United States
Department
of Agriculture

Forest Service

**Rocky Mountain
Research Station**

Proceedings
RMRS-P-69

December 2013

National Proceedings: Forest and Conservation Nursery Associations – 2012

Haase DL, Pinto JR, Wilkinson KM, technical coordinators. **2013. National Proceedings: Forest and Conservation Nursery Associations—2012**. Fort Collins (CO): USDA Forest Service, Rocky Mountain Research Station. Proceedings RMRS-P-69. 114. Available at: http://www.fs.fed.us/rm/pubs/rmrs_p069.html.

Abstract

These proceedings are a compilation of 20 papers that were presented at the regional meetings of the forest and conservation nursery associations and the Intertribal Nursery Council meeting in the United States in 2012. The **Joint Meeting of the Southern Forest Nursery Association and Northeastern Forest and Conservation Nursery Association** was held at the Sheraton Read House Hotel, Chattanooga, TN, July 16 to 19, 2012. Subject matter for the technical sessions included southern nursery history, nursery insect and disease management, water quality, chilling hour review, root architecture, and soil fumigation regulations and alternatives. Field trips included tours of the Native Forest Nursery, in Chatsworth, GA, and East Tennessee State Nursery in Delano, TN. The **Joint Meeting of the Intertribal Nursery Council, Western Forest and Conservation Nursery Association, and Intermountain Container Seedling Growers' Association** was held at the Riverhouse in Bend, OR on August 11 to 13, 2012. Subject matter for the sessions was themed around seed technology for forest and conservation nurseries. This included sowing preparation, sowing strategies, advances in germination technology, seed orchards, and seed zones related to climate change and assisted migration. Additional meeting content included hands-on demonstrations with seed equipment. An afternoon field trip included tours of the USDA Forest Service Bend Seed Extractory and Wintercreek Native Plant Nursery, both in Bend, OR. The Intertribal Nursery Council portion of the meeting was also held at the Riverhouse, in Bend, OR on September 11, 2012. The meeting was hosted by the Confederated Tribes of the Warm Springs Indian Reservation and USDA Forest Service. Subject matter for the technical sessions included reforestation and restoration, low-tech tools for seed collecting and processing, seed storage and inventory, seed dormancy, Mescalero Apache greenhouse production, native plant materials development, and greenhouse structure and function.

Key Words—bareroot nursery, container nursery, nursery practices, fertilization, pesticides, seeds, reforestation, restoration, tree physiology, hardwood species, native species

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National Proceedings:
Forest and Conservation Nursery Associations—2012

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Acknowledgments:

Funding for this publication was provided as a technology transfer service by the USDA Forest Service, State and Private Forestry through the National Reforestation, Nurseries, and Genetic Resources (RNGR) Program. The compilers thank Jim Marin, Lane Eskew, Loa Collins, Nancy Chadwick, and Richard Schneider for their assistance in the preparation, printing, and distribution of this publication.

Searchable Internet Database—www.rngr.net

The National Nursery Proceedings database includes papers published in the regional nursery proceedings (Western, Intermountain, Northeastern, and Southern) since 1949. The database can be searched by date, author, or keyword and papers are available in portable document format (PDF).

Table of Contents

Joint Meeting of the Southern Forest Nursery Association and Northeastern Forest and Conservation Nursery Association, Chattanooga, Tennessee, July 16 to 19, 2012

Joint Meeting of the Intertribal Nursery Council, Western Forest and Conservation Nursery Association, and Intermountain Container Seedling Growers' Association, Bend, Oregon, August 11 to 13, 2012

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Illustration courtesy of College of Natural Resources, University of Idaho

Chilling Hours: Myths and Facts

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South DB, 2013. Chilling hours: myths and facts. In: Haase DL, Pinto JR, Wilkinson KM, technical coordinators. National Proceedings: Forest and Conservation Nursery Associations—2012. Fort Collins (CO): USDA Forest Service, Rocky Mountain Research Station. Proceedings RMRS-P-69. 3-10. Available at: http://www.fs.fed.us/rm/pubs/rmrs_p069.html

Abstract: This paper is a critical review of over four decades of research on chilling with southern pine seedlings. For most pines, freeze tolerance, seed dormancy, and endodormancy of terminal buds are affected by natural chilling (0° to 8 °C [32 to 46 °F]). Unfortunately, in the field of reforestation, several myths have emerged regarding the importance of chilling. One myth is that chilling seedlings in a dark cooler will increase freeze tolerance of southern pine seedlings and another myth states that chilling must occur before pine seedlings can be successfully "hot-planted." I once believed in the common myth that bud ecodormancy (a.k.a. quiescence) is directly responsible for acceptable storage potential of pines. However, a true "cause and effect" relationship does not exist. Several independent studies have shown that pine seedlings can survive four weeks of storage (2 °C [36 °F]) without a "well-formed" terminal bud and without any natural chilling. A critical analysis reveals that most chilling studies have confounded planting date, chilling, freeze tolerance, rainfall amounts, and photoperiod. Conclusions from these "confounded" studies were used to spread the ecodormancy=storage myth. To dispel this myth may prove difficult, since it requires establishment of studies that do not involve confounding factors. This paper also discusses a new theory about why root growth potential (RGP) of cooler-stored seedlings sometimes drops quickly when bareroot seedlings are lifted in the fall. The theory suggests low RGP occurs when certain fungi (e.g. *Pythium*) grow on succulent, wounded roots in a cool, dark, damp environment. Knowledge about early storage of pine seedlings would increase if research is directed at explaining why RGP can drop quickly after only 1 week of cooler storage. Data are not required to keep a myth alive; it only requires unquestioning faith in a theory.

Keywords: dormancy, freeze tolerance, seedling storage, nursery management, disease

Introduction

Pines grown in southern nurseries include sand pine (*Pinus clausa* [Chapm. Ex Engelm.] Sarg.), shortleaf pine (*P. echinata* Mill.), slash pine (*P. elliottii* Engelm.), longleaf pine (*P. palustris* Mill), loblolly pine (*P. taeda* L.) and Virginia pine (*P. virginiana* Mill.). The range of these species is generally below 38 °N latitude (sand pine is below 31°N) and, therefore, they receive less chilling in the nursery than pines from more northern regions. A lack of chilling will delay the formation of flower buds on trees and, therefore, chilling is economically important to fruit and nut industries.

Inadequate chilling can explain slow germination of pine seed in nursery beds and it occasionally explains low outplanting survival after a hard freeze. This paper is a critical review of over four decades of research on chilling with southern pine seedlings. The discussion regarding seed stratification is brief and more detail will be placed on bud-break and freeze tolerance. A critique will be made on the often assumed relationship between bud-dormancy status and cool-storage potential of pine seedlings.

Endodormancy and Ecodormancy

Use of the word "dormancy" can be confusing since there are many definitions for this term. When asked to explain the relationship between seedling quality and "dormancy", "few are able to articulate a clear view of what dormancy is, how it works, or how it affects quality" (Landis and others 2010). In theory, the word "dormancy" refers only to the ability of seeds to germinate or the ability of buds to elongate. However, in general practice, dormancy is used to describe a variety of conditions such as tolerance of seedlings to: desiccation, freezing temperatures, storage diseases, rough handling, high temperatures, or certain herbicides. Some believe seedlings are dormant just after shoot growth stops in the fall and they remain dormant until growth resumes in the spring. For this reason, the word dormancy will not be used in this paper (except in quotations). Instead, the words endodormancy (a.k.a rest) and ecodormancy (a.k.a. quiescence) will be used to describe the status of terminal buds (Boyer and South 1989).

The transition date when endodormancy ends and ecodormancy begins is not easy to determine. For a species like longleaf pine, it is almost impossible to determine due to the lack of bud elongation during the first year. For the purpose of this paper, the transition date occurs when the speed of bud-break is quickest (after being placed in a warm environment with, perhaps, a 15-hr photoperiod). For example if it takes 45 days before 50% of the seedlings have signs of "broken buds" in a greenhouse, then the seedlings are still in an endodormant state. In contrast, seedlings have achieved ecodormancy if it takes ≤15 days to achieve 50% bud-break.

Types of Chilling

I classify above-freezing chilling into four types. Natural-light chilling occurs under a natural photoperiod. The amount of natural-light chilling obtained on a given date depends on latitude, altitude and weather. For example, seedlings grown at Delano, Tennessee would receive more natural-light chilling by 1 January than seedlings grown at Chiefland, Florida. Artificial-light chilling is used by researchers who are investigating the effect of photoperiod on seedling physiology in storage. Artificial-light chilling occurs in growth chambers, lighted greenhouses, or lighted coolers where light-bulbs are used. Typically, natural-light chilling hour studies have confounded factors while well designed artificial-light-chilling studies are relatively free of confounding factors.

Natural-dark chilling and artificial-dark have a 24-h dark cycle (i.e. no photoperiod). Natural-dark chilling may occur when seed are heavily mulched or when seedlings are stored in an underground cellar (Dierauf and Marler 1971). Artificial-dark chilling is used by nursery managers to stratify seed and to store seedlings. Seed are chilled in a dark cooler at 2 °C (36 °F) (a.k.a. cool storage). Seedlings stored in a cooler may also be in the dark when packaged in bags or boxes. The response of seedlings to natural-light and artificial-dark chilling differs (see below).

Below-freezing temperatures can be grouped into two types. Freeze chilling occurs in the range of 0 to -2 °C (32 to 28 °F) and has a minimal effect on endodormancy status (Landis and others 2010). Hypo-chilling temperatures are below -2 °C (28°F) and most agree these temperatures do not affect the endodormany status of seedlings.

Chilling Hours

There is no universally accepted temperature range to define a "chilling hour" and reference temperatures can vary with species and nursery (Landis 2010). Several researchers in the South count hours within a range of 0 to 8 °C (32 to 46 °F; i.e. the range used in this paper). Some managers might not record chilling if it occurs before October 15 (Lantz 1989), but in some years this could reduce the number counted by 100 hours or more (DeWald and Feret 1987). Most researchers do not count temperatures below zero since freeze-chilling affects endodormancy only to a limited extent and hypo-chilling likely has no effect. However, some researchers do include freeze-chilling and hypo-chilling when summing chilling hours (Table 1). For example, Ritchie (1989) adds time in freezer-storage to the chilling hour sum even though -2°C (28 °F) is not as effective in releasing endodormancy as 2 °C (36 °F). In contrast, a few do not even count temperatures when they are less than 1.5 °C (34.7 °F; Cesaraccio and others 2004). The temperature range selected is very important to a nursery manager since, for a given date (e.g. January 31), the number might be less than 250 hours or more than 800 hours. Using a narrow temperature range might mean that a chilling hour target (developed for a wider range) is never met at some southern nurseries (Table 1).

Table 1. Temperature ranges for 13 definitions for "chilling hours" and the respective accumulation by 31 January 2012 at Claxton, Georgia.

Maximum temperature	Minimum temperature	Hours by 31 Jan	Date for 400 chilling hr	Date for 600 chilling hr	Reference
10 °C (50 °F)	None	825	14 Dec	5 Jan	Jenkinson and others (1993)
8 °C (46 °F)	None	779	16 Dec	10 Jan	Landis and others (2010)
7.2 °C (45 °F)	None	681	30 Dec	19 Jan	Weinberger (1956)
8 °C (46 °F)	0 °C (32 °F)	657	28 Dec	10 Feb	Garber (1983)
7.2 °C (45 °F)	0 °C (32 °F)	559	5 Jan	12 Feb	Voth (1989)
7 °C (45 °F)	None	547	7 Jan	12 Feb	Olson and Nienstaedt (1957)
6.7 °C (44 °F)	None	547	7 Jan	Did not achieve	Kainer and others (1991)
6 °C (43 °F)	None	456	19 Jan	Did not achieve	Ritchie (1989)
5.6 °C (42 °F)	None	455	19 Jan	Did not achieve	Ritchie (2004)
5 °C (41 °F)	None	363	12 Feb	Did not achieve	Omni and others (1994)
4.4 °C (40 °F)	None	362	12 Feb	Did not achieve	van den Driessche (1977)
5 °C (41 °F)	0 °C (32 °F)	334	26 Feb	Did not achieve	Bailey and Harrington (2006)
4.5 °C (40 °F)	0.5 °C (33 °F)	241	Did not achieve	Did not achieve	Ezell (2011)

Fact: Natural-light and Artificial-dark Chilling Increase Seed Germination

For more than two decades, researchers at Yale University conducted germination tests with pines without stratification (Toumey and Stevens 1928). At that time, the importance of pre-treating pine seed with chilling was not well known. However, some managers realized that sowing seed in January produced more pine seedlings than waiting to sow dry seed in April (Wakeley 1935). Sowing in January allowed the seed to be chilled naturally. Other managers would soak seed in cool water for a few days prior to sowing (Schenck 1907). The importance of chilling southern pine seeds was not fully realized until Lela Barton (1928) demonstrated that artificial-dark chilling would greatly increase the speed of germination. Nursery managers now use artificial-dark chilling to increase the speed of germination of several pine species.

Fact: Natural-light and Artificial-dark Chilling Increase Bud Break

It is generally believed that natural-light chilling is primarily responsible for shifting terminal buds from a state of endodormancy to a state of ecodormancy. However, a long photoperiod can also substitute for a lack of natural-light chilling (Garber 1983).

Artificial-dark chilling can be as effective as natural-light chilling in releasing endodormancy (Carlson 1985; Ritchie 2004). Similar results were observed with hardwood seedlings (Webb 1977). However, temperatures below freezing can retard the release of endodormancy of Douglas-fir (*Pseudotsuga menziesii* [Franco]; Ritchie 1984a). Although freeze-chilling had some effects on endodormancy, these findings illustrate why some researchers do not count hours below freezing toward a chilling hour accumulation.

Some Bud-break Myths

For the southern pines, it has been said that "Most sources reach maximum dormancy after 400 chilling hours" (Lantz 1987). This myth was started by those who say all genotypes of any given pine respond to chilling in a like manner. For example, Ritchie (1984b) said the relationship between the release of endodormancy for Douglas-fir and chilling sum "does not vary appreciably among seed lots and nurseries from year to year. Therefore, once the relationship has been empirically established for a given species in a given region, dormancy status during winter can be accurately predicted from monitoring chilling sums."

In contrast to Ritchie's claim, the beginning of ecodormancy of loblolly pine varies by genotype (Garber 1983; Carlson 1985; Boyer and South 1989). For some genotypes, it may be less than 415 chilling hours (Garber 1983) or over 1000 chilling hours (Carlson 1985). In fact, the same seed source may enter ecodormancy at different chilling-hour times, since the number of hours apparently varies with year and likely also with nursery management (DeWald and Feret 1988). Although a lack of chilling apparently delays the onset of ecodormancy, it is wrong to assume that 400 chilling hours are sufficient to overcome endodormancy for all southern pine genotypes, in every year, and in every nursery.

Another myth is that natural-light chilling is required for pine seedlings to enter a state of endodormancy. Although natural-light chilling typically occurs while buds are entering a state of endodormancy, chilling is not required. Natural-light chilling does not cause terminal buds of pines to become endodormant. Garber (1983) showed that endodormancy can exist in late October.

Landis and others (2010) say that "refrigerated storage has the effect of slowing the release of dormancy." For the southern pines, this is a myth because rarely do seedlings below 36 °N latitude receive 24 natural-light chilling hours/day. In contrast, each day of cooler-storage (2 °C [36 °F]) equals 24 artificial-dark chilling hours. For example, 28 days of cooler-storage will result in 672 chilling hours while 44 days of winter at Claxton, GA (28 December to 10 February) might provide only 200 chilling hours (Table 1). Obviously, at this location the release of endodormancy of loblolly pine would be quicker for artificial-dark chilling than for natural-light chilling. Regardless, the original claim about "slowing the release of dormancy" was made in regards to freeze-chilling, not artificial-dark chilling (Ritchie 1989).

Chilling Injury Myth

Cool temperatures during the fall will affect the physiology of a number of plants. Some tropical plants may experience "chilling injury" after exposure to nonfreezing temperatures below 10 °C (50 °F; Lyons 1973). In southern pine nurseries, exposure to nonfreezing temperatures below 8 °C (46 °F) can alter needle color (Grossnickle 2012). Loblolly pine seedlings from a northern seed source may turn purple (due to an increase in the production of anthocyanin combined with a decline in production of chlorophyll) while a southern source in adjacent plots may remain green. However, it is a myth to consider the purple color to be "chilling injury." In fact, this color change is considered to be beneficial since it indicates seedlings have acquired some freeze tolerance (Grossnickle 2012).

Fact: Natural-light Chilling Increases Freeze Tolerance

Much has been written about the development of freeze tolerance in conifers (Bigras and Colombo 2001). Most agree that chilling is required for tissues to become freeze tolerant. In general, seedlings of loblolly, slash, and shortleaf pine that are planted deep and have not received chilling may tolerate a -2 °C (28 °F) freeze. However, natural-light chilling is likely required for loblolly pine seedlings to develop a tolerance to a -6 °C (21 °F) freeze (Mexal and others 1979; South 2007). Seedlings kept in a heated greenhouse do not acclimate to that level of tolerance by December or January.

Some Freeze Tolerance Myths

The myth that placing bareroot loblolly pine seedlings in a cooler will increase freeze tolerance might be traced back to research conducted with eastern white pine (*P. strobus* L.) and red pine (*P. resinosa* Ait.) in Ontario (Racey 1988). Racey found that tolerance to long-term freezer storage (-3 °C [27 °F]) was increased when 3+0 stock was conditioned first by 4 weeks of storage in a cooler (1 °C [34 °F]), primarily for a 11 October lifting date. However, container-grown loblolly pine clones did not acquire tolerance to a -3 °C (27 °F) freeze after 5 weeks of artificial-dark chilling (Grossnickle 2012). Apparently, longleaf pine seedlings also do not acclimate with artificial-dark chilling. For example, survival of longleaf pine seedlings can be reduced when the cool-stored seedlings are outplanted just prior to a hard freeze (South and Loewenstein 1994; Pickens 2012).

Some have claimed that a well-formed terminal bud is required before a pine seedling can become tolerant to a -10 °C (14°F) freeze. This myth can easily be proven false by observing seedlings after a hard-freeze in a nursery (South and others 1993) or greenhouse (Duncan and others 1996). In fact, proper top-pruning of pine seedlings can increase tolerance of the stem to a freeze (South and others 1993). Apparently, the idea that setting a terminal bud was a necessary step may have come from those who claimed that endodormancy and freeze tolerance was a "cause and effect" relationship.

Lifting by Chilling Hours or by the Calendar?

Prior to 1980, nursery managers typically started lifting bareroot southern pine seedlings at about the same time each year. For example, during the late 1950s lifting at the Coosa Nursery in Alabama was near the end of November (range 17 November to 2 December). A similar period (16 November to 2 December) occurred at the Ashe Nursery in Mississippi during the late 1960s and early 1970s.

Early on, some realized that lifting stock in October or November and storing them for five months or more would kill bareroot loblolly pine seedlings (Kahler and Gilmore 1961). In contrast, seedlings lifted in late December (or early January) could be safely stored for 12 weeks in a cooler. Perhaps due to their recommendation that loblolly pine "probably should not be lifted during normal years before the middle of December for placing in cold storage," some mangers changed their target lifting date. For example, the initiation date for lifting at the Ashe Nursery during the early 1980s was mid-December. To date, researchers have not demonstrated that delaying lifting for storage till mid-January (due to a lack of chilling), is statistically better than starting to lift in late December.

It is not known why bareroot pine seedlings generally do not store well when lifted in October or early November. Several theories have emerged to explain this phenomenon. One school of thought believes that the physiological status of the terminal bud determines how long seedlings can be stored. They say terminal buds must achieve ecodormancy before they can tolerate 4 weeks or more of cooler storage. Others claim ecodormancy likely has nothing to do with the seedling storage since (1) bareroot seedlings without terminal buds can tolerate long-term storage, (2) container-grown seedlings can be stored in the fall, and (3) occasionally bareroot seedlings can be stored for 4 weeks or more when lifted in late October (Stumpff and South 1991) or early November (van den Driessche 1977). Some believe that bareroot seedlings are more vulnerable to deterioration in storage because there is greater likelihood of damage to roots during lifting in the fall (Mohammed and others 2001).

Some chilling hour myths are relatively benign (e.g. the myth that chilling is required to achieve endodormancy) since they do not impact nursery economics or regeneration success. However, when chilling hour myths delay lifting and planting windows, this can have serious economic consequences. Extending the planting season into March is not desirable for southern pines (South and Mexal 1984). An exception might occur in locations with winters that have extended periods of frozen ground. Planting in February or March would then be preferred to planting in December in the Piedmont and Mountains of Virginia (Marler 1963; Garner 1972).

Hot-Planting Myths

"Hot-planting" is a tree-planting term to describe the practice of planting seedlings within a few days of lifting (Landis and Jacobs 2008; Landis and others 2010). The term "hot" can be misleading since planting within three days of lifting can occur in any month and these seedlings may be transported in a refrigerated van. A less ambiguous term would be "<72 hour-planting" which emphasizes the time limit between lifting and planting. The "<72 hour-planting" method can occur when temperature is below freezing (in late October), and it can occur when the air temperature is above 25 °C (77°F; in January). In a perfect world, there only would be "<72 hour-planting" of southern pine seedlings (from October to February) since cooler-storage of pine seedlings is "a necessary evil" (South and Mexal 1984).

Some believe the myth that southern pine seedlings need 200 chilling hours before they are ready for no more than 3 days of storage (Lantz 1989; Ezell 2011). However, there are numerous examples where both container-grown and bareroot seedlings have been successfully "hot-planted" without any chilling. Planting during rainy months in the summer has been successful in the USA (McGregor 1965; Jordan 1966; Goodwin 1976; Woods and others 1979; Landis and others 2010) and South Africa (Donald 1976; Rolando and Little 2005). Keys to successful "hot-planting" of loblolly pine seedlings during summer months include; machine-plant seedlings when soil moisture is adequate, plant large-diameter seedlings deep (so that the root-collar is about 15 cm below the surface and roots are closer to lower, moister soil profiles), make sure the soil is not too wet (Jordan 1966) and use lignified, container-stock when hand-planting is required. In the south, perhaps 10% of container-grown seedlings are planted prior to any chilling (Dumroese and Barnett 2004).

In some regions in North America, "hot-planting" in October or November is preferable to planting in summer. In Florida, initial survival was greater than 95% when sand pine seedlings were hot-planted in mid-November (Hebb 1982). In Oklahoma, initial survival was greater than 80% when fungicide-treated shortleaf pine seedlings were hot-planted with only 48 chilling hours (Hallgren and Ferris 1995). In one study with loblolly pine, survival was 90% when seedlings were hot-planted on October 27 (Stumpff and South 1991). Although planting failures can occur during any month for many reasons, 200 chilling hours are not required in order to achieve good survival of hot-planted seedlings, regardless of stock type.

A new myth recently emerged with the claim that shortleaf pine should be hot-planted "if they have less than 600 chilling hours." At some nurseries, adherence to this myth would mean that nursery managers could not store shortleaf pine for most or all of the lifting season (Table 1). This myth apparently originated from assumptions based only on RGP data from one nursery and one genotype. However, conclusions regarding the need for chilling should be based on survival data obtained for "hot-planting" more than a single genotype from more than one nursery. In fact, authors of the RGP study clearly stated that "no attempt is made to define optimum lifting windows or storage length" (Brissette and others 1988). Their warning apparently had no effect, and another myth was born.

Cooler Storage Myths

Operational constraints "often necessitate prolonged storage (or holding) of seedlings" (Garber and Mexal 1980). For storage of bareroot southern pine seedlings, the "prime" lifting season is from late-December to early-February (Garber and Mexal 1980).

Kahler and Gilmore (1961) said that "loblolly pine seedlings cannot survive cold storage unless they are hardened off and dormant before being placed in cold storage." A decade later, Lavender and Wareing (1972) said that "a period of chilling, following short-day pretreatment, greatly increases the seedlings' resistance to the adverse effects of root damage and dark storage." Later, Weyerhaeuser researchers began to examine when loblolly pine seedlings could withstand cooler storage and they determined that one seed source could be lifted in mid-December and stored for 9 weeks (Garber and Mexal 1980). About the same time, Garber (1978) demonstrated that for another seed source, terminal buds also achieved ecodormancy by mid-December. Taken together, these independent studies were used to assume the start of ecodormancy coincided with tolerance to cooler storage. As a result, Garber and Mexal (1980) suggested that guidelines relating the stages of bud break to storage potential could be developed with a minimum amount of research. Weyerhaeuser researchers developed guidelines and nursery managers started to store seedlings based on the accumulation of chilling hours.

Instead of conducting an experiment with a testable null hypothesis, some (including me) incorrectly assumed that tolerance to storage was regulated from within the terminal bud or apical meristem. For example, Barden and Feret (1986) stated that "loblolly pine seedlings do not store well until they are fully quiescent." Instead of questioning the theory, I looked for data to support the dogma that the amount of chilling determined storage potential. Eventually, the data convinced me that the ability to survive cool storage was not related to the satisfaction of the chilling requirement for terminal buds (van den Driessche 1977; Boyer and South 1985; Stumpff and South 1991).

A common myth is that southern pine seedlings, regardless of stock type or latitude, require 400 chilling hours before they can tolerate 4 weeks of cool storage. Based on declines in RGP, DeWald and Feret (1988) said that between 400 and 500 hours of natural-light chilling are necessary for satisfactory cool storage of loblolly pine seedlings in Virginia. Based on outplanting survival for a single year, Williams and South (1995) reported that container-grown seedlings exposed to 406 chilling hours could tolerate 10 weeks of cool storage (in plastic bags) when lifted on 6 January. The magic "400" number has been mentioned in several tree planting guides (e.g. Lantz 1989), but in order to be true, the 400 number must be repeatable. However, there are no studies that show the 400 number is repeatable from different latitudes, years, or genotypes. In fact, several studies have demonstrated that container-grown seedlings have been stored for a month without any chilling (Table 2). Likewise, Boyer and South (1985) reported that bareroot seedlings could tolerate 11 weeks of cooler storage when lifted on 6 December with just 223 chilling hours. Donald and South (2002) reported good storage (4 weeks) with only 113 chilling hours and concluded that "Although chilling is beneficial to pines, since it increases the resistance to freeze injury, successful cool storage of loblolly pine seedlings may not be directly related to chilling as once believed."

Another myth says artificial-dark chilling will increase seedling tolerance to cool storage. This myth assumes that placing bareroot pine seedlings in a cooler (4 °C [39 °F]) for 17 days would harden the seedlings enough so they will then tolerate an additional 40 days of cooler-storage. This myth originates from those who claim the theory (that stress resistance increases as endodormancy weakens) applies not only to natural-light chilling, but also to freeze-chilling and artificial-dark chilling (Landis and others 2010). Some believe the theory that stress resistance of Douglas-fir seedlings (exposed to 500 natural-light chilling hours) will increase by placing the seedlings in freezer-storage for 12 weeks (Ritchie 1989). Storage data to verify this theory have not been "repeatable from year to year with different crop types (bareroot and container) and species (Douglas-fir, pines, spruces, some hardwoods) and across nurseries." In fact, when compared to seedlings left in the nursery, artificial-dark chilling can prevent an increase in seedling quality (i.e. achievement of freeze tolerance). Therefore, instead of increasing seedling quality, outplanting survival could be decreased (due to a killing hard freeze) when seedlings were lifted early and cool-stored (without receiving an adequate amount of natural-light chilling).

Table 2. Selected examples of good seedling survival of container-grown stock cooler-stored in the fall without natural chilling.

Species	Lift date	Storage length (weeks)	% survival	Reference
loblolly pine	20-Sept-2007	7	100%	South unpublished
loblolly pine	Oct-2007	4	100%	Grossnickle 2012
longleaf pine	3-Oct-2001	6	95%	Pickens 2012
longleaf pine	3-Nov-2008	4	97%	Jackson and others 2012b
shortleaf pine	3-Nov-2008	4	85%	Jackson and others 2012b
slash pine	3-Nov-2008	4	99%	Jackson and others 2012b
loblolly pine	3-Nov-2008	4	99%	Jackson and others 2012b
longleaf pine	6-Nov-2000	4 to 10	88%	South and others 2005
longleaf pine	6-Nov-2000	4 to 10	84%	South and others 2005
longleaf pine	6-Nov-2000	4 to 10	71%	South and others 2005
longleaf pine	6-Nov-2000	4 to 10	69%	South and others 2005
shortleaf pine	18-Dec-2007	4	84%	Jackson and others 2012c
slash pine	18-Dec-2007	4	83%	Jackson and others 2012c
loblolly pine	18-Dec-2007	4	88%	Jackson and others 2012c

A New Root Growth Potential- Disease Theory

A new school-of-thought regarding seedling storage has formulated a theory that may eventually replace the ecodormancy=storage theory. Researchers from this school (Jackson and others 2012a) have attempted to determine why RGP often declines rapidly when seedlings are placed in storage. Occasionally bareroot seedlings lifted in October and stored for 4 weeks can have similar RGP to non-stored seedlings. At other times, a 55% decline in RGP might occur when seedlings are stored for only one week. Understanding what factors are responsible for such diverse responses could go a long way in unraveling the reasons why results from 4 weeks of storage of October lifted bareroot seedlings have been so variable.

Some suggested that disease organisms play a major role in determining why bareroot seedlings often do not perform well after storage in the fall while container-grown seedlings can be packaged and cool-stored with acceptable survival (Table 2). Fungi (e.g. *Pythium*) might explain why the RGP can drop quickly when October lifted seedlings are placed in a cool and moist storage environment. It is known that adding too much water before storage can reduce the RGP of loblolly pine (Barden and Feret 1986). Also, when roots of Douglas-fir are kept warm (15 °C [59 °F]) in dark, cool storage (2 °C [36 °F]), seedling survival increased from 55% (cool) to 90% (warm) (Lavender and Wareing 1972). Most *Pythium* species grow well in cool, moist environments and perhaps warm roots are not conducive to their growth. Also, treating roots with certain fungicides can, under some situations, improve the storability of southern pines (Barnett and others 1988; Hallgren and Ferris 1995; Brissette and others 1996). Sometimes the correct amount of a fungicide will suppress disease and increase RGP (Hallgren and Ferris 1995). Finally, recent research indicates that RGP can be reduced in the fall when seedlings have been inoculated with certain *Pythium* species (Jackson and others 2012a). Taken together, these findings suggest the primary factor that controls storage potential of pine seedlings resides in the roots (instead of within the terminal bud).

Conclusions

Although natural-light chilling is beneficial to pines (since it increases freeze tolerance), successful cooler-storage of loblolly pine seedlings (either container or bareroot) is not directly related to the level of endodormancy. Most conclusions about natural-light chilling and cooler-storage were made from date-of-lifting studies that confounded lifting date with factors like freeze tolerance and seedling age. The conclusions were not based on studies that were designed to test a hypothesis. We need researchers who are willing to question dogmas and who are willing to expose seedling quality myths. Otherwise, we may continue to see individuals make claims about chilling that are not true.

Acknowledgements

The author wishes to thank Dr. John Mexal for his input and special thanks go to Dr. Steve Grossnickle for his comments and insights on how to successfully cooler-store container-grown loblolly pines (for four weeks) without prior exposure to natural-light chilling.

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Control of Rhizoctonia Foliar Blight in Forest Seedling Nurseries: A 3-Year Study

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Abstract: Laboratory and field trials have shown Proline® (prothioconazole) to be efficacious against the causal agent of Rhizoctonia foliar blight on loblolly pine (*Pinus taeda*). A biweekly application of Proline® at 5 fl oz/ac in nursery field tests significantly reduced *Rhizoctonia* foliar blight on loblolly pine when compared to applications of Abound® azoxystrobin (24 fl oz/ac; 1 fl oz/ac = 73.1 ml/hectare) and the non-treated control. The potential monetary loss due to Rhizoctonia foliar blight per acre was $967 for non-treated, $209 for azoxystrobin treated, and <$1 per acre for prothioconazole treated. A second trial was conducted applying prothioconazole and azoxystrobin every 3 weeks. The potential monetary loss per acre was $1,294 for non-treated, $693 for azoxystrobin treated, and <$1 per acre for prothioconazole treated. In addition to disease control, Proline®-treated seedlings were significantly larger and appeared greener than either non-treated seedlings or seedlings treated with azoxystrobin. In a third trial comparing 5 and 3 fl oz/ac of Proline®, loss of seedlings occurred at the lower rate after seedling canopy closure. Disease spread within test areas was not correlated with the prevailing winds indicating the inoculum source was within the test area. Forest seedling nurseries should change their initial fungicide application from canopy closure to 1-2 fungicide applications prior to canopy closure to reduce inoculum and disease pressure later in the growing season. Proline® is currently labeled for use in forest seedling nurseries.

Keywords: loblolly pine, longleaf pine, slash pine, chemical control

Introduction

The availability of fungicides to control specific forest seedling nursery diseases is either nonexistent, limited, or faces possible loss of US label registration. Of the many insects and diseases that occur in forest-tree nurseries, three fungal pathogens stand out as problematic in southern US nurseries. These diseases include fusiform rust, pitch canker, and *Rhizoctonia* foliar blight. Nearly all nurseries in the southern US routinely apply fungicides to prevent fusiform rust on seedlings. *Rhizoctonia* foliar blight is the second most frequently occurring disease in this region.

Longleaf (*Pinus palustris*) and loblolly (*P. taeda*) pines are particularly susceptible to *Rhizoctonia* foliar blight (English and others 1986, Runion and Kelley 1993). The disease is caused by a species of *Rhizoctonia* spp. or binculeate forms of sexual states belonging to the genera *Thanatephorus* or *Ceratobasidium*. *Rhizoctonia* foliar blight can cause significant pine mortality in nursery beds and typically occurs in late July when the seedling canopy closes in (Carey and McQuage 2003). Symptoms of dead and dying needles and seedling mortality appear in patches within the bed where moisture and temperature favor infection. Often the disease is not observed until seedlings are top-clipped to maintain seedling shoot-to-root ratios and heights. Varying degrees of resistance among seedling families can be found, with US Gulf Coastal seedlots more susceptible than Piedmont sources, and the disease has not been observed on slash pine (*P. elliotti*) (McQuage, 2009 personal communication). *Rhizoctonia* foliar blight generally is not distributed uniformly throughout a nursery and is limited to foci within nursery beds. The disease is also more severe in second or third year crops post soil fumigation. While there are fungicides registered for *Rhizoctonia* foliar blight, they are not always efficacious (Carey and McQuage 2004) with azoxystrobin being the most commonly used fungicide (McQuage, 2009 personal communication). In most nurseries in the southern region, fungicide applications begin in mid-July when seedling canopy closure occurs.

In an attempt to find alternatives for the control nursery diseases, trials examining numerous fungicides by have been conducted by the Southern Forest Nursery Management Cooperative since 2004. In 2008, Proline® 480 SC (41% prothioconazole, Bayer CropScience) (Table 1), was examined as it had a broad spectrum systemic control of ascomycetes, basidiomycetes, and deuteromycetes on numerous field food crops. Prothioconazole belongs to the new chemical class of triazolinthiones (Mauler-Machnik and others 2002) and inhibits the demethylation process at position 14 of lanosterol or 24-methylene dihydrolanosterol, which are precursors of sterols in fungi. Prothioconazole efficiently stops many steps of the fungal infection chain like appressoria and haustoria formation, mycelial growth as well as spore formation. When these research studies were initiated, Proline® was only registered in the US for food crops including peanuts, barley, wheat, sugar beets, beans, soybeans, and rapeseed. Beginning in 2008, data collected from the studies reported in this paper and other studies by the Southern Forest Nursery Management Cooperative were used to obtain a full-use label in December 2011 for disease control in forest-tree nurseries in the southern US.

Table 1. Fungicide rates, active ingredient and manufacturer.

Fungicide	Active Ingredient	Manufacturer
Proline® 480 SC	prothioconazole 41%	Bayer CropScience
Abound®	azoxystrobin 23%	Syngenta Crop Protection

The creation and expansion of these programs had a profound effect on state nurseries. An examination of seedling production shows this effect. In 1939, the 17 state nurseries that were operating produced 77,205,000 seedlings, but by 2010, the 16 state nurseries still in operation produced 118,299,000 seedlings. This dramatic increase was the result of increased mechanization, improved seed quality, and an improved understanding of seedling growth and development. These improvements made it possible for production to reach 2.3 billion tree seedlings in one year at the peak of the CRP. At the same time, the numbers of state nurseries were also at their all-time high of 42. Correspondingly, as the CRP slowed down, the number of state nurseries also decreased.

Methods

Rhizoctonia Foliar Blight Laboratory Trials

Fungal growth studies were conducted in the laboratory to determine if *Rhizoctonia solani* was able to grow on agar media amended with Proline® at 1x, 0.25x and 0.0625x the label rate of 5 fl oz/ac (1 fl oz/ac = 73.1 ml/hectare). Potato Dextrose Agar (Difco® PDA) was amended with Proline® after autoclaving and just prior to pouring the plates. There were 20 PDA plates of each fungicide concentration and 20 non-amended PDA plates used as a control. A #4 cork-borer (0.31 in; 8 mm) plug of *Rhizoctonia solani* taken from a 12-day old culture was placed at the center of each plate. The radial fungal growth was measured over a period of 7 days and recorded.

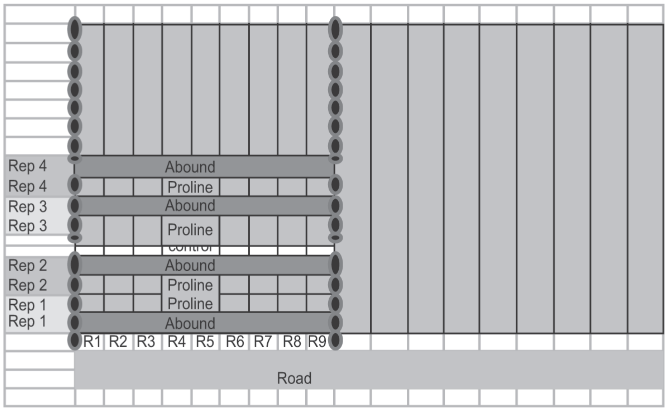

Figure 1. Experimental plot design used in each study 2008, 2009, and 2011.

Rhizoctonia Foliar Bight Field Trials

In 2008, Proline®, at 5 fl oz/ac, and Abound® (23% azoxystrobin) at 24 fl oz/ac were tested at the Pearl River, MS nursery and was applied operationally for the control of *Rhizoctonia* foliar blight. A randomized block design with four replications was used in a nursery section growing its second seedling crop following soil fumigation. Each replication plot was 40 ft x 60 ft (12.2 m x 18.3m) wide with a non-treated plot 20 ft x 60 ft (3.7m x 18.3m) left as the disease control (Figure 1). Seedling sample plots were assigned to bed-rows 2, 4, 6, and 8. Fungicides were applied on a two week interval beginning July 15, 2008 using a Hardee 1532 liter sprayer with a 9-bed spray boom; nozzles on 1.5 ft (0.5 m) centers. A total of 8 applications of both fungicides were made. Temperature and relative humidity were recorded just above the seed bed using a HOBO® data logger.

In early December 2008, seedling densities, disease incidence, severity, and seedling loss were calculated in 2 subplots within each treatment plot. From each subplot, 30 seedlings were hand-lifted and, root collar diameter, height, dry weight, and root morphology measured to determine seedling quality for each treatment.

In 2009, the identical study was established at the same nursery using the same experimental design and application methods. However, the fungicides were applied every 3 weeks, to determine the minimal spraying time interval for disease control beginning mid-July.

In 2011, Proline® was tested at, 5 fl oz/ac and 3 fl oz/ac. Fungicide applications were made every 2 weeks, beginning mid-July at canopy closure and applied operationally using the same experimental design described above. The purpose of this study was to determine if reduced rates of Proline® effectively controlled *Rhizoctonia* foliar blight. Seedling counts within each treatment were made at germination, prior to canopy closure and at prior to lifting to determine when seedling losses occurred.

Results and Discussion

Rhizoctonia Foliar Blight Laboratory Trials

Agar media amended with Proline® resulted in 100% control of *Rhizoctonia solani* as fungal growth did not occur on any of the Proline®-amended PDA plates for any concentration used for the 7 day experiment (Figure 2). This control of fungal growth with all concentrations of Proline® cannot be directly extrapolated to field use, but it does indicate that rates lower than recommended label rates may be effective.

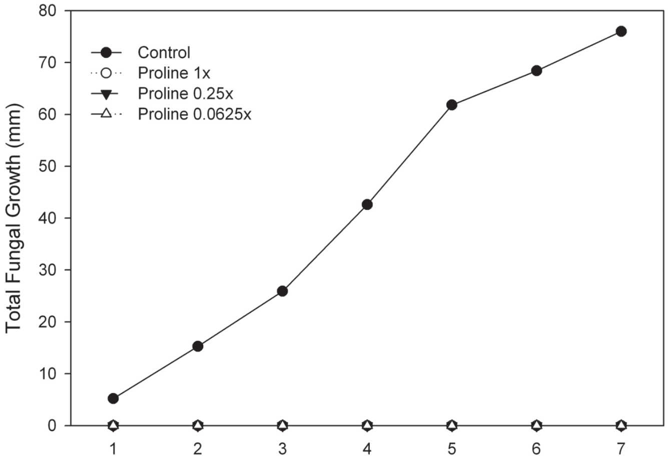

Figure 2. Radial growth of *Rhizoctonia* solani on fungicide-amended and non-amended media.

Figure 3. Control plot photo taken late September showing *Rhizoctonia* foliar blight.

Figure 4. Abound® plot photo taken late September showing *Rhizoctonia* foliar blight.

Figure 5. Proline® plot photo taken late September showing inhibited senescence and greening effect.

Rhizoctonia Foliar Blight Field Trials

In 2008, when Proline® and Abound® where sprayed at label rates at two week intervals, disease incidence, severity and number of seedling mortality in Proline® treated plots was significantly less than in the Abound® and non-treated control plots (Table 2). The potential monetary loss due to *Rhizoctonia* foliar blight was $967, $209 and <$1, per acre for non-treated, azoxystrobin, and prothioconazole, respectively. The potential monetary loss in Table 2 reflects the seedling loss in the test plot, not the whole nursery as *Rhizoctonia* foliar blight tends to occur in isolated foci in susceptible seedlots. There were no significant differences in either seedling quality or root morphology between the two fungicides tested, although the control plots had numerically fewer seedlings.

Seedlings sprayed with Proline® exhibited a "greening-up" effect that remained until the final application of Proline®. This "greening-up" effect had never been observed with any other fungicides at this nursery previously. Figures 3, 4 and 5 represent the control, Abound® and Proline® sprayed plots, respectively. The greening up effect has been observed on other crops treated with Proline® and it is reported that triazole fungicides can act to delay senescence by the generation of H_2O_2 as an intermediate metabolite (Audenaert and others 2010).

When the interval between fungicide sprays was increased from 2 to 3 weeks, Abound® had a disease incidence of 8.6% compared to <1% for the Proline® (Table 2). When comparing the two studies, the disease intensity doubled for the Abound® applications and the potential loss per acre increased over 300% when applied every 2 weeks versus

Table 2. Seedling density and disease loss as measured by incidence, severity and seedling loss per ft^2 and potential loss per acre caused by Rhizoctonia foliar blight in 2008 and 2009.

2008					
TRT	**Seedlings per ft^2**	**Disease Incidence***	**Disease Severity‡**	**Seedling loss per ft^2**	**Potential Loss per Acre**
Control†	22.9 (0.81)	0.089 (0.03)	0.3637 (0.14)	0.74	$967
Abound®	23.6	0.041	0.167	0.16	$209
Proline®	23.7	0.0008	0.003	0.00006	<$1
Prob > F	*0.7762*	*0.0004*	*0.0004*	-	-
2009					
TRT	**Seedlings per ft^2**	**Disease Incidence***	**Disease Severity‡**	**Seedling loss per ft**	**Potential Loss per Acre**
Control	16.8 (0.92)	0.13 (0.03)	0.43 (0.11)	0.99	$1,294
Abound®	20.5	0.086	0.30	0.53	$693
Proline®	19.7	0.003	0.001	0.00006	<$1
Prob > F	*0.32*	*0.0044*	*0.007*	-	-

** Incidence = proportion of RFB infected seedling per square foot of bed.*

‡ Severity = proportion of tissue infected with RFB per square foot of bed.

† Controls were not included in the statistical analysis due to lack of replication among blocks. Number in parenthesis is standard error of the mean.

every 3 weeks. The potential monetary loss was $1,294, $693, and <$1 per acre for non-treated, azoxystrobin, and prothioconazole, respectively. When using a fungicide other than Proline®, it may not be possible to increase the spray interval greater than what is specified on the label. This study suggests that the time interval between Proline® sprays using suggested label rates is not as critical as with Abound®.

The goal of the disease management programs at this nursery within these susceptible seedlots would be to keep seedling mortality to less than 0.5% (McQuage, 2009 personal communication). Proline® was effective in reducing seedling mortality due to Rhizoctonia sp. below the nursery disease threshold.

In 2011, the appearance of *Rhizoctonia* foliar blight in the nursery was limited to the control plots in our study and the field edges that received uneven fungicide applications due to stopping and starting of the sprayer. In addition, the appearance of *Rhizoctonia* foliar blight did not occur until early September which is 3-4 weeks later than previous growing seasons. When comparing Proline® sprayed at 5 and 3 fl oz/ac, more seedlings were lost at the 3 fl oz/ac than 5 fl oz/ac following canopy closure (Figure 6). After canopy closure the temperature and moisture conditions, along with seedling-to-seedling contact facilitated the aerial spread of *Rhizoctonia* foliar blight.

The appearance of *Rhizoctonia* foliar blight within the field plots in 2008 and 2009 was limited to the unsprayed control plot followed by plots treated with Abound®. There was little movement from either the control or Abound® plots into the Proline® plots. In 2011, *Rhizoctonia* foliar blight was limited to the control plots followed by the Proline® plots sprayed at 3 fl oz/ac. In each year the study-plot location was in a different area of the nursery. There was no correlation of disease spread and the prevailing wind direction during any year indicating that the inoculum within the field was the primary source for plot to plot and row to row spread.

Rhizoctonia foliar blight has 2 phases of disease development (Yang and others 1990). The first phase occurs before canopy closure, when the inoculum spreads within the field to seedlings by rain splash and irrigation. The second phase occurs after canopy closure when aerial spread of the fungus is facilitated by seedling-to-seedling contact in the presence of free moisture. Favorable fungal growth is reported to occur between 75° and 86° F (Copes and Scherm 2010; Frisina and Benson 1987) when there are 6 to 8 hours of relative humidity > 95% (Copes and Scherm 2010). There is minimal fungal growth when the temperatures exceed 90° F (Frisina and Benson 1987).

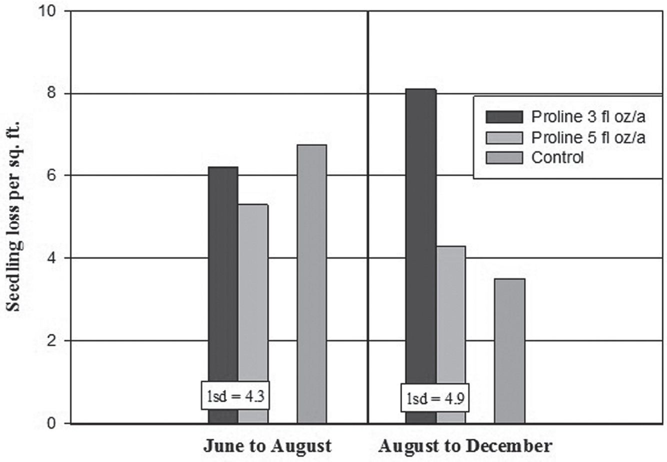

Figure 6. Loss of seedlings before canopy closure (June to August) and after canopy closure (August to December).

Figures 7-9 show the environmental conditions over the growing season within each trial and indicate (red star) the time of occurrence of *Rhizoctonia* in the nursery. The shaded boxes are the period when the temperature and free moisture fell within the bounds favorable for *Rhizoctonia* reported above. The earliest occurrence of *Rhizoctonia* occurred in 2008 and the latest was in 2011. In 2011, it is possible that the aerial spread on *Rhizoctonia* was inhibited due to the high temperatures that summer. The temperatures in 2011 were the 3rd hottest temperatures on record in 117 years. Temperatures exceeded 90° F 69% of the days from canopy closure to the first appearance of Rhizoctonia foliar blight.

In December 2011, Proline® was approved by EPA for use in forest-tree nurseries. Proline® can be used to control diseases on nursery seed and seedlings of shortleaf, loblolly, slash and longleaf pines in addition to other pines, conifers and hardwoods. Before using any new pesticide, it is always a safe practice to apply it to a test area before larger areas in the nursery. The Proline® label can be viewed at http://www.cdms.net/LDat/ld89K000.pdf.

Management Implications

Laboratory studies have shown Proline® is capable of controlling fungi in vitro at rates much lower than the label rate of 5 fl oz/ac. In field studies, Proline® effectively controlled the spread of *Rhizoctonia* using 5 fl oz/ac which is within the range of 2.5 – 5.7 fl oz/ac for registered crops. Proline® provided significantly better control than Abound® when applied at a spray interval of every 2 or 3 weeks. Increasing spray intervals with fungicides other than Proline® may not be feasible in nurseries prone to *Rhizoctonia* foliar blight.

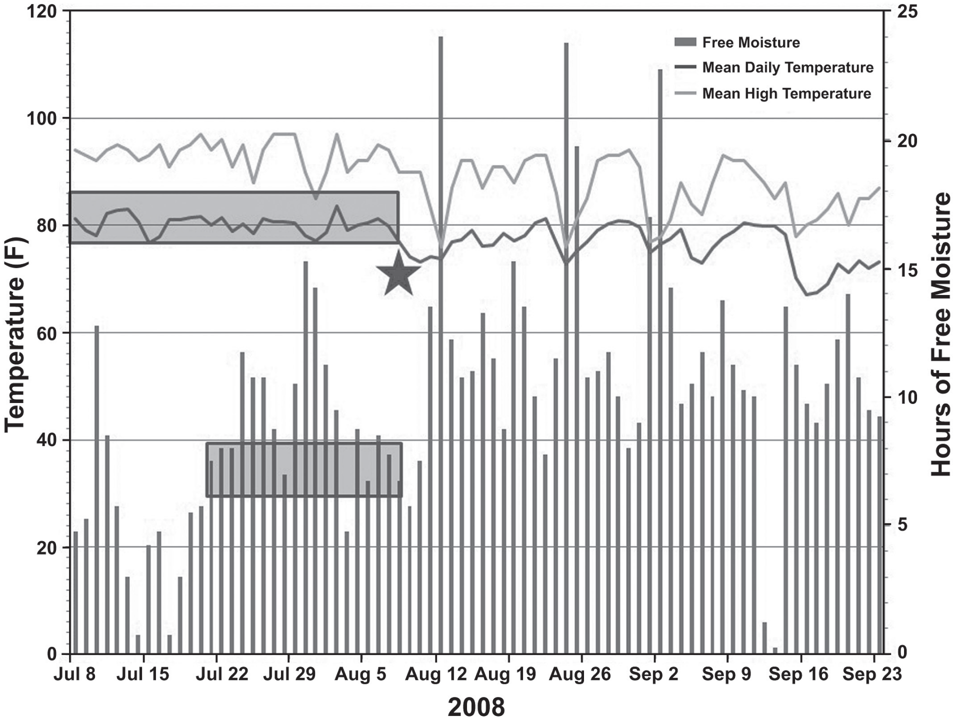

Figure 7. 2008 environmental data showing temperature, free moisture, date first Rhizoctonia foliar blight observed (star), and period in which environmental parameters favored fungal growth (shaded boxes).

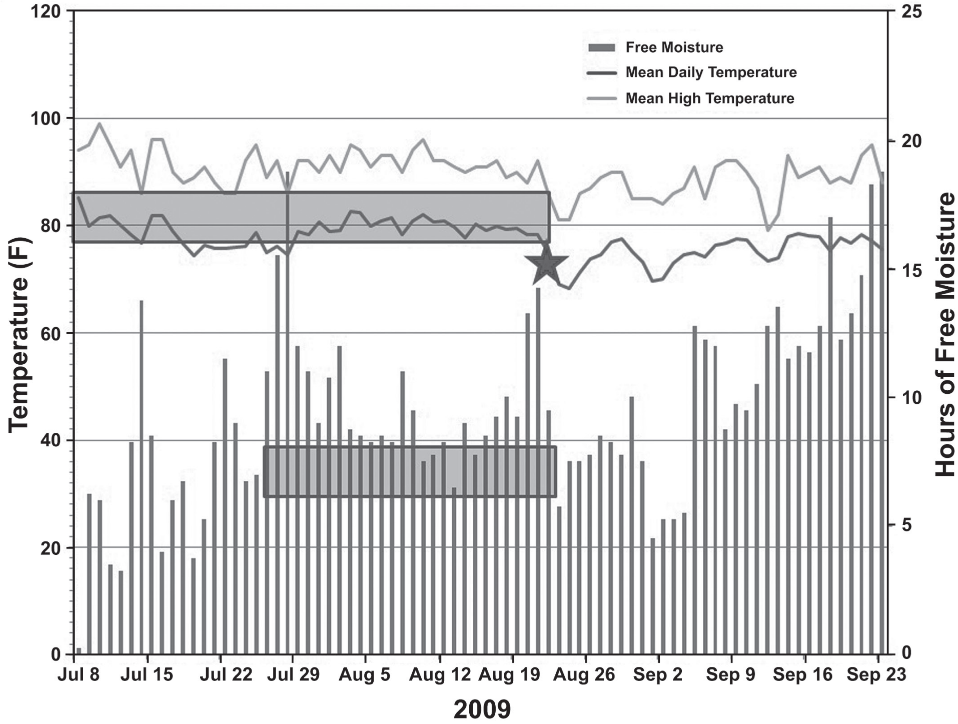

Figure 8. 2009 environmental data showing temperature, free moisture, date first Rhizoctonia foliar blight observed (star), and period in which environmental parameters favored fungal growth (shaded boxes).

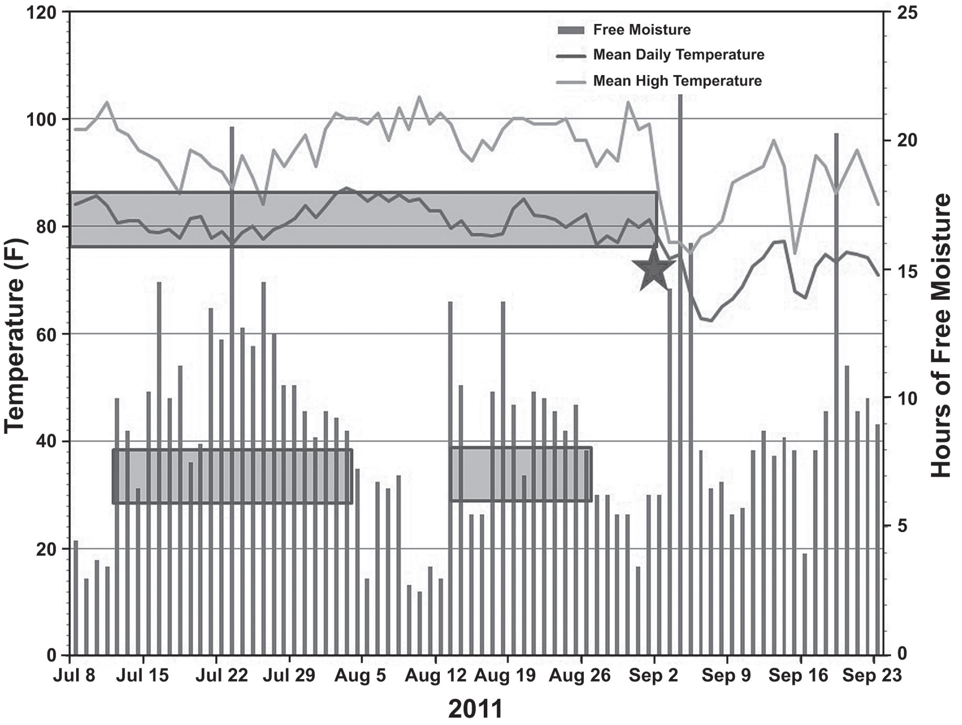

Figure 9. 2011 environmental data showing temperature, free moisture, date first Rhizoctonia foliar blight observed (star), and period in which environmental parameters favored fungal growth (shaded boxes).

The current practice of initiating fungicide applications for the control of *Rhizoctonia* foliar blight at canopy closure needs to be changed. Nurseries should start applying 1-2 fungicide applications before canopy closure when it is easier to apply fungicides to the lower stem and needles of the seedling. This will help to reduce the initial amount of inoculum found within the nursery beds and decrease disease pressure later in the growing season. In soybeans, 60% of the primary infection of *Rhizoctonia* foliar blight occurred before canopy closure (Yang and others 1990).

Mulching may also help prevent initial infection within a nursery bed. In dry beans, (*Phaseolus vulgaris* L.), mulching was highly effective for the control of *Rhizoctonia* web blight (Galindo and others 1983). The mulched layer acted as a physical barrier to prevent or reduce the splashing of the inoculum up onto the bean tissue.

The aerial spread of the fungus depends upon free moisture in the canopy. Therefore, in nurseries where *Rhizoctonia* is a problem, irrigating early in the day so as to allow the foliar to dry before nightfall will reduce the available number of hours of free moisture.

Rhizoctonia foliar blight overwinters on seedling debris in the field. Use caution when sowing susceptible families on 2nd or 3rd year land following fumigation.

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Insects and Their Life Cycle: Steps to Take to Assess Threats

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Bray AM, Oliver JB. 2013. Insects and their life cycle: steps to take to assess threats. In: Haase DL, Pinto JR, Wilkinson KM, technical coordinators. National Proceedings: Forest and Conservation Nursery Associations—2012. Fort Collins (CO): USDA Forest Service, Rocky Mountain Research Station. Proceedings RMRS-P-69. 17-19. Available at: http://www.fs.fed.us/rm/pubs/rmrs_p069.html

Abstract: This paper provides a brief overview of the importance of wood-boring insects to the forest nursery industry. Descriptions of the major insect groups are provided with special attention to the life stages that are most problematic within each group. Steps are provided to guide individuals to mitigate potential threats if a new insect is detected causing damage to trees.

Keywords: forest pest, Buprestidae, Cerambycidae, Scolytinae

Introduction

There are more insect species in the world than all other animals combined. Although there are thousands of insects accidentally introduced each year, very few become established in the introduced range and many that do establish have no significant impact. Most insects (99%) are of minor importance to humans beings; they are food for other insects and animals, scavengers, and so on. Beneficial insects are the next largest category comprising predators, parasitoids, pollinators and sources of human products (silk, dyes, honey, etc.). Humans have intentionally introduced some beneficial insects into ecosystems if the benefits out-weighted the cost of introduction. The final category of insects, destructive insects, is the smallest category. These insects receive the most attention due to the impact they have on humans, animals, and the environment. The remainder of this paper will focus on destructive insects of forest and nursery systems.

Types of Insect Pests and the Conditions that Favor Them

Within insects, beetles are the most diverse insect group. Wood-boring beetles, such as metallic borers (Buprestidae), long-horned borers (Cerambycidae), and bark and ambrosia beetles (Scolytinae), are very problematic to the forest ecosystem and the nursery industry. Bark and ambrosia beetles are extremely problematic being implicated in as much as 60% of insect-related forest mortality (Anderson 1960). Wood-boring beetles are becoming an increasing problem due to the number of non-indigenous borers introduced into the U.S. by international trade (Haack 2006; Aukema and others 2010).

A variety of environmental and biological conditions can cause an explosion of destructive forest and nursery pest populations. Environmental conditions may increase the availability of stressed trees to attack (e.g., drought, flood), and conducive temperatures or moisture may create favorable conditions for insect populations to thrive. A couple of biological conditions that may allow an increase in destructive forest-nursery pest populations could include the reduction of natural enemies that feed on the pest, or the pest switching hosts to one that has reduced defenses in a new environment.

Forest/nursery insect pests can be divided into four broad categories:

1) Defoliating forest pests, such as the gypsy moth, forest tent caterpillar and eastern tent caterpillar are damaging to large number of trees when populations exponentially increase.
2) Piercing-sucking forest pests, such as the hemlock wooly adelgid, have killed thousands of hemlock trees throughout the eastern U.S.
3) Terminal feeders, such as the pales weevil and pine tip moths, are problematic to younger trees by affecting the growth form of the tree.
4) Finally, borer pests are becoming increasingly problematic due to the cryptic nature of their life history and the damage they cause to vascular tissues in trees.

Knowledge on the life cycle of the borer pest group plays a critical role in the ability to mitigate their effects. The larvae of borers are the most destructive life stage to trees because they feed under the bark and reduce the tree's ability to transport water and nutrients. Unfortunately, borer larvae are not easily visible during pest scouting and are therefore difficult to detect, so most efforts in beetle detection are focused on the adults. Adults are most often detected when they fly to new host trees or during their search for mates. Many borer traps exploit host plant or mate-associated lures to attract the adults.

What to Do Once a Pest Problem is Detected

Once a pest problem is detected, there are several steps one should follow to determine which species is causing the damage and how to control or reduce the damage. Steps given here are written for an insect problem; however, these steps would be similar if the problem was caused by a fungus, bacteria, or virus.

Detect and Identify Pest

The first step should be identification of the pest. Collection of adults and/or larvae should be accomplished and sent to the state entomologist, extension agent, pest diagnostic center, or university entomologist (if available) for identification.

Gather Information on Biology and Life Cycle

If it is a new pest, research will need to be conducted to understand the biology of the insect, including determination of the host range, number of generations and offspring per year, sex ratio of offspring, and identification of potential native biological control organisms. Once insect identification is confirmed, available knowledge on the pest should be obtained to determine if control strategies have already been developed.

Assess Impact and Develop Monitoring and Control Strategies

A critical assessment of the economic impact should also be conducted in addition to the biological information obtained. Unfortunately, in our current economic climate of decreasing budgets, the decision to control or eradicate a forest nursery pest will most likely be based on the economic and environmental benefits of control relative to the financial cost of developing and implementing a control program. During evaluation of the biology of the insect, control strategies should be assessed to facilitate any eradiation or control program. Control strategies may include chemical control, semiochemical control (host or insect produced volatiles), host plant resistance, cultural control, and biological control (native or exotic predators and parasitoids). Other control methods may include generating sterile males of the pest population, exclusion, or legal methods (e.g., quarantines).

Emerald Ash Borer Case Study

The emerald ash borer provides a good example of the steps taken when a new pest is detected in forest and urban trees.

Detect and Identify Pest

Emerald ash borer (EAB) was first detected in Michigan and Windsor Ontario in the summer of 2002. Since its detection, it is now the most destructive introduced forest insect pest in recent U.S. history, causing the death of millions of ash trees (*Fraxinus* spp.) to date in the mid-west and eastern U.S. (USDA 2010). Specimens were first reared from ash in May 2002 in southeastern Michigan by an extension agent and sent to several experts in identification of metallic wood-boring beetles. These experts were able to determine the beetles were in the genus *Agrilus*, but the specific species was undetermined at that time. Digital images and specimens were sent to an expert in Asian *Agrilus* species, Dr. Eduard Jendek in Slovakia, who was able to make a positive identification of *A. planipennis* in July 2002.

Gather Information on Biology and Life Cycle

Research on the general biology of EAB was already underway, while it was being identified (Haack 2002). It is thought to have arrived in packing material from Asia in the early 1990's (Siegert and others 2007). Females are capable of laying 60-90 eggs with larvae boring under the bark and feeding on the phloem. All known native ash species in the U.S. are susceptible to EAB attack and several can be killed within as little as 2 years (Haack and others 2004; Anulewicz and others 2008).

Assess Impact and Develop Monitoring and Control Strategies

Due to the potential devastation of EAB in the U.S., legal control was established by implementing federal and state quarantines in hopes to limit the spread of EAB throughout the U.S. A number of new methods to detect the beetle at new locations have been developed (e.g., girdled trees, traps) and these have become an important part of the quarantine program. Effective chemical control strategies currently are targeting the destructive larval stage of EAB. Examples of chemical control are tree injections of Tree-äge (active ingredient emamectin benzoate) providing multiple years of ash tree protection or basal drench treatments of imidacloprid providing single year protection (Herms and others 2009; Smitley and others 2010). Biological control has been developed by identifying parasitoids from EAB's native range in Asia (*Spathius agrili*, *Tetrastichus planipennisi*, and *Oobius agrili*) and releasing them into the introduced range in the U.S. (Bauer and others 2007). A native predator, *Cerceris fumipennis* (Careless and others 2009) and a native parasitoid, *Atanycolus hicoriae* (Cappert and McCullough 2008) have also been identified to attack EAB. Work on semiochemical control and host plant resistance is ongoing.

Summary

Once a pest problem is detected, there are several steps one should follow to determine which species is causing the damage and how to control or reduce the damage. These steps include: 1) detect and identify the pest; 2) gather information on pest biology and life cycle; and 3) assess the impact and develop monitoring and control strategies.

The emerald ash borer case study is a good example of the steps to take when a new pest is detected in forest and urban trees. Beetle identification was accomplished within a couple months of detection using an international group of experts. The biology of the beetle has been determined in the introduced range, including host range and reproductive potential. Monitoring strategies have been developed and control strategies have been identified utilizing chemical control as well as biological control. The long-term survival of ash trees in North America is yet to be determined; however, current control strategies against EAB and continued research to develop other control methods will be critical to ensure ash remains in our environment. Lessons learned from successes and failures in detecting, identifying, assessing and mitigating new insect pests can be applied to other pest problems in forests and forest nurseries.

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The History and Future of Methyl Bromide Alternatives Used in the Production of Forest Seedlings in the Southern United States

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Abstract: This paper gives a brief history of the Southern Forest Nursery Management Cooperative's (SFNMC) efforts in testing methyl bromide (MBr) alternatives for soil fumigation. In the southeastern United States, fumigation with MBr has been the most commonly used method for producing high quality, pest-free forest-tree seedlings in an environment that is conducive for soil-borne pathogens, nematodes, and weeds. As a result of the Montreal Protocol, the production and use of MBr was to be incrementally phased out beginning in 2005. Included in this process are exemptions allowing for continued use and testing of fumigants with the goal of finding an alternative that is economically feasible and efficacious. Testing by the SFNMC has shown that, although there are alternatives to MBr, they are not as efficacious. Any choice of currently available alternatives will most likely require an increase in pesticide use to compensate for alternative short-falls. The effects of all alternatives following 4-5 crop rotations without methyl bromide are unknown. Currently, recommended alternatives vary in their effectiveness from one nursery to another. The most significant development in soil fumigant research in the last 5 years has been the availability of high barrier plastics that will allow lower fumigant rates to be used. The most efficacious alternative for forest seedling nurseries in the southern United States is one that contains a significant percentage of chloropicrin as its active ingredient.

Keywords: soil fumigation, chloropicrin, loblolly pine, high barrier plastics, broadcast fumigation

Introduction

Soil fumigation with methyl bromide (MBr) has been the standard method for producing high quality, pest-free forest-tree seedlings in the southeastern United States (Jang and others 1993, South and Enebak 2005). Methyl bromide has shown broad efficacy in the control of soil insects, nematodes, soil-borne pathogenic fungi, and problematic weeds such as nutsedge (*Cyperus* spp.) In the southern United States, *Fusarium*, *Pythium* and *Rhizoctonia* are three fungal genera that are of primary concern in the production of pine seedlings as they are associated with seedling root and foliage diseases. Over the years, methyl bromide has been effective in controlling all three of these soil-borne pathogens in a wide variety of soil types (South and others 1997).

Since soil fumigant alternatives vary in efficacy between nurseries, a description of forest seedling bareroot culture in the South may be beneficial. Loblolly pine (*Pinus taeda* L.) is the primary tree species produced in southern forest-tree nurseries. Seeds are sown in mid-April and lifting begins in December of that same year. The range of soil pH is from 5.0 to 6.0 and soil organic matter from 0.8% to 1.9%. Most nursery soils are in the sandy-loam or loamy-sand classification. Generally, forest-tree nurseries operate on a 3-yr cropping system with 2 seedling production years per soil fumigation. Fumigation can occur in either October or March. October fumigation provides a greater biological and operational window to obtain proper soil moisture and temperatures. The average nursery fumigates about 20 acres (8 ha) per year using a certified fumigation contractor. All fumigations are broadcast/flat fume using 13ft (4 m) rolls of plastic glued together (Gao and others 2011; Carey 1995).

Due to the concern over ozone depletion in the stratosphere, the Montreal Protocol under the Clean Air Act began a phase-out program for MBr use in 1991. The Southern Forest Nursery Management Cooperative (SFNMC) actually began looking for an alternative to MBr before the official phase-out program began and this paper will outline the sequence of products tested and their results. While finding an alternative for MBr has been a priority within the forest nursery industry, it has been difficult to find a soil fumigant that is as broad-spectrum as MBr.

Alternatives for MBr can be classified into two groups: non-conventional and conventional/chemical. Non-conventional alternatives include: 1) solarization, which is the use of solar energy to control soil pathogens; 2) biofumigation which uses gases from the biodegradation of organic matter; 3) hot water to heat up the soil to temperatures that kill weeds, nematodes, and other organisms; and 4) other miscellaneous alternatives such as chicken litter, yard waste, crab processing residues, and cricket litter and management of soil microorganisms (Enebak and others 1998; Vonderwell and Enebak 2000). These non-conventional alternatives can be effective under limited conditions such as small plots, row crops and container systems. However, they do not have consistent efficacy in large acreages such as bare-root production nurseries where soil types can change across a nursery section (Carey 1998).

The second group would be considered conventional alternatives which include chemicals, both individual compounds and combinations. This later group of alternatives has been the focus of the SFNMC research program since they are more easily adapted to large acreages (Carey 1994). The nursery industry realizes the importance of testing new fumigants, rates and application techniques and consequently, since 1972, the SFNMC and its cooperators have invested over $2.8 million in alternative research in 57 research studies in cooperation with many member nurseries (Enebak and others 2011a, 2011b). The largest number of studies has been undertaken in Georgia forest-tree nurseries. The following discussion of alternative research has been organized by decades beginning with the 1970's.

1970 – 1979: Decade of Methyl Bromide Acceptance

In 1975, a survey of 55 southern nurseries determined that 39 nurseries were using methyl bromide, and 28 of those nurseries were fumigating on a yearly basis. During this decade, ten studies were conducted in cooperation with the Weed Control Cooperative at Auburn University comparing herbicides with methyl bromide (South 1976; South and Gjerstad 1980).

Methyl bromide (98:2) (98% methyl bromide plus 2% chloropicrin) was being used up to 450 lbs/a (504 kg/ha) by most nurseries. At one nursery in Georgia, 1,3-dichloropropene (1,3 D) was tested. During this decade, research studies compared the economics of fumigation versus hand-weeding or herbicides for controlling weeds (South and Carey 2000). Several interesting conclusions came from these studies (South 1975).

1. Due to the low hourly labor cost, fumigation was not justified for weed control, unless nutsedge was a problem.
2. Control of nutsedge with MBr 98:2 at 444 lbs/a (497 kg/ha) in the fall was recommended.
3. Supplementing soils with endomycorrhizal fungi was justified if using MBr.
4. Alternatives to MBr were needed that would not reduce endomycorrhizae levels.
5. 1,3-D did not significantly reduce endomycorrhize levels.

1980 – 1989: Decade of Herbicides

During the 1970's the use of MBr became widespread and its broad efficacy was recognized and accepted in the production of forest-tree seedlings. In fact, during the decade following 1980, the SFNMC did not conduct a single soil fumigation study. Instead, research efforts focused on obtaining new herbicide registrations for use in nurseries over conifer seedlings. These herbicides included, Goal® (July 1979), Modown®, Poast®, Fusilade®, Roundup®, and Cobra®, most of which are still being used in 2011 (Carey and South 1998). Nursery research also focused on increasing seed efficiency and seedling quality (South 1980).

1990 – 1999: Decade of Losers & Winners

In the Spring 1992 issue of the SFNMC's Newsletter, nurseries were notified for the first time that there was a chance of losing MBr due to Environmental Protection Agency (EPA) regulations mandating a MBr phase-out under the Clean Air Act. At that time it was estimated that MBr would be phased out by the year 2000. Early on, chloropicrin was recognized as a possible MBr alternative but required additional research. While the compound had been shown to be efficacious on soil-borne fungi, insects and nematodes, the compound was not as effective on weeds, especially nutsedge.

In 1993 and 1994, small plot alternative research trials were established to compare dazomet, chloropicrin, metham sodium with and without chloropicrin, and 1,3-D in addition to soil bio-amendments. In some studies, high density plastic tarps (HDPE) were used and in other cases no tarp was used. As a result of these studies, applications of less than 250 lbs/a (280 kg/ha) chloropicrin or less than 280 lbs/a (314 kg/ha) dazomet were not recommended. Metham sodium produced seedlings similar in quality to those grown in MBr treated soil. There was no significant difference in the results whether HDPE tarps were used or not. Dazomet reduced the beneficial soil fungus, *Trichoderma*, in one trial by 91% whereas, chloropicrin more than doubled *Trichoderma* in other trials. These studies were the first to indicate that dazomet resulted in variable seedling quality and fungal control and was therefore not a strong alternative (Carey 1996). Nurseries were strongly encouraged to plan alternative soil fumigant trials and evaluations in their own nurseries before the final phase-out of MBr.

Also in 1994, a fumigation trial using hot water was established in Camden, AL. Hot water at 110°F (43°C) was shank-injected and mechanically mixed in the soil up to 6 in (15 cm) (Figure 1). This process used the equivalent of 37,000 gal (140,060 l) of water per

Figure 1. Hot water treatment of soil showing water tank and boiler system transferring hot water via hose to tractor / rotavator alongside.

acre traveling at 0.5 mph (0.8 km/hr) and produced inconsistent soil temperatures. The amount of diesel fuel required to heat this water was not reported. Because of the inconsistent results and unknown costs associated with this system, the SFNMC concluded that this was not a viable alternative for large scale alternative to MBr.

By spring 1996, only 30% of nurseries in the South fumigated their soils following every crop and 66% fumigated every two or more seedling crops (South and Enebak 2005). Alternatives that appeared to be effective were: chloropicrin, chloropicrin plus 1,3-D, and metham sodium plus chloropicrin both tarped and untarped. There was still concern about weed control using these alternatives. Therefore, the SFNMC began evaluating EPTC (Eptam®) for nutsedge control at 6 lbs ai/a (6.72 kg ai/ha) rotovated through 6 in (15 cm) of soil (Carey 1996, 1998). Initial results showed good weed activity, however, by the end of the decade the use of EPTC diminished due to the stunting of seedlings (carry over) and the necessity to rotovate this product into the soil (Cram and others 2007). Soil fumigation applicators did not have the equipment to both rotovate EPTC and simultaneously inject soil fumigants using 13ft (4 m) broadcast tarp applications.

Between 1997 and 1999, the SFNMC was optimistic with research using chloropicrin in combination with metham sodium and believed that this combination could be used without a tarp. By not using a plastic tarp, the additional problem of disposing of the tarp following fumigation was avoided. However, the optimism was short-lived. In the fall of 1999, a nursery in Texas fumigated more than 10 acres (4 ha) with metham sodium plus chloropicrin without a tarp. Following a temperature inversion that night, the fumigant did not dissipate in the atmosphere but rather settled onto areas of adjacent seedlings ready to be lifted. More than 20,000,000 seedlings were killed that evening. As a result, all non-tarped soil fumigation applications in forest-tree nurseries (experimental and operational) were halted.

2000 – 2010: The Decade of Chloropicrin

During the early years of this decade, the dazomet manufactures changed their protocol in an attempt to identify a treatment that would provide consistent results in southern US nurseries. Further tests continued with metham sodium plus chloropicrin and metham potassium plus chloropicrin (Carey 2000a, b). Studies also examined shank injected and tarped applications of: methyl iodide plus chloropicrin, methyl iodide and Telone C-35® (65% 1,3-D plus 35% chloropicrin).

The results of these studies showed metham sodium, 1,3-D and dazomet were marginally better than methyl iodide and metham potassium. The high cost of methyl iodide (nearly 5 times that of MBr and chloropicrin mixtures) was a concern to nursery managers. Telone C-35® provided good nematode control and enhanced weed control. Although metham sodium plus chloropicrin showed promising results, both metham sodium and metham potassium was dropped from further testing due to application difficulties. Broadcast/flat tarp fumigation equipment technology would not allow a 1-pass rotovation plus shank injected fumigant followed by the standard 13 ft (4 m) tarp application. Thus, until market forces bring about new application technologies, all broadcast alternatives that require some sort of rotovation will not be part of the MBr alternatives used in southern forest nurseries.

In 2003, the first small test-plots using high barrier plastic tarp (VIF – virtually impermeable film) were established. Due to the inability to glue consecutive strips of VIF using conventional HDPE plastic glue, both ends of the tarp were buried in the ground. A new chloropicrin formulation was also evaluated, PIC+®, which was 85% chloropicrin plus 15% solvent. This formulation of chloropicrin with a solvent performed akin to a slow release fertilizer, keeping the chloropicrin in the soil for a longer period of time. The presence of a tarp improved the efficacy of nutsedge control using PIC+®. There was no difference in weed control between PIC+® and chloropicrin. Also, chloropicrin and PIC+® enhanced *Trichoderma* in the soil. These studies suggested that application rates of MBr and chloropicrin could be reduced by as much 50% when using high barrier plastics (Carey and others 2005).

In 2004, dimethyl disulfide (DMDS) was first tested in small plots. Seedling quality and the amount of *Trichoderma* in soils treated with this new compound were equal to MBr. However, DMDS had an unpleasant smell, described as similar to propane, which remained in the soil for most of the growing season (Carey and Godbehere 2004).

In 2005, two fumigation studies were established that would evaluate fumigant efficacy over two growing seasons. The first trial in Georgia compared both methyl iodide and MBr under both VIF and HDPE plastic with dazomet using another new protocol and a water seal (Carey and others 2005). The results of the two year study showed methyl iodide had more weeds than other fumigants tested. The seedling quality with methyl iodide was similar to MBr. Seedling quality using VIF were similar to those using HDPE at twice the fumigant rate. However, seedling quality and growth were compromised using dazomet. At the end of the first growing season, seedlings that received dazomet never grew tall enough to be top clipped. At the end of the second growing season, only seedlings in the edge drills of the beds were top clipped. In addition, *Trichoderma* counts for the dazomet plots were the lowest compared to other treatments (Carey and others 2005). During the third year, a cover crop of corn was sown in the test area, and corn sown in the dazomet plots had poor germination (Figure 2).


Figure 2. Nursery section showing stunted corn three growing seasons after being treated with dazomet in the foreground. Methyl bromide treated soil is in the background.

A second 2-year fumigation study was established in Texas testing Chlor 60® (60% chloropicrin plus 40% 1,3-D), PIC +®, 100% chloropicrin, and dazomet. At the end of both the first and second growing seasons, the PIC+® plots were visibly taller than any other soil fumigation treatment (Starkey and Enebak 2008). Other seedling quality data confirmed that PIC+® was the best alternative in this study. Dazomet again produced the lowest quality seedlings in both growing seasons. Following the results of these 2 studies, the decision was made to stop further testing of dazomet as an alternative to MBr.

Beginning in 2007, the MBr alternative research program of the SFNMC began focusing on replicated large plot studies (greater

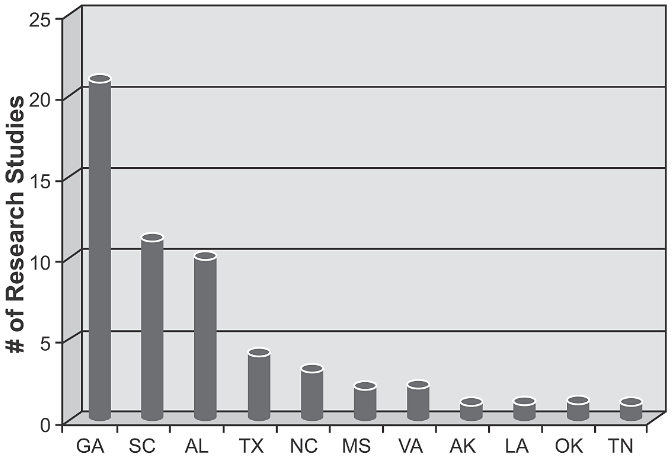

Figure 3. Summary of MBr alternative research conducted by the SFNMC; over 57 studies and $2,800,000 dollars since 1972.

Table 2. Seedling quality parameters measured and frequency.

Seedling Parameter	Frequency
RCD	at lifting
Height	at lifting
Seedling density	2 times/season
Soil assay for Nematodes	2 times/season
Soil assay for Trichoderma	2 times/season
Seedling biomass	at lifting
Root architecture: Root length Root diameter Root volume Root tips	at lifting

than 4 acres [1.6 ha]), testing of similar alternatives (when possible), in different nurseries (Table 1) and the collecting of similar data (Table 2) over 2-3 year growing cycles (Figure 3).

This new research approach was taken with the assistance of a 5-year grant from a USDA-ARS - South Atlantic Area-wide Pest Management Program for Methyl Bromide Alternatives (Anonymous 2011). This grant allowed the SFNMC Nursery Cooperative to have large-scale studies (10 acre [4 ha]) replicated studies across nurseries in the South. The data collected through this project has been used by EPA in their evaluation of the criteria needed for the soil fumigant Re-registration Eligibility Decisions (REDs) (EPA 2012).

During the first year of this project a new soil fumigant was tested. New PIC+ was a re-formulation of Pic +® but containing a different solvent. This fumigant produced similar seedling characteristics, control of nematodes and soil-borne pathogens, and *Trichoderma* to that of Pic+® but resulted in a significant annual sedge (*Cyperus compressus*) problem. Because of the weed pressure when this compound was used, it was subsequently dropped from the program after one year.

Latest Findings on Methyl Bromide Alternatives

One of the limiting factors in broadcast soil fumigations has been the inability to glue two pieces of impermeable film together along the seams to form an air-tight barrier. Since the start of the USDA Area-wide project in 2007, the largest private fumigation contractor in the southern United States developed new technologies for gluing the high barrier plastic films used in broadcast fumigation. This glue technology will allow forest nurseries to use high barrier plastics and thus significantly reduce the amount of soil fumigants used. The use of the high barrier plastics will also increase soil fumigation efficacy by allowing the soil fumigant to remain in the soil at a higher concentration and possibly over a longer period of time. By reducing application rates, the buffer zones associated with the new EPA soil fumigant labels will also be reduced, allowing greater access to nursery operations

Research by the SFNMC to date has shown that there are 3 competitive alternatives available for nursery use. These are: Pic+®, 100% chloropicrin, and DMDS plus chloropicrin (Enebak and others 2011a, b). These choices were made based upon overall seed efficiency, seedling quality at the end of the growing season, root biomass and morphology, *Trichoderma* levels after fumigation, with no excessive nematode or weed problems. There are several other points to consider when using these MBr alternatives. They all need to be used with high barrier plastics, either TIF or VIF. Chloropicrin needs to be applied at minimum rate of 250 lbs/a (280 kg/ha). While a decent alternative, the strong, lingering odor of DMDS may limit its use and acceptance by nursery managers. Chlor 60® was an effective alternative in most nurseries with respect to seedling quality and would be recommended

Table 1. Fumigant tested, rates, plastic tarps and number of research studies conducted since 2005 by the SFNMC.

Fumigant	Rate	Components	Plastic1	# of studies
Chloropicrin	300, 250, 200, 150, 100 lbs/a (336, 280, 168,112 kg/ha)	100% chloropicrin	HDPE, LDPE, VIF, TIF	7
Pic+®	300 lbs/a (336 kg/ha)	85% chloropicrin plus 15% Solvent A	HDPE, LDPE, VIF, TIF	7
New Pic+	300 lbs/a (336 kg/ha)	85% chloropicrin plus 15% Solvent B	HDPE	2
DMDS + Chlor	74, 70 gal/a (690, 653 l/ha)	79% DMDS plus 21% chloropicrin	HDPE	5
Chlor 60®	300, 250, 200, 150, 100 lbs/a (336, 280, 168, 112 kg/ha)	60% chloropicrin plus 40% 1,3-D	HDPE, LDPE, VIF, TIF	7
Midas® 50/50	160 lbs/acre (179 kg/ha)	50% methyl iodide plus 50% chloropicrin	VIF	1
Midas® 98/2	100 lbs/acre (112 kg/ha)	98% methyl iodide plus 2% chloropicrin	VIF	1

[1] LDPE – low density polyethylene; HDPE – high density polyethylene; VIF – virtually impermeable; TIF – totally impermeable.

to nurseries with a nematode problem. Weeds may become an issue with Chlor 60® if managers do not aggressively control them.

We have not had sufficient experience to adequately evaluate Midas® (methyl iodide). Arista Life Science, the manufacturer of Midas®, has not fully cooperated with our efforts to further evaluate methyl iodide in southern forest-tree nurseries (Enebak and others 2013). The manufacturer has not been willing to extend research studies much beyond Florida. The cost for a nursery to put in a study with methyl iodide is $5,000/a ($12,350/ha), a minimum of 20 acres (8 ha), and the nursery is responsible to remove all tarps. In June 2011, EPA opened up a new comment period to examine some concerns of methyl iodide and its US label. Less than a year later, in May 2012, Arista LifeSciences pulled the label on Midas® in the US. The decision came down to whether Arista could afford to keep financially supporting the registration. It typically costs $50 million to register a new active ingredient and Midas® was well north of that. Not only were there very few applications of the product, as growers were waiting to see how the situation shook out, but there the pressure from environmental groups to re-evaluate the safety of the compound. Thus, the “drop-in” replacement for MBr touted by EPA, USDA and APHIS was now gone from the US market and growers we are back to square one.

Summary

After more than 35 years of MBr alternative research, we have reached the following conclusions.

1. There are soil fumigant alternatives to methyl bromide.
2. We have yet to find an alternative as efficacious as methyl bromide.
3. Any choice of current alternatives will most likely require an increased use of pesticides (especially herbicides) to compensate for alternative short falls.
4. We do not know the long-term benefits of the alternatives. That is, what will happen in 4 or 5 fumigation cycles without methyl bromide? In row-crops there is evidence of soil-borne pathogens such as charcoal root rot appearing.
5. Methyl bromide is highly efficacious under many soil types and environmental conditions; however, alternatives do not have the same physical and chemical properties as MBr. Nurseries must pay close attention to factors such as soil moisture and temperature when using alternatives.
6. An effective alternative in one nursery may not be as effective in another nursery. All nurseries should be testing alternatives at varying rates whenever possible.
7. The most significant development in alternative research in the last 5 years has been the availability of high barrier plastics (TIF and VIF) and the technology to glue this plastic for broadcast fumigation applications.
8. When transitioning from low barrier plastic such as HDPE to high barrier plastics such as TIF and VIF, fumigation rates can be reduced by half. This recommendation should be used with caution since fumigant efficacy varies between nurseries.
9. In our studies, a soil fumigant becomes more efficacious when chloropicrin is part of the formulation at rates above 20%. Three examples are below, however, methyl iodide (Midas®) is no longer available in US markets.
    a. DMDS versus DMDS plus chloropicrin (Paladin®)
    b. Methyl iodide versus Methyl iodide plus chloropicrin (Midas®)
    c. Telone® versus Telone® plus chloropicrin (Chlor 60®)

Future Research with MBr Alternatives

With EPA buffer zone restrictions coming in place in the spring of 2013, low barrier plastics (HDPE and LDPE) will become used less frequently. Since high barrier plastics (VIF and TIF) cost significantly more than low barrier plastics, fumigation costs can be reduced by decreasing the amount of soil fumigant used. In the future, we can expect new plastic technology for controlling emission rates. Although effective, high barrier plastics like TIF have been criticized for not allowing any gas to permeate through the barrier thus potentially creating a problem with outgassing and bystander exposure when the tarps are cut for removal after 10-14 days. New, untested soil fumigants will be harder to register in the future than compounds already labeled and in the market. For example, the SFNMC was evaluating sulfuryl fluoride as a soil fumigant until EPA expressed concern over the release of fluoride into the environment. Opportunities exist for new application technologies to be developed in broadcast fumigation that would allow a combination rotovator/injector/flat tarp applicator or a combination potassium thiosulfate applicator/injector/flat tarp applicator. There is also a need to explore changes in fumigant chemistry that will allow injections of several fumigants in single pass using existing application techniques similar to what nurseries now do by tank mixing pesticides to make them more efficacious. Nurseries also need to look at current management practices that can be altered to reduce the impact of buffer zones (reduce emissions). For example, increasing soil organic matter will make seedling management easier, and will also provide additional buffer zone credits for fumigation (EPA 2012).

In the last few years, the ability to use soil fumigation in forest-tree nurseries has dramatically changed. With respect to fumigant options, the future does not look optimistic for increasing the use of soil fumigants. The choices for viable alternatives will most likely be limited and decrease as each soil fumigant is reexamined again for registration that is scheduled to begin after 2013 (EPA 2012). The forest nursery community must keep aware of regulatory changes that may impact future soil fumigation, for example, there was discussion concerning the possible elimination of chloropicrin as a soil fumigant. This idea was dropped for now. If it ever becomes an issue, a unified response from the nursery community to advocate for the continued use of this fumigant may be warranted, since chloropicrin is part of every efficacious alternative the forest nursery industry currently has available today.

Acknowledgements

The author and staff of the SFNMC would like to acknowledge the support of TriEst Ag Group (formerly Hendrix & Dail), Tifton, Georgia, the USDA – ARS for a 5 year grant “ Area-wide Pest Management Project for Methyl Bromide Alternatives – South Atlantic Region” and the pioneering MBr research efforts of Dr. Bill Carey (deceased) who was killed by a drunk driver on his way back to Auburn from a MBr Alternatives Meeting in Georgia.

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Root System Architecture: the Invisible Trait in Container Longleaf Pine Seedlings

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Abstract: Longleaf pine (*Pinus palustris* Mill.) seedlings cultured in four cavity volumes (60 to 336 ml [3.7 to 20.5 cubic inches]), two root pruning treatments (with or without copper coating), and 3 nitrogen levels (low to high) were grown for 29 weeks before they were outplanted into an open area in central Louisiana. Twenty-two months after outplanting, 3 seedlings were excavated from each of the 24 treatment combinations to evaluate effects of nursery cultural treatments on seedling growth and root system architecture. This paper reports some preliminary observations from that sample. Seedlings cultured in copper coated cavities had more lateral roots egressing into the top 10 cm (3.9 in) of soil whereas those cultured without copper root pruning had most of their lateral roots egressing into deeper (> 10cm [> 3.9 in]) soil layers. Regardless of nursery treatments, adventitious roots that originated near the air-pruned taproot end in some seedlings grew horizontally instead of vertically downward as in most container seedlings. Relationships between root system architecture and longleaf growth and mechanical stability are discussed.

Keywords: artificial regeneration, first-order lateral roots, horizontal root anchorage, mechanical stability, *Pinus palustris*, taproot, vertical root anchorage

Introduction

The longleaf pine ecosystem is one of the most biologically diversified ecosystems. During the last two decades, public and private land managers and owners have actively committed to restore this ecosystem, of which 97% has been lost since the turn of the 20th century (Landers and others 1995; Outcalt 2000). One of the 15-year goals in the Range-Wide Conservation Plan for Longleaf Pine calls for increasing the area of longleaf forests from the current 1.4 million hectares (3.5 million acres) to 3.2 million hectares (7.9 million acres; America's Longleaf 2009). Natural regeneration is only feasible on a small portion of the existing longleaf forests and it depends on bumper seed crops that take place every 5 to 7 years. Therefore, establishment of most new longleaf forests will rely on artificial regeneration with bareroot or container stock.

Improvements made in seedling container technology and nursery cultural practices in the last few decades resulted in the preference of container to bareroot stock for longleaf pine regeneration (Brissette and others 1990; Barnett and McGilvray 2000; Barnett and others 2002; Dumroese and others 2009). Percentages of container stock in longleaf seedlings grown in the southern U.S. increased from 70% in 2005 (McNabb and Enebak 2008) to 84% in 2008 (Dumroese and others 2009). Greater first year field survival and early stem growth of container longleaf seedlings compared with that of bareroot seedlings is one reason for this preference (Barnett and McGilvray 2000; South and others 2005). Another advantage is that the outplanting window can be extended from the 10 days or so with bareroot stock to 1-3 months (in cold storage for several weeks after extracting from the containers) with container stock (Barnett and McGilvray 2000; Pickens 2012). Research showed that field performance of container longleaf pine seedlings increases with increasing container cavity volume (South and others 2005; Sword Sayer and others 2009, 2011; Sung and others 2010), nitrogen fertilization level in the nursery (Jackson and others 2012), and copper root pruning treatments (Haywood and others 2012).

The stand establishment benefits gained from planting container stock, however, may not be fully realized without considering root system. For example, 11 years after outplanting, container lodgepole pine (*P. contorta* var. *contorta* Dougl.) saplings grew less and had different root system architecture than naturally regenerated trees (Halter and others 1993). The container lodgepole pine trees had less structural lateral root symmetry, a concentration of lateral roots 10 cm (3.9 in) below the soil surface, and a greater number of constricted, kinked, or coiled roots compared to their natural counterparts (Halter and others 1993). Naturally regenerated longleaf pine seedlings have straight taproots extending deep into the soil profile from which most first-order lateral roots originate and then extend in a horizontal plane at a uniform depth throughout their entire length (Heyward 1933). Hodgkins and Nichols (1977) found that most lateral roots of natural longleaf trees are within the top 10 cm (3.9 in) of soil. As expected, root system architecture of container longleaf pine differs from that of naturally grown trees in at least two aspects. First, taproots are air pruned when they reach the container drainage holes. Once outplanted, adventitious roots originate near the site of air pruning and usually grow downward (South and others 2001). Second, lateral roots of longleaf pine seedlings, similar to the roots of all container seedlings, are deflected when they contact cavity walls. Although vertical ribs mitigate root circling common in early types of containers (Burdett 1979; Barnett and Brissette 1986), the downward extending lateral roots result in a cage-like appearance of the root plug (Burdett 1978; Barnett and McGilvray 2002). Numerous studies have shown that growing tree seedlings in cavities having their interior surface coated with copper compounds can stop lateral root extension and prevent formation of the cage-like appearance (Ruehle 1985; see Dumroese and others forthcoming). As with other conifers grown in copper-treated containers (for example, Wenny and others 1988), egress of lateral roots of longleaf pine seedlings after outplanting was uniform along the length of root plugs, contrasting with most lateral roots egressing from the bottom of the root plug when cultured in non-root pruning cavities (Sword Sayer and others 2009; Sung and others 2009, 2012).

Changes in lateral root architecture of container seedlings have been attributed to physical instability after outplanting (Burdett 1978, 1979; Burdett and others 1986). Most of the regenerated longleaf pine forests are within 240 km of the Atlantic and Gulf States coasts, which have experienced increasing frequency and intensity of tropical wind storms, including hurricanes, in recent years. Although stems of longleaf pine trees suffered less wind damage by hurricanes than loblolly pine (Gresham and others 1991; Johnsen and others 2009), concern remains that longleaf pine stands originated from container stock may be more prone to juvenile stem instability, such as toppling and leaning. Therefore, studies elucidating the association between sapling stem instability and root system architecture in container longleaf pine saplings are ongoing (Sung and others 2009, 2012).

This paper reports preliminary results of root system architecture in outplanted longleaf pine seedlings cultured in combinations of four cavity volumes, two root pruning treatments, and three relative nitrogen rates.

Materials and Methods

Greenhouse Study

The first phase of this study was conducted in a USDA Forest Service, Rocky Mountain Research Station's greenhouse located in Moscow, Idaho USA (46.72,-117.00) and was described in detail by Dumroese and others (forthcoming). Briefly, longleaf pine seeds of mixed seedlots from Louisiana were sown into cavities filled with a 1:1 (v:v) Sphagnum peat moss:vermiculite medium on 15 May. The study was a randomized complete block design with 4 cavity volumes x 2 copper root pruning treatments (copper coating of the cavity or no copper coating) x 3 nitrogen (N) rates x 3 replications. Styroblock™ containers (no copper) and their equivalent-sized Copperblock™ containers (interior portions of each cavity except the ribs coated with copper oxychloride) were used. Specifications for the containers are in Table 1.

We calculated our N rates relative to those used in Jackson and others (2012). Therefore, we used the low (0.5 mg N [1 mg = 0.00004 oz] per seedling per week for 20 weeks [hereafter simply mg N]), medium (2 mg N), and high (4 mg N) rates of Jackson and others (2012) but calculated the exact amount of N based on container volume relative to the Ropak #3-96 used by Jackson and others (2012). See Dumroese and others (forthcoming) for a complete description. Fertigations (irrigation with soluble fertilizer added) began 4 weeks after sowing and continued once per week for 19 weeks (20 applications total). Frequency of irrigation or fertigation was determined gravimetrically. Every time container mass reached 75% of the field capacity mass, we irrigated or fertigated seedlings. Once each week, we calculated the amount of fertilizer to add to a sufficient amount of irrigation water in order to apply the appropriate nutrient regime and return the containers to field capacity. We custom blended fertilizers. Our stock fertilization solution was 110, 77, 63, 28, and 20 mg per l P, K, S, Ca, and Mg, respectively, plus micronutrients (Peters Professional® S.T.E.M.™, The Scotts Company, Marysville, Ohio USA) applied at 15 mg per l (1mg per liter = 0.0001 oz per gallon) and Sprint 330 (chelated Fe; 10% Fe; Becker Underwood, Inc., Ames, Iowa USA) added at 20 mg per l. To that we added ammonium nitrate to achieve the desired N amount per seedling per container size and N rate. Fertigation solutions were carefully applied by hand to ensure an even distribution of nutrients and minimize leaching. From the end of the fertigation period (22 October) until harvested on 4 December, seedlings were irrigated when container mass reached 75%.

Table 1. Characteristics of Styroblock™ and Copperblock™ containers (Beaver Plastics, Ltd., Acheson, Alberta, Canada).

Designation (US or Canada)	Cavities (number)	Volume (ml [in^3])	Depth (cm [in])	Diameter (cm [in])	Density (cavities m^{-2} [ft^{-2}])
4A or 313A	198	60 (3.7)	13 (5.1)	2.8 (1.1)	936 (87.0)
6B or 412B	112	95 (5.8)	12 (4.7)	3.6 (1.4)	530 (49.4)
10S or 412A	77	125 (7.6)	12 (4.7)	4.2 (1.7)	364 (34.0)
20 or 615A	45	336 (20.5)	15 (5.9)	5.9 (2.3)	213 (19.8)

Field Study

Seedlings were extracted from containers on December 4, pooled by replication, boxed, shipped, stored at 5 °C (41 °F) for one week, and outplanted on December 11. The study site is in an open area on the Palustris Experimental Forest on the Kisatchie National Forest near McNary, Rapides Parish, Louisiana (Lat./Long.: 31.0, -92.6). The area is gently sloping with Beauregard silt loam (fine-silty, siliceous, thermic Plinthaquic Paleudult) soils that are moderately drained and slowly permeable. The site develops a perched water table during prolonged wet periods in winter and can be droughty in summer (Kerr and others 1980).

The experimental design for the field portion of the experiment was a randomized complete block design with split-plots replicated three times. Whole plots were combinations of container volume, copper root pruning, and relative N rates, and the split plots were soils amended with either 0 (control) or 100 kg P per hectare (89.1 lbs per acre) of diammonium phosphate incorporated using a tractor and disc. Fifteen seedlings from each of the original 24 nursery treatments were outplanted at 0.6 × 0.9 m (2.0 × 3.0 ft) spacing in each of the split-plots.

Seedling root collar diameter (RCD) was measured before outplanting. Seedling height and ground-line diameter was monitored from year 1 through 3. One seedling from each treatment was excavated 22 months after outplanting in October. Seedlings were excavated at 15 cm (5.9 in) radius from the stem with a shovel. After carefully washed residual growth medium and soil off the root system, seedlings were severed at the root collar. Growth parameters, such as height, RCD, and dry weight of needle, stem, taproot, and lateral roots were recorded. Root system architecture was assessed by placing a root system over a root plug template of each cavity size. Zone A was the upper 5 cm (2 cm) of the root plug, zone B included the next 5 cm (2 cm) of root plug basipetal zone A, and zone C included the remainder of the root zone (> 10 cm [3.9 in] below the top of the original root plug). Only those lateral roots that originated within root plug and had at least 3 mm diameter were counted as first-order lateral roots (FOLRs). Assessment methodology and preliminary results of root system architecture from selected seedlings are reported here.

Results and Discussion

Sapling stability is supported by vertical anchorage provided by a taproot or sinker roots (Burdett 1978; Mason 1985; Burdett and others 1986; Coutts and others 1999). Sapling stability may also be supported by symmetrical, horizontal lateral roots (Coutts and others 1999). The upper soil layers in forests usually have a greater amount of organic matter and mineral nutrients. Exploration of the upper soil layers by horizontal lateral roots and their mycorrhizal associations can benefit tree growth (Balisky and others 1999; Sword Sayer and others 2009). Based on the criteria for sapling stability and growth, each seedling was assessed with a set of root system architecture parameters. The following descriptive results from the excavation study are shown in Tables 2 and 3 and in Figures 1-4 (All figures show seedlings that were cultured in a greenhouse in Moscow, Idaho for 29 weeks, harvested in early December and promptly outplanted in central Louisiana, and sampled 22 months later. Each horizontal zone between two lines on the root plug template was 1 cm.)

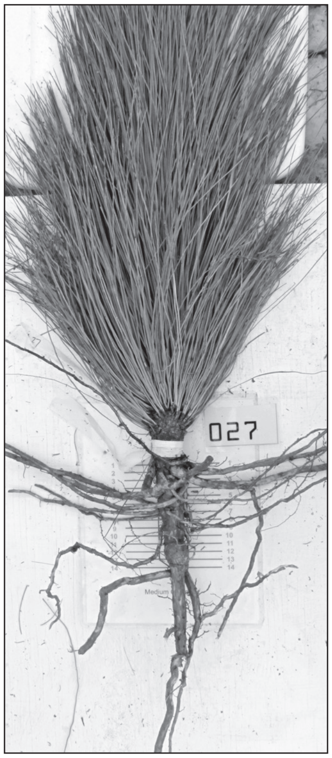

Figure 1. Longleaf pine Seedling #27 was raised in a 95 ml cavity coated with copper and given the medium rate of nitrogen each week for 20 weeks starting 4 weeks after sowing.

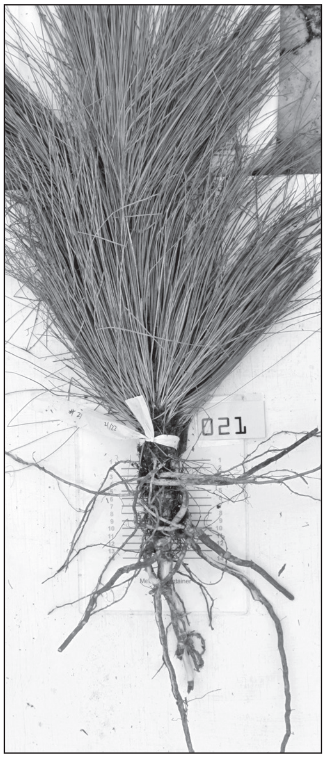

Figure 2. Longleaf pine Seedling #21 was raised in a 95 ml cavity without a copper coating and given the medium rate of nitrogen each week for 20 weeks starting 4 weeks after sowing.

Figure 3. Longleaf pine Seedling #68 was raised in a 60 ml cavity coated with copper and given the medium rate of nitrogen each week for 20 weeks starting 4 weeks after sowing.

Figure 4. Longleaf pine Seedling #29 was raised in a 336 ml cavity without a copper coating and given the high rate of nitrogen each week for 20 weeks starting 4 weeks after sowing.

Table 2. Root collar diameter (RCD) at outplanting and other growth parameters for four longleaf pine seedlings excavated 22 months after outplanting in central Louisiana.

Seedling designation	Cavity volume (ml)[1]	Copper root pruning	Relative N rate[2]	RCD (mm)	Ground line diameter (mm)	Height (cm)	Dry weights (g)			
							Seedling	Needle	Stem	Root
27	95	Yes	Medium	6.85	36.7	40	327	195	55	77
21	95	No	Medium	5.64	42.1	45	348	199	63	86
68	60	Yes	Medium	3.76	28.2	26	173	112	27	34
29	336	No	High	6.94	40.5	58	397	189	85	123

[1] Conversions: 1 in3 = 16.4 ml; 1 in = 25.4 mm = 2.5 cm; 1 oz = 28.3 g)

[2] N application rate was relative to the rates used by Jackson and others (2012) for 90-ml Ropak #3-96 containers. See Dumroese and others (forthcoming) for a complete description of the fertilizer calculations.

Less than 0.1% seedling mortality was observed through year 5. Most of the excavated seedlings had straight taproots that grew the length of the root plug. After seedlings were outplanted, adventitious roots emerged from the callus tissue at the end of the taproot and usually grew downward. South and others (2001) designated such roots as type A sinker roots. An example of this is seen with Seedling #27, which was from the 95-ml container treated with copper, and grown with medium N (Figure 1). This seedling type represented most of the seedlings grown with copper in terms of root system architecture and dry weight allocation. It had a top:root dry weight ratio of 3.2 (Table 2), a straight taproot, two sinker roots extending from the air-pruned end of the taproot, and 12 FOLRs. More than 40% of the FOLRs egressed from the top 5 cm of the root plug (zone A) (Table 3). Only two lateral roots in Seedling #27 showed some spiraling, oblique, or vertical growth within the original root plug.

In contrast, Seedling #21 was from 95-ml container not treated with copper and grown with medium N (Figure 2). This seedling had a shoot-to-root ratio (S:R) of 3.0 (Table 2) and its taproot did not show any sign of being air-pruned, extending to a depth of at least 32.5 cm (12.8 in) in soil (taproot end broke off during excavation). This lack of visible air-pruning on the taproot was also observed in some of the copper-pruned seedlings, and was also observed by South and others (2001). Unlike copper-pruned seedlings, Seedling #21 had more than 40% of its FOLRs egressing from zone C (> 10 cm [>3.9 in]) of its root plug (Table 3). This was typical for longleaf pine seedlings grown without lateral root pruning treatment (Sword Sayer and others 2009; Sung and others 2009, 2012).

Not all adventitious roots extending from the air-pruned end of taproots are type A sinker roots because some adventitious roots extend horizontally. Formation of these horizontal, thus non-sinker, adventitious roots maybe due to root plug end being in contact with either a hardpan or a rock or compaction of fine-textured soils by the dibble used for outplanting (Landis and others 2010). An example is Seedling #68 grown in the 60-ml container treated with copper and given medium N (Figure 3). It had a S:R dry weight ratio of 4.1 (Table 2), a straight but short taproot, 2 adventitious roots extending horizontally from the air-pruned end of the taproot, and 8 FOLRs. Non-sinker, adventitious root formation was also observed in some of the excavated seedlings not treated with copper. A sapling with vertical anchorage provided only by the taproot may be at greater risk to topple when exposed to strong winds. Sung and others (2009, 2012) found young longleaf pine saplings with stem instability had very short taproots and/or without sinker roots.

Our final example is Seedling #29, grown in the 336-ml container not treated with copper and given the highest rate of N (Figure 4). It had a S:R dry weight ratio of 2.2 (Table 2), a straight taproot, 3

Table 3. Parameters in root system architecture of the four longleaf pine seedlings excavated 22 months after outplanting and previously described in Table 2.

Seedling designation	Taproot		Sinker root		First order lateral root (number)				
	Length (cm)[1]	Dry wt (g)	Longest (cm)	Total dry wt (g)	Total	Egressed			Deformed in root plug [2]
						Zone A (0 to 5 cm)	Zone B (5 to 10 cm)	Zone C (> 10 cm)	
27	11.5	24.6	28.0	19.2	12	5	6	1	2
21	32.5	43.0	-	-	12	3	4	5	6
68	10.0	13.8	-	7.7[3]	8	4	2	2	6
29	13.5	34.8	40.0	21.9	18	0	2	16	15

[1] Conversions: 1 in3 = 16.4 ml; 1 in = 2.5 cm; 1 oz = 28.3 g)

[2] Deformed first-order lateral roots had their segments of roots within root plug spiraling or extending obliquely or vertically.

[3] Adventitious roots extended horizontally from the taproot end and were not sinker roots.

sinker roots, and 18 FOLRs. This seedling retained a cage-like appearance for its FOLRs 22 months after outplanting. All of its FOLRs egressed from the bottom of the root plug except for 2 FOLRs in zone B (Figure 4). Although this seedling lacked root exploration in the uppermost portions of the soil profile, which is more nutrient rich than soil below, the robust growth of this seedling was most likely influenced by luxury consumption of nutrients during nursery production that were stored in stem or roots and subsequently exploited after outplanting, as was the case with black spruce (*Picea mariana*) in Canada (Malik and Timmer 1996).

Summary

Effects of nursery cultural treatments were found to persist in longleaf pine seedlings for 22 months (almost 2 years) after outplanting. For example, we observed that seedlings grown without copper root pruning had most of their lateral roots egressing into deeper soil layers compared to those grown in cavities with copper coating. Root system of some non-root pruning seedling still maintained the cage appearance resulted from the vertical downward extension of the lateral roots within root plug. Formation of sinker roots from taproot end did not seem to be affected by cultural treatments.

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The Pitfalls of Container Production

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Abstract: This paper summarizes ten of the biggest “pitfalls” or challenges I have encountered in my experience growing southern pine seedlings in containers over the past 30 years. Learning from challenges is an important part of growing successful nursery operations.

Keywords: container choice, water quality, irrigation

Introduction

Container seedling production has increased significantly over the last 30 years in the Southeast U.S. Currently, it is estimated to be between 150 to 180 million seedlings annually. This paper addresses some of the “pitfalls” or challenges encountered in my experience in growing container seedlings. I have narrowed it down to what I consider to be the ten most important challenges. My comments pertain primarily to southern pine production. I hope you can avoid some of these pitfalls by reading this paper.

Ten Pitfalls of Container Production

1. Container Size and Shape

The challenge: In my opinion, the most pivotal decision for any container production is what container will be used. Species that will be produced will dictate the seedling attributes needed. Container choice will have a huge impact on economics, efficiency, and quality. The number of cavities per tray can be a huge consideration. The size of the cavity will also drive economics. In my opinion, the range of density for cavities must be from 45 to 52 per square foot to produce a quality seedling and for economical production. Cell length is a debatable effect. I have not seen any research on southern pine to indicate this is an issue if root systems are well developed. There can be sensitivity if some species are planted too deeply in the field. Field planting method must be taken into consideration with the container choice. Root volume is more important than root length in my opinion.

The pitfall: Inappropriate container choice was the first pitfall we experienced. Our operation chose a small tray of 40 cells. However, as production started to build, handling a huge number of trays increased our costs significantly. We increased the number of cavities per tray to 120 to increase efficiency and improve this problem.

To avoid this pitfall, carefully consider the size operation you will have in the future and evaluate how you will handle the large numbers of containers. Labor will be your number one cost and containers will be your largest investment in capital.

2. Other Container Features

The challenge: Configuration of your container is also very important as it will affect all your equipment used for filling with growing media and for sowing seed. A mixture of container types is often necessary because of the different species grown. Drainage features of containers are very important in root development in a seedling crop. The size of the drainage hole in the bottom will affect all aspects of root development. Our company has custom developed two different containers to improve drainage aspects. Drainage features will affect the irrigation rate necessary to grow seedlings. Another important aspect of container is raised ribs inside of the container to prevent root spiraling. Most manufacturers know that this is essential.

The pitfall: Our nursery has 6 different container sizes. This mixture of container types makes growing more difficult as it also affects watering schedules and plant development. For example, each container type differs in the rate of drying and how quickly root systems develop.

To avoid pitfalls with containers, talk with customers who use your product to evaluate what their desired seedling size will be and what they are willing to spend to purchase the product. Also, talk with other growers who have used the container to see what they consider the advantages as well as disadvantages.

3. Container Durability

The challenge: Color of the material used to make containers is important. This can affect the temperature of the growing medium in heat conditions and can affect the life of the container if ultraviolet inhibitors are less in lighter-colored trays.

The pitfall: We bought containers that lasted only a few years because ultraviolet inhibitors were poor. Containers we purchased from a cheaper source lasted only half the life of containers made with better materials.

To avoid this pitfall, be sure to ask about the expected life of the materials used and, if possible, visit someone who is using the material in similar conditions to see what their container life is.

4. Benches

The challenge: Benching systems are a huge part of the financial investment for production. Things to consider are initial investment, ease of use, and life of the material. We currently use galvanized metal posts and aluminum rail benching for the majority of our production. We have also used wire panels on concrete blocks. Neither of these systems is easily moved. Another consideration in choosing a bench system is whether the system can be reconfigured as production changes or if you have to move operations.

The pitfall: We made some benches from cheap metal and the life of these benches was half the length of better quality metal benches. Also, as our production sites changed we needed to reconfigure our bench system. After a number of years in production in different locations, we decided to consolidate operations and some of our benches were not able to be moved as they were permanently installed. This required the investment in new benches.

Allowing the appropriate time for construction with weather delays and contactor issues must be planned. Many people thought they had plenty of time and later realized they could not complete construction in time to meet biological windows.

To avoid this pitfall, I recommend you carefully consider bench configuration, material life-span, construction time, and the need for movability so that you invest in the most appropriate benches for your needs and don’t waste your resources.

5. Irrigation

The challenge: A key question to production is how to irrigate the crops. There are a number of options and choosing which one to use often depends on local conditions, water sources, water quality, and production volumes required. We currently use pivot irrigation but have used traveling booms and fixed irrigation. We like the pivot irrigation due to uniformity of water distribution and cost effectiveness. Fixed irrigation requires less up front capital but has the most variation in watering. Booms are effective but can require more maintenance and investment.

The pitfall: When water control systems fail and irrigation does not run we have lost seedlings (Figure 1). There is very little buffer if you cannot irrigate during the growing season. In warm conditions, seedlings dry very quickly when rainfall is not abundant. You can lose seedlings to dehydration in a matter of two to three hours in extreme cases.

To avoid this pitfall, invest in water sensors.

6. Growing Media

The challenge: The choice of growing media affects your crop from the beginning to the end. We have tried several different growing media but prefer peat moss mixes due to uniformity.


Figure 1. Effects of loss of water for a few hours.

Handling of media can be a big issue as production increases. When growing 500,000 seedlings, one system may work but increasing to 5 million seedlings can require a dramatically different system. We currently use 220 cubic feet sky bales to handle our mix.

The pitfall: We experienced a huge downfall in production when some batches of media mistakenly had increased pH (Figure 2).

To avoid this pitfall, check pH of the media and be sure to work with a quality media producer.

7. Water Quality

The challenge: Water quality is essential for growing any plant. The pH of water can vary largely in the Southeastern U.S.

Figure 2. Effects of high pH media on seedlings.

The pitfall: We lost over 2 million seedlings because the water pH changed during the growing season (Figure 3).

To avoid this pitfall, acidify water that has a high pH.

8. Filling and Seeding Containers

The challenge: Filling cavities with growing media is important. Again, if production is small, one system may work but as production increases it another system may be needed to meet biological deadlines. Careful evaluation must be made of this process. Sowing equipment and procedures can present the same issues for meeting deadlines. Accuracy is critical as nurseries cannot afford empty spaces due to poor sowing. We currently use vacuum sowing equipment. Container production can require large amounts of workers during sowing and shipping (Figure 4).

The pitfall: authorities can show up to verify the legal status of all the workers. This can be difficult for everyone involved, including the nursery which can lose its labor force overnight.

To avoid this pitfall, plan carefully to ensure the nursery has workers when workers are needed. Meet with contractors to discuss needs for documentation of all workers and get copies for your records several weeks ahead of critical production times.

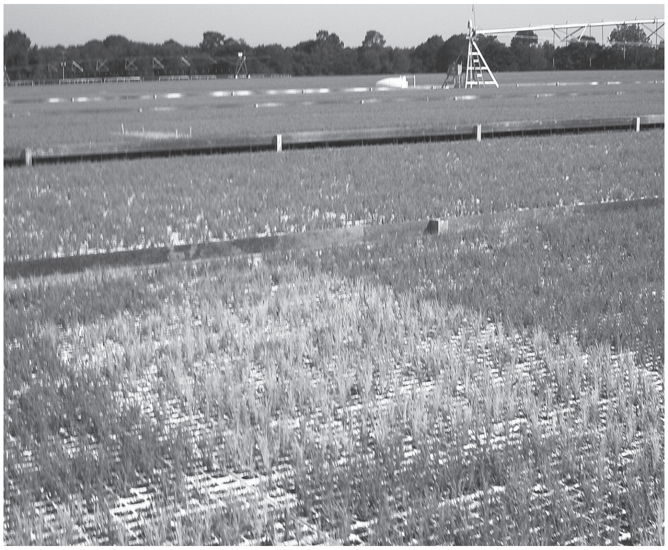

Figure 3. The effects of high water pH and media differences.

Figure 4. Production activities such as sowing require many people.

9. Finding Customers

The challenge: If production goes well, knowing where you can sell the seedlings is a major consideration. Planting of seedlings has been decreasing over the last several years. Finding buyers is no simple process. Everyone has experienced producing seedlings that they cannot sell.

The pitfall: unsold seedlings kill profitability.

To avoid this pitfall, have a quality marketing and sales plan.

10. Keeping Customers

The challenge: Customers are hard to find and hard to keep. They must be treated with respect. Nurseries must learn to adapt to customer needs and also to communicate nursery requirements.

The pitfall: Customers can go away as a result of no fault of the nursery. There have been huge changes in land ownership changes in the U.S. in recent years, for example.

To avoid this pitfall, develop new customers as well as diversify with different types of customers.

Conclusion

Even with these pitfalls and challenges, nursery production and sales can be very satisfying. With the improvements in genetics and technology, along with the need for trees, I see an excellent future for container seedling production. I hope that sharing some of the stories of "pitfalls" I've encountered can help you avoid these pitfalls as you grow your nursery!

Importance of Water Quality in Container Plant Production

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Abstract: High substrate pH is a major problem for producers of container-grown plants and seedlings. The primary cause of high substrate pH is irrigation water with high alkalinity. Alkalinity is defined as the capacity of water to neutralize acids. Some alkalinity in irrigation water is beneficial as it serves as a buffer to large swings in pH levels, but high alkalinity in the water often leads to micronutrient deficiencies. Alkalinity of irrigation water should be monitored for changes on a regular basis. Be sure to check with the laboratory being used to determine if they test for alkalinity, carbonates and bicarbonates, or water hardness. Guidelines and suggestions for dealing with alkalinity in irrigation waters are given.

Keywords: alkalinity, bicarbonates, carbonates, hardness, pH

Introduction

High quality water is essential to the production of plants grown in container nurseries. Production time can be increased and quality of seedlings decreased when water quality and quantity are not managed properly. For further information and a general review of water quality issues focusing on container-grown tree seedlings, see Landis (1989) and Moorhead and Ruter (1999).

The Importance of pH

During production of container-grown trees, the pH of the growing substrate needs to monitored and adjusted as needed. pH is the measurement of the hydrogen ion concentration of a solution, or how acidic or basic a solution is. Values of pH can range from 0 (very acidic), to 14 (very basic or alkaline), with 7.0 being neutral. Lemon juice for example has a pH of 2.2-2.4, while baking soda has a pH near 8.0. Pure water would have a pH of 7.0. The pH scale is logarithmic, which means that each unit increase or decrease is a 10 fold difference in the acidic or basic nature of a solution. As an example, coffee at pH 5.0 is 100 times less acidic than orange juice at pH 3.0.

The ideal pH for soilless substrates used in nursery production is in the range of 5.2 to 6.2, while most conifers grow best around pH 5.5 (Landis 1989). Once familiar with the pH of the nursery's irrigation water and crop substrate, growers can begin to manage production practices to prevent pH related problems. One factor where pH plays an important role in plant nutrition is how it influences the availability of plant nutrients. In general, metal micronutrients (Cu, Fe, Mn, Ni, and Zn) are most available at a pH of below 5.5, whereas nutrients such as calcium and magnesium are most available above a pH of 6.5 (Reed 1996). Based on 35 years of experience, iron deficiency is by far the most common cause of foliar yellowing in different species of pines both in California (Ruter 1986) and in the eastern United States. Chelated products such as Sprint 330 (useful up to pH 7.5) and Sprint 138 (useful up to pH 9.0 or above) can be used with alkaline irrigation water to help manage iron deficiency issues.

Table 1. Acidic, Neutral, or Basic reactions of common fertilizer products.

Acidic	Neutral	Basic
Ammonium nitrate	Monocalcium phosphate	Calcium nitrate
Ammonium sulfate	Monopotassium phosphate	Magnesium nitrate
Diammonium phosphate	Treble superphosphate	Sodium nitrate
Monoammonium phosphate	Potassium sulfate	Potassium nitrate
Nitric Acid	Superphosphate	-
Phosphoric Acid	-	-
Sulfuric Acid	-	-
Urea	-	-
20-20-20	-	-
21-7-7	-	-

Factors that influence substrate pH include 1) substrate components, 2) incorporated fertilizers, 3) fertilizers used during production, and 4) irrigation water quality. While pine bark and peat moss are acidic substrate components, hardwood bark and some types of vermiculite often have a pH above 7.0. An example of an acidic-forming fertilizer is ammonium sulfate, while potassium nitrate would be basic. A further list is shown in Table 1.

What is Alkalinity and Why is it Important

Alkalinity is a measure of the capacity of water to neutralize acids, whereas alkaline describes a pH measurement above 7.0. Although not the same, alkalinity is related to pH. Alkalinity establishes the buffer capacity of water. Since alkalinity is the main cause of buffering, it influences how much acid is required to change the pH of a given water source. In a study looking at the chemical characteristics of water used for the production of cranberries, there was a general increase in alkalinity as pH increased but the authors noted that several samples with a pH above 7.0 had relatively low levels of alkalinity (Hanson and others 2000).

Dissolved bicarbonates and carbonates are the major ions causing alkalinity in irrigation water. Bicarbonates are generally present at a pH below 8.3 whereas carbonates are the main ions above pH 8.3. As water evaporates, carbonates and bicarbonates are left behind. These ions then neutralize hydrogen ions in the water, thus increasing pH. Water with low alkalinity is not very buffered and the pH can be quickly changed depending on the type of fertilizer used. In areas with moderate to high alkalinity in the irrigation water low rates of dolomitic limestone are recommended (5.0 lbs. per cubic yard or less) whereas in areas with low alkalinity higher rates are recommended for incorporation into the substrate so that the pH does not drop too low.

How is Alkalinity Measured

In the laboratory, alkalinity of a water sample is measured as the amount of acid required to bring the pH of a water sample to a known endpoint. Alkalinity is expressed in terms of milligrams per liter of calcium carbonate equivalents (mg/l $CaCO_3$) or milliequivalents per liter of calcium carbonate equivalents (me/l $CaCO_3$). The two measurements can be compared using the following:

1 me/l $CaCO_3$ = 50.04 mg/l $CaCO_3$

A water source alkalinity of 2.5 me/l $CaCO_3$ or less is considered ideal for the long term production of nursery crops while 1.3 me/l $CaCO_3$ is preferred for plugs or seedling production.

Not all testing laboratories report alkalinity with a standard water test. A water sample sent to The University of Georgia Soil Testing lab would come back with a report of water hardness, whereas other labs might report alkalinity or carbonates plus bicarbonates. Similar to pH, water hardness is related to alkalinity but is not the same. The hardness of water is calculated as:

Hardness = (mg/l Ca × 2.5) + (mg/l Mg × 4.1)

Water with a hardness rating of 0-75 is considered soft, 75-150 is moderate, 150-300 is hard, and >300 is very hard. Water quality for five locations in Alabama and Georgia is shown in Table 2. In a survey of greenhouse irrigation water from around the country Argo and others (1997) found the average alkalinity from 4306 samples to be 3.19 me/l $CaCO_3$.

Countering Alkalinity

The battle against alkalinity can be won by 1) acid injection into the irrigation water, 2) application of acidic amendments, or 3) the use of acidic fertilizers. Sulfuric acid is often preferred for injection into irrigation systems for safety reasons, though some growers may utilize nitric or phosphoric acids. See Reed (1996) for further information. To acidify a substrate, iron sulfate or elemental sulfur can be used. The rate of pH change in the substrate will be moderate for iron sulfate compared to slow for sulfur. See Table 1 for acidic-forming fertilizers. Peters Excel pHLow is a new water-soluble line of fertilizers designed to correct water alkalinity while being safer than using acids for injection (Hulme 2012).

Table 2. Ground water characteristics from five locations in Alabama and Georgia. Data given in mg/l.

	Auburn, AL	Blairsville, GA	Cairo, GA	Dearing, GA	Tifton, GA
Alkalinity	32	64	-	-	190
Hardness	41	51	327	27	146
Calcium	13	17	75	5	47
Magnesium	2	2	33	3	7

An online alkalinity calculator known as "ALKCALC" is available at: Extension.unh.edu/Agric/AGGHFL/Alkcalc.cfm

This application allows growers to enter the alkalinity and pH of their irrigation water, select an acidifying agent, and determine the amount needed to reach a determined target alkalinity or pH.

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Growing Difficult Hardwoods: Experiences at the George O. White State Forest Nursery

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Abstract: This paper will describe techniques for growing bareroot seedlings of some of the "trickier" species that nursery managers often times have limited success growing. In addition, some information is provided about hardwood seed management and how that has improved nursery successes.

Keywords: seed treatment, seed storage, sowing, bareroot

Seed Collection and Storage

At the George O. White State Forest Nursery (Missouri Department of Conservation, Licking, MO), most of our hardwood seed is collected locally and cleaned by our staff. We control how much we buy, when we buy it, and how much we pay for it. There is an old saying in the seed business that "in good seed years, you get good seed"; in our experience, we have found this to be very true. In years of abundance of a particular seed, we will often buy three, four, or five years' worth of seed. We clean it, dry it, and store it. If the seed turns out to be a good seed lot (and it almost always does in good seed years), then we are set for years to come with the necessary seed for fall and spring plantings. We freezer-store (2 °F [-16.7 °C]) our seed in plastic bags, in cans. With this practice, when we need 75 pounds of flowering dogwood seed in the fall, we can go to our freezer and get it. There are no frantic phone calls to seed vendors or other nurseries. We have stored some seed for more than 20 years and still get excellent germination. When we do buy seed from vendors, we buy two or three years' worth of seed; this helps take the pressure off of the nursery manager in future fall sowing seasons. In addition, if we needed 30 pounds of seed, we might buy 20 pounds from each of three vendors then plant 10 pounds of each and track them to determine which seed performed best for us. Another benefit of this method is if one seed lot failed, we only lost a third of the seed, not all of it.

Sycamore (*Platanus occidentalis*)

Sycamore is a species for which we can use old seed. For instance, sycamore seed balls were purchased for the George O. White Nursery in the fall of 1994 from which nearly 400 pounds of clean sycamore seed was processed. Seed out of those cans was used for the next 17 years until it was used up. The seed quality was excellent; in fact, it may have improved each year in storage (or perhaps we got better at germinating it over time). We typically sow sycamore seed in mid- to late-May. If we sow much earlier than this the seedlings get too big (we do not top clip our sycamore). The seed is sown right on the surface of the seedbeds. We raise the disks on our Love seeder so that they seed is not covered at all with any soil; the packing wheels press the seed into the seedbed. Immediately after sowing, we cover the seed with hydromulch and then begin watering. Normally, we water sycamore with overhead irrigation for about an hour in the morning and an hour in the afternoon. This is done seven days a week for at least two weeks, until we are sure the seed has germinated. Using this method of long-stored seed, surface sowing, hydromulching, and daily watering, we have not had a single season of failure on our sycamore crop and we typically grow about 150,000 sycamore seedlings per year.

River Birch (*Betula nigra*)

When sowing river birch, it is important that there be no wind since the seed can easily blow out of the funnel on the Love seeder. It is also important that the soil not be wet because the seed will stick to the rollers. If there is any debris in the seed lot (and there usually is), it will plug up the Love seeder. River birch seed must continuously be pushed out of the funnel; gravity has little to no effect on river birch seed. It is inevitable that the tubes will plug up and the tractor driver will have to stop. As with sycamore, river birch seed should be sown right on the soil surface and covered with hydromulch as quickly as possible. As with the sycamore, water it twice daily until it is up.

For river birch, we always plant one-year-old seed. In many years, it is about June 1 before current year seed is available. We prefer to sow river birch by the first week of May or even the end of April. So, in May 2012, we sowed seed from June 2011. In late May or June we got our 2012 seed that we will store and plant in 2013. This way we did not have to worry or wonder if we were going to get any seed and when. We store the river birch seed for the year in a plastic bag, in a seed can in our walk-in cooler at about 34 °F (1.1 °C). We do not attempt to dry and freeze it.

Buttonbush (*Cephalanthus occidentalis*)

We grow buttonbush much the same way as we do sycamore and river birch. Unlike river birch, however, buttonbush is very easy to sow. You must have patience with buttonbush; sycamore often germinates in seven to ten days, river birch slightly longer, but the buttonbush will take up to a month, with twice daily watering, to germinate.

Hazelnut (*Corylus americana*)

Hazelnut is an important species for us; we can sell 100,000 hazelnut seedlings a year if we can grow that many. We do not buy our hazelnut seed commercially, but collect it locally. The problem with hazelnut seed, however, is if you wait until it is ripe on the shrub, some critter has already eaten it. We collect ours in mid-August, while it is still very green. We then spread the green husks out on screen boxes, inside a building (we use our idle seedling coolers), and let the seed husks dry out and the seed ripen. This protects it from some wildlife, although we have had squirrels and rats come into the cooler to eat hazelnuts. We have a dehumidifier in the cooler to assist in drying the husks and we stir the seed about once a week. It can get a lot of white surface mold, but this does not appear to hurt the seed. By late September or early October we run the dried husks through our HA400 brush machine to clean off the husks. We then hand sow the seed in late October. Over the last few years our germination has not been what it had been in previous years; this could be because of overly wet conditions in the winter.

We have also been successful storing clean seed over for a year by putting it in plastic bags, in seed cans in our cooler for the year. But this rarely happens, as we usually cannot even find all the seed we need, much less have surplus.

Chokecherry (*Prunus virginiana*)

We have tried to grow chokecherry for about six years. We sow in fall and normally get excellent germination and early growth. However, a leaf disease hits the seedbeds by the first of June resulting in the seedlings' leaves falling off and the seedlings stop growing. We end up having to toss 25,000 five-or-six inch trees. Initially, we tried a mix of fungicides until 2010 when we sent samples of our diseased chokecherry to Michelle Cram (Plant Pathologist, USDA Forest Service, Region 8 Forest Health Protection) and found out that we did not have a leaf fungus, but a bacterial blight. Last year, we tried the bactericide, Kocide, but it did not have much success in controlling the leaf disease. We may be done growing this species.

Deciduous Holly (*Ilex decidua*)

It takes two years of seed in the ground to grow deciduous holly; there is no way around it. Seed sown the first of October 2012, won't germinate until April 2014! The other holly species – American holly (I. opaca) or winterberry (I. verticillata) take as long or even longer to germinate.

Spicebush (*Lindera benzoin*)

Spicebush is becoming a more popular species for us and we have been growing it for about seven or eight years. This is a small, shade-loving shrub. The bright red fruit contains a very thin shelled, delicate seed. Normal cleaning of the seed, such as we would do with plum, dogwoods, and other hard seeds will break the spicebush seed. It is cleaned in a macerator, but done very slowly. The employee that cleans this seed, must not be in a hurry. In the past, we just dried the berries, but cleaning the seed carefully has greatly increased our germination. We try to sow fresh seed each year, but have had success storing the seed for one year (not frozen, but cold stored). We have stored seed for more than one full year, but germination diminished greatly by year two. The newly emerged seedlings are susceptible to damping off disease, more so than most hardwoods. We have not had good germination from seed purchased from commercial vendors.

Acid Treating Seed

Acid treating can be an excellent way to make seed germinate. Hot water, cold and wet soak, or other forms of stratification or scarification may work, but we have had great success using sulfuric acid. Below is a description of how we do it and some procedures for specific species.

It's important to use plastic containers and that the workers wear safety equipment. There should always be two workers doing this; never have an employee move seed out of the tubs alone. They can be alone to watch and stir, but only briefly. This helps to avoid accidents. We put the sulfuric acid about 10 to 12 inches (25 to 30 cm) deep in a large plastic trashcan. The seed is placed in a 5-gallon bucket with a lot of holes drilled into the bucket. The bucked is lowered into the acid. Employees track how much time the seed is in the acid and stir it occasionally using a wooden stir stick. Keep metal away from the acid! Once the target time has been reached, the bucket containing the seed is pulled out of the acid, allowed to drain, and then dumped onto screen boxes where the seed is thoroughly rinsed.

Kentucky Coffeetree (*Gymnocladus dioicus*)

We soak Kentucky coffeetree seeds for two hours in the acid. This takes us many hours to complete, as we usually sow about 300 pounds and we can only treat about 20 pounds at a time in each of the two tubs we have acid in. We have found that it is best to treat Kentucky coffeetree seeds with acid, clean it very well with cold water, then sow it as soon as possible. It is important to not let the seed dry out because the seed coat can reharden. We treat enough for a bed, then hand sow that bed as soon as the seed is treated and before it dries.

Redbud (*Cercis canadensis*)

We soak redbud seed for 45 minutes in the acid. We surface dry the treated seed just enough to get it to feed through the Love seeder.

Aromatic Sumac (*Rhus aromatic*)

Unlike other species, we acid treat and sow aromatic sumac in the fall. We give the seed a 45-minute acid soak, dry it, and sow with our Love seeder, usually in late October. We were told that fall-sown aromatic sumac does not need acid treatment. We did that one fall and the seed germinated, but it was a very poor stand. The next fall, we acid treated seed from the same seedlot and had an excellent stand. Our advice is to not just fall sow it.

Other Species

We also acid treat false indigo (Baptisia australis) for 7 minutes and spring sow; black locust (Robinia pseudoacacia) for 45 minutes and late spring sow; and smooth sumac (Rhus glabra) for one hour and late spring sow.

Conclusions

When it comes to difficult-to-grow hardwoods, the difficulty is often a seed issue. Success can depend on proper seed handling and sowing at the correct time. There are certain patterns that must be followed to be successful. Shortcuts are not good. Seed is too expensive and the product we grow is too valuable to not follow a set procedure.

Early History of Tree Seedling Nurseries in the South

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Abstract: The forests in the South were devastated by aggressive harvesting that began following the Civil War. By the early in the 20th century, many millions of acres of land needed reforestation. Foresighted individuals began a committed effort to restore this land to a productive condition. This effort required dedication, innovation, cooperation, and leadership. The pioneering work of people including Carl A. Schneck, Henry Hardtner, J.T. Johnson, F.O. “Red” Bateman, and Philip Wakeley helped create the foundation of reforestation and nursery technology in the South, and the forests they helped restore have become the basis of the South’s economy today.

Keywords: restoration of southern forests, southern pines, nursery managers, nursery production

The Problem

As early as the late 1910s, millions of acres of deforested land spread across the South. Development of the lumbering industry following the Civil War brought jobs and businesses, but after the timber was cut out, there was bleakness and a spirit of desolation. The magnitude of the cutover land was brought into focus when a survey was conducted by the Southern Pine Association in 1919. The cutover land equaled the combined areas of Alabama, Mississippi, and Louisiana. This survey reported that 92 million acres of land had most of the timber removed (Heyward 1958).

Development of steam-powered logging equipment did much to increase the damage from harvesting practices. For example, some sawmills made use of steam skidders, a logging practice which caused great damage to any timber left standing (Figure 1). Not all of this cutover land was barren stump-land since all sawmills did not practice the same degree of utilization, nor did all use steam skidders. However, little of the cutover acreage was capable of becoming productive again without help. Cutover lands were a man-made problem and required a man-made solution (Figure 2).

Figure 1. Steam-powered skidders manufactured by the Clyde Ironworks in Duluth, Minnesota, greatly increased logging capability in the early 1900s. Forty acres of timber could by skidded to the railroad track for loading on train cars with one setting of the skidder.

Figure 2. This is typical of the cutover land in the West Gulf Coastal Plain in the early 20th century. Many millions of acres of such cutover land needed reforestation.

Slowly lumbermen and the general public began to become interested in developing some sort of reforestation effort. The leader of this effort was Henry Hardtner of the Urania Lumber Company at Urania, LA. Some felt his vision of reforestation was foolish, but he persisted and convinced others that there was a future in second-growth forests (Burns 1978).

The Coming of Forestry to the South

As the 20th century began, the newly created Forest Service began receiving requests for assistance and information on reforestation from lumber companies and individuals scattered across the South. To meet these requests, the Forest Service recruited a few individuals with forestry experience related to the issues of concern. Although they had little forestry training, these individuals had exceptional ability to observe nature, draw tentative conclusions, and make practical recommendations. The most notable of these Forest Service foresters who traveled widely throughout the South were Austin Cary, W.W. Ashe, and W.T. Mattoon (Barnett 2011).

Also at the turn of the century, it was apparent that there was a critical need for forestry training and education. Gifford Pinchot, who later became Chief of the Forest Service, established a forestry program in the late 1800s at George Vanderbilt's Biltmore Estate near Asheville, NC. After leaving the Biltmore Estate, he recommended that Carl A. Schenck, a professionally trained forester from Germany, be hired as his replacement and to establish a forestry school. Schneck established the Biltmore Forest School in 1898 and its curriculum focused on providing one year of practical forestry management training. It is considered as the first forestry school in the United States, but Cornell, Minnesota, Michigan, and Yale created forestry schools shortly after the Biltmore experiment began. In the South, the University of Georgia (1906) and Louisiana State University (1926) led in establishing 4-year forestry programs.

Schenck's Biltmore Forest School closed after 15 years, but as unconventional as it was, it trained about 400 students, some of which made notable contributions to forestry in the United States. Schenck and his students established a few plantations, but their focus was more on stand management.

Henry Hardtner, President of the Urania Lumber Company in Urania, LA, began to realize that cutover lands were a serious problem. Although he had no formal forestry training, he read widely about forestry and crusaded for the forestry cause. His belief that a second crop of trees could be grown profitably after the virgin timber was cut was ridiculed (Figure 3). In 1909, the Forest Service sent W.W. Ashe, and later, W.R. Mattoon, to assist Hardtner. It is interesting to

Figure 3. Carl Schenck (left) established the Biltmore Forest School in 1898 and Henry Hardtner (right) President of Urania Lumber Company pioneered the concept of reforestation of cutover land in the South.

note that Hardtner's ideas on reforestation were ahead of the professional knowledge. However, Ashe and Mattoon did give credibility to Hardtner's actions.

In 1921, the Forest Service established the Southern Forest Experiment Station headquartered in New Orleans and the Appalachian Forest Experiment Station in Asheville, NC. The Southern Station was responsible for research in the southern pine types. This included all of the Coastal Plain areas in Georgia and South Carolina; all of Alabama, Mississippi, and Louisiana; Texas and Oklahoma as far of the pine type went; and Arkansas south of the Arkansas River. The Appalachian Station had emphasis on mountainous hardwood types. Even in 1924, there were fewer than twenty professional foresters in the entire South (Wakeley and Barnett 2011).

Early Nursery Practices

In 1908, the Great Southern Lumber Company began operation at Bogalusa, LA, and it became the world's largest sawmill with four 8-foot band saws producing 1 million board feet of lumber every 24 hours. W.H. Sullivan, General Manager of the company, visited with Hardtner at Urania and, as a result, was convinced to begin a reforestation program. In 1919, J.T. Johnson was assigned as forester in charge of reforestation. Johnson had no formal forestry training, but "contributed an immeasurable quality of skill, labor and ingenuity to the building of the South's great pine forests" (Wakeley and Barnett 2011). Johnson established a one-half-acre pine seedling nursery in 1921-22 across from city hall in Bogalusa—believed to be the first pine seedling nursery in the South (Wakeley and Barnett 2011). The company established other nurseries soon after.

Johnson was fortunate to have F.O. "Red" Bateman as his assistant. Bateman was the company's head ranger (Figure 4). With only a ninth-grade education, Bateman became the prime mover in developing nursery and planting principles and techniques. By 1924, when Philip Wakeley was recruited by the Southern Forest Experiment Station and assigned to Bogalusa to begin a cooperative program on reforestation, Bateman had worked out the general principles still employed today—slit planting of bare-rooted seedlings grown at moderate seedbed densities in the nursery without shade (Wakeley 1976). He invented a dibble planting tool that is still in use today, and he developed the 6- by 8-foot planting spacing that became the almost universal standard used throughout the South for decades. Before the Great Depression caused the Great Southern Lumber Company to go into receivership, Bateman had planted 12,700 acres. At that time, no other successful pine plantation in the south exceeded 100 acres, with exception of the Biltmore Estate in North Carolina —and their planting stock were white pine seedlings grown in Europe (Wakeley and Barnett 2011; Schenck 2011).

Figure 4. F.O. (Red) Bateman of the Great Southern Lumber Company developed many Southern nursery practices still in use today. (Photo source: C.W. Goodyear 1929).

An example of Red Bateman's ingenuity was the development of nursery seeding tool for longleaf pine seeds. Wakeley commented one morning on his frustration in the inability to drill sow longleaf pine seeds due to their persistent seed coat wing. Before noon, Bateman came by Wakeley's work site and asked Wakeley to stop by the nursery. When he arrived, Bateman demonstrated a seeder for nursery sowing of longleaf seeds that he devised that morning—it was a wooden trough 5 feet long to fit across nursery beds. It was hinged at the bottom to drop seeds on the bed. A pair of tall, curved handles at each end permitted opening it without stooping or kneeling, which made the devise easy to use (Figure 5). The seeder resulted in marked improvement in the uniformity and quality of longleaf pine nursery stock.

Figure 5. This seed drill for longleaf pine seeds was developed by F.O. (Red) Bateman of the Great Southern Lumber Company.

Refining Nursery Technology

The results of Wakeley's cooperative research with the Great Southern Lumber Company on nursery production spread to other organizations interested in reforestation. A number of forestry companies developed small nurseries to evaluate the potential for beginning reforestation efforts. In 1929, Wakeley developed the idea of writing a bulletin on the results of their seed, nursery, and planting research. He decided to visit existing nurseries outside of the one at Great Southern to gain prospective from their nursery managers. The survey included six nurseries: Louisiana State University School of Forestry at Baton Rouge, Louisiana Division of Forestry at Woodworth, LA, Industrial Lumber Company at Elizabeth, LA, Long Bell Lumber Company at DeRidder, LA, and the Texas Forest Service nurseries at Kirbyville and Conroe, TX. Wakeley found the nursery managers were "observant, ingenious, and uninhibited men" (Wakeley and Barnett 2011).

The Louisiana Department of Conservation, Division of Forestry nursery was on the Alexander State Forest near Woodworth. Charles Delaney and his brother Luther were managers of the nursery and interacted frequently with Wakeley to develop the South's first state tree seedling nursery (Barnett and Burns 2011, 2012). The Texas Forest Service nurseries followed soon afterward.

Philip Wakeley's collaboration with Johnson and Bateman at the Great Southern Lumber Company ended in the early 1930s with the advent of the Great Depression. During Wakeley's association with the Great Southern, he began developing information on seed collecting, processing, and treatments; on seedling stock specifications; and on a variety of nursery cultural treatments. With the demise of the Great Southern Lumber Company, Wakeley moved his reforestation research program to the Forest Service's newly created Stuart Nursery in Central Louisiana.

The Stuart Nursery was established by the Kisatchie National Forest (KNF) in conjunction with the creation of the Civilian Conservation Corps (CCC) in 1933. Although the KNF employees managed the nursery, a nearby CCC camp provided man-power for its operation. Nursery seedling production was about 25 million annually with most of these seedlings shipped to CCC projects that had reforestation emphases. Wakeley's reforestation research program was transferred to the Stuart Nursery. The Southern Station established an office and laboratory at the nursery and took advantage of the CCC crews to apply nursery cultural treatments and establish outplanting studies. Over the duration of the CCC involvement and support, nearly 750,000 tree seedlings were planted in research studies on the Palustris Experiment Forest (Barnett and others 2011).

The resources available at the Stuart Nursery facilitated the development of Wakeley's southern pine seedling grade specifications that are still used across the South (Wakeley 1954).

By the end of the 1930s, Wakeley and his colleagues were able to publish guidelines for southern pine seed (Wakeley 1938a), seedling production (Huberman 1938; Wakeley 1938b), and planting technology (Wakeley 1935). Early versions of these publications were used by the organizations using CCC crews to grow seedlings for reforestation projects. Most of these CCC supported projects ended with the closure of the CCC program at beginning of World War II. The availability of the CCC program provided an opportunity to field test seed, seedling, and planting research results and pioneer reforestation guidelines for southern pines.

Developing Nurseries across the South

Following World War II, a concerted effort to develop and apply reforestation technology began. In 1954, Wakeley published his "*Planting the Southern Pines*" document which incorporated the results of the research programs with the Great Southern Lumber Company and the Stuart Nursery (Wakeley 1954). This one publication provided the basis for nursery development and plantation establishment. Its thoroughness resulted in it becoming the 'bible' for restoration technology for the southern pines (Figure 6).

Soon nurseries were developed by all southern state forestry organizations and by most major forestry companies. Few nurseries established prior to WWII remained in operation. The Stuart Nursery and W.W. Ashe Nursery in southern Mississippi did continue in operation for many years, but now are closed. The Soil Bank Program in the early 1960s did much to increase the demand for planting stock and nursery development continued to expand. In the late 1970s and early 1980s, reforestation programs of forest industry continued to expand to the point that major companies developed or expanded their nursery production. So, during the late 20th century, large portions of nursery production shifted from Forest Service and state operated nurseries to large commercially operated forest industry nursery operations.

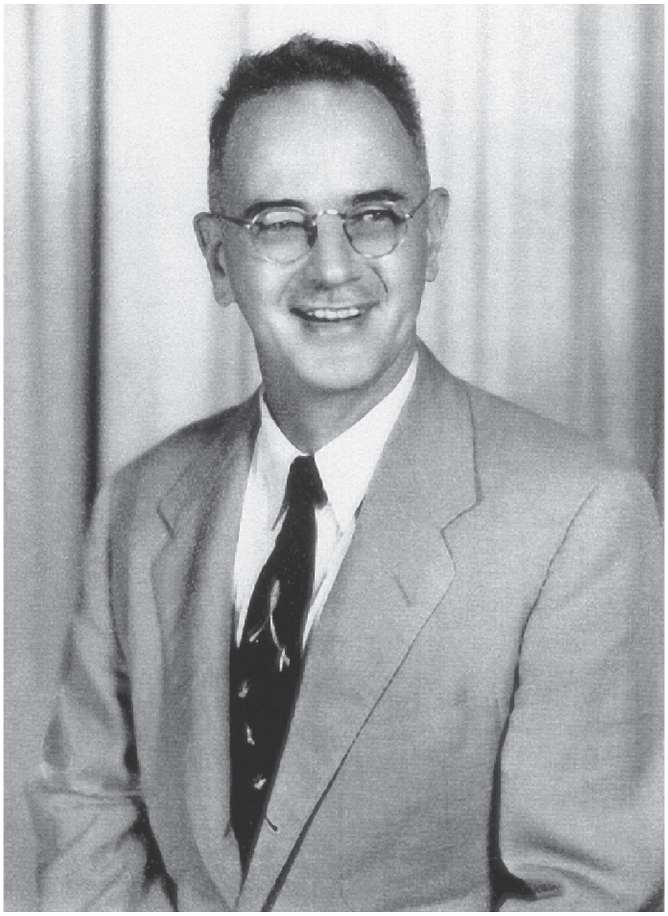

Figure 6. Philip C. Wakeley pioneered development of reforestation technology for southern pines that facilitated the reforestation of the South's devastated forest land.

Although there have been many refinements and improvements in nursery technology over the last 75 years, the basic guidelines that Wakeley and his colleagues developed in the early 20th century remain as the foundation for these efforts.

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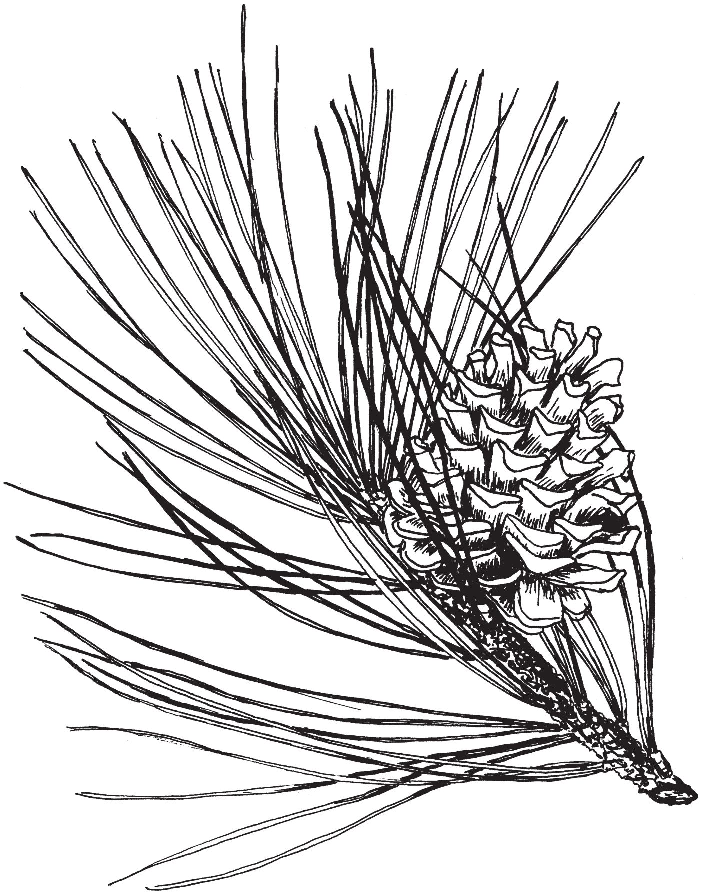
Joint Meeting of the Intertribal Nursery Council, Western Forest and Conservation Nursery Association, and Intermountain Container Seedling Growers' Association

Bend, Oregon

September 11 to 13, 2012



Ponderosa pine drawing by Lorraine Ashland, College of Natural Resources, University of Idaho

The Importance of Good Seed

Robert P. Karrfalt

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Karrfalt RP. 2013. The importance of good seed. In: Haase DL, Pinto JR, Wilkinson KM, technical coordinators. National Proceedings: Forest and Conservation Nursery Associations—2012. Fort Collins (CO): USDA Forest Service, Rocky Mountain Research Station. Proceedings RMRS-P-69. 49-52. Available at: http://www.fs.fed.us/rm/pubs/rmrs_p069.html

Abstract: The importance of seed to human culture and conservation of the natural world is briefly discussed. The effect of seed on seedling quality and cost is described through several examples and illustrations.

Keywords: seed germination, seed vigor, seedling cost

Introduction

What is a seed? Biologically, it is an embryo that is often accompanied by some nutritive tissue for the embryo (endosperm or gametophyte) and enclosed in a seed coat. In most cases, seeds are the source of plants for regenerating native plant communities. From a philosophical and spiritual point of view, seeds are our past, present, and future. They provide cultural connections to past generations of people through foods and other plant materials. Natural selection worked in plant populations over the centuries to produce well adapted plants, and this adaptation is delivered to us in the seeds of today. Therefore, seeds sustain us in our present. Climates are changing. The strongest and most basic response to mitigating the risks of climate change is to preserve a maximum of genetic diversity among and within species of plants. Therefore, our plants determine what we can become in the future. The quality and abundance of our plants depends on high quality seeds.

Good Seed Defined

Good seed will have high germination, high vigor, and produce genetically adapted plants.

Germination, expressed as a percentage, is the ratio of the number of seeds that produce a normal seedling to the number of seeds that were sown. What is considered high germination will be relative to species, year, and nursery protocols. Pine and spruce will generally have higher germination than will true firs. In a bareroot nursery, germination as low as 90% might be considered high, but in a container nursery, germination below 90% begins to significantly affect cost of seedlings.

A *high vigor* seed is one that will germinate rapidly and perform better under suboptimal conditions. A second definition for high vigor seed is that it will maintain high germination over many years in storage.

The final characteristic of good seed is being *genetically adapted*. This is important because regardless of germination or seed vigor, if the plants are not adapted well to the growing conditions, they (and the new plant community they form) will fail to thrive. Only well-adapted plants or plants with the capacity (i.e. high genetic variability) to adapt to new conditions will survive.

Table 1. The consequences of decreasing seed germination in a container seedling nursery.

Germination %	Seeds/cell	% Filled cells	% double seedlings	Some Consequences
100	1	100	0	Life is good
98	1	98	0	Life is still pretty good
95	1	95	0	5% space lost/cost per seedling up
90	1	90	0	10% space lost/cost per seedling up
90 + Thinning	2	99	81	Thinning required, higher seed costs
85	1	85	0	15 % space lost/cost per seedling up
85 + Thinning	2	98	72	Thinning required, higher seed costs

The Economic Case for High Quality Seeds

Table 1 gives an overview of the effect of changing seed quality on container seedling production. As the table shows, 100% germination is ideal as all the cells are filled and no expense is incurred that does not return a seedling. As germination drops, even to 90%, significant losses begin to occur. While 90% might seem high, the cost to maintain the 10% of the cells that are empty has to be added to the cost of seedlings, and our production is decreased by 10%. One solution is to put two seeds in each cell. In this case the number of empty cells drops to 1%.

The number of filled cells is computed in this manner: at 90% germination, the probability of a seed not germinating is 10% (100 – 90). So the chance that the two seeds in any one cell both fail to germinate is 0.10 x 0.10 or 0.01. 100 cells – 1 cell that is empty makes for 99 full cells. However, seed costs had to be doubled because we used twice as many seeds. In addition, 81 cells have two seedlings and one seedling must be thinned out, which increases labor costs. There are 81 cells with two seedlings because the probability or chance that both seeds in a cell germinate is the product of the likelihood that each one geminates which is 0.90 x 0.90 or .81 (81% or 81 cells in 100 cells have two seedlings).

Table 2 illustrates more specifically how seed quality affects seedling costs. On the first line in this table 100% seed germination and a cost of $200 per thousand is taken as the baseline for all other comparisons. With 100% germination then a seedling would cost $0.20. The second line of Table 2 shows that if germination is 98%, and one seed is sown per container cell, then 980 seedlings are produced. This is 20 seedlings less per 1000 seeds sown than if germination was 100%. Costs of production remain the same so now the $200 per 1000 seedlings has to be spread over 980 seedlings. $200/980 seedlings gives a cost of $0.204 per plant, an increase of $0.004 per plant ($0.204 - $0.200). This amounts to a 2% increase cost per plant ($0.004/$0.20 = .02). In line 3 of Table 2, germination is further reduced to 95% while still sowing just one seed per cell. Repeating the calculations used in line 2 with this 95% germination shows that cost have increased 5.5%. Dropping germination to 90% with single seed sowing raises costs up 11%. An additional drop in germination to 85% raises seedling costs 17.5%. Cost increases are almost directly proportional to drops in germination.

Sowing two or more seeds per cell is one strategy to compensate for lower seed germination. In our example, double sowing reduces cost increases by half (line 6 of Table 2). However, to achieve this we had to waste 720 seeds for every 980 plants produced. That is 73% increase in the amount of seeds required. This strategy requires an abundant supply of seeds, and could lead to seed shortage if certain sources are harder to acquire. The thinning to remove the double seedlings also requires good timing to avoid major disturbance of the seedling that is kept.

Transplanting the thinned seedlings can recover some of the seed loss. In our example, line 7 of Table 2, seedling production costs are comparable to costs from double sowing and throwing away the extra seedlings. This operation is very time sensitive as germinates have a narrow window during which they can be transplanted without stunting or death occurring. This is not a very common practice because it is difficult to do successfully.

Detailed calculations for Table 2 are presented at the end of this paper. These calculations are only for illustrating general trends

Table 2. The cost of seedlings increases in a container nursery with decreasing seed germination.

Germination %	Seeds/cell	% Filled cells	% double seedlings	Cost per 1000 plants/ cost per plant	% Cost increase over 100% germination
100	1	100	0	$200/$0.20	0
98	1	98	0	$200/$0.204	2
95	1	95	0	$200/$0.211	5.5
90	1	90	0	$200/$0.222	11
85	1	85	0	$235/$0.235	17.5
85 + Thinning	2	98	72	$213.50/$0.214	8.75
Transplanted Seedlings	-	100	0	$214/$0.214	7

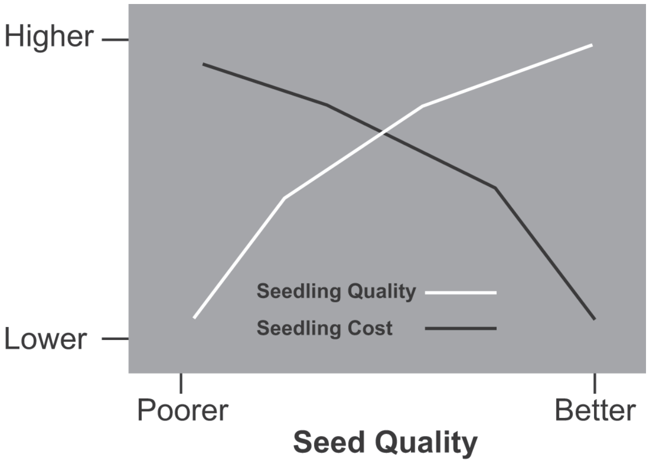

Figure 1. Relative seedling costs and quality vs. seed quality.

and each nursery would need to make these calculations in accordance with the local conditions and financial constraints.

Figure 1 graphically illustrates the general relationship between seed quality and the cost and quality of seedlings. Better quality seed results in lower seedling costs and higher seedling quality.

The Role of Seed Vigor

Vigor is the ability of a seed to germinate under adverse conditions and/or produce vigorous seedlings. High vigor seeds also will store better than lower vigor seeds. Therefore, high vigor seeds are needed for routine seed banking and especially for genetic conservation through long term seed storage. High viability usually means high vigor, but not always. This can be illustrated as in Figure 2.

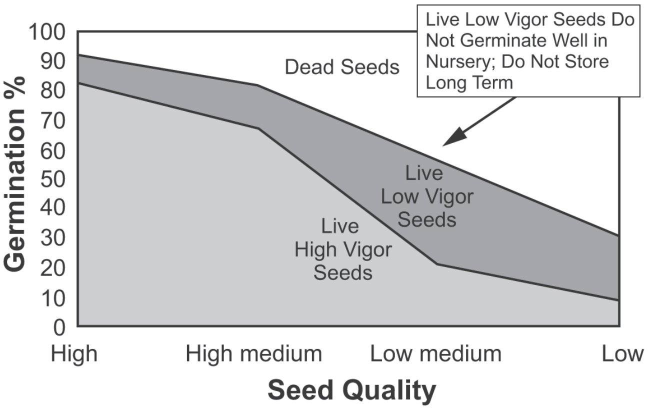

Figure 2. Fractions of viability and vigor of a seed lot.

All seed lots are made up of three portions: live high vigor seeds, live low vigor seeds, and dead seeds. Vigor tends to decline faster than germination. Therefore, germination in the nursery can take a sudden drop. This can be predicted with a current germination test. A significant drop in germination, usually more than 5%, would indicate vigor has probably changed to a greater degree. Although in tree seeds there is not an official test for vigor, paired tests have often been useful in detecting seed lots of low or declining vigor. A paired test, sometimes called a double test, is where an unstratified and stratified test are both conducted on the same sample submitted for testing. Alternatively, two stratified tests can be conducted but of different stratification lengths (e.g. one test with 30 days stratification and one with 45 days stratification.) If both tests are equal in viability or the one with longer stratification is higher, the seed lot is of good vigor. If the test with longer stratification is inferior, then the seed lot is likely to be declining in vigor. It should either be used as soon as possible or not at all. Which alternative to choose will depend on the circumstances.

Summary

Good seeds are the foundation of native plant work. Good seeds enable significant benefits in cost control and higher quality plants. Even in a noncommercial environment, poor seeds will consume more resources than good seeds, resources that could and likely should go to furthering the main objectives. Good seeds ensure that plant production targets are met and that restoration projects will be completed and successful. For orthodox seeds, good seeds cost less to store and store for longer periods of time than poorer quality seeds. This better storability is very important for routine seed banking and especially important for long term seed storage for genetic conservation. Good seeds ensure our future survival and prosperity, and that of generations of people yet unborn.

Detailed Calculations for Table 2

Germination = 95%, 1 seed sown per cell, production costs of $200 per 1000 cells.

Price: 950 plants produced, $200/950 = $0.211/plant
Price increase: $0.211 - $0.200 = $0.011 per plant,
$0.011/$0.20 = 5.5%

Germination = 90%, 1 seed sown per cell, production costs of $200 per 1000 cells.

Price: 900 plants produced, $200/900 = $0.222/plant
Price increase: $0.222 - $0.200 = $0.022 per plant,
$0.022/$0.20 = 11%

Germination = 85%, 1 seed sown per cell, production costs of $200 per 1000 cells.

Price: 850 plants produced, $200/850 = $0.235/plant
Price increase: $0.235 - $0.200 = $0.035 per plant,
$0.035/$0.20 = 17.5%

Germination = 85%, 2 seed sown per cell, production costs of $213.50 per 1000 cells.

Price: 980 plants produced per 1000 cells sown, $200/980 = $0.204/plant

Seed costs double: 2000 seeds are needed. At $300/pound and 50,000 seeds per pound one seed costs $0.006/seed, or 1000 additional seeds x $0.006 = $6.00. This $6.00 of additional seed produces 980 plants. Therefore, per seedling cost of additional seed is $6.00/980 seedlings = $0.0061/seedling. (100 – (.15 x .15) = 100 - .02 = .98 chance of filled cell. 1000 cells x .98 = 980 seedlings.)

Thinning costs: Minimum wage of $7.25 per hour/3600 seconds in an hour = $0.002/sec. Thinning rate of 5 seconds per cell, 720 cells to thin = 5 x 720 = 3600 seconds, 3600 seconds x $0.002/sec = $7.25. 720 cells to thin is the number of double seedlings which from Figure 1 is 0.85 x 0.85 = .72 or 72%. The chance that one seed germinates is .85 and the chance the second seed in the double sow germinates is .85. Chance that both germinate is the product. These thinning costs are shared over the 980 seedlings produced. Cost per seedling for thinning is $7.25/980 = $0.0074 price increase per seedling.

Total cost increase for extra seeds and thinning is: $.0061 + $0.0074 = $0.0135 per seedling or $13.50 per thousand seedlings. From above, the base cost of 980 seedlings was $0.204 per seedling or an increase of $0.004 per seedling in base cost from what they were if germination was 100%. Total cost increase from all sources is, therefore, $0.0175.

Price increase: $0.2175 - $0.200 = $0.0175 per plant, $0.0175/$0.20 = 8.75%

Germination = 85%, transplant the extra seedlings.

Here, there is the attempt to save the thinned seedlings and recoup the extra seed cost. If it takes 10 seconds to transplant a seedling and labor is the minimum of $7.25 per hour or $0.002per second ($7.25/hour divided by 3600 seconds/hour), then transplanting 1000 seedlings would cost $20. Add this to the base cost of $200 per thousand to produce seedlings and subtract the $6.00 in seed cost which was part of the last example and we arrive at $214 per thousand transplanted seedlings. These seedling are 7% more expensive than seedlings had it been possible to have 100% germination and produce seedlings for $200 per thousand (14/200 = .07). Timing the transplanting of seedlings is very critical and would require an adequate labor supply to get the job done quickly. These costs do not also take into account the number of seedlings that might become stunted or die because of transplanting.

Low-Cost, High-Tech Seed Cleaning

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Karrfalt RP. 2013. Low-cost, high-tech seed cleaning. In: Haase DL, Pinto JR, Wilkinson KM, technical coordinators. National Proceedings: Forest and Conservation Nursery Associations—2012. Fort Collins (CO): USDA Forest Service, Rocky Mountain Research Station. Proceedings RMRS-P-69. 53-57. Available at: http://www.fs.fed.us/rm/pubs/rmrs_p069.html

Abstract: Clean seeds are a great asset in native plant restoration. However, seed cleaning equipment is often too costly for many small operations. This paper introduces how several tools and materials intended for other purposes can be used directly or made into simple machines to clean seeds.

Keywords: seed cleaning, seed drying, seed storage

Introduction

Clean seeds are important in restoration for many reasons. Germination is more accurately estimated on cleaned seed lots, and until seed tests can predict how many plants to expect, it cannot be known how well establishment protocols work. Cleaner seed lots can be examined for weeds more easily, helping ensure that weeds are not brought onto the restoration site. Cleaned seeds also require less storage space.

Often, however, equipment to clean seeds is too costly for small operations. With a good understanding of the principles of seed cleaning and an average mechanical ability, a person can construct relatively inexpensive devices that in many cases are comparable to high priced equipment. Principles of seed handling will be briefly presented here. More detail is provided in the introductory chapters of the Woody Plant Seed Manual (Bonner and Karrfalt 2008). All procedures and apparatuses discussed here have actually been tried by the author or the author observed them being used by others.

Seed Drying

Texts on seed management universally emphasize controlling seed moisture as the single most important action in preserving seed quality in storage. Therefore, it is necessary to be able to dry seeds rapidly and efficiently. For millennia people dried seed by spreading them out in the sun. This works well if you have enough sun (when you need it) and have the space to spread out the seed. Also, sun drying requires protection from predation, contamination, and wind. Even when done indoors this process is often inadequate. Therefore, effective seed drying often involves pressurized dryers. In a pressurized dryer air is forced through mesh bottom containers of seeds giving uniform and rapid drying with minimal labor because there is no turning of seeds.

Figures 1 and 2 show dryers made using stacks of paint strainers for the dryer trays. Paint strainers come in bucket size and barrel size with a variety of mesh sizes for the bottoms. Using the most open mesh size possible is best to minimize air resistance. Less air resistance allows more trays and more seed on the dryer in one charge. Very small seeds of course require using a very fine mesh. As long as a gentle air flow is felt coming from the top tray of seeds, then the dryer is properly loaded.

Figure 1. Pressurized seed dryer using barrel sized paint strainer.

Figure 2. Pressurized seed dryer using bucket sized paint strainer.

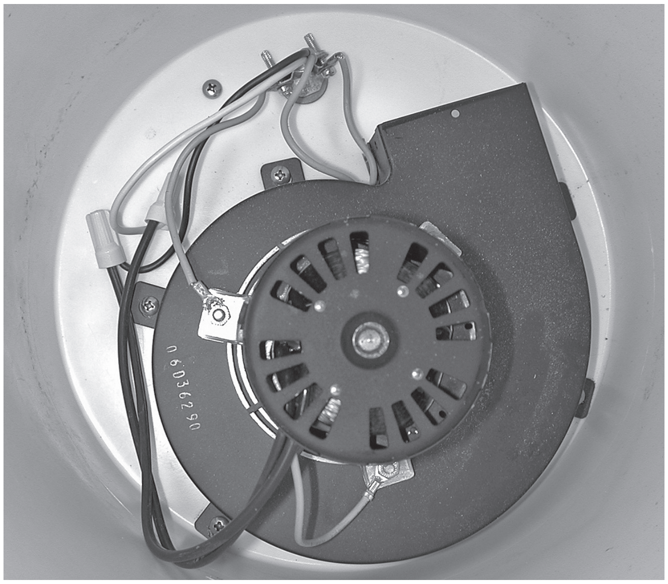

Figure 4. Induced draft blower installed in the pressurized seed dryer.

The trays need to be sealed tightly together within the stacks. Otherwise, the air will come out the sides of the tray stack since air flow follows the path of least resistance. The small trays must be separated with a collar made from a pail lid. Figure 3 shows how this collar is constructed. The opening in the lid is cut with a sharp utility knife. A piece of quarter inch (0.64 cm) foam weather stripping seals the edges.

Figure 3. Collar for sealing bucket sized paint strainers when stacked on the pressurized dryer.

The dryer fans must operate against the high resistance of the seeds and trays. High resistance would be 1.5 to 2.0 inches (3.8 to 5 cm) of water column. An induced draft blower motor is a relatively inexpensive (under $150) motor that will do this. The blower motor is mounted in the dryer plenum (bucket, barrel, or box at the base; Figure 4) so it draws air from outside the plenum and forces it up through the stack of trays. The name "pressurized dryer "comes from this pressurizing of the stack of trays.

The final step in making the dryer work is to supply it with dry air; air that is ideally at 30% relative humidity. Some environments naturally are very dry, while in others it is necessary to use supplemental heat, a dehumidifier, or a dehumidifier and an air conditioner in combination. When using one of supplemental methods to dry air, the dryer must be placed in a closed room. It is important to measure the relative humidity of the air entering the dryer. This is done with either a hygrometer or a psyc hrometer, instruments that can be purchased or that you can make using instructions from the internet.

Extracting Seeds

Extraction is one of the first steps in producing native plant seed. Drying is often part of this because drying makes the fruits or cones open up or become brittle enough to break apart. A shop vacuum works very well to extract aspen or milkweed seeds from the fluff. Starting with a clean vacuum, simply vacuum up the seed with fluff attached (Figure 5). Then open the vacuum canister and lift out the fluff which collects at the top and the extracted seed will be in the bottom of the canister, ready for cleaning.

Figure 5. Vacuuming milkweed seeds from pods separates the fluff from the seeds.

Rubber palmed gloves or rubber faced blocks and boards work well to rub appendages off of seeds. Kitchen blenders with the blades covered with rubber or plastic tubing make good cleaners for fleshy fruits.

Figure 6. A small hand operated tumbler for extracting seeds from dried open fruits or cones.

The seed dryers will be needed to dry the finished seeds. Tumbling is another way to separate seeds from the fruit or cone. Figure 6 shows a small homemade tumbler.

Dimensional Separations

Once extracted, the seeds are usually full of leaves, stems, and other trash. Separating seeds and trash by dimension is one important method. Most dimensional separation is done with screens. There are two basic screening operations, scalping and sieving. Scalping is when the seeds pass through the screen and the trash stays on top. Sieving is when the seeds remain on top of the screen and the trash passes through. Different sizes of hardware cloth, window screens, or kitchen sieves can help. For small seeds and sieving out very fine trash, the paint strainers used with the seed dryers (as described above in the section about drying) are useful and come in 4 different mesh sizes. Ready-made inexpensive screens offer only a limited range of opening sizes. The patient person might use a set of twist drills and perforate some sort of rigid sheet material to make more screen sizes. Hand screens can be purchased for about $50 each and come in over 100 sizes. These are much more expensive than home kitchen utensils but will last for decades if taken care of.

Weight Separation

Much trash is lighter than the seeds and is taken away when the seed passes into a carefully regulated column of flowing air. There are two ways to move the air, push it or pull it. Blowers push air and aspirators pull air. Aspirators have been relatively simpler to construct compared to blowers so two types of aspirators will be discussed here: the pipe aspirator and the box aspirator.

Figure 7. A pipe aspirator made from a shop vacuum and 2 inch (5.1 cm) diameter pvc drain pipe.

Pipe Aspirator

A very simple and easy-to-build aspirator can be assembled from pvc DWV (Polyvinyl chloride, drain waste vent) pipe, a small shop vac, and long neck funnel, and a tray (Figure 7). The neck of the funnel needs to extend to just below the bottom of the pipe fittings. The vacuum cost $20 and the pipe about the same, making the total cost $40. The air gate detail is shown in Figure 8. Use pipe the same diameter as the inlet opening for the vacuum cleaner. Smaller diameter pipe might stress the motor and larger diameter would cause too great a pressure drop to maintain sufficient vacuum. The machine works by turning on the vacuum cleaner, gently feeding seeds down the funnel on the top, and closing the air gate until only trash is lifted and clean seed (more or less) falls out the bottom into the tray. You can then increase the feed rate to as fast as the machine can handle and still deliver the clean seeds to the tray at the bottom. Feeding in too many seeds at once will result in trash caught under the seeds and falling

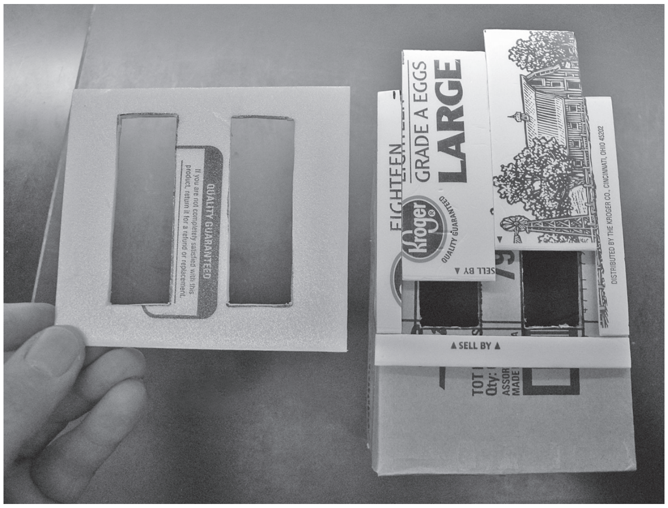

Figure 8. Detail of the sliding doors on the pipe aspirator’s air gate.

down the chute rather than being lifted up into the vacuum. If you find too many seeds in the vacuum, then too much air was used and the air gate needs to be opened up enough to prevent the seeds from being lifted with the trash. One problem that can occur with this aspirator is the buildup of static electricity along the pvc. It may need regular wiping with an antistatic cleaner or window cleaner. Be sure to have the parts thoroughly dried before putting seeds back into the cleaner.

Box Aspirator

A little more sophisticated, but possibly cheaper is a box aspirator (Figure 9). This machine has a wide seed chute that appears to be better suited to smaller seeds that have lots of fluffy trash. Because the chute is wide the seeds can be spread out well for good separation as they enter the air column rather than tangling together. The box aspirator can be made from rigid cardboard, and this might be a good way to start, ensuring the design is correct before investing in a more permanent material such as plywood. The sheets of cardboard are held together with packaging tape. The tape makes a tight seal at all joints which is necessary to maintain the vacuum in the system. The main parts of the box aspirator are the seed chute, the settling chamber, the vacuum control gates, and the vacuum source (Figure 10). The settling chamber is the foundation of the box aspirator to which all other parts are attached. It can be any conveniently sized cardboard box.

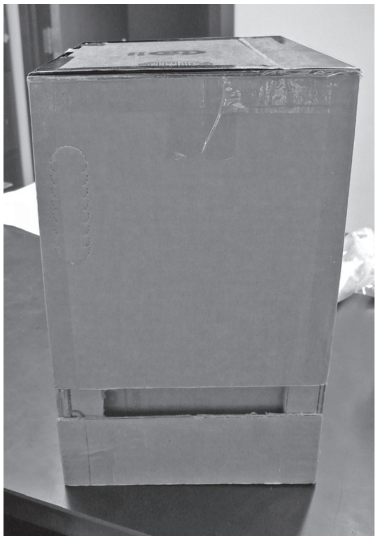

Figure 9. Front view of the cardboard box aspirator.

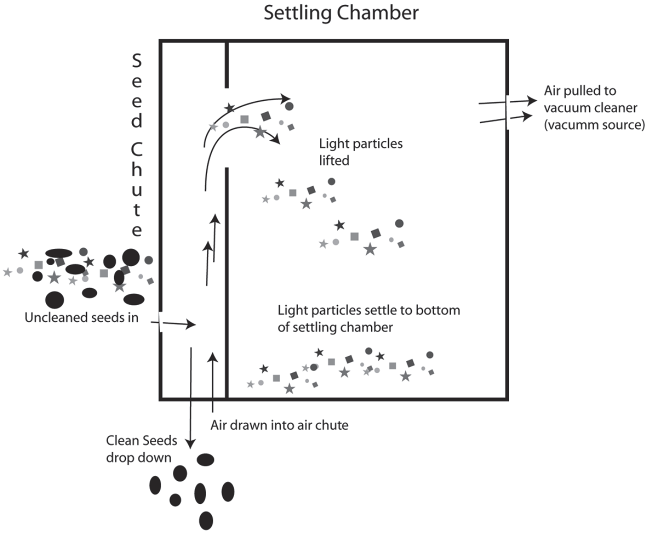

Figure 10. Diagram of the box aspirator showing the major sections and the flow of seeds and trash particles.

Seed Chute

The first step in building the seed chute (Figure 11) is to compute its cross sectional area (width × depth) which will equal the area of the vacuum source inlet. For the vacuum with a 2 inch (5 cm) round inlet, the seed chute will have a cross sectional area of about 3 square inches (area of circle =). With a 6 inch (15.15 cm) wide chute, the depth can be ½ inch (1.25 cm). Step 2 is to cut the top opening into one side of the settling chamber. Make it 4 to 6 times larger than the area of the chute. In our example, that would be about 2 to 3 inches (5.1 to 7.6 cm) high and 6 inches (15.2 cm) wide. The top opening needs to have the same width as the chute. Step 3 is to attach ½ inch (1.3 cm) thick strips to the outside of the settling chamber to form the top and sides of the chute. The thickness of the strips must match the width of the chute. A deeper chute would need thicker strips to match. In our cardboard box aspirator, the strips were made of two layers of ¼ inch (0.6 cm) cardboard attached to settling chamber with white glue. The final step is to close the chute by attaching a face sheet over the strips that is wide enough to reach completely across the chute and cover the side and top strips. The length of the face sheet should extend at least 4 inches (10.1 cm) below the bottom of the top opening and about 2 to 4 inches (5.1 to 10.1 cm) above the bottom of the chute. Attach another shorter sheet over the chute extending from the very bottom to about ½ inch (1.25 cm) from the bottom of the top sheet. This leaves a ½ inch (1.3 cm) slot in the chute through which seeds are fed into the air column.

Figure 11. View of the bottom or outlet of the seed chute on the box aspirator.

Vacuum Source Connection

Cut a hole for the vacuum source into the settling chamber on the side opposite the seed chute. Cut it near the top of the chamber (Figure 12). The connection to the vacuum must be as tight as possible to maintain good vacuum on the settling chamber.

Figure 12. Vacuum source connection for 2 inch (5.1 cm) pipe on the box aspirator.

Vacuum Control Gates

These gates (Figure 13) determine the strength of the vacuum in the seed chute and consequently the weight of particles that can be lifted. The vacuum cleaner runs at a constant speed pulling air out of the settling chamber. When the control gates are fully open, there is little to no vacuum in the seed chute. This is because the gates have about twice as much area of opening as the chute. Air draft will take the path of least resistance which will be through the control gates when they are open. The gates are gradually closed, gradually increasing the vacuum in the seed chute until it is strong enough to lift all or most of the light trash and let the seeds fall to the bottom. These gates are rectangular and narrow (1 inch [2.5 cm] wide) and long. This shape allows for more gradual and even changes in seed chute pressure compared to a wider or round opening. The gate doors are made of strips of material (cardboard in this case) 25% wider than the gate width (1 ½ inch [3.8 cm]). Track strips, the same thickness as the doors, are attached parallel to and ¼ inch (0.6 cm) back from the side of the gate opening. These track strips provide a track for the door strips to travel in. The total gate construction is finished by putting strips on top of the track strips that will overlap the track strip by ¼ inch (0.6 cm) to hold the door strip against the side of the settling chamber. Vacuum control gates are located on either side adjacent to the seed chute side of the settling chamber.

Figure 13. View of the vacuum control gates on the box aspirator.

Access to the Settling Chamber

Access to the chamber is necessary to remove the light trash that has collected there. This access is provided by a door on one side. In this version of the aspirator, a sheet of cardboard is used as the door and packaging tape serves as the door hinge. The vacuum in the chamber will keep the door closed during operation (Figure 14).

Adjusting the Aspirators

Both the pipe and box aspirators must be precisely adjusted to obtain the best seeds possible and to keep the yield as high as possible. The accuracy of separated seeds from trash is determined by the air pressure in the seed chute. A manometer (Figure 15) is a liquid filled tube that can be attached to the chute to measure the changes in pressure as the air gate is opened or closed. It will quickly help find the best setting and to find it again on future seed lots. An inexpensive manometer can be purchased for about $60 or one can be constructed from plans found on the internet.

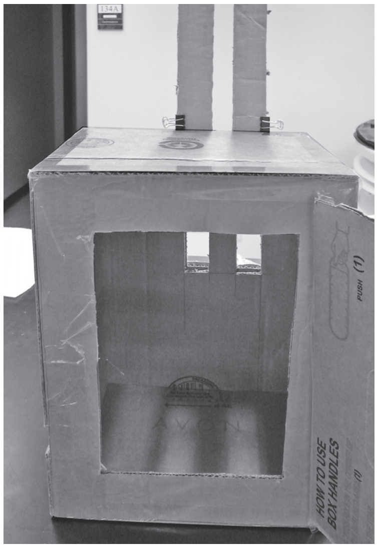

Figure 14. View of the access door into the settling chamber of the box aspirator.

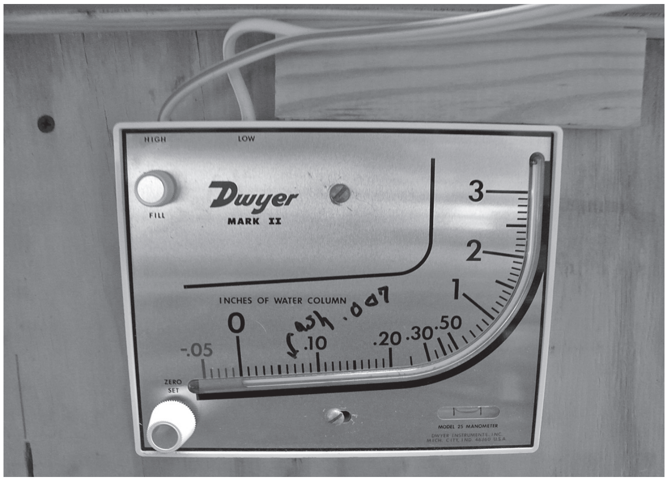

Figure 15. Manometer used to measure the strength of the vacuum in the seed chute of the aspirator.

Seeds Into the Aspirators

A seed scoop made from a 12 oz (355 ml) drink bottle can be used to feed seeds into the aspirators. It is especially well suited to the pipe aspirator and seeds that do not clump together with the trash. Short quick back and forth motions will scatter the seeds into the funnel and into the air column.

An aluminum pie pan (Figure 16) can be formed into a wide seed feeder for the box aspirator. This works better for seeds that clump with the trash because the uncleaned seeds can be sprinkled in a thin layer across the pan. The pan is then gently tapped to vibrate the seed into the seed chute.

Figure 16. Aluminum pie pan cut to form a hand held feeder to place seeds into the seed chute of the box aspirator.

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Designing Propagation Environments in Forest and Native Plant Nurseries

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Abstract: Propagation environments are areas that have been modified for plant growth, and can be designed using the law of limiting factors. Identifying critical factors that are most limiting to optimal plant growth is helpful when developing both bareroot and container nurseries. Propagation environments can be categorized into minimally-controlled, semi-controlled, and fully-controlled. The defining characteristics of each are discussed. When planning a nursery, three things should be considered: the type of crop, local soil and climate conditions, and available budget.

Keywords: limiting factors, nursery design, seedling, greenhouse, bareroot

Using Limiting Factors to Design Propagation Environments

A propagation environment can be defined as any area that has been modified to promote faster and better plant growth. Although most people immediately think of a greenhouse, a propagation environment may or may not involve a structure of some sort. When designing or managing a nursery, I like to think in terms of limiting factors. Liebig originally developed the concept of limiting factors and his law of the minimum for mineral nutrients (Wikipedia 2012). It was often depicted as a wooden barrel where the amount of water that the barrel could contain is limited by the shortest stave (Figure 1A). In actual practice, limiting factors are not independent but act sequentially (Figure 1B). Water is almost always the most limiting factor to plant growth and development, but when that factor has been culturally resolved, another will become limiting - such as nitrogen. Once that limitation has been managed another factor such as the absence of beneficial microorganisms will become limiting, and so on. The ideal environment where all potentially limiting factors have been resolved is a growth chamber, but the energy costs are prohibitive except for specific functions such as seed germination chambers. Once all the growth limiting factors have been resolved, this demonstrates the true genetic growth potential of the plants (Figure 1B).

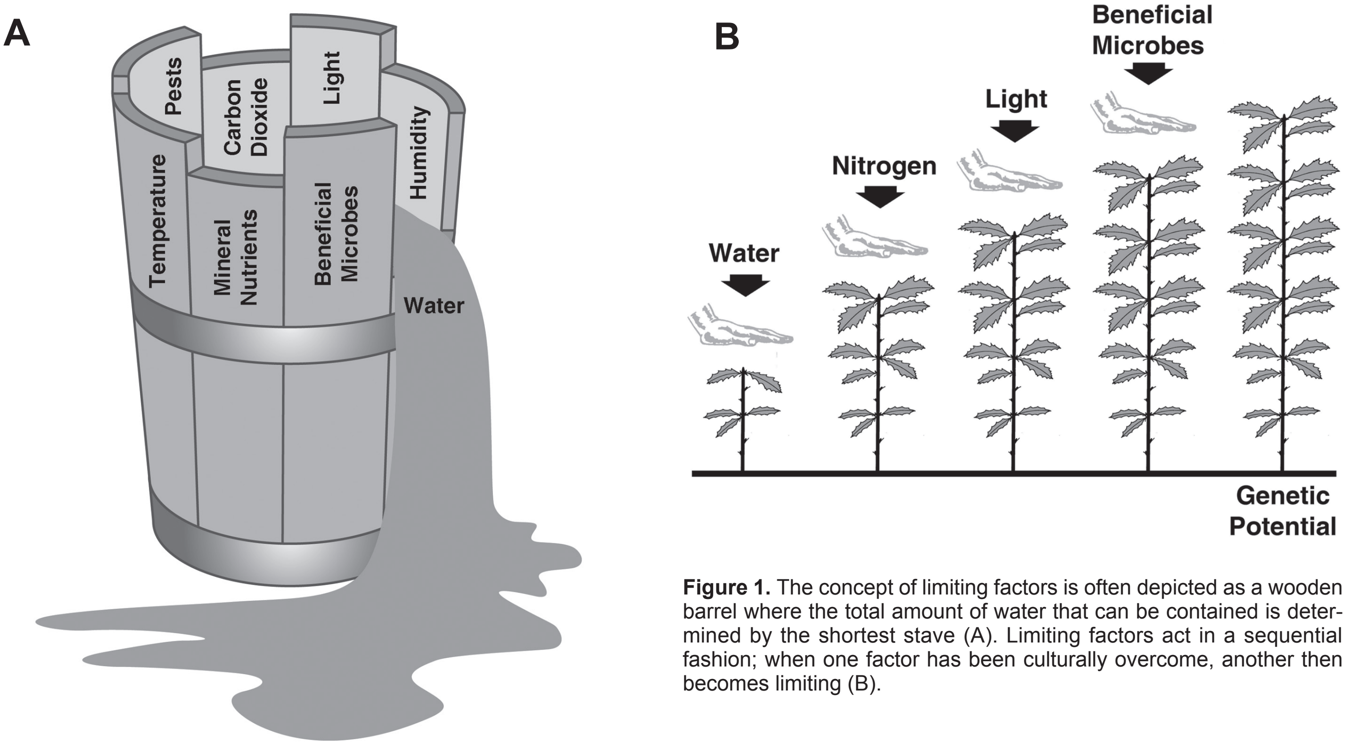

Figure 1. The concept of limiting factors is often depicted as a wooden barrel where the total amount of water that can be contained is determined by the shortest stave (A). Limiting factors act in a sequential fashion; when one factor has been culturally overcome, another then becomes limiting (B).

So, for our purposes, an ideal propagation environment is one where all environmental factors that are potentially limiting to plant growth (Table 1) are kept at optimum levels. Although water is almost always limiting to plant growth (Figure 1), this factor is relatively easy and cheap to control with irrigation in a propagation environment. Some factors, such as light intensity, cannot be economically supplied because photosynthetic lighting requires large amounts of electricity.

In addition to physical and chemical factors, the propagation environment also contains a biological component - other organisms that often limit plant growth. Pathogenic fungi and insect pests can injure or even kill succulent nursery plants and, because of the lack of natural biological controls in nurseries, pests can build up to damaging levels very quickly. One of the primary attractions of container nursery culture is that growers have more control over these biological factors and can design propagation environments to exclude most pests. On the other hand, beneficial microorganisms such as nitrogen-fixing bacteria and mycorrhizal fungi can greatly affect plant growth and development so their absence can be considered a limiting factor (Figure 1; Table 1).

Types of Propagation Environments

The limiting factors concept can be applied to design and management of both bareroot and container nurseries; although, greenhouses and other specialized propagation structures offer many more options for managing limiting factors.

Minimally Controlled

All bareroot nurseries fall into this category because they can only manage two potentially limiting environment factors: water and mineral nutrients. All bareroot facilities feature some sort of irrigation system to supply water during dry periods. Even nurseries in the mild climates, where rain occurs at regular intervals throughout the growing season, have to supply irrigation at some point to prevent moisture stress. Irrigation can also be used to cool seedbeds during germination or to provide some degree of frost protection during periods of freezing weather in the fall or spring.

Smaller scale nurseries can use raised beds filled with special growing media to overcome cool soil temperatures in the spring. The wooden frames can also be fitted with hoops of wire or plastic pipes,

Table 1. Potentially limiting factors that can be controlled in a propagation environment.

Environmental Factors	Supplied in Nurseries By:
1. Water	Irrigation
2. Mineral nutrients	Fertilization
3. Light	Type of covering, photoperiod lighting, photosynthetic lighting, blackout curtains
4. Temperature	Heaters, ventilation, shadecloth
5. Humidity	Irrigation, ventilation
6. Carbon dioxide	Ventilation, carbon dioxide generators
7. Beneficial microorganisms	Inoculation with nitrogen-fixing bacteria or mycorrhizal fungi
8. Pests	Exclusion screens, pesticides, biocontrol agents

Table 2. Amount of Control of Limiting Factors in 3 Types of Propagation Environments.

Limiting Factors	Minimally-Controlled	Semi-Controlled	Fully-Controlled
1. Water	All High – Irrigation can be performed any number of ways for each		
2. Mineral Nutrients	All High - fertigation or incorporation of controlled-release fertilizers into growing media		
3. Light	Generally none, some use of photoperiod lights & blackout curtains	Generally none, some use of photoperiod lights & blackout curtains	Medium - coverings, photoperiod lights, blackout curtains
4. Temperature	Generally none, some use of irrigation & fabric covering for frost protection	Portable heaters, and some use of irrigation & fabric covering for frost protection	High - heaters, fans & vents
5. Humidity	No	Low	High - irrigation, heat & vents
6. Carbon Dioxide	No	No	Medium - CO2 generators
7. Beneficial microorganisms	All High - apply inoculum as seed coating, top dressing, or incorporate into growing media		
8. Pests	Low – fencing to exclude deer	Moveable sidewalls prevent bird predation of seed	High - permanent walls exclude insects and birds

which are then covered with clear plastic sheeting. These minimal structures capture the heat of the sun to allow earlier sowing during the spring or prevent frost damage during the fall (Table 2). Some larger bareroot nurseries have also used hoop structures over their seedbeds to support coverings with frost fabric to prevent cold injury (Moench 1994).

Minimally-controlled container nurseries are known as open growing compounds, and were developed to produce an inexpensive container seedling that was well acclimated to the environment. Although they have been most popular for growing southern pines in the southeastern US (Barnett and others 2002), open compounds have been the standard propagation environment in tropical and subtropical nurseries. In the Maritime provinces of Canada and coastal British Columbia, open compounds are used to produce a 2-year container stocktype. Typical compounds are graded for good drainage and either covered with weed barrier fabric and gravel or paved with asphalt. Semipermanent irrigation lines supply water and can also be used to supply mineral nutrients through fertigation (Table 2). Some open growing compounds are equipped with photoperiodic lighting to extend the growing season, and blackout curtains to induce dormancy and cold hardiness. Although open growing compounds are the least expensive way to produce container stock, growth rates are slow and, depending on the climate, it may take 1 to 2 years to produce a shippable seedling. Weather damage, such as a killing frost or torrential rain, is also a constant concern and so the risk of crop loss is the highest of all types of propagation environments (Landis and others 1995).

Semi-controlled

The only instance of semi-controlled propagation environments being used in bareroot nurseries were the bedhouses used at Wind River Nursery in the early 1980's (Hansen 1983). These bedhouses consisted of moveable high tunnels that protected the seedbeds early in the growing season and then were physically removed when ambient growing conditions became favorable. Although these bedhouses did improve seedling growth rates, and shorten the growing season for some conifer species, their use was eventually discontinued. Bedhouses of clear poly sheeting over metal hoops (Figure 2) were also tested in northern British Columbia for growing white spruce and lodgepole pine bareroot stock (Simpson 1990). These trials demonstrated increases in seed germination due to warmer soil temperatures and increased growth rates that produced larger 1+0 seedlings that were less prone to frost heaving. Although the bedhouse technology showed some advantages, it has not been widely adopted.

A wide variety of semi-controlled propagation environments have been used in container nurseries (Landis and others 1995). Crops can be grown in semicontrolled structures in all but the most severe climates. Some types of semicontrolled structures, especially shadehouses and tunnels, are also used for hardening and intermittent seedling storage. From an economic standpoint, semi-controlled environments are cheaper to build and operate than fully controlled environments, although there are considerable variations between the different types of structures.

Shelterhouses are a modification of the traditional greenhouse with a permanent transparent roof with movable walls that can be rolled up after the danger of frost has past (Hahn 1982). These structures can be outfitted with environmental control equipment that allow control of many of the potentially growth-limiting factors (Table 2). In the spring or in unusually cold weather at any time during the growing season, the sidewalls are kept down and portable heaters can used to raise temperatures. As soon as ambient temperatures become favorable, the sides can be raised to permit natural ventilation, eliminating the need for forced air cooling.

Semi-controlled environments also include hoop houses and tunnels that are used much more for ornamental or food crops than for

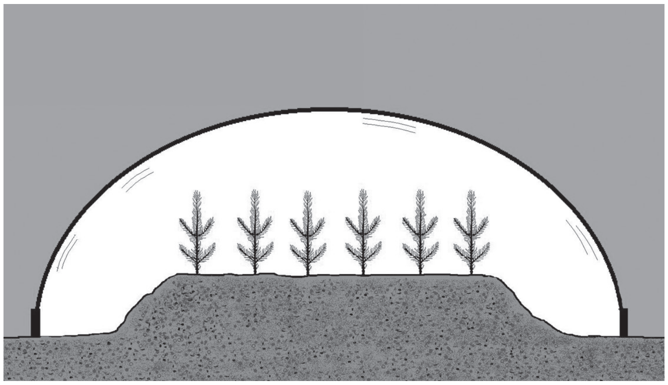

Figure 2. Bedhouses of clear poly sheeting over metal hoops are a type of semi-controlled propagation environment.

forest or native plant propagation. Hoop houses, also known as row tunnels or low tunnels, are low-profile metal bow-arch structures covered with poly sheeting that only retrain solar heat early in the growing season (Wells 1996). High tunnels can be equipped with portable heaters to prevent frost damage and accelerate seed germination (Kleinhenz 2011). During warm weather, the ends or even the sides of the tunnels can be rolled up to provide ventilation. They can also be covered with shadecloth. Hoop houses and tunnels are also equipped with ground-based irrigation lines to provide water and mineral nutrients through fertilizer injection (Table 2).

Shadehouses or lathhouses are semi-controlled propagation environments that have been widely used for growing forest seedlings and other native plants (Landis and others 1995). Traditionally, shadehouses were constructed of a wood frame covered with snowfence or wooden slats, but metal frames covered with shadecloth are also common. Shadehouses are usually equipped with basal or overhead irrigation so fertigation is also possible. Although traditionally used as hardening or holding areas, shadehouses can also be used to propagate many forest and native plants. In colder climates, shadehouses are also used for overwinter storage. Shadehouses with a permanent roof and open mesh sides have found considerable acceptance in the Tropics and the Subtropics, where sunlight can be too intense for young seedlings and torrential rains and wind can damage crops.

Fully Controlled

Greenhouses are the traditional propagation structure for producing container plants, and they can be equipped to fully control the propagation environment (Table 2). Greenhouses use natural sunlight that is trapped inside the transparent structure and converted to heat (the "greenhouse effect"). The drawback of the transparent covering is that greenhouses are inherently poorly insulated and require both high-capacity heating and cooling equipment for good temperature control. Depending on whether the climate is arid or humid, the greenhouse environment may need humidification or dehumidification. Many forest and native plant conservation species are sensitive to changes in daylength, and so photoperiodic lighting is often installed to prevent dormancy. Blackout curtains can be used to shorten the daylength and induced hardiness. Although carbon dioxide generators can be used to promote faster growth rates, they can only be run when the structure is completely closed. Irrigation systems with fertilizer injectors supply ideal levels of water and all the essential mineral nutrients. Computer-controlled equipment can keep potentially growth-limiting factors at optimal levels as well as provide a permanent computer record for growth comparisons and trouble shooting.

Greenhouses with retractable roofs and sides are the most recent innovation, and have useful applications for forest and native plant crops (Svenson 1996). Early in the growing season, the roof and sides are closed and the structure functions like a traditional greenhouse. Later, when ambient conditions improve, the roof and/or sides can be opened to allow for full air exchange. Retractable roof greenhouses are equipped with sophisticated computer controls that can open and close as needed to minimize the use of energy intensive heating and cooling equipment. The roofs and sides can be left closed early in the season and during cool weather, but opened later to allow natural hardening to under ambient conditions. This feature is ideal for forest and native plant crops which can be gradually hardened yet still be protected from climatic extremes (Landis and others 1995).

Things to Consider When Planning a Nursery

As you can see, there are a wide variety of possible propagation environments; the trick is to design one that is appropriate for your own situation. Here are three things to consider (Figure 3):

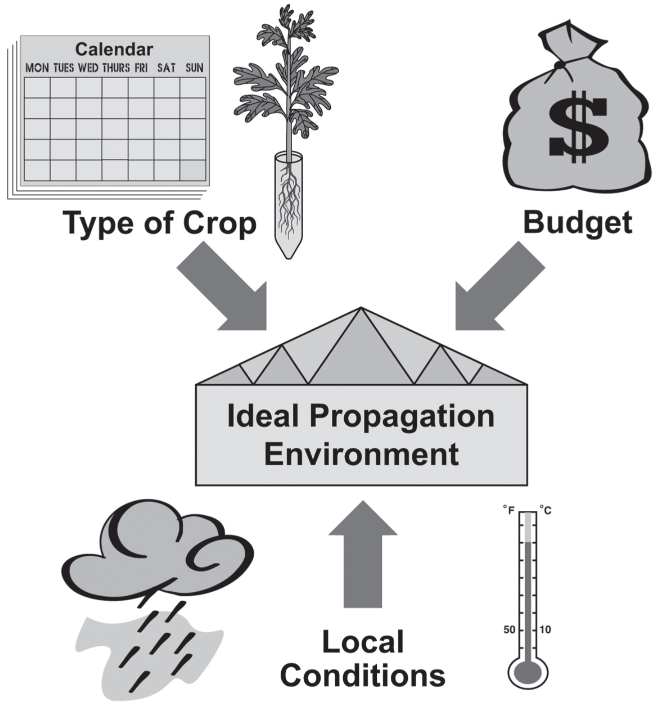

Figure 3. Several varied factors must be considered when designing a propagation environment, but one of the most important is to make certain that structures are appropriate for local conditions.

1. Type of Crop

Although this may seem obvious, all too often people wanting to start a nursery just assume "plants are plants" and can be grown in some average propagation environment. So, they spend most of their time on the economics of the situation or get caught up in design specifics. There's no such thing as an average propagation environment. The type of crop that you want to grow will have an enormous impact on your choice. The first decision is whether to grow crops as bareroot or container plants (Landis and others 1995).

Bareroot seedlings are grown in open fields in native soil, and consequently, the soil, water supply, and climate of the nursery site must be suitable for tree growing. The rate of seedling growth and length of the growing season are largely controlled by the climate at the nursery site. Quality sites are often difficult to find in convenient locations, and good agricultural land is almost always expensive. A considerable capital investment is usually required to develop a bareroot nursery of any size. Bareroot nurseries are also sensitive to the economies of scale. Once a nursery is established and operations have begun, it is important to function at near-capacity levels to have reasonable unit production costs. Compared to container nurseries, energy requirements and associated expenses are relatively low.

Container nurseries can be constructed on land with low agricultural value that would be unsuitable for bareroot seedling production. The amount of capital investment varies with the type of facility. Fully controlled greenhouses require expensive structures and en-

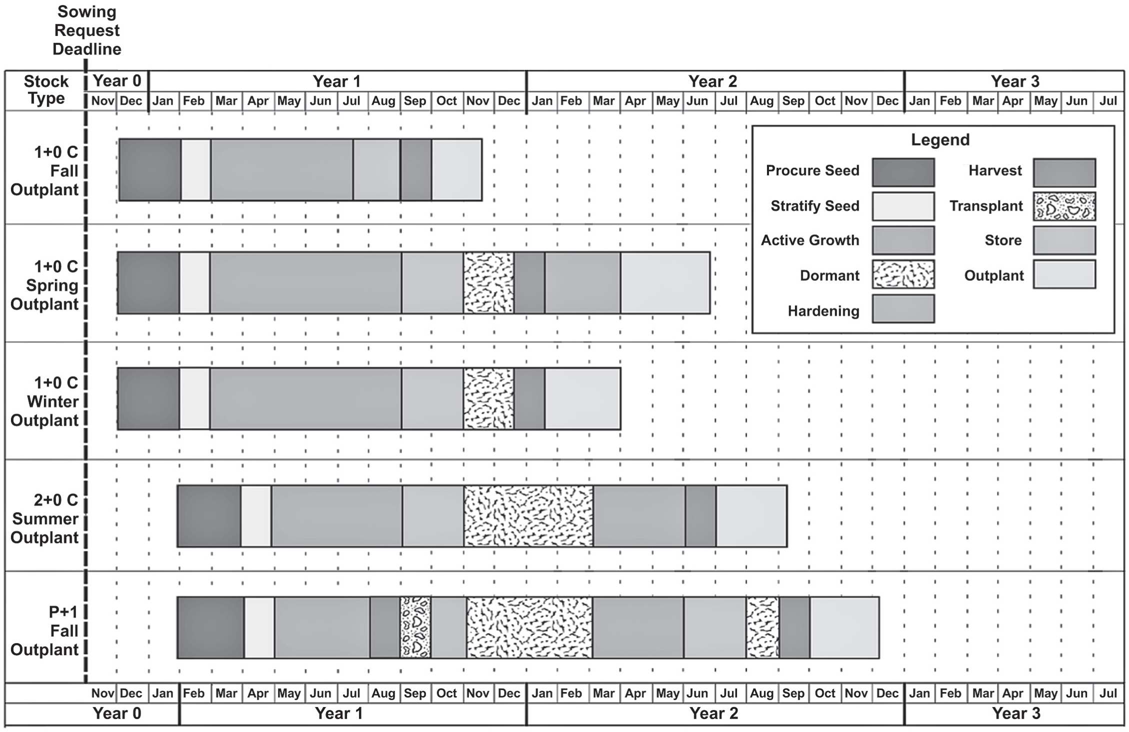

Figure 4. Growing schedules are useful during nursery planning to illustrate the time required for each phase of the nursery cycle from seed procurement to outplanting (Landis 2008).

vironmental controls, but open growing compounds are much less costly. Because container seedlings are grown at high densities, less land is required compared to a bareroot nursery. Container nurseries are less sensitive to economies of scale and, in extreme situations, part or all of the nursery can be shut down to reduce operating costs. Container seedlings have high growth rates, especially in fully controlled environments, and so crops can be produced in one growing season. From a business standpoint, this means that container nursery managers can respond quickly to changes in the market.

Once you've decided on either a bareroot or container nursery, the next things to consider are what plants you want to grow and how best to grow them. Let's say that you want to grow woody native shrubs in containers. Do you really have an idea of how long it will take to grow a saleable plant? Luckily, a source of "recipes" is available. In addition to information on seed collection and processing, the Woody Plant Seed Manual (Bonner and Karrfalt 2008) contains a section on Nursery and Field Practices for each plant genera. This book also has a chapter on the basics of plant propagation including growing schedules which show how long typical native plant crops take to produce (Figure 4). More detailed information can be found online at the native plant network (www.nativeplantnetwork.org) where several thousand propagation protocols can be found (Landis and Dumroese 2000).

2. Local Conditions

As we've already discussed, there is no ideal propagation environment; instead, each must be appropriate for the local situation. Irrigation water quality is of paramount importance for both container and bareroot nurseries, and there is no economical treatment for poor water quality. For bareroot nurseries, the next most important site quality factor is the soil. The ideal soil for a bareroot nursery is a sandy loam, primarily due to the ease of root culture and harvesting during the wet winter weather (Landis 1995). An excellent discussion of all the factors that must be considered during bareroot nursery site selection can be found in Morby (1984).

Container nurseries can be located on sites that would be totally inappropriate for a bareroot nursery because seedlings are grown in artificial growing media and with structures and equipment to modify the physical environment. Container nursery developers should allow adequate time to analyze potential sites because many biological and operational problems that develop later in nurseries can be traced back to site problems. The things to look for in a potential container nursery site can be divided into essential factors and desirable factors (Table 3). Essential site selection criteria consist of factors that are essential to a successful nursery operation. By comparison, desirable site factors are not absolutely necessary but will increase the economy and efficiency of the nursery operation. More detailed discussion on container nursery site selection is provided in Landis and others (1995).

3. Budget

Of course, economic considerations will always be paramount when planning a nursery operation. Unfortunately, it is impossible to provide detailed economic data because the size and objectives of for-

Table 3. Site selection criteria for container nurseries (Landis and others 1995).

Essential Factors	Desirable Factors
Good solar access	Protected microclimate
High quality water	Gentle topography
Inexpensive and reliable energy	Seasonal labor supply
Adequate land area including room for expansion	Year round accessibility
Ecopolitical concerns, especially zoning	Distance to markets

est and native plant nurseries is so varied. The economic constraints for a small mom-and-pop native plant nursery have little in common with that of a large commercial forest nursery. Still, nursery developers must give careful consideration to the economic aspects of starting and operating a nursery through a comprehensive business plan.

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Advanced Techniques to Prepare Seed to Sow

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Karrfalt RP. 2013. Advanced techniques to prepare seed to sow. In: Haase DL, Pinto JR, Wilkinson KM, technical coordinators. National Proceedings: Forest and Conservation Nursery Associations—2012. Fort Collins (CO): USDA Forest Service, Rocky Mountain Research Station. Proceedings RMRS-P-69. 64-66. Available at: http://www.fs.fed.us/rm/pubs/rmrs_p069.html

Abstract: This paper reviews research on improving the basic technique of cold stratification for tree and shrub seeds. Advanced stratification techniques include long stratification, stratification re-dry, or multiple cycles of warm-cold stratification. Research demonstrates that careful regulation of moisture levels and lengthening the stratification period have produced a more vigorous response in several species. Advanced stratification techniques have also produced more uniform germination in species that, when treated in the basic manner, have failed to germinate or have germinated erratically. Nursery managers can improve seed germination at their nurseries by carefully and gradually adopting one of the advanced stratification techniques reviewed in this paper.

Keywords: cold stratification, warm-cold stratification, germination temperature, seed moisture

Introduction

For at least the last 60 years, cold stratification has been a primary method for preparing tree and shrub seeds for sowing. Cold stratification was necessary to overcome dormancy factors that prevented seeds from germinating in the fall when they were first shed from the mother tree. The basic technique was to soak seeds overnight, drain off the excess water, bag the seeds in a polythene bag ("polybag"), and place the seeds at temperatures just above freezing for 30 to 60 days. Several researchers explored variations on this basic technique, and there is now enough evidence to support refined practices at production nurseries. These advanced techniques involve:

- long stratification periods
- stratification re-dry, or
- multiple cycles of warm-cold stratification.

The one common factor among all these more advanced approaches is a more precise control of moisture levels than was attempted under the basic stratification procedures. The 1974 edition of the Woody Plant Seed Manual (Schopmeyer 1974) stated simply that, "Full imbibition is essential for stratification…" In contrast, all of the advanced techniques make use of specific targeted moisture content.

Long Stratification and the Stratification of Non-dormant Species

Basic stratification approaches generally work well for moderately dormant species such as most spruce and pine. “Long stratification” means extending the stratification period beyond the basic stratification length. The length of long stratification varies depending on the dormancy of the species. Basic stratification periods for dormant species are mostly 30 to 45 days, extended to 60 days for more dormant species. Long stratification for dormant species therefore involves extending stratification periods beyond the basic 30 to 45 days. Non-dormant species are species that do not require stratification to germinate under favorable conditions. Therefore a general definition of long stratification for non-dormant species is the use of 14 to 28 days or longer of stratification than would be used with basic seed treatments.

Sitka spruce (*Picea sitchensis* (Bong.) Carrière) is a non-dormant species. Gosling and Rigg (1990) showed that unstratified Sitka spruce seeds germinated best at 20 ˚C and that germination dropped dramatically when the temperature was increased to 25 ˚C or decreased to 15 ˚C. Following 21 days of stratification, the seeds were able to germinate equally well at all three temperatures (Figure 1). Stratification also increased germination percentages and speed of germination for longleaf pine (Pinus palustris Mill) another non-dormant species (Karrfalt, 1988).

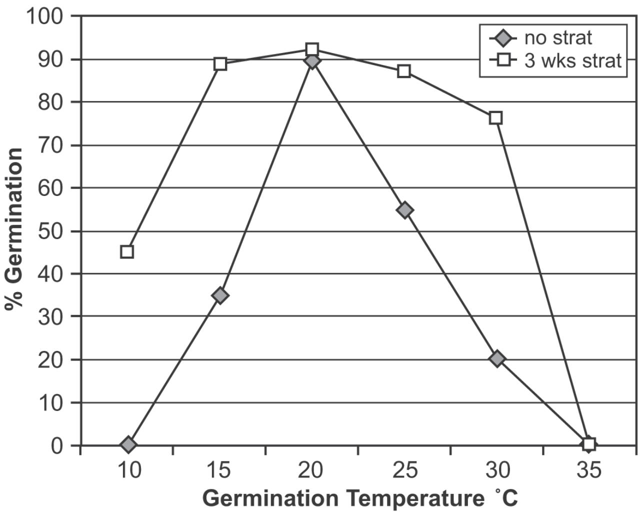

Figure 1. Stratification makes Sitka spruce seeds able to germinate well over a range of temperatures (Gosling 1990).

Douglas-fir (Pseudotsuga menziesii (Mirb.) Franco) is a moderately dormant species. Allen (1962) tested germination on 26 seed lots using 40, 80, and 120 days of stratification and germination temperatures of 25, 15, and 10 ˚C. Germination was best at 25 ˚C following all stratification periods, but the longer stratification time sharply improved the germination at the lower germination temperatures (Figure 2) just as occurred with the non-dormant Sitka spruce.

In basic stratification, there usually is a film of capillary water on at least some of the seeds. This is excess water that can lead to sprouting as the stratification period is extended. This is formally demonstrated by Gosling and Riggs (1990) with Sitka spruce. Seeds at 30% moisture content and no water film never sprouted even when the stratification period was extended to 140 days (20 weeks). Seeds that had a water film did begin sprouting in stratification (Figure 3). Therefore, removal of the water film is a mandatory requirement for long stratification because protruding radicles are usually damaged during sowing resulting in lost or stunted seedlings.

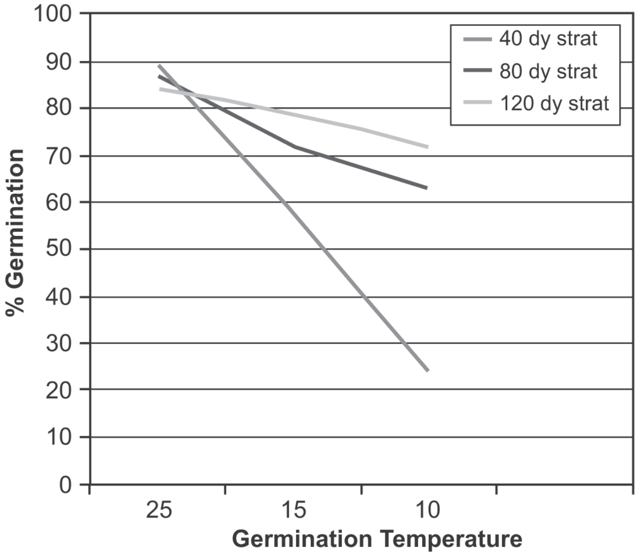

Figure 2. Long stratification makes Douglas fir seeds germinate better at cooler temperatures (Allen 1962).

Removal of the water film can be accomplished in several ways after draining the soaked seeds. The first is to simply spread the seeds out in thin layers for air drying. This takes a large flat area and continuous monitoring and turning of the seeds until the film of water is gone. A quicker way to do this is to use a pressurized drier (Karrfalt 2012). After draining the seeds, the seeds are placed in the drying tray and gently stirred continuously until the surface water is removed. Stirring is necessary or else seeds on the bottom of the tray might get too dry. A third way is to place bags of soaked seeds in a laundry spinner (Gosling and others 1994). When properly surfaced dried, the seeds will look damp but no longer have the shiny film of water.

Identifying the best length of stratification is done by simply testing different periods to determine which ones give the best germination responses. A qualified seed laboratory can run a series of tests using varying stratification lengths and even possibly germination temperatures to assist in identifying optimal stratification periods.

As with any new procedure at a nursery, a careful transition should be made when adopting longer stratification periods. The right balance must be found between removing the excess film of moisture that can cause sprouting and keeping the seed moist enough for effective stratification.

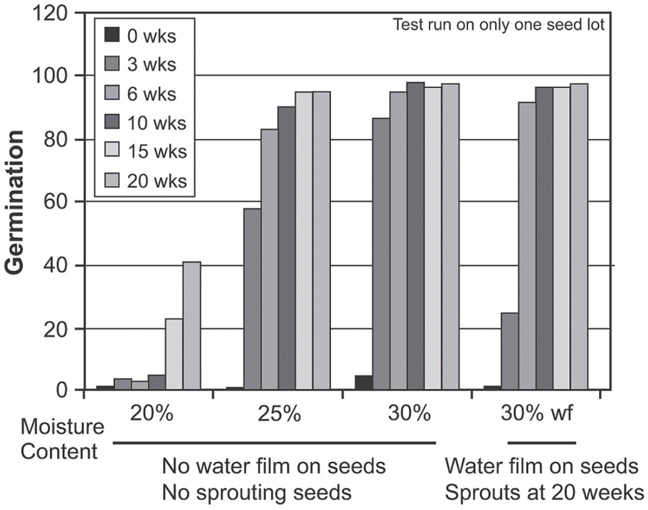

Figure 3. A film of water is not needed for effective stratification of Sitka spruce but can eventually lead to sprouted seeds in stratification (Gosling 1990).

Stratification-redry

The stratification-redry used with true firs (*Abies* spp.) (Edwards 1981; Leadem 1986) is similar to the long stratifications already discussed with two differences. First the initial 30 days of stratification is conducted in the basic manner with some surplus water with the seeds. This initial 30 days gives more complete imbibition of water. Following the initial 30 days, the seed is surface dried as described in long stratification above. Secondly, the length of the stratification is measured for each lot by pulling small samples from the stratification bag and running a small germination test. Once a good germination is obtained the stratification is terminated. To determine when the best germination has been obtained it would be useful to have had an estimate of viability made with a tetrazolium test. In a tetrazolium test, the chemical tetrazolium chloride stains the viable seeds a light pink so they can be distinguished from the non-viable seeds. When the tetrazolium estimate is close to the germination then a good germination in the nursery would be expected.

Multiple Cycles of Warm and Cold Stratification

This approach holds promise for species of deep and variable dormancy such as rocky mountain juniper *(Juniperus scopulorum*) and cherries (*Prunus* spp.). Suszka and others (1996) describe methods employing multiple cycles of warm and cold stratification to achieve complete and uniform germination. These multiple cycles presumably mimic several cycles of growing and dormant seasons. Those species requiring this treatment would be ones that use a regeneration strategy of being able to germinate seeds from one seed crop over a period of years.

In the Suszka procedure, seeds are first imbibed to a moisture content of 35%, slightly less than full imbibition. Next the seeds are generally put through cycles of approximately 30 days at 20 ˚C and 60 days at 2 or 3 ˚C. How many such cycles depends on the species. The length of the final cold cycle is determined similarly to the stratification-redry. A small sample of seeds is placed in germination and when a good germination is obtained, the cold stratification is terminated and the seed can be sown. Just as with the stratification-redry procedure, a tetrazolium test is useful to estimate the viability of the seed for comparison to the germination.

Typically species of deep and variable dormancy, when kept completely in cold stratification with a little excess moisture, will germinate in stratification over an extended period of time. In the nursery bed they can germinate over two, sometimes three growing seasons. Reducing the moisture content to 35% prevents germination but allows the dormancy breaking process to continue until all seeds are non-dormant.

Storing Non-dormant Seeds

With careful drying of treated seeds, some authors stated that storing seeds in a stratified condition without re-inducing dormancy appears to be possible. Drying stratified seeds generally puts seeds back into dormancy requiring a second stratification. Suszka and others (1996) reported that by slowly drying the seeds they could be stored in a non-dormant condition. This would be a great help to nurseries planning seedling production and responding to late orders. Allen (1962) reported a similar response in Douglas-fir. More research on how to conduct this procedure of bringing seed to low enough moisture status for storage and yet not inducing dormancy needs to be conducted before recommendations can be made for nurseries.

Summary

All of the more advanced approaches of preparing seed to sow involve a more precise control of moisture levels than the basic stratification procedures. The main key is to control the moisture content of the seeds by surface drying the seeds after they are fully imbibed. This allows for the stratification process to proceed and apparently reach an optimal state of preparation without starting germination.

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Calculating Optimum Sowing Factor: A Tool to Evaluate Sowing Strategies and Minimize Seedling Production Cost

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Abstract: This paper illustrates how to use an excel spreadsheet as a decision-making tool to determine optimum sowing factor to minimize seedling production cost. Factors incorporated into the spreadsheet calculations include germination percentage, seeder accuracy, cost per seed, cavities per block, costs of handling, thinning, and transplanting labor, and more. In addition to numerical outputs, the spreadsheet generates a graphical representation of results to present and evaluate options. Example scenarios demonstrate how the tool can be used. A copy of the spreadsheet tool is available by emailing the author: eric@tlhort.com or eric.vansteenis@gmail.com.

Keywords: seed, seedlot, sowing, cost, efficiency

Introduction

Seed is fundamental to the nursery industry. This paper illustrates how to use an excel spreadsheet to calculate optimum sowing factor (number of seeds per cell) and over-sowing factor (number of extra seeds to sow per cell). Some of the math involved is covered, and a graphical method for presenting and evaluating options is given. The objective is to evaluate different options for sowing and determine the best sowing strategy to minimize seedling production cost.

Selection Criteria Included in the Excel Spreadsheet Tool

The objective is for the nursery to produce 100% of the seedlings ordered by clients, all meeting contract specifications. The nursery also needs to be competitive and remain profitable. Hence the desire is to conserve seed, limit thinning, minimize extra non-salable green stems, and thereby arrive at the Minimum Seedling Production Cost. Employing the criteria listed below, the spreadsheet tool allows comparison of specific sowing factor strategies and alternatives.

Seedlot Germination Percentage

This is the number one selection criteria, and what sowing guidelines and seed allotments are largely based on. Sowing factor is calculated to limit empty cavity count. This varies with container type and nursery specific goals and costs, but the general goal is to have no more than a few percent of cells empty after sowing. An example is a seedlot with 80% germination. Sowing 2 seeds per cell gives a probability of >1 viable seed in 96% of the cells, leaving 4% empties and a requirement for thinning. A minimum over-sow factor of 104.67% accounts for these empty cavities. Over-sow factors in excess of this minimum are designed to increase the "green stem count".

Seeder Accuracy

Inaccuracy in seed placement and/or pickup is mathematically similar to a reduction in seedlot germination percentage. In my calculations, I apply 50% of the inaccuracy to generation of empties, and the other 50% to generation of a multiple sown cell. In other words, 50% of the inaccuracy is expressed through lowering seedlot germination percentage, resulting in the "*Adjusted Germination Capacity*."

Cost per Seed

If calculated, cost per seed is a huge incentive to conserve seed. If borne by the nursery it becomes part of seedling production cost. It then weighs against thinning cost, and as a percentage of seedling production cost can be seen to carry less weight when producing larger and more valuable seedlings. This relates to the cost of carrying an individual empty cavity, which is higher for larger stock-types.

Cavities per Block

This is the # of cells (cavities) per seedling growing tray (styroblock), and in the calculations determines seedling growing density. i.e. the potential number of seedlings/unit growing area depending on whether or not every cell (cavity) in each block (seedling tray = styroblock) contains a seedling. The majority of the industry centers around growing seedlings in "styroblocks" with a standard outside dimension (format 600), and varying numbers of cells/cavities http://www.bpgrower.com/styroblock.html

Cost to Grow/Produce a Block

This relates to the per square meter growing space production cost. A 160 cavity block takes as much space as a 77 cavity block, hence costs the same to produce. However, the number of seedlings produced per unit area changes (from 756 to 364 per square meter), thereby affecting seedling production price, and how other input costs weigh against it.

Cost to Thin

Extra germinants per cell has a cost. There is a basic cost per block to enter the crop, which is spread over the number of cavities per block. In addition, there is the per cavity cost depending on the number of extra seedlings that require thinning in each cavity.

Desired/Required Nursery Handling Factor

This factor is instated to account for the fact that seeding machines are not 100% "tidy". It allows for spillage, damage and other "wasted" seed. This is normally a very low number such as 0.15 seeds per cavity sown.

Desired/Required Green Stem Count

This refers to the total number of seedlings required from which to choose 100% of requested seedlings. It must account for culls generated by seedling specifications, pests, diseases, and so on. 125% is usually adequate, but many growers strive to reduce this < 110%. Previous nursery proceedings papers have focused on seedling specifications and how they interact with chosen container type, seedling growing density, nursery growing context, species, genetics, and so on. This is nursery specific information based on experience.

Transplant Thinned Seedlings into Empty Cells

Transplanting thinned seedlings into empty cells has a cost, carries a risk of failure, but if done well, can be worthwhile. This option can be used to reduce both the sowing factor as well as the over-sow factor. It only takes a small increase in sowing factor to generate enough "thinnings" to allow transplanting to 100% cavity fill. Far less seed is required than merely multiple sowing and discarding the thinned seedlings. If 100% cavity fill is achieved this way, then the desired green stem count can be minimized. The risk relates to the ability for transplanted seedlings to achieve contract specifications, given that the shock sets them back.

Assumptions in the Spreadsheet Tool

A basic assumption throughout is that seedling customers are not interested in receiving overruns, and the nursery is not interested in producing overruns. The desire is to have all nursery space allotted to growing on contract. The assumptions are basic and simplified. Incorporation of more detailed, more accurate, and additional nursery costs and biological/physical concepts will increase the spreadsheet's predictive value as a decision making tool.

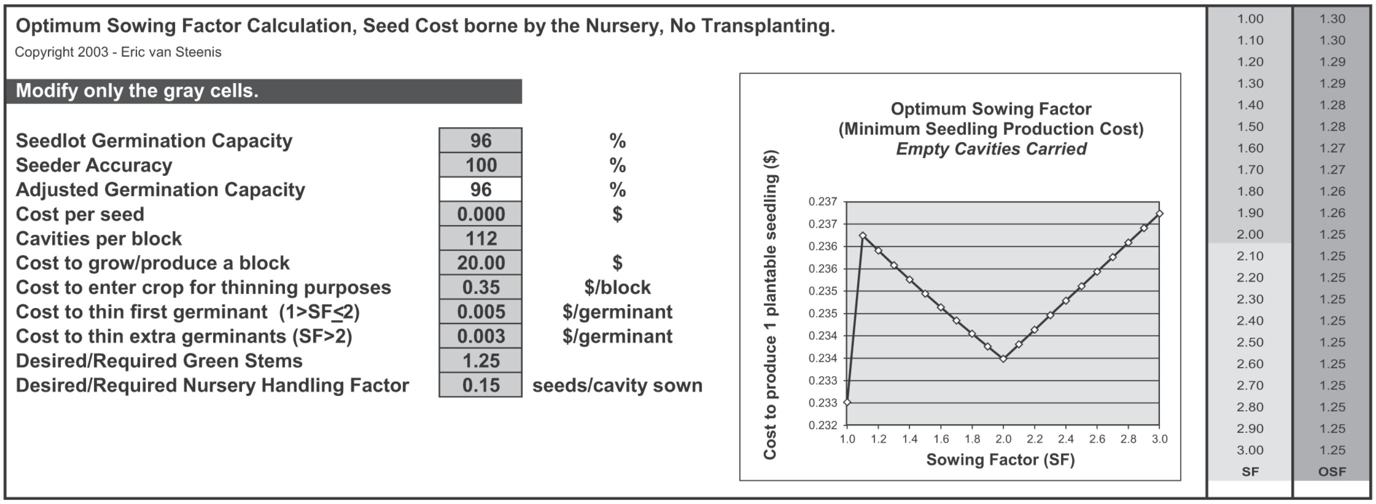
Example Scenarios Using the Spreadsheet Tool to Calculate Optimum Sowing Factor

Several situational examples are provided below to illustrate how the tool can be used.

Example Scenario 1 (Figure 1)

Scenario 1 assumes seed is free, empty cavities are carried (no transplanting), and nursery space is available to allow oversow factor adjustment as needed to provide for required green stems. Seeder accuracy is assumed to be 100% so we can easily see relationships between seedlot germination %, thinning cost, and seedling growing density when seed has no cost. The chosen seedlot quality of 96% shows the benefits of high quality seed, which encourages single sowing, and all the benefits that go along with that (minimum seed use, reduced disease transfer, maximum retention of genetic variability). The production cost of $20 per Styroblock is arbitrarily chosen, but should reflect reality for many in 2012. Dividing this cost by the number of seedlings in a block, provides the minimum seedling production cost for a single sown, 100% germination capacity seed, where all seedlings meet contract specification by end of season. One moves up from this production cost by requiring extra green stems to select from, employing less than perfect seed and equipment, and so on.

Figure 1 shows that if sowing multiple seeds and thinning is chosen, there is a basic minimum jump in seedling production cost just to enter the crop for this purpose. Single sowing and carrying the empty cavities is the best scenario here (lowest seedling production cost).



Optimum Sowing Factor Calculation, Seed Cost borne by the Nursery, No Transplanting.

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Modify only the gray cells.

Seedlot Germination Capacity	96	%
Seeder Accuracy	100	%
Adjusted Germination Capacity	96	%
Cost per seed	0.000	$
Cavities per block	112	
Cost to grow/produce a block	20.00	$
Cost to enter crop for thinning purposes	0.35	$/block
Cost to thin first germinant (1>SF≤2)	0.005	$/germinant
Cost to thin extra germinants (SF>2)	0.003	$/germinant
Desired/Required Green Stems	1.25	
Desired/Required Nursery Handling Factor	0.15	seeds/cavity sown

1.00	1.30
1.10	1.30
1.20	1.29
1.30	1.29
1.40	1.28
1.50	1.28
1.60	1.27
1.70	1.27
1.80	1.26
1.90	1.26
2.00	1.25
2.10	1.25
2.20	1.25
2.30	1.25
2.40	1.25
2.50	1.25
2.60	1.25
2.70	1.25
2.80	1.25
2.90	1.25
3.00	1.25
SF	**OSF**

Figure 1. Optimum sowing factor calculation, seed cost borne by the nursery (no transplanting).

As sowing factor increases, required oversow factor decreases until we reach 2 seeds per cavity. For a 96% germination seed lot, the probability of an empty cavity remaining beyond 2 seeds/cavity is essentially zero. At greater than 2 seeds/cavity, thinning extra seeds/cavity drives increasing cost. In this case we cannot beat the production cost of single sowing. Please keep "2 seeds per cavity" in mind as we examine other scenarios below.

The only reason to sow multiple seed is in the event nursery space is limited and will result in having to turn away additional contracts. By going from 1 to 2 seeds per cavity, we reduce oversow factor from 130 to 125%.

Example Scenario 2 (Figure 2)

In Scenario 2, seed is also free, but a drastic reduction in seed quality to 85% is imposed, along with some seeder inaccuracy. The seedling growing density is the same as Scenario 1, so we can observe the cost influence of empty growing space due to seedlot germination capacity weighed against benefits of increasing sowing factor.

Thinning the crop increases seedling production cost, but due to the large number of empty cavities, as soon as we move beyond a sowing factor of 1.1 seeds/cavity we start reducing seedling production cost relative to single sowing. Note the fastest reduction in empty cavity count and subsequent seedling production cost occurs between 1 and 2 seeds per cavity. Increasing sowing factor beyond 2 seeds per cavity reduces seedling production at a much decreased rate. Thinning costs weigh more heavily since extra seed expended does little in the way of eliminating empty cavities to offset additional labor costs.

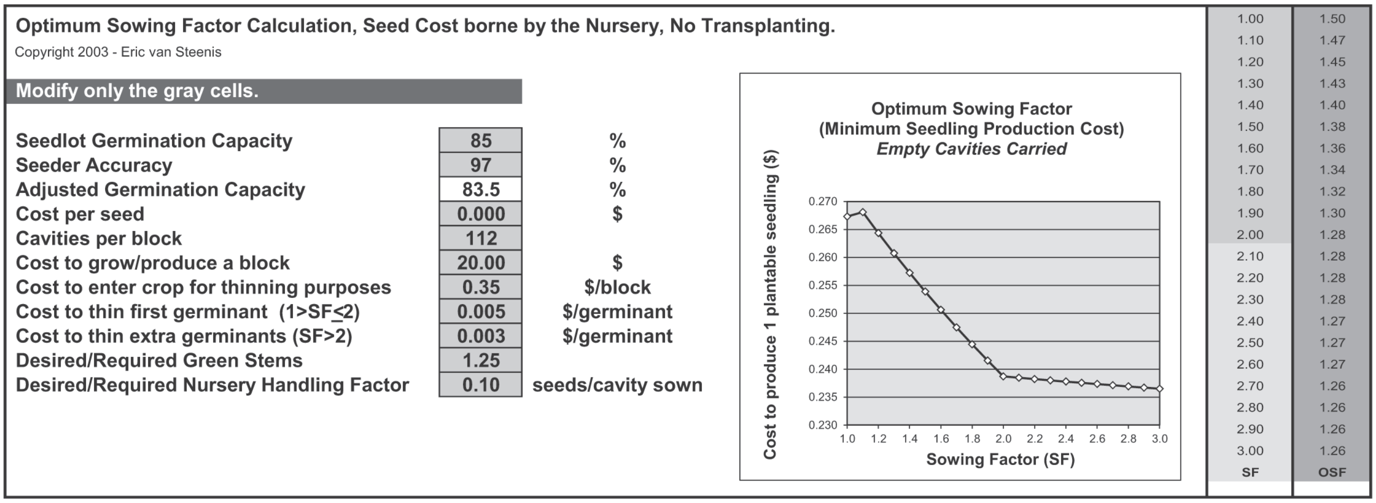
Note that low germination seedlots require a larger commitment of nursery growing space at low sowing factors. Best approach in this case is to sow 2 seeds per cavity.

Example Scenario 3 (Figure 3)

Scenario 3 introduces a seed cost of 1 cent each. This might seem high/low depending on your situation, but gives an interesting result. We have raised germination percent to 94, but left seedling growing density and thinning costs the same as Scenarios 1 and 2.

Note the immediate impact on seedling production cost. Single sowing raises minimum cost per seedling by 1 cent/seedling. With a 94% seedlot in a relatively high density block (112), any increase in sowing factor adds proportionally significant (seed and thinning) costs to the price of each seedling.

Note that costs increase gradually up to 2 seeds per cavity, but then the law of diminishing returns takes effect in earnest. In this case, the lowest seedling production cost is at 1 seed per cavity. However, if nursery growing space is limiting and extra contracts are available, one could consider sowing up to 2 seeds/cavity. This



Optimum Sowing Factor Calculation, Seed Cost borne by the Nursery, No Transplanting.

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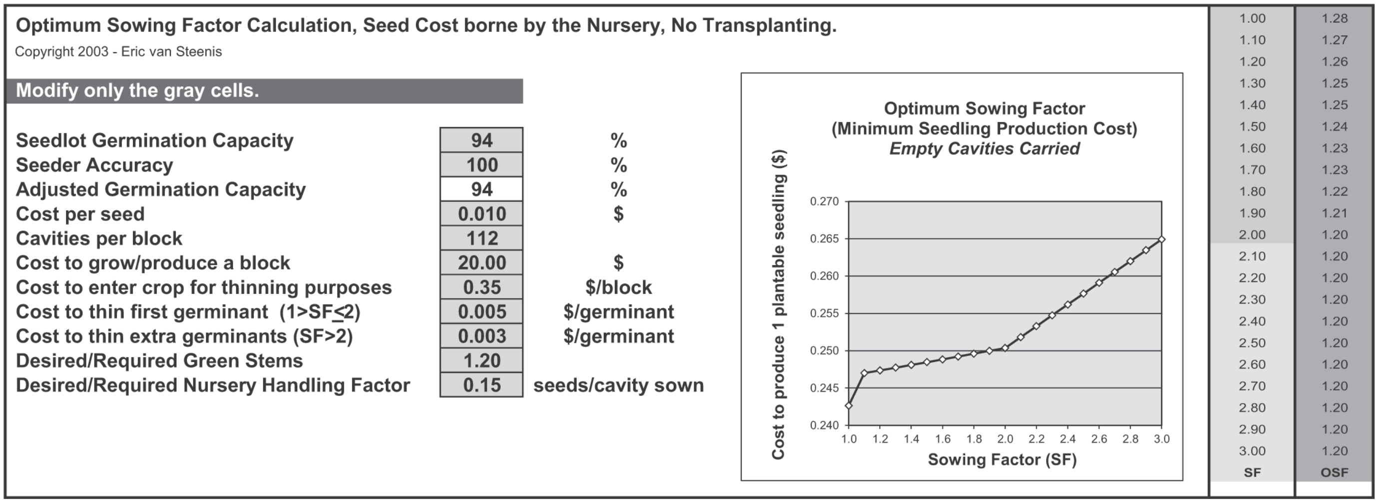
Modify only the gray cells.

Seedlot Germination Capacity	85	%
Seeder Accuracy	97	%
Adjusted Germination Capacity	83.5	%
Cost per seed	0.000	$
Cavities per block	112	
Cost to grow/produce a block	20.00	$
Cost to enter crop for thinning purposes	0.35	$/block
Cost to thin first germinant (1>SF≤2)	0.005	$/germinant
Cost to thin extra germinants (SF>2)	0.003	$/germinant
Desired/Required Green Stems	1.25	
Desired/Required Nursery Handling Factor	0.10	seeds/cavity sown

1.00	1.50
1.10	1.47
1.20	1.45
1.30	1.43
1.40	1.40
1.50	1.38
1.60	1.36
1.70	1.34
1.80	1.32
1.90	1.30
2.00	1.28
2.10	1.28
2.20	1.28
2.30	1.28
2.40	1.27
2.50	1.27
2.60	1.27
2.70	1.26
2.80	1.26
2.90	1.26
3.00	1.26
SF	**OSF**

Figure 2. Optimum sowing factor calculation, seed cost borne by the nursery (no transplanting).



Optimum Sowing Factor Calculation, Seed Cost borne by the Nursery, No Transplanting.

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Modify only the gray cells.

Seedlot Germination Capacity	**94**	**%**
Seeder Accuracy	**100**	**%**
Adjusted Germination Capacity	**94**	**%**
Cost per seed	**0.010**	**$**
Cavities per block	**112**	
Cost to grow/produce a block	**20.00**	**$**
Cost to enter crop for thinning purposes	**0.35**	**$/block**
Cost to thin first germinant (1>SF≤2)	**0.005**	**$/germinant**
Cost to thin extra germinants (SF>2)	**0.003**	**$/germinant**
Desired/Required Green Stems	**1.20**	
Desired/Required Nursery Handling Factor	**0.15**	**seeds/cavity sown**

SF	OSF
1.00	1.28
1.10	1.27
1.20	1.26
1.30	1.25
1.40	1.25
1.50	1.24
1.60	1.23
1.70	1.23
1.80	1.22
1.90	1.21
2.00	1.20
2.10	1.20
2.20	1.20
2.30	1.20
2.40	1.20
2.50	1.20
2.60	1.20
2.70	1.20
2.80	1.20
2.90	1.20
3.00	1.20

Figure 3. Optimum sowing factor calculation, seed cost borne by the nursery (no transplanting).

will reduce growing space for this contract by 8%. However, beyond 2 seeds per cavity it gets pricey, and we are not saving any more nursery growing space either. As seed price increases, single sowing becomes "economically" viable at lower seed-lot germination capacities, especially in small cavity blocks. This is in a 112 cavity block; results would be different for other sizes, such as a 240 cavity block.

Example Scenario 4 (Figure 4)

With seed cost at 1 cent each, in Scenario 4 we introduce a lower seedling growing density with a 77 cavity block. Notice that one can afford to throw extra 1 cent seeds at bigger cells (more valuable seedlings due to occupation of more growing space per seedling) to help eliminate empties, thereby reducing seedling production cost.

Again, sowing beyond 2 seeds per cavity does not make economic sense. At that point the minimum 1.20 oversow is realized, more seeds do not garner additional nursery space, and costs rise. In larger cavity blocks it is often economical to multiple seed even at higher germination capacities and incorporated seed costs. Basically, as the ratio of seedling production cost to seed cost increases, the more the economics favors multiple sowing.

Example Scenario 5 (Figure 5)

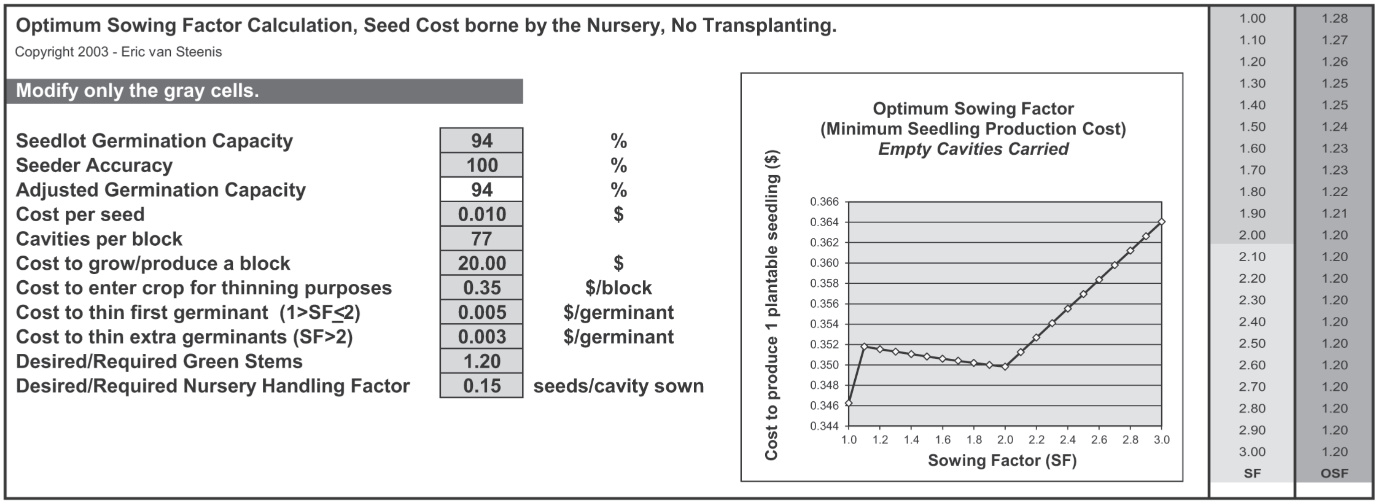
With seed cost remaining at 1 cent each, we introduce transplanting thinned seedlings. Note that at a sowing factor of ~1.4 you have enough thinned seedlings to transplant to 100% cavity fill. After that, the seed cost effects increasing seedling production cost, and there is no further gain in nursery growing space.

You can use the spreadsheet to insert your nursery's cost and success rate for thinned transplants. These are very important numbers to have. If in doubt, stay conservative. Even the 50% success rate we have assumed in this scenario can be optimistic depending on your nursery context.

Example Scenario 6 (Figure 6)

Scenario 6 compares carrying empties to transplanting thinned seedlings into empties as they become available with increasing sowing factor. Carrying empties has a ~1.7 cent/seedling higher "minimum seedling production cost". This is perhaps the most interesting spreadsheet in the workbook.

The spreadsheet assumes thinning costs are linear as sowing factor increases, which may not be correct. Note that in many cases a sow-



Optimum Sowing Factor Calculation, Seed Cost borne by the Nursery, No Transplanting.

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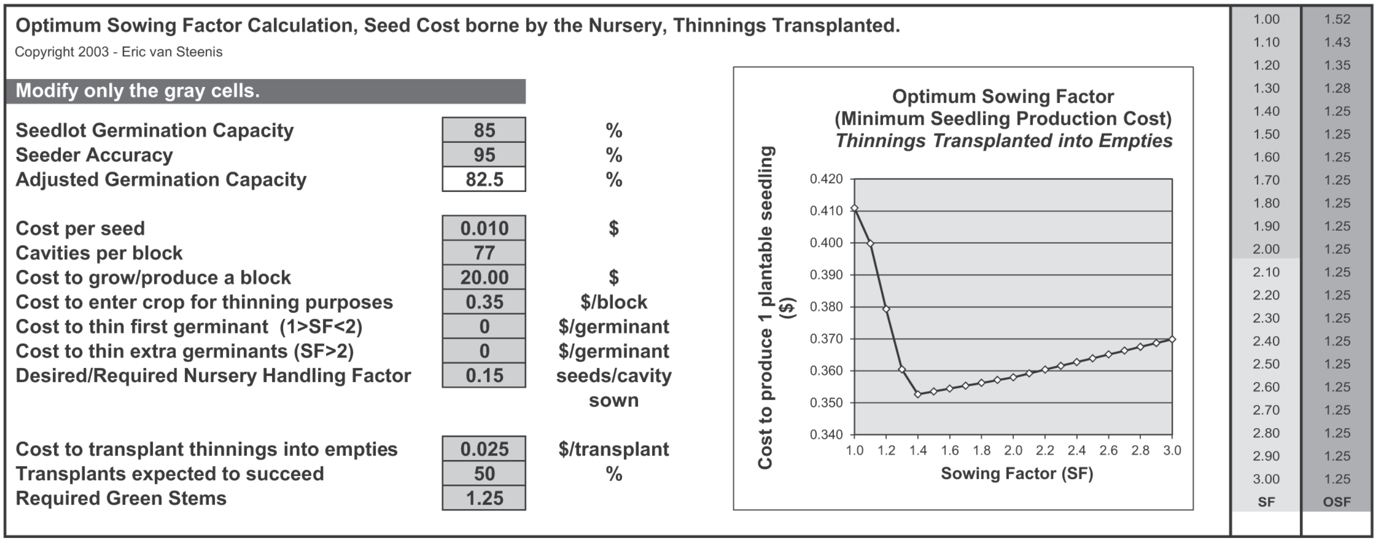
Modify only the gray cells.

Seedlot Germination Capacity	**94**	**%**
Seeder Accuracy	**100**	**%**
Adjusted Germination Capacity	**94**	**%**
Cost per seed	**0.010**	**$**
Cavities per block	**77**	
Cost to grow/produce a block	**20.00**	**$**
Cost to enter crop for thinning purposes	**0.35**	**$/block**
Cost to thin first germinant (1>SF≤2)	**0.005**	**$/germinant**
Cost to thin extra germinants (SF>2)	**0.003**	**$/germinant**
Desired/Required Green Stems	**1.20**	
Desired/Required Nursery Handling Factor	**0.15**	**seeds/cavity sown**

SF	OSF
1.00	1.28
1.10	1.27
1.20	1.26
1.30	1.25
1.40	1.25
1.50	1.24
1.60	1.23
1.70	1.23
1.80	1.22
1.90	1.21
2.00	1.20
2.10	1.20
2.20	1.20
2.30	1.20
2.40	1.20
2.50	1.20
2.60	1.20
2.70	1.20
2.80	1.20
2.90	1.20
3.00	1.20

Figure 4. Optimum sowing factor calculation, seed cost borne by the nursery (no transplanting).



Optimum Sowing Factor Calculation, Seed Cost borne by the Nursery, Thinnings Transplanted.

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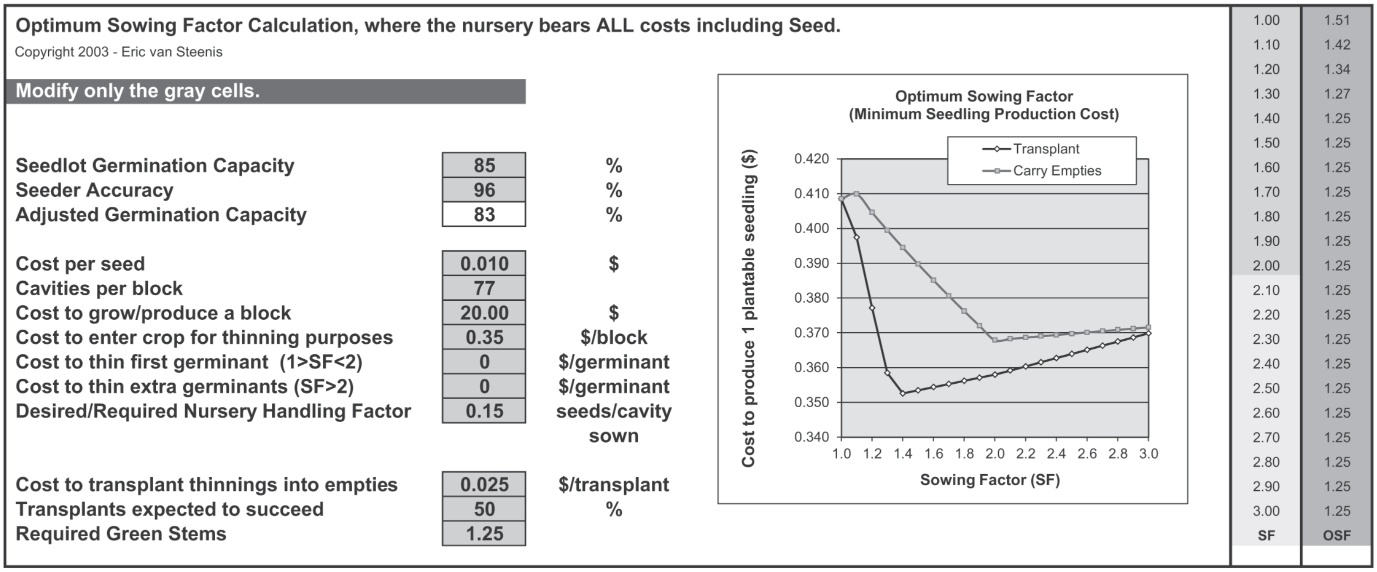
Modify only the gray cells.

Seedlot Germination Capacity	85	%
Seeder Accuracy	95	%
Adjusted Germination Capacity	82.5	%
Cost per seed	0.010	$
Cavities per block	77	
Cost to grow/produce a block	20.00	$
Cost to enter crop for thinning purposes	0.35	$/block
Cost to thin first germinant (1>SF<2)	0	$/germinant
Cost to thin extra germinants (SF>2)	0	$/germinant
Desired/Required Nursery Handling Factor	0.15	seeds/cavity sown
Cost to transplant thinnings into empties	0.025	$/transplant
Transplants expected to succeed	50	%
Required Green Stems	1.25	

SF	OSF
1.00	1.52
1.10	1.43
1.20	1.35
1.30	1.28
1.40	1.25
1.50	1.25
1.60	1.25
1.70	1.25
1.80	1.25
1.90	1.25
2.00	1.25
2.10	1.25
2.20	1.25
2.30	1.25
2.40	1.25
2.50	1.25
2.60	1.25
2.70	1.25
2.80	1.25
2.90	1.25
3.00	1.25

Figure 5. Optimum sowing factor calculation, seed cost borne by the nursery (thinnings transplanted).



Optimum Sowing Factor Calculation, where the nursery bears ALL costs including Seed.

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Modify only the gray cells.

Seedlot Germination Capacity	85	%
Seeder Accuracy	96	%
Adjusted Germination Capacity	83	%
Cost per seed	0.010	$
Cavities per block	77	
Cost to grow/produce a block	20.00	$
Cost to enter crop for thinning purposes	0.35	$/block
Cost to thin first germinant (1>SF<2)	0	$/germinant
Cost to thin extra germinants (SF>2)	0	$/germinant
Desired/Required Nursery Handling Factor	0.15	seeds/cavity sown
Cost to transplant thinnings into empties	0.025	$/transplant
Transplants expected to succeed	50	%
Required Green Stems	1.25	

SF	OSF
1.00	1.51
1.10	1.42
1.20	1.34
1.30	1.27
1.40	1.25
1.50	1.25
1.60	1.25
1.70	1.25
1.80	1.25
1.90	1.25
2.00	1.25
2.10	1.25
2.20	1.25
2.30	1.25
2.40	1.25
2.50	1.25
2.60	1.25
2.70	1.25
2.80	1.25
2.90	1.25
3.00	1.25

Figure 6. Optimum sowing factor calculation, where the nursery bears ALL costs, including seed.

ing factor of 2 seeds per cavity gives an inflection point in the graph. Thinning (and seed) costs start to assume a larger role in seedling production cost than the reduction in empties generated by incremental increases in sowing factors. An interesting discussion ensues if we introduce the genetic value of seed instead of merely its production cost. This can be a fun brainstorm.

Summary

This spreadsheet is a useful tool to evaluate options for sowing factors incorporating multiple nursery costs. Constructive criticism and ideas for improvements to this tool are welcome.

Lengthened Cold Stratification Improves Bulk Whitebark Pine Germination

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Robertson N, Eggleston K, Overton E, McLaughlin M. 2013. Lengthened cold stratification improves bulk whitebark pine germination. In: Haase DL, Pinto JR, Wilkinson KM, technical coordinators. National Proceedings: Forest and Conservation Nursery Associations—2012. Fort Collins (CO): USDA Forest Service, Rocky Mountain Research Station. Proceedings RMRS-P-69. 72-76. Available at: http://www.fs.fed.us/rm/pubs/rmrs_p069.html

Abstract: Crucial to the restoration of whitebark pine (*Pinus albicaulis*) ecosystems is the ability of forest managers to locate, propagate, and reintroduce viable, disease-resistant populations to these jeopardized systems. Currently, one of the most limiting steps in this process is the slow, labor-intensive, and expensive process of producing whitebark seedlings at forest nurseries. From a nursery production standpoint, whitebark seed dormancy is complex and more problematic that other western conifers. Although seedling culture has evolved and become more streamlined, overcoming seed dormancy is still a major challenge to efficient seed use and large-scale seedling production. Releasing seed dormancy through scarification and stratification needs to result in adequate and consistent germination percentages, and also needs to be practical and efficient at a restoration-production scale. This paper describes trials comparing germination percentages of whitebark seedlots grown under operational conditions at the Forest Service Coeur d'Alene Nursery to determine the relative influence of seed source elevation and location, seedlot (collection) age, and 60 or 90-days of cold stratification. The results of these studies indicate that, given proper seed collection, handling, cleaning, and storage: 1) 90-day cold stratification results in significantly increased germination over the 60-day treatment; 2) within the first decade of storage, seedlot age may not play as crucial a role in reducing germinative capacity as was previously thought; and 3) seedlot source geography may not have a strong enough influence on germinative capacity to merit altering seed use calculations or culture regimes for greenhouse production.

Keywords: *Pinus albicaulis*, scarification, nursery, seedling, restoration, seedcoat, dormancy

Introduction

Whitebark pine (Pinus albicaulis), the sole North American member of the Cembrae pine subsection, faces restoration challenges unique among the western conifers. Chief among these challenges is matching the pace of recruitment with an unnaturally accelerated mortality rate. The species faces the triple-pronged threat of introduced disease (*Cronartium ribicola*), native pine beetle (*Dendroctonus ponderosae*) epidemics, and historically uncharacteristic fire regimes (Mahalovich and others 2006). In the past several decades, much effort has been dedicated to identifying and securing seed from apparently disease resistant forest trees for the purposes of understanding disease resistance genetics and establishing seed banks for future seedling propagation and restoration efforts.

The success of such efforts hinges on the ability of tree nurseries to reliably germinate seed from various collections. The germination strategy of whitebark differs considerably from other western pine species. Most notably, in addition to a thick, hard seedcoat, which hampers imbibition, whitebark seeds have complex physiological dormancy release mechanisms (Riley and others 2007; Tillman-Sutela and others 2007). Because whitebark cone crops vary widely from year to year, and predation claims many of the nutrient-rich seeds, these mechanisms are presumably an adaptive strategy to delay the germination of dispersed seeds over the course of several years (Tomback and others 2001). This seed banking strategy may help offset periodic cone crop and seedling establishment failures, and balance recruitment through time. At the same time, these seed dormancy and germination characteristics make uniform artificial germination of whitebark seeds very difficult to achieve.

Past practices for producing whitebark seedlings in nurseries evolved out of germination and growth strategies developed for western white pine (*Pinus monticola*) (Burr and others 2001). However, stratification protocols for this species proved to be inadequate for whitebark pine, with its additionally complex dormancy mechanisms. Because of the difficulty of protecting, collecting, and cleaning whitebark seed, investment in collections is significant compared to other western conifers (Keane and others 2012). Due to this value, and the historically limited volume of seed being processed and seedlings being grown, very labor-intensive scarification and growing techniques have been used in an attempt to maximize the productivity of a given seed collection. These processes have included various chemical scarification regimes, hand- or machine-knicking individual seeds to disrupt the seed-coat integrity, germinating seeds in artificial germinators, hand-transplanting individual germinants when radicals appeared, and re-stratifying un-germinated seeds to produce additional germinant flushes (Gasvoda and others 2002; Pitel and Wang 1990; Wick and others 2008).

It is possible, through a combination of stratification, scarification, and highly controlled environmental parameters, to achieve nearly 100% germination of mature, viable seeds (Riley and others 2007; McCaughney 1992). However, replicating such conditions on the scale needed for mass seedling production for the purpose of restoration plantings has continued to be very problematic for nurseries, and at times prohibitively expensive (Eggleston 2012). These germination challenges, along with the slow growth of whitebark seedlings compared to other western conifers, has resulted in prices double or triple that of comparable products for other species (Eggleston 2012). Efforts to streamline seedling culture have increased mass production efficiency tremendously (Eggleston 2012). Still, overcoming low, erratic, and latent germination in whitebark seed at a large scale continues to be problematic.

At the USDA Forest Service, Coeur d'Alene Nursery (CDA Nursery, Coeur d'Alene, Idaho), whitebark seedling production has increased steadily in the past decade, and production levels are now near 200,000 seedlings per year (Eggleston, 2012). At this level, hand-knicking and hand-transplanting are logistically and economically impractical, so new methods must be developed to ensure adequate germination with a minimal investment of time and labor. Prior to the 2012 growing season, the CDA Nursery whitebark seed treatment protocols consisted of a 30-day warm strat, followed by a 60-day cold strat, after which seeds were scarified in a rotary drum sander (Missoula Technology & Development Center [MTDC]) (Gasvota and others 2002) for three hours. (Past trials at CDA Nursery have indicated that sanding beyond three hours does not increase germination [unpublished data]). This dormancy release treatment, in combination with direct sowing, has allowed the CDA Nursery to produce large numbers of restoration seedlings, while avoiding the costs of hand-knicking and hand-transplanting. Unfortunately, germination percentages using this method have historically ranged from 13-75% (Eggleston 2012). This wide range, coupled with the regular incidence of significant numbers of latent germinants, indicates that seed dormancy mechanisms were not entirely overcome, and/or that other factors influencing germination were at play.

If whitebark pine seedlings are to be produced in large quantities for the purpose of restoration plantings, nursery practices must be aimed at overcoming the complications associated with seed dormancy. Seed waste must be minimized by more fully realizing germinative capacity, while simultaneously avoiding laborious and expensive processes such as altering growing regimes to accommodate significant latent germination. In an effort to avoid seed and labor waste in future whitebark crops, we conducted a study comparing the current CDA Nursery stratification regime to one with an extended cold stratification treatment. We also considered potentially influencing factors, such as seed source and growing schedule. These studies were conducted in the 2011 and 2012 growing seasons at the CDA Nursery.

Materials, Methods, and Treatments

Studies were performed in conjunction with operational whitebark seedling production for National Forest and National Park System clients at the CDA Nursery. In total, 25 operational seedlots were sown, representing all six of the USFS Northern Rockies whitebark seed zones (Table 1). Four of these seedlots had comparable sowings in 2011 and 2012; the others were sown in the 2012 growing season only. Two studies were conducted using germination data collected from these operational (client-requested, large-volume nursery stock order) whitebark sowings.

The first study was designed to compare germination under a single stratification regime using variations in seed source and growing schedule as factors. Namely, seedlot age, source elevation, seed zone, and sowing date were considered as potentially influencing germination rate. Only lots sown during the 2012 growing season were considered in this trial. The second study compared germination rates of four seedlots using differing stratification protocols (60 or 90 days cold stratification) sown in 2011 and 2012.

For both studies, operational whitebark seedlots collected from various locations and years were cleaned, stored, scarified, and sown under standard operational conditions for whitebark seedling production at the CDA Nursery. Seed was cleaned to 98% or better purity, and 90% or better seeds filled. All seed was warm stratified at 18 °C (65 °F) for 30 days, then cold stratified at 0.5-1.7 °C (33-35 °F) for either 60 (2011 sowings) or 90 (2012 sowings) days. Following stratification, seeds were surface dried and scarified using a rotary drum sander by sanding 0.25 lbs (0.11 kg) of seed at a time for three hours, then washing to remove dust. Seeds were immediately sown into containers for operational seedling production by inserting the seed below the media horizon so as to be completely covered with moist media, but no more than 0.25 in (0.64 cm) deep, and covered with no more than 0.25 in (0.64 cm) of inert top-dressing. Containers were placed in greenhouses heated to 18 °C (65 °F), with upward daytime temperature fluctuated minimally, with a cooling set-point at 24 °C (75 °F). Due to the similar and controlled climate parameters in the greenhouses, differences in germination conditions between the 2011 and 2012 growing seasons were assumed to be non-significant for the purposes of this trial. Media was kept moist throughout the germination and growing process.

Seeds were sown at various dates ranging from 19 January to 7June of 2011 and 2012. Final germination counts were taken in early July 2011 and late August 2012. Containers were randomly selected from within a large seedlot block, and seeds (germinated or not germinated) counted as individual replicates. Seedlot sample sizes ranged from 7%-100% of seeds sown, with no less than 392 seeds being sampled for any one lot.

Germination data was compiled and statistical analyses were performed to assess the influences of potential variables on germination performance. Only data from seedlings grown in 2012 were used to assess potential influences of seedlot age, sowing date, and elevation. Least squares regression analyses were used to determine the relative influence and importance of each variable on germination performance in each grouping. Germination percentages for each lot were used as data points and tested for seed zone significance using lot germination averages in an analysis of variance. For the four seedlots sown in both 2011 and 2012, the Pearson's chi-square test was used to compare germinative performance and determine significance. Each seed lot was analyzed using a separate test.

Table 1. Whitebark pine seedlots sown in 2011 and 2012 for cold stratification length trial, with associated sowing dates, collection geography, seed zones, and germination percentages.

Seedlot	Sow Year	Sow Date	Seed Zone	Collection Year	Elevation	Cold Strat Days	Germ %
GROUSEMTN09	2011	4-May	GYGT	2009	6.2	60	36.5%
UNIONPASS09	2011	25-Jan	GYGT	2009	6.5	60	36.1%
SAWTELL09	2011	2-Feb	GYGT	2009	6.7	60	23.5%
WB02091081	2011	18-Mar	BTIP	2009	8.1	60	21.0%
WBP2066	2012	7-Jun	GYGT	2006	6.4	90	86.2%
WBP2067	2012	7-Jun	GYGT	2006	6.0	90	90.6%
WBP2068	2012	7-Jun	GYGT	2006	6.4	90	86.0%
NUMA	2012	7-Jun	MSGP	2010	6.5	90	59.9%
WBP1262-09	2012	4-Apr	GYGT	2009	8.4	90	73.5%
PRESTONPARK07	2012	20-Mar	MSGP	2007	8.7	90	57.9%
SURPRISE10	2012	20-Mar	GYGT	2010	9.0	90	60.3%
BURKE09	2012	20-Mar	SKCS	2009	9.3	90	58.0%
WHITECALF	2012	20-Mar	MSGP	2010	8.9	90	88.8%
WB14091093	2012	28-Feb	BTIP	2009	8.1	90	63.0%
GROUSEMTN09	2012	26-Jan	GYGT	2009	6.2	90	59.9%
RISINGWOLF	2012	26-Jan	MSGP	2010	9.0	90	71.4%
OLDMAN	2012	24-Jan	MSGP	2010	9.1	90	78.6%
BIGMTN11	2012	8-Feb	MSGP	2011	6.9	90	89.3%
BETA_DESERT_NI	2012	7-Jun	MSGP	2011	7.0	90	73.0%
NAPA_SUNSET11	2012	9-May	MSGP	2011	9.1	90	82.7%
HORNET11	2012	12-Apr	MSGP	2011	6.2	90	70.6%
WB02091081	2012	23-Feb	BTIP	2009	8.1	90	80.6%
DEADLINE11	2012	19-Jan	GYGT	2011	10.0	90	66.6%
LITTLEJOE10	2012	20-Mar	SKCS	2010	9.5	90	66.9%
VIPONDPARK10	2012	27-Feb	CLMT	2010	8.6	90	67.3%
FREEZEOUT10	2012	4-Feb	CFLP	2010	9.2	90	75.8%
WB03030092	2012	24-Feb	GYGT	2003	6.3	90	77.3%
SAWTELL09	2012	23-Feb	GYGT	2009	6.7	90	74.5%
UNIONPASS09	2012	1-Feb	GYGT	2009	6.5	90	62.8%

Results and Discussion

In the first study, regression analyses were used to determine the effect of seed source variables and sowing date, rather than traditional significance tests, due to large sample sizes (n>391 for each lot tested). Regression results for seedlot age (R^2=0.046; Figure 1), sowing date (R^2=0.053), and elevation (R^2=0.10) indicated that these factors held relatively little influence on germinative performance in this trial. Seed zone did not show a significant influence on germination either (p =0.73). In the second study, the results of the a Pearson's chi-square test indicated significant differences in germination between those seeds cold stratified for 60 days and those cold stratified for 90 days. Each of the four seed lots tested showed significantly increased germination when subjected to the longer stratification regime, with germination more than doubling in two of the lots (Figure 2).

It is to be expected that differences in seed collections result in differing germination rates among seedlots. Seed cleaning, handling, storage condition, and storage longevity also influence germinative capacity post-collection (Tomback and others 2001). To what degree variations in collections and seedlot age influence germination in whitebark pine seed, has yet to be determined. From a nursery operational standpoint, these factors are only important if they significantly influence germination rates at the time of seedling production. For the seedlots used in the first study of this trial, none of the source related variables proved to have a strong determining influence on germination. Based on this observation, seed-to-seedling ratios for whitebark pine are not likely be adjusted to accommodate small influences on germination arising from differences in source elevation or seed zone.

Germination is directly correlated to sowing date in an outdoor growing facility due to changing environmental conditions. However, in a greenhouse environment with artificially controlled light, moisture, and temperature, sowing date should not influence germination. This proved to be true in our trial. Of more importance is considering the time required to produce a containerized whitebark seedling, even under optimal growing conditions, and adjusting the planting date accordingly.

All conifer seed has a limited shelf-life; although, it varies considerably from species to species. Historically, much of the whitebark seed at this facility has been sown for seedling production within sev-

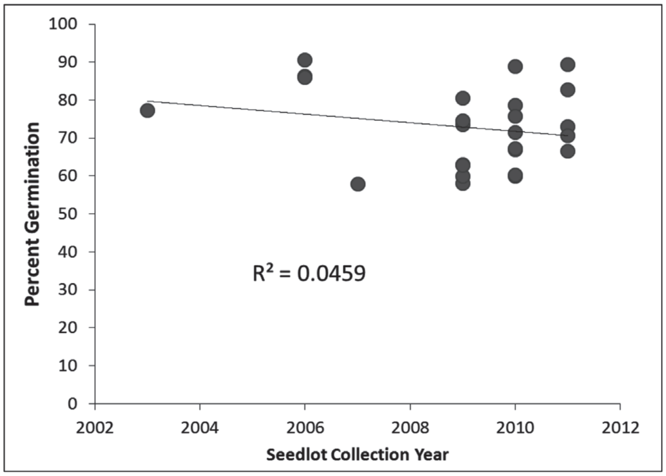

Figure 1. Percent germination by seedlot collection year (age) for lots sown in 2012, with 90-day cold stratification.

eral years after collection for two reasons. First, whitebark seed collections have barely kept pace with seed use for seedling production and banking, which resulted in minimal long-term storage. Second, it has been the experience of personnel at this facility (Burr and others 2001) that whitebark has very limited storage longevity, despite its considerable size and nutrient content. Most clients were encouraged to have their seed sown within 1-5 years of collection, to avoid viability losses in cold-storage. However, this assumption arose under older stratification, scarification, and germination protocols (Burr and others 2001). Our results and others (Berdeen and others 2007; McCaughney and others 1990) indicate that seedlot age plays a much less significant role in reducing germinative capacity than was previously thought. Granted, seedlots held in cold-storage necessarily begin to lose viability at some point; and our sample represents primarily young seedlots (<4 years in storage; Table 1). However, the strong germinative capacity of older seedlots in this trial (up to 9 years in storage; Figure 1), leads us to reconsider the role of seedlot age in reducing germination. When cleaned to a high purity and percentage of filled seeds, whitebark seed may have considerable longevity, likely exceeding a decade in cold storage without considerable loss of germinative capacity. Furthermore, empirical observations of seedlots being grown at the CDA Nursery suggests an improvement in germination rates for seedlots held in cold storage for at least a year post-collection.

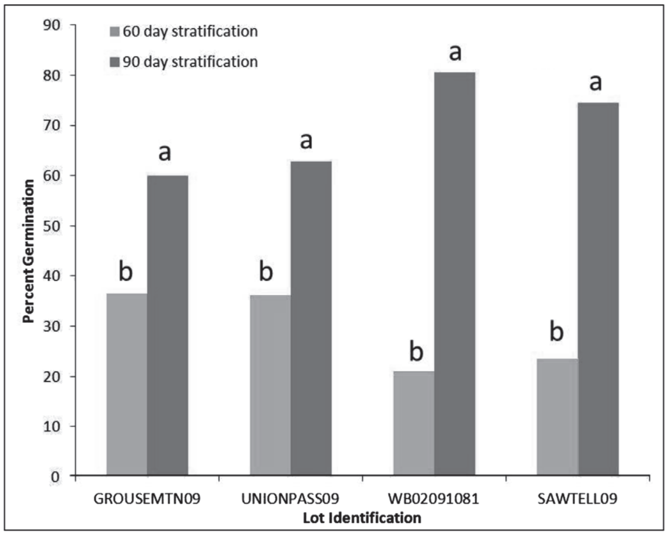

Figure 2. Effect of length of seed stratification on germination percentage. A chi-square test was performed individually on each seedlot. Different letters denote significance at α=0.05.

The second study in this trial revealed the importance of stratification length in obtaining high germination percentages in whitebark. Although similar trials have been conducted on a relatively small scale (Riley and others 2007; Wick and others 2008), these works were research-oriented and used scarification and germination techniques not practical at an operational restoration scale. This combination of 90-day cold stratification and mass scarification resulted in higher and more consistent germination than has been seen before at this facility for operational whitebark crops (unpublished data). Because the two stratification groups were grown in separate years, it is possible that factors beyond those considered here influenced germination. However, as already discussed, greenhouse conditions and scarification regimes were unchanged between the two growing seasons. Theoretically, an additional year in cold-storage would have had no effect or a small negative effect on germination, and because all four of the lots used for the second study were collected in 2009, any storage influence would be shared equally amongst them. These factors fail to explain the significant increase in germination apparent in all four seedlots, which indicates that a 90-day cold stratification is instrumental in obtaining strong germination for direct-sown, restoration-level whitebark pine seedling production.

Summary

Whitebark pine seedling production levels continue to rise at the CDA Nursery, as forest managers are increasingly in a position to bolster recruitment in compromised stands using disease-resistant seedlings. At the production scale being seen now, original scarification and stratification methods are no longer economically viable, and waste of hard-won whitebark seed is not acceptable at these levels. In an effort to maximize germinative capacity without sacrificing production efficiency, dormancy release factors must be understood and overcome. Given proper seed collection, handling, cleaning, and storage, the results of these two studies indicate that: 1) 90-day cold stratification results in significantly increased germination over the 60-day treatment; 2) within the first decade of storage, seedlot age may not play as crucial a role in reducing germinative capacity as was previously thought; and 3) seedlot source geography may not have a strong enough influence on germinative capacity to merit altering seed use calculations or culture regimes for greenhouse production.

Although cold stratification lengths in excess of 90 days become logistically burdensome at this facility, further study should be conducted to see if longer cold stratification periods result in higher germination rates. Additionally, more research will be needed to better understand true whitebark seed longevity in cold-storage, especially with regards to variant embryo maturity (Tillman-Sutela and others 2008), and the potential positive effect of storing seed for at least a year post-collection. Seed managers and horticulturists at the CDA Nursery will use this data and future studies to increase whitebark seed use and production efficiency, in an effort to better contribute to the restoration of this high-elevation cornerstone species.

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The Importance of Bees in Natural and Agricultural Ecosystems

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Abstract: As the world's most important group of pollinators, bees are a crucial part of agricultural production and natural ecosystem function. Bees and the pollination they provide are relevant to the nursery industry because of their role in the performance of seed increase plots as well as the importance of pollination in supporting persistent plant communities in restored areas. Agricultural producers can increase seed or fruit production with colonies of European honey bees, managed native bees, or by managing land to increase populations of native bees. By meeting requirements for food and nesting resources restored areas can support similar levels of species richness and abundance of native bees. Although the specific species of bees present may differ between restored and remnant sites, pollination function and community resilience can be restored.

Keywords: pollination, seed production, seed increase, bees, restoration

The Importance of Bees in Natural and Agricultural Ecosystems

Pollination services provided by insects are an indispensable component to both natural and agricultural ecosystems (Kremen and others 2002, Pauw 2007, Klein and others 2007). Estimates of the value of insect pollination of agricultural crops in the United States range from $150 million paid for pollination services to $3.07 billion in total crop value (Morse and Calderone 2000; Losey and Vaughan 2006). While agricultural intensification and urbanization may be reducing the numbers of wild pollinators (Kremen and others 2002), native (as opposed to managed) bees can still provide abundant crop visitation in a variety of landscape types (Winfree and others 2008). Although many taxa, including moths, flies, beetles, hummingbirds, and bats, function as pollinators, bees are most effective in many cases (Steffan-Dewenter and Tscharntke 1999). This is true for a few reasons. Bee larvae and adults both rely almost entirely on pollen and nectar for sustenance. Therefore the number of visits bees make to flowers, as well as the distance moved between flowers, are greater than in other pollinator taxa (Willmer 2011). As well, bees as a group have a wide range of sizes and morphological adaptations that enable mutual relationships with a wide range of host plants (Thorp 1979, 2000; Michener 2000). Conversely, wasps, the most similar group of organisms, feed on nectar only as adults, hunting other arthropods to provide the nitrogen needed for larval development. Other groups of animal pollinators important in temperate areas (butterflies, flies and beetles) also only feed on pollen and nectar as adults.

The mutual relationship between bees and plants is complex. The vigor of a bee community is determined by plant species richness and diversity at both small and large scales (Steffan-Dewenter and Tscharntke 1999; Hendrix and others 2010). Similarly, seed production and, potentially, eventual plant recruitment is dependent on a species rich and diverse bee community (Steffan-Dewenter and Tscharntke 1999; Slagle and Hendrix 2009). A variety of floral visitors is important as different bees have different habits and interact with the flower in different ways, improving pollination; a variety of accessible plants provides greater niche space (Potts and others 2003).

Providing Supplemental Pollination Using Honey Bees

Ensuring high levels of pollination can produce larger yields and higher quality fruit. Supplemental crop pollination is most commonly provided with managed colonies of the European honey bee. Convenience and predictable efficacy has made the honey bee an integral part of modern agriculture. About 150,000 honey bee colonies are rented to U.S. growers for pollination annually, with almonds, apples, and cherries comprising about half of all colony rentals (Burgett and others 2010). The European honey bee is very well suited to commercial pollination. Colony strength can be visually inspected and extremely high numbers of pollinators can be placed anywhere within the agroecosystem at a time that suits the grower. These traits allow growers certainty there will be sufficient pollination service when and where it is needed.

However, relying on pollination by managed honey bees has drawbacks. Pollination efficiency varies by crop, and some pants (such as alfalfa) are not effectively pollinated by honey bees. Additionally, Colony Collapse Disorder and honey bee colony death due to mites and disease continue to be problems. Although there has been much research into honey bee health recently (Figure 1), rentals of honey bee colonies are becoming increasingly expensive (about $90/colony in the western U.S.) and may be unavailable in certain areas (Burgett and others 2010).

Encouraging Native Bee Pollination

Because of these drawbacks, growers in some systems have chosen to actively manage native bees for pollination. A robust population of native bees can provide pollination service throughout the growing season, which is important if the grower has a variety of crops requiring pollination that may flower at different times. In agricultural systems, diverse and species rich plant communities near pollinator dependent crops can increase pollination and greatly add to crop value (Kremen and others 2004).

The amount of land hosting diverse floral resources in the few hundred meters surrounding a flowering crop is directly related to pollen deposition (Kremen and others 2004). Additionally both small and large alterations to the farmscape, such as leaving areas fallow, planting strips of wildflowers, or reducing tillage can increase local presence of pollinating insects (Vaughan and others 2007). Limiting pollinator exposure to pesticides cannot be stressed enough. Avoiding treatment of flowering crops or spraying in the evening with a low residual insecticide is the most important single thing a grower can do to limit pollinator mortality (Johansen and Mayer 1990). For more information see 'Farming for Bees' published by the Xerces society.

Figure 1. Bees feeding on a special diet formulated by the USDA-ARS. Honey bee die off may be caused by a combination of poor nutrition, pesticide exposure, pests, or pathogens. Honey bee colony rental is becoming increasingly expensive despite recent progress in understanding and mitigating honey bee stressors. (Photo: Stephen Ausmus USDA-ARS).

Effect of Restoration on Bee Populations

In natural settings a robust plant-pollinator community fosters ecosystem resilience because each supports the other (Fontaine and others 2005). A strong bee community requires a diverse selection of plants to provide places for nesting as well as sustenance throughout the season (Potts and others 2005; Franzén and Nilsson 2010). The diversity of a flowering plant community is closely linked to the functional diversity of a complementary community of pollinating insects (Fontaine and others 2005). Seed production in most plants is, in some years, limited by inadequate pollen deposition (Burd 1994), and many native forbs greatly increase seed production with pollinator visitation (Figure 2) (Cane 2008). Pollen limitation may be the most significant cause of reproductive failure in fragmented habitats (Aguilar and others 2006). For all these reasons, a robust community of native bees is necessary for thriving plant communities in restored areas (Handel 1997).

Although there may be structural differences in bee communities between remnant and restored areas, bee species richness and pollination function can be restored to levels similar to remnant native habitat (Exeler and others 2009; Williams 2011) as long as necessary food and nesting resources are available within foraging range (Potts and others 2005; Winfree 2010). Nesting resources can take the form of bare soil, dead woody substrate, pithy or hollow stems, or rodent burrows depending on the bee species. Food for bees is entirely composed of pollen and nectar produced by flowers. The timing and variety of floral resources available are important mediators of the bee community at a site. Restored areas should have plant species that provide pollen and nectar for the duration of the growing season. These plants have been referred to as 'framework' and 'bridging' plants depending on their role in the support of the pollinator community (Dixon 2009).

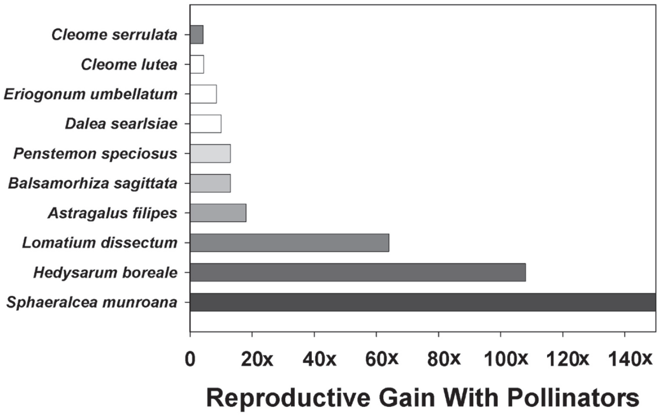

Figure 2. Pollinator visitation can greatly increase plant seed production. Increased seed production may increase resilience of plant communities.

Framework plants provide copious amounts of pollen and nectar to a wide range of bee species. This will ideally create a large and diverse bee community that then provides pollination to a number of less attractive plant species (Ghazoul 2006). However this strategy may fail if the framework plants chosen compete with other plants through pollination. It is difficult to predict if plant species sharing pollinators will compete for or mutually facilitate pollination (Menz and others 2011).

Bridging plants provide nectar and pollen in resource-limited times of year. The necessity of bridging plants depends on the length of the growing season and the pollinators involved (Dixon 2009). If the growing season is short enough bridging plants may not be needed because floral resources may be very common during the short time bees are actively foraging (Menz and others 2011).

Summary

Pollination is a crucial part of seed or fruit production; many native forbs and annuals produce much more seed when pollinators are present (Cane 2008; Slagle and Hendrix 2009). Pollination can be increased or ensured through introduction of European honey bee colonies or by managing the agro-ecosystem for native bee habitat. Honey bees may be an attractive choice for some growers because of their simplicity and general efficacy. However the cost of importing colonies may be high and honey bees are ineffective pollinators for some crops. By providing food and nesting resources near crops requiring pollination a species rich community of native bees can be maintained providing quality pollination service throughout the growing season.

An abundance of floral and nesting resources will also foster a strong community of native bees in restored areas. Replanting shrubs or woody plants, if appropriate, will complement existing soil nesting sites to provide nesting opportunities for a wide variety of bees. Restoring a site with a mixture of plants that offer nectar and pollen throughout the growing season will support a variety of bee species with different periods of activity. A diverse bee community can increase the likelihood restored plantings will persist by ensuring ecosystem function is restored along with the plant community.

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Current Seed Orchard Techniques and Innovations

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Miller LK, DeBell J. 2013. Current seed orchard techniques and innovations. In: Haase DL, Pinto JR, Wilkinson KM, technical coordinators. National Proceedings: Forest and Conservation Nursery Associations—2012. Fort Collins (CO): USDA Forest Service, Rocky Mountain Research Station. Proceedings RMRS-P-69. 80-86. Available at: http://www.fs.fed.us/rm/pubs/rmrs_p069.html

Abstract: As applied forest tree improvement programs in the US Northwest move forward into the third cycle, seed orchards remain as the primary source of genetically improved forest tree seed used for reforestation. The vast majority of seed orchards in this region are coastal Douglas-fir (*Pseudotsuga menziesii* (Mirb.) Franco), consistent with the high economic importance of this species. However, productive seed orchards are also in place for western hemlock (*Tsuga heterophylla* (Raf.) Sarg.), noble fir (*Abies procera* Rehd.), western redcedar (*Thuja plicata* Donn), ponderosa pine (*Pinus ponderosa* Laws.), lodgepole pine (*Pinus contorta* Dougl.), western larch (*Larix occidentalis* Nutt.), western white pine (*Pinus monticola* Dougl.), sugar pine (*Pinus lambertiana* Dougl.), and Port-Orford-Cedar (*Chamaecyparis lawsoniana* (A. Murr.) Parl.). To be successful, seed orchards must be managed intensively, including: control of weeds, mammals, and cone and seed insects; graft and crown maintenance; strict identity control; irrigation; fertilization; crop stimulation; and ultimately, harvest of high quantities of genetically improved seed. Over the past 40+ years, seed orchard management practices have been developed to improve the reliability and size of cone and seed crops and reduce damage and loss from cone and seed insects, thereby increasing the efficiency of orchard operations. In this paper, we discuss the current state of the art in seed orchard management in the Northwest, with particular emphasis on Douglas-fir.

Keywords: graft compatible rootstock, flower stimulation, cone and seed insect control, irrigation, weed control, Douglas-fir

Introduction

Although people have harvested seeds and fruit from trees for centuries, only after World War II did the science and theories of forest genetics begin to be seriously applied to and practiced in operational forestry around the world. Early tree breeders and geneticists showed that traits important to the production of timber and pulpwood were inherited and, as such, could be improved to increase forest productivity and wood quality. At some point however, these genetic improvements, or gains, need to be captured, packaged, and mass produced so that these gains could be deployed in operational forestry systems. Since the mid-to-late 1950's through to today, the most common approach is the use of seed orchards.

A seed orchard may be defined as:

> "…a plantation of selected clones or progenies which is isolated or managed to avoid or reduce pollination from outside sources, and managed to produce frequent, abundant, and easily harvested crops of seed." (Feilburg and Soegaard 1975).

Today in the Northwestern US, much of the coastal Douglas-fir (*Peudotsuga menziesii* (Mirb.) Franco) and western hemlock (*Tsuga heterophylla* (Raf.) Sarg.) seed used for reforestation on industrial and some public forest lands is produced in seed orchards (Figure 1). Many of these seed orchards comprise second generation (or cycle) selected material from progeny tests, and either are, or soon will be, producing seed with genetic gain estimates in the range of 20-30% for volume. Seed for a number of "minor" species is also being produced in Northwest US seed orchards, including:

1. Noble fir *(Abies procera* Rehd.)
2. Western redcedar (*Thuja plicata* Donn)
3. Ponderosa pine (*Pinus ponderosa* Laws.)
4. Lodgepole pine (*Pinus contorta* Dougl.)
5. Western larch (*Larix occidentalis* Nutt.)
6. Western white pine (*Pinus monticola* Dougl.)
7. Sugar pine (*Pinus lambertiana* Dougl.)
8. Port-Orford-Cedar (*Chamaecyparis lawsoniana* (A. Murr.) (Parl.)
9. Sitka spruce (*Picea sitchensis* (Bong.) Carr.)

Figure 1. The production of genetically improved seed in orchards is robust, mature technology.

Much of the current management practices in Northwest US seed orchards have been adapted from those first developed in southern pine orchards. In proportion to its economic importance, most of seed orchard research and application in this region has been devoted to Douglas-fir. Many of the techniques and practices used on Douglas-fir are also used successfully with other Northwest species, but there are a number of distinct differences. In this paper, we will discuss current advancements in seed orchard management in the Northwest, with particular emphasis on Douglas-fir. We will outline key practices that are important in successful seed orchards and briefly discuss areas of ongoing operational research.

Graft Compatible Rootstock

When forest geneticists identify phenotypically superior selections, elite (proven superior) material, or both, we want to make multiple copies of each selection for inclusion in the seed orchard. By far the most common method of vegetative propagation used in seed orchards is grafting. Grafting is a time-honored, very successful process of vegetative propagation used broadly in fruit and nut orchards and in forest tree seed orchards. It works well, is relatively simple, and very quickly can produce multiple copies of elite selections. That is of course, in almost all tree species except Douglas-fir.

Douglas-fir stands alone as the only major forest tree species that suffers from serious graft incompatibility (Figure 2). Graft incompatibility is analogous to tissue or organ rejection in human transplant cases. In the late 1960's to early 1970's, early tree improvement workers hopes for success were cruelly dashed when, one by one, they watched grafted Douglas-fir in first generation seed orchards begin to die from graft incompatibility. In some of these early orchards, mortality from graft incompatibility ran 80% or more, leaving an uneconomical enterprise in its wake. Graft incompatibility was so bad in early Northwest seed orchards that many landowners switched to seedling seed orchards. This compromised genetic gain, but at least the orchard trees survived to produce seed!

Figure 2. Graft incompatibility in Douglas-fir.

However, one researcher at the PNW Research Station in Corvallis didn't throw in the towel. Over the course of more than 20 years, Don Copes conducted research designed to identify specific genotypes that were highly graft compatible. By the late 1970's, he identified 16 clones that were highly graft compatible. These were propagated in the thousands as rooted cuttings, and used as rootstock for new orchard establishment (Copes 1981). Later, controlled crosses were made between the compatible selections to produce highly graft compatible seed. Use of this seed for the production of Douglas-fir rootstock is standard practice, and has allowed the rapid development of new seed orchards. There is probably no other Douglas-fir seed orchard practice that has had more positive effect on program success than has the Copes graft compatible rootstock.

Flower Stimulation

Although it is taxonomically imprecise, tree breeders commonly use the term, "flowers" when referring to floral structures in trees. Thus, female flowers produce cones, and male flowers produce pollen. To efficiently produce seed, the only important goal of the seed orchard, trees must flower at an early age, reliably, and heavily. In natural stands, flowering occurs periodically and erratically, 3-7 or more years apart. In a seed orchard, such performance is unacceptable.

Thus, early researchers began looking into practices that might improve both the regularity and the abundance of flowering. Flower stimulation includes practices applied at key developmental points in year 1, which lead to significantly increased flowering in the spring of year 2. Looking to practices used in the US South, fertilization was tried with some success. However, the results weren't consistent across orchards, and applying the large amount of fertilizer needed for larger orchard trees has gotten quite expensive. Eventually, two practices were developed that consistently resulted in regular and abundant flowering – partial girdling and application of gibberellic acid (GA).

Partial Girdling

In many lower elevation coastal Douglas-fir seed orchards, partial girdling is a very safe, low cost, very predictable technique for stimulating consistent and reliable flower crops. It can be applied when the trees are at least 2 inches (5 cm) in diameter at the base, although in practice, most orchard managers wait until orchard trees are 6-7 years old. There are varying recommendations regarding optimal dates: at the time of vegetative bud swell (Ross and Bower 1989; Ross and Bower 1991), 6 weeks before vegetative bud break (Clemo, personal communication), 1-3 weeks before vegetative bud flush (Woods 1989), or at the beginning of pollen bud swell (Reno 2008). Orchard managers typically test different application dates, then settle on the time that works best for their orchard.

Girdling involves the application of two overlapping half-circumferential saw cuts that go through the bark and cambium just until the saw teeth reach the xylem (wood). The first girdle should be placed at a comfortable working height, with the second cut being placed roughly 1.5 times the stem diameter above or below the first cut (Figure 3). For large trees, cuts are spaced no more than a foot apart. Each year, girdles are made in fresh wood, not in old scars. Practiced with care on otherwise healthy trees, girdling can be applied every other year, producing very predictable flowering and cone crops. In orchard complexes containing multiple blocks of different material, undesirable cross pollination between blocks can be managed by the schedule of girdling. If we do not want Orchard A pollinating the trees in Orchard B, we simply girdle these orchards in alternating years. The flowering response occurs the following year, thereby minimizing pollen contamination.

Figure 3. Double, overlapping, partial girdling is a very successful means of flower stimulation in low elevation west side orchards.

Partial girdling works very well in Douglas-fir, but has been less predictable in other species. For some of these species, the application of GA has been shown to work well.

Application of Gibberrellic Acid (GA)

Much of the research on flowering and GA was done with Douglas-fir in British Columbia in the 1970's and 80's (Ross and Bower 1989). This research showed that proper timing, technique, and choice of GA are the keys to success. There are many GAs, usually designated by number. The combination of GA4 and GA7 has been shown to be very effective in stimulating flower production in Douglas-fir. GA 4/7 is available in either crystalline, or in liquid, ready-to-use formulations. Crystalline GA must be dissolved in ethyl alcohol before use. The liquid form is known by the trade name, ProCone™ (Valent Corporation), and is considered the industry standard. As with all chemicals, consult the label for safe and proper use.

Application is accomplished by drilling holes in each tree, and injecting a pre-measured amount of ProCone in each hole (Figure 4). The application rate is based on the cross-sectional area at the point of injection. First treatments can usually start when ramets are three or four years from grafting. A recent study indicated that some treatments applied 2 years after grafting could be effective (Cherry and others 2007). There are different opinions on best timing: two weeks before vegetative budbreak (Reno 2008), about the time of vegetative budbreak (Cherry and others 2007), when 50% of the trees have flushed (Ross and Bower 1991), when most of the trees have flushed (Ross and Bower 1989), and up to the time of that 50 - 90% of the year's vegetative growth has occurred (ProCone label). Best results are usually obtained when using freshly purchased ProCone.

Figure 4. Gibberellic acid is also used to stimulate flowering.

In low elevation coastal Douglas-fir, GA 4/7 is used more in breeding orchards, where trees are smaller and younger, and could be damaged by girdling. However, GA gives excellent results in western hemlock, and has shown promise in ponderosa pine and noble fir.

GA is also used to stimulate flowering in western redcedar and Port-Orford-Cedar, but both the formulation and the method of application is different. For these species, research shows that GA 3 applied as a foliar spray in mid-summer stimulates significant flowering the following spring (Russell and Hak 2007).

Control of Cone and Seed Insects

A thorough discussion of seed and cone insect control is beyond the scope of this paper, so only a brief outline of key management practices will be presented. Successful seed orchards are intensively managed plantations, where maximum seed production per acre is the goal. Thus, anything that reduces seed yield negatively affects economic rate of return. Because orchards flower and produce cones much more frequently and more heavily than natural stands, damaging insect populations can build up and cause significant damage to developing crops. Seed orchard managers must become experts on the detection and control of a wide variety of insect pests. With time and experience, managers learn which insect pests are most important, and usually focus their control efforts accordingly.

The first step in any control program is to know which insect is causing damage to cones and loss of seed. An excellent reference for identifying cone and seed insects is "Cone and Seed Insects of North American Conifers" (Hedlin and others 1980). In the Northwest, several of the state forestry and natural resource departments have entomologists on staff that can assist with identification and control options. The USDA Forest Service also has trained staff, which may be able to help.

Over the years, control strategies for the most important cone and seed insects have been developed. Forestry is a small business compared to agriculture, so the available list of insecticides labeled for use in seed orchards is limited, and tends to change with time. No attempt will be made in this paper to list individual insecticides – it is better to work with other seed orchard managers and entomologists to determine which are labeled for use, and known to be effective. Rather, we will focus on application practices commonly in use in Northwest US seed orchards. As well, there are some technologies relatively new to forestry that may well become established as common use in the not-too-distant future.

Application Practices

Aerial Application

Where the surrounding landscape permits, aerial application is very effective and clearly the most cost effective means of applying insecticides to seed orchards in the US Northwest. Helicopters are used most often, effective in treating trees in blocks with widely different ages and thus, tree heights. Excluding ferry time, aerial application is very fast, which is helpful when the window for wind speed is open for only a short period of time (Figure 5).

Figure 5. Aerial spraying provides excellent, low cost control of cone and seed insects.

Ground Application

Where neighbor issues make aerial spraying problematic, ground systems using high pressure mist blowers are an effective alternative. Such equipment makes efficient use of chemical, but small droplet size means that drift must be carefully monitored. Maximum tree height is a limitation, so orchards should be managed for height with due consideration to performance of the available mist blower. Ground application is much slower than aerial, so spraying mat be stretched out over several days because of wind speed limitations. Hydraulic sprayers may also be used to apply insecticides in seed orchards, but these high volume systems are slow and have a higher risk of worker exposure.

Individual Tree Application

In cases where either non-farm land use begins to encroach on seed orchard sites, or internal organization policies prohibit aerial and ground spraying, some technologies relatively new in forestry are being considered, and used in some cases. Individual tree treatments typically involve stem injections of systemic insecticides, and come to forestry from the landscape and horticulture industry. When Dutch elm disease was killing American elm trees across much of the Eastern US, some towns and cities were able to keep large boulevard trees alive longer with stem injections to control the disease vector, the European elm bark beetle. Individual tree treatment is slow and expensive, but given the high value of trees in cities, the cost could often be justified.

Today, individual tree treatment is still practiced on town and city trees, but targets now include emerald ash borer, hemlock woolly adelgid, and mountain pine beetle (Doccola and others 2012). Fortunately for seed orchard use, techniques and equipment have been significantly improved, making application much faster per tree than in the past (Figure 6). Individual tree treatment is still quite slow, when compared to aerial and ground application, but in some orchard locations it may be the only viable method available to the seed orchard manager. Current technologies still rely upon drilling several holes in each tree, but the injectors used are considerably faster than previous versions. This technology holds considerable promise because some

Figure 6. Where aerial spraying cannot be practiced, individual injection provides another option.

of the research suggests that the control effect may last for several years (McCollough and others 2009). If multiple year control is achieved, the cost effectiveness of individual tree treatment will improve significantly.

Vegetation Management

When seed orchards are established, it is important to control vegetation within the newly planted tree rows so that the trees grow as free as possible from competition. The date of first flowering and cone production is correlated with tree size, so the sooner trees get bigger, the sooner genetically improved seed will be produced. Seed orchard managers typically use readily available forestry herbicides to maintain a weed free strip within the tree row. This weed free strip also reduces habitat for voles, which can cause significant damage to newly planted grafts.

Between rows, it is important to maintain a good running surface to lessen compaction and possible rutting from the regular equipment travel necessary in everyday orchard management. For many years, orchard managers would accept whatever grass came up between rows, spending much of each summer mowing to maintain access and reduce fire danger. Mowing is a necessary and often costly expense. Some orchards have established cover crops that are low growing to reduce mowing costs. More recently, short growing grass varieties classically bred to be tolerant of glyphosate have become available, and some managers are establishing new cover crops with this seed (Figure 7). Orchards containing this grass need to be mown once, rarely twice, and the grass never gets any taller than about knee high. Weeds between rows are easily cleaned up with glyphosate. In orchards where this grass variety has been established, mowing costs have dropped significantly.

Figure 7. Low growing grass varieties, classically bred to be tolerant of glyphosate, create an excellent orchard cover crop.

Crown Management

In the US Northwest, the tree species established in seed orchards have the inherent ability to grow quite tall. Harvesting cones from trees as they grow taller increases in cost as man lifts with greater reach must be either rented or acquired. The equipment needed to harvest trees that are 15-20 feet (4.5-6 m) tall is much less costly than that needed for trees 50-60 feet (15-18 m) tall. Thus some managers are testing the feasibility of regular tree topping to manage the height of their trees. One orchard is using a sickle bar mounted on a loader to accomplish automated topping of Douglas-fir (Figure 8). In this system, the orchard tree height is being managed so that all cone harvesting may be done from the ground or from short ladders. No man lift equipment will be needed. However, because cone production is correlated to tree size, shorter trees produce fewer cones. Thus, to increase cone production in such topped orchards, planting density must be increased. Compared to more traditional spaced orchard that may have 50-100 trees per acre (tpa; 125-250 trees per hectare), a topped orchard may have up to 500 tpa (1250 tph).

Figure 8. Sickle bar mower for automated tree topping in a Douglas-fir seed orchard.

Other Douglas-fir orchards are being managed with lower density, and allow the trees to get proportionally taller. As these trees grow, man lifts are needed for cone harvest. However, large trees produce more cones than small trees, so the added cost of mechanized lifts may be justified (Figure 2).

For other species, topping has been shown to actually enhance cone and seed production. An example of this is western larch. While western larch is a regionally important reforestation species in the Interior West, until recently there were very few seed orchards, and none were producing. Again in an attempt to manage tree height to control cone harvesting costs, western larch orchard trees were topped to maintain a maximum height of 15 feet (4.5 m). In doing so, the orchard trees were stimulated to produce a higher proportion of so-called “hanger” branches, from which most larch flowers arise (Figure 5). With this result, topping is now standard practice in western larch seed orchards that are actively managed.

Topping has also been shown to work quite well in western hemlock orchards (Ross 1989), and is used on occasion with Sitka spruce, western redcedar, and lodgepole pine.

Controlled Mass Pollination (CMP)

In the US West, seed orchards not uncommonly comprise 30 clones, sometimes as many as 60-80. The genetic gain estimates for the individual clones in the orchard often vary widely, from very high to modest. Most orchards rely upon open, wind pollination amongst the orchard trees, resulting in an averaging effect on overall genetic gain. Recently, some orchards have started to practice controlled mass pollination (CMP) on an operational scale to increase genetic gain.

With operational CMP, controlled crosses are made between only the very highest gain clones in the orchard, producing targeted amounts of very high genetic gain seed. Ahead of CMP, large volumes of pollen must be collected from high genetic gain clones, and stored for future use. In the spring, orchard workers apply hundreds to sometimes thousands of pollination bags to branches bearing female cone buds. When the flowers become receptive, pollen is applied to each bag. To achieve good seed set, it is often necessary to visit and pollinate each bag two times (Figure 9). CMP is

Figure 9. Controlled mass pollination (CMP) is employed to significantly increase genetic gain.

expensive, and the amount of seed produced to date has been modest, especially compared to open pollinated production. However, techniques have improved over the past several years, so that yields per bushel of cones often equal, and sometimes exceed that of open pollinated cones.

Irrigation

Many west side, low elevation seed orchards are located in areas with significant summer drought. Irrigation can be critical to early orchard survival and establishment, and later to producing large trees that bear more cones in a shorter time frame. Some orchards are establishing drip irrigation systems, either temporary or permanent, to meet these needs. Once an orchard becomes well established, temporary systems are designed to be rolled up and used in a new orchard (Figure 10).

Figure 10. Temporary drip irrigation may be used until newly planted trees are established, then moved to a new orchard.

More conventional overhead irrigation is also used in some seed orchards, primarily for bloom delay and frost protection in the spring. Overhead sprinkling of seed orchards on temperate days in the spring has a cooling effect, affecting flower phenology. Development of clones that tend to flower early in the spring is retarded, resulting in more clones in the orchard flowering synchronously. This produces a more diverse orchard pollen cloud and thus, reduces pollen contamination from outside sources and creates a broader range of open-pollinated combinations from the desired orchard trees (Fashler and Devitt 1980). Overhead sprinkling has been used for many years in fruit and nut orchards to protect flowers from freezing temperatures. This treatment has been used in forest tree seed orchards, but care must be taken to avoid breakage of tops and branches from ice loading.

DNA Fingerprinting

Since the 1960's, forestry organizations and forest industry have invested, collectively, many tens of millions of dollars in applied forest tree improvement in the US Northwest. Considerable progress has been made through two cycles of tree improvement, and several cooperative Douglas-fir and western hemlock programs are entering their third cycle of breeding, testing, and selection. These tree improvement programs are the source of new selections that are propagated and established in new seed orchards. It is critical to long term, sustainable genetic improvement that parents and selections are accurately identified, and that pedigrees contain no errors. Unfortunately, despite the best efforts of tree breeders and orchard managers, identification errors occasionally occur.

A detailed discussion of various DNA fingerprinting techniques is beyond the scope of this paper. Suffice it to say that protocols and procedures have been developed that are effective in confirming the genetic identities of parents, and their putative offspring. In other words, we have the ability to determine whether or not a given selection could be the progeny of the two parents listed in the pedigree. Furthermore, we can test multiple ramets of a clone, to determine if any have been mislabeled. This is key to long term improvement programs, because it is critical to know that a tagged tree is actually what we think it is. With DNA fingerprinting, when we apply pollen or use a tree as a female, we have confidence that the cross pedigree is 100% correct.

Summary

The production of genetically improved forest tree seed in seed orchards is a mature, robust technology. Starting with selections arising from a linked tree improvement program, the establishment and management of successful seed orchards requires intensive culture and close attention to detail. Over the past 40+ years, applied research and development programs have helped develop the orchard management regimes in widespread use today. Key practices in seed orchards include: the use of graft compatible rootstock for Douglas-fir; flower stimulation for regular and abundant cone and seed production; effective control of cone and seed insects; vegetation management; crown shaping techniques to assist cone production and harvesting; controlled mass pollination to increase genetic gain; irrigation to improve orchard establishment, increase individual tree growth, and manage orchard phenology; and DNA fingerprinting to ensure accurate identification of selections and maintain pedigree control. Using these practices and techniques, plus many more mundane daily tasks, seed orchard managers in the US Northwest are very successfully producing predictably large, abundant, and easily harvested crops of genetically improved seed for reforestation programs.

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Climate Change and the Future of Seed Zones

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Kilkenny F, St. Claire B, Horning M. 2013. Climate change and the future of seed zones. In: Haase DL, Pinto JR, Wilkinson KM, technical coordinators. National Proceedings: Forest and Conservation Nursery Associations—2012. Fort Collins (CO): USDA Forest Service, Rocky Mountain Research Station. Proceedings RMRS-P-69. 87-89. Available at: http://www.fs.fed.us/rm/pubs/rmrs_p069.html

Abstract: The use of native plants in wildland restoration is critical to the recovery and health of ecosystems. Information from genecological and reciprocal transplant common garden studies can be used to develop seed transfer guidelines and to predict how plants will respond to future climate change. Tools developed from these data, such as universal response functions and trait shift maps, can help managers make informed decisions regarding restoration strategies, such as assisted migration, in the face of climate change.

Keywords: seed transfer guidelines, seed zones, assisted migration, common garden studies

Introduction

The use of native plants in wildland restoration is critical to the recovery and health of ecosystems and to ecosystem resilience in the face of climate change. Seed zones and seed transfer guidelines help ensure that adapted plant material is reintroduced after disturbances, such as fire or grazing, and may be particularly important for the long-term resilience of re-established native plant populations (Ying and Yanchuk 2006; see also Table 1 for a definition of adaptation). Seed transfer guidelines can also help land managers select plant material that is most likely to be adapted to future climates (Thomson and others 2010). Thus, the development of seed transfer guidelines forms an integral piece of the native plant restoration infrastructure.

Table 1. Definitions.

Adaptation: An adaptation is a trait with a functional role in the life history of an organism that is maintained and evolved by means of natural selection. An adaptation refers to both the current state of being adapted and to the dynamic evolutionary process that leads to the adaptation. Adaptations contribute to the fitness and survival of individuals.
Universal Response Function: Combines individual response functions - the expected change in a trait value due to climate differences across a set of seed sources - and individual transfer functions - the expected change in a trait value for a given seed source due to climate differences across a set of possible transfer locations - into a single equation. Universal response functions can be used to model expected changes in trait values for any given seed source due to transfers to new locations or due to changes in climate.

Development of Seed Transfer Guidelines

Information from genecological studies, in which multiple populations are grown in one or a few common gardens, has been successfully used to develop seed zones for a number of tree species (Sorenson 1992, St. Clair and others 2005). Work is now being performed to develop seed zones for native grasses and forbs (Horning and others 2010; Johnson and others 2010). Genecological studies have both benefits and limitations in developing seed transfer guidelines. The primary benefit of genecological studies is that a large number of populations are sampled, such that adaptive differences can be determined across large areas of a species' range. However, because gardens represent only a small portion of the climatic variation experienced by the study populations, interpretation of genecological data must assume that plant populations are adapted to local conditions at their source and that demonstrated differences are due to those adaptations. This is generally a safe assumption for native plant species; however, it may not always be the case.

Seed Transfer Guidelines and Climate Change

Reciprocal transplant studies, where plants from several populations are planted in a set of sites that represent local and non-local climates, are effective at testing whether and how plants from specific populations are adapted to their local environments (Kawecki and Ebert 2004). When sites represent extreme environments, these studies have been used effectively to predict how plants will respond to future climate change as climates shift towards new extremes, particularly in cases with a large number of both populations and garden sites. For example, a long term study on lodgepole pine (*Pinus contorta*) in British Columbia, which tested 140 provenances at 60 sites, used a universal response function (defined in Table 1) to determine expected growth rates under future climate conditions (Wang and others 2010). This study found that growth rates of lodgepole pine were likely to increase in much of the northern range, primarily because marginal habitats in that region would become more hospitable due to warming.

When large reciprocal transplant studies are not feasible, data from genecological studies can be used to estimate the impact of future climate change on seed transfer guidelines. For example, a study on white spruce (*Picea glauca*) in Ontario determined future seed zones under three different climate change scenarios (Thomson and others 2010). Interestingly, this study found that two out of the three climate change scenarios predicted little change from current seed zones, but the third scenario predicted substantial shifts from current seed zones, indicating inherent uncertainty.

We performed a genecological study to determine seed zones for bluebunch wheatgrass (*Pseudoroegneria spicata*) throughout the intermountain west (St. Clair and others in press). As a follow-up study we are developing models to determine how optimal trait values will shift under future climate change scenarios. To do this we use regression models to link population level differences in adaptive traits, determined from common garden data, with the local climates at each source population. These regression models are then used within a geographical information system (GIS) to map expected optimal trait values across the landscape for both current and future climates. For example, we found that optimal heading date values for bluebunch will shift toward both earlier and later dates in 2050, depending on location (Figure 1).

Assisted Migration

Assisted migration is a strategy for helping ecosystems to adapt to climate change by moving species from locations with suboptimal climates to more optimal climates. While this strategy is controversial, due mostly to the possibility of introducing species which subsequently

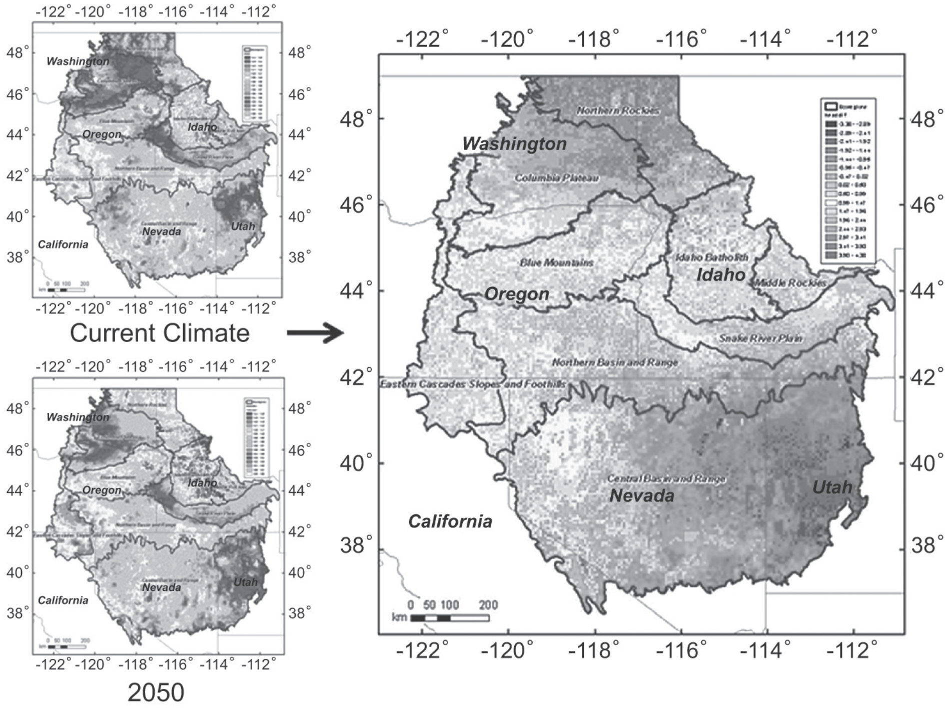

Figure 1. Map of predicted trait values for heading date of bluebunch wheatgrass (*Pseudoroegneria spicata*) in the intermountain west under current and future climate scenarios, and the difference between the maps indicating the expected shift in optimal heading date values under climate change.

become invasive, it may become necessary if climate change continues to accelerate. Estimates of natural species migration rates during past periods of climate change range from 100-400 m (328-1312 ft) per year (Davis and Shaw 2001; Aitken and others 2008). However, current rates of climate change may require migration rates of 3000-5000 m (9843-16404 ft) per year, well beyond the movement capacity of many native species. Species that are long-lived, have low dispersal potential, and/or have low genetic variation will be particularly threatened by this rate of climate change.

Genecological and reciprocal transplant studies can help inform both the necessity and expected efficacy of management decisions related to assisted migration. Trait shift maps such as the one presented in Figure 1 can show areas where current trait values of a species are out of synch with predicted future optimums, which will help determine areas where populations may be at risk of local extinction. Universal response functions can also help determine the expected outcomes of proposed transfers. For example, the British Columbia lodgepole pine study found that using population specific transfer guidelines to move seed to locations with optimal future climates could increase lodgepole pine growth rates beyond the predicted rates if no transfers occurred (Wang and others 2010).

Conclusion

Genecological and reciprocal transplant common garden studies are critical to the development of seed zones and seed transfer guidelines. Current modeling techniques using data from these studies can help determine how seed transfer guidelines will shift due to future climate change and will be particularly useful in making decisions regarding assisted migration. Design of future common garden studies, and the models developed from them, will need to take into account the inherent uncertainty of climate models predicting future change in order to help managers determine the best strategies for future native plant restoration.

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Growing Assisted Migration: Synthesis of a Climate Change Adaptation Strategy

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Abstract: Assisted migration may be necessary as a climate change adaptation strategy for native plant species that are less adaptive or mobile. Moving plants has been practiced a long time in human history, but movement of species in response to climate change is a new context. First proposed in 1985, assisted migration has gained attention since 2007 as a strategy to prevent species extinction, minimize economic loss, and sustain ecosystem services. We present a synthesis of proposed assisted migration guidelines and provide resources for nurseries, landowners, and researchers.

Keywords: climate change, decision framework, implementation, managed relocation, native plant transfer guidelines, seed transfer zones

Introduction

Climate change adaptation strategies may not be at the forefront of everyone's mind, but within the context of seed technology for forest and conservation nurseries they have significant merit. If temperature and precipitation predictions are correct, plant populations in their native settings will have to adapt or move to avoid maladaptation and/or extinction (Peters and Darling 1985). Current climate predictions would require plants to migrate 3000 to 5000 m (9842 to 16404 ft) per year far exceeds their observed maximum rates of less than 500 m (1640 ft) per year (Davis and Shaw 2001; Aitken and others 2008; Lempriere and others 2008).

Assisted migration of plants, that is, human-assisted movement, may be necessary for species that are less mobile or adaptive (Peters and Darling 1985; Hoegh-Guldberg and others 2008; Vitt and others 2010). Short-lived and annual species will likely adapt faster to changes in climate than long-lived species (Jump and Penuelas 2005; Vitt and others 2010). Despite disparity in rates between climate change and observed plant migration, survival may be more determined by available geophysical connections among landscapes needed for plants to move (Hannah 2008) and whether or not suitable recipient ecosystems exist (Aubin and others 2011). Furthermore, impacts from climate change can be so abrupt, for example, the mountain pine beetle outbreak on populations of lodgepole pine (*Pinus contorta*) (Regniere and Bentz 2008) that management options will be limited.

Moving plants has been practiced for a long time in human history, but the movement of species in response to climate change is a relatively new concept (Aubin and others 2011). First proposed in 1985 (Peters and Darling), assisted migration has gained attention since 2007 as a climate-change adaptation strategy (Hewitt and others 2011). Preventing species extinction, minimizing economic loss (for example timber production), and sustaining ecosystem services (for example wildlife habitat, recreation, and water and air quality) are three reasons for assisted migration (Aubin and others 2011). The only known assisted migration program in the U.S. is a grassroots effort to save Torreya taxifolia (*Florida torreya*), a southeastern evergreen conifer, from extinction (McLachlan and others 2007; Barlow 2011). Since 2008, Florida torreya has been planted on private lands in five southern states (Torreya Guardians 2012). To prevent economic loss in the timber industry, some Canadian provinces have adjusted their planting guidelines. (Pedlar and others 2011). Using assisted migration to sustain ecosystem services has been addressed, but is not well-studied (Jones and Monaco 2009; Aubin and others 2011). If ecosystem function and structure become a main focus in assisted migration plans, it will prompt ecologists to consider moving assemblages of species rather than moving a single species (Harris and others 2006; Park and Talbot 2012).

Risks such as establishment failure and negative effects on the recipient and donor ecosystem are associated with assisted migration (Aubin and others 2011). Establishment failure can result from moving the species before the donor site is suitable and from any number of factors familiar to traditional planting efforts (Vitt and others 2010). The species could have negative effects on the recipient ecosystem, such as genetic pollution, hybridization, function/structure impairment, pathogens, and invasion. The risk of invasion, however, is subject to debate in regards to assisted migration and climate change because the definition itself depends upon human perception (Mueller and Hellman 2008). Some degree of "invasiveness" in an assisted-migratory might be necessary for establishment. Effects on the donor ecosystem are less definitive. Over-harvesting a population at risk of decline or extinction is a concern (Pedlar and others 2011). Removing seeds or plant materials from a donor ecosystem could hinder natural adaptation and migration (Vitt and others 2010; Aubin and others 2011).

Whether or not assisted migration is implemented or even possible, management and conservation plans need to incorporate climate change research as soon as it becomes available (Peters and Darling 1985). Unfortunately, since 1985, only a handful of assisted migration guidelines have been proposed (Hoegh-Guldberg and others 2008; Vitt and others 2010; Lawler and Olden 2011; Pedlar and others 2011; Schwartz and others 2012), largely born out of conservation biology, restoration ecology, and forestry. We present a synthesis of these guidelines and include examples of current efforts and available resources for nursery managers, land managers, and restorationists.

Informed Decisions

An overwhelming conundrum for assisted migration lies in the matching of existing plant materials (that is, seed, nursery stock, or genetic material) with ecosystems of the future that have different climate conditions (Potter and Hargrove 2012). To alleviate the challenge, a few tools are available to make informed decisions about assisted migration (Lawler and Olden 2011; Schwartz and others 2012). Bioclimatic models coupled with species genetic information in a GIS can be used to identify current and projected distribution (for example Rehfeldt and Jaquish 2010, McLane and Aitken 2012, and Notaro and others 2012). These forecasts can assist land managers in their long-term management plans, such as, where to collect seeds and plants. In Rehfeldt and Jaquish (2010), western larch (*Larix occidentalis*) distribution and seed zones are mapped under a combination of climate change scenarios for 2030 and 2060. Although the modeled projections have some uncertainty, they provide some indication of how seed zones will change over time.

We can gain much information from past reintroductions given our long history of moving and re-establishing species, not only from forestry, agriculture, and horticulture, but from restoration ecology (for example coal mine reclamation). Experiments such as the Assisted Migration Adaptation Trial (Marris 2009) in Canada and the Florida torreya project in the southeastern U.S. can inform us of how species respond to migration and warming. Further, we can use pollen and fossil records to understand how species responded to past climate changes.

Of the published frameworks, Hoegh-Guldberg and others (2008) present a decision matrix to help identify species risk and feasibility of migration under climate change (Figure 1). Addressing ethical, legal and policy, and ecological questions such as "What are the priority taxa, ecosystem functions, and human benefits for which to consider assisted migration?" and "Do existing laws and policies enable assisted migration actions?" (Aubin and others 2011; Schwarz and others 2012) are central to species selection and navigating through the matrix. Maintaining or improving conservation plans would be sufficient for species at low risk, whereas species at moderate or high risk require more involved actions (Figure 1).

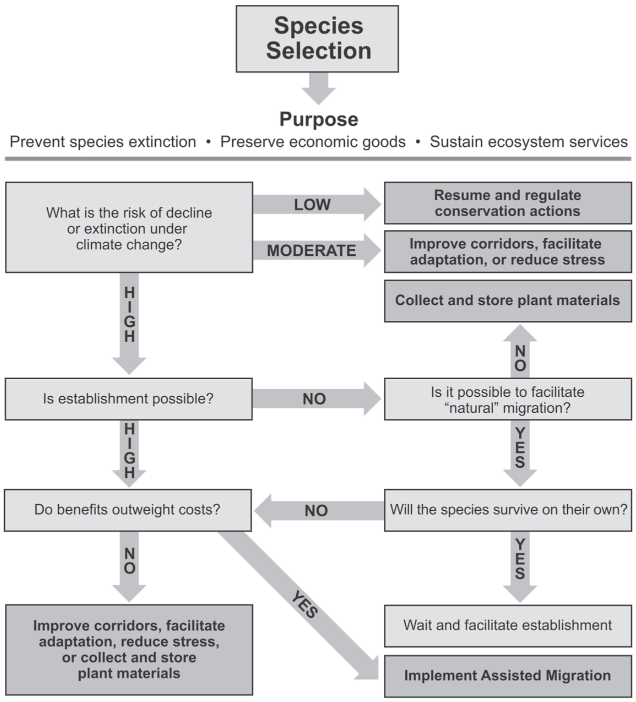

Figure 1. An assisted migration decision matrix can be used to determine adaption strategies for a plant species that has conservation, economic, or social value. Genetic information, bioclimatic models, historical records, and current assisted migration experiments should be consulted in navigating through the matrix. In order to implement assisted migration the species must be at high risk of decline or extinction, establish well, and provide more biological, economic, and social benefits than costs. (From Hoegh-Guldberg and others 2008).

Assisted migration may be warranted if: 1) a species is at high risk of extinction or if loss of the species would create economic or ecosystem loss, 2) can be established, and 3) provides more benefit than cost. In the event that establishment is not possible or costs constrain assisted migration, alternative options to facilitate migration or conservation would be considered. For example, reducing fragmentation, increasing landscape connections, collecting and storing seed, and creating suitable habitats could facilitate "natural" migration. Risk status will change over time. Existing programs (see Beardmore and Winder 2011) such as the Forest Tree Genetic Risk Assessment System (ForGRAS, Devine et al. 2012), NatureServe Climate Change Vulnerability Index (NatureServe 2011), System for Assessing Species Vulnerability (SAVS, Bagne and others 2011), and Seeds of Success program (Byrne and Olwell 2008) are available to determine a species' risk to climate change. Species most vulnerable to climate change are rare, long-lived, locally adapted, geographic and genetically isolated, and threatened by fragmentation and pathogens (Erickson and others 2012). Suitable candidates are those that may decline in growth and productivity under climate change. Listing species as candidates for assisted migration is a practical first step (Vitt and others 2010; Pedlar and others 2011), but requires a substantial amount of knowledge about the species and their current and projected habitat conditions. Provenance data exist for several commercial tree species and should be used to estimate their response to climate scenarios (for example Rehfeldt and Jaquish 2010). In the U.S. we know a lot about conservation and commercial species because of their social and economic value. Regardless, the decision matrix is a proactive starting point that can be tailored over time, and not just to plants.

Implementation

In the following sections, we outline guidelines, including issues to consider, in an assisted migration plan (Figure 2). Largely from Pedlar and others (2011) and Vitt and others (2010), the guidelines are not unlike conventional reforestation and restoration approaches. We illustrate each component from an assisted migration and climate change perspective. We do not detail conventional guidelines. The Nursery Manual for Native Plants (Dumroese and others 2009), Raising Native Plants in Nurseries: Basic Concepts (Dumroese and others 2012), Seedling Nutrition and Irrigation (Landis and others 1989), Seedling Processing, Storage, and Outplanting (Landis and others 2010), Seedling Propagation (Landis and others 1998), The Society for Ecological Restoration International Primer on Ecological Restoration (SER 2004) and the Woody Plant Seed Manual (Bonner and others 2008) are appropriate resources to consult for seed and plant collection, propagating, site selection and preparation, outplanting, and maintenance.

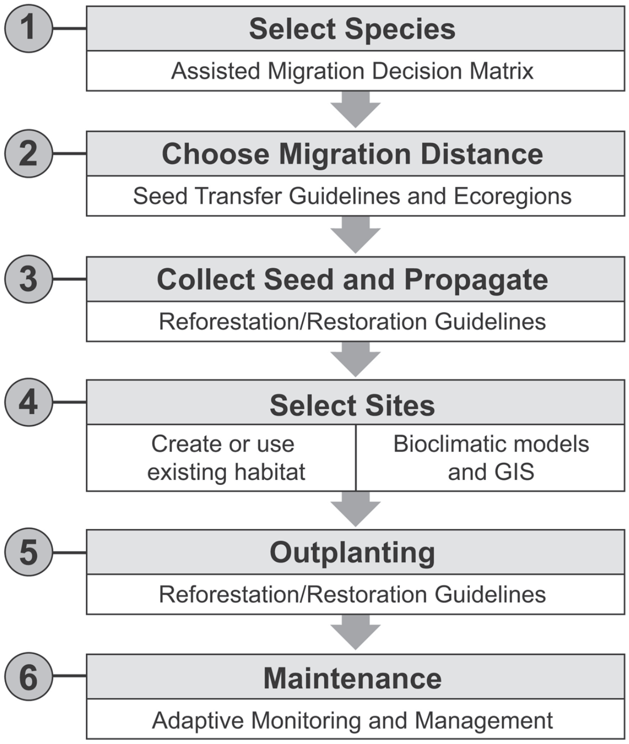

Figure 2. A guide for implementing assisted migration which can be adapted to address a single species or an assemblage of species. Although species selection (1) and migration distance (2) are principle components in an assisted migration program, cost, location, and public support will determine implementation. (From Pedlar and others 2011; Vitt and others 2011).

Select Species

Whether the species is of commercial and/or conservation value, the decision matrix (Figure 1) can help identify a candidate species for assisted migration. Species selection will dictate migration distance, collection, propagation, planting site, outplanting method, and maintenance. Species may be selected on the basis of their risk of decline or extinction, importance to economic services, or contribution to ecosystem sustainability. For example, assisted migration could target commercial tree species that are predicted to decline in productivity under climate change (O'Neill and others 2008). Suitability of assisted migration for conservation species could be determined by a number of indicators such as available habitat, endangered status, and migration potential (Vitt and others 2010).

Determine Suitable Migration Distance

Distance is the safest geographic and/or climatic distance that populations can be moved to avoid maladaptation (reduction in fitness, health, or productivity as a result of growing in an unsuitable environment). Seed transfer zones and guidelines developed using species-specific genetic and climatic information can be used to determine distances. Guidelines and zones are available for many commercial tree species and some conservation species (Table 1). Empirical guidelines and zones created from common garden studies are available for a few grasses and shrubs, such as blue wildrye (*Elymus glaucus*) (Kitzmiller and Hanson 2011) and sagebrush (*Artemisia* spp.) (Mahalovich and McArthur 2004).

The paucity of transfer zones and guidelines established for shrubs, grasses, and forbs is a major limitation in making informed decisions about assisted migration. At best, we can rely on provisional seed zones (for example Seed Zone Mapper - Table 1) developed from temperature and precipitation data and Omernick level III and IV ecoregion boundaries (Omernik 1987) to evaluate candidates for assisted migration where species provenance data and bioclimatic data are lacking. Another option is to match the seed source climate with projected climate at the outplanting site with the assumption that the intended site is within the projected habitat of the species. This option requires knowing when the migration or outplanting will occur (Pedlar and others 2011).

Seed transfer functions can be used to calculate migration distances under climate change (Thomson and others 2010; Ukrainetz and others 2011). These functions relate performance of provenances at given test sites to climatic distance between the test site and outplanting site (Raymond and Lindgren 1990). Online tools are available to assist forest managers and researchers in making decisions about matching seedlots with outplanting sites and seed transfer (Table 1). The Seedlot Selection Tool (Howe and others 2009) is a mapping tool that matches seedlots with planting sites based on current or future climates and Seedwhere (McKenney and others 1999) can map out potential seed collection or outplanting sites based on climatic similarity of chosen sites to a region of interest. Rehfeldt and Jaquish (2010) employed bioclimatic models to map current and projected seed transfer zones for western larch. Others have performed similar assessments for aspen (*Populus tremuloides*) (Gray and others 2011), longleaf pine (*Pinus palustris*) and dogwood (*Cornus florida*) (Potter and Hargrove 2012), and whitebark pine (*Pinus albicaulis*) (McLane and Aitken 2012).

Identify Collection Sites, Collect Seeds, and Propagate Plants

Seed collection sites and collection and propagation methods will depend on the target species and purpose of assisted migration (that

Table 1. Resources related to native plant transfer guidelines, climate change, and assisted migration for the U.S. and Canada. Most programs are easily located by searching their names in common web browsers. All URLs were valid as of 15 October 2012.

Resource or Program	Description	Authorship
Center for Forest Provenance Data http://cenforgen.forestry.oregonstate.edu/index.php	Database for tree provenance and genecological data that allows public access. Users are able to submit and retrieve data.	USDA Forest Service and Oregon State University
Centre for Forest Conservation Genetics http://www.genetics.forestry.ubc.ca/cfcg/	Portal for forest genetics and climate change research conducted in British Columbia, Canada.	Ministry of Forest and Range, BC
Climate Change Resource Center http://www.fs.fed.us/ccrc/	Information and tools about climate change for land managers and decision-makers.	USDA Forest Service
Climate Change Tree Atlas http://www.nrs.fs.fed.us/atlas/tree/tree_atlas.html	An interactive database that maps current (2000) and potential status (2100) of eastern US tree species under different climate change scenarios.	USDA Forest Service
Forest Seedling Network http://www.forestseedlingnetwork.com	Interactive website connecting forest landowners with seedling providers and forest management services and contractors	Forest Seedling Network
MaxEnt (Maximum Entropy) http://www.cs.cmu.edu/~aberger/maxent.html	Software that uses species occurrences and environmental and climate data to map potential habitat. It can be used to develop seed collection areas.	Carnegie Mellon University
Native Seed Network http://www.nativeseednetwork.org/	Interactive database of native plant and seed information and planting guidelines for restoration, native plant propagation, and native seed procurement by ecoregion.	Institute for Applied Ecology
Seed Zone Mapper http://www.fs.fed.us/wwetac/threat_map/SeedZones_Intro.html	An interactive seed zone map of western North America. User selects areas to identify provisional and empirical seed zones for grasses, forbs, shrubs, and conifers. Map displays political and agency boundaries, topography, relief, streets, threats, and resource layers.	USDA Forest Service
Seedlot Selection Tool http://sst.forestry.oregonstate.edu/index.html	An interactive mapping tool to help forest managers match seedlots with planting sites based on current climate or future climate change scenarios. Can also be used to map present or future climates defined by temperature and precipitation.	USDA Forest Service and Oregon State University
Seedwhere https://glfc.cfsnet.nfis.org/mapserver/seedwhere/seedwhere-about.php?lang=e	GIS tool to assist nursery stock and seed transfer decisions for forest restoration projects in Canada and the Great Lakes region. It can identify geographic similarities between seed sources and planting sites.	Natural Resources Canada, Canadian Forest Service
System for Assessing Species Vulnerability (SAVS) http://www.fs.fed.us/rm/grassland-shrubland-desert/products/species-vulnerability/savs-climate-change-tool/	Software that identifies the relative vulnerability or resilience of vertebrate species to climate change. It provides a framework for integrating new information into climate change assessments.	USDA Forest Service

is, commercial or conservation). Seed collection areas, zones, and orchards exist for most commercial tree species. Species of concern are not regularly collected or propagated at the same scale as commercial species making assisted migration a challenge, but provisional seed zones can be used to select collection areas (Table 1).

Guidelines that maximize genetic diversity within outplanted materials provide some long-term insurance that would counter against uncertainty in climate predictions and species reactions to climate change (Ledig and Kitzmiller 1992; Vitt and others 2010). Seed collection guidelines to increase genetic diversity with assisted migration in mind are synthesized by Vitt and others (2010). Selecting a few extreme variants within seed collections or allowing for physiological or morphological variation in nursery stock might serve to facilitate migration (Pedlar and others 2011). For example, drought tolerance in nursery stock would be a desirable trait for planting sites projected to experience warmer and drier conditions. Establishing seed orchards and collecting seed from low elevations or southern latitudes so that the resulting material is adapted to these conditions are other options (Pedlar and others 2011).

Select Outplanting Sites

Creating suitable outplanting sites might be necessary for species at moderate or high risk of decline or extinction (Hoegh-Guldberg and others 2008; Aubin and others 2011). The target species and its habitat requirements will dictate outplanting site selection. Some species have well-defined habitat conditions that can help with site selection. Soil surveys and ecological site descriptions provide additional support for site selection (Herrick and others 2006) as well as current and projected seed transfer zones and guidelines (Table 1). Site selection for commercial tree species, which have a long history of human-assisted propagation, is largely determined by harvest and reforestation operations, which by their very nature produce planting sites (Pedlar and others 2011). Conversely, species of conservation value have a short history of human-assisted propagation and outplanting sites are not routinely created through commercial activities. However, using disturbed areas as outplanting sites to test assisted migration has been suggested (Jones and Monaco 2009; Aubin and others 2011).

Outplanting

Volume 7 of the Container Tree Nursery Manual - Seedling Processing, Storage and Outplanting - provides thorough outplanting guidelines for trees including outplanting window, or, best time to plant (Landis and others 2010). Outplanting window can vary year to year even within current climate conditions, therefore the “window” will be difficult to determine for assisted migration. In other words, when and where do you plant a long-lived species in a rapidly changing climate? Maladaptation may occur if a species is introduced too soon to its “new” environment or it may competitively interact with other species causing loss of ecosystem function or structure (Aubin and others 2011). Assisted migration experiments coupled with projected climate change may help determine the best time to deploy plant materials (Lawler and Olden 2011).

Monitoring and Maintenance

Adaptive monitoring and management is imperative to any natural resource program, especially in an assisted migration program given the uncertainty in climate change projections and adaptation to changes in climate. Programs need to encourage feedback and learning which can be used to change and/or create management actions. Short-(months to years) and long-term (several years) monitoring of survival and growth will provide valuable feedback about plant performance and measures of success to nursery and land managers (Landis et al. 2010). Post-establishment maintenance such as watering, herbicide application, and pest/predation control can be employed post-planting to help the species establish (Pedlar and others 2011). Questions such as “Which reference ecosystem should be used to evaluate an assisted migration effort?” and “What measures do we use to determine success?” will help determine what characteristics to monitor in the species and receiving ecosystem (Aubin and others 2011). Growth measurements, reproduction, ecosystem health (structure and function), and degree of invasiveness are indicators to consider (Herrick and others 2006; Pedlar and others 2011).

Assisted Migration Examples

Other than the Florida torreya assisted migration project in the southeastern U.S., only a few assisted migration efforts are underway in North America, and all of them are in Canada. In response to a changing climate, seed transfer guidelines for Alberta have been revised to extend current zones northward by 2° latitude and upslope by 200 m (656 ft). Alberta is also considering the evaluation of ponderosa pine (*Pinus ponderosa*) and Douglas-fir (*Pseudotsuga menziesii*) as replacements for lodgepole pine because it is predicted to decline in productivity or suffer from extinction under climate change (Pedlar and others 2011). In British Columbia, a large, long-term experiment called the Assisted Migration Adaptation Trial (AMAT), a collaborative effort between B.C. Ministry of Forests and several agencies and stakeholders, tests both assisted migration and climate warming (Marris 2009). The program evaluates the adaptive performance of 16 tree species collected from a range of sources in B.C., Washington, Oregon, and Idaho and planted in several sites in the same areas. Two components of the trial are to test how sources planted in northern latitudes perform as the climate changes and evaluate endurance of northern latitude sources to warmer conditions in southern latitudes.

Limitations

We cannot reliably predict future climates so it is difficult to know which or how ecosystems will be affected. We have a long history of moving plants, but limited knowledge about establishing native plant materials outside their range in anticipation of different climate conditions. To further complicate matters, we know little about the long-term ecological effects of assisted migration, such as, invasiveness, maladaptation, and site stability (Aubin and others 2011). One way to address uncertainty is to maximize genetic and geographic diversity in plant materials (Ledig and Kitzmiller 1992), but seed collection efforts will need to factor this into their budgets (Vitt and others 2010).

Research Needs

To make informed decisions about implementation, we need a central, standardized database of species-specific genetic, ecological, and geographic information. Databases listed in Table 1 can serve as templates for non-commercial species, but we need to solicit and organize existing data in order to identify gaps. Discussion and evaluation of complementary actions, such as ecosystem engineering (for example using drastically disturbed areas as sites to test assisted migration) and increasing landscape connectivity (for example reduce fragmentation) are also warranted (Jones and Monaco 2009; Lawler and Olden 2011).

Dynamic seed transfer zones and guidelines are also needed. Transfer guidelines based on geographic boundaries and provisional zones may not be suitable, especially in regions without supporting genetic and climatic information (Mahalovich 1995). This was demonstrated, for example, by blue wildrye, where supporting common garden information showed that seed zones based solely on ecoregions mapped the species’ adaptive variation poorly (Erickson and others 2004). Climate-based seed transfer guidelines should overcome these restrictions (Rehfeldt 2004), but the guidelines need to factor in future climate conditions – a major challenge for nursery and land managers given uncertainty about which climate to prepare for (Park and Talbot 2012; Potter and Hargrove 2012). This is especially true for long-lived species and populations that take several decades to reach reproductive maturity and become adapted through evolution to a new climate (Potter and Hargrove 2012). Park and Talbot (2012) suggest that managers prepare for all future climate scenarios. This might entail small-scale experiments, such as, planting fast-growing trees adapted to projected climate in the next 15 to 30 years (Park and Talbot 2012) or randomly planting a variety of seed sources in one area and monitoring their adaptive response (similar to provenance testing) (Pedlar and others 2011).

Not only must one factor in performance of delineating seed zones and transfer guidelines but also cost. Cost increases with an increase in the number of seed zones in terms of seed and nursery productions (stock, storage, and delivery), administrative regulations, and record keeping (Lindgren and Ying 2000). The biological, operational, and administrative tradeoffs are vital considerations in transfer guideline development for future climate scenarios.

Conclusion

Regardless of the debate on assisted migration, we have little time to act given current climate change predictions and restricted ability of plants to adapt or migrate rapidly on their own. Framing the discussion to identify objectives and produce frameworks that lead to strategies is pertinent (McLachlan and others 2007; Lawler and Olden 2011; Park and Talbot 2012). Ultimately our capacity to implement projects will be limited by cost, location, and time (Park and Talbot 2012), but recognizing and synthesizing what we already know about plant adaptation and climate change is a necessary start.

Acknowledgements

This collaborative work between Michigan Technology University, School of Forest Resources and environmental Science and the USDA Forest Service, Rocky Mountain Research Station, Grassland, Shrubland, and Desert Ecosystems Program is accomplished through Joint Venture Agreement 11-JV- 11221632-130.

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Phytosanitation: A Systematic Approach to Disease Prevention

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Abstract: Phytosanitation is not a new concept but has received renewed attention due to the increasing threat of nursery spread *Phytophthora ramorum* (PRAM), the fungus-like pathogen that causes Sudden Oak Death. This disease has the potental to become the most serious forest pest since white pine blister rust and chestnut blight. Phytosanitation can help prevent the spread of this and other pathogens to or from nursery operations. Phytosanitation can most simply be viewed as an input-output model: prevent pests from entering your nursery and make certain that your plants are not carrying pests when they leave your nursery for sale or outplanting. Two major approaches to phytosanitation can be employed. The systems approach is based on a Hazard Analysis of Critical Control Points and comprehensive programs that have been developed for ornamental nurseries can easily be modified for forest, conservation, and native plant facilities. A second approach based on target pests might be easier for smaller nurseries with limited funds and manpower. Here, the idea is to learn as much as possible about pests that are found in your nursery or ones, like *Phytophthora ramorum*, that could threaten it. By focusing on the type of pest and its methods of spread, nurseries can adapt their scouting and cultural practices to minimize adverse affects. Because their stock is outplanted directly into forests and other wildland plant communities, nursery managers should be especially vigilant to make sure that PRAM isn't spread to or from their operation.

Keywords: nursery, forest, native plant, seedling, *Phytophthora ramorum* (PRAM)

Introduction

A good working definition of phytosanitation is "concerning the health of plants; especially the freedom from pests requiring quarantine" (Wiktionary 2012). So, phytosanitation is similar to integrated pest management but is especially concerned with nursery pests that are subject to quarantine regulations. A nursery pest can be defined as any biological stress factor that interferes with healthy seedling development and causes a sustained departure from the normal physiological or morphological condition that characterizes a healthy plant (Dumroese 2012). The most common nursery pests are microorganisms such as fungi and bacteria but insects and weeds also fit this definition (Landis and others 1990). So, a working definition of phytosanitation means that you work to prevent pests from entering your nursery, as well as ensure that your nursery stock isn't infected or infested when it leaves your nursery (Figure 1).

Phytosanitation is not a new concept, but has been discussed for over 50 years in ornamental nurseries. The subtitle of The U.C.

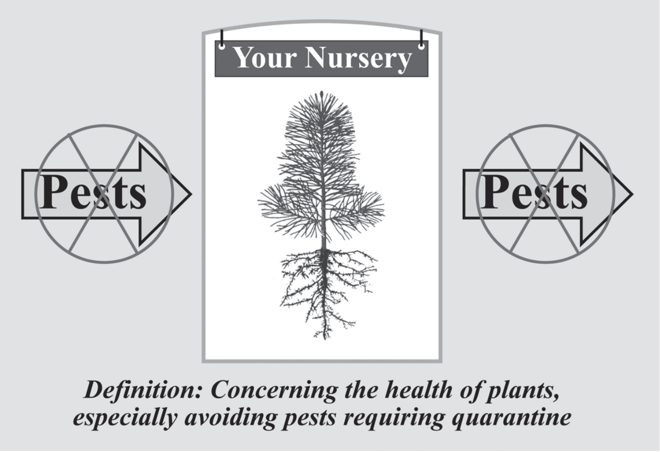

Figure 1. Phytosanitation means that you prevent pests from entering your nursery as well as make certain that your plants are not carrying pests when they leave your nursery for sale or outplanting.

System for Healthy Container-Grown Plants (Baker 1957) was "Through the Use of Clean Soil, Clean Stock, and Sanitation." This classic nursery manual introduced steam sterilization of soils and the development of artificial growing media as a way to prevent the introduction of damping-off and other root diseases in container nurseries.

In the United States, phytosanitary inspections are regulated by the Plant Protection and Quarantine (PPQ) program of the Animal and Plant Health Inspection Service (APHIS), US Department of Agriculture (USDA 2012), but individual states can also impose phytosanitary restrictions. The current interest in phytosanitation was stimulated by the sudden oak death (SOD) disease which is caused by the fungus-like pathogen *Phytophthora ramorum* (PRAM).

The Systems Approach to Phytosanitation

The PRAM situation in California, Oregon and Washington has focused renewed interest in developing phytosanitation programs for ornamental nurseries (Parke and Grunwald 2012; Griesbach and others 2011). Because of problems with contaminated food back in the 1970's, the US Food and Drug Administration developed a systematic approach called Hazard Analysis of Critical Control Points (HACCP). A control point is any step in a production system that can be measured, monitored, controlled, and corrected, and a critical control point is the best step at which significant hazards can be prevented or reduced. The HACCP system consists of a series of logical steps to identify, evaluate, and correct sources of hazards (USFDA 2012).

The HAACP approach has been developed to prevent the spread of pests and diseases in ornamental nurseries in Oregon (Parke and Grunwald 2012). The Oregon Association of Nurseries has recently published the "Safe Procurement and Production Manual: a Systems Approach for the Production of Healthy Nursery Stock" (Griebasch and others 2011). This comprehensive guide integrates HAACP principles into system approach and, although some of the production systems are different, the same basic concepts can be applied to forest and native plant nurseries. A free PDF version is available online at website: (http://www.science.oregonstate.edu/bpp/labs/grunwald/publications/SafeProduction.pdf) , or a print version is available from the OAN office, 503-682-5089 or 800-342-6401.

The first step is to view your nursery in terms of production systems, and then to identify the control points and critical control points (CCP) in each system. For example in a container nursery, the sowing operation consists of a series of consecutive steps which can be analyzed for their potential to spread diseases and pests. The steps at which hazards can be reduced or eliminated are your critical control points for the sowing operation (Figure 2A). For example, we know that fungal spores or weed seeds can be introduced in growing media, so the components should be tested and then pasteurized if necessary. Likewise, fungal spores can be introduced from soil or root fragments so used containers should be washed and sterilized. The last CCP in this operation are the seeds. The spores of pathogenic fungi, such a *Fusarium* spp., have been proven to be carried into nurseries on seedcoats of conifer seeds (Figure 2B). Large and rough textured seeds are particularly susceptible so seed samples should be tested and cleansed before sowing. A "running water rinse" has been shown to be very effective in this regard, a quick soak in a dilute bleach solution also works (Figure 2C).

A good bareroot nursery example where the HAACP process can be applied is the transplanting operation, where there are 2 CCPs (Figure 3A). Many nurseries either purchase seedlings for transplanting from other nurseries or obtain them from a customer. The introduction of transplants has been shown to be a significant risk for introducing pests, especially root rot fungi, into the transplant nursery (Figure 3B). The major problem is when bareroot seedlings are transplanted into another nursery (Cram and Hansen 2012); the risk of spreading root disease on container transplants is much less. Root rot fungi and nematodes can also be introduced into a bareroot nursery on cultivation or transplanting equipment. For this reason, savvy nursery managers insist that operators clean and sterilize their equipment (Figure 3C) when it is moved from one field to another, and especially when equipment is leased or borrowed from other nurseries.

Once you have analyzed all your production systems then the final step is to develop Best Management Practices that address the potential problems at each CCP.

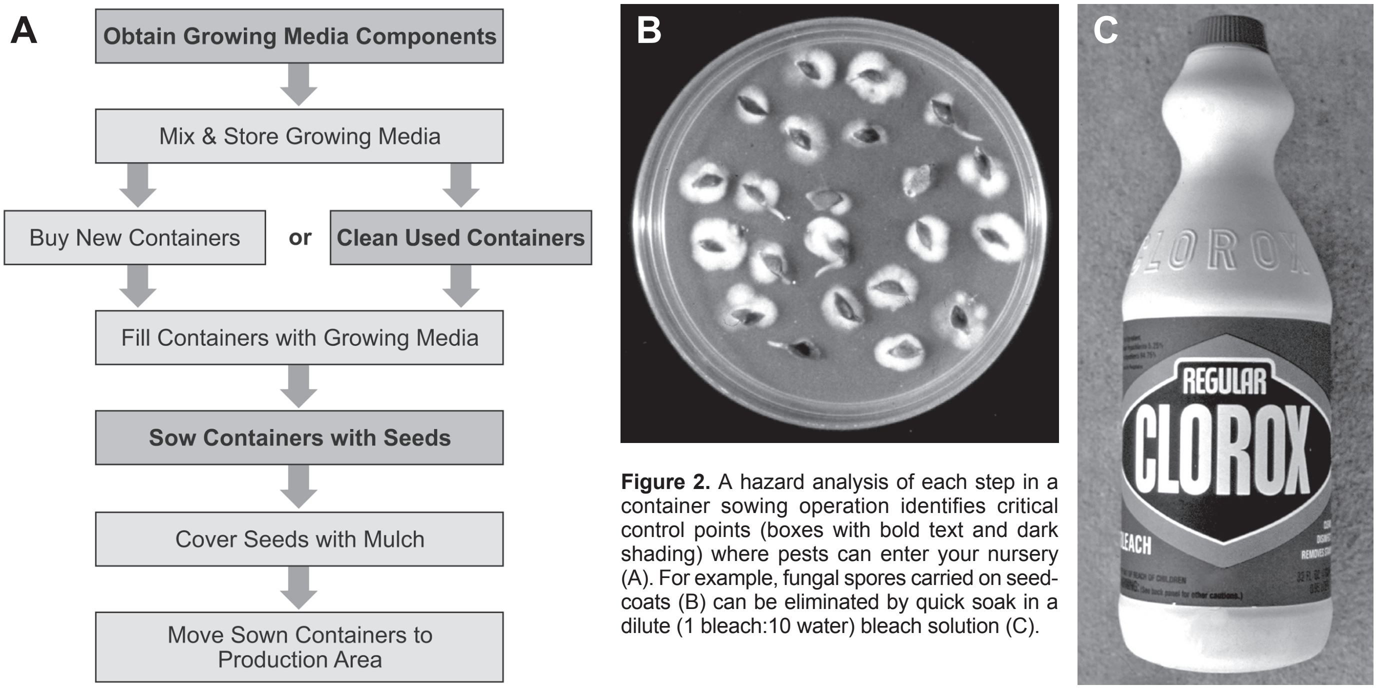

Figure 2. A hazard analysis of each step in a container sowing operation identifies critical control points (boxes with bold text and dark shading) where pests can enter your nursery (A). For example, fungal spores carried on seedcoats (B) can be eliminated by quick soak in a dilute (1 bleach:10 water) bleach solution (C).

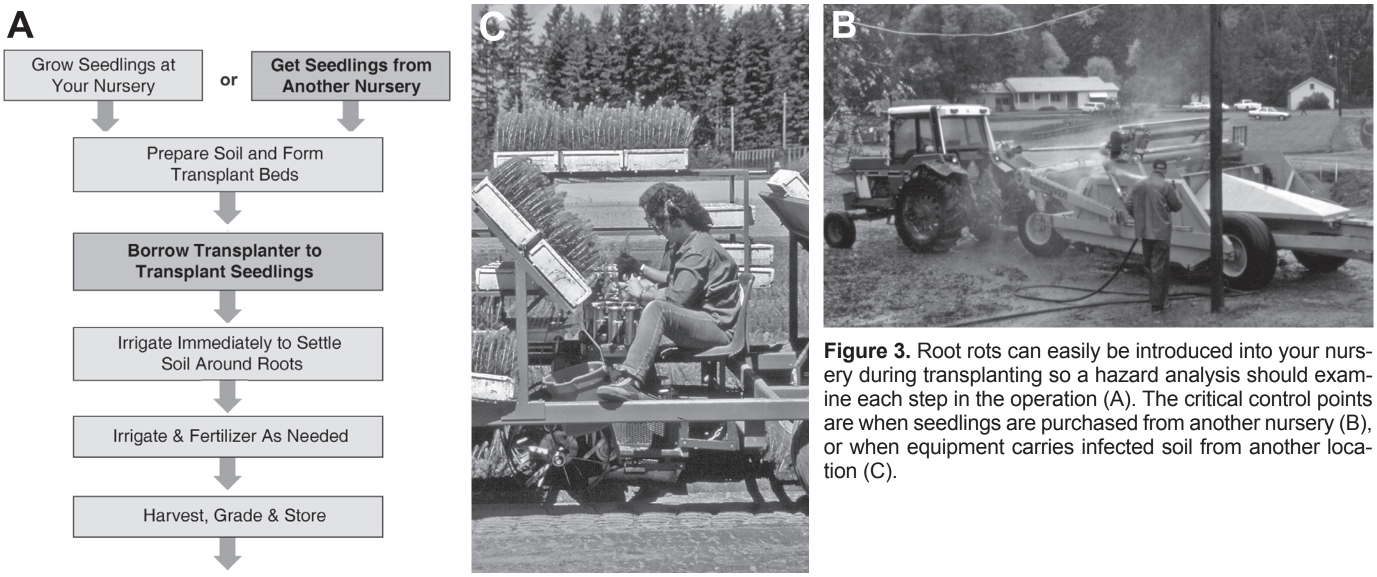

Figure 3. Root rots can easily be introduced into your nursery during transplanting so a hazard analysis should examine each step in the operation (A). The critical control points are when seedlings are purchased from another nursery (B), or when equipment carries infected soil from another location (C).

Phytosanitation Techniques for Specific Target Pests

A simpler yet still effective approach to phytosanitation is to make a list of your most significant nursery pests, and do some research into how they spread. This approach is probably more practical for small nurseries that don't have the funding or manpower to implement the systematic approach. There is a wealth of good information published on nursery pests. For example, Forest Nursery Pests (Cram and others 2012) has just been published and contains excellent information on the most common pest problems that you might encounter in your nursery, and well as other useful information on diagnosis and integrated pest management.

1. Damping-Off

This is one of the oldest diseases of forest nursery plants, and affects germinating seeds or just-emerged seedlings before their stems become lignified. Most conifer and broadleaved plants can be affected (James 2012).

Type of Pest:

Several genera of fungi, such as *Fusarium* and Rhizoctonia, or Oomycetes including *Pythium*, and *Phytophthora*.

Method of Spread:

Spores on seeds, in soil or growing media, or in water.

Critical Control Points:

Spores can be transmitted in nursery soil or can be introduced on seedcoats. Certain damping-off fungi have motile zoospores which can move in water or wet soil.

Phytosanitary Risk to Your Nursery:

Damping-off is a nursery disease that's been around forever, and nursery managers have to be constantly vigilant. It can easily be controlled, however, by learning how it spreads and taking preventative measures that are well documented (James 2012, Landis and others 1990).

Phytosanitary Risk to Your Customers:

Because damping-off that is only seen during germination and early growth, it would not be carried on healthy nursery stock that are shipped to the field.

2. Grey Mold or Botrytis Blight

Like damping-off, this is a very common nursery disease and can affect most plants grown in nurseries (Haase and Taylor 2012).

Type of Pest:

Botrytis cinerea, a fungus.

Method of Spread:

Aerial spores, or from seedling to seedling.

Critical Control Points:

Botrytis is one of those diseases that seem to come out of nowhere, so it's hard to identify specific control points.

Phytosanitary Risk to Your Nursery:

It would be almost impossible to prevent Botrytis but both research and practical experience have shown that constant vigilance to catch infections early and continuous rogueing of diseased plants are effective.

Phytosanitary Risk to Your Customers:

Botrytis is often identified during packing on the senescent foliage of plants that have been grown close together. Because this fungus can spread at temperature above freezing, many nurseries have converted to freezer storage. Otherwise healthy plants with minor infections will not spread the fungus after outplanting as this disease will not survive under drier conditions.

3. Sudden Oak Death

Althought this is a relatively new disease that has caused serious damage in forests in the US and Europe, *Phytophthora ramorum* (PRAM) also infects nursery plants as a shoot or leaf blight.

Type of Pest:

PRAM a fungus-like pathogen that produce relatively minor symptoms in nursery stock, but research has shown that it can persist on plant material or even organic matter.

Method of Spread:

This pest produces 3 types of spores: motile zoospores, which can actively disperse in water; chlamydospores, which can survive long periods in plant tissue or even organic matter (Figure 4a); and thick walled oospores that are sexually produced by the combination of two mating types (Chastagner and others 2012).

Critical Control Points:

Due to its many spore types, PRAM has multiple modes of transmission. It is most commonly spread through any type of plant material shared between nurseries including cuttings and transplants. Seed transmission has not been proven so far. Zoospores can spread through any form of water such as rain splash and surface runoff, and has been shown to persist in waterways around nurseries (Chastagner and others 2012).

Phytosanitary Risk to Your Nursery:

The disease potential for this pathogen is extreme. Because over 100 species of trees and shrubs from 36 different families are susceptible (Chastagner and others 2012), PRAM has the potential to become the most serious forest pest since white pine blister rust and chestnut blight. Although PRAM has only been positively identified on ornamental nursery stock as of the current date, it is only a matter of time until infections are discovered on forest, conservation, and native plant species. Although PRAM has not proven to be a serious nursery disease, it can still have serious economic impacts due to plant quarantine regulations. At one ornamental nursery in Southern California, over 1 million camellias worth $9 million had to be destroyed because of a PRAM infestation (Alexander 2006). Therefore, nursery managers must become familiar with disease symptoms and keep up-to-date on the latest developments.

Phytosanitary Risk to Your Customers:

Disease symptoms on nursery stock are relatively minor. What's most worrisome is that many infected plants show no visible symptoms at all (Vercauteren & others 2012). Genetic testing has proven that long-range spread can be attributed to the shipping of infected nursery stock, and that PRAM can then be transmitted to surrounding forests (Mascheretti and others 2008). Because they ship their plants directly into forests and other natural settings, forest and native plant nurseries represent a serious transmission threat. Unfortunately, this has already happened in the United Kingdom. In this case, nursery stock has been shown to be the cause of a devastating forest disease outbreak in Japanese larch plantation where 3 million trees have been killed (Brasier 2012).

The PRAM epidemic has resulted in both state and federal quarantine restrictions (Kliejunas 2010). The state of Oregon instituted a quarantine on nursery stock coming from California in 2001, and APHIS issued a federal regulation in 2004 to regulate interstate transportation for PRAM host materials, including nursery stock, from the states of California, Oregon, and Washington. By 2009, more than 68 countries had some quarantine regulations concerning PRAM nursery stock (Sansford and others 2009).

Although little has been published on the effects of PRAM in forest, conservation, and native plant nurseries, a comprehensive article is being written for the Winter 2013 issue of Forest Nursery Notes. The most current information on PRAM can be found on-line at the following websites:

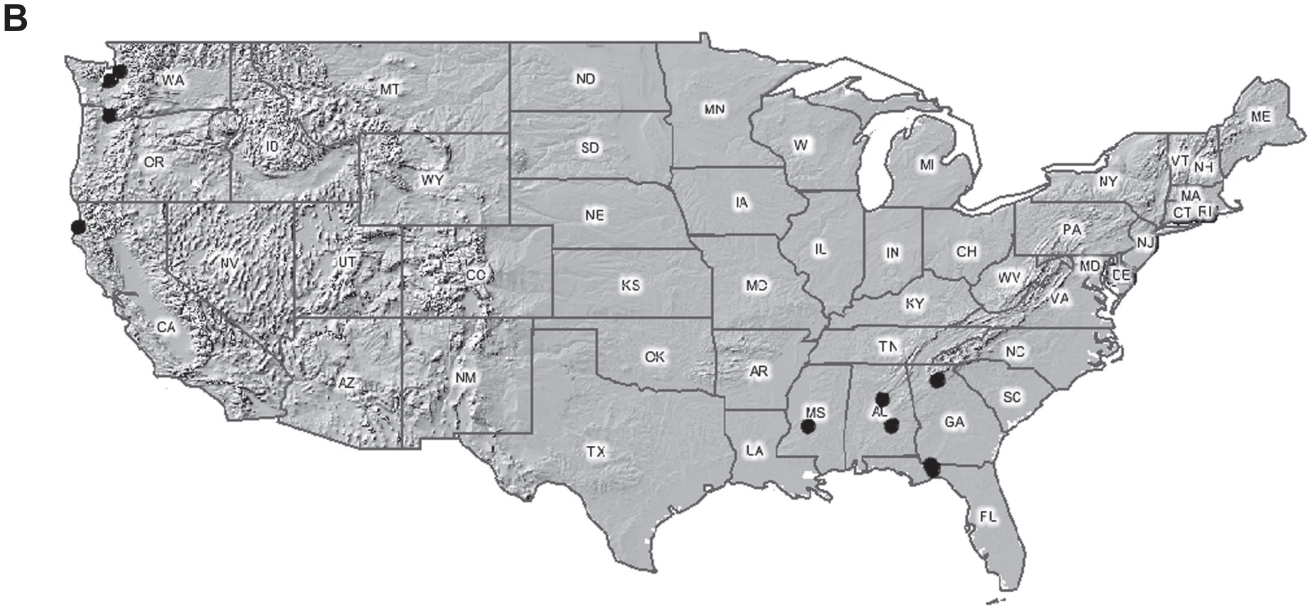

Figure 4. Phytophthora ramorum is a new insidious nursery pest because, although nursery symptoms are very minor, it can persist in root systems and leaf litter (A). This fungus-like pest has motile zoospores and can spread in water; this map shows PRAM detected in waterways around nurseries (B). (A from Elliott 2012; B from Chastagner and others 2010)

1. <www.suddenoakdeath.org> - This website contains a section on *Phytophthora ramorum* in nurseries including diagnostic guides. It also has contact information for your local state.

2. <http://www.aphis.usda.gov/plant_health/plant_pest_info/pram/index.shtml> - This APHIS website has a section on *Phytophthora ramorum*/Sudden oak death, which includes the most current host lists and legal information on quarantine restrictions

Summary

Phytosanitation should become a part of your overall nursery management. Due to the increased concern about PRAM, a wealth of recent information on phytosanitary concerns in nurseries is available. Either the systems approach based on Hazard Analysis of Critical Control Points or, for smaller nurseries, a targeted approach based on pests of greatest concern can be effective. Phytosanitation is an essential practice to help prevent the spread of PRAM and other pathogens to or from your nursery operations.

Acknowledgements

Special Thanks to: Gary Chastagner and Marianne Elliott, WA State University; Susan Frankel & Ellen Goheen, USDA Forest Service; Prakash Hebbar & Scott Pfister, USDA, APHIS; Jennifer Parke, OR State University, and Jane Alexander, University of California.

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Drawing of Douglas-fir cones

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