Spring Fumigation Using Totally Impermeable Film May Cause Ectomycorrhizal Deficiencies at Sandy Loblolly Pine Nurseries

David B. South, Justin Funk, and C.M. Davis

Emeritus Professor, School of Forestry and Wildlife Sciences, Auburn University, AL; Nursery Manager, Garland Gray Forestry Center, Courtland, VA; Nursery Manager, Claridge State Nursery, Goldsboro, NC.

Abstract

Stunted 1-0 loblolly pine (*Pinus taeda* L.) seedlings occurred at two bareroot nurseries in 2017. At both nurseries, soil was spring fumigated and covered with a totally impermeable film (TIF). During the summer, the stunted seedlings contained less than 0.11 percent foliar phosphorus, while normal seedlings had more than 0.12 percent foliar phosphorus. The mosaic pattern of stunting was identical to new-ground syndrome, which occurs from an ectomycorrhizal deficiency on newly established pine seedbeds (i.e., on nursery areas not previously in seedling production). Although new-ground syndrome has occurred at several nurseries in the past, 2017 may be the first time spring-fumigation syndrome has occurred at established loblolly pine nurseries. This phenomenon is due to insufficient airborne spores after fumigation and a lack of soil inoculum due, in part, to a deeper fumigation zone resulting from longer periods of exposure to fumigants under TIF. Suggestions for future research directions are provided.

Introduction

Sowing loblolly pine (*Pinus taeda* L.) seed after soil fumigation with methyl bromide (< 500 kg/ha) typically does not result in stunted seedlings at time of lifting (Cram et al. 2007, Davey 1990, Enebak et al. 2013a, Marx et al. 1984). A mycorrhizal deficiency will sometimes occur, however, when pine seed are sown at a new nursery (or new field) for the first time and the fumigated soil is not subsequently recolonized with airborne spores (Hatch 1936, Kessell 1927, Marx et al. 1978, McComb 1938, McComb and Griffith 1946, Molina and Trappe 1984). When this type of ectomycorrhizal deficiency occurs, it may be referred to as "new-ground syndrome" (South et al. 1988). New-ground syndrome has been observed at loblolly pine nurseries in Alabama, Florida, Georgia, Mississippi, North Carolina, Oklahoma, South Carolina, and Virginia.

Growing agricultural crops before sowing conifers can reduce the formation of ectomycorrhiza (Sinclair 1974). At one established loblolly pine nursery in South Carolina, seedbeds were taken out of production and kept in cover crops for 5 years. Five years was apparently enough time to deplete ectomycorrhizal soil inocula; after pines were sown on the area, the new-ground syndrome appeared (figure 1).

Figure 1. Stunted pine seedlings growing in soil where pine seedlings had not been grown for the past 5 years (Cantrell 2017). (Photo by David South, 2008)

The term "old ground" is used for seedbeds formed with soil that has produced an ectomycorrhizal seedling crop within the last 5 years (South et al. 1988). When an ectomycorrhizal deficiency occurs on spring-fumigated soil that produced pines during at least 1 of the previous 5 years, it is called "spring-fumigation syndrome." Except for the occasional occurrence of "new-ground syndrome," ectomycorrhizal deficiencies in spring-fumigated loblolly pine seedbeds are rare (Davey 1990, Marx et al. 1984, South et al. 2016). About one-third of southern pine nurseries currently fumigate soil in the spring (South et al. 2016), and the pine seedlings typically have mycorrhiza colonization by midseason. For example, in 1978, loblolly pine seedlings growing in March-fumigated seedbeds (old ground) at the New Kent Nursery in Virginia had mycorrhiza on 20 to 40 percent of the short roots by July (Marx et al. 1984).

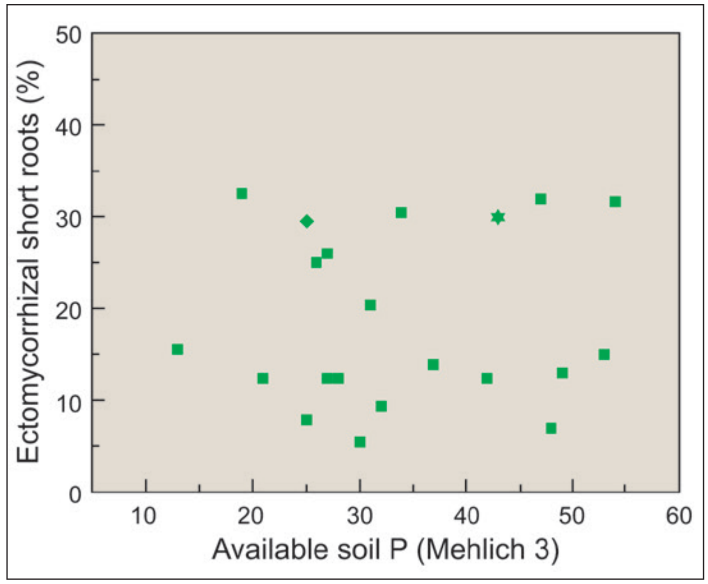

Figure 2. A survey of 21 nurseries (1977 to 1980) determined that 10 to 30 percent of loblolly pine short roots are typically mycorrhizal in the summer (Marx et al. 1984). Seedbeds at one nursery (star) were established on new ground, and seedbeds at another nursery (diamond) were fumigated with 67:33 methyl bromide:chloropicrin. All others were established on soil fumigated with 98:2 methyl bromide:chloropicrin at rates varying from 356 to 672 kg/ha (average 437 kg/ha).

The percentage of short roots that are mycorrhizal by August is typically greater than 5 percent (figure 2). A few ectomycorrhizal deficiencies in loblolly pine seedbeds have been attributed to extended periods of saturated soil and a lack of soil oxygen. But in 2017, we were surprised when spring-fumigation syndrome occurred on "old ground" at two nurseries. These deficiencies occurred on sandy soils that were in production for more than three decades. The objective of this article is to document two cases of spring-fumigation syndrome and to discuss probable causes for these recent cases and potential practices that may avoid similar events in the future.

Garland Gray Nursery

When the Garland Gray Nursery (Virginia Department of Forestry, Courtland, VA) was established in 1984, some areas in nonfumigated fields exhibited ectomycorrhizal deficiencies (South et al. 1988). Since then, fields have been fumigated many times without further incidence of stunted pine seedlings until 2017. The nursery's Gray field produced a cover crop in 2014 and produced three crops of 1-0 loblolly pines seedlings since. The Spain and Hughes fields have produced loblolly pine seedlings (using continuous cropping with spring fumigation every 2 years) for the past two decades. Nursery staff knows of no year when fumigation caused stunted pine seedlings in operational seedbeds.

Soil samples were collected from three fields (Hughes, Gray, and Spain) in December 2016 and analyzed for nutrients using the Mehlich 3 extraction method (Waypoint Analytical, Richmond, VA). Because soil phosphorus (P) levels (table 1) were greater than 25 ppm (South and Davey 1983), phosphorus was not applied before sowing. Fields were fumigated on April 12 with methyl bromide

Table 1. Soil characteristics from samples (n = 34) taken December 2016 from three bareroot fields at the Garland Gray Nursery in Courtland, VA.

Field	pH	OM	CEC	P	K	Ca	Mg	S	B	Cu	Fe	Mn	Zn	Na
-	-	%	Meq/100g	ppm	ppm	ppm	ppm	ppm	ppm	ppm	ppm	ppm	ppm	ppm
Hughes	5.0	1.3	1.5	68	20	127	15	11	0.1	0.8	130	6	2.1	13
Gray	5.0	1.4	1.7	78	24	182	21	17	0.1	0.7	117	8.9	2.2	14
Spain	5.3	1.2	1.7	60	22	164	25	7	0.1	0.8	146	4.8	2.9	16

B = boron. Ca = calcium. CEC = cation exchange capacity. Cu = copper. Fe = iron. K = potassium. Mg = magnesium. Mn = manganese. Na = sodium. OM = organic matter. P = phosphorus. pH = potential of hydrogen. S = sulfur. Zn = zinc. ppm = parts per million

(263 kg/ha) and chloropicrin (131 kg/ha) using swept-back shanks at a 25 to 30 cm depth. The soil was covered immediately with a totally impermeable film (TIF) that was later removed on April 19. The average maximum air temperature from April 12 to April 19, 2017, was 25.8 °C, which is 4.6 °C higher than the historical average for April. Loblolly pine seeds were sown on April 27. The fungicide prothioconazole (0.175 kg/ha) was applied on May 17, May 30, and June 12.

Stunted seedlings (figure 3) were observed in all three fields during the third week of July 2017. Foliage samples were collected from each field in July from stunted seedlings and from adjacent normal seedlings. Waypoint Analytical (Richmond, VA) analyzed all six foliage samples, and the results were analyzed using the PROC CORR procedure of statistical analysis software (edition 9, SAS Institute, Cary, NC). A one-sided T-test ($\alpha = 0.05$) was used to test the hypothesis that foliar nutrients were lower in stunted seedlings. It was determined that P was the only element that was significantly lower in stunted seedlings (table 2). This event is the first documented case of spring-fumigation syndrome on pines in Virginia.

To stimulate growth of stunted seedlings, an application of liquid fertilizer was applied on July 20. The application contained 28 kg/ha of P (as phosphoric acid) and 28 kg/ha of nitrogen (urea + ammonium nitrate). An increase in height and a color change were noticed by the end of July, and therefore, a second application (same rate) was made on August 3. The taller seedlings were top pruned August 1–9 (18 cm), August 14–23 (20 cm), September 1–14 (22 cm), and September 18–29 (25 cm). In December, the stunted seedlings were 18 to 25 cm tall, and normal seedlings were 25 to 30 cm tall (figure 4).

Claridge Nursery

Soon after the Claridge Nursery (North Carolina Forest Service, Goldsboro, NC) was established in 1954,

Figure 3. At the Garland Gray Nursery, soil phosphorus (P) in the Spain field ranged from 51 to 77 ppm in December 2016. The field was fumigated in April 2017. In July 2017, stunted seedlings had 0.05 percent foliar P, suggesting delayed mycorrhizal development, while normal seedlings had 0.14 percent foliar P, suggesting typical mycorrhizal development. The seedbeds in this photo have been producing seedlings (without stunting) since 1986. (Photo by Justin Funk, 2017)

Figure 4. Although taller seedlings at the Garland Gray Nursery were top pruned four times, variability in seedling height due to stunting in some seedbeds was still evident in December 2017. (Photo by Justin Funk, 2017)

Table 2. Foliage samples (n = 6) taken July 18, 2017, from stunted and normal seedlings at the Garland Gray Nursery in Courtland, VA. A one-sided T-test indicates phosphorus (P) levels were lower in stunted seedlings than in normal seedlings.

Stock	N	S	P	K	Mg	Ca	Na	B	Zn	Mn	Fe	Cu	Al
-	%	%	%	%	%	%	%	ppm	ppm	ppm	ppm	ppm	ppm
Stunted	1.82	0.097	0.057	0.91	0.100	0.31	0.037	37	52	329	1864	35	1210
Normal	1.89	0.103	0.127	1.06	0.107	0.34	0.030	26	74	319	1247	27	875
LSD	1.5	0.079	0.058	0.607	0.80	0.19	0.009	17.7	39.3	340	2736	13.6	1299

Al = aluminum. B = boron. Ca = calcium. Cu = copper. Fe = iron. K = potassium. LSD = least significant difference (a = 0.05). Mg = magnesium. Mn = manganese. N = nitrogen. Na = sodium. S = sulfur. Zn = zinc. ppm = parts per million

Figure 5. In October 2016, many seedbeds at the Claridge Nursery were inundated by floodwaters from Hurricane Matthew. Rainfall on October 8 exceeded 378 mm, and the nearby Little River crested on October 12. On April 30, 2017, the river crested again, and the nursery was flooded for a second time. During both flooding events, the problem area in Field R was not inundated. (Photo by Drew Hennant, 2016

fumigation trials demonstrated significant gains in seedling production. The Claridge Nursery staff cannot remember any cases of fumigation causing stunted pine seedlings in operational seedbeds before 2017. Although spring fumigation can delay the formation of ectomycorrhiza by a few weeks (Danielson and Davey 1969), the 2017 event is the first documented case of spring-fumigation syndrome on pines in North Carolina.

During the summer of 2016, Claridge Nursery's Field R contained forage radish (*Raphanus sativus* L. var. *niger* J. Kern.). Most of the nursery's 2016 loblolly pine seedling crop was destroyed in October due to flooding from Hurricane Matthew. At that time, Field R was fallow, and most of it remained above the flood (figure 5). Typically, Field R is fumigated in the fall, but the soil remained saturated due to above average rainfall (table 3). As a result, soil fumigation was delayed until early spring. On March 20, 2017, several fields were injected with methyl bromide (358 kg/ha) and chloropicrin (90 kg/ha) using swept-back shanks at a 25 to 30 cm depth. The soil was covered with TIF at the time of fumigation that was later removed on April 3. The average maximum air temperature from March 20 to April 11, 2017, was 22.4 °C, which is 2.5 °C higher than normal. Seeds were sown into Field R on April 11, and the soil was treated with the herbicide pendimethalin (2.1 kg/ha). The fungicide tridimefon (0.42 kg/ha) was applied on May 25 and July 13, and the fungicide prothioconazole (0.156 kg/ha) was applied on May 3, June 14, and June 28.

Stunted seedlings were observed in a section of Field R in July, and photos were taken in August (figure 6). Some of the primary needles had a purple color (Hobbs 1944, Lyle 1969, South et al. 1988). Soil samples (table 4) and foliar samples (table 5) were collected from an area of stunted seedlings and from an adjacent area of normal seedlings. Waypoint Analytical (Wilson, NC) analyzed the samples, and soil nutrients were extracted using the Mehlich 3 procedure.

Table 3. Monthly precipitation totals for locations near the Claridge Nursery (Goldsboro, NC) and Garland Gray Nursery (Wakefield, VA). Values in parentheses are the deviation from historical averages.

Year	Month	Goldsboro, NC	Wakefield, VA
-	-	mm	mm
2016	Aug	65.5 (– 83.5)	18.3 (– 111.7)
2016	Sept	330.5 (+ 178.5)	191.3 (+ 60.3)
2016	Oct	397.2 (+ 321.2)	98.5 (+ 17.5)
2016	Nov	17.8 (– 60.2)	25.1 (– 71.9)
2016	Dec	76.4 (– 5.6)	51.1 (– 36.9)
2017	Jan	70.3 (– 22.7)	104.4 (+10.4)
2017	Feb	27.7 (– 59.3)	17.3 (– 56.7)
2017	March	85.8 (– 16.2)	130.0 (+ 24.0)
2017	April	115.1 (+ 30.1)	84.3 (– 9.7)
2017	May	143.8 (+ 47.8)	127.0 (+ 23.0)
2017	June	102.1 (+ 4.1)	100.8 (– 0.2)
2017	July	39.9 (– 101.1)	106.7 (– 15.3)

Table 4. Soil samples (n = 2) taken near stunted or normal seedlings growing in Field R in August 2017 at the Claridge Nursery in Goldsboro, NC.

Stock	pH	OM	CEC	P	K	Ca	Mg	S	B	Cu	Fe	Mn	Zn	Na
-	-	%	Meq/100g	ppm	ppm	ppm	ppm	ppm	ppm	ppm	ppm	ppm	ppm	ppm
Stunted	5.4	0.4	3.7	203	41	298	41	8	0.3	1.2	199	27	3.5	18
Normal	5.4	0.4	5.7	155	27	220	36	8	0.2	0.7	148	14	1.2	19

B = boron. CEC = cation exchange capacity. Cu = copper. Fe = iron. K = potassium. Mg = magnesium. Mn = manganese. Na = sodium. OM = organic matter. P = phosphorus. pH = potential of hydrogen. S = sulfur. Zn = zinc. ppm = parts per million

Table 5. Foliage samples taken from stunted or normal seedlings in August 10, 2017 at the Claridge Nursery in Goldsboro, NC.

Stock	N	S	P	K	Mg	Ca	Na	B	Zn	Mn	Fe	Cu	Al
-	%	%	%	%	%	%	%	ppm	ppm	ppm	ppm	ppm	ppm
Stunted	3.04	0.17	0.09	1.45	0.11	0.3	0.04	128	73	827	539	10	520
Normal	1.91	0.16	0.16	1.35	0.14	0.41	0.03	112	56	475	474	10	331

Al = aluminum. B = boron. Ca = calcium. Cu = copper. Fe = iron. K = potassium. Mg = magnesium. Mn = manganese. N = nitrogen. Na = sodium. P = phosphorus. S = sulfur. Zn = zinc. ppm = parts per million

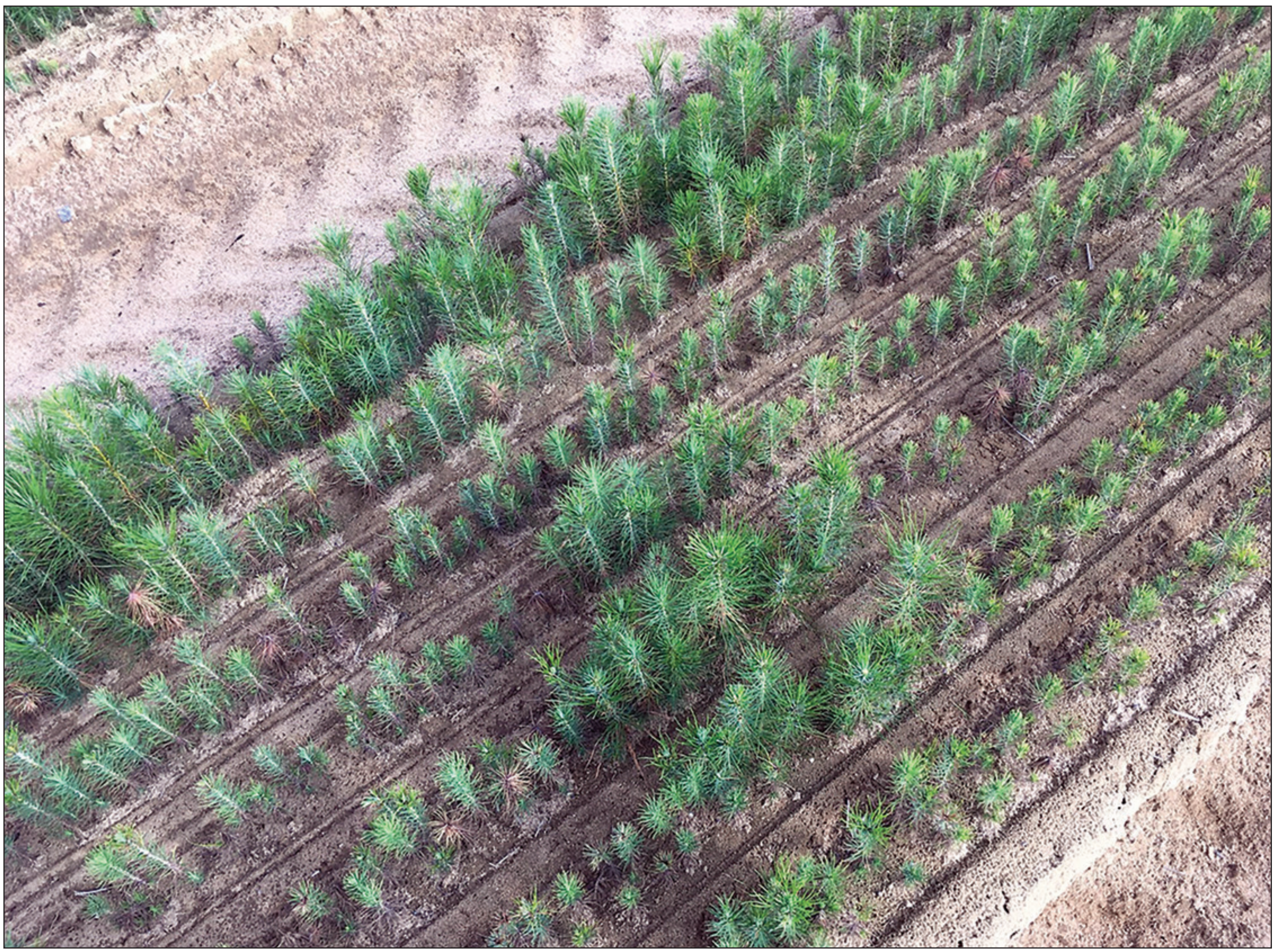

Figure 6. The soil at the Claridge Nursery had more than 150 ppm phosphorus (P) in August 2017. Stunted seedlings had 0.09 percent foliar P, suggesting insufficient mycorrhizae. The normal seedlings had 0.16 percent foliar P, suggesting sufficient mycorrhizal development. (Photo by McClain Davis, 2017)

To stimulate growth of stunted seedlings, a solution of ammonium polyphosphate was applied to all seedlings on August 28 (21.5 kg P/ha and 14.8 kg N/ha). A second treatment (same rate) was applied on September 4. A substantial change in the size and color of stunted seedlings was noticed by the middle of September. The taller seedlings were top pruned on August 28 (20 cm), September 15 (25 cm), September 25 (30 cm), and October 10 (35 cm). Stunted seedlings were typically shorter than the top-pruning height, and most never achieved the same height. In December, normal seedlings were 35 cm tall, while stunted seedlings were 20 to 30 cm tall (figure 7).

Discussion

Spore and Mycelia Inoculum in Pine Seedbeds

Ectomycorrhizal deficiencies in loblolly pine seedbeds are due to a lack of airborne spores and insufficient soilborne inoculum. Even on new ground, airborne inoculum may be sufficient for loblolly pine to have mycorrhiza in midseason (Marx et al. 1984). Sufficient airborne inoculum (figure 8) is why most new southern pine nurseries (established after 1978) produced a successful first crop of mycorrhizal pine seedlings. Spring fumigation 3 weeks before sowing in April, however, may not allow enough time for airborne spores to uniformly cover treated soil (South et al. 1988).

When bareroot 1-0 pine seedlings are harvested, roots and mycorrhiza will be stripped during the lifting process, providing the source of soilborne inoculum for succeeding crops (Henderson and Stone 1970). Spring fumigation in subsequent years may eliminate inoculum in the topsoil (0 to 25 cm), but inocula typically remain viable in soil below the fumigation zone. Therefore, once the taproot reaches viable inoculum, the roots become infected with ectomycorrhiza (even when airborne spores are lacking). Because roots can reach the inoculation zone, ectomycorrhiza can usually be detected on roots 6 to 10 weeks after seedling

Figure 7. The taller seedlings at the Claridge Nursery were top pruned four times; stunted seedlings were generally shorter than the pruning height. Variability in seedling size was still evident in December 2017. (Photo by McClain Davis, 2017)

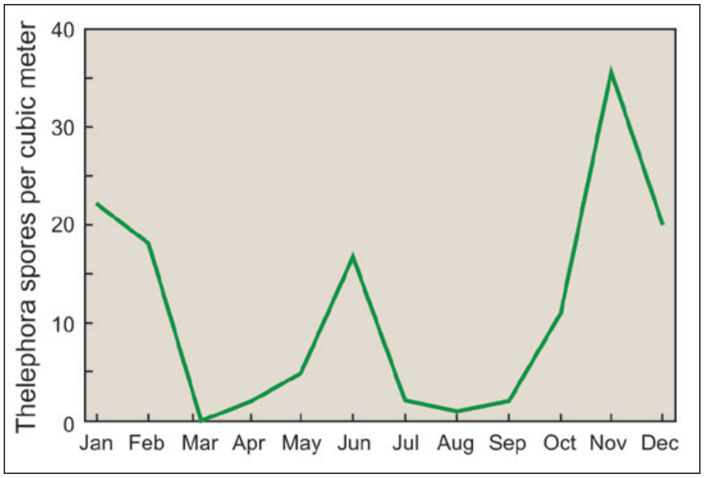

Figure 8. The average number of airborne spores (Thelephora spp.) per cubic meter of air sampled at Mérida, Spain (adapted from Trejo et al. 2013).

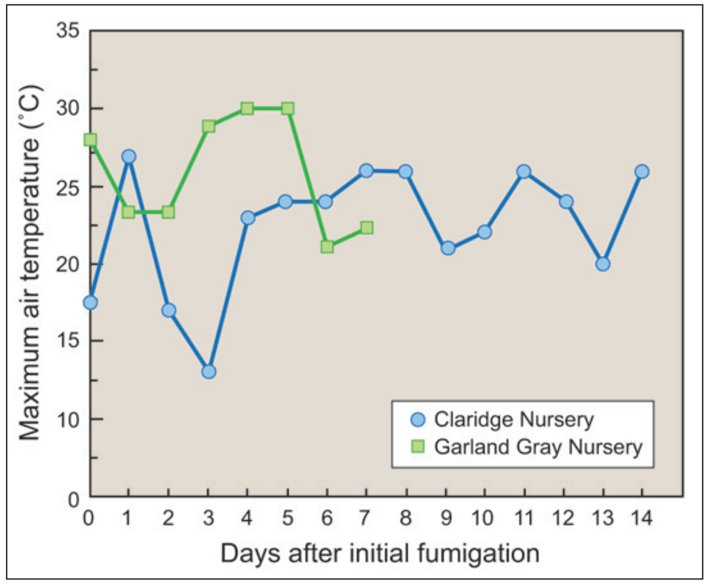

Figure 9. Maximum air temperatures during the time the totally impermeable film tarp was in place at the Claridge Nursery (dots) and the Garland Gray Nursery (squares). The 30-year average maximum temperature for April is 23.0 °C at Goldsboro, NC and 21.2 °C at Wakefield, VA.

emergence (Marx et al. 1976, Molina and Trappe 1984). The expectation that sufficient inoculum will persist after spring fumigation is so high that most managers of loblolly pine nurseries see no need to use either vegetative inoculum (Marx et al. 1978, Mitchell and South 1992), basidiospores (Marx et al.1979), or extra P fertilizer on spring-fumigated soil (South et al. 1988).

Effect of Tarp Permeability on Soil Mycorrhiza

In the past, soil fumigation included the use of low-density polyethylene plastic tarps, and the occurrence of stunted, purple loblolly pine seedlings was rare. Fumigation in the spring was common (Boyer and South 1984), and the rate of fumigant sometimes exceeded 500 kg/ha (Marx et al. 1984). For example, no stunting occurred even when a nursery (where soils were 94 percent sand) was spring fumigated (March 1978; average maximum air temperature 23 °C) with 549 kg/ha of a 67:33 mixture of methyl bromide and chloropicrin (Marx et al. 1984). Methyl bromide and chloropicrin typically would escape through the polyethylene plastic (Qin et al. 2011, Wang et al. 2005), but the use of TIF, a relatively new technological innovation (Enebak 2013, Enebak et al. 2013b), effectively increases the fumigation dosage (i.e., concentration over time), because it retains the fumigant in the soil for longer periods of time (Weiland et al. 2013). Longer retention times plus warmer temperatures (figure 9) likely contributed to killing mycelia in deeper depths of sandy soils and caused the stunting at the Garland Gray Nursery and Claridge Nursery in 2017.

For half a century, it was believed that ectomycorrhizal deficiency was more likely to occur when fumigating sandy soils (Stone et al. 1966). Indeed, fumigation is more effective on sandy soils (Collins et al. 2006, Lembright 1990). For example, no stunting occurred when TIF was used to fumigate silt loam seedbeds in Alabama (Enebak et al. 2013a) or when less sandy fields at the Claridge Nursery were fumigated in the spring of 2017.

How To Avoid Spring-Fumigation Syndrome

Fumigating in the fall is the simplest way to lower the risk of producing nonmycorrhizal seedlings in July. Even if deep fumigation eliminates the soil inoculum in lower root zones, airborne spores would inoculate the soil after the TIF was removed. Fall fumigation also allows nursery managers and contractors more flexibility to decide when to fumigate. Fall fumigation cannot be used, however, when pine seedlings are still in the fields.

When spring fumigation is required, managers may need to consider lowering the fumigant rate when the soil contains more than 84 percent sand. Effective pathogen control has been achieved using lower rates under TIF (Enebak et al. 2013b). A less expensive, high-density polyethylene (HDPE) film could be used at rural locations. For example, in Georgia, a loamy sand was fumigated with 263 kg/ha of methyl bromide plus 130 kg/ha of chloropicrin (the maximum air temperature in early April was 31 °C), and the soil was covered with HDPE (Enebak et al. 2011). This treatment did not produce stunted seedlings with purple primary needles.

Research Needs

Detection

Nursery managers who choose to fumigate in the spring need a quick, nondestructive way to detect nonmycorrhizal seedlings during the first week of July. One simple method is to monitor seedlings for reddish-purple color on tips of older primary needles (Lyle 1969). For some genotypes, however, this might be more difficult than in the past. Research at the Auburn University Southern Forest Nursery Management Cooperative determined that certain pesticides will make pine seedlings greener. For example, the herbicide pendimethalin (South and Hill 2009) and the fungicide prothioconazole (Starkey and Enebak 2011, Starkey et al. 2013) will cause loblolly pine seedlings to be greener than normal. Both chemicals were applied to seedbeds at the Claridge Nursery, and stunted seedlings still exhibited some purple primary needles.

Phosphorus Monitoring

Foliar analyses can be used to evaluate the level of P in young seedlings (Potvin et al. 2014, Rousseau and Reid 1990). When needles of young, stunted pine seedlings contain less than 0.11 percent P, then the seedlings are likely nonmycorrhizal. When pine seedlings are stunted for other reasons, the needles of mycorrhizal seedlings will have more than 0.11 percent P (table 6).

Seedlings that are 14 weeks old can have 0.07 percent foliar P, and 2 weeks later, they can have 0.17 percent foliar P (Rousseau and Reid 1991). For this reason, it is important to sample seedlings as soon as stunting or purple needles are detected. Sampling after stunted seedlings have formed mycorrhiza may be too late to detect a difference in foliar P.

Table 6. Published examples of foliar phosphorus (P) concentrations in stunted conifer seedlings from various nurseries and growth chamber studies. A lack of ectomycorrhiza is indicated when foliar P values are less than 0.11 percent.

Species	Nursery Location	P (%)		Reference
		Stunted	Normal	
Pinus resinosa Ait.	Growth chamber	0.04	0.13	Campagna and White (1973)
Pinus taeda L.	Growth chamber	0.05	0.33	Rousseau and Reid (1990)
Picea glauca (Moench) Voss	Quebec	0.05	0.16	Campagna and White (1973)
Pseudotsuga menziesii (Mirb.) Franco	Oregon	0.05	0.17	Trappe and Strand (1969)
Pinus taeda L.	Greenhouse	0.07	0.11	Ford et al. (1985)
Pinus thunbergii Parlat.	Greenhouse	0.07	0.12	Shi et al. (2017)
Pinus taeda L.	Alabama	0.07	0.15	South et al. (1988)
Pinus strobus L.	Iowa	0.07	0.16	McComb and Griffith (1946)
Pinus strobus L.	Greenhouse	0.07	0.19	Hatch (1936)
Pinus strobus L.	New York	0.08	0.13	Mitchell et al. (1937)
Pinus elliottii Engelm.	Greenhouse	0.08	0.14	Lamb and Richards (1971)
Pinus virginiana Mill.	Iowa	0.10	0.18	McComb (1938)
Pinus banksiana Lamb.	Michigan	0.12*	0.28	Potvin et al. (2014)
Pinus ponderosa Dougl. Ex Laws.	Idaho	0.15*	0.18	Morby et al. (1978)

* Chlorotic and or stunted 1-0 seedlings might be due to too much water (Idaho) or too much organic matter (Michigan).

Phosphorus Fertilizers

To reduce the risk of stunted seedlings due to endomycorrhzal deficiencies (Cram and Fraedrich 2015, South et al. 1980), some managers apply P fertilizers to hardwood seedlings soon after germination is complete in the spring (South et al. 2016). Since P deficiency is rare in pine seedbeds, routine fertilization with P is not practiced. Once an ectomycorrhizal deficiency is detected, however, several types of P fertilizers may be used to stimulate the growth of stunted seedlings. These fertilizers include phosphoric acid (South et al. 1988), superphosphate (Stone et al. 1966), triple super phosphate (Henderson and Stone 1970), ammonium phosphate, diammonium phosphate, potassium phosphite, and ammonium polyphosphate (Claridge Nursery). Research could determine which fertilizer would cause stunted seedlings to grow as rapidly as those treated with phosphoric acid.

Fungicide Effects

The fungicide triadimefon will affect the formation of ectomycorrhiza (Kelley 1982, Marx et al. 1986, South and Kelley 1982) but not enough to stunt seedlings in the nursery or to affect growth after outplanting (Rowan and Kelley 1986). As a result, triadimefon is used on loblolly pine seedlings to reduce the need to cull diseased seedlings. Researchers demonstrated that the fungicide prothioconazole can increase the number of root tips and may increase seedling growth (Starkey and Enebak 2011). Although the direct effects on ectomycorrhizal roots are not known, eight applications of prothioconazole did not stunt loblolly pine seedlings in Mississippi (Starkey et al. 2013). Multiple applications of prothioconazole on fumigated soil at the Claridge Nursery did not cause stunted seedlings on other spring-fumigated fields. Future research could determine if prothioconazole has any effect on the formation of ectomycorrhiza.

Influence of Flooding

Flooding can reduce the level of viable endomycorrhiza inoculum and, therefore, cause a P deficiency in the following year (Ellis 1998). Although several spring-fumigated fields at the Claridge Nursery flooded after fumigation in April, surviving seedlings in these fields were not stunted. Ten weeks of flooding will reduce ectomycorrhiza (Stenström 1991), but little is known about the effects of flooding on the viability of soil inoculum. Research might determine if a "postflood syndrome" also exists for ectomycorrhizal fungi.

Conclusions

For more than five decades, spring fumigation with methyl bromide and chloropicrin did not cause stunting on "old ground" until the 2017 incidences described here. Using TIF with spring fumigation (390 to 448 kg/ha) on sandy and loamy sand soils may result in purple, stunted seedlings. Where feasible, nursery managers should consider fumigating in the fall (Enebak et al. 1990, Hansen et al. 1990, Molina and Trappe 1984) to allow enough time for ectomycorrhizal spores to cover treated soil. When seedbeds are fumigated in the spring using TIF, managers may need to check for signs of purple primary needles in early July and to test foliage for P deficiencies.

Address correspondence to—

David South, Emeritus Professor, School of Forestry and Wildlife Sciences, Auburn University, AL 36849; email: southdb@auburn.edu.

Acknowledgments

The authors thank Wayne Bell (International Forest Company), Ken McQuage (International Forest Company), Scott Enebak (Auburn University), Diane Haase (U.S. Department of Agriculture, Forest Service), and Steve Godbehere (Triest Ag Group, Inc.) for providing helpful comments.

REFERENCES

Boyer, J.N.; South, D.B. 1984. Forest nursery practices in the South. Southern Journal of Applied Forestry. 8(2): 67–75.

Campagna, J.P.; White, D.P. 1973. Nursery soil fumigation affects growth and phosphorus nutrition of pine and spruce seedlings. Forestry Chronicle. 49(5): 219–223.

Cantrell, S. 2017. Personal communication. Nursery manager, Arborgen, Claxton, GA.

Collins, H.P.; Alva, A.; Boydston, R.A.; Cochran, R.L.; Hamm, P.B.; McGuire, A.; Riga, E.; 2006. Soil microbial, fungal, and nematode responses to soil fumigation and cover crops under potato production. Biology and fertility of Soils. 42(3): 247–257.

Cram, M.M.; Enebak, S.A.; Fraedrich, S.W.; Dwinell, L.D.; Zarnoch, S.J. 2007. Evaluation of fumigants, EPTC herbicides, and *Paenibacillus macerans* in the production of loblolly pine seedlings. Forest Science. 53(1): 73–83.

Cram, M.M.; Fraedrich, S.W. 2015. Inoculation of fumigated nursery beds and containers with arbuscular mycorrhizal products for eastern redcedar production. Tree Planters' Notes. 58(2): 33–39.

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

Davey, C.B. 1990. Mycorrhizae and realistic nursery management. In: Rose, R; Campbell, S.J.; Landis, T.D., eds. Proceedings, target seedling symposium. Gen. Tech. Rep. RM-200. Fort Collins, CO: U.S. Department of Agriculture, Forest Service, Rocky Mountain Forest and Range Experiment Station: 67–77.

Ellis, J.R. 1998. Post flood syndrome and vesicular-arbuscular mycorrhizal fungi. Journal of Production Agriculture. 11(2): 155–204.

Enebak, S.A. 2013. The history and future of methyl bromide alternatives used in the production of forest seedlings in the southern United States. In: Haase, D.L.; Pinto, J.R.; Wilkinson, K.M., tech. coords. Proceedings, forest and conservation nursery associations. RMRS-P-69. Fort Collins, CO: U.S. Department of Agriculture, Forest Service, Rocky Mountain Research Station: 20–25.

Enebak, S.A.; Palmer, M.A.; Blanchette, R.A. 1990. Managing soilborne pathogens of white pine in a forest nursery. Plant Disease. 74(3): 185–198.

Enebak, S.A.; Jackson, D.P.; Starkey, T.E.; Quicke, M. 2013a. Evaluation of methyl bromide alternatives on loblolly pine production and seedling quality over three growing seasons at the Pine Hill Nursery in Camden, Alabama. Journal of Horticulture and Forestry. 5(3): 41–47.

Enebak, S.A.; Starkey, T.E.; Quicke, M. 2011. Effect of methyl bromide alternatives on seedling quality, nematodes and pathogenic soil fungi at the Jesup and Glennville Nurseries in Georgia: 2007 to 2008. Journal of Horticulture and Forestry. 3(5): 150–156.

Enebak, S.A.; Starkey, T.E.; Quicke, M.; Jackson, D.P. 2013b. Evaluation of plastic tarps, reduced rates and low-impact application methods of soil fumigants on loblolly pine seedling production. The Open Forest Science Journal. 6(1): 7–13.

Ford, V.L.; Torbert, J.L.; Burger, J.A. 1985. Comparative effects of four mycorrhizal fungi on loblolly pine seedlings growing in a greenhouse in a Piedmont soil. Plant and Soil. 83(2): 215–221.

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 seedlings quality in conifer nurseries. Phytopathology. 80(8): 698–704.

Hatch, A.B. 1936. The role of mycorrhizae in afforestation. Journal of Forestry. 34(1): 22–29.

Henderson, G.S.; Stone, E.L. 1970. Interactions of phosphorus availability, mycorrhizae, and soil fumigation on coniferous seedlings. Soil Science Society of America. 34(2): 314–318.

Hobbs, C.H. 1944. Studies on mineral deficiency in pine. Plant Physiology. 19(4): 590–602.

Kelley, W.D. 1982. Effect of triadimefon (Bayleton) on ectomycorrhizae of loblolly and slash pines in Alabama. Forest Science. 28(2): 232–236.

Kessell, S.L. 1927. Soil organisms: the dependence of certain pine species on a biological soil factor. Empire Forestry Journal. 6(1): 70–74.

Lamb, R.J.; Richards, B.N. 1971. Effect of mycorrhizal fungi on the growth and nutrient status of slash and radiate pine seedlings. Australian Forestry. 35(1): 1–7.

Lembright, H.W. 1990. Soil fumigation: principles and application technology. Journal of Nematology. 22(45): 652–644.

Lyle, E.S. 1969. Mineral deficiency symptoms in loblolly pine seedlings. Agronomy Journal. 61(3): 395–398.

Marx, D.H.; Bryan, W.C.; Cordell, C.E. 1976. Growth and ectomycorrhizal development of pine seedlings in nursery soils infested with the fungal symbiont Pisolithus tinctorius. Forest Science. 22(1): 91–100.

Marx, D.H.; Cordell, C.E.; France, R.C. 1986. Effects of triadimefon on growth and ectomycorrhizal development of loblolly and slash pines in nurseries. Phytopathology. 76(8): 824–831.

Marx, D.H.; Cordell, C.E.; Kenney, D.S.; Mexal, J.G.; Artman, J.D.; Riffle, J.W.; Molina, R.J. 1984. Commercial vegetative inoculum of *Pisolithus tinctorius* and inoculation techniques for development of ectomycorhizae on bare-root tree seedlings. Forest Science. Monograph 25(3): a0001–z0001.

Marx, D.H.; Mexal, J.G.; Morris, W.G. 1979. Inoculation of nursery seedbeds with Pisolithus tinctorius spores mixed with hydromulch increases ectomycorrhizae and growth of loblolly pines. Southern Journal of Applied Forestry. 3(4): 175–178.

Marx, D.H.; Morris, W.G.; Mexal, J.G. 1978. Growth and ectomycorrhizal development of loblolly pine seedlings in fumigated and nonfumigated soil infested with different fungal symbionts. Forest Science. 24(2): 193–203.

McComb, A.L. 1938. The relation between mycorrhizae and the development and nutrient absorption of pine seedlings in a prairie nursery. Journal of Forestry. 36(11): 1148–1154.

McComb, A.L.; Griffith, J.E. 1946. Growth stimulation and phosphorus absorption of mycorrhizal and nonmycorrhizal northern white pine and Douglas fir seedlings in relation to fertilizer treatment. Plant Physiology. 21(1): 11–17.

Mitchell, H.L.; Finn, R.F.; Rosendahl, R.O. 1937. The relation between mycorrhizae and the growth and nutrient absorption of coniferous seedlings in nursery beds. Black Rock Forest Papers. 1(10): 58–73.

Mitchell, R.J.; South, D.B. 1992. Cultural enhancement of mycorrhizal fungi on southern pines? In: Chiang, C.H.; Wang, Y.N., eds. Proceedings, joint international symposium on air pollution, soil microbiology and biotechnology of forestry. Taipei, Taiwan: National Taiwan University: 145–153.

Molina, R.; Trappe, J.M. 1984. Mycorrhiza management in bareroot nurseries. In: Duryea, M.I.; Landis, T.D., eds. Forest nursery manual: production of bareroot seedlings. The Hague, The Netherlands: Nijhoff/Junk: 211–223.

Morby, F.E.; Thatcher, R.H.; Iyer, J.G. 1978. Deterioration of mycorrhiza-forming fungi and nursery stock caused by periodically impeded drainage. Tree Planters' Notes. 29(2): 31–34.

Potvin, L.R.; Jurgensen, M.F.; Dumroese, K.R.; Richter, D.L.; Page-Dumroese, D.S. 2014. Mosaic stunting in bareroot *Pinus banksiana* seedlings is unrelated to colonization by mycorrhizal fungi. New Forests. 45(6): 893–903.

Qin, R.; Gao, S.; Ajwa, H.; Sullivan, D.; Wang, D.; Hanson, B.D. 2011. Field evaluation of a new plastic film (VaporSafe) to reduce fumigant emissions and improve distribution in soil. Journal of Environmental Quality. 40(4): 1195–1203.

Rousseau, J.V.D.; Reid, C.P.P. 1990. Effects of phosphorus and ectomycorrhizas on the carbon balance of loblolly pine seedlings. Forest Science. 36(1): 101–112.

Rousseau, J.V.D.; Reid, C.P.P. 1991. Effects of phosphorus fertilization and mycorrhizal development on phosphorus nutrition and carbon balance of loblolly pine. New Phytologist. 117(2): 319–326.

Rowan, S.J.; Kelley, W.D. 1986. Survival and growth of outplanted pine seedlings after mycorrhizae were inhibited by use of triadimefon in the nursery. Southern Journal of Applied Forestry. 10(1): 21–23.

Shi, L.; Wang, J.; Liu, B.; Nara, K.; Lian, C.; Shen, Z.; Xia, Y.; Chen, Y. 2017. Ectomycorrhizal fungi reduce the light compensation point and promote carbon fixation of *Pinus thunbergii* seedlings to adapt to shade environments. Mycorrhiza. 27(8): 823–830.

Sinclair, W.A. 1974. Development of ectomycorrhizae in a Douglas-fir nursery: II. Influence of soil fumigation, fertilization and cropping history. Forest Science. 20(1): 57–63.

South, D.B.; Davey, C.B. 1983. The southern forest nursery soil testing program. Circular 265. Auburn, AL: Auburn University, Alabama Agricultural Experiment Station. 38 p.

South, D.B.; Gjerstad, D.H.; Campbell, S.J. 1980. Comparison of methyl bromide and herbicide effects on endomycorrhizal formation, seedling production, and weed control in sweetgum seedbeds. European Journal of Forest Pathology. 10(6): 371–377.

South, D.B.; Hill, T.E. 2009. Results from six *Pinus taeda* nursery trials with the herbicide pendimethalin in the USA. Southern Forests: a Journal of Forest Science. 71(3): 179–185.

South, D.B.; Kelley, W.D. 1982. The effect of selected pesticides on short-root development of greenhouse-grown *Pinus taeda* seedlings. Canadian Journal of Forest Research. 12(1): 29–35.

South, D.B.; Mitchell, R.J.; Dixon, R.K. 1988. New-ground syndrome: an ectomycorrhizal deficiency in pine nurseries. Southern Journal of Applied Forestry. 12(4): 234–239.

South, D.B.; Starkey, T.E.; Enebak, S.A. 2016. Forest nursery practices in the Southern United States. Reforesta. 1(1): 106–146.

Starkey, T.E.; Enebak, S.A. 2011. The use of Proline (Prothioconazole) to control pitch canker, Rhizoctonia foliage blight, and Fusiform rust in forest seedling nurseries and efforts to acquire registration. In: Riley, L.E.; Haase, D.L.; Pinto, J.R., tech. coords. Proceedings, forest and conservation nursery associations. RMRS-P-65. Fort Collins, CO: U.S. Department of Agriculture, Forest Service, Rocky Mountain Research Station: 49–57.

Starkey, T.E.; Enebak, S.A.; McQuage, K.; Barfield, K. 2013. Control of Rhizoctonia foliar blight in forest seedlings nurseries: a 3-year study. In: Haase, D.L.; Pinto, J.R.; Wilkinson, K.M., tech. coords. Proceedings, forest and conservation nursery associations. RMRS-P-69. Fort Collins, CO: U.S. Department of Agriculture, Forest Service, Rocky Mountain Research Station: 11–16.

Stenström, E. 1991. The effects of flooding on the formation of ectomycorrhizae in *Pinus sylvestris* seedlings. Plant and Soil. 131(2): 247–250.

Stone, E.; Henderson, G.; Terrell, E.C. 1966. Soil fumigation effects on seedling nutrition. In: Nance, D., ed. Proceedings, Northeastern area nurserymen's conference. Upper Darby, PA: U.S. Department of Agriculture, Forest Service, State and Private Forestry: 7–8.

Trappe, J.M.; Strand, R.F. 1969. Mycorrhizal deficiency in a Douglas-fir region nursery. Forest Science. 15(4): 381–389.

Trejo, F.H.; Rodriguez, A.F.M.; Molina, R.T.; Palacios, I.S. 2013. Airborne spores of Basidiomycetes in Mérida (SW Spain). Annals of Agricultural and Environmental Medicine. 20(4): 657–553.

Wang, D.; Juzwik, J.; Fraedrich, S.W.; Spokas, K.; Zhang, Y.; Koskinen, W.C. 2005. Atmospheric emissions of methyl isothiocyanate and chloropicrin following soil fumigation and surface containment treatment in bare-root forest nurseries. Canadian Journal of Forest Research. 35(5): 1202–1212.

Weiland, J.E.; Littke, W.R.; Haase, D.L. 2013. Forest nurseries face critical choices with the loss of methyl bromide fumigation. California Agriculture. 57(3): 153–161.