0.05$. Seedling mortality in the other bare fallow treatments were not statistically different from the fumigation treatment. Mean seedling densities were similar for fumigation and bare fallow alone, and these two treatment means were significantly different from bare fallow with tilling and both bare fallow treatments amended with either sawdust or mushroom compost (Table 6).

*Placerville Nursery*:

At Placerville Nursery, *Fusarium* levels increased in all treatments between the initial sampling and sowing. Seedling mortality, however, was high only for the treatment with late sowing and soil covering of seed. Seedling densities were correspondingly low for this treatment compared to all others (Table 7). Surviving seedlings from this treatment were more vigorous than seedlings from the other treatments and mean caliper and height were significantly greater than the other treatments (Table 7). All other treatments had similar mean bed densities, caliper, and height. All treatments resulted in mean caliper exceeding the 4 mm minimum and mean heights exceeding the 8cm minimum.

## DISCUSSION

Seedling root collar diameter is the most important measure of seedling quality specified by reforestation customers. Seedbed density determines the cost per unit area of growing space. These two measures of seedling quality should, therefore, provide a suitable basis for comparison of seedlings produced under non-fumigation alternatives with standard fumigation. In experiments at nurseries comparing the effects of chemical soil fumigation before sowing with non-fumigation management alternatives, seedling densities and caliper were comparable for fumigated and non-fumigated treatments after two growing seasons. Similar results have been previously reported (Hildebrand et al. 1995; Stone and Hansen 1994). Seedbed density reflects a combination of factors including seed quality, sowing density, first-year losses due to disease, and non-disease mortality. In this study, mortality losses due to post-emergence disease were determined separately, but pre-emergence losses were not determined. Final seedbed densities, therefore, reflect a combination of undetermined pre-emergence mortality, post-emergence mortality, and other incidental losses.

For some nurseries, conventional practices may make use of chemical fumigation necessary. Of the nurseries participating in this study, only Bend Pine Nursery routinely uses inter-rotational cover crops and methyl bromide (MC-33) fumigation. Incorporation of the cover crop as a green soil amendment at the end of the growing season results in increased levels of soil *Fusarium* spp. as well as *Pythium* spp. and leads in turn to high levels of first-year seedling mortality unless corrected by preplant fumigation (Hansen et al., 1990; Stone and Hansen 1994). Our results indicated that bare fallowing may eliminate the need for routine fumigation in some nurseries.

Table 7. Effects of selected soil treatments sowing date, and seed covering on Shasta red fir seedling density, morphology, mortality and *Fusarium* populations at the Placerville Nursery, CA[1]

| Treatment[2] | Density[3] | Diameter (mm) | Height (mm) | Mortality[4] | Initial Fusarium[5] | Pre-sow Fusarium[5] |
|---|---|---|---|---|---|---|
| S-BS-late | 199a | 5.1a | 16.5a | 41.4a | 3386 | 5285 |
| S-H-early | 322b | 5.0ab | 15.6ab | 12.2b | 1050 | 4460 |
| SA-H-early | 288b | 4.6b | 14.4b | 14.9b | 874 | 3821 |
| SA-SA-early | 299b | 4.8ab | 15.5ab | 14.8b | 872 | 3244 |
| NE-H-early | 284b | 5.0ab | 15.4ab | 10.5b | 1004 | 4708 |
| H-H-early | 279b | 4.9ab | 15.7ab | 13.1b | 1680 | 5406 |
| BS-H-early | 259b | 4.6b | 14.4b | 15.7b | 966 | 3233 |

[1] Within each column, means followed by the same letter are not significantly different (P=0.05) using Tukey's multiple comparison procedure.

[2] Sawdust and nitrogen was incorporated in all plots at the beginning of treatments. The first letter(s) refer to pre-sowing treatment, the second to seed covering, and the "early" or "late" refer to time of sowing (see text). S=straw; BS=bare soil; H=hydromulch; SA=sawdust NE=pine needles

[3] Number of 2-0 seedlings per/m².

[4] Percent of seedlings killed by disease during the first growing season.

[5] CFU per gram dry weight of soil.

Populations of soil-borne *F. oxysporum*, a pathogenic fungus responsible for damping-off, hypocotyl rot, and root disease losses of conifer seedlings in the Pacific Northwest (Cordell et al., 1989), are not always reliable indicators of disease potential. Strains of *F. oxysporum* differ in virulence; some strains cause different diseases and certain strains may be nonpathogenic (Bloomberg 1981; Bloomberg and Lock 1972; James 1996; James et al., 1991). Species of *Fusarium* other than *F. oxysporum* can also be responsible for conifer seedling diseases (James et al., 1991; Ocamb and Juzwik 1995). Estimates of *F. oxysporum* in soil were used in this study as a basis for comparing effectiveness of different soil treatments in reducing levels of a soilborne pathogen that is commonly controlled by soil fumigation. Presow levels of soilborne *Fusarium* remained near intitial levels in the bare fallow treatments and were statistically equivalent to levels in fumigated plots. Fumigation was equivalent to bare fallow with or without tilling with respect to seedling bed densities, mortality, and seedling quality at Bend Pine Nursery.

Similar results were obtained in nurseries that do not routinely use cover crops. Dazomet fumiation at the J. Herbert Stone Nursery had no significant beneficial effect on seedling height, caliper, density or mortality for either Douglas-fir or ponderosa pine compared to bare fallow with tilling. The importance of weed control, and the interactions between weed infestation, soil-borne pathogens, and seedling quality were demonstrated in the study at this nursery. High levels of weeds and soil-borne *Fusarium* in one treatment, bare fallow without tilling, were related to significantly higher seedling mortality, reduced bed densities and less vigorous seedlings. Other bare fallow treatments with periodic tilling did not have such serious weed infestation, and seedling densities and quality factors in non fumigated treatments were equivalent to those in the fumigated treatment. Other than a slight difference in seedling height, no beneficial effect from dazomet fumigation was apparent in Douglas-fir seedlings at the Coeur d'Alene Nursery. Similarly, MC-33 fumigation at the Lucky Peak Nursery did not effectively diminish levels of soil-borne *Fusarium* at pre-sow, and seedling densities, mortality, and quality factors were comparable among different bare fallow treatments and fumigation. Placerville Nursery has not been fumigated in recent years because of regulations affecting pesticide use in federal nurseries in the Pacific Southwest Region. Earlier sowing in March and non-soil seed cover reduced first-year mortality compared to the conventional mid- to late April sowing with a soil seed cover.

Nurseries that routinely fumigate prior to planting do so for several reasons. These include control of pests, i.e., pathogenic fungi, weeds, insects, and nematodes, as well as for obtaining vigorous, uniform seedlings. Soil fumigation is a convenient and reliable management tool, since it often effectively eliminates several pest problems simultaneously. The most basic principle of disease managment is to reduce the source of the pest problem, and this often can be achieved by means other than fumigation. Sutherland and Sluggett (1974) found that numbers of the pathogenic nematode *Xiphinema bakeri* Williams declined in bare fallowed nursery soil, particularly if the soil was frequently cultivated during hot, dry weather. Similar declines in pathogenic fungi were also observed from this treatment that were sufficient to eliminate the need for preplant fumigation in bareroot nurseries in British Columbia (Sutherland, personal communication). Hansen et al. (1990) reported that more packable seedlings were produced in a bare root nursery from a bare fallow treatment than from treatments employing cover crops, whether these were fumigated or not, and despite relatively high incidence of *Fusarium* hypocotyl rot.

Chemical fumigation achieves pest elimination through broad spectrum biocidal activity which removes beneficial as well as harmful organisms. For nurseries that routinely include an inter-rotational fallow year in their production cycle, bare fallowing may be a suitable management alternative for reducing pathogen populations; periodic tilling may further suppress pathogen and weed infestation. Our results suggest that additional fumigation in combination with bare fallow with tilling provides slight, if any, benefit.

Growers who routinely fumigate have fine-tuned watering, fertilizing, and other cultural practices within a fumigated soil system. Seedlings grown under alternative systems may be less uniform than those grown in soil fumigated with methyl bromide/ chloropicrin or other chemical fumigants. Cultural modifications, however, should enable fine tuning of watering, fertilization, and other cultural inputs aimed at improving seeding performance in the absence of fumigation. Modification of cultural practices that can also help reduce or eliminate the need for soil fumigation and other chemical pest control. Our results showed that bare fallowing and other non-fumigation approaches achieved comparable conifer seedling densities, heights, and calipers. Cultural modification such as time of sowing and use of non-soil seed covering can also reduce disease by presenting physical and temporal barriers to infection. Incorporation of slowly decomposing organic soil amendments may encourage increased populations of beneficial microorganisms.

Nurseries have the capability to implement these measures immediately and at reduced cost compared to routine chemical fumigation. Additional disease prevention measures, such as biological control seed treatments can be expected to further reduce disease incidence and severity, in combination with other disease and pest control measures.

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