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Alternatives to Preplant Soil Fumigation for Western Forest Nurseries

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Abstract

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Field trials at six bare-root forest tree nurseries in the Western United States compared cultural treatments including timing and depth of sowing; bare fallow (with and without periodic tilling); organic amendments including sawdust, composts, and cover crops; mulches including pine needles, sawdust, and rice straw; and fumigation with methyl bromide/chloropicrin or dazomet. Measured effects included population levels of potential soil-borne pathogens (species of *Fusarium* and *Pythium*), disease incidence, seedbed density, and sizes of conifer seedlings. Several nonfumigation treatments resulted in production of seedlings with densities and sizes similar to or better than those produced in beds treated with chemical fumigation. Results varied within the nurseries depending on conifer species, field history, and disease presence. Beneficial cultural practices included (1) incorporation of slowly decomposing organic soil amendments, e.g., aged sawdust with additional nitrogen provided later to seedlings; (2) bare fallowing with periodic tilling, and bare fallowing without periodic tilling plus supplemental weed control; and (3) sowing of conifer seed earlier and more shallow than sown conventionally, and covering seed with a nonsoil mulch such as aged sawdust or hydromulch.

Keywords: Methyl bromide, chloropicrin, dazomet, conifer seedlings, bare fallowing, *Fusarium, Pythium.*

Contents

Introduction

Many forest tree nurseries use soil fumigation prior to sowing to reduce populations of pathogenic fungi, insects, nematodes, and weeds. Methyl bromide with chloropicrin formulations are among the most commonly used fumigants (Smith and Fraedrich 1993), and are generally considered the best for achieving a uniform, vigorous crop of quality seedlings (Cordell 1983). Where soil-borne fungal pathogens are important, the fumigant formulation with 67 percent methyl bromide and 33 percent chloropicrin (MBC) is preferred (Cordell et al. 1989). Control of soil-borne diseases and weeds is the main reason nursery managers use soil fumigation (Boyd 1971). In some cases, nursery managers use fumigants to protect their crops from catastrophic diseases that do not occur every year, such as charcoal root rot, caused by *Macrophomina phaseolina* (Tassi) Goidanich (Frankel et al. 1999). Growing seedlings without fumigation is considered to increase the risk of crop failure. Dazomet is an alternative fumigant, and its granular form may be easier and safer to handle than gaseous formulations containing methyl bromide (James and Beall 1999, Kelpsas and Campbell 1994).

Chemical fumigation is expensive (costing approximately $1,500 per acre) and may be hazardous to human and environmental health. Methyl bromide is thought to have a high potential to deplete stratospheric ozone and is scheduled to be phased out for soil fumigation in the United States after January 2005 (USDA 1999). The amount of methyl bromide available for soil fumigation on January 1, 2001, was 50 percent of the 1991 production level (USDA 2000). Reliance on chemical biocides for production of forest seedlings is inherently risky over the long term because such chemicals may become restricted owing to environmental concerns (Smith and Fraedrich 1993).

Fumigation disrupts soil microbiota, eliminating both beneficial and detrimental organisms (Munnecke and Van Gundy 1979). Opportunistic pathogens, including *Fusarium* spp., may be among the first micro-organisms to recolonize fumigated soil, from residual survivors in roots and debris, or air-borne soil, or soil fragments on equipment (Vaartaja 1967). Although *Trichoderma* spp. tend to quickly reinvade (Danielson and Davey 1969, Gandy and Chanter 1976, Vaartaja 1967), populations of beneficial micro-organisms, including those antagonistic to pathogens, may develop more slowly. Ectomycorrhizal fungi can recolonize soil within the first growing season. Tanaka et al. (1986) found that mycorrhizal development in 1+0 and 2+0 Douglas-fir (*Pseudotsuga menziesii* (Mirb.) Franco) was not affected by preplant soil fumigation with MBC when compared to nonfumigated soil. *Fusarium* spp. have been detected on conifer seed, and this source may contribute to reinfestation of fumigated soil (Axelrood et al. 1995). Populations of many opportunistic pathogenic fungi can increase rapidly under favorable conditions (Hansen et al. 1990), which may include the absence of natural competitors or antagonists owing to fumigation. Hence, disruption of microbial communities owing to fumigation may result in the need for continued fumigation for disease control. On the other hand, fumigation also can produce microbial and nutrient conditions beneficial for seedling growth (Danielson and Davey 1969).

Expression of seedling diseases involves interactions among the host, pathogen, and the environment. Likelihood of infection depends on the susceptibility of the host, the population level of pathogen (inoculum) present, and the virulence of the pathogen. Environmental conditions affect susceptibility of the host to infection, disease expression, and vigor of the pathogen. Even after the pathogen infects host tissue, disease expression may be delayed or reduced if environmental conditions are not favorable for disease development. A delay between initial infection and the expression of disease symptoms (incubation period) often occurs. For *Fusarium* root disease, infection often takes place quite early, soon after seed germination (Hamm 1990, James et al. 1991). For seedlings that do not succumb early to damping-off, the root disease is expressed later, usually by midsummer, when temperatures and moisture stress begin to adversely affect the host (Hamm 1990). Disease can be avoided by preventing or reducing infection, or by preventing or reducing disease expression. The goal of disease control is to suppress activity by pathogens and favor conditions for optimum host vitality by manipulating the seedling environment.

The most effective means of disease control is to prevent infection, which can be done by reducing pathogen populations or by providing physical or temporal barriers to infection. Preplant chemical fumigation reduces pathogen populations by killing pathogenic organisms. An alternative approach is to reduce pathogen populations by removing the available food base and encouraging competitive saprobes. Many pathogenic fungi, including *Fusarium* spp., can function as facultative saprobes, enabling them to persist in soil on organic residues when living hosts are not available. "Green manures" from cover crops incorporated into soil tend to stimulate increases in populations of these facultatively saprobic pathogens because they flourish on the abundant simple organic substrates available in crop residues (Hansen et al. 1990, James et al. 1996, Stone and Hansen 1994). Weeds and weed residues also can provide nutritional resources for facultative saprobes. Few facultative saprobes, however, are able to grow on more complex organic polymers, e.g., cellulose and lignin. One approach to disease control, therefore, is to eliminate cover crops, maintain weed control, and supplement soils with sawdust or other complex organic substrates to favor soil saprobes over pathogens and help improve soil tilth.

Differences among nurseries in local climate, topography, soil characteristics, crop species, disease and other pest problems, and management history can influence disease management, making it difficult to implement a single disease management strategy that would be effective for several nurseries. The objective of our multiyear effort was to compare the efficacy of alternative disease management strategies designed for six bare-root nurseries, with the standard fumigation procedures used by the nurseries, as measured by seedling size and density and populations of soil-borne pathogens. Our goal was to develop alternatives to fumigation specific to the particular conditions, needs, and practices at each nursery that would reduce pathogen populations or limit disease and produce operational quantities of high-quality forest tree seedlings. Portions of these results were reported earlier (Hildebrand et al. 1995, Stone et al. 1997). Previously reported results were based on preliminary statistical analyses, and some statistical significance reported here may differ.

Materials and Methods

Field trials were conducted at six U.S. Department of Agriculture, Forest Service nurseries: Bend Pine Nursery in Bend, Oregon; J. Herbert Stone Nursery in Central Point, Oregon; Coeur d'Alene Nursery in Coeur d'Alene, Idaho; Lucky Peak Nursery near Boise, Idaho; Humboldt Nursery near McKinleyville, California; and Placerville Nursery near Camino, California. Study plots were set up generally in randomized complete block designs or complete randomized designs in production beds, with four or five replicates per treatment. Replicate treatment plots were at least 50 ft (15 m) long, with at least a 20-ft (6.1-m) buffer between plots. Treatments differed among nurseries according to individual nursery pest problems, soil conditions, and management concerns. Preplant soil treatments included cover cropping, bare fallowing, chemical fumigation, incorporation of organic soil amendments, and timing and depth of sowing.

Chemical fumigants used for comparison were those conventionally used at each nursery at the application rate and timing routinely employed. Methyl bromide fumigant was MBC (67 percent methyl bromide and 33 percent chloropicrin) (MC-33, Terr-O-Gas®, Great Lakes Chemical, West Lafayette, IN).[1] The MBC was injected into soil, and the soil was covered by polyethylene sheeting for several days. Dazomet fumigant was granular Basamid® (BASF AG, Limbergerhof, Germany). Dazomet was incorporated into the soil, then the soil was packed firmly with a roller and sufficient water applied (usually 1 inch over 1 to 1.5 hours) to make a crust to seal in the fumigant. Daily watering for 1 to 2 weeks kept the soil moist and maintained a ½- to ¾-inch crust on the soil surface.

Conifer species tested represented a major crop species produced at each nursery. A single seed lot for each species was sown into all treatment plots within a given nursery, except as noted. All study plots were established in spring 1993 prior to soil treatments followed by sowing of conifer seed in spring 1994, and final measurements were taken in fall 1995. Soil treatments were repeated in 1995 followed by sowing of conifer seed in spring 1996 and final measurements in fall 1997.

Bend Pine Nursery

The study area was a block 400 by 48 ft (122 by 14.6 m), divided into 32 plots, each 50 by 12 ft (15 by 3.7 m). Five replicates of each of five treatments were randomly assigned to the plots, leaving seven unused plots. The entire study block received the standard nursery soil amendment at 1.5-in (3.8-cm) depth or 200 yd^3/acre (380 m^3/ha) of aged pine sawdust incorporated into the soil with 300 lb/acre (337 kg/ha) of ammonium nitrate (34-0-0) (S+N) at the beginning of summer in 1993 and 1995. Soils at the nursery are sandy loams and loamy sands, organic matter content is about 2 percent, and cation exchange capacities range from 10 to 12 meq/100 g.

Three treatments were bare fallow from June through September, two without tilling (BF) and one with tilling (BFT) at 3-week intervals. One of the bare fallow without tilling treatments received a mulch of pine needles (collected locally the previous fall from natural needle abscission), applied after sowing to cover the seed. The pine mulch treatment was not repeated in the second trial (1995-97). The other bare fallow without tilling treatment used Geotech® soil stabilizer (a hygroscopic spray-on gel designed to hold soil in place) as mulch. The remaining two treatments had a pea (*Lathyrus hirsutus* L.) cover crop (Pea CC) sown in May 1993 and 1995, and incorporated into the soil in August. One of the pea cover crop treatments was fumigated with MBC, in September 1993 and 1995, at 350 lb/acre (393 kg/ha), after incorporation of the pea cover crop. This treatment represented nursery standard practice, whereas the pea cover crop treatment without fumigation provided a comparison.

[1] The use of trade or firm names in this publication is for reader information and does not imply endorsement by the U.S. Department of Agriculture of any product or service.

Treatments were sawdust plus N with pea cover crop and MBC fumigation ("S+N, pea CC, MBC"), sawdust plus N with bare fallow and tilling ("S+N, BFT"), sawdust plus N with bare fallow ("S+N, BF"), sawdust plus N with bare fallow and pine needle mulch ("S+N, BF, pine needle mulch"), and sawdust plus N with pea cover crop ("S+N, pea CC"). One continuous seedling bed was sown through the center of each plot in four linear strips in the study area in late April 1994 and 1996, with a single seed lot of ponderosa pine (*Pinus ponderosa* Dougl. ex Laws.).

J. Herbert Stone Nursery

The study area was a 3- by- 9 plot block, with each of the 27 plots measuring 50 by 11 ft (15 by 3.4 m). Five replicates of each of five treatments were randomly assigned to the plots, leaving two unused plots. Each plot had one bed of ponderosa pine and one bed of Douglas-fir sown in continuous beds through the center of the plots. One set of soil samples per replicate of each treatment provided preplant pathogen information for both Douglas-fir and ponderosa pine. Soils at the nursery are uniformly sandy loams, organic matter content ranges from 3 to 5 percent, and cation exchange capacities range from 7.5 to 12.5 meq/100 g.

The entire study block was kept bare fallow (BF) for the year before sowing. Treatments consisted of soil amendments and modifications to bare fallow. Amendments of aged conifer sawdust were applied at 1-in (2.45-cm) depth or 133 yd^3/acre (250 m^3/ha), and were incorporated into the soil at the beginning of summer in 1993 and 1995. All but one sawdust amendment treatment included additional ammonium nitrate (34-0-0) (N) incorporated into the soil at 300 lb/acre (337 kg/ha) (S+N). In one sawdust treatment, extra N was provided only after seedling emergence (S, delayed N). All but one treatment had tilling at 3-week intervals June through September (BFT). The treatment representing nursery standard practice was sawdust plus N, periodic tilling, and fumigation with dazomet applied at 350 lb/acre (393 kg/ha) in September 1993 and 1995.

Treatments were sawdust plus N with tilling and fumigation ("S+N, BFT, dazomet"), sawdust plus N with tilling ("S+N, BFT"), sawdust plus N without tilling ("S+N, BF"), no sawdust with tilling ("BFT"), and sawdust with delayed N and tilling ("S, BFT, delayed N"). Seedbeds were formed, and a single seed lot of Douglas-fir and another of ponderosa pine were sown in late April 1994 and 1996.

Coeur d'Alene Nursery

The study plots were each 50 ft by one bed width (4 ft) (15 by 1.2 m) except the fumigation treatment, which covered two bed widths. Five replicates of five treatments were arranged in a randomized block design. All treatments included bare fallow with periodic tilling (BFT) and hand weeding. Two organic amendment treatments were incorporated into soil in late June 1993 and 1995. These were composted bark chips (bark compost) and sewage sludge composted with wood waste (sludge), both applied at a rate of approximately 29 yd^3/acre (55 m^3/ha). In the first trial, one treatment had a layer of pine needles (collected locally the previous fall from natural needle abscission) applied after sowing to cover the seed (pine needle mulch). The fumigation treatment was dazomet applied at the standard rate of 350 lb/acre (393 kg/ha), in late September 1993 and 1995. Soils at the nursery are gravelly sandy loam, sandy loam, and silt loam. Organic matter content ranges from 1.1 to 5.2 percent, and cation exchange capacities range from 6.2 to 14.2 meq/100 g. Soil pH ranges from 5.8 to 7.5.

The five treatments were bare fallow with tilling ("BFT"), bark compost amendment and bare fallow with tilling ("bark compost, BFT"), sewage sludge amendment and bare fallow with tilling ("sludge, BFT"), bare fallow with tilling and pine needle mulch ("BFT, pine needle mulch"), and bare fallow with tilling and dazomet fumigation ("BFT, dazomet"). Seedbeds were formed and Rocky Mountain Douglas-fir (*Pseudotsuga menziesii* var. *glauca* (Beissn.) Franco) sown along the center of each plot in early May 1994 and 1996.

Lucky Peak Nursery

Two identical study areas were established in different parts of the nursery. Treatment plots were each 50 ft by one bed width (15 by 1.2 m) except the fumigation treatment, which covered two bed widths. Five replicates of five treatments were arranged in a randomized block design. One study area was sown with a single seed lot of ponderosa pine and the other with three seed lots of lodgepole pine (*Pinus contorta* Dougl. ex Loud.). The seedbeds were formed and sown along the center of each plot in late May 1994 and 1996. In the 1995-97 trial, only one study area was treated, and sown with ponderosa pine. Soils at the nursery are loam, loamy sand, sandy clay loam, and sandy loam, with more clay occurring generally to the south and east. Organic matter content ranges from 2.9 to 5.7 percent, and cation exchange capacities average 9.2 to 16.7 meq/100 g. Soil pH ranges from 5.2 to 6.

All treatments included bare fallow and hand weeding. One treatment was tilled at monthly intervals between mid-June and late September. Two of the no-tilling treatments had soil amendments incorporated in early June 1993 and 1995. One amendment was composted waste material from the commercial production of mushrooms (compost), added at approximately 22 yd^3/acre (42 m^3/ha). The other amendment was commercial sawdust containing supplemental nitrogen (S+N) added at approximately 22 yd^3/acre (42 m^3/ha), with 82 lb/acre (92 kg/ha) ammonium nitrate (34-0-0). The third no-tilling treatment was the nursery standard fumigation with MBC applied at 350 lb/acre (393 kg/ha) in September 1993 and 1995. The five treatments were bare fallow ("BF"); bare fallow with tilling ("BFT"); mushroom compost and bare fallow ("compost, BF"); sawdust plus N and bare fallow ("S+N, BF"); and bare fallow and MBC ("BF, MBC").

Placerville Nursery

Study plots were 30 by 4 ft (9 by 1.2 m), with treatments replicated four times and arranged in a randomized block design. Seven treatments began with bare fallow with tilling (BFT), then bed formation in October, and an overwinter soil mulch of rice straw, sawdust, pine needles, hydromulch, or nothing. Weeds were controlled by flaming during winter and hand weeding prior to conifer sowing in spring. Shasta red fir (*Abies magnifica* A. Murr. var. *shastensis* Lemm.) seed was sown in mid-March (early) or mid-April (late) 1994, and covered with soil, hydromulch, or sawdust. In the first trial (1993-95), there was no fumigation treatment. Soils at the nursery are predominantly loams, organic matter content ranges from 4 to 6 percent, and cation exchange capacities range from 15 to 19 meq/100 g.

The seven treatments in the first trial were bare fallow with tilling and rice straw winter mulch and late sowing with soil covering seed ("BFT, rice straw mulch, late sow, soil over seed"); bare fallow with tilling and rice straw winter mulch and early sowing with hydromulch covering seed ("BFT, rice straw mulch, early sow, hydromulch over seed"); bare fallow with tilling and sawdust winter mulch and early sowing with hydromulch covering seed ("BFT, sawdust mulch, early sow, hydromulch over seed"); bare fallow with tilling and sawdust winter mulch and early sowing with sawdust covering seed ("BFT, sawdust mulch, early sow, sawdust over seed"); bare fallow with tilling and pine needle winter mulch and early sowing with hydromulch covering seed ("BFT, pine needle mulch, early sow, hydromulch over seed"); bare fallow with tilling and hydromulch winter mulch and early sowing with hydromulch over seed ("BFT, hydromulch, early sow, hydromulch over seed"); and bare fallow with tilling and bare soil over winter and early sowing with hydromulch covering seed ("BFT, bare, early sow, hydromulch over seed").

In the second trial (1995-97), eight treatments began with bare fallow with tilling, followed by bed formation and an overwinter soil mulch of sawdust, hydromulch, or vetch (*Vicia narbonensis* L.) cover crop, with bed formation in spring. Two of these treatments included fumigation with MBC applied at 350 lb/acre (393 kg/ha) at the end of summer before the vetch cover crop; the other six treatments had no fumigation. Shasta red fir seed was sown in February (early) or mid-April (late) 1996, either on the surface of the soil and covered with sawdust or under the surface covered with soil in the conventional way. The past nursery standard treatment was late-summer fumigation with MBC, followed by a vetch cover crop to hold the soil over winter, bed formation in spring, and late sowing of conifer seed, covered with soil.

The eight treatments in the second trial were bare fallow with tilling and sawdust winter mulch and early sowing with sawdust covering seed ("BFT, sawdust mulch, early sow, sawdust over seed"); bare fallow with tilling and sawdust winter mulch and early sowing with soil covering seed ("BFT, sawdust mulch, early sow, soil over seed"); bare fallow with tilling and MBC fumigation and vetch winter cover crop and late sowing with sawdust covering seed ("BFT, MBC, vetch cover crop, late sow, sawdust over seed"); bare fallow with tilling and MBC fumigation and vetch winter cover crop and late sowing with soil covering seed ("BFT, MBC, vetch cover crop, late sow, soil over seed"); bare fallow with tilling and hydromulch winter mulch and late sowing with sawdust over seed ("BFT, hydromulch, late sow, sawdust over seed"); bare fallow with tilling and hydromulch winter mulch and late sowing with soil over seed ("BFT, hydromulch, late sow, soil over seed"); bare fallow with tilling and vetch winter cover crop and late sowing with soil covering seed ("BFT, vetch cover crop, late sow, soil over seed"); and bare fallow with tilling and vetch winter cover crop and late sowing with sawdust covering seed ("BFT, vetch cover crop, late sow, sawdust over seed").

Humboldt Nursery

Study plots were 24 by 4 ft (7 by 1.2 m), with five treatments replicated five times in a randomized block design. In the first trial (1993-95), all treatments began with bare fallow with tilling. Shasta red fir was sown in spring 1994. In three treatments, seed was sown conventionally and covered with soil. Two treatments had seed sown shallow and covered with a mulch of composted redwood chips or hydromulch. Two treatments had fumigation, one with MBC and one with dazomet. Fumigants were applied at 350 lb/acre (393 kg/ha) in fall. Soils at the nursery are loam and fine sandy loam, organic matter content ranges from 3.2 to 8.4 percent, and cation exchange capacities range from 10 to 20 meq/100 g.

Treatments in the first trial were bare fallow with tilling and soil covering seed ("BFT, soil over seed"); bare fallow with tilling and composted redwood mulch covering seed ("BFT, redwood mulch over seed"); bare fallow with tilling and hydromulch covering seed ("BFT, hydromulch over seed"); bare fallow with tilling and MBC fumigation and soil covering seed ("BFT, MBC, soil over seed"); and bare fallow with tilling and dazomet fumigation and soil covering seed ("BFT, dazomet, soil over seed").

In the second trial (1995-97) at Humboldt Nursery, study plots were 4 by 50 ft (1.2 by 15 m), with five replicate plots for each of five treatments arranged in a randomized block design. All treatments began with bare fallow and three included tilling. One of the bare fallow without tilling treatments had glyphosate herbicide applied as needed. One of the bare fallow with tilling treatments had fumigatiion with MBC; one had phosphate buffer seed treatment; and one had seed treatment with a biocontrol agent in phosphate buffer. The biocontrol agent was an experimental mixture of three strains of *Pseudomonas chlororaphis* (Guig. & Sauv.) Bergey, a nonpathogenic bacterium that inhabits soil and the rhizosphere of conifers. Preliminary experiments at BC Research Inc.[2] had indicated that these bacterial strains might be useful as biocontrol agents against the pathogenic fungus, *Fusarium oxysporum* Schlechtend.:Fr. Shasta red fir seed was sown in spring 1996, and covered with soil in the conventional way.

Treatments in the second trial were bare fallow and glyphosate herbicide ("BF, herbicide"); bare fallow with tilling and phosphate buffer seed treatment ("BFT, phosphate buffer"); bare fallow ("BF"); bare fallow with tilling and MBC fumigation ("BFT, MBC"); and bare fallow with tilling and biocontrol seed treatment ("BFT, biocontrol").

Measurement of Seedling Density and Mortality

For the first growing season, seedling densities (seedlings/area) were recorded about 3 weeks after emergence, at midseason (about 8 weeks postemergence), and at the end of the growing season (1+0). Three fixed plots 0.5 by 4 ft (0.15 by 1.2 m), oriented across beds, were established in each replicate treatment plot at each nursery. Total numbers of live seedlings, seedlings killed by disease (with symptoms of postemergence damping-off or *Fusarium* root disease), and seedlings killed by other causes were recorded for each fixed plot at each measurement period. Cumulative percentage of mortality from disease during the first growing season, beginning with emergence and ending in mid-October (1+0), was used for statistical analyses. Final seedling density was determined in mid-October at the end of the second growing season (2+0) for three randomly located plots of the same size as above, in each treatment plot.

Measurement of Seedling Size

Seedling shoot length (height) and diameter were recorded for a sample of 50 trees from each replicate treatment plot in each nursery at the end of the first growing season (1+0) and again at the end of the second growing season (2+0). Seedling height and diameter were measured by using "Machine Vision," a line-scanning image-analysis system developed by the University of Oklahoma for seedling inspection.

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[2] Axelrood, P.E. 1996. Personal communication. Plant pathologist, Microbiology and Plant Pathology Group, B.C. Research Inc., 3650 Wesbrook Mall, Vancouver, BC V6S 2L2, Canada.

Soil Sampling

Soil samples were collected three times at each nursery for determining population levels of species of *Fusarium* and *Pythium*: (1) in spring at the time treatment plots were established; (2) in October, about 3 weeks following fumigation treatments; and (3) in spring of the following year immediately prior to sowing (preplant). Soil samples were collected in polyethylene bags, transported to the laboratory in cooler boxes, stored at 39.2°F (4 °C), and processed within 48 hours of receipt at the laboratory. Soil samples were passed through a 0.24-in (6-mm) screen, and 3.5 oz (10 g) (fresh weight) were added to flasks containing 3 fl oz (90 mL) of 0.1 percent water agar. These samples were mixed and serially diluted (1:10, 1:100) in 0.1 percent water agar for plating. A portion of each soil sample was oven dried for determining water content and conversion of propagule counts on a dry-weight basis.

Four plates of each sample, with 0.017 fl oz (0.5 mL) diluted soil on each plate, were prepared on two selective media: Komada's medium (Komada 1975) and a modified V-8 medium. Komada's medium, modified with the amendment of 0.33 oz/qt (1 g/L) of lithium chloride for suppression of *Trichoderma* spp. (Wildman 1991) was used for enumeration of *Fusarium* species, primarily *F. oxysporum*. Dilution plates of Komada's medium were incubated under fluorescent light and read after 6 days. For enumeration of *Pythium* spp., a modified V-8 medium was used, containing 6.8 fl oz (200 mL) clarified V-8 juice, 0.0035 oz (10 mg) rifampicin, 0.007 oz (20 mg) rose Bengal, 0.0875 oz (250 mg) ampicillin, 0.0035 oz (10 mg) pimaricin, and 7 oz agar (20 g) per 1.06 qt (per 1 L). Plates were inoculated with soil dilutions as above, incubated in the dark at room temperature, and read after 2 days. For both fungal assays, the average number of colonies on four plates multiplied by the dilution factor and corrected for water content, yielded colony forming units (CFU) per gram of oven-dried soil.

Statistical Analyses

Analyses of data were carried out by using Systat 8.0 (Systat 1998) or SAS statistical software (SAS 1992). Analysis of variance (ANOVA) with Tukey's multiple comparison procedures were used for comparisons of seedling size factors among treatments at each nursery. Seedling density and mortality data were logit transformed as recommended for proportional data containing zeros (Sabin and Stafford 1990) and analyzed by using ANOVA. Mean CFU for each replicate plot was analyzed by using the Kruskal-Wallis procedure and the Mann-Whitney U statistic for comparisons between treatments. Differences were declared statistically significant by using an α-level of 0.05.

Results

Bend Pine Nursery

For both trials of the study, average seedling densities and mortality were not significantly different between the fumigated ("S+N, Pea CC, MBC") and the nonfumigated bare fallow treatments ("S+N, BFT"; "S+N, BF"; and "S+N, BF, pine needle mulch") (table 1). The pea cover crop without fumigation treatment ("S+N, Pea CC") resulted in significantly lower densities and significantly higher mortality than all other treatments in both trials.

In the 1993 trial, average ponderosa pine seedling diameter and shoot height were significantly greater in the fumigated treatment ("S+N, Pea CC, MBC") than the three nonfumigated bare fallow treatments ("S+N, BFT"; "S+N, BF"; and "S+N, BF, pine needle mulch"). In the 1995 trial, seedling heights and diameters were not significantly different between the fumigated ("S+N, Pea CC, MBC") and nonfumigated bare fallow ("S+N, BFT" and "S+N, BF") treatments. The bare fallow with pine needle mulch treatment ("S+N, BF, pine needle mulch") was not repeated because it was operationally difficult and apparently delayed seedling emergence.

Table 1—Effect of soil treatments on 2+0 ponderosa pine seedling density, diameter, height, mortality, and preplant levels of *Fusarium* and *Pythium* spp., at Bend Pine Nursery

Treatment[a]	Density[b]	Diameter	Height	Mortality[c]	Preplant *Fusarium*[d]	Preplant *Pythium*[d]
	No. per ft²	*mm*	*cm*	*Percent*	------ *CFU* ------	
1993-95:						
S+N, Pea CC, MBC	20.3 a[e]	6.8 b	25.4 a	5.5 a	170 a	2 a
S+N, BFT	21.3 a	6.2 a	19.1 b	11.4 a	620 a	14 b
S+N, BF	20.3 a	6.1 a	20.4 b	9.3 a	950 a	18 b
S+N, BF, pine needle mulch	20.3 a	5.8 a	15.9 b	na	220 a	na
S+N, Pea CC	7.0 b	8.5 c	19.6 b	39.1 b	3,710 b	158 c
1995-97:						
S+N, Pea CC, MBC	15.1 x	6.2 x	19.3 x	6.6 x	1,200 x	16 x
S+N, BFT	13.5 x	6.0 x	19.8 x	8.4 x	510 x	23 x
S+N, BF	17.5 x	6.2 x	19.8 x	10.6 x	2,230 x	77 xy
S+N, Pea CC	6.0 y	7.8 y	18.6 x	44.0 y	5,090 y	129 y

na = data not available.

[a] BF = bare fallow, T = with tilling, S = sawdust soil amendment, N = ammonium nitrate, Pea CC = pea cover crop incorporated as green manure, MBC = fumigation with 67 percent methyl bromide/33 percent chloropicrin.

[b] 2+0 seedlings per square foot (per 0.09 m^2).

[c] Percentage of seedlings killed by disease in the first growing season.

[d] Colony-forming units (CFU) per gram dry weight of soil.

[e] Means followed by the same letter are not significantly different at $p \leq 0.05$: a-c for 1993-95 trial, x-y for 1995-97 trial.

In both trials, all treatments resulted in seedlings with average heights well above the minimally acceptable 3.9 in (10 cm) for 2+0 ponderosa pine (table 1). Average seedling diameters in all treatments also were well above the minimally acceptable 0.16 in (4 mm). Average seedling diameter in the pea cover crop without fumigation treatment ("S+N, Pea CC") was significantly greater than in the other treatments, the result of reduced competition owing to very low bed densities (one-third that of the other treatments; table 1).

The MBC fumigation left detectable levels of *Fusarium* in the soil. Average preplant population levels of *Fusarium* in the nonfumigated bare fallow treatments ("S+N, BFT"; "S+N, BF"; and "S+N, BF, pine needle mulch") were not significantly different than the fumigated treatment ("S+N, Pea CC, MBC"). Preplant *Fusarium* populations were significantly greater in the pea cover crop without fumigation treatment ("S+N, Pea CC"), and seedling mortality was correspondingly much greater, for both trials of the study (table 1). Preplant population levels of *Pythium* were similarly significantly higher in the pea cover crop without fumigation ("S+N, Pea CC") than in other treatments. In the

Table 2—Effect of soil treatments on 2+0 ponderosa pine seedling density, diameter, height, mortality, and preplant levels of *Fusarium* and *Pythium* spp., at J. Herbert Stone Nursery

Treatment[a]	Density[b]	Diameter	Height	Mortality[c]	Preplant *Fusarium*[d]	Preplant *Pythium*[d]
	No. per ft²	*mm*	*cm*	*Percent*	------ *CFU*	------
1993-95:						
S+N, BFT, dazomet	19.3 ab[e]	8.5 a	31.5 a	9.1 a	130 a	19 a
S+N, BFT	20.7 a	8.8 a	31.0 a	2.7 a	2,190 a	22 ab
S+N, BF	16.2 b	7.8 a	22.6 b	3.3 a	3,470 b	82 c
BFT	20.3 a	8.8 a	31.7 a	6.5 a	1,110 a	56 bc
S, BFT, delayed N	22.5 a	8.1 a	29.8 a	6.0 a	810 a	67 c
1995-97:						
S+N, BFT, dazomet	14.9 x	7.6 x	17.9 x	9.8 xy	870 x	4 x
S+N, BFT	14.8 x	7.9 x	17.3 x	12.0 y	7,990 y	60 y
S+N, BF	15.1 x	7.1 x	16.2 x	9.2 xy	4,800 xy	45 y
BFT	13.1 y	7.9 x	16.7 x	7.0 x	4,300 xy	46 y
S, BFT, delayed N	15.2 x	8.0 x	17.9 x	7.4 x	2,650 xy	46 y

[a] BF = bare fallow, T = with tilling, S = sawdust soil amendment, N = ammonium nitrate.

[b] 2+0 seedlings per square foot (per 0.09 m²).

[c] Percentage of seedlings killed by disease in the first growing season.

[d] Colony-forming units (CFU) per gram dry weight of soil.

[e] Means followed by the same letter are not significantly different at $p \leq 0.05$: a-c for 1993-95 trial, x-y for 1995-97 trial.

1993 trial, preplant *Pythium* population levels were significantly lower in the fumigated ("S+N, Pea CC, MBC") than nonfumigated bare fallow ("S+N, BFT"; "S+N, BF"; and "S+N, BF, pine needle mulch") treatments, but these treatments were not significantly different in the 1995 trial (table 1).

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Average ponderosa pine density was significantly lower in the bare fallow without tilling treatment ("S+N, BF") compared to the three nonfumigated bare fallow with tilling treatments ("S+N, BFT"; "BFT"; and "S, BFT, delayed N") in the 1993 trial (table 2). The bare fallow without tilling treatment ("S+N, BF") had heavy weed growth in the 1993 trial for both ponderosa pine and Douglas-fir. Ponderosa pine densities in all four nonfumigated bare fallow treatments ("S+N, BFT"; "S+N, BF", "BFT"; and "S, BFT, delayed N") were not significantly different from that in the dazomet fumigation treatment ("S+N, BFT, dazomet") in the 1993 trial. In the 1995 trial, ponderosa pine density was significantly lower in the bare fallow without sawdust ("BFT") treatment than in all other treatments. All the other nonfumigated bare fallow treatments resulted in ponderosa pine densities equivalent to that with dazomet fumigation, in the 1995 trial (table 2).

Table 3—Effect of soil treatments on 2+0 Douglas-fir seedling density, diameter, height, mortality, and preplant levels of *Fusarium* and *Pythium* spp., at J. Herbert Stone Nursery

Treatment[a]	Density[b]	Diameter	Height	Mortality[c]	Preplant *Fusarium*[d]	Preplant *Pythium*[d]
	No. per ft^2	*mm*	*cm*	*Percent*	------ *CFU* ------	
1993-95:						
S+N, BFT, dazomet	18.9 a[e]	7.4 ab	29.2 a	9.9 a	130 a	19 a
S+N, BFT	16.4 a	6.5 a	21.8 ab	13.1 a	2,190 a	22 ab
S+N, BF	14.4 a	6.6 ab	17.8 b	15.7 a	3,470 b	82 c
BFT	18.5 a	8.0 b	29.6 a	11.7 a	1,110 a	56 bc
S, BFT, delayed N	23.0 b	6.9 ab	27.4 ab	9.8 a	810 a	67 c
1995-97:						
S+N, BFT, dazomet	11.3 x	7.3 x	25.3 x	20.2 x	870 x	4 x
S+N, BFT	9.7 xy	7.3 x	26.2 x	34.2 y	7,990 y	60 y
S+N, BF	10.4 xy	7.2 x	26.2 x	23.6 x	4,800 xy	45 y
BFT	6.8 y	9.0 y	30.7 x	44.0 y	4,300 xy	46 y
S, BFT, delayed N	10.1 xy	7.6 x	28.3 x	25.9 x	2,650 xy	46 y

[a] BF = bare fallow, T = with tilling, S = sawdust soil amendment, N = ammonium nitrate.

[b] 2+0 seedlings per square foot (per 0.09 m^2).

[c] Percentage of seedlings killed by disease in the first growing season.

[d] Colony-forming units (CFU) per gram dry weight of soil.

[e] Means followed by the same letter are not significantly different at $p \leq 0.05$: a-c for 1993-95 trial, x-y for 1995-97 trial.

For Douglas-fir in the 1993 trial, density was significantly higher in the delayed N treatment ("S, BFT, delayed N") than for all other treatments (table 3). The other three nonfumigated bare fallow treatments ("S+N, BFT"; "S+N, BF"; and "BFT") resulted in Douglas-fir densities equivalent to that with dazomet fumigation ("S+N, BFT, dazomet") in the 1993 trial (table 3). For Douglas-fir in the 1995 trial, the only significant difference was the low density in the no sawdust treatment ("BFT") compared to the dazomet treatment ("S+N, BFT, dazomet"). Douglas-fir densities in the other three nonfumigated bare fallow treatments ("S+N, BFT"; "S+N, BF"; and "S, BFT, delayed N") were not significantly different from that of the dazomet treatment ("S+N, BFT, dazomet") in the 1995 trial (table 3).

Average diameters of both species in both trials in all treatments were well above the minimum acceptable 0.16 in (4 mm) for ponderosa pine and 0.2 in (5 mm) for low-elevation Douglas-fir (tables 2 and 3). For ponderosa pine in both trials, treatments did not result in significantly different diameters (table 2). Diameters were significantly different for Douglas-fir in the 1993 trial between the no sawdust treatment ("BFT") and the sawdust plus N with tilling treatment ("S+N, BFT") (table 3). These differences were apparently not related to density. In the 1995 trial for Douglas-fir, the only significant increase in diameter was in the no sawdust treatment ("BFT"), and was related to significantly lower density (table 3).

In the 1993 trial, average ponderosa pine heights exceeded the target 9.8 in (25 cm) for all treatments except the bare fallow without tilling ("S+N, BF"), which had significantly shorter seedlings (table 2). In the 1995 trial, none of the treatments had a significant effect on average ponderosa pine heights, which exceeded the minimum acceptable 5.9 in (15 cm), but did not reach the target 9.8 in (25 cm). For both trials, average Douglas-fir heights were mostly slightly shorter than the target 11.8 in (30 cm) for low-elevation Douglas-fir (table 3). In the 1993 trial, average Douglas-fir heights were not significantly different between the dazomet ("S+N, BFT, dazomet") and the three nonfumigated bare fallow with tilling ("S+N, BFT"; "BFT"; and "S, BFT, delayed N") treatments (table 3). In the 1993 trial, average Douglas-fir height was significantly shorter in the bare fallow without tilling treatment ("S+N, BF") compared to the dazomet ("S+N, BFT, dazomet") and the no sawdust ("BFT") treatments. In the 1993 trial, average seedling height in the bare fallow without tilling treatment ("S+N, BF") did not meet the minimum acceptable 7.8 in (20 cm) for low-elevation Douglas-fir. In the 1995 trial, none of the treatments had a significant effect on average Douglas-fir height (table 3).

Dazomet fumigation left detectable preplant population levels of *Fusarium* and *Pythium* in both trials of the study (tables 2 and 3). In the 1993 trial, preplant *Fusarium* populations were significantly greater in the bare fallow without tilling treatment ("S+N, BF") compared to all other treatments. Preplant *Pythium* populations in the 1993 trial were significantly greater in the bare fallow without tilling ("S+N, BF") and delayed N ("S, BFT, delayed N") treatments compared to the dazomet ("S+N, BFT, dazomet") and the nonfumigated sawdust plus N with tilling ("S+N, BFT") treatments. Excessive weed growth, mainly *Portulaca oleracea* L., in the bare fallow without tilling treatment ("S+N, BF") in the 1993 trial was associated with higher populations of both *Fusarium* and *Pythium*. In the 1993 trial, none of the treatments had a significant effect on mortality in ponderosa pine and Douglas-fir. In the 1995 trial, significantly higher population levels of *Fusarium* occurred in the nonfumigated sawdust plus N with tilling treatment ("S+N, BFT") compared to the dazomet treatment ("S+N, BFT, dazomet"). In the 1995 trial, dazomet fumigation ("S+N, BFT, dazomet") significantly reduced *Pythium* populations compared to all other treatments (tables 2 and 3). In the 1995 trial, mortality in ponderosa pine was significantly greater in the nonfumigated sawdust plus N with tilling treatment ("S+N, BFT") compared with the no sawdust ("BFT") and delayed N ("S, BFT, delayed N") treatments. In the 1995 trial, mortality in Douglas-fir was significantly greater in the nonfumigated sawdust plus N with tilling treatment ("S+N, BFT") and no sawdust ("BFT") treatments compared to the dazomet ("S+N, BFT, dazomet"), bare fallow without tilling ("BFT"), and delayed N ("S, BFT, delayed N") treatments. Mortality caused by disease was not consistently related to preplant population levels of *Fusarium* or *Pythium* or with seedling density.

Coeur d'Alene Nursery

None of the treatments had a significant effect on average density of Douglas-fir seedlings in either the 1993 or 1995 trials (table 4). In the 1993 trial, average diameters were not significantly different and met the minimum acceptable diameter of 0.2 in (5 mm) for interior 2+0 Douglas-fir. Average seedling heights in the 1993 trial were significantly shorter in the bark compost treatment ("bark compost, BFT"). All treatments resulted in seedlings exceeding the minimum acceptable height of 5.9 in (15 cm) in the 1993 trial. In the 1995 trial, seedling diameters were equivalent statistically

Table 4—Effect of soil treatments on 2+0 Douglas-fir seedling density, diameter, height, loss, and preplant levels of *Fusarium* and *Pythium* spp., at Coeur d'Alene Nursery

Treatment[a]	Density[b]	Diameter	Height	Loss[c]	Preplant *Fusarium*[d]	Preplant *Pythium*[d]
	No. per ft²	*mm*	*cm*	*Percent*	- - - - - - *CFU*	- - - - - -
1993-95:						
BFT, dazomet	28.4 a	6.0 a	24.1 a[e]	64 a	70 a	12 a
Bark compost, BFT	26.7 a	5.0 a	16.1 b	62 a	220 a	26 b
BFT	25.7 a	6.0 a	20.0 a	53 a	170 a	31 b
Sludge, BFT	26.6 a	na	na	54 a	2,180 b	41 b
BFT, pine needle mulch	26.1 a	6.0 a	20.0 a	na	1,330 ab	na
1995-97:						
BFT, dazomet	26.2 x	5.0 x	21.0 x	na	110 x	3 a
Bark compost, BFT	28.7 x	4.0 y	14.0 y	na	340 xy	35 b
BFT	26.3 x	4.5 x	16.7 z	na	530 y	38 b
Sludge, BFT	32.1 x	4.0 y	12.6 y	na	470 xy	38 b

na = data not available.

[a] BFT = bare fallow with tilling; bark compost and sewage sludge (sludge) were soil amendments.

[b] 2+0 seedlings per square foot (per 0.09 m^2).

[c] Percentage of seedlings missing at end of first growing season compared to the number of emerged seedlings.

[d] Colony-forming units (CFU) per gram dry weight of soil.

[e] Means followed by the same letter are not significantly different at $p \leq 0.05$: a-b for 1993-95 trial, x-z for 1995-97 trial.

in the dazomet ("BFT, dazomet") and the nonfumigated bare fallow without amendment treatment ("BFT"), but only the dazomet treatment resulted in average seedling diameters meeting the minimum acceptable diameter. In the 1995 trial, seedling diameters and heights were significantly smaller for the bark compost ("bark compost, BFT") and sewage sludge ("sludge, BFT") treatments and did not meet the minimum acceptable diameter or height. The reduced sizes in these two treatments may have been related to higher seedbed densities. Although densities were not significantly different by statistical tests, trends in the data indicate that the bark compost treatment ("bark compost, BFT") had an additional 2.4 (per 0.09 m^2) square foot, and the sludge treatment ("sludge, BFT") had an additional 5.8 seedlings per square foot (per 0.09 m^2) compared to the dazomet ("BFT, dazomet") and bare fallow without amendment treatment ("BFT"). In the 1995 trial, average seedling height was significantly greater in the dazomet treatment ("BFT, dazomet") than all other treatments.

Dazomet fumigation left detectable preplant population levels of *Fusarium* and *Pythium* in both trials. In 1993, average preplant population levels of *Fusarium* were significantly greater in the sewage sludge treatment ("sludge, BFT") than in the dazomet ("BFT, dazomet"), bark compost ("bark compost, BFT"), and bare fallow alone ("BFT") treatments. In 1995, preplant population levels of *Fusarium* were significantly higher in the

Table 5—Effect of soil treatments on 2+0 ponderosa pine seedling density, diameter, height, mortality, and preplant levels of *Fusarium* and *Pythium* spp., at Lucky Peak Nursery

Treatment[a]	Density[b]	Diameter	Height	Mortality[c]	Preplant *Fusarium*[d]	Preplant *Pythium*[d]
	No. per ft²	*mm*	*cm*	*Percent*	------ *CFU*	------
1993-95:						
BFT	20.6 a[e]	6.5 b	25.4 b	13.9 ab	500 a	25 a
BF	17.2 a	7.0 b	27.0 b	17.1 b	240 ab	38 a
Compost, BF	18.5 a	6.0 a	20.5 a	11.3 ab	230 ab	24 a
S+N, BF	22.4 b	6.0 a	22.5 a	7.9 ab	210 ab	21 a
BF, MBC	20.6 a	6.6 b	27.1 b	3.7 a	80 b	7 b
1995-97:						
BFT	30.6 x	6.6 x	24.5 x	na	380 x	21 x
BF	25.6 y	7.1 y	24.9 x	na	490 x	29 x
Compost, BF	27.5 y	6.1 z	22.1 x	na	430 x	32 x
S+N, BF	33.5 z	6.2 z	23.3 x	na	340 x	27 x
BF, MBC	30.9 x	6.7 x	26.8 y	na	60 y	4 y

na = data not available.

[a] BF = bare fallow, T = with tilling, S = sawdust soil amendment, N = ammonium nitrate, compost = mushroom compost soil amendment, MBC = fumigation with 67 percent methyl bromide/33 percent chloropicrin.

[b] 2+0 seedlings per square foot (per 0.09 m²).

[c] Percentage of seedlings killed by disease in the first growing season.

[d] Colony-forming units (CFU) per gram dry weight of soil.

[e] Means followed by the same letter are not significantly different at $p \leq 0.05$: a-b for 1993-95 trial, x-z for 1995-97 trial.

bare fallow alone treatment ("BFT") compared to the dazomet treatment ("BFT, dazomet"). Dazomet fumigation significantly reduced preplant population levels of *Pythium* compared to the other treatments for both trials. However, these differences in population levels of *Fusarium* and *Pythium* had no apparent effect on seedling densities (table 4).

Lucky Peak Nursery

Average ponderosa pine seedling density in the bare fallow with sawdust treatment ("S+N, BF") was significantly greater than the other four treatments for both trials (table 5). In the 1993 trial, ponderosa pine densities were not significantly different among the remaining four treatments. In the 1995 trial, ponderosa pine densities in the bare fallow with tilling ("BFT") and MBC ("BF, MBC") treatments were significantly greater than those in the bare fallow alone ("BF") and mushroom compost ("compost, BF") treatments. For lodgepole pine in the 1993 trial, significantly greater densities occurred in the bare fallow alone ("BF") and MBC treatments ("BF, MBC"), compared to the other three treatments ("BFT"; "compost, BF"; and "S+N, BF") (table 6).

Ponderosa pine seedling diameters in all treatments for both trials exceeded the minimum acceptable 0.16 in (4 mm) (table 5). In the 1993 trial, ponderosa pine diameters in the mushroom compost ("compost, BF") and sawdust treatments ("S+N, BF") were significantly smaller than in the other three treatments ("BF"; "BFT"; and "BF, MBC"). In the case of the sawdust treatment ("S+N, BF"), smaller diameter was related to greater seedbed density. In the 1995 trial, ponderosa pine diameters in the bare fallow

Table 6—Effect of soil treatments on 2+0 lodgepole pine seedling diameter and height, 1+0 seedling density, mortality, and preplant levels of *Fusarium* spp., at Lucky Peak Nursery, 1993-95 trial

Treatment[a]	Density[b]	Diameter	Height	Mortality[c]	Preplant *Fusarium*[d]
	No. per ft²	*mm*	*cm*	*Percent*	*CFU*
BFT	16.4 a[e]	4.7 a	16.8 ab	18.3 ab	460 a
BF	19.8 b	4.5 a	16.4 ab	16.0 ab	510 a
Compost, BF	13.5 a	4.4 a	13.4 b	29.7 b	650 a
S+N, BF	16.0 a	4.6 a	15.9 ab	21.0 ab	1,020 a
BF, MBC	19.4 b	4.8 a	18.9 a	11.0 a	110 a

[a] BF = bare fallow, T = with tilling, S = sawdust soil amendment, N = ammonium nitrate, compost = mushroom compost soil amendment, MBC = fumigation with 67 percent methyl bromide/33 percent chloropicrin.

[b] 1+0 seedlings per square foot (per 0.09 m^2).

[c] Percentage of seedlings killed by disease in the first growing season.

[d] Colony-forming units (CFU) per gram dry weight of soil.

[e] Means followed by the same letter are not significantly different at $p \leq 0.05$.

with tilling ("BFT") and MBC treatments ("BF, MBC") were significantly larger than in the mushroom compost ("compost, BF") and sawdust ("S+N, BF") treatments. Again, the smaller diameter in the sawdust treatment ("S+N, BF") was related to greater density. The significantly larger diameter in the bare fallow alone treatment ("BF") was related to lower seedbed density. For lodgepole pine in the 1993 trial, diameters were not significantly different across all treatments, and exceeded the minimum acceptable 0.16 in (4 mm) (table 6).

Average ponderosa pine seedling heights were well above the minimum acceptable 3.9 in (10 cm) for all treatments in both trials (table 5). In the 1993 trial, average ponderosa pine heights were similar in the two bare fallow alone ("BF" and "BFT") and fumigation ("BF, MBC") treatments, and these were significantly greater than either soil amendment treatment ("compost, BF" and "S+N, BF"). In the 1995 trial, average ponderosa pine height in the MBC treatment ("BF, MBC") was greater than in the other four treatments. For lodgepole pine in the 1993 trial, average heights in the MBC treatment ("BF, MBC") were greater than those in the bare fallow and mushroom compost treatment ("compost, BF"). For all other treatment comparisons, lodgepole pine heights were not significantly different (table 6).

Methyl bromide fumigation left detectable preplant population levels of *Fusarium* and *Pythium* (tables 5 and 6). In the 1993 trial for the ponderosa pine block, MBC fumigation ("BF, MBC") reduced preplant population levels of *Fusarium* compared to the bare fallow with tilling treatment ("BFT"). In the 1995 trial, MBC reduced preplant population levels of *Fusarium* compared to all other treatments. In the lodgepole pine block in the 1993 trial, preplant population levels of *Fusarium* were not significantly different for all treatments. In the ponderosa pine block for both trials, MBC reduced preplant population levels of *Pythium* compared to all other treatments. Mortality was significantly less

Table 7—Effect of soil treatments on 2+0 Shasta red fir diameter, height, and 1+0 density, mortality, and preplant population levels of *Fusarium* spp., at Placerville Nursery, 1993-95 trial

Treatment[a]	Density[b]	Diameter	Height	Mortality[c]	Preplant *Fusarium*[d]
	No. per ft²	*mm*	*cm*	*Percent*	*CFU*
BFT, rice straw mulch, late sow, soil over seed	18.5 a[e]	5.1 a	16.5 a	41 a	5,290 a
BFT, rice straw mulch, early sow, hydromulch over seed	29.9 b	5.0 ab	15.6 ab	12 b	4,460 a
BFT, sawdust mulch, early sow, hydromulch over seed	26.7 b	4.6 b	14.4 b	15 b	3,820 a
BFT, sawdust mulch, early sow, sawdust over seed	27.8 b	4.8 ab	15.5 ab	15 b	3,240 a
BFT, pine needle mulch, early sow, hydromulch over seed	26.4 b	5.0 ab	15.4 ab	11 b	4,710 a
BFT, hydromulch, early sow, hydromulch over seed	25.9 b	4.9 ab	15.7 ab	13 b	5,410 a
BFT, bare, early sow, hydromulch over seed	24.1 b	4.6 b	14.4 b	16 b	3,230 a

[a] BFT = bare fallow with tilling; mulches were used to cover the soil over winter.

[b] 1+0 Seedlings per square foot (per 0.09 m^2).

[c] Percentage of seedlings killed by disease in the first growing season.

[d] Colony-forming units (CFU) per gram dry weight of soil.

[e] Means followed by the same letter are not significantly different at $p \leq 0.05$.

for the MBC treatment ("BF, MBC") compared with the bare fallow alone treatment ("BF") in the ponderosa pine, and compared with the mushroom compost treatment ("compost, BF") in the lodgepole pine. Preplant population levels of *Fusarium* and *Pythium* were not consistently related to mortality or seedling density.

Placerville Nursery

For the 1993 trial in Shasta red fir, the conventional late sowing with soil covering the seed ("BFT, rice straw mulch, late sow, soil over seed") resulted in significantly lower seedling density and greater mortality caused by disease, compared to all other treatments, which had seed sown early and covered with a nonsoil mulch (table 7). Seedling diameters and heights were significantly greater in the same late sowing treatment, compared to the treatment with sawdust winter mulch and hydromulch seed covering ("BFT, sawdust mulch, early sow, hydromulch over seed"), and the treatment with no winter mulch and hydromulch seed covering ("BFT, bare, early sow, hydromulch over seed"). This increase in seedling size was apparently related to the lower density in the late sowing treatment. None of the other treatments had significant effects on seedling size.

Table 8—Effect of soil treatments on 2+0 Shasta red fir seedling density, diameter, height, loss, and preplant population levels of *Fusarium* and *Pythium* spp. at Placerville Nursery, 1995-97 trial

Treatment[a]	Density[b]	Diameter	Height	Loss[c]	Preplant *Fusarium*[d]	Preplant *Pythium*[d]
	No. per ft²	*mm*	*cm*	*No. per ft²*	- - - - - - *CFU* - - - - - -	
BFT, sawdust mulch, early sow, sawdust over seed	39.7 a[e]	4.7 c	13.2 c	31.8 a	3,860 ab	49 a
BFT, sawdust mulch, early sow, soil over seed	25.2 b	5.0 c	14.1 c	39.3 a	2,650 bc	55 a
BFT, MBC, vetch cover crop, late sow, sawdust over seed	17.9 c	5.8 ab	15.8 b	17.2 b	3,810 ab	71 a
BFT, MBC, vetch cover crop, late sow, soil over seed	11.2 c	5.8 ab	15.1 b	33.8 a	930 c	72 a
BFT, hydromulch, late sow, sawdust over seed	16.3 c	5.7 b	16.7 a	17.6 b	650 c	67 a
BFT, hydromulch, late sow, soil over seed	4.4 d	6.0 a	15.9 ab	50.0 c	5,770 a	64 a
BFT, vetch cover crop, late sow, soil over seed	na	na	na	na	690 c	71 a
BFT, vetch cover crop, late sow, sawdust over seed	na	na	na	na	990 c	57 a

na = data not available owing to crop failure.

[a] BFT = bare fallow with tilling; mulches and cover crop were used to cover the soil over winter; MBC = fumigation with 67 percent methyl bromide/33 percent chloropicrin.

[b] 2+0 seedlings per square foot (per 0.09 m^2).

[c] Difference between maximum and final 2+0 density in number of seedlings per square foot.

[d] Colony-forming units (CFU) per gram dry weight of soil.

[e] Means followed by the same letter are not significantly different at $p \leq 0.05$.

In both the 1993 and 1995 trials, all treatments (with the exception of the crop failures with vetch cover crop without fumigation in the second trial) yielded seedlings with average diameters exceeding the acceptable minimum 0.16 in (4 mm), and average heights exceeding the acceptable minimum 5.1 in (13 cm) for Shasta red fir (tables 7 and 8).

In the 1995 trial, there were significant treatment effects on density, but differences in seedling sizes were apparently density-dependent effects (the greater the density, the smaller the seedlings) (table 8). The treatment with sawdust winter mulch, early sowing, and sawdust covering the seed ("BFT, sawdust mulch, early sow, sawdust over seed") had significantly greater density than all other treatments, including those with MBC fumigation. The treatment with the next highest density was sawdust winter mulch, early sowing, and soil covering the seed ("BFT, sawdust mulch, early sow, soil over seed"). This treatment was significantly different from the remaining treatments, including those with MBC fumigation. The vetch cover crop treatments without fumigation ("BFT, vetch cover crop, late sow, sawdust over seed" and "BFT, vetch cover crop, late

Table 9—Effect of soil treatments on 1+0 Shasta red fir density, diameter, and height, mortality, and preplant population level of *Fusarium* spp., at Humboldt Nursery, 1993-95 trial

Treatment[a]	Density[b]	Diameter	Height	Mortality[c]	Preplant *Fusarium*[d]
	No. per ft²	*mm*	*cm*	*Percent*	*CFU*
BFT, soil over seed	19.3 a[e]	2.2 a	4.0 a	7.3 a	530 a
BFT, redwood mulch over seed	19.6 a	2.3 a	4.9 a	5.0 a	1,180 a
BFT, hydromulch over seed	21.6 a	2.1 a	4.0 a	4.7 a	850 a
BFT, MBC, soil over seed	20.1 a	2.2 a	3.8 a	0. a	110 a
BFT, dazomet, soil over seed	20.1 a	2.4 a	4.2 a	0.6 a	30 a

[a] BFT = bare fallow with tilling, MBC = fumigation with 67 percent methyl bromide/33 percent chloropicrin, redwood mulch = composted redwood chips, redwood mulch and hydromulch used to cover seed.

[b] 1+0 seedlings per square foot (per 0.09 m^2).

[c] Percentage of seedlings killed by disease in the first growing season.

[d] Colony-forming units (CFU) per gram dry weight of soil.

[e] Means followed by the same letter are not significantly different at $p \leq 0.05$.

sow, soil over seed") were crop failures, with seedling emergence too low to count. The treatment with hydromulch winter mulch, late sowing, and soil covering the seed ("BFT, hydromulch, late sow, soil over seed") had significantly lower density than all other treatments.

In the 1993 trial, preplant population levels of *Fusarium* spp. were not significantly different among all treatments (table 7). In the 1995 trial, preplant population levels of *Pythium* spp. were not significantly different among all treatments (table 8). In the 1995 trial, preplant population levels of *Fusarium* spp. were significantly lower in four treatments, including the crop failures ("BFT, MBC, vetch cover crop, late sow, soil over seed"; "BFT, hydromulch, late sow, sawdust over seed"; "BFT, vetch cover crop, late sow, soil over seed"; and "BFT, vetch cover crop, late sow, sawdust over seed"), compared to two treatments, including the one with the highest seedling density ("BFT, sawdust mulch, early sow, sawdust over seed" and "BFT, MBC, vetch cover crop, late sow, sawdust over seed") (table 8). Preplant population levels of species of *Pythium* and *Fusarium* did not correlate with seedling density or loss after emergence.

Humboldt Nursery

Shasta red fir seedling density, diameter, and height were not significantly different in any of the treatments after the first growing season in the 1993 trial (table 9). Emergence was uneven for all treatments, with many patches without seedlings, resulting in high variation between measurement plots within treatments. Although not statistically significant, trends in the data suggest that the bare fallow with tilling and hydromulch treatment ("BFT, hydromulch over seed") resulted in an average of two seedlings per square foot (per 0.09 m^2) more than the bare fallow with tilling ("BFT, soil over seed") and the bare fallow with tilling and composted redwood mulch covering seed ("BFT, redwood mulch over seed") treatments (table 9). Differences between treatments in

Table 10—Effect of soil treatments on 2+0 Shasta red fir density, diameter, height, first year loss, and preplant population levels of *Fusarium* spp., and *Pythium* spp. at Humboldt Nursery, 1995-97 trial

Treatment[a]	Density[b]	Diameter	Height	Loss[c]	Preplant *Fusarium*[d]	Preplant *Pythium*[d]
	No. per ft²	*mm*	*cm*	*No. per ft²*	------ *CFU* ------	
BF, herbicide	7.2 a[e]	4.4 ab	11.1 ab	4.0 a	1,330 a	286 a
BFT, phosphate buffer	6.6 a	4.0 c	9.3 c	1.8 a	1,430 a	272 a
BF	6.9 a	4.1 bc	10.4 abc	2.2 a	1,300 a	232 a
BFT, MBC	5.2 a	4.6 a	11.4 a	4.1 a	0 b	3 b
BFT, biocontrol	7.3 a	4.2 bc	10.7 ab	3.1 a	1,330 a	323 a

[a] BF = bare fallow, T = with tilling, MBC = fumigation with 67 percent methyl bromide/33 percent chloropicrin; phosphate buffer and biocontrol were seed treatments.

[b] 2+0 seedlings per square foot (per 0.09 m^2).

[c] Difference in numbers of seedlings per square foot emerged and final stand.

[d] Colony-forming units (CFU) per gram dry weight of soil.

[e] Means followed by the same letter are not significantly different at $p \leq 0.05$.

population levels of *Fusarium* spp. and in seedling losses also were not significant. Data for the 2+0 seedlings were not available. Whether treatments resulted in 2+0 seedlings meeting the minimum acceptable diameters and heights was not recorded.

In the 1995 trial at Humboldt Nursery, treatments had no significant effect on density of 2+0 Shasta red fir seedlings (table 10). However, trends in the data suggest that density with the MBC treatment ("BFT, MBC") was two seedlings per square foot (per 0.09 m^2) fewer than the density in the bare fallow and herbicide ("BF, herbicide") and the bare fallow with tilling and biocontrol ("BFT, biocontrol") treatments (table 10). Seed treated with phosphate buffer, including the biocontrol seed treatment, apparently flowed through the seeder more smoothly, and slightly more seed was applied per unit area, as evidenced by the seeder running out of seed several feet short of the expected end of the seeding run for both treatments ("BFT, phosphate buffer" and "BFT, biocontrol"). Differences in seedling diameter and height were statistically significant. Biologically significant differences are indicated in that bare fallow with tilling and phosphate buffer seed treatment ("BFT, phosphate buffer") and bare fallow alone ("BF") treatments resulted in diameters 0.5 mm less than that after MBC fumigation ("BFT, MBC"), but this may have been density related. Similarly, some heights differed by at least 2 cm, with the MBC treatment ("BFT, MBC") resulting in taller seedlings than the bare fallow with tilling and phosphate buffer seed treatment ("BFT, phosphate buffer"). However, trends in the data suggest the MBC treatment resulted in the lowest density (although not significant statistically), and the larger morphology may be a density effect. All treatments resulted in seedlings meeting the minimum acceptable diameter of 0.16 in (4 mm) for Shasta red fir. However, all treatments failed to produce seedlings with the minimum acceptable height of 5.1 in (13 cm). Fumigation with MBC ("BFT, MBC") reduced preplant population levels of *Fusarium* spp. to undetectable levels. Preplant population levels of species of *Pythium* and *Fusarium* were significantly lower in the fumigation treatment ("BFT, MBC") than in all other treatments, but did not correlate with seedling density or seedling loss.

Discussion

Seedling diameter (and proportionate root development) is the most important measure of seedling quality and outplanting performance specified by reforestation customers in the West. Seedbed density determines the cost per unit area of growing space, and a difference of two seedlings per square foot (per 0.09 m^2) can mean a difference in production of millions of seedlings. For these reasons, seedbed density and seedling diameter are the two measures of seedling production quality that provide the best basis for comparison between standard soil fumigation and nonfumigation alternatives. Seedling diameter is inversely related to seedbed density; i.e., when all other conditions are equal, higher seedbed density produces smaller seedlings. Seedbed density reflects a combination of factors including seed quality, sowing density, losses owing to disease, and nondisease mortality. In our study, mortality losses owing to postemergence disease were determined, whereas losses owing to preemergence mortality were not determined. Final seedbed densities reflect a combination of the sowing density, the undetermined preemergence mortality, postemergence mortality, and other incidental losses.

Seedling diameters, and to a lesser extent, heights, reflected density-dependent effects in some trials. Where densities differ, interpretation of differences in seedling size can be confounded. For example, at Bend Pine Nursery in both trials, very low ponderosa pine density in the pea cover crop without fumigation treatment ("S+N, Pea CC") was associated with significantly larger seedling diameter (table 1). Similarly, at J. Herbert Stone Nursery in the 1995 trial, very low Douglas-fir density in the bare fallow with tilling/no-sawdust treatment ("BFT") was associated with significantly larger seedling diameter (table 3). Conversely, at Lucky Peak Nursery in both trials, significantly greater ponderosa pine density in the bare fallow/sawdust treatment ("S+N, BF") was associated with significantly smaller seedling diameter (table 5). Similarly, at Placerville Nursery in the 1995 trial, significantly greater densities in the bare fallow with tilling/sawdust mulch/early sow treatments ("BFT, sawdust mulch, early sow, sawdust over seed" and "BFT, sawdust mulch, early sow, soil over seed") were associated with significantly smaller seedling diameters (table 8).

Growers who routinely fumigate have tailored watering, fertilizing, and other cultural practices to fumigation as a key component of the cultural system. While alternative systems are under development, seedlings grown under alternative systems may be smaller or less uniform than those grown in fumigated soil. Modifications in irrigation, fertilization, and other cultural practices, however, should improve seedling production and quality, while reducing or eliminating the need for soil fumigation.

Strategies for preventing infection of seedlings by soil-borne pathogens include reducing pathogen populations and providing barriers to infection (Agrios 1969). In our tests, treatments that reduced pathogen populations included bare fallowing with or without tilling, and incorporation of slowly decomposing organic soil amendments. Bare fallowing depletes the food base for facultatively saprobic pathogens (Bloomberg 1965, 1985). Periodic tilling may mechanically damage pathogen propagules as well as bring propagules to the soil surface where they may be exposed to desiccation and lethal temperatures.

Weeds can provide a food base for pathogens, shade the soil surface, and may diminish the beneficial effects of bare fallowing, as demonstrated in the 1993-95 trials at J. Herbert Stone Nursery. Severe weed infestation before and after sowing in the bare fallow without tilling treatment ("S+N, BF") corresponded to significantly higher levels of soil-borne *Fusarium* and significantly reduced ponderosa pine densities compared to all other treatments, with a similar trend for Douglas-fir (tables 2 and 3). The apparent low mortality of ponderosa pine in this treatment may have reflected the difficulty of detecting seedlings emerging in plots with a dense weed cover. Mortality of Douglas-fir also may have been underestimated in this treatment because of the difficulty of finding dead emerged seedlings in the dense weed cover. The trend toward smaller seedlings in both species in this treatment in the 1993 trial compared to the other treatments, also was probably related to the weed infestation, and may reflect combined competition with the weeds and injurious but nonlethal root colonization by *Fusarium* or other pathogens.

For some nurseries, conventional practices can aggravate disease problems and may make chemical fumigation necessary. Incorporation of a cover crop as a green manure before sowing conifer seed results in increased levels of soil *Fusarium* spp., *Pythium* spp., and other micro-organisms (Hansen et al. 1990). High soil populations of *Fusarium* and *Pythium* can lead to severe first-year seedling mortality (Hansen et al. 1990, James et al. 1996, Stone and Hansen 1994). Our tests showed this at Bend Pine Nursery, in the pea cover crop without fumigation treatment ("S+N, pea CC") (table 1). More seedlings meeting size specifications can be produced from bare fallow treatment than from treatments using cover crops, whether fumigated or not (Hansen et al. 1990).

In our tests, we found that population levels of *Fusarium* and *Pythium* spp. were not consistently related to first-year mortality or seedbed density. This is not surprising considering the diversity of populations of these potential pathogens often characteristic of forest nursery soils (Bloomberg 1976, Bloomberg and Lock 1972). Soil populations of *F. oxysporum*, the major species consistently isolated from the test nurseries, often yield both pathogenic and saprobic isolates (Gordon and Martyn 1997, Gordon and Okamoto 1992, James et al. 2000) that are morphologically similar. Therefore, our *Fusarium* assays yielded populations of both pathogens and nonpathogens, and the proportion of populations capable of causing disease was unknown.

Slowly decomposing organic soil amendments, such as aged sawdust or compost, may tend to favor the growth of competitive soil saprobes to the detriment of soil pathogens, which use simple organic substrates. Amendments with high carbon to N ratios may be difficult for facultatively saprobic pathogens to use as a food base, which would promote other soil saprobes, enabling them to outcompete pathogens. A low proportion of N will eventually stunt tree seedlings, and they require supplemental N. Delay in N application until well after seedling germination may help limit the growth of pathogens until after seedlings are vigorous enough to withstand infection. Care must be taken to provide N early enough to prevent stunting.

Sawdust soil amendments had a beneficial effect in some of our trials. As a soil amendment, sawdust and ammonium nitrate fertilizer are commonly incorporated at the same time, but when N application was delayed until after seedling germination ("S, BFT, delayed N"), higher seedling densities tended to result at J. Herbert Stone

Nursery (tables 2 and 3). Treatment without sawdust amendment ("BFT") resulted in significantly lower ponderosa pine and Douglas-fir densities at J. Herbert Stone Nursery in the 1995 trial (tables 2 and 3). Sawdust amendment ("S+N, BF") resulted in higher seedbed densities of ponderosa pine in both the 1993 and 1995 trials at Lucky Peak Nursery (table 5), but not for lodgepole pine. Incorporation of other organic amendments had variable results. For example, at Coeur d'Alene Nursery, addition of bark compost ("bark compost, BFT") or sewage sludge ("sludge, BFT") tended to increase Douglas-fir density only in the 1995 trial, and at Lucky Peak Nursery, addition of mushroom compost ("compost, BF") did not increase density for ponderosa pine or lodgepole pine compared to the unamended treatments.

Treatments that provide barriers to infection include early sowing, and shallow sowing with mulching. Early sowing provides a temporal barrier by allowing conifer seed to germinate, and the radicle to become suberized, before soil temperatures reach optimum for pathogens. Covering the seed with mulch, rather than soil, provides a spatial barrier that partially separates the germinating seedling from soil pathogens. Slowly decomposing mulch, like sawdust, also may provide a biological barrier, where competitive saprobes displace pathogens. For example, covering seed with sawdust or hydromulch rather than soil resulted in increased density of Shasta red fir at Placerville Nursery (tables 7 and 8).

For nurseries in this study that do not routinely use cover crops, fumigation appeared to contribute little toward increased seedling survival or size. For example, at J. Herbert Stone Nursery, dazomet fumigation ("S+N, BFT, dazomet") did not increase seedling density, height, or diameter for Douglas-fir or ponderosa pine compared to nonfumigated bare fallow with tilling and sawdust amendment treatments ("S+N, BFT" and "S, BFT, delayed N") (tables 2 and 3). At Coeur d'Alene Nursery, dazomet fumigation resulted only in a consistent increase in Douglas-fir seedling height, compared to nonfumigated bare fallow treatments (table 4). At Lucky Peak Nursery, bare fallow/sawdust ("S+N, BF") and bare fallow with tilling ("BFT") treatments resulted in similar or greater density and diameter of ponderosa pine compared to MBC fumigation treatment ("BF, MBC") (table 5). For lodgepole pine at Lucky Peak Nursery, bare fallowing ("BF") resulted in similar seedling density and diameter as the MBC treatment ("BF, MBC") (table 6). At Humboldt Nursery, fumigation with dazomet or MBC ("BFT, dazomet" or "BFT, MBC") did not significantly increase Shasta red fir seedling density in both the 1993 and 1995 trials (tables 9 and 10). In contrast, at Placerville Nursery, summer bare fallowing with tilling followed by vetch cover crop without MBC fumigation ("BFT, vetch cover crop, late sow, soil over seed" and "BFT, vetch cover crop, late sow, sawdust over seed") resulted in failure of the Shasta red fir crop owing to disease. However, nonfumigated alternatives without cover crop at Placerville Nursery (summer bare fallowing with tilling, followed by sawdust as winter mulch and early sowing of Shasta red fir seed, "BFT, sawdust mulch, early sow, sawdust over seed" and "BFT, sawdust mulch, early sow, soil over seed") resulted in greater seedbed densities than the vetch cover crop with MBC treatments ("BFT, MBC, vetch cover crop, late sow, sawdust over seed" and "BFT, MBC, vetch cover crop, late sow, soil over seed") (table 8).

Our tests indicated that at many nurseries, modification of cultural practices can greatly reduce the need for chemical fumigation. At every nursery in our tests, some combination of bare fallowing and other cultural practices produced equivalent or greater seedling numbers and diameters compared to fumigation. Similar results have been reported for two Southern nurseries (Barnard et al. 1997) and in a previous study at Bend Pine nursery (Stone and Hansen 1994). The best treatments were different at each nursery, and sometimes varied between trials and species at the same nursery.

Including bare fallowing in the rotation of crops can reduce the need for fumigation, although many industrial growers use fumigants periodically to help avoid unexpected losses owing to disease. Given the ever-shrinking list of registered fungicides and herbicides, and the high value and limited source of genetically improved stock, a nursery cannot afford unexpected disease development.[3]

In nursery operations where enough space is available to make bare fallowing feasible, the advantages include immediate implementation, lack of regulatory restrictions, less expense compared to routine chemical fumigation, and freedom from related human health and environmental concerns associated with fumigation. Unfortunately, alternatives to preplant soil fumigation may alleviate one problem and aggravate another, e.g., bare fallowing may increase soil erosion by wind and water. In many cases, compensating strategies are available, e.g., soil coverings that stabilize the soil surface and abate the effects of wind.

Fine-tuning of alternative practices may be necessary. For example, at Placerville Nursery, we had initial success with overwinter soil mulches and early sowing without the need for chemical fumigation to produce high-quality seedlings. However, after a few years, the nursery suffered excessive losses caused by *Macrophomina phaseolina*, a pathogen previously controlled by methyl bromide/chloropicrin (Frankel et al. 1999). Appropriate cultural practices are under continual development to address the specific needs of individual nurseries. Long-term reductions in dependence on chemical fumigation depend on development of cultural alternatives that favor microbial antagonists of pathogens and promote diverse soil microbial communities.

In our study, bare-fallowing with tilling, bare fallow without tilling and with weed control, early sowing, sawdust with N soil amendment, sawdust soil amendment with N application delayed until after conifer germination, and nonsoil seed coverings were treatments that produced conifer seedlings with similar or better densities and diameters compared to chemical fumigation. The same combinations of treatments were not the most effective among nurseries, and even among crops at the same nursery. Clearly, there is no one alternative to chemical fumigation, and each nursery needs to adapt cultural practices that are most effective for the given conditions and crop requirements.

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[3] Littke, W. 2003. Personal communication. Forest pathologist, Nursery and Forest Regeneration Research and Development, Weyerhaeuser Company, WTC 1A3, 32901 Weyerhaeuser Way South, Federal Way, WA 98001.

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Metric and English Equivalents

To convert:	Multiply by:	To find:
Inches (in)	25.4	Millimeters
Inches (in)	2.54	Centimeters
Feet (ft)	.3048	Meters
Acres	.405	Hectares
Square feet (ft^2)	.0929	Square meters
Pounds per acre (lb/acre)	1.12	Kilograms per hectare
Cubic yards per acre (yd^3/acre)	1.89	Cubic meters per hectare
Millimeters (mm)	.0394	Inches
Centimeters (cm)	.394	Inches
Milligrams (mg)	.000035	Ounces (oz)
Grams (g)	.0352	Ounces (oz)
Milliliters (mL)	.03378	Fluid ounces (fl oz)
Liters (L)	1.057	Quart (qt)
Milliequivalents per 100 grams (meq/100 g)	.284	Milliequivalents per ounce
Degrees Celsius (°C)	1.8 and add 32	Degrees Fahrenheit (°F)

Literature Cited

Agrios, G.N. 1969. Control of plant diseases. In: Agrios, G.N. Plant pathology. New York: Academic Press. Chapter 8.

Axelrood, P.E.; Neumann, M.; Trotter, D. [et al.] 1995. Seed-borne *Fusarium* on Douglas-fir: pathogenicity and seed stratification method to decrease *Fusarium* contamination. New Forests. 9: 35-51.

Barnard, E.L.; Kannwischer-Mitchell, M.E.; Mitchell, D.J.; Fraedrich, S.W. 1997. Development and field performance of slash and loblolly pine seedlings produced in fumigated nursery seedbeds and seedbeds amended with organic residues. In: James, R.L., ed. Proceedings, third meeting of IUFRO working party S7.03-04, diseases and insects in forest nurseries. Forest Health Protection Report 97-4. Coeur d'Alene, ID: U.S. Department of Agriculture, Forest Service, Northern Region: 86-91.

Bloomberg, W.J. 1965. The effect of chemical sterilization on the fungus population of soil in relation to root disease of Douglas-fir seedlings. Forestry Chronicle. 41: 182-187.

Bloomberg, W.J. 1976. Distribution and pathogenicity of *Fusarium oxysporum* in a forest nursery soil. Phytopathology. 66: 1090-1092.

Bloomberg, W.J. 1985. The epidemiology of forest nursery diseases. Annual Review of Phytopathology. 23: 83-96.

Bloomberg, W.J.; Lock, W. 1972. Strain differences in *Fusarium oxysporum* causing diseases of Douglas-fir seedlings. Phytopathology. 62: 481-485.

Boyd, R.J. 1971. Effects of soil fumigation on production of conifer nursery stock at two northern Rocky Mountain nurseries. Res. Pap. INT-91. Ogden, UT: U.S. Department of Agriculture, Forest Service, Intermountain Forest and Range Experiment Station. 19 p.

Cordell, C.E. 1983. Effective soil fumigation. In: Proceedings, 1982 Southern nursery conferences. R8-TP-4. Atlanta, GA: U.S. Department of Agriculture, Forest Service, Southern Region: 196-201.

Cordell, C.E.; Kelley, W.D.; Smith, R.S. 1989. Integrated nursery pest management. In: Cordell, C.E.; Anderson, R.L.; Hoffard, W.H. [et al.], tech. coords. Forest nursery pests. Agric. Handb. 680. Washington, DC: U.S. Department of Agriculture, Forest Service: 5-13.

Danielson, R.M.; Davey, C.B. 1969. Microbial recolonization of a fumigated nursery soil. Forest Science. 15(4): 368-380.

Frankel, S.J.; Stone, J.K.; Cram, M.M. [et al.]. 1999. Progress towards alternatives to methyl bromide fumigation in bare-root forest nurseries in the United States. In: Methyl Bromide Alternatives Newsletter. Baltimore, MD: U.S. Department of Agriculture, Agricultural Research Service. 5(3): 10-12.

Gandy, D.G.; Chanter, D.O. 1976. Some effects of time, temperature of treatment, and fumigant concentration on the fungicidal properties of methyl bromide. Anals of Applied Biology. 82: 279-290.

Gordon, T.R.; Martyn, R.D. 1997. The evolutionary biology of *Fusarium oxysporum*. Annual Review of Phytopathology. 35: 111-128.

Gordon, T.R.; Okamoto, D. 1992. Population structure and the relationship between pathogenic and nonpathogenic strains of *Fusarium oxysporum*. Phytopathology. 82: 73-77.

Hamm, P.B. 1990. *Fusarium* hypocotyl rot. In: Hamm, P.B.; Campbell, S.J.; Hansen, E.M., eds. Growing healthy seedlings: identification and management of pests in Northwest forest nurseries. Spec. Publ. 19. Corvallis, OR: College of Forestry, Oregon State University: 6-7.

Hansen, E.M.; Myrold, D.D.; Hamm, P.B. 1990. Effects of soil fumigation and cover crops on potential pathogens, microbial activity, nitrogen availability, and seedling quality in conifer nurseries. Phytopathology. 80: 698-704.

Hildebrand, D.M.; Stone, J.K.; James, R.L. [et al.]. 1995. Alternatives to chemical fumigation technology development project: preliminary results. In: Landis, T.D.; Cregg, B., tech. coords. National proceedings, Forest and Conservation Nursery Associations—1995. Gen. Tech. Rep. PNW-GTR-365. Portland, OR: U.S. Department of Agriculture, Forest Service, Pacific Northwest Research Station: 15-22.

James, R.L.; Beall, K. 1999. An evaluation of the effects of dazomet on soil-borne diseases and conifer seedling production, USDA Forest Service Lucky Peak Nursery, Boise, Idaho. Report 99-9. Coeur d'Alene, ID: U.S. Department of Agriculture, Forest Service, Northern Region, Forest Health Protection. 15 p.

James, R.L.; Dumroese, R.K.; Wenny, D.L. 1991. *Fusarium* diseases of conifer seedlings. In: Sutherland, J.R.; Glover, S.G., eds. Proceedings, first meeting of IUFRO Working Party S2.07-09 (diseases and insects in forest nurseries). Info. Rep. BC-X-331. Victoria, BC: Forestry Canada, Pacific and Yukon Region: 181-190.

James, R.L.; Page-Dumroese, D.S.; Kimball, S.K.; Omi, S. 1996. Effects of *Brassica* cover crop, organic amendment, fallowing, and soil fumigation on production of bare-root Douglas-fir seedlings, USDA Forest Service Nursery, Coeur d'Alene, Idaho. Report 96-5. Coeur d'Alene, ID: U.S. Department of Agriculture, Forest Service, Northern Region, Forest Health Protection. 16 p.

James, R.L.; Perez, R.; Dumroese, R.K.; Wenny, D.L. 2000. Virulence of *Fusarium oxysporum* on Dougals-fir germinants: comparison of isolates from nursery soil and roots of healthy and diseased seedlings. In: Lilja, A.; Sutherland, J.R., eds. Proceedings, fourth meeting of IUFRO working party 7.03.04 (diseases and insects in forest nurseries). Res. Pap. 781. Vantaa, Finland: Finnish Forest Research Institute: 49-64.

Kelpsas, B.R.; Campbell, S.J. 1994. Influence of mechanical incorporation method on dazomet distribution in conifer nursery soil. Tree Planters' Notes. 45(2): 53-57.

Komada, H. 1975. Development of a selective medium for quantitative isolation of *Fusarium oxysporum* from natural soil. Review of Plant Protection Research. 8: 114-125.

Munnecke, D.E.; Van Gundy, S.D. 1979. Movement of fumigants in soil, dosage responses and differential effects. Annual Review of Phytopathology. 17: 405-429.

Sabin, T.E.; Stafford, S.G. 1990. Assessing the need for transformation of response variables. Spec. Publ. 20. Corvallis, OR: College of Forestry, Oregon State University. 31 p.

SAS Institute. 1992. The SAS system for Windows, version 3.10. Cary, NC: SAS Institute, Inc.

Smith, R.S., Jr.; Fraedrich, S.W. 1993. Back to the future—pest management without methyl bromide. Tree Planters' Notes. 44(3): 87-90.

Stone, J.K.; Hansen, E. 1994. Green manure effects on soil-borne pathogens. In: Landis, T.D., tech. coord. Proceedings, Northeastern and Intermountain Forest and Conservation Nursery Association meeting. Gen. Tech. Rep. RMRS-243. Fort Collins, CO: U.S. Department of Agriculture, Forest Service, Rocky Mountain Research Station: 57-64.

Stone, J.K.; Hildebrand, D.M.; James, R.L.; Frankel, S.J. 1997. Alternatives to chemical fumigation in bare-root forest nurseries: effects on pathogen levels, and seedling density, mortality and quality. In: James, R.L., ed. Proceedings, third meeting of IUFRO working party S7.03-04 (diseases and insects in forest nurseries). Forest Health Protection Report 97-4. Coeur d'Alene, ID: U.S. Department of Agriculture, Forest Service, Northern Region: 59-69.

Systat. 1998. Systat version 8.0. Evanston, IL: SPSS Inc.

Tanaka, Y.; Russell, K.W.; Linderman, R.G. 1986. Fumigation effect on soil-borne pathogens, mycorrhizae, and growth of Douglas-fir seedlings. In: Proceedings, meeting of combined Western Forest Nursery Council and Intermountain Nursery Association. Gen. Tech. Rep. RM-137. Fort Collins, CO: U.S. Department of Agriculture, Forest Service, Rocky Mountain Forest and Range Experiment Station: 147-152.

U.S. Department of Agriculture [USDA]. 1999. Administration extends deadline on methyl bromide ban to 2005. In: Methyl Bromide Alternatives Newsletter. Baltimore, MD: Agricultural Research Service. 5(1): 1. http://www.ars.usda.gov/is/np/mba/mebrhp.htm. (December 2003).

U.S. Department of Agriculture [USDA]. 2000. What if? The strawberry industry without methyl bromide. In Methyl Bromide Alternatives Newsletter. Baltimore, MD: Agricultural Research Service. 6(3): 1-3. http://www.ars.usda.gov/is/np/mba/mebrhp.htm. (December 2003).

Vaartaja, O. 1967. Re-infestation of sterilized nursery seedbeds by fungi. Canadian Journal of Microbiology. 13: 771-776.

Wildman, H. 1991. Lithium chloride as a selective inhibitor of *Trichoderma* species on soil isolation plates. Mycological Research. 95: 1364-1368.

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