Keynote Address

Investigations of *Fusarium* Diseases within Inland Pacific Northwest Forest Nurseries

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Abstract – *Fusarium* spp. cause important diseases that limit production of seedlings in forest nurseries worldwide. Several aspects of these diseases have been investigated for many years within Inland Pacific Northwest nurseries to better understand disease etiology, pathogen inoculum sources, and epidemiology. Investigations have also involved improving disease control efforts to limit impacts. Major diseases caused by *Fusarium* spp. include pre- and post-emergence damping-off, root disease, stem cankers, and top blight. The major *Fusarium* pathogen of bareroot nurseries is *F. oxysporum*. It is a common soilborne species with pathogenic and nonpathogenic strains readily isolated from conifer seeds, diseased and healthy seedlings, and nursery soil. Pathogenic strains appear to be genetically distinct from common saprophytic strains. The major *Fusarium* pathogen of container nurseries is *F. proliferatum*. This species is especially adapted for rapid spread throughout greenhouses. Most tested isolates of *F. proliferatum* are highly virulent. Other *Fusarium* species commonly associated with seedling diseases include *F. solani*, *F. acuminatum*, *F. sporotrichioides*, *F. sambucinum*, and *F. avenaceum*. Several other *Fusarium* spp. are encountered infrequently. Most other *Fusarium* spp. are less virulent on conifer seedlings than *F. oxysporum* and *F. proliferatum*. Improved disease control has been obtained by reducing pathogen inoculum on seeds, reused containers, greenhouse environments, and within nursery soil. Biological control has not yet proven as effective as fungicides in reducing disease severity. Pathogens colonizing roots of seedlings are usually replaced by other mycoflora following outplanting on forest sites. Efforts to reduce dependence on pre-plant soil fumigation have been successful in some, but not all bareroot nurseries. Keeping fallow fields free of plants with periodic cultivation for at least one year may often be as effective as fumigation. Conversely, growing cover crops, incorporating organic amendments into soil, and rotating seedling production with *Brassica* green manure crops have usually proven unsuccessful because of stimulation of *Fusarium* populations following addition of organic matter to soil. Future research efforts should involve using molecular probes to quantify pathogenic *Fusarium* populations to allow better prediction of requirements for implementation of disease controls.

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Introduction

Diseases caused by Fusarium spp. within forest nurseries have been investigated in North America for nearly a century. However, they still severely impact production of high-quality seedlings at many nurseries. Most previous investigations focused on diseases in bareroot nurseries and very little was known about disease epidemiology or procedures to reduce disease impacts in container nurseries. Therefore, we began investigating diseases associated with Fusarium spp. more than 20 years ago. Our goal was to understand disease etiology, sources of pathogen inoculum, and various aspects of disease epidemiology specific to greenhouse environments. This information would lead to developing improved disease control.

Production of container seedlings within greenhouses has greatly increased in western North America during the past two decades. Seedlings can be grown in shorter time periods to provide reforestation stock resulting from changing demands from land managers. Seedling sizes, especially root systems, can be tailored to particular specification requirements. As such, seedling stock may be more adaptable to forest site differences, thereby improving the performance of outplanted seedlings.

Types of Diseases

Fusarium spp. commonly infest conifer seeds, particularly contaminating outer seedcoats (Axelrood and others 1995; James 1985b, 1986a, 1987c, 1999). This inoculum allows rapid colonization of young, succulent seedling tissues upon seed germination which may result in both pre- and post-emergence damping-off (James 1986a, 2004; James and Genz 1981; James and others 1991). Although seedlings are usually susceptible to damping-off for only short time periods, losses can be extensive, particularly if seedlots are extensively contaminated with

populations of *Fusarium* (Hoefnagels and Linderman 1999; James 1986a; James and others 1991). *Fusarium oxysporum* is the most common conifer seed-contaminating *Fusarium* species; other common seed colonizers include *F. solani*, *F. acuminatum*, and *F. sambucinum* (James 1987c; James and others 1991).

Root diseases caused by *Fusarium* spp. can occur throughout the life of the crop. Within bareroot nurseries, most mortality occurs during the first growing season (James 1987b, 2001b, 2002d), with little or no mortality associated with root disease occurring during the second or subsequent years. With container seedlings, however, the highest root disease mortality often occurs at the end of the growing cycle when seedlings are stressed to stop growing and initiate bud formation (James 1986a; James and Gilligan 1984; James and Perez 1998; James and others 1987). Stresses induced by reduced watering and restriction of nutrients can cause seedlings to begin to show disease symptoms. Many of these seedlings were infected with potential pathogenic *Fusarium* early in their growth cycle (James and Gilligan 1988a; James and others 1987) but disease did not appear because seedlings were provided with plenty of water and optimum fertilization. As seedlings become stressed, colonizing *Fusarium*, which previously acted like non-pathogenic root endophytes, begin to induce tissue necrosis and disease symptoms subsequently appear.

Fusarium spp. can potentially cause stem cankers, particularly in dense bareroot seedbeds within coastal nurseries where high humidity prevails (Hansen and Hamm 1988; James 1986c, 2003b). These cankers are either produced low on the stem, just above the ground line, or higher in the seedling near foliage. Incidence and severity of stem cankers vary from year to year and may be related to weather influences as well as level of soilborne inoculum (Hansen and Hamm 1988; Hansen and others 1990; James 2003b).

Top blight of container seedlings associated with attack by *Fusarium* is usually rare. Ponderosa pine (*Pinus ponderosa*) is the most susceptible conifer species to this type of damage (James 1992a, 2003a), probably because seedcoats may persistently remain attached to cotyledons. Seedborne inoculum may result in cotyledon infection with subsequent colonization of stem and root tissues resulting in seedling mortality.

Major *Fusarium* Pathogens

Fungi in the *Fusarium oxysporum* species complex are the most important *Fusarium* pathogens in bareroot forest nurseries (James 2004; James and others 1991, 1996b, 2000). These organisms also occur on container seedlings, particularly as a result of seed contamination (Dumroese and others 1988; James 1987c; James and Genz 1981). Organisms classified as *F. oxysporum* may actually comprise several genetically distinct species (Gordon and Martyn 1997; Kistler 1997). Pathogenic and nonpathogenic strains are common within forest nurseries and usually appear very similar morphologically. Pathogenicity tests have indicated a wide range of potential virulence on conifer seedlings under controlled conditions (James and others 2000). Genetic markers may be useful in separating pathogenic from nonpathogenic isolates (Donaldson and others 1995; Gordon and Martyn 1997; Stewart and others 2004).

Isolates of *F. oxysporum* commonly reside in nursery soil and can remain viable for prolonged periods because of production of long-lived chlamydospores and sclerotia (James and others 1991; Nelson and others 1983). These fungi are excellent colonizers of soil organic matter, regardless of its source (Hansen and others 1990; James 1988b, 2002a; James and others 1996b, 2004a, 2004b, 2004c). When susceptible seedling crops are sown in infested soil, seedlings can become readily infected following stimulation of chlamydospores by host root exudates (James and others 1991; Schippers and others 1981). Once infected, seedlings can exhibit root disease symptoms, probably due to infection by virulent isolates. However, some infected seedlings may remain infected but not become diseased (James and Gilligan 1988b). In this case, *F. oxysporum* acts more like a nonpathogenic root endophyte than a true pathogen. Pathogenic isolates usually induce cortical cell necrosis resulting in root decay (James 2004; James and others 1991), and may readily colonize most root and stem tissues. Seedling mortality occurs when decayed root systems no longer function.

In container seedlings, the most important *Fusarium* pathogen is usually *F. proliferatum* (James 1997a; James and others 1995a, 1997). This *Fusarium* species is taxonomically placed in the section *Liseola*, which includes other important pathogens such as *F. circinatum*, cause of pitch canker of pines (Gordon and others 2001). *Fusarium proliferatum* is not commonly found on conifer seeds, nor is it a very common nursery soil inhabitant (James 1987c, 1997a, 1998a, 1998b, 2002b). This species does not

produce chlamydospores that would allow long-term survival (James 1997a; Nelson and others 1983). However, it is an excellent colonizer of organic matter and may colonize a wide range of plants without inducing disease symptoms (James 1997a; James and Gilligan 1988a; Nelson and others 1983). This species spreads rapidly throughout greenhouses, primarily from microconidia that are readily produced in chains (James 1997a; Nelson and others 1983). Roots of container seedlings may become infected by *F. proliferatum* when seedlings are relatively young (James 1997a; James and others 1987). However, they may or may not exhibit disease symptoms. Production of disease symptoms is primarily related to level of seedling stress (James and others 1990a). Most tested isolates of *F. proliferatum* exhibited high virulence (James and others 1986, 1989, 1997) under controlled pathogenicity tests that utilize a perlite-cornmeal-potato dextrose agar inoculum (James 1996; Miles and Wilcoxin 1984). Therefore, these fungi are capable of causing serious losses to conifer seedling crops grown in greenhouses. In some cases, entire crops have been lost to this pathogen, resulting in extensive economic consequences. However, healthy appearing seedlings can have roots that are extensively colonized by *F. proliferatum* by the end of the growth cycle (James and Gilligan 1988a). When seedlings with *Fusarium* root colonization are outplanted on forest sites, *Fusarium* spp. gradually declines on roots systems and are usually replaced of other mycoflora (Dumroese and others 1993a; Smith 1967).

Several other *Fusarium* spp. are encountered in forest nurseries. Those most commonly isolated include *F. solani, F. acuminatum, F. sporotrichioides, F. sambucinum,* and *F. avenaceum*. Several of these are routinely isolated from roots of diseased or healthy appearing seedlings (James and Gilligan 1988a, 1988b; James and others 1991), nursery soil (James 1984, 2002b, 2002c), peat-based container growing media (James 1985a, 2005), conifer seeds (Dumroese and others 1988; James 1987b), and the inner walls of reused styrofoam or plastic containers (Dumroese and others 1995; James 1989b, 1992b, 2001a). Tests to evaluate potential virulence of some of these species indicated that they are mostly saprophytes, although selected isolates may be capable of eliciting disease on conifer seedlings (James 2000b; James and Perez 1999, 2000). It is possible that some of these other *Fusaria* contribute to disease when associated with more aggressive pathogenic species such as *F. oxysporum* and *F. proliferatum*.

Fusarium Disease Management

Successful management of *Fusarium* diseases in forest nurseries requires emphasis on prevention (James and others 1990a, 1995b). Most approaches are designed to reduce inoculum of potential pathogens within and near seedling growing areas. In addition, it is important to maintain the vigor of nursery seedlings by proper manipulation of water and fertilizer (James 1997b; James and others 1990a). If pathogen inoculum is reduced to a minimum and seedlings are kept vigorous, *Fusarium* disease losses are usually small.

Seedborne inoculum can be greatly reduced by treating seeds with running water rinses or surface sterilization chemicals (James 1985a, 1986a, 1987a; James and others 1996a; Lock and others 1975). This type of treatment may be preferable prior to stratification because *Fusarium* spp. are known to spread throughout seedlots during prolonged stratification (Axelrood and others 1995; James 1987a, 1987c; Kliejunas 1985). Some chemical seed treatments are routinely used for particular conifer species (Sutherland and van Eeerden 1980; Wenny and Dumroese 1987). However, care must be taken to ensure that chemicals do not adversely affect seed germination or emergence of young germinants (Dumroese and others 1988; James 1986a; James and others 1995b; Pawuk 1979). The most effective and least potentially harmful treatment is exposing seeds to running water rinses for at least 48 hours during which seeds are periodically agitated (James 1985b, 1987a; James and others 1996a). This water treatment greatly reduces fungi, including pathogens, which commonly contaminate seedcoats.

Container seedlings are usually produced within either plastic or styrofoam containers. Because these containers are costly, several seedling crops must be grown within individual containers. As a result, potential pathogenic fungi, especially *Fusarium* spp., often contaminate the inner walls of reused containers (James 1989a, 2001a; James and others 1988). This inoculum presents an important potential hazard to subsequent seedling crops. Procedures for cleaning reused containers have changed over the years. Initially, containers were either washed superficially to remove most residual organic matter or steam treated. These treatments, however, were ineffective in significantly reducing populations of potential pathogens. Chemical treatments such as sodium hypochlolrite (James and Sears 1990), sodium metabisulfite (Dumroese and others 1993b), or coating containers with copper solutions (Dumroese and others 1995) were more effective, but

were hazardous to use or resulted in chemical disposal problems. Immersion in hot water (at least 68°C for 30 seconds) became the most widely used, effective container treatment (Dumroese and others 2002; James 1982b; James and Eggleston 1997; James and Woollen 1989). However, high costs of energy required to maintain sufficient water temperatures, stimulated investigations into effective alternatives. Tests of radio frequency waves (James and Trent 2001), dry heat (James and Trent 2002), and large capacity steam rooms (Trent and others 2005) indicated that alternatives to hot water immersion are not only effective, but may be less expensive.

Cleaning greenhouse interiors (walls, floors, benches) with surface sterilants between seedling crops is necessary to reduce inoculum of potential pathogens, including *Fusarium* spp., which tend to accumulate within greenhouses during typical crop cycles (James 2004; James and others 1990a, 1995b). In addition, if greenhouse floors are not made of concrete, weeds growing within houses may harbor important pathogens (James and Gilligan 1984; James and others 1990a) and should be periodically removed. Sanitation procedures, such as periodically removing diseased plants, also helps reduce disease impacts (James 2004).

Soil is a major source of potential pathogen inoculum in forest nurseries. Several *Fusarium* spp. are particularly well adapted to maintain high populations in nursery soil. The most effective and widely used technique for reducing soil pathogens is pre-plant soil fumigation with non-specific biocide chemicals (Hansen and others 1990; Hildebrand and others 2004; James 1989a; James and Beall 1999; James and Ziedler 2004; James and others 1990b, 1996b). Such treatments are very expensive. Although potential pathogens are killed by soil fumigation, all other microorganisms, including beneficial and potential biocontrol fungi and bacteria, are killed as well. Therefore, once a nursery begins soil fumigation, growers usually have to repeat treatments prior to sowing each subsequent seedling crop (James 1989a; James and Beall 2000).

Biological control has potential for reducing *Fusarium* disease losses in forest nurseries. Several commercial biocontrol products are available with proven efficacy against *Fusarium* (James and others 1993). Unfortunately, most tests of fungal (Dumroese and others 1996; James 200a; Mousseaux and others 1998) and bacterial (Dumroese and others 1998) preparations in controlling diseases have so far been disappointing. This may be because tested formulations were developed for specific agricultural crops rather than for use in forest nurseries. Perhaps biocontrol formulations of effective pathogen competitors that routinely occur in forest nurseries, such as nonpathogenic isolates of *F. oxysporum* (James 2000a), may be more effective.

Most growers still rely heavily on applications of chemical fungicides to control many nursery diseases, including those caused by *Fusarium* spp. For some parts of the seedling growing cycle, such as the damping-off stage, chemical treatments are usually quite effective. However, to control root diseases of older seedlings, drenching soil or container media with fungicides has generally been ineffective (James 1984, 1988, 1998a; Shrimpton and Williams 1989). Incorporating chemicals into growing media prior to sowing container seedlings has also been ineffective (Dumroese and others 1990). Although *Fusarium* spp. are generally sensitive to particular fungicides, such as thiophanate methyl, treatments may not result in sufficient chemical concentrations reaching infected roots. In addition, most fungicides are good at preventing diseases rather than acting therapeutically (James 1988) so that treating seedlings already extensively colonized by potential pathogens has little value.

Alternatives to Pre-Plant Soil Fumigation

As indicated above, pre-plant soil fumigation has become widely used in many bareroot nurseries in the United States. Traditionally, the chemical of choice for fumigation is a mixture of methyl bromide (67%) and chloropicrin (33%). However, methyl bromide was recently identified as an important contributor to the destruction of stratospheric ozone (Hildebrand and others 2004; James and others 1994). As a result, it was programmed for reduction and eventual elimination as a soil fumigant and other applications worldwide. Although the deadline for use of methyl bromide in the United States was January 2005, exemptions have been allowed for industries for which no other viable alternatives exist. Some forest nurseries have applied for these exemptions.

When we first learned of the phaseout and eventual elimination of methyl bromide as a soil fumigant, we began a series of trials at different bareroot nurseries to evaluate potential alternatives. Our goal was primarily to find effective alternatives to chemical soil fumigation altogether rather than finding a replacement chemical fumigant. We found that fallowing fields for a least one year (preferably 2-3

years) with periodic cultivation to keep soil aerated, remove weeds, and expose propagules of potential pathogens can be as effective as chemical soil fumigation (Hildebrand and others 2004; James and Ziedler 2004; James and others 1996b). Fallowing is especially effective at nurseries with well-drained loam soils containing limited amounts of clay (James and Beall 2000). The beneficial effects of fallowing, however, can be eliminated by incorporating organic matter into soil, either as a direct amendment or incorporating a green manure crop (James 1998b; James and others 1996b). *Fusarium* populations greatly increase within soils to which high amounts of organic matter have been added (Hansen and others 1990; Hildebrand and others 2004). This effect occurs even if the green manure crop is a *Brassica* spp. (James and others 1996b, 2004a, 2004bg, 2004c), which is grown and incorporated into soil because residues produce methyl isothiocyanate, the active ingredient in some chemical soil fumigants such as dazomet (Smolinska and others 2003). Apparently, the amount of added organic matter overrides the potential toxicity to resident pathogens afforded by *Brassica* tissues.

Our investigations indicated that some nurseries can effectively replace methyl bromide by prolonged fallowing of fields or substituting with another chemical fumigant, such as dazomet (James and others 1990b, 1996b). However, other nurseries have yet to have effective alternatives to methyl bromide and will probably use this chemical as long as the law allows. One additional alternative is conversion of most seedling production to containers, which has been used effectively throughout much of Canada.

Future Directions

Over the century we have learned a great deal about *Fusarium* diseases in forest nurseries. Losses to these fungi are now usually much less in both bareroot and container nurseries than previously. However, these diseases are usually still present at some level in most seedling crops and disease losses may become unacceptable on occasion. When new inexperienced growers are employed at nurseries or when new container facilities are installed, initial disease losses may be quite high. As growers become more experienced, they learn how to prevent diseases more effectively and losses from Fusarium usually decline over time.

Plant pathology entered the era of molecular biology several years ago. As a result, many plant diseases are often routinely diagnosed using molecular probes that can be developed for specific strains of particular pathogens (Gordon and Martyn 1997; Kistler 1997; Summerell and others 2003). Preliminary work with *F. oxysporum* in forest nurseries (Donaldson and others 1995; Stewart and others 2004) indicates that these tools have great potential application. If the pathogenic strains of this important fungus can be easily identified and quantified in nurseries, growers can more accurately predict expected disease levels and make appropriate adjustments to implementing control measures. Identifying saprophytic strains that are genetically different from pathogens opens the possibility of using these strains as more reliable biological control agents because they behave similarly, i.e., occupy the same niches, to pathogens.

More emphasis on cultural manipulations rather than chemical pesticides will be needed in the future. Many standard chemical fungicides used at high levels in the past are either currently or will shortly be unavailable in forest nurseries. Environmental concerns, such as worker exposure and groundwater contamination, are important considerations for the future of nursery disease management. More benign, but efficacious, treatments will be required in the future. Biological control has an important part to play in the future of nursery disease management. Evaluating new commercial products as they become available will be important.

As nursery growers reach the end of their careers, it is important that their replacements become knowledgeable about disease management. Successful disease management often evolves over time at particular nurseries and much of this important information can be lost to new growers. Continued support for nursery pathology is an important way to ensure that disease management information remains available to growers in federal, state, tribal, and private nurseries. This "extension" role is very important for agencies mandated to provide pathology assistance. Hopefully, nursery pathology assistance will continue to receive high priority.

References

Axelrood, P.E., M. Neumann, D. Trotter, R. Radley, G. Shrimpton and J. Dennis. 1995. Seedborne *Fusarium* on Douglas-fir: pathogenicity and seed stratification method to decrease *Fusarium* contamination. New Forests 9:35-51.

Donaldson, G.C., L.A. Ball, P.E. Axelrood and N.L. Glass. 1995. Primer sets developed to amplify conserved genes from filamentous Ascomycetes are useful in differentiating *Fusarium* species associated with conifers. Applied and Environmental Microbiology 61:1331-1340.

Dumroese, R.K., R.L. James and D.L. Wenny. 1990. Trial of a granular etridiazole and thiophanate-methyl mixture to control *Fusarium* root disease of container-grown Douglas-fir seedlings. New Forests 4:231-236.

Dumroese, R.K., R.L. James and D.L. Wenny. 1993a. *Fusarium* root infection of container-grown Douglas-fir: effect on survival and growth of outplanted seedlings and persistence of the pathogen. New Forests 7:143-149.

Dumroese, R.K., R.L. James and D.L. Wenny. 1993b. Sodium metabisulfite reduces fungal inoculum in containers used for conifer nursery crops. Tree Planters' Notes 44(4):161-165.

Dumroese, R.K., R.L. James and D.L. Wenny. 1995. Interactions between copper-coated containers and Fusarium root disease: a preliminary report. USDA Forest Service, Northern Region, Insect and Disease Management. Report 95-9. 8p.

Dumroese, R.K., R.L. James and D.L. Wenny. 1996. *Gliocladium virens* in an alginate prill ineffective as a biological control of Fusarium root disease in container-grown Douglas-fir. New Forests 12:113-124.

Dumroese, R.K., R.L. James and D.L. Wenny. 1998. Interactions among *Streptomyces griseoviridis*, *Fusarium* root disease, and Douglas-fir seedlings. New Forests 15:181-191.

Dumroese, R.K., R.L. James and D.L. Wenny. 2002. Hot water and copper coatings in reused containers decrease incoulum of *Fusarium* and *Cylindrocarpon* and increase Douglas fir seedling growth. HortScience 37:943-947.

Dumroese, R.K., R.L. James, D.L. Wenny, and C.J. Gilligan. 1988. Douglas-fir seed treatments: effects on seed germination and seedborne organisms. *In*: Landis, T.D. (Tech. Coord.). Proceedings: Combined Meeting of the Western Forest Nursery Associations. USDA Forest Service, Rocky Mountain Research Station, General Technical Report RM-167. pp. 155-160.

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

Hansen, E.M. and P.B. Hamm. 1988. Canker diseases of Douglas-fir seedlings in Oregon and Washington bareroot nurseries. Canadian Journal of Forest Research 18:1053-1058.

Hansen, E.M., D.D. Myrold and P.B. Hamm. 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., J.K. Stone, R.L. James and S.J. Frankel. 2004. Alternatives to preplant soil fumigation for western forest nurseries. USDA Forest Service, Pacific Northwest Research Station. General Technical Report PNW-GTR-608. 27p.

Hoefnagels, M.H. and R.G. Linderman. 1999. Biological suppression of seedborne *Fusarium* spp. during cold stratification of Douglas-fir seeds. Plant Disease 83:845-852.

James, R.L. 1984. Evaluation of fungicides to control root diseases at the Champion Timberlands Nursery, Plains, Montana. USDA Forest Service, Northern Region, Forest Pest Management. Report 84-9. 19p.

James, R.L. 1985a. Diseases associated with containerized seedling soil mixes. Tree Planters' Notes. 36(2):3-5.

James, R.L. 1985b. Pathogenic *Fusarium* on spruce seed from the Towner Nursery, North Dakota. USDA Forest Service, Northern Region, Forest Pest Management. Report 85-23. 9p.

James, R.L. 1986a. Diseases of conifer seedlings caused by seed-borne *Fusarium* species. *In*: Shearer, R. C. (compiler). Proceedings: Conifer Tree Seed in the Inland Mountain West Symposium. USDA Forest Service, Intermountain Research Station, General Technical Report INT-203. pp. 267-271.

James, R.L. 1986b. Relationships between extent of root colonization and foliar symptom production in containerized Douglas-fir, ponderosa pine, and lodgepole pine seedlings infected with *Fusarium* at the Montana State Nursery, Missoula. USDA Forest Service, Northern Region, Forest Pest Management. Nursery Disease Notes #28. 19p.

James, R.L. 1986c. Root collar necrosis of Colorado blue spruce seedlings, Plato Nursery, Bonners Ferry, Idaho. USDA Forest Service, Northern Region, Forest Pest Management. Nursery Disease Notes #42. 3p.

James, R.L. 1987a. Effects of water rinse treatments on occurrence of fungi on spruce seed from the Towner Nursery, North Dakota. USDA Forest Service, Northern Region, Forest Pest Management. Report 87-5. 4p.

James, R.L. 1987b. *Fusarium oxysporum* associated with mortality of 1-0 bareroot Douglas-fir seedlings - Montana State Nursery, Missoula. USDA Forest Service, Northern Region, Forest Pest Management. Nursery Disease Notes #60. 2p.

James, R.L. 1987c. Occurrence of *Fusarium* on conifer tree seed from Northern Rocky Mountain nurseries. *In*: Landis, T. D. (tech. coord.). Proceedings: Combined Western Forest Nursery Council and Intermountain Nursery Association Meeting. USDA Forest Service, Rocky Mountain Forest and Range Experiment Station, General Technical Report RM-137. pp. 109-114.

James, R.L. 1988. Principles of fungicide usage in container tree seedling nurseries. Tree Planters' Notes 39(2):22-25.

James, R.L. 1989a. Effects of fumigation on soil pathogens and beneficial microorganisms. *In*: Landis, T. D. (tech. coord.) Proceedings: Intermountain Forest Nursery Association Meeting. USDA Forest Service, Rocky Mountain Research Station. General Technical Report RM-184. pp. 29-34.

James, R.L. 1989b. Spatial distribution of fungi colonizing Leach pine cell containers - USDA Forest Service Nursery, Coeur d'Alene, Idaho. USDA Forest Service, Northern Region, Forest Pest Management. Report 90-3. 7p.

James, R.L. 1992a. *Fusarium* sporodochia on container-grown ponderosa pine seedlings - USDA Forest Service Nursery, Coeur d'Alene, Idaho. USDA Forest Service, Northern Region, Forest Pest Management. Nursery Disease Notes #126. 6p.

James, R.L. 1992b. Hot water sterilization of styroblock containers - Plum Creek Nursery, Pablo, Montana. USDA Forest Service, Northern Region, Forest Pest Management. Nursery Disease Notes #128. 6p.

James, R.L. 1996. Technique for quantifying virulence of *Fusarium* and *Cylindrocarpon* spp. on conifer germinants. USDA Forest Service, Northern Region. Forest Pest Mgt., Nursery Disease Notes #132. 8p.

James, R.L. 1997a. A short review of *Fusarium* section *Liseola*: implications for conifer seedling production. *In*: James, R. L. (editor). Proceedings of the third meeting of IUFRO Working Party S7.03-04 (Diseases and Insects in Forest Nurseries). USDA Forest Service, Northern Region, Forest Health

James, R.L. 1997b. Effects of fertilizer on selected potential plant pathogens in bareroot forest nurseries. *In*: Haase, D. L. and R. Rose (editors). Symposium Proceedings: Forest Seedling Nutrition from the Nursery to the Field. Nursery Technology Cooperative. Oregon State University, Corvallis, OR. pp. 27-39.

James, R.L. 1998a. Effects of benomyl soil drench treatment on soil populations of *Fusarium, Trichoderma* and *Pythium* - USDA Forest Service Nursery, Coeur d'Alene, Idaho. USDA Forest Service, Northern Region, Forest Health Protection. Nursery Disease Notes #140. 6p.

James, R.L. 1998b. Effects of incorporating corn green manure crops on soil populations of *Fusarium*, *Trichoderma*, and *Pythium* - USDA Forest Service Nursery, Coeur d'Alene, Idaho. USDA Forest Service, Northern Region, Forest Health Protection. Nursery Disease Notes # 137. 8p.

James, R.L. 1999. Ponderosa pine seed fungal contamination: effects of stratification and sterilizing treatments. USDA Forest Service, Northern Region, Forest Health Protection. Report 99-3. 11p.

James, R.L. 2000a. Effects of topical application of the biological control agent Biotrek® on production of bareroot Douglas-fir and western white pine seedlings – USDA Forest Service Nursery, Coeur d'Alene, Idaho. USDA Forest Service, Northern Region, Forest Health Protection. Report 00-5. 8p.

James, R.L. 2000b. Pathogenic characteristics of *Fusarium acuminatum* isolated from inland Pacific Northwest nurseries. USDA Forest Service, Northern Region, Forest Health Protection. Report 00-16. 8p.

James, R.L. 2001a. Fungal distribution within plastic Super Cell® containers - USDA Forest Service Lucky Peak Nursery, Boise, Idaho. USDA Forest Service, Northern Region, Forest Health Protection. Nursery Disease Notes #145. 7p.

James, R.L. 2001b. Root disease of 1-0 bareroot Douglas-fir seedlings – USDA Forest Service Lucky Peak Nursery, Boise, Idaho. USDA Forest Service, Northern Region, Forest Health Protection. Nursery Disease Notes #144. 10p.

James, R.L. 2002a. Biological control of *Fusarium oxysporum* and *Fusarium proliferatum* on young Douglas-fir seedlings by a nonpathogenic strain of *Fusarium oxysporum*. USDA Forest Service, Northern Region, Forest Health Protection. Report 02-2. 14p.

James, R.L. 2002b. Effects of preplant soil treatments on *Fusarium* and *Trichoderma* populations and fungal root colonization of 1-0 nondiseased ponderosa pine seedlings - USDA Forest Service Lucky Peak Nursery – Boise, Idaho. USDA Forest Service, Northern Region, Forest Health Protection. Report 02-3. 9p.

James, R.L. 2002c. Effects of preplant soil treatments on *Fusarium* and *Trichoderma* populations and fungal root colonization of 2-0 nondiseased western white pine seedlings - USDA Forest Service Nursery, Coeur d'Alene, Idaho. USDA Forest Service, Northern Region, Forest Health Protection. Report 02-8. 11p.

James, R.L. 2002d. Root disease of 1-0 bare root ponderosa pine seedlings – Lone Peak Nursery, Draper, Utah. USDA Forest Service, Northern Region, Forest Health Protection. Nursery Disease Notes No. 147. 8p.

James, R.L. 2003a. Fusarium blight of container-grown ponderosa pine seedlings – Montana State Nursery, Missoula, Montana. USDA Forest Service, Northern Region, Forest Health Protection. Nursery Disease Notes No. 149. 14p.

James, R.L. 2003b. Stem lesions and dieback of Douglas-fir seedlings – Washington Department of Natural Resources, Webster Nursery, Olympia, Washington. USDA Forest Service, Northern Region, Forest Health Protection. Nursery Disease Notes No. 152. 14p.

James, R.L. 2004. The role of *Fusarium* species in the etiology of conifer seedling diseases in forest nurseries. In: Proceedings of the Hawaii International Conference on Sciences, January, 2004, Honolulu, Hawaii. 17p.

James, R.L. 2005. *Fusarium* populations within peat-based growing media - USDA Forest Service Nursery, Coeur d'Alene, Idaho. USDA Forest Service, Northern Region, Forest Health Protection. Nursery Disease Notes No. 162. 7p.

James, R.L. and K. Beall. 1999. An evaluation of the effects of dazomet on soil-borne diseases and conifer seedling production-USDA Forest Service Lucky Peak Nursery, Boise, Idaho. USDA Forest Service, Northern Region, Forest Health Protection. Report 99-9. 15p.

James, R.L. and K. Beall. 2000. Effects of fallowing on *Fusarium*-associated root diseases and production of bare root ponderosa pine seedlings at the USDA Forest Service Lucky Peak Nursery, Boise, Idaho. USDA Forest Service, Northern Region, Forest Health Protection. Report 00-3. 13p.

James, R.L. and K. Eggleston. 1997. Hot water treatments of plastic and styrofoam containers - USDA Forest Service Nursery, Coeur d'Alene, Idaho. USDA Forest Service, Northern Region, Forest Health Protection. Nursery Disease Notes #133. 10p.

James, R.L. and D. Genz. 1981. Ponderosa pine seed treatments: effects on seed germination and disease incidence. USDA Forest Service, Northern Region, Forest Pest Management. Report 81-16. 13p.

James, R.L. and C.J. Gilligan. 1984. Studies of *Fusarium* associated with containerized conifer seedling diseases: pathogenicity tests of isolates from the Alpine Nursery, Kalispell, Montana. USDA Forest Service, Northern Region, Forest Pest Management. Report 84-14. 29p.

James, R.L. and C.J. Gilligan. 1988a. Association of *Fusarium* with nondiseased containerized ponderosa pine seedlings at the USDA Forest Service Nursery, Coeur d'Alene, Idaho. USDA Forest Service, Northern Region, Forest Pest Management. Report 88-5. 10p.

James, R.L. and C.J. Gilligan. 1988b. Occurrence of *Fusarium* on the roots of nondiseased bareroot Douglas-fir seedlings - USDA Forest Service Nursery, Coeur d'Alene, Idaho. USDA Forest Service, Northern Region, Forest Pest Management. Report 88-12. 4p.

James, R.L. and R. Perez. 1998. *Fusarium proliferatum* root disease on container-grown Douglas-fir seedlings from Pacific Northwest Region seedlots - USDA Forest Service Nursery, Coeur d'Alene, Idaho. USDA Forest Service. Northern Region, Forest Health Protection. Nursery Disease Notes # 138. 6p.

James, R.L. and R. Perez. 1999. Pathogenic characteristics of *Fusarium sporotrichioides* isolated from inland Pacific Northwest forest nurseries. USDA Forest Service, Northern Region, Forest Health Protection. Report 99-8. 11p.

James, R.L. and R. Perez. 2000. Pathogenic characteristics of *Fusarium solani* isolated from inland Pacific Northwest forest nurseries. USDA Forest Service, Northern Region, Forest Health Protection. Report 00-15. 12p.

James, R.L. and D. Sears. 1990. Bleach treatments of Leach pine cell containers - USDA Forest Service Nursery, Coeur d'Alene, Idaho. USDA Forest Service, Northern Region, Forest Pest Management. Nursery Disease Notes #101. 4p.

James, R.L. and A. Trent. 2001. Effects of radio frequency waves on fungal colonization of styroblock containers. USDA Forest Service. Northern Region, Forest Health Protection. Report 01-10. 10p.

James, R.L. and A. Trent. 2002. Effects of dry heat treatment of styroblock containers on colonization by selected fungi. USDA Forest Service, Northern Region, Forest Health Protection. Report 02-4. 10p.

James, R.L. and R.L. Woollen. 1989. An evaluation of the efficacy of hot water-chemical treatments to clean styroblock containers - Champion Timberlands Nursery, Plains, Montana. USDA Forest Service, Northern Region. Forest Pest Management. Report 89-5. 8p.

James R.L. and S. Zeidler. 2004. Preplant soil treatment effects on production of bare root bitterbrush seedlings, Lone Peak Conservation Nursery, Draper, Utah. USDA Forest Service, Northern Region, Forest Health Protection. Report 04-14. 14p.

James, R.L., R.K. Dumroese and D.L. Wenny. 1988. Occurrence and persistence of *Fusarium* within styroblock and Ray Leach containers. *In*: Landis, T.D. (Tech. Coord.). Proceedings: Combined Meeting of the Western Forest Nursery Associations. USDA Forest Service, Rocky Mountain Research Station, General Technical Report RM-167. pp. 145-148.

James, R.L. , R.K. Dumroese and D.L. Wenny. 1990a. Approaches to integrated pest management of Fusarium root disease in container-grown conifer seedlings. *In*: Rose, R., S.J. Campbell and T.D. Landis (eds.). Target Seedling Symposium: Proceedings, Combined Meeting of the Western Forest Nursery Associations. USDA Forest Service, Rocky Mountain Research Station, General Technical Report RM-200 pp. 240-246.

James, R.L., R.K. Dumroese and D.L. Wenny. 1991. *Fusarium* diseases of conifer seedlings. *In*: Sutherland, J.R. and S.G. Glover (eds.). Proceedings of the first meeting of IUFRO Working Party S2.07-09 (Diseases and Insects in Forest Nurseries). Forestry Canada. Pacific and Yukon Region. Information Report BC-X-331. pp. 181-190.

James, R.L., R K. Dumroese and D L. Wenny. 1993. Principles and potential for biocontrol of diseases in forest and conservation nurseries. *In*: Landis, T.D. (tech. coord.). Proceedings, Western Forest Nursery Association, Fallen Leaf Lake, CA. USDA Forest Service, Rocky Mountain Research Station, General Technical Report RM-221. pp. 122-131.

James, R.L., R.K. Dumroese and D.L. Wenny. 1995a. *Fusarium proliferatum* is a common, aggressive pathogen of container-grown conifer seedlings. Phytopathology 85(10):1129.

James, R.L., R.K. Dumroese and D.L. Wenny. 1995b. Management of fungal diseases of western larch seed and seedlings. *In*: Schmidt, W.C. and K.J. McDonald (compilers). Ecology and Management of *Larix* Forests: A Look Ahead. Proceedings of an International Symposium. USDA Forest Service, Intermountain Research Station. General Technical Report GTR-INT-319. pp. 300-306.

James, R.L., R.K. Dumroese and D.L. Wenny. 1996a. Western larch seed contaminating fungi and treatments to reduce infection and improve germination USDA Forest Service, Northern Region, Forest Health Protection. Report 96-7. 14p.

James, R.L., R.K. Dumroese and D.L. Wenny. 1997. Pathogenicity of *Fusarium proliferatum* in container-grown Douglas-fir seedlings. *In:* James, R. L. (editor). Proceedings of the third meeting of IUFRO Working Party S7.03-04 (Diseases and Insects in Forest Nurseries). USDA Forest Service, Northern Region, Forest Health Protection. Report 97-4. pp. 26-33.

James, R.L., G.R. Knudsen and M.J. Morra. 2004a. Effects of preplant soil treatments on production of western white pine seedlings - USDA Forest Service Nursery, Coeur d'Alene, Idaho. USDA Forest Service. Northern Region, Forest Health Protection. Report 04-12. 10p.

James, R.L., G.R. Knudsen and M.J. Morra. 2004b. Preplant soil treatment effects on production of Douglas-fir seedlings at the USDA Forest Service Nursery, Coeur d'Alene, Idaho. USDA Forest Service, Northern Region, Forest Health Protection. Report 04-10. 14p.

James, R.L., G.R. Knudsen and M.J. Morra. 2004c. Preplant soil treatment effects on production of ponderosa pine seedlings at the USDA Forest Service Lucky Peak Nursery, Boise Idaho. USDA Forest Service, Northern Region, Forest Health Protection. Report 04-13. 12p.

James, R.L., S. Metzger and C.J. Gilligan. 1990b. Effects of soil fumigation on conifer seedling production at the USDA Forest Service Nursery, Coeur d'Alene, Idaho. USDA Forest Service, Northern Region, Forest Pest Management. Report 90-11. 18p.

James, R.L., R.K. Dumroese, C.J. Gilligan and D.L. Wenny. 1989. Pathogenicity of *Fusarium* isolates from Douglas-fir seed and container-grown seedlings. Idaho Forest, Wildlife and Range Experiment Station Bulletin. No. 52. 10p.

James, R.L., E.P. Militante, J.Y. Woo and C.J. Gilligan. 1986. Pathogenicity of *Fusarium* from forest seedling nurseries on Douglas-fir and ponderosa pine seedlings. USDA Forest Service, Northern Region, Forest Pest Management. Report 86-8. 12p.

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

James, R.L., R. Perez, R.K. Dumroese and D.L. Wenny. 2000. Virulence of *Fusarium oxysporum* on Douglas-fir germinants: comparison of isolates from nursery soil and roots of healthy and diseased seedlings. *In*: Lilja, A. and J.R. Sutherland (eds.). Proceedings of the 4th Meeing of IUFRO Working Party 7.03.04 – Diseases and Insects in Forest Nurseries. Finnish Forest Research Institute, Research Papers 781. pp. 49-64.

James, R.L., R.K. Dumroese, D.L. Wenny, J.F. Myers and C.J. Gilligan. 1987. Epidemiology of *Fusarium* on containerized Douglas-fir seedlings. I. Seed and seedling infection, symptom production, and disease progression. USDA Forest Service, Northern Region, Forest Pest Management. Report 87-13. 22p.

James, R.L., D.M. Hildebrand, S.J. Frankel, M.M. Cram and J.G. O'Brien. 1994. Alternative technologies for management of soil-borne diseases in bareroot forest nurseries in the United States. *In*: Perrin, R. and J. R. Sutherland (eds.). Diseases and Insects in Forest Nurseries. Dijon, France, October 3-10, 1993. Institut National De La Recherche Agronominque. Les Colloques No. 68. pp. 237-246.

Kistler, H.C. 1997. Genetic diversity in the plant pathogenic fungus *Fusarium oxysporum*. Phytopathology 87:474-479.

Kliejunas, J. 1985. Effect of selected chemicals on mold development during conifer seed stratification and on subsequent germination. USDA Forest Service, Pacific Southwest Region, Forest Pest Management. Report 85-35. 7p.

Lock, W., J.R. Sutherland and L.J. Sluggett. 1975. Fungicide treatment of seeds for damping-off control in British Columbia forest nurseries. Tree Planters' Notes 26(3):16-18.

Miles, M.R. and R.D. Wilcoxsin. 1984. Production of fungal inoculum using a substrate of perlite, cornmeal, and potato dextrose agar. Plant Disease 68:310.

Mousseaux, M.R., R.K. Dumroese, R.L. James, D.L. Wenny and G.R. Knudsen. 1998. Efficacy of *Trichoderma harzianum* as a biological control of *Fusarium oxysporum* in container-grown Douglas-fir seedlings. New Forests 15:11-21.

Nelson, P.E., T.A. Toussoun and W.F.O. Marasas. 1983. *Fusarium* species: an illustrated manual for identification. The Pennsylvania State University Press, University Park. 193p.

Pawuk, W.H. 1979. Fungicide coverings affect the germination of southern pine seeds. Tree Planters' Notes 30(1):3-4.

Schippers, B. and W.H. van Eck. 1981. Formation and survival of chlamydospores in *Fusarium*. In: Nelson, P.E., T.A. Toussoun and R.J. Cook (eds.). *Fusarium*: Diseases, Biology and Taxonomy. The Pennsylvania State University Press, University Park. pp. 250-260.

Shrimpton, G. and F. Williams. 1989. Benomyl drenches: no control for *Fusarium* of *Cylindrocarpon* caused root rot of container-grown conifer seedlings. Canada-British Columbia Economic & Regional Development Agreement. Memo no. 128. 1p.

Smith, R.S., Jr. 1967. Decline of *Fusarium oxysporum* in the roots of *Pinus lambertiana* seedlings transplanted into forest soils. Phytopathology 57:1265.

Smolinska, U., M.J. Morra, G.R. Knudsen and R.L. James. 2003. Isothiocyanates produced by Brassicaceae species as inhibitors of *Fusarium oxysporum*. Plant Disease 87:407-412.

Stewart, J.E., M.-S. Kim, R.L. James, R.K. Dumroese and N.B. Klopfenstein. 2004. Molecular characterization of *Fusarium oxysporum* from tree nurseries: Tools for early detection of pathogens. Phytopathology 94:S99.

Summerell, B.A., B. Salleh and J.F. Leslie. 2003. A utilitarian approach to Fusarium identification. Plant Disease 87:117-128.

Sutherland, J.R. and E. van Eerden. 1980. Diseases and insect pests in British Columbia forest nurseries. British Columbia Ministry of Forests/Canadian Forestry Service Joint Report No. 12. 55p.

Trent, A., R. James, C. Fleege and G. Hileman. 2005. Using a steamroom to sterilize pallets of styrofoam seedling container blocks. USDA Forest Service. Technology & Development Program. Technical Report 0524-2808-MTDC. 11p.

Wenny, D.L. and R.K. Dumroese. 1987. Germination of conifer seeds surface sterilized with bleach. USDA Tree Planters' Notes 38(3):18-21.

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