Tree Planters' Notes

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Fall 2017

Dear TPN Reader

Welcome to another lengthy issue of TPN—I don't believe an issue has ever exceeded 100 pages before now! This issue includes proceedings papers from the 2016 annual nursery meetings:

- Joint Meeting of the Northeast Forest and Conservation Nursery Association and Southern Forest Nursery Association (Lake Charles, LA, July 18–21, 2016)
- Joint Meeting of the Western Forest and Conservation Nursery Association and the Intermountain Container Growers Association (Troutdale, OR, September 14–15, 2016)

Since 2014, proceedings papers from the annual nursery meetings are published in TPN. All proceedings papers from the annual nursery meetings (1949 to now) are available online at: http://www.rngr.net/publications/proceedings/.

This issue contains eight articles from the above-mentioned nursery meetings, three other technical articles, the annual report on forest seedling production in the United States, and a new article for TPN's "Tree Planting State by State" series (profiling current and historical reforestation activities in the U.S. Virgin Islands). To date, 20 States and the U.S. Virgin Islands have been profiled for the "Tree Planting State by State" series. I would love to see all 50 States and all American-affiliated Islands included in the series before I retire. That's not any time soon. Following is a list of States and Islands that have not yet been included:

- Alabama
- Arizona
- California
- Colorado
- Connecticut
- Florida
- Hawaii
- Illinois
- Kansas
- Kentucky
- Maine
- Massachusetts
- Minnesota
- Mississippi
- Montana
- Nevada
- New Hampshire
- New Jersey
- Ohio
- Oklahoma
- Oregon
- Rhode Island
- South Carolina
- South Dakota
- Tennessee
- Texas
- Utah
- Vermont
- West Virginia
- Wyoming
- American Samoa
- Commonwealth of the Northern Mariana Islands
- Federated States of Micronesia
- Guam
- Puerto Rico
- Republic of the Marshall Islands
- Republic of Palau

Is your State or Island on the above list? If so, are you willing to (or nominate someone to) write an article for the TPN series? I always encourage folks to recruit co-authors, too. Please contact me (DLHaase@fs.fed.us) and I will provide guidelines, examples, and assistance in editing to develop an outstanding article about your State's or Island's past, present, and future tree planting activities.

Until next time —

Diane

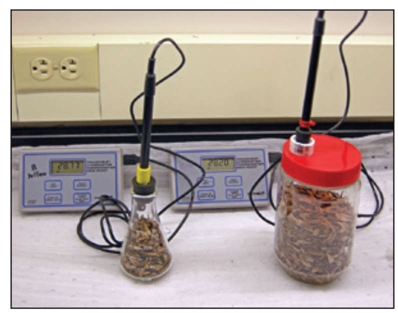
Diane L. Haase

People who will not sustain trees
will soon live in a world
which cannot sustain people.

~ Bryce Nelson

Contents

SEE PAGE 19



SEE PAGE 63

SEE PAGE 74

SEE PAGE 98

A Reforestation Profile of the U.S. Virgin Islands

Michael Morgan, Brian Daley, Louis Hilgemann, and Thomas W. Zimmerman

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Abstract

This article profiles past and present deforestation and reforestation in the U.S. Virgin Islands, along with the geography and ecology of the three islands. The islands of St. Thomas and St. John form one ecological and cultural unit, whereas St. Croix, located approximately 40 mi to the south, makes up another unit. Different periods of human occupation have left their marks on the islands, including extinctions and introductions of plant and animal species. Owing to the small size and population density of the U.S. Virgin Islands, tree planting is generally for landscaping or small-scale ecological restoration projects rather than timber production. Therefore, trees are grown in containers and tend to be planted as saplings rather than as seedlings.

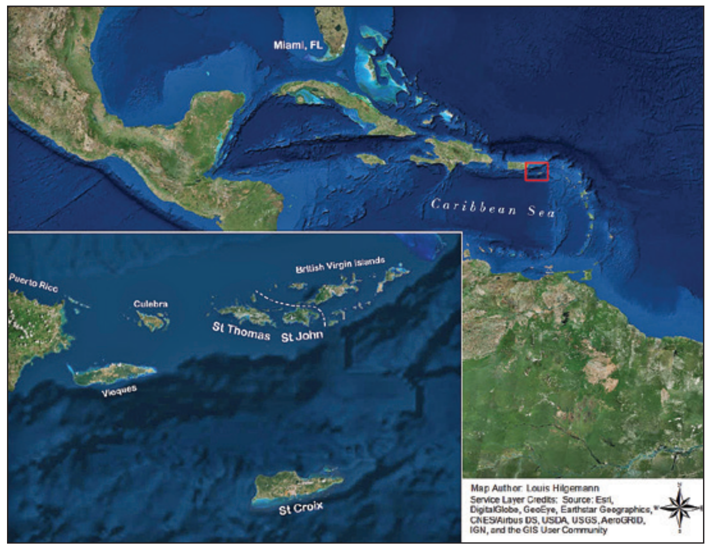


Figure 1. Map of the U.S. Virgin Islands in reference to the continental United States, Puerto Rico, the island of Hispaniola, Cuba, and Jamaica. (Map created by Louis Hilgemann)

Introduction

The U.S. Virgin Islands (USVI) is an unincorporated territory of the United States and is composed of three principal islands: St. Croix, St. John, and St. Thomas. The islands are located in the Caribbean Sea, east of Puerto Rico (figure 1). St. Croix is 1,136 mi (1828 km) from Miami, and St. Thomas and St. John are approximately 1,640 mi (2640 km) from New York City. Cuba and Jamaica are closer to the continental United States than either the USVI or another U.S. territory, Puerto Rico. On a clear day, one can look over the sea from the island of St. Croix and see the islands of St. Thomas, St. John, Tortola, and Virgin Gorda to the north (figure 2).

Figure 2. View from St. Croix of U.S. Virgin Islands St. Thomas (left) and St. John (center) and British Virgin Islands. (Photo by Michael Morgan, 2016)

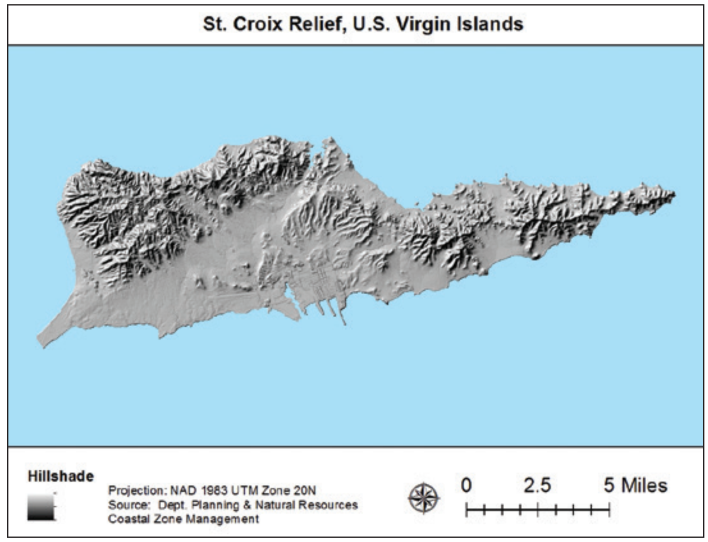
Although all three USVI islands are administratively treated as one unit, St. John and St. Thomas are part of the Virgin Islands archipelago and St. Croix is not. St. Thomas and St. John are historically and ecologically very different from St. Croix. The island of St. Croix is approximately 40 mi (64 km) to the south of the other islands. St. Thomas and St. John are only 4 mi (6.5 km) apart from each other. The Virgin Islands archipelago also includes Culebra and Vieques, which belong to Puerto Rico, and Tortola, Virgin Gorda, Jost Van Dyke, and Anegada, which comprise the British Virgin Islands. Both the USVI and British Virgin Islands have several dozen smaller islands and islets associated with them.

U.S. citizenship was granted to Virgin Islanders in 1927. People who live in USVI cannot vote in presidential elections because the USVI is not a State. They do however, elect local officials, the governor, and a delegate to Congress with restricted voting rights. The majority of people living in the USVI are of African descent. The population density on all three islands is such that they are considered urban or urbanizing. Currently, the main economic activity of all three USVI islands is tourism (Chakroff 2010).

Topography

St. Croix

St. Croix is the largest of the three islands. It is 28 mi long and shaped like a teardrop running from east to west, with a total area of 83 mi^2 (215 km^2). The easternmost tip is about 1 mi (1.6 km) wide, and the widest point, mid-island, is about 6 mi (9.7 km) wide. The island had two towns: Christiansted on the north shore and Frederiksted in the west. The population from the 2010 census is 51,000.



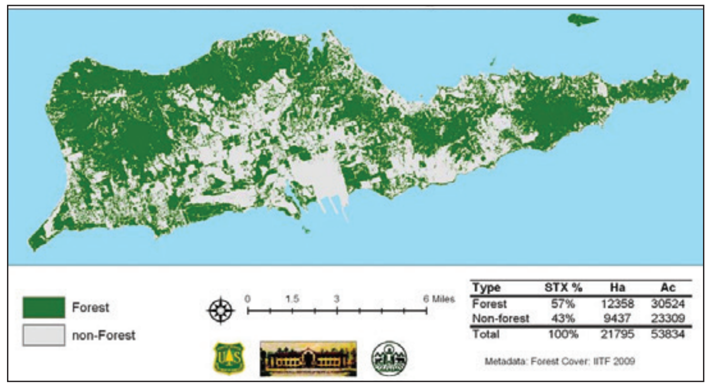


Figure 3. Topographic (top) and forest cover (bottom) maps of St. Croix. (Topographic map created by Louis Hilgemann; forest cover map created by Geographic Consulting, LLC, for Chackroff, 2010)

The island has a mountainous spine running east to west. The highest point is Mount Eagle (1,165 ft [3580m]) (figure 3). A fertile coastal plain is in the wide part of the island where sugarcane was once cultivated. In pre-Columbian and colonial times, streams flowed year-round to the ocean and were navigable by canoe or rowboat. In more recent decades, however, these streams flow to the sea only when rainfall is abundant. In the hillier parts of the island, ravines drain off excess rainfall. Soils tend to have a limestone origin with pH above 8.

Forest cover of the island (figure 3) is 56.1 percent in 2014, an increase from 49.6 percent in 2009 (Brandeis and Turner 2013, Marcano and Williamson 2017). The predominant vegetation type on St. Croix is mostly subtropical secondary dry forest or thorn woodland dominated by almost pure stands of white leadtree (*Leucaena leucocephala* [Lam.] de Wit), an invasive exotic tree species (figure 4). It is locally known as tan-tan. Only 3 percent of the forest cover is considered mature secondary forest; the hilly northwest quadrant of the island is locally referred to as “the rainforest,” but is really subtropical moist forest in its undisturbed condition (Brandeis and Oswalt 2004).

St. Croix is separated from the other islands in the Virgin Islands archipelago and from Puerto Rico by deep marine trenches. This isolation from the other Virgin Islands is reflected in the ecological and human history of the island and its limited suite of native plants and animals.

Figure 4. Typical stands of white leadtree, locally called tan-tan (*Leucaena leucocephala*). This pioneer species forms almost pure dense stands on disturbed sites, with a tree every 2 to 3 ft (60 to 90 cm). (Photos by Michael Morgan, 2016)

St. Thomas

St. Thomas is one-third the size of St. Croix but with the same amount of people. It is so hilly (figure 5) that the airport had to be built on top of dredging spoil that was used to fill in a shallow part of the ocean. The island's total area is 31 mi^2 (82 km^2). The highest point is Crown Mountain (1,550 ft [475 m]). The island has only one town, Charlotte Amalie, which also functions as the capitol of the USVI. The island had 43.6 percent forest cover in 2014 down from 50.1 percent in 2009 (Brandeis and Turner 2013, Marcano-Vega and Williamson 2017). In 2004, 8 percent of the existing forest on St. Thomas was considered mature secondary forest (Brandeis and Oswalt 2004) (figure 5). Most of the forest is considered tropical or subtropical moist forest, with the eastern portion of the island being subtropical dry forest or thorn woodland. Ravines, locally called "ghuts" or "guts," drain the islands after rainfall events. Soils tend to have volcanic origins.

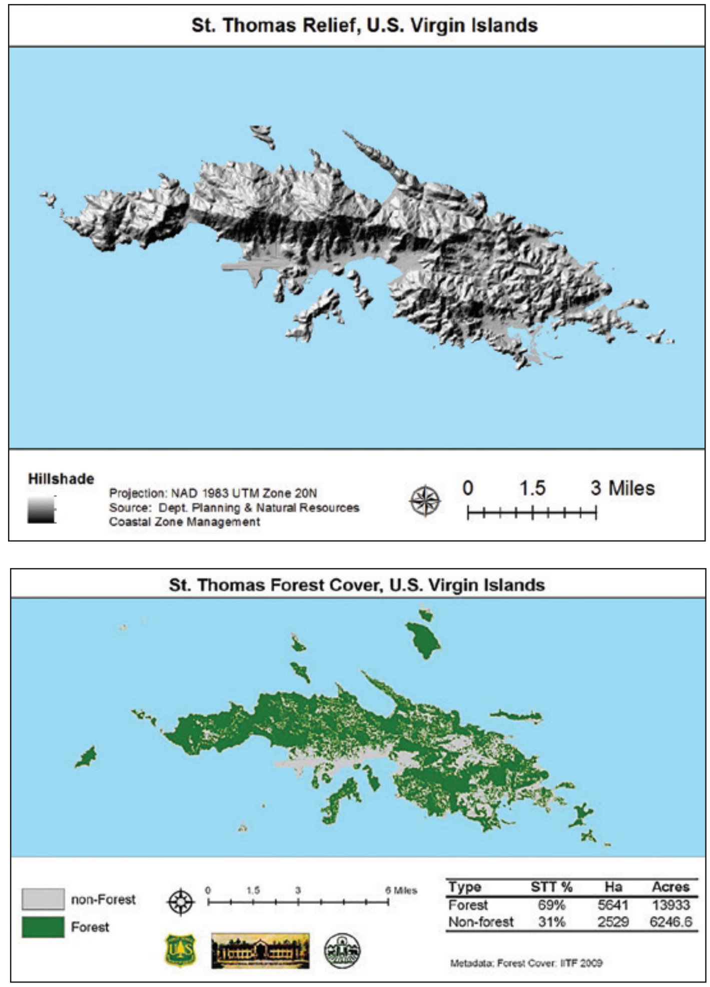


Figure 5. Topographic (top) and forest cover (bottom) maps of St. Thomas. (Topographic map created by Louis Hilgemann; forest cover map created by Geographic Consulting, LLC, for Chackroff, 2010)

St. John

St. John is east of St. Thomas with a total land area of 20 mi^2 (51 km^2). The landscape rises quickly from the coast to form an upland ridge (figure 6). The highest point is Bordeaux Mountain (1,227 ft [778 m]). Two settlements are of note: Coral Bay and Cruz Bay. The population from the 2010 census is 4,170. The forest cover on St. John was 81.3 percent in 2014, down from 85.1 percent in 2009. About 20 percent could be considered mature secondary forest. The eastern part of the island is drier than the rest. About 60 percent of the island is protected as part of the Virgin Islands National Park (figure 6). Like St. Thomas, soils in St. John tend to have volcanic origins (Brandeis and Oswalt 2004, Brandeis and Turner 2013, Marcano-Vega and Williamson 2017).

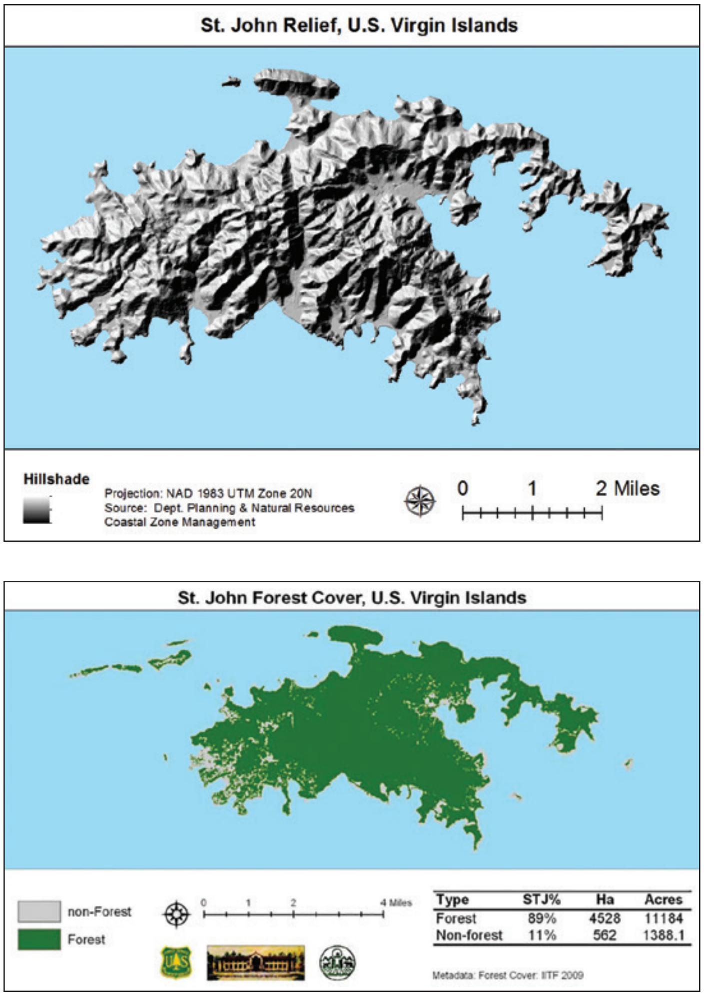


Figure 6. Topographic (top) and forest cover (bottom) maps of St. John. (Topographic map created by Louis Hilgemann; forest cover map created by Geographic Consulting, LLC, for Chackroff, 2010)

Climate

All three USVI islands are significantly below the Tropic of Cancer, with St. Thomas and St. John being at 18°20' N latitude and St. Croix at 17°44' N. Therefore, the climate and vegetation should be considered tropical based on a mean temperature of 75 °F (24 °C) or above. Thomas and Devine (2005) report an average annual temperature of 79 °F (26 °C). According to more recent climate data, the mean USVI temperature is 81.6 °F (27.6 °C) (World Climate Guide 2013). Government and scientific documents, however, often consider the islands to be "subtropical" because of the moderating effect that the ocean has upon the climate, and because the winter winds out of the north keep average "bio-temperatures" just below 75 °F (24 °C) (Ewel and Whitmore 1973, Holdridge 1979).

Average yearly rainfall on the three islands is 55 in (1,400 mm), although rainfall amounts vary among islands and even within individual islands (Thomas and Devine 2005). For example, St. Croix is generally drier than St. Thomas or St. John (Weaver 2006a). On St. Croix, a marked east-to-west rainfall gradient has resulted in thorn woodland on the east end and subtropical moist forest in the northwest of the island. This gradient exists but is less pronounced on the other islands. Also north-facing slopes are wetter than south-facing slopes, especially on St. Thomas and St. John (figure 7). Rainfall can vary dramatically from year to year, due to the presence or absence of hurricanes and droughts.

The rainiest months are April and November, the dry season is from January through March, and most rain falls during the hurricane season (June through November). The winds come predominantly out of the east, and in certain times, bring Saharan dust from Africa.

Figure 7. The incidence of green plants differs significantly between the north side of this hill (left) and the south side of the hill. The view is from Goathill on St. Croix facing directly east toward Point Udall, the easternmost point in the United States. (Photo by Michael Morgan, 2010)

Plant Communities

Using the Holdridge life zone system, two main types of woody plant communities are found on the USVI: moist subtropical forest and dry subtropical forest (Chakroff 2010, Ewel and Whitmore 1973). The reason these forests are considered subtropical and not tropical is because Holdridge uses "bio-temperature" and not mean temperature to classify life zones (Holdridge 1979). Bio-temperatures are calculated using average temperatures, but with an important caveat: temperatures ≤ 0 °C (32 °F) are all treated as 0 °C (32 °F) and temperatures ≥ 30 °C (86 °F) are all treated as 30 °C (86 °F).

Although maps divide the islands into dry forest and moist forest (figure 8), the reality is much more complex. The islands' landscapes are a mosaic of the two forest types, depending on the presence of watercourses, aspect, slope, soil, and past disturbances. Moist (sub) tropical forests are evergreen, with the presence of

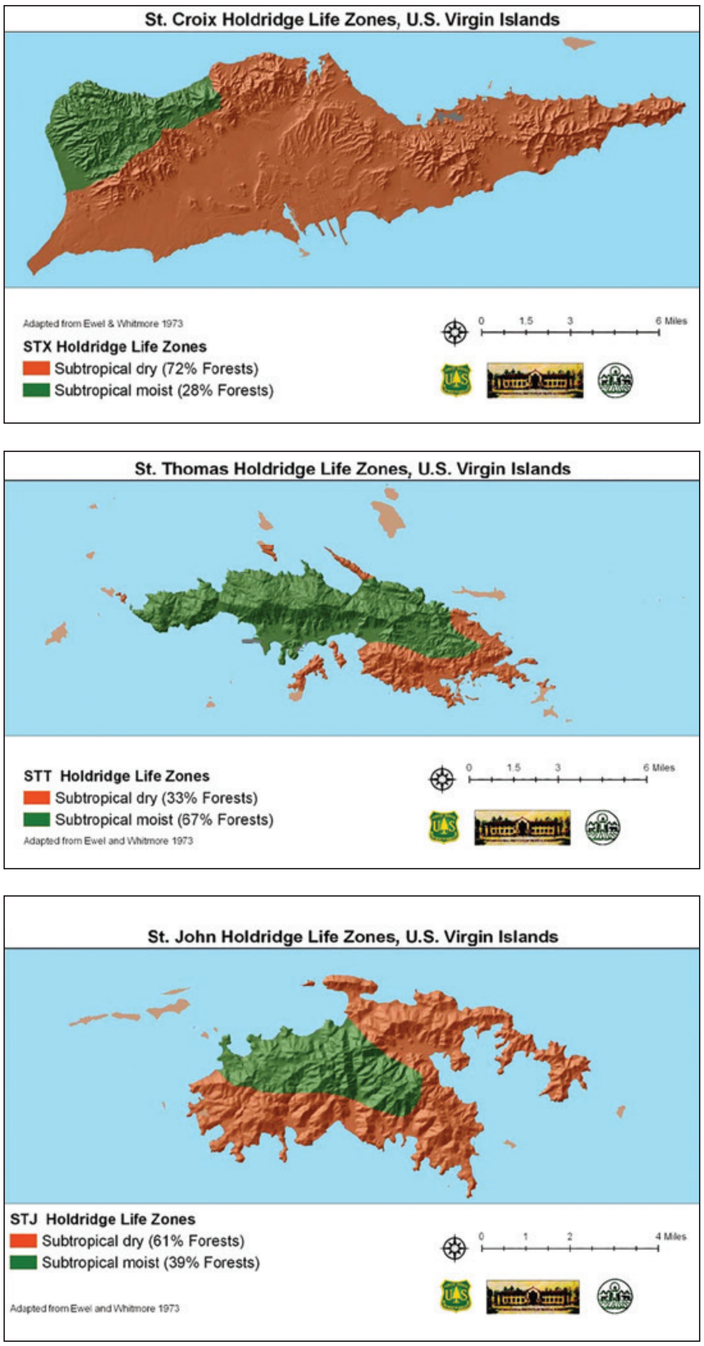


Figure 8. Holdridge zones of St. Croix, St. Thomas, and St. John showing subtropical dry forest and subtropical moist forest. (Maps created by Geographic Consulting LLC for Chackroff, 2010, adapted from Ewel and Whitmore, 1973)

Figure 9. Subtropical moist forests of USVI. Top: St. Croix, view from Mount Eagle (1,155 ft [355m]). Bottom: St. Thomas, note the presence of silvery crowned Tyre Palm (*Coccothrinax barbadensis*) poking above the main canopy; this species is much more common on St. Thomas and St. John than St. Croix. (Photos by Michael Morgan, 2014.)

palms, and occur in areas that generally receive 25 to 50 in (1,000 to 2,000 mm) of rainfall annually (Ewel and Whitmore 1973, Holdridge 1979). These forests are found on the higher mountains above 1,000 ft (300 m) or in valleys where water from mountain streams collect (figure 9). Dry subtropical forests are either deciduous or semi-deciduous depending on the moisture stress they receive. These forests are the most common type of forest found in the USVI. Some trees lose all of their leaves during the dry season; other trees have sclerophyllous or leathery leaves to conserve water. These forests grow in areas that receive 12.5 to 25 in (500 to 1,000 mm) of rain annually (Ewel and Whitmore 1973, Holdridge 1979) (figure 10).

Figure 10. Subtropical dry forests of the U.S.Virgin Islands. Top: Buck Island, National Monument, St. Croix; note the reddish trunk of Turpentine tree (*Bursera simaruba*). Bottom: east end of St. Croix during the dry season; note many trees have lost their leaves. (Photos by Michael Morgan, 2012.)

Figure 11. Tropical thorn woodland (top) and tropical thorn scrub (bottom) on U.S. Virgin Islands (Photos by Michael Morgan, 2016.)

Other plant communities found on the three USVI islands include thorn scrub, mangroves, coastal grasslands and scrub, rock pavements, salt ponds and salt flats, sandy beaches, and rocky beaches. Thorn woodland and scrub forests are characterized by short-statured trees and bushes with thorns. Cacti are often present. These forests occur in areas, such as the eastern third of St. Croix, that receive 10 to 20 in (250 to 500 mm) of rain annually (Holdridge 1979) (figure 11). Mangrove forests are subtropical tree communities that grow in the presence of salt water. Formerly, the biggest expanse of mangrove forest in the eastern Caribbean existed on St. Croix at Krauss Lagoon, but, in the 1960s, it was mostly destroyed and filled in to make room for an aluminum smelter, an oil refinery, and a container port. Mangroves now mainly exist as shallow coastal fringes to the islands (figure 12). All of the islands are surrounded by coral reefs.

Figure 12. Top: black mangrove (*Avicennia germinans*); note the presence of pneumatophores in the foreground. Bottom: red mangrove (*Mangle rhizophora*) in the U.S. Virgin Islands. (Photos by Michael Morgan, 2017.)

History

Different groups of people arrived and impacted the natural environment of the islands over the centuries. The timeline of the Virgin Islands includes a prehistoric or (prehuman) period, an Amerindian phase, a period of European discovery, a colonial period, and then a modern period starting in 1917, when the United States purchased what is now the USVI from Denmark. Each period is marked by periods of forestation and deforestation, as well as the extinction and introduction of various plant and animal species.

Prehistory (≈8000 B.C.E. to 1000 B.C.E.)

The first phase of island history is perhaps best considered a period of afforestation. The last Ice Age was ending, the world had a cooler, drier climate, and sea levels were approximately 390 ft (120 m) lower than present levels. The landscape of these islands was grassland and savanna (Weaver 2006a). When the climate became warmer, the ice began to melt. Sea levels rose and the climate became wetter. Savannas turned into forests; what once were mountains turned into islands (Weaver 2006a).

St. Thomas, St. John, and the rest of the Virgin Islands archipelago were connected to Puerto Rico via a land bridge that is now, because it is under water, called the Puerto Rican Bank. The Virgin Islands archipelago would have had the same suite of plants and animals as Puerto Rico. St. Croix was always an island, however. The colonization of St. Croix by plants was limited to only species whose seeds could be transported by the wind, the sea, or by birds and bats. Animals were limited to whatever could fly, float, or swim to St. Croix.

First Peoples (1000 B.C.E. to 1515 C.E.)

This is the Amerindian period during which people arrived in roughly two waves. People started to leave South America in 2,000 B.C.E., and over generations, travelled by raft and canoe up the chain of islands that forms the Antilles (Highfield 1995, Rouse 1992). The first groups of people arrived in the Virgin Islands around 1,000 B.C.E. It appears that these groups stayed mainly on the shorelines of the islands, gathering shellfish, fishing, hunting, and gathering edible plants. They left little evidence of their presence in the Virgin Islands other than shell middens. Maybe these first people should be considered visitors rather than settlers (Highfield 1995, Rouse 1992).

The very first peoples were replaced in about 0 to 100 C.E. by other, more numerous Amerindian groups, also originally from northern South America. In addition to fishing, hunting, and gathering, they also farmed (Rouse 1992). They were present on the islands until approximately 1515, when war with the Spanish forced the abandonment of St. Croix and the other Virgin Islands (Highfield 1995).

These first peoples had both positive and negative impacts upon the islands' ecosystems. They caused the extinction of some endemic animal species via overhunting. For example, bones of extinct animals, such as the St. Croix macaw (*Ara autochtones*) and the Antillean Cave rail (*Nesotrochis debooyi*), have been discovered in pre-Columbian kitchen middens on St. Croix (Highfield 1995, Olson 1978, Wetmore 1918, Wetmore 1937).

The Amerindians who farmed brought with them food crops, large-seeded fruit trees, and animals from northern South America (Highfield 1995, Rouse 1990). Each fruit of the mammey apple (*Mammea americana* L.) has one or two seeds inside that are far too large to be dispersed by any bird or bat. They also brought the fruit tree genip (*Meliococcus bijugatus* Jacq.), which nowadays is so common it is considered to be an invasive exotic, yet scientists believe it to have been present in the islands for at least 1,000 years (Francis 1992, Little and Wadsworth 1964). A large forest rodent from northern South America, the agouti (*Dasyprocta* spp.), was brought to serve as a source of meat. In addition to being tasty, agoutis are important dispersers of tree seeds. Their presence in the Virgin Islands is known via excavated kitchen middens (Highfield 1995, Rouse 1992). Although locally extinct, agoutis are still found on other islands of the Lesser Antilles.

Archaeological evidence shows that St. Thomas and St. John supported only three or four villages each because they were so rugged and without permanent streams (Dookhan 1973). Because St. Croix has abundant flat land for agriculture and, during this time, some small rivers, it supported more people. Remains of around 20 villages have been found. Archaeologists believe that at its peak, the Amerindian population was 3,000 to 5,000 (Highfield 1995). Because they farmed, these early people would have to clear land for crops and cut down trees for home construction, canoes, and firewood.

Discovery and Abandonment (1493–1615 C.E.)

In 1493, Columbus visited St. Croix on his second visit to the New World and skirmished with the Amerindian residents. The next day, he sailed to the archipelago of islands he saw across the water. He called them the Virgin Islands after a St. Ursula, who had a multitude of virgin followers. Soon after European arrival, an approximately 100-year period of reforestation by way of abandonment occurred. By 1515, most inhabitants of St. Croix and the other Virgin Islands either were dead through war and disease, enslaved, or fled to more remote islands. Although the Virgin Islands were considered abandoned, Spain did not bother to colonize them because the Spaniards were too busy extorting gold and silver from the mainland of the Americas to care much for small Caribbean islands (Knight 1990).

In the late 16th century, ships of Spain's European rivals (England, Holland, and France) cruised the Caribbean; the Virgin Islands were a perfect place to lie in wait for a Spanish galleon laden with gold and silver leaving Puerto Rico for Spain. In 1595, Sir Francis Drake, a famous 16th century English sea captain launched an unsuccessful attack on the port and fortress of San Juan, Puerto Rico from the Virgin Islands. Drake's Channel, the channel between the islands of St. John and Tortola that was named after Sir Francis Drake, is a vestige from the era of piracy.

During the time of Amerindian abandonment and Spanish neglect, the fields around Amerindian settlements would have had time to turn into forest, although some localized woodcutting must have been performed by visiting ships for repairs and fuel. The introduction of livestock, like goats and pigs, to provide fresh meat to passing ships probably made the main impact upon the islands forests during that time (Knight 1990). These farm animals soon went feral. Shipboard rats were also probably another introduction to the islands.

First Colonies (1615–1733 C.E.)

In 1615, a Dutchman established a settlement on the island of Tortola in what is now the British Virgin Islands. This was followed by English and Dutch settlements on opposite sides of St. Croix in 1625 and a Dutch settlement on St. Thomas in 1656. In 1672, the Danes established possession of St. Thomas and claimed St. John. St. Croix became a French colony from 1650 to 1695 and was sold to the Danish in 1733.

The first African slaves arrived in St. Thomas in 1672 (Hall 1985) after which deforestation of the islands began in earnest to clear land for crops and to construct buildings. Slaves were essential to the success of the new colonies. Soon, lumber from all three islands of the (now) USVI was exported to other islands or to Europe. Tobacco, cotton, and sugarcane followed (Hall 1985). Slaves were bought from Africa because the English, French, and Dutch colonists kept dying of fever and disease, especially the European indentured servants and convicts who were supposed to supply the manual labor for the colonies. Of the first 190 Danish colonists sent to St. Thomas, only 29 were alive after a year (Dookhan 1974). Africans also died at alarming rates, but were used to working in tropical heat and were slightly more resistant to tropical diseases. On St. Croix, under the mistaken belief that forests cause fevers, large expanses of the island were set on fire to clear land and prevent fevers (Highfield 2013).

It appears that introductions of horses, cattle, and other "Old World" livestock like goats, sheep, pigs, and chickens continued during this period. Herds of wild horses in 17th century St. Croix were referenced (Highfield 2013). Two tree species with African origins, tamarind (*Tamarindus indica* L.) and baobab (*Adansonia digitata* L.), were likely introduced to the Virgin Islands during the 17th century. Tamarind trees are still found in the hundreds, whereas only a dozen or more baobab trees, some of which are more than 300 years old, can be found (Nicholls 2006). Another interesting African addition to the islands is the Guinea fowl (*Numidea meleagris* L.), which has been present in the Caribbean basin since as early as the 1500s. Flocks of them are often seen on St. Croix (Bond 1993).

The Sugar Years (1730–1917 C.E.)

By the early 1700s, agriculture—cotton, tobacco, and especially sugar—was not working out so well on St. Thomas. The island is very hilly, and cultivated soils erode away on steep slopes. The economy started to put more emphasis on trade because of the deepwater harbor at Charlotte Amalie, which was described "as the place you have to go through, to get to any other place in the Caribbean" (Dookhan 1974).

It was not until 1718, 46 years after the settlement of St. Thomas, that the Danes made an active attempt to colonize St. John, even though the two islands are only 4 mi apart (Weaver 2006b). It was just too hilly and rugged. In fact, earlier in the 17th century, because both St. Thomas and St. John were so rugged and forested, the French governor of another Caribbean island, St. Kitts, used the two islands as penal colonies where he could exile dissidents to his rule (Du Tertre 1978).

By 1728, no large trees remained on St. John, and by the 1760s, plantations occupied 98 percent of the island, yet only 35 to 40 percent of the island had been completely cleared. This last fact had positive implications for the natural reforestation of the island in future years because seed sources remained for many, if not all, of the original plant species on the island (Weaver 2006b).

The Danes looked longingly at the flatter, fertile island of St. Croix, abandoned by French settlers since 1695. The forests had had 35 years to recover. Aide et al. (2000) noted that, in Puerto Rico, it usually takes only 35 to 40 years for a regrown forest to recover the original number of stems per acre, biomass, and basal area of the original forest, although it takes at least 80 years (if at all) for the new forest to have the same species composition as the original forest.

In 1730, France sold St. Croix to the Danes. The land began to be cleared in earnest for sugarcane in the wetter western half of the island and cotton in the eastern half. Reimert Haagensen (1995), an early Danish settler of 18th century St. Croix, wrote that many trees were burnt on site in the process of clearing land simply because they were too big to cut up and move. Some tree species, however, such as lignumvitae (*Guaiacum officinale* L.) and fustic (*Maclura tinctoria* (L) Steud) were left standing because they were so valuable. Spanish cedar (*Cedrela odorata* L) was used for canoes and shipbuilding (Carstens 1997). Another timber species exported from St. Croix was maststick or mastwood (*Sideroxylon foetidissisum* Jacq.). As its name suggests, this species was used for ship masts because of its straightness (Highfield 2013).

In the 1750s, sugarcane production took off on St. Croix with the arrival of 1,000 Irish settlers and their accompanying slaves from the Caribbean island of Monserrat (Hall 1985). In addition, more slaves were imported from Africa. By 1796, one-half of the island was devoted to sugar plantations, with their accompanying pastures and garden allotments for the plantation slaves, and the other one-half was devoted to cotton and pasture. The population of St. Croix reached 30,000 by 1800 (Weaver 2006a). By the 1820s, however, the island's sugarcane industry started to decline as other tropical countries started to cultivate sugarcane, and a method was developed to extract sugar from sugar beets. In 1803, the King of Denmark ended the importation of new slaves, and, in 1848, slavery was abolished, resulting in a shortage of labor. Agriculture shifted from sugar to livestock, although it was not until 1963 that the last sugarcane harvest occurred on St. Croix (Dookhan 1974).

Very early on, St. Thomas and St. John started to differ from St. Croix. Nearly from the very start, St. Thomas was more of a port of commerce for the other islands rather than a center of agricultural production. In the 1750s, the population was already 50-percent urban (by the 1840s it was 80-percent urban), whereas St. Croix was 75-percent rural, and St. John was described as "a mere sheep path" (Dookhan 1974). After the early 1700s, very little plantation agriculture was on St. Thomas, but the island had plenty of cattle grazing, charcoal making, and subsistence agriculture. On both St. Thomas and St. John, trees on steep slopes were only selectively cut (Gibney 2017).

Besides clearing the land for agriculture, some Danish forestry activity occurred, which mainly resulted in the introduction of new tree species. For example, little leaf or West Indian mahogany (*Swietenia mahoganii* (L) Jacq.) was introduced to St. Croix from Jamaica in the 1770s (Weaver 2006a). Big leaf or Honduran mahogany (*Swietenia macrophylla* King) was introduced in 1907. Mangos (*Mangifera indica* L.) and tibbets (*Albizia lebbek* L. Benth.) were introduced from Asia (Nicholls 2006). White lead tree or tan-tan (*Leucaneana leucocephala* Lam. de Wilt) is a small tree ubiquitous on St. Croix and is believed to have been introduced by one of two Danish agricultural experiment stations on St. Croix between 1890 and 1910 as a forage species. In 1793, the English Captain Bligh brought cuttings of breadfruit (*Artocarpus attilus* Parkinson Fosberg) from Polynesia to the British colonies of the Caribbean as an alternative starchy staple food for African slaves. Although not initially well received as a food source, breadfruit is now part of traditional Virgin Islands cooking (Little and Wadsworth 1964).

The Danes also impacted the ecosystems of the islands in other ways. In the 1790s, they introduced white-tailed deer (*Odocoileus virginiana* Zimmermann) as a game species. The deer continue to be abundant on St. Croix and St. John and negatively affect forest regeneration. The South Asian mongoose (*Herpestes auropunctatus* Hodgson) was introduced in 1884 in an effort to control rats in the cane fields. Instead of exterminating rats, however, they preyed upon ground nesting birds and their eggs. The mongoose introduction led to the extinction of an endemic snake, the St. Croix racer (*Borikenophis sanctaecrucis*) and eradicated the St. Croix ground lizard (*Ameiva polops*) from the island. These days, the lizard is found only on Buck Island and three islets off the coast of St. Croix (Weaver 2006a).

Modern Times (1917 C.E. to the Present)

After the sugarcane industry declined, the islands stopped being profitable for Denmark and became a financial burden. In 1917, the United States bought the three islands from Denmark due to St. Thomas' strategic location in the Caribbean. Forests began to grow back as agricultural fields were abandoned and people emigrated. St. Croix has transitioned from an almost completely forested landscape to almost completely deforested during the height of sugarcane production (Chakroff 2010), to modern times where data indicate a steady state of over 50 percent forested landscape (Chakroff 2010).

Little written information can be found about St. Thomas, but this is what the botanist and lifelong St. John resident, Eleanor Gibney (2017) has to say: "The reason there's few records from St. Thomas is that no one ever did much about tree planting—but because of the lack of plantation agriculture after the early 1700s, clearing was patchy and small scale over most of the island, so recovery was fairly fast with the seed sources nearby. On both St. Thomas and St. John, the steep slopes were often only selectively cut. But there was a lot of livestock grazing and fuel-wood/charcoal cutting on both islands. St. John (and British Virgin Islands) wood resources were heavily exported to both St Thomas and St Croix, up through the mid-20th century. I can remember the burlap sacks—crocus bags—full of charcoal sitting on the Cruz Bay dock in the early 1960s, waiting for transport. It's hard to over-emphasize how heavily the St Thomas/St John population was centered in Charlotte Amalie and how really empty the country was until the 1960s."

Meanwhile, on the island of St. John in 1917, only 3 percent of the land was cultivated, much of it was grazed, and the rest was forested. Oil from the leaves of the bay rum tree (*Pimenta racemosa* [Mill.] J.W [Moore)] was the primary export of that island at its peak in 1920 (Weaver 2006b). Wild donkeys, sometimes thought to have existed since colonial times, only became wild during the late 1970s. Gibney (2017) writes: "before that every donkey was (very much) owned, but after about 1970 people let them wander off—because cars and trucks were abundant enough to do the heavy carrying...." Currently, both wild donkeys and deer negatively impact forest regeneration in the Virgin Islands National Park.

Things were quiet in the USVI until the 1950s, when the Virgin Islands Tourism Board was created to promote tourism, especially to St. Thomas and St. John. Industry was attracted to St. Croix via tax breaks. An aluminum smelter was established in 1962 and then an oil refinery in 1964. A serious environmental impact of these two large installations was the destruction of the 1,000-ac (405-ha) Krause Lagoon, the largest expanse of mangroves in the Eastern Caribbean, to build a port so raw materials could be processed and refined oil and aluminum exported. The aluminum smelter closed in the 1990s, and the refinery stopped refining in 2012, although it is currently a storage facility.

Forestry and Tree Planting Activities in the 21st Century

In the 1930s, the Federal Government began to show interest in the forests and natural areas of the USVI. During the Great Depression, a short-lived Federal public works program was created to plant shade trees in pastures and windbreaks (Weaver 2006a). In 1956, the Virgin Islands National Park was created by Congress on the island of St. John. The park protects 60 percent of the island. Meanwhile, the U.S. Department of Agriculture (USDA), Forest Service acquired a 150-ac (60-ha) tract on St. Croix called Estate Thomas for forestry experiments, in particular, provenance trials of various tree species such as mahogany (*Swietenia* spp.), teak (*Tectona grandis* L.f.), Spanish cedar (*Cedrela odorata* l.), and Caribbean pine (*Pinus caribaea* Morelet.). It is currently used for monitoring natural forest succession and environmental education.

As far as the authors know, very little forestry activity (urban or otherwise) is currently on St. Thomas. The territorial park of Magen's Bay has an arboretum. The only other forestry activity we know about is the cryptic tale of aerial seeding of St. Thomas with seeds of flamboyant (*Delonix regia* L.) by the founder of the *Virgin Islands Daily News* and a pilot friend in 1947 or 1950. Flamboyant or flame tree is now a common pan-tropical ornamental tree with attractive red flowers, although it is originally from Madagascar (Nicholls 2006).

The primary protected area in the USVI is the Virgin Islands National Park on St. John. Other protected natural areas include Buck Island National Monument off the coast of St. Croix and Hassel Island off the coast of St. Thomas; both are administered by the National Park Service. Salt River Columbus Landing is a park jointly administered by the National Park Service and the Virgin Islands Department of Planning and Natural Resources. The U.S. Fish and Wildlife Service administer Sandy Point National Wildlife Refuge (NWR) on St. Croix, along with two islets: Green Cay and Ruth Cay. The Nature Conservancy manages Jack and Isaac's Bay on the East End of St. Croix. The nongovernmental organization, or NGO, St. Croix Environmental Association manages the Southgate Reserve on the northeastern shore of St. Croix (Weaver 2006a).

Figure 13. Reforestation project at a forest stewardship property. (Photo by Michael Morgan, 2015)

The USDA Forest Service State and Private Forestry program funds the Forest Stewardship, Forest Legacy, and Urban and Community Forestry programs, which are administered through the Virgin Islands Department of Agriculture Forestry Division. The Stewardship Program has provided technical assistance to forest owners across the territory since 1998. Thus far, 45 private properties have been enrolled in the Stewardship Program, which offers a property tax reduction in return for active forest management. This generally involves maintaining existing forest cover and biodiversity enrichment by planting native trees species (figure 13).

The Forest Legacy program seeks to identify and preserve ecologically, historically, and culturally important forested land, either by outright purchase or through conservation easements. Priority tracts were identified by the Forest Stewardship Coordinating Committee after public meetings discussions with natural resource professionals through an Assessment of Need process. The main priority area is in northwest St. Croix due to its rich biodiversity and cultural significance as a Maroon (runaway slave) area. To date, several properties have been purchased through the Legacy Program totaling 215 ac (87 ha), with plans to someday create a territorial park.

The Urban and Community Forestry Program (U&CFP) offers opportunities to provide and enhance the islands' urban forests by providing small grants to organizations interested in projects related to tree planting, tree preservation, educational workshops, skills trainings, and inventory. The U&CFP recently partnered with a homeowner's association to transform a former empty lot dump site into a beautiful community park with many native tree species (figure 14). The program also funded a project that installed permeable pavement in a downtown area to mitigate storm water runoff and preserve historic mahogany trees. U&CFP also sponsored a survey of trees on the public roads of St. Croix. More than 9,000 trees were inventoried and assessed for health by Geographic Consulting, LLC. Based on these data, species lists and protocols were developed for installation of roadside and urban trees. The protocols were adopted by multiple government and nonprofit organizations, and posters with these Urban Forestry Best Management Practices (BMPs) were printed and distributed. Additionally, demonstration tree-planting projects using these BMPs were completed in high-visibility sites including main roads and in front of the airport of St. Croix. It should also be mentioned that the Virgin Islands Department of Agriculture Forestry Division is working on nursery renovations to meet the demand for native shade and fruit trees for various planting projects and for the public.

Figure 14. Through the urban and community forestry program, an empty lot was transformed into a beautiful park. (Photos by Michael Morgan, 2016)

Since 2007, most tree planting on St. Croix has been performed by Geographic Consulting, LLC, an environmental-consulting service on USVI comprised of a diverse team of natural resources specialists, scientists, and field staff. Some of their projects have been ecological restoration work at Salt River National Historic Site Territorial Park where they planted 750 trees in 2007 with a 60-percent survival rate. In 2017, Geographic Consulting, LLC, is preparing for additional planting projects with the National Park Service at Salt River National Historic site and Buck Island National Monument.

In 2013, fieldwork began on a court-ordered restoration of a site that previously processed bauxite into alumina. A by-product of the process was a phytotoxic red mud, which occupied hundreds of acres along the south shore of St. Croix. The red mud is very resistant to either natural or assisted revegetation. To determine the best way to revegetate the site, Geographic Consulting, LLC, established greenhouse and field trials upon the red mud with various plant species and soil amendments. The revegetation plan called for 3,000 plants from 16 native taxa of trees, shrubs, and vines. The majority of 3,000 plants were in 3-gal (11.4-L) pots and were installed using an 18-in (46-cm) hydraulic auger mounted on a skid steer loader. The third and final stage of the revegetation planting was completed in March 2016.

Other tree planting projects on St. Croix have included the planting of 28 individuals of the federally endangered shrub *Buxus vahlii* (Baillon) at the Sandy Point NWR (figure 15) by the U.S. Fish

Figure 15. Seedlings of the federally endangered shrub *Buxus vahlii* (Baillon) have been planted at the Sandy Point National Wildlife Refuge on St. Croix. (Photo by Michael Morgan, 2017)

September 2017 Hurricane Effects

The U.S. Virgin Islands (USVI) were devastated by two Category 5 hurricanes in September 2017. Hurricane Irma struck St. Thomas and St. John on September 6, and Hurricane Maria struck St. Croix on September 19.

Hurricane Irma's winds were clocked at 185 mph (160 knots) for a 24-hour period, resulting in trees being stripped bare of leaves, being knocked down, or having broken branches. Even the grass turned brown because of the wind. At least 5 people were killed or died of hurricane-induced causes. Many buildings were destroyed or damaged. More than 5 weeks after Irma struck St. John, the island was still completely without power.

Hurricane Maria struck in the evening, dumping heavy rain until after 6 a.m. the next morning. There appeared to be localized down bursts and small tornados with the hurricane. No one was killed, but most houses received some damage. There were branches and downed trees everywhere. Unlike Hurricane Irma's effects on St. Thomas and St. John, however, plants below 10 ft (3 m) tall, especially palm trees, kept their leaves, and the grass remained green.

The hurricanes have had a significant impact on USVI forests. The tree nurseries at the Virgin Islands Department of Agriculture and at the University of the Virgin Islands Agricultural Experiment Station were completely destroyed. On a positive note, however, most of the tree seedlings inside these greenhouses survived. Once roadsides, public spaces, and yards are cleared, replanting can begin. Ideally, the right seedlings will be planted in the right places. For example, large trees will not be planted directly under powerlines. In this regard, the hurricanes may have provided an opportunity to improve future forests and landscapes.

and Wildlife Service, the University of the Virgin Islands Agroforestry program, and Geographic Consulting LLC in December 2015. In addition, 72 seedlings of other native species were planted with the Buxus. In 2017, 17 more Buxus plants were planted at Sandy Point NWR at a new site within the Sandy Point NWR. As of the time this article was written, the Buxus shrubs are still alive.

The University of the Virgin Islands Agricultural Experiment Station (UVI-AES) has had an agroforestry program since 1997 that specializes in developing protocols for the production of native tree species, especially those suitable for use in landscape plantings. Thus far, five fact sheets have been published, and five more are ready to be published in the near future.

Three research UVI-AES articles about Virgin Islands-native trees work have been published in *Tree Planters' Notes*. Two articles discuss germination for seeds of *Bursera graveolens* (Kunth) Triana and Planch (Morgan and Jose 2013) and *Bursera simaruba* (L.) Sarg. (Morgan and Zimmerman 2016), and the other describes results of an experiment about drought tolerance of five Caribbean tree species (Morgan and Zimmerman 2014). Tree seedlings produced in this program are not wasted. Some are planted out in the UVI-AES agroforestry plot as future seed sources, and the excess is donated to ecological restoration projects or other public groups.

The current demand for tree planting and the local production of planting material exists because society sees a need for ecological restoration projects and landscape plantings in public spaces as the islands become more urban. Trees tend to be grown in 3-gal pots or larger because most plantings are for the landscaping of public spaces or small ecological restoration projects. Areas to be planted tend to be measured in square yards and not acres. In spite of this demand, local native plant nurseries have trouble being sustainable. Sales and projects are small and infrequent. Transport of planting stock among islands is difficult if not impossible and may not be ecologically desirable. Other so-called nurseries and garden centers sell plants, but these businesses are really just points of resale for plants produced outside of the USVI.

Looking Forward

The values of the USVI society are changing and are putting increased emphasis on biodiversity and ecological restoration. Since the USVI continue to become more urbanized, both public and private spaces will see an increased need for landscape plantings incorporating native trees. Currently, a tree ordinance in draft form is in the USVI legislature; once passed, the law will protect historically cultural and heritage trees throughout the territory. Much potential exists for continued outreach and education on planting native species and proper pruning techniques or tree maintenance through public workshops and educational events. In addition, abandoned industrial sites are in need of ecological restoration and will also need trees and shrubs for revegetation. Planting trees and shrubs on disturbed sites reduces the amount of soil sediment that flows into the Caribbean Sea. This, in turn, protects coral reefs, which provide valuable ecological services and also make the USVI an important destination for dive tourism. Hopefully, the increased need for the ecological and aesthetic services of trees will result in increased demand for nursery-grown planting stock.

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Root Growth Potential of Loblolly Pine Seedlings After Defoliation To Mimic Browsing Damage

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Abstract

Defoliation of recently planted pine seedlings by mammalian herbivores and insects can hinder seedling establishment. The extent of browsing damage is often reported using aboveground tissue assessments. The effect on root growth belowground from the removal of photosynthetic tissue, however, may also contribute to poor seedling establishment and growth. Loblolly pine (*Pinus taeda* L.) seedlings were subjected to five defoliation treatments to mimic a range of browsing damage. Their root systems were then suspended in aerated aquariums for 28 days to determine root growth potential (RGP) and root-collar diameter (RCD) growth. Removing all foliage resulted in very low RGP and negative RCD growth. Removal of the bottom half, top half, and side foliage from seedlings resulted in some root production but significantly less than seedlings with no foliage removed. This study demonstrates the need for current photosynthate to support root development and also shows the potential growth and vigor reductions depending on browsing severity.

Introduction

In areas of the South where cattle ranged in proximity to pine (*Pinus* sp.) seedling outplanting sites, foraging and trampling were an issue for seedling growth and survival (Boyer 1967). Today, with less impact from free-ranging cattle, pine seedling growth and survival are often affected by herbivore browsing, such as by deer (*Odocoileus* sp.) (Burney and Jacobs 2010) and rabbits (Leporidae family) (Burns 1961). In many cases, even insects such as the pine sawfly (*Neodiprion* sp.), for example, can severely defoliate seedlings after outplanting (Raffa et al. 1998). Seedling damage can range from partial browsing of the foliage and branches to a complete removal of the shoot (stem, branches, and foliage) near the ground. Such damage could cause seedling mortality or the seedling to be stunted in growth after the shoot is able to somewhat recover and grow new flushes of foliage. As a result, the return on investment that was initially calculated for a reforested site may be reduced if seedlings require re-planting or become of less merchantable quality. Graham et al. (2010) recommend being strategic when re-foresting an area by considering the land use of animals to minimize the potential of seedling damage.

Shelton and Cain (2002) evaluated the response of 1-year-old loblolly pine (*Pinus taeda* L.) seedlings to simulated browsing and reported that when clipped below the cotyledon, all seedlings in the trial died because of the lack of a dormant bud. In the same trial, when loblolly pine seedlings were clipped above the cotyledons in February (dormant season) and in April, seedling survival was above 95 percent and height growth was good at both clipping times, especially in the dormant season clipping (Shelton and Cain 2002). In another trial, when 50 percent or 75 percent of the terminal shoot was removed from western redcedar (Thuja plicata Donn.), Douglas-fir (*Pseudotsuga menziesii* (Mirb.) Franco), and western hemlock (*Tsuga heterophylla* (Raf.) Sarg.) seedlings, controlled-release fertilizer applications assisted in the initiation of height growth and recovery from the damage (Burney and Jacobs 2010).

Seedling outplanting success and subsequent recovery from browse damage is often assessed using aboveground responses such as height growth. Another important factor to outplanting success is a seedling's ability to produce new roots immediately following outplanting or browse damage to enable access to water and nutrients in the soil. Nursery managers try to produce seedlings with large, fibrous root systems to give seedlings the best chance for survival after outplanting. The larger root systems are thought to establish the seedling more rapidly by exploring a larger volume of soil for resources while utilizing stored photosynthates (carbohydrate molecules produced from photosynthesis that are transported throughout the plant) to build new root tissue. However, larger root systems do not always translate to better survival, as seedlings are dependent, not as much on stored photosynthates in the roots, but on the amount of new photosynthates produced in the existing foliage (Larsen et al. 1989). Seedlings that have endured defoliation by insects and mammalian herbivores may have reduced photosynthetic capacity, and subsequently, a reduced ability to produce new roots.

Seedling root growth potential (RGP) is a measure of new root growth when a seedling is placed in a favorable environment to produce new roots. This measure may give some indication of seedling vigor and potential performance after outplanting and is often used to evaluate nursery treatments or to compare genetic quality (Ritchie and Dunlap 1980). The objective of this trial was to determine the RGP of loblolly pine seedlings after foliage was removed from the main stem to simulate a range of indiscriminate browsing. The null hypothesis of the trial was that foliar removal would have no effect on new root production when placed in a hydroponic system for 28 days.

Materials and Methods

Bareroot loblolly pine seedlings from a half-sib source were grown under standard operational practices at the Louisiana State nursery (Columbia, LA), lifted in February 2014, and placed in cooler storage at Louisiana Tech University (Ruston, LA) on February 21. On February 27, seedlings were subjected to five defoliation treatments designed to mimic browsing damage: (1) complete removal of all needles, (2) removal of the top 50 percent of needles along the main stem, (3) removal of the bottom 50 percent of needles along the main stem, (4) removal of 100 percent of needles along one side of the main stem, and (5) no defoliation (control) (figure 1). No woody tissue was removed in any of the treatments.

Immediately following defoliation treatments, loblolly pine seedlings were randomized and placed in aerated 10-gal (37.9-L) aquariums and covered with a wooden top that enabled seedling roots to be suspended in water (hydroponic system) (figure 2). Prior to the study, the aquariums were spray-painted black to prevent light penetration and algal growth. Each of the 14 aquariums (experimental units) held 24 seedlings with a total of 336 seedlings in the trial. Four seedlings per treatment were represented in each aquarium, with the exception of the side removal treatment, which had eight seedlings per aquarium. The aquariums were arranged in a randomized complete block design on two greenhouse benches.

Figure 1. The defoliation treatments in this study consisted of: (a) complete removal of foliage, (b) top 50 percent of foliage removed, (c) bottom 50 percent of foliage removed, (d) one complete side of foliage removed, and (e) no foliage removed (control). (Photos by Paul Jackson, 2014)

Seedlings were measured after 28 days in the hydroponic system. The number of new white roots greater than 0.25 in (0.63 cm) was counted on each seedling to quantify RGP (figures 3 and 4). In addition, the root-collar diameter (RCD) of each seedling was measured before being placed in the aquariums and again after the 28-day period to determine growth. Analysis of variance was conducted using a General Linear Model and multiple comparisons of means were conducted using Duncan's Multiple Range Test using statistical analysis software (9th ed., SAS Institute, Cary, NC).

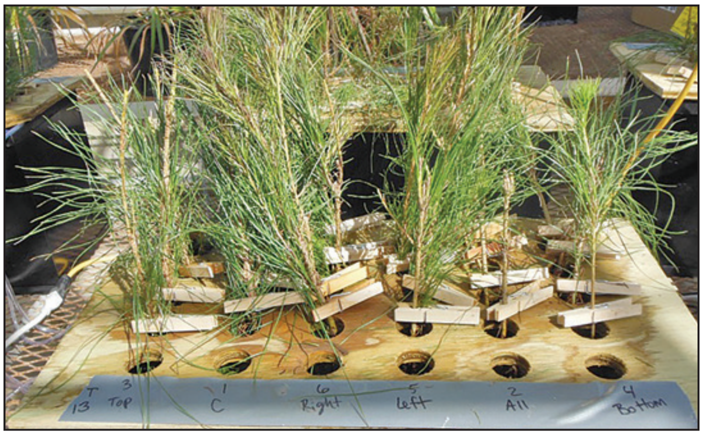

Figure 2. Seedlings from all six defoliation treatments were kept in a hydroponic system for 28 days. (Photo by Paul Jackson, 2014)

Results and Discussion

Root Growth Potential

Root production was significantly influenced by foliar removal treatments to mimic browse damage (figure 5). Removing all of the needles from the seedlings resulted in very low RGP, with a total of 19 new roots produced from all 56 seedlings combined. Removing needles from the top half, bottom half, and the side of seedlings resulted in significantly lower RGP compared with control seedlings (figure 5).

New root growth immediately following outplanting encourages more rapid uptake of water and nutrients, which in turn, increases seedling field establishment (Ritchie and Dunlap 1980). In this trial, very few new roots were produced when all foliage was removed from seedlings. Our findings are similar to those with longleaf pine (*Pinus palustris* Mill.), in which no new roots were produced when all foliage was removed, and intermediate root growth was observed with various amounts of foliage removed (South et al. 2011).

Figure 3. To determine root growth potential in each treatment, new white roots were counted after 28 days in the hydroponic system. (Photo by Paul Jackson, 2014)

Figure 4. An example of new white root growth after 28 days in the hydroponic system. (Photo by Paul Jackson, 2014)

These results confirm that southern pines rely on photosynthetic activity from current foliage to produce root tissue. The fact that any roots were produced at all in the absence of green foliage could be attributed to the woody portions of the stem and young branches remaining intact on the seedlings. The woody tissue may have provided enough stored photosynthates to generate the 19 roots counted on 11 of the 56 seedlings subjected to 100 percent foliar removal.

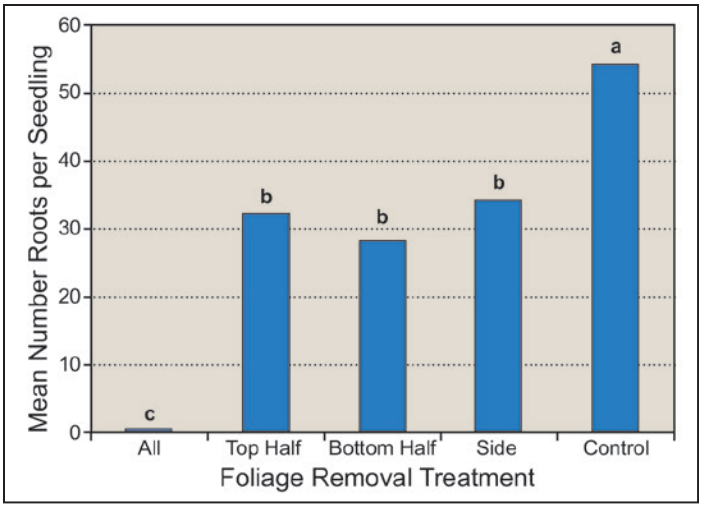

Figure 5. Mean number of new white roots (root growth potential) on loblolly pine seedlings subjected to varying levels of foliage removal to mimic browsing damage after 28 days in a hydroponic system. Means with the same letter are not significantly different based on Duncan's Multiple Range Test. Least significant difference = 16 roots; P > F = 0.0001.

Root-Collar Diameter

Removal of foliage from the entire seedling, the top half, or the bottom half resulted in significantly less RCD growth compared to the control seedlings (figure 6, table 1). In fact, the RCD growth of seedlings subjected to complete foliage removal was negative (figure 6, table 1). This may be the first report of loblolly pine RCD shrinking in a hydroponic RGP trial. Slash pine has exhibited similar RCD shrinkage in a hydroponic trial after being inoculated with the water mold *Pythium* then subjected to 3 weeks of cold storage (Jackson et al. 2012). Barnett (1984) reported a reduction in RCD 1 year after outplanting with container-grown longleaf pine seedlings that were clipped to 5 cm (1.9 in) in the nursery. Without foliage available to carry out photosynthesis, it appears that RCD growth, along with RGP, will be compromised in cases where severe browsing results in total foliar loss. The top and bottom half defoliation treatments also had reductions in RCD compared to control seedlings. This type of browsing damage could directly impact estimated economic gains for a reforested site, as a larger RCD has been correlated to more growth in the field (South et al. 1985).

Future Research Direction and Considerations

The defoliation treatments in this trial were intended to mimic indiscriminate browsing by herbivores and possible removal by insect populations. That is why treatments involving the removal of the top half, bottom half, and side foliage were used in this trial. Researchers that investigate effects from defoliating seedlings usually do so with removal of some percentage of the main stem, moving from the terminal bud downward to the hypocotyl area of the stem, as seen with loblolly pine (Shelton and Cain 2002; South 1998). Therefore, future trials that intend to mimic browsing and test RGP may consider also removing the woody portions in some way, as browsing from animals such as deer could sever the entire stem at the ground level to halfway up the seedling. Many different types of wildlife have a number of different browsing habits.

Table 1. Mean root-collar diameter of loblolly pine seedlings when placed in the hydroponic system (Day 1) and when removed from the hydroponic system (Day 28). Growth differences are shown in figure 6.

Foliage removal treatment	Root-collar diameter (mm)	
	Day 1	Day 28
None (control)	4.81	5.11
100 percent	4.97	4.88
Top 50 percent	5.08	5.09
Bottom 50 percent	4.26	4.35
Side removed	4.94	5.11

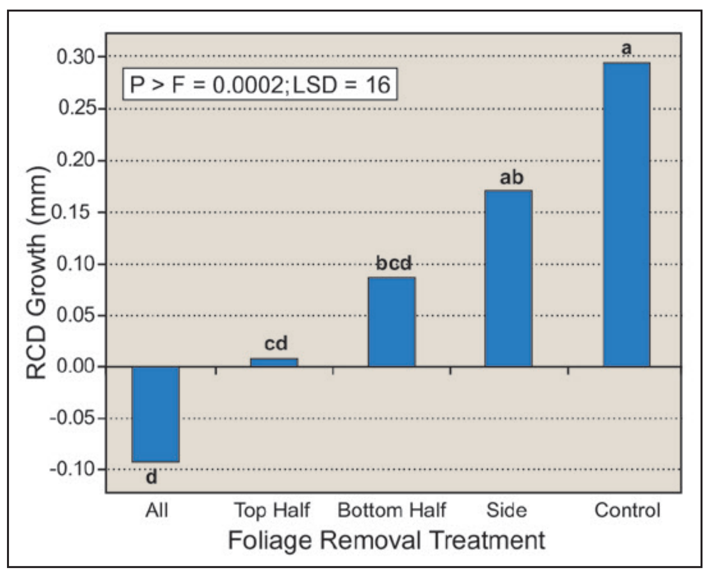

Figure 6 . Mean root-collar diameter growth of loblolly pine seedlings subjected to varying levels of foliage removal to mimic browsing damage after 28 days in a hydroponic system. Means with the same letter are not significantly different based on Duncan's Multiple Range Test. Least significant difference = 0.16 mm; P > F = 0.0002.

It is clear that the amount of foliage present to photosynthesize can determine seedling RGP after outplanting. The location of foliar removal may not serve as a determinant of how seedling RGP or RCD respond. With full foliar removal, however, seedling vigor is severely compromised and can result in no RGP or RCD growth. Seedling response to browsing damage is hard to estimate without testing a range of species, genetic qualities, defoliation treatments, seedling sizes, and outplanting sites. Seedling responses also hinge on seedling quality, which encompass all of these aforementioned factors.

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Forest Nursery Seedling Production in the United States—Fiscal Year 2016

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Abstract

Forest nursery production for the 2016 planting season was more than 1.2 billion forest tree seedlings, with nearly 2.5 million ac (1 million ha) of trees planted. The majority of production and planting (82 percent) occurred in the Southern States. Approximately 75 percent of outplanted trees are bareroot stock.

Background

This annual report summarizes forest nursery seedling production in the United States. The number of seedlings reported is used to estimate the number of acres of forest planting per year. Prepared by the U.S.Department of Agriculture (USDA), Forest Service, Forest Inventory and Analysis (FIA) and State and Private Forestry (S&PF), this report includes State-by-State breakdowns, regional totals, and an analysis of data trends. Universities located in the southern, northeast, and western regions of the United States made an effort to collect data from all the major producers of forest and conservation seedlings in the 50 States. Forest and conservation nursery managers provided the information presented in this report. As far as we know, it is the most complete compilation of such data in the country. Because all data are provided voluntarily by outside sources, and some data are estimated, however, caution must be used in drawing inferences.

Methodology

The empirical data for this report were produced by S&PF in collaboration with Auburn University, the University of Idaho, and Purdue University. All of these universities collected forest tree seedling production data directly from the forest and conservation nurseries that grow forest tree seedlings in their region of the United States. Auburn University collected from 13 States in the Southeast, the University of Idaho collected from 17 States in the West, and Purdue University collected from 21 States in the Northeast and Midwest. The approximation of planted acres for each State is derived from FIA estimates of tree-planting area based on ground plots collected by States during 5-, 7-, or 10-year periods and compiled as an average annual estimate for the associated period. FIA estimates of acres of trees planted by State may not correlate with the estimates produced by nursery production surveys because nurseries do not report shipments across State lines. Total acres by region, however, provide a reasonable comparison between the two methods. Data collected are reported by hardwood and conifer seedlings produced and acreage planted of each (table 1) and by bareroot and container seedlings produced (table 2). A complete list of the assumptions used in compiling this report appear in the *Forest Nursery Seedling Production in the United States—Fiscal Year 2013* (Harper et. al. 2014).

Table 1. Hardwood and conifer tree seedling production and acres planted for each State and each region during the 2015-2016 planting year.

State	Hardwood seedlings produced	Hardwood acres planted[1]	Conifer seedlings produced	Canadian conifer imports	Conifer acres planted[1]	Total seedlings produced	Total acres planted[1]	FIA data acres planted[10]
Southeast								
Florida[2]	3,023,129	5,497	57,415,000	—	104,391	60,438,129	109,888	152,359
Georgia[2]	4,595,369	8,355	330,238,125	—	600,433	334,833,494	608,788	239,619
North Carolina[2]	506,650	921	65,331,000	—	118,784	65,837,650	119,705	99,215
South Carolina[2]	1,061,880	1,931	138,241,398	—	251,348	139,303,278	253,279	76,808
Virginia[2]	838,000	1,524	30,202,000	—	54,913	31,040,000	56,436	74,872
Regional Totals	**10,025,028**	**18,227**	**621,427,523**	**0**	**1,129,868**	**631,452,551**	**1,148,096**	**642,873**
South Central								
Alabama[2]	101,624	185	115,900,035	—	210,727	116,001,659	210,912	223,021
Arkansas[2]	9,186,275	16,702	89,632,550	—	162,968	98,818,825	179,671	117,744
Kentucky[3]	540,000	1,241	20,000	—	45.98	560,000	1,287	1,155
Lousiana[2]	—	—	23,735,000	—	43,155	23,735,000	43,155	160,801
Mississippi[2]	1,012,734	1,841	83,035,100	—	150,973	84,047,834	152,814	178,998
Oklahoma[2]	454,275	826	858,250	—	1,560	1,312,525	2,386	21,521
Tennessee[2]	2,302,000	4,185	5,136,000	—	9,338	7,438,000	13,524	28,005
Texas[2]	28,175	51	71,699,800	—	130,363	71,727,975	130,415	262,584
Regional Totals	**13,625,083**	**32,589**	**390,016,735**	**0**	**709,131**	**403,641,818**	**734,163**	**993,829**
Northeast								
Connecticut	—	—	—	—	—	—	—	—
Delaware	—	—	—	—	—	—	—	647
Maine[5,9]	—	—	—	13,500,000	22,500	13,500,000	22,500	8,168
Maryland[2]	651,375	1,184	1,333,609	—	2,425	1,984,984	3,609	1,445
Massachusetts	—	—	—	—	—	—	—	—
New Hampshire[3]	17,200	40	79,600	—	183	96,800	223	—
New Jersey[3]	472,710	1,087	95,650	—	220	568,360	1,307	—
New York[5]	209,000	348	751,500	—	1,253	960,500	1,601	—
Pennsylvania[3]	2,621,419	6,026	3,402,720	—	7,822	6,024,139	13,849	2680
Rhode Island	—	—	—	—	—	—	—	—
Vermont[3]	51,000	117	500	—	—	—	—	—
West Virginia[3]	394,00	906	47,000	—	329	664,375	1527	870
Regional Totals	**4,416,704**	**9,708**	**5,710,579**	**13,500,000**	**34,512**	**23,627,283**	**44,220**	**13,810**
North Central								
Illinois[3]	961,610	2,211	170,700	—	392	1,132,310	2,603	2,498
Indiana[4]	2,812,000	4,326	1,137,000	—	1,749	3,949,000	6,075	1,753
Iowa[5]	657,319	1,096	197,255	—	329	854,574	1,424	621
Michigan[2]	3,661,265	6,657	14,375,255	—	26,137	18,036,520	32,794	9,467
Minnesota[2,9]	431,571	785	4,931,077	8,365,000	24,175	13,727,648	24,959	17,470
Missouri[3]	4,536,714	10,429	1,497,000	—	3,441	6,033,714	13,871	—
Ohio[3]	8,800	20	20	—	—	8,800	20	3,018
Wisconsin[6]	984,200	1,230	6,330,958	—	4,951	4,944,781	6,181	10,459
Regional Totals	**14,053,479**	**26,754**	**26,268,868**	**8,365,000**	**61,174**	**48,687,347**	**87,928**	**45,286**

State	Hardwood seedlings produced	Hardwood acres planted[1]	Conifer seedlings produced	Canadian conifer imports	Conifer acres planted[1]	Total seedlings produced	Total acres planted[1]	FIA data acres planted[10]
Great Plains								
Kansas[2]	8,475	15	35,150	—	64	43,625	79	—
Nebraska[2]	516,697	939	1,376,067	—	2,502	1,892,764	3,441	1182
North Dakota[2]	17,234	31	832,220	—	1,513	849,454	1,544	—
South Dakota[2]	755,233	1,373	398,295	—	724	1,153,528	2,097	—
Regional Totals	**1,297,639**	**2,359**	**2,641,732**	**0**	**4,803**	**3,939,371**	**7,162**	**0**
Intermountain								
Arizona[2]	500	1	—	—	—	500	1	597
Colorado[2]	344,999	627	263,345	—	479	608,344	1,106	—
Idaho[2]	9,075,607	16,501	5,207,297	800,000	10,922	15,082,904	27,423	7108
Montana[2]	145,427	264	603,196	—	1,097	748,623	1,361	8082
Nevada[2]	10,845	20	3,183	—	6	14,028	26	—
New Mexico[2]	20,301	37	122,346	—	222	142,647	259	872
Utah[2]	605,425	1,101	215,820	—	392	821,245	1,493	—
Wyoming	—	—	—	—	—	—	—	997
Regional Totals	**10,203,104**	**18,551**	**6,415,187**	**800,000**	**16,465**	**17,418,291**	**31,670**	**17,656**
Alaska								
Alaska[2]	7500	14	4,250	10,000	26	21,750	40	—
Pacific Northwest								
Oregon[7,9]	4,679,470	13,370	45,888,630	2,834,000	139,208	53,402,100	152,577	133,374
Washington[7,9]	724,031	2,069	52,566,885	76,000	150,408	53,366,916	152,477	97,872
Regional Totals	**5,403,501**	**15,439**	**98,455,515**	**2,910,000**	**289,616**	**106,769,016**	**305,054**	**231,246**
Pacific Southwest								
California[8]	109,675	244	24,225,500	—	53,834	24,335,175	54,078	33,657
Hawaii[8]	125,462	279	198,012	—	440	323,474	719	—
Regional Totals	**235,137**	**523**	**24,423,512**	**0**	**54,274**	**24,658,649**	**54,797**	**33,657**
Totals	**59,267,175**	**116,607**	**1,175,363,901**	**25,585,000**	**2,296,523**	**1,260,216,076**	**2,413,129**	**1,978,357**

[1] Acres planted were estimated assuming:

[2] 550 stems/acre

[3] 435 stems/acre

[4] 650 stems/acre

[5] 600 stems/acre

[6] 800 stems/acre

[7] 350 stems/acre

[8] 450 stems/acre

[9] Totals include an estimate of conifers produced in Canada for distribution to neighboring States; bareroot imports for Maine and containers for other States.

[10] FIA = Forest Inventory and Analysis; average annual acreage planted estimated for all States (2017) on 5-year cycles, except for Alabama, Louisiana, Mississippi, and North Carolina, which are on 7-year cycles, and for Alaska, Arizona, California, Colorado, Idaho, Montana, Nevada, New Mexico, Oregon, and Washington, which are on 10-year cycles. Data generated by Andy Hartsell, USDA Forest Service.

Table 2. Bareroot and container tree seedling production for each State and each region during the 2015-2016 planting year.

State	Bareroot	Container[1]	Total Seedlings Produced
Southeast			
Florida	52,566,263	7,871,866	60,438,129
Georgia	190,526,822	144,306,672	334,833,494
North Carolina	52,460,000	13,377,650	65,837,650
South Carolina	138,920,008	383,270	139,303,278
Virginia	31,038,000	2,000	31,040,000
Regional Totals	**465,511,093**	**165,941,458**	**631,452,551**
South Central			
Alabama	109,012,259	6,989,400	116,001,659
Arkansas	98,818,825	—	98,818,825
Kentucky	560,000	—	560,000
Louisiana	—	23,735,000	23,735,000
Mississippi	74,947,834	9,100,000	84,047,834
Oklahoma	1,281,025	31,500	1,312,525
Tennessee	7,438,000	—	7,438,000
Texas	71,727,975	—	71,727,975
Regional Totals	**363,785,918**	**39,855,900**	**403,641,818**
Northeast			
Connecticut	—	—	—
Delaware	—	—	—
Maine[5,9]	—	13,500,000	13,500,000
Maryland	1,926,484	58,500	1,984,984
Massachusetts	-	—	-
New Hampshire	96,800	—	96,800
New Jersey	193,360	375,000	568,360
New York	902,500	58,000	960,500
Pennsylvania	6,016,239	7,900	6,024,139
Rhode Island	—	—	—
Vermont	—	1,000	51,500
West Virginia	50,500	—	441,000
Regional Totals	**9,626,883**	**14,000,400**	**23,627,283**
North Central			
Illinois	1,130,000	2,310	1,132,310
Indiana	3,799,000	150,000	3,949,000
Iowa	854,574	—	854,574
Michigan	17,684,750	351,770	18,036,520
Minnesota	4,546,648	9,181,000	13,727,648
Missouri	4,533,714	1,500,000	6,033,714
Ohio	—	8,800	8,800
Wisconsin	4,891,581	53,200	4,944,781
Regional Totals	**37,440,267**	**11,247,080**	**48,687,347**
Great Plains			
Kansas	43,625	—	43,625
North Dakota	1,082,692	810,072	1,892,764
Nebraska	766,146	83,308	849,454
South Dakota	1,145,746	7,782	1,153,528
Regional Totals	**3,038,209**	**901,162**	**3,939,371**
Intermountain			
Arizona	—	500	500
Colarado	174,483	433,861	608,344
Idaho	5,188,783	9,894,121	15,082,904
Montana	103,080	645,543	748,623
New Mexico	—	14,028	14,028
Nevada	20,000	122,647	142,647
Utah	—	821,245	821,245
Wyoming	—	—	—
Regional Totals	**5,486,346**	**11,931,945**	**17,418,291**
Alaska			
Alaska	—	21,750	21,750
Pacific Northwest			
Oregon	18,176,080	35,226,020	53,402,100
Washington	33,277,585	20,089,331	53,366,916
Regional Totals	**51,453,665**	**55,315,351**	**106,769,016**
Pacific Southwest			
California	700,000	23,635,175	24,335,175
Hawaii	90,554	232,920	323,474
Regional Totals	**790,554**	**23,868,095**	**24,658,649**
Totals	**937,132,935**	**323,083,141**	**1,260,216,076**

[1] Alaska, Idaho, Maine, Michigan, Minnesota, Oregon, and Washington received container seedlings produced in Canada.

Data Trends

An estimated total of 1,260,216,076 forest tree seedlings were shipped from forest and conservation nurseries in the United States in FY 2016, a decrease of 3 percent compared with seedling production reported for FY 2015 (Hernández et al. 2016). Based on the total number of seedlings shipped and the average number of seedlings planted per acre in each State, an estimated 2,413,129 ac (976,559 ha) of trees were planted during the planting season from fall 2015 through spring 2016. Although seedling production decreased, acreage planted increased 3 percent compared with the number of acres reported for the previous planting season (Hernández et al. 2016); this increase is attributed to the varying plant densities used in each State.

Table 3. Total forest nursery seedling production, including region, by year, from FY 2012 through FY 2015.

Year	Total seedling production	West	East	South
FY 2016	1,260,216,076	152,785,327	72,314,630	1,035,094,369
FY 2015	1,302,237,795	175,464,446	95,417,986	1,031,355,363
FY 2014	1,217,607,888	115,620,820	85,684,417	1,015,564,370
FY 2013	1,181,554,535	96,344,063	102,066,671	983,143,801
FY 2012	1,190,552,819	170,975,830	81,672,547	936,918,542

FY = fiscal year.
Sources: This report, Harper et al. (2013, 2014), and Hernández et al. (2015, 2016).

Trends by regions (table 3) are as follows:

West—The 17 States in the USDA Forest Service western regions produced more than 150 million seedlings (12 percent of the U.S. total), a decrease from the previous season.

East—The 20 States in the USDA Forest Service Northeastern Area reported more than 72 million seedlings (6 percent of the U.S. total), a decrease compared with the previous four planting seasons.

South—The 13 States in the USDA Forest Service Southern Region produced more than 1 billion forest tree seedlings (82 percent of the U.S. total), an increase of more than 1 million over the FY 2015 planting season.

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Seedling Quality of Southern Pines: Influence of Plant Attributes

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Abstract

Good seedling quality is a part of successful reforestation programs. Nursery managers use various cultural practices (e.g. seedbed density and root pruning for bareroot seedlings; cell density and volume for container seedlings; fertilization, irrigation, and top-pruning for all stock types) to produce southern pine seedlings with desired morphological and physiological attributes. Opinions vary on which of these attributes should be assessed in a seedling quality program. Growers generally agree that seedling height, root-collar diameter, root mass, nutrient status, and shoot/root balance are important, measurable plant attributes. Root growth, drought resistance, and freezing tolerance are also suggested as desirable plant attributes. Appropriate ranges of these attributes increase the probability for successful establishment of southern pine seedlings.

Introduction

The proper application of nursery practices to produce quality seedlings is a key component of successful restoration programs (Grossnickle 2000, Mexal and South 1991). Studies established in the 1930s (Wakeley 1954) were the first to define desirable morphological parameters with the goal of improving southern pine plantation establishment. By the mid-20th century, researchers began to critically examine plant morphological and physiological attributes that conferred improved survival and growth (i.e. performance) for bareroot (Duryea 1984; Stone 1955; Wakeley 1948, 1954) and container (Tinus 1974) seedlings. Defining appropriate morphological and physiological attributes is important to ensure successful seedling field performance (Dumroese et al. 2016, Grossnickle 2012, Grossnickle and Folk 1993), which can result in successful plantation establishment (figure 1).

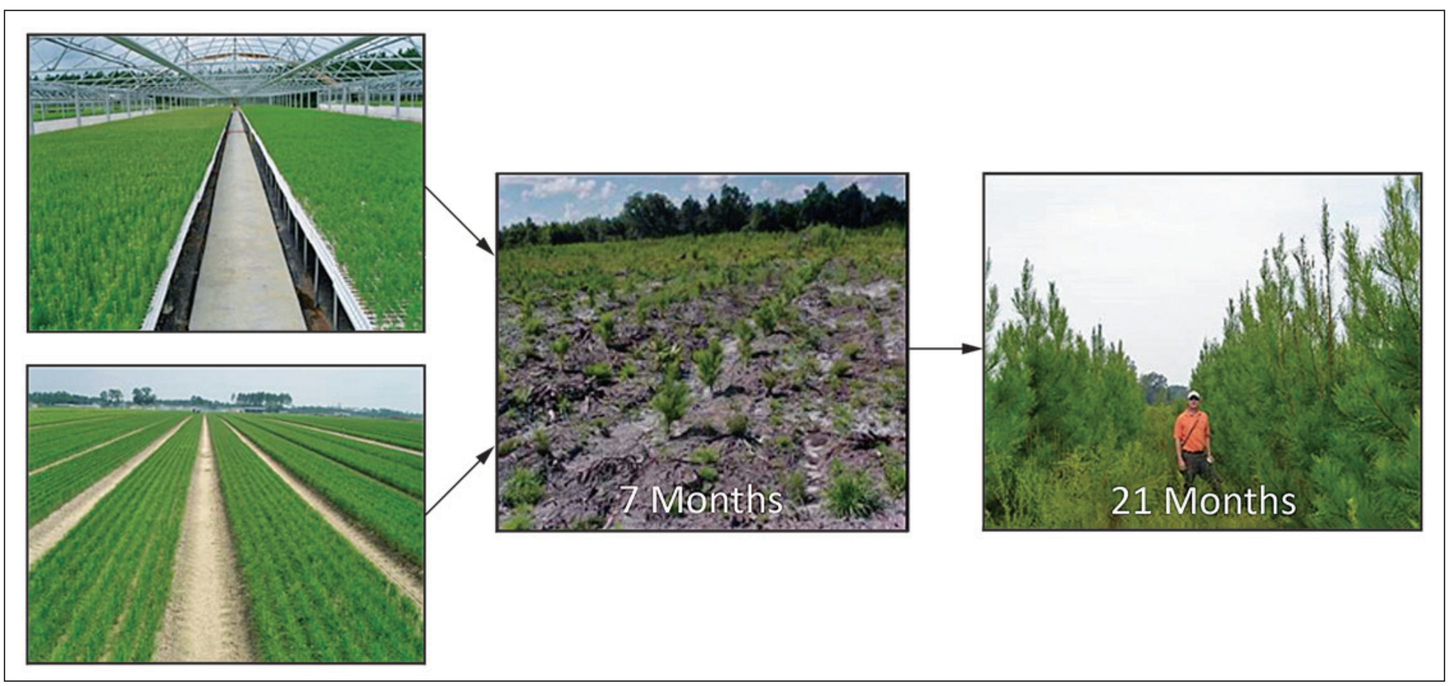

Figure 1. Container-grown and bareroot loblolly pine (*Pinus taeda* L.) stock grown with appropriate cultural practices and assessed to ensure they have desirable morphological and physiological attributes typically have good initial establishment and subsequent growth in forest plantations. (Adapted from Grossnickle 2011)

During 2014–2015, more than 1 billion seedlings were produced in the South, with approximately 80 percent being bareroot and 20 percent being container-grown seedlings (Hernández et al. 2016). In this article, seedling quality of both stock types is discussed based on material attributes of morphology, nutrition, drought resistance, and performance attributes of frost hardiness and root growth potential (attributes defined by Ritchie 1984). An understanding of how bareroot and container-grown southern pine seedlings respond to these attributes would enable practitioners to define their appropriate ranges to improve seedling field performance.

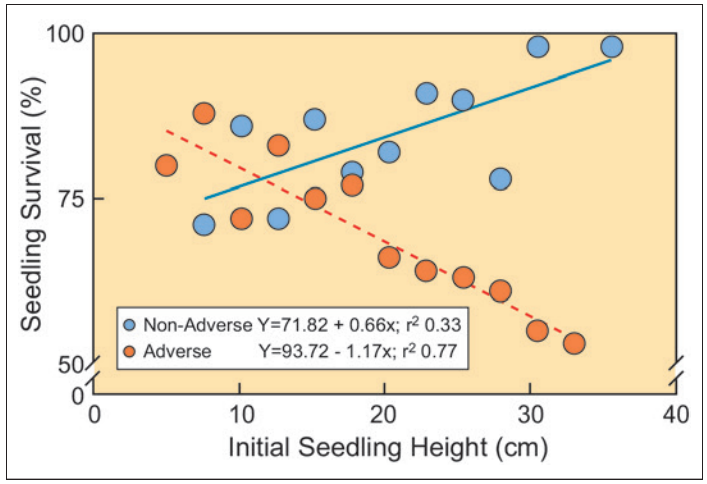

Figure 2. The relationship between survival (year 2) and initial seedling height for bareroot loblolly pine (*Pinus taeda* L.) seedlings differs greatly between adverse sites (i.e., greater temperature extremes and higher vapor pressure deficits) and non-adverse sites (i.e., little environmental stress and extensive competition). (Adapted from Tuttle et al. 1987)

Morphological Attributes

Most morphological attributes are non-destructive, easy to measure, and considered to be reliable measures of seedling quality (Puttonen 1997) because they do not change appreciably from lifting to outplanting (Ritchie et al. 2010). Caution should be used in relying solely on morphological attributes because of interactions involving site factors, container size, handling, and environmental conditions. Morphological attributes measure only overall size and balance, not physiological quality, because they are only a subset of plant attributes required for defining successful seedling establishment of southern pines (Wakeley 1948, 1954). Southern pine seedlings must also have the optimum physiology and vigor for morphological attributes to forecast field performance (Mexal and Landis 1990; Pinto 2011; Wakeley 1948, 1954).

Height

Tall seedlings have been recommended for sites with little environmental stress but with the potential for excessive competition (Haase 2008). Large stock of southern pines will perform well on sites where competition is prevalent (South et al. 1993). This attribute is exhibited by taller bareroot loblolly pine (*Pinus taeda* L.) seedlings at planting, which have higher survival on sites with little environmental stress and extensive competition (figure 2). A height advantage is beneficial on sites with competing vegetation because they can capture more of the site environmental resources (Grossnickle 2005b), allowing them to outgrow competitors (South et al. 1985, 1989, 1993, 2001b, 2015).

Planting taller seedlings on stressful droughty sites can result in lower survival (Boyer and South 1987, Larsen et al. 1986, South et al. 2012, Tuttle et al. 1988). For example, shorter bareroot loblolly pine seedlings had higher survival on sites with limited soil water and greater environmental stress (i.e. greater temperature extremes and higher vapor pressure deficits) (figure 2). Tall seedlings are exposed to greater water stress than smaller seedlings under harsh conditions (Grossnickle 2005b) because root systems cannot supply enough water to transpiring foliage to maintain a proper water balance (Grossnickle 2005a). Thus, shorter seedlings can have an advantage on stressful sites (Grossnickle 2012, Mexal and Landis 1990, South et al. 2012).

Root-Collar Diameter and Root Mass

Seedling root-collar diameter (RCD) is a general measure of seedling sturdiness, root system size, and protection against drought and heat damage (Mexal and Landis 1990). RCD indirectly describes a number of desirable plant attributes (i.e., water absorption—roots, water transport—stem) considered important for ensuring seedling survival during drought (Mexal and Landis 1990). RCD is considered to be the single most useful morphological measure of seedling quality to forecast outplanting performance of southern pines (Johnson and Cline 1991, VanderSchaaf and South 2008). RCD is easily measured at the time of lifting and should be assessed in any southern pine seedling quality program.

RCD is important because it correlates well with root mass (Mexal and South 1991, Rodriguez-Trejo and Duryea 2003, South and Mitchell 1999, South et al. 2015). For example, RCD was related to root volume of both bareroot and container-grown loblolly pine stock types grown in operational nurseries (figure 3a). Studies show that, as root mass increases, seedling survival can increase (Boyer and South 1987, Larsen et al. 1986, South and Mitchell 1999). Greater root system size means a seedling has a greater root absorptive surface for water uptake, providing southern pines seedlings (Carlson and Miller 1990) with the capacity to overcome planting stress (Grossnickle 2005a).

Southern pine seedlings with large RCD have higher survival, e.g. bareroot (Kabrick et al. 2011; Lauer 1987; McGrath and Duryea 1994; South 1993; South and Mexal 1984; South and Mitchell 1999; South et al. 1985, 2001a, 2005b, 2015) and container-grown (Barnett 1988, Haywood et al. 2012, South et al. 2005a) (figure 3b). One should also consider root fibrosity (i.e., fibrous root system with many growing tips) to ensure the reliability of RCD to forecast survival (Hatchell and Muse 1990). Greater root system size also confers greater root growth potential (RGP) in southern pines (South and Mitchell 1999; South et al. 2005b, Sword Sayer 2009). A positive relationship between initial RCD and field growth has been reported for southern pines (McGrath and Duryea 1994, South and Mitchell 1999, South et al. 1989, 2015) (figure 3c and figure 4).

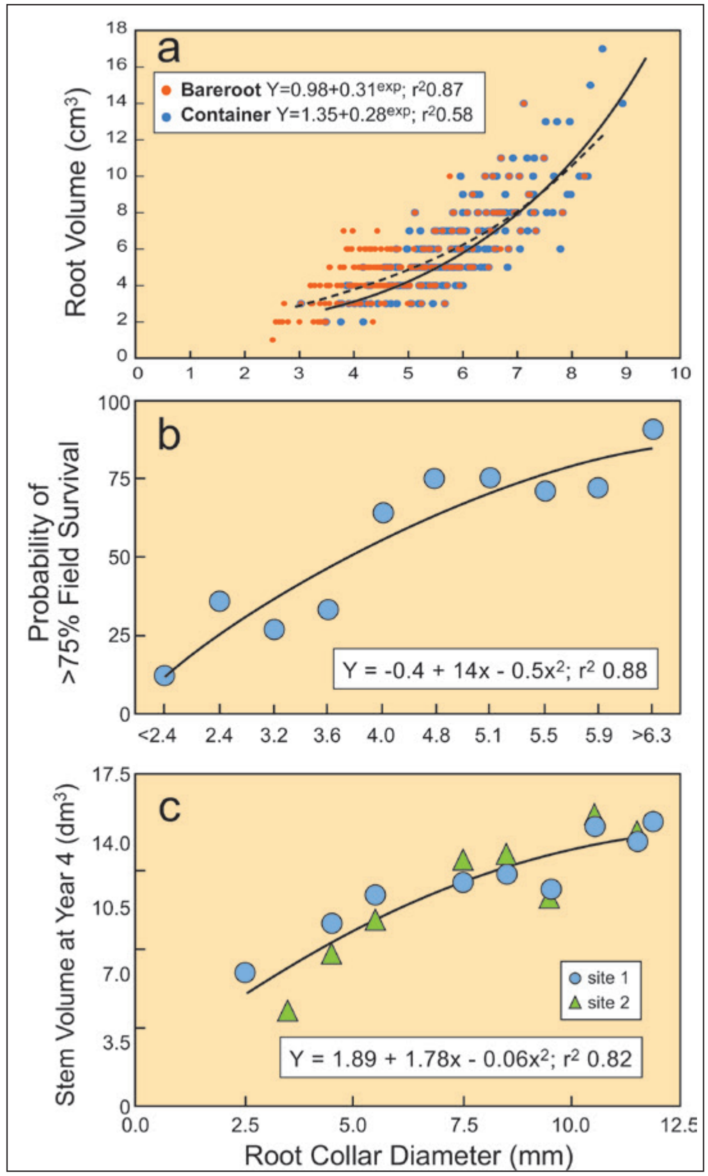

Figure 3. Root-collar diameter affects southern pine field performance including (a) root volume at lift for loblolly pine (*Pinus taeda* L.) in bareroot (----) and container (- - -) nurseries (Grossnickle unpublished); (b) the probability of seedling field survival (>75 percent) for bareroot loblolly pine and slash pine (*Pinus elliottii* Engelm.) seedlings graded into stem-diameter classes (adapted from South et al. 1985); and (c) bareroot loblolly pine stem volume after 4 years on two intensively managed field sites. (Adapted from South et al. 2001a)

Seedling Ratios

A balance between the shoot and root system is considered a desirable attribute for seedling survival (Grossnickle 2012, Grossnickle and Folk 1993, Mexal and South 1991, Puttonen 1997, Ritchie 1984). Views on this attribute's influence on seedling growth are mixed, since some believe that this ratio is not related to field growth (Thompson 1985), whereas others (Close et al. 2005) believe that low shoot-to-root ratio, along with high RGP, are important for maximizing seedling growth. Nonetheless, proper proportionality between shoot and root systems has long been recognized as a desirable plant attribute (Toumey 1916) because water status is directly tied to the shoot-to-root ratio of bareroot (Baldwin and Barney 1976) and container-grown (Grossnickle and Reid 1984) seedlings. Another definition of seedling balance that defines field performance is the root-weight ratio (root dry weight divided by total seedling dry weight) (South 2016). Studies have found that southern pine seedling survival increases as the shoot-to-root ratio decreases (Mexal and Dougherty 1983) or root-weight ratio increases (Larsen et al. 1986, Boyer and South 1987, South and Mitchell 1999). Having a desirable root-weight ratio is one reason managers apply undercutting for bareroot pine seedlings

Figure 4. Slash pine (*Pinus elliottii* Englm.) seedlings were sorted into nine groups (50 seedlings each) by root-collar diameter (RCD). From left to right, the seedling RCD groups are: 2.5, 3.5, 4.5, 5.5, 6.5, 7.5, 8.5, 9.5, and 10.5 mm. Three years after planting, groups to the right of the vertical stick (7.5 to 10.5 mm RCD) had greater survival and grew taller than those to the left of the stick (2.5 to 6.5 mm RCD). (Photo by David South, 1991)

(South and Donald 2002) and top pruning for all stock types (South 1998, South et al. 2011).

Morphological Ideotypes

Morphological standards for southern pine bareroot and container seedling ideotypes have been proposed (table 1). Bareroot ideotype A has all of the morphological attributes that, on average, confer higher survival and growth (Mexal and South 1991). Bareroot ideotype B is preferred by hand planters since seedlings with small roots are relatively easy to transplant, even though subsequent field performance is less than ideotype A. The proposed ideotypes for container-grown seedlings of varying cell volumes are not based on performance trials, but instead were developed from measuring typical seedlings. Stock type standards for shoot development and height-to-diameter ratios are similar for both bareroot and container-grown seedlings. For a given diameter, root volume is typically greater for container-grown stock compared with bareroot stock (South et al. 2016). Greater root mass and fibrosity help explain why survival is usually greater for container-grown seedlings of similar shoot size (Grossnickle and El-Kassaby 2016). The ideotypes listed in table 1 and their associated field performance can be verified with well-designed field tests. Field performance, however, is also dictated by seedling physiology, handling practices, and site environmental conditions.

Physiological Attributes

Field performance is determined, in part, by the ability of seedlings to withstand potentially stressful environmental conditions affecting the establishment

Table 1. Morphological attributes and expected field performance of two bareroot southern pine seedling ideotypes (adapted from Mexal and South 1991) and three container-grown seedling ideotypes (Wayne Bell personal communication and Grossnickle unpublished).

Morphological attributes	Bareroot		Container size (Cell volume)		
	Ideotype A	Ideotype B	94 cm³	122 cm³	152 cm³
Species	*P. taeda* *P. elliottii* *P. echinata*	*P. taeda* *P. elliottii* *P. echinata*	*P. taeda* *P. elliottii*	*P. taeda* *P. elliottii*	*P. palustris*
Median height (mm) or needle length (bold, mm)	150–250	150–300	175–300	200–350	**200–250**
Median root-collar diameter (mm)	> 5.0	> 4.0	3.0–5.5	3.5–6.5	5.0–6.5
Median root volume (cm³)	> 4.0	> 2.0	2.9–5.7	3.4–7.3	4.9–7.3
Height-diameter ratio	< 50	> 50	50–60	50–60	< 8
Expected field 2-year survival (%)	> 90	> 80	> 90	>90	> 80
Expected 4-year field height (m)	> 3	< 3	> 3	> 3	> 1

m = meter. cm = centimeter. mm = millimeter. P. = *Pinus.*

Note: Container cell densities for pines typically range from 525 to 570 m^{-2}.

of forest stands, such as site fertility, water balance, and heat exchange processes (Grossnickle 2000). The following discussion focuses on seedling physiological attributes related to nutrient status, drought resistance, and freezing tolerance of southern pines.

Nutrient Status

Nutrition is considered an important attribute in recent seedling quality discussions (Hawkins 2011, Ritchie et al. 2010); therefore, foliar nutrition standards (Boyer and South 1985) are important for determining southern pine seedling quality. Accumulating seedling nutrient reserves is a significant component of conifer nursery culture (Benzian et al. 1974, Brix and van den Driessche 1974). Some of these nutrient reserves can then be remobilized to improve seedling establishment after planting (Irwin et al. 1998). Increasing nutrient reserves through nursery fertilization is considered efficient, compared with nutrient acquisition on the planting site (Binkley 1986, Tinus 1974). The practice of late-season nitrogen fertilization has been successfully applied in southern nurseries (Irwin 1995; South et al. 2016). According to Dumroese (2003), an ideal fertilization program will achieve a target foliar nitrogen-concentration range of 1.5 to 2.5 percent for adequate nutrient reserves.

Field trials with southern pines found that increased nutrient reserves prior to planting resulted in higher survival rates (Hinesley and Maki 1980, Irwin et al. 1998, South and Donald 2002). van den Driessche (1991) cautioned, however, that increased nutrient reserves do not increase survival under all field situations. For example, when field conditions are such that the survival rate of non-fertilized seedlings is high, one should not expect extra nitrogen to increase survival (Switzer and Nelson 1967). In addition, fertilization might stimulate the growth of *Pythium* in cool storage. These factors could explain why high nitrogen levels reduced the survival rate of bareroot seedlings of various southern pine species that were stored for 6 weeks prior to planting (Rodriguez-Trejo and Duryea 2003, South and Donald 2002).

Seedlings outplanted with increased nutrient reserves typically have greater shoot and root growth (Grossnickle 2012). Longleaf pine (*Pinus palustris* Mill.) with additional nitrogen reserves exhibited increased diameter (Jackson et al. 2007) and shoot (Jackson et al. 2012) growth in the field. Nursery fertilization with additional nitrogen can also increase shoot growth of loblolly pine seedlings after planting (Switzer and Nelson 1967, VanderSchaaf and McNabb 2004). For example, loblolly pine seedlings with a higher nitrogen content at planting were taller after 3 years in the field than those with a lower nitrogen content at planting (figure 5a). Some have postulated that nitrogen content is more useful than nitrogen concentration in forecasting seedling field performance, as it is a measure of both initial seedling size and nutrient status (Cuesta et al. 2010).

The lack of a consistent positive response to additional nutrient reserves has been attributed to sufficient internal seedling nutrient status prior to nutrient enrichment (Hawkins 2011), nutrient availability on the planting site (Andivia et al. 2011), or other site factors limiting growth (e.g., water stress) (Wang et al. 2015). For example, growth of loblolly pine on a sandy site was not improved with fall fertilization in the nursery (South and Donald 2002). Thus, a beneficial response to increased nutrient reserves may not occur for southern pines under all field conditions.

Drought Resistance

Nursery cultural practices that develop drought resistance in southern pines can mitigate planting stress and maintain a desirable seedling-water balance, thereby improving survival and growth after outplanting. Drought resistance is considered important for the establishment of southern pine seedlings (Wakeley 1954). Drought-hardening cultural practices, in some cases, have beneficial effects on seedling field survival (Grossnickle 2012), especially under harsh site conditions (Villar-Salvador et al. 2004).

Drought resistance takes many forms (e.g. drought tolerance as osmotic adjustment and drought avoidance as cuticular development). The application of water stress results in "physiological adjustments in plants" (Kozlowski and Pallardy 2002). Loblolly pine seedlings develop drought resistant in response to drought (Bongarten and Teskey 1986) and during hardening nursery cultural practices where watering is restricted (Hennessey and Dougherty 1984, Seiler and Johnson 1985) (figure 5b). Nursery managers use reduced irrigation to slow shoot growth and develop drought resistance in years with a dry fall

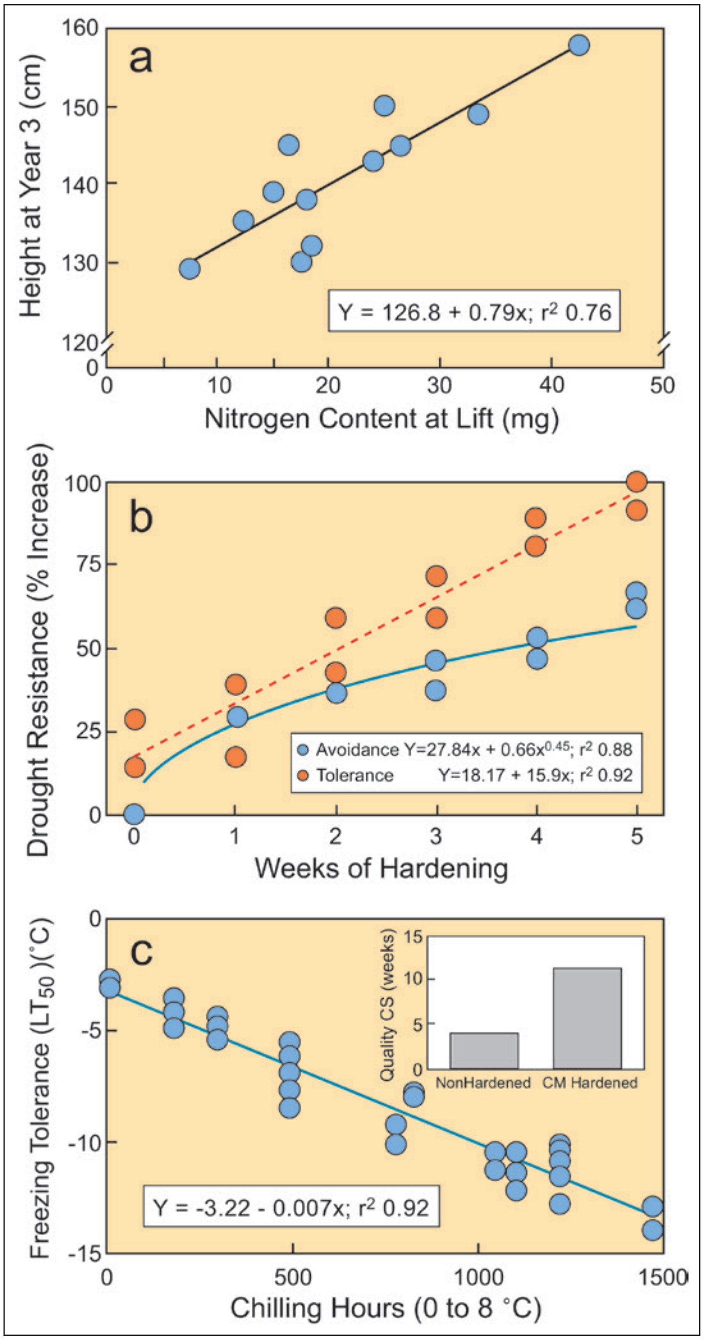

Figure 5. The performance of loblolly pine (*Pinus taeda* L.) is affected by various seedling quality attributes. (a) Third-year field height was influenced by nitrogen content at lift (adapted from Larsen et al. 1988). (b) The shift in drought resistance as measured by drought avoidance (cuticular transpiration that declined from 3.8 to 2.3 percent water loss h-1 after stomatal closure) and drought tolerance (osmotic potential at turgor loss point that declined from -1.0 to -2.0 MPa) during nursery hardening (i.e. reduced fertilization and watering) (Grossnickle unpublished). (c) As photoperiod decreases, seedling freezing tolerance (FT; temperature causing 50 percent electrolyte leakage from needles) responds to chilling hours (0 to 8 °C) and (c-insert) weeks of quality cooler storage (CS at 2–4 °C) for nonhardened miniplug clones or those seedlings exposed to 750 chilling hours (CH-hardened) in the fall. (Adapted from Grossnickle and South 2014)

(Duryea 1984, Lantz 1985, Mexal and South 1991). Southern pine seedlings are typically grown outdoors, which improves various drought avoidance attributes (e.g. cuticular development, secondary needles, increased RCD, reduced height-diameter ratio) (Barnett 1988, Boyer and South 1984, Mexal et al. 1979).

Drought resistance of southern pine seedlings is also achieved by manipulating the shoot and root systems. Root culturing practices (e.g., ripping soil to increase soil porosity, properly timed root pruning) are sometimes applied to increase root system fibrosity of bareroot seedlings (Duryea 1984, Lantz 1985, Mexal and South 1991). Root wrenching also creates stress and hardens bareroot seedlings during latter stages of seedling development (Duryea 1984, Kainer and Duryea 1990). Finally, careful mechanical lifting of bareroot seedlings minimizes root damage and maintains a fibrous root system, thereby resulting in higher root growth (Starkey and Enebak 2013). These desirable attributes are important because they can increase survival of loblolly pine (South and Donald 2002) and longleaf pine (Hatchell and Muse 1990). In contrast, container-grown seedlings are typically extracted from hard-walled containers in a manner resulting in minimal root damage, which aids in improving their field performance compared with bareroot seedlings (Grossnickle and El-Kassaby 2016, South et al. 2005b). Shoot pruning of seedlings is a standard practice used to develop drought avoidance by reducing the amount of transpiring foliage and improving the shoot-to-root balance (South 1998, South et al. 2011, 2016). Shoot pruning controls the height growth of southern pine seedling stock types and increases the probability of higher survival after outplanting (South and Blake 1994, South 1998, South et al. 2011).

Freezing Tolerance

Temperate-zone tree species undergo many changes during the annual phenological cycle in response to seasonal environmental conditions; freezing tolerance is at its highest level in the winter (Burr 1990). Freeze tolerance in loblolly pine has been related to the cessation of shoot growth and seasonal shifts in temperature (Grossnickle and South 2014, Mexal et al. 1979, South 2007) and top pruning (South 1998). Nitrogen status in longleaf pine has been positively related to freezing tolerance (Davis et al. 2011).

North of the southern pine range, many programs measure freezing tolerance to determine the level of stress resistance, and thus how long conifer seedlings can be stored frozen for extended periods (i.e., up to 4-6 months) while maintaining seedling quality (Colombo et al. 2001). Freezing tolerance is considered important when northern conifers are fall-lifted and stored before planting (Glerum 1985, Ritchie 1984). Since southern pine seedlings are not freezer-stored (Grossnickle and South 2014), nurseries in the South do not test for freeze tolerance prior to lifting seedlings.

Measurable seedling attributes for determining when seedlings may be stored for 4 weeks in a cooler (2 to 3°C) are not readily apparent for southern pines. For example, the development of a well-formed bud is required for storage of northern latitude conifers (Colombo et al. 2001), whereas southern pines can undergo long-term storage without the presence of a "winter" bud (with bud scales) (South 2013). Since the planting season of southern pines typically runs from late November through early March, and seedlings are lifted throughout the fall and winter, the lifting for cooler storage is typically dictated by calendar date (Dumroese and Barnett 2004) or operational planting schedules. The timing of when to extract container-grown seedlings is also determined by plug integrity. Typically, short-term storage of bareroot stock is practiced prior to December 21; thereafter, seedlings may be stored for up to 4 weeks (Grossnickle and South 2014). In contrast, container seedlings can tolerate 4 weeks of cooler storage more than bareroot seedlings (Grossnickle and South 2014). Research shows that loblolly pine seedlings develop freezing tolerance as chilling hours accumulate and photoperiod decreases. This capability to develop freezing tolerance (figure 5c) was used as an operational practice for extended cool storage of southern pine miniplug clones at a Canadian nursery (Grossnickle unpublished).

Root Growth Potential

The view that root growth is important for seedling survival and successful field establishment is why RGP is used to evaluate seedling quality (Simpson and Ritchie 1997). RGP is determined through a testing procedure that records the number of new roots after a defined period of time. Numerous reviews have discussed the merits of measuring RGP within a seedling quality assessment program (Burdett 1987, Ritchie and Dunlap 1980, Ritchie and Tanaka 1990). RGP is considered an indicator of a seedling's ability to grow roots, which generally suggests that all physiological systems are functioning properly (Burdett 1987, Ritchie 1984). These indications are why root growth in newly planted seedlings has long been recognized for its importance to ensuring successful field performance (Stone 1955, Tinus 1974, Toumey 1916, Wakeley 1954). Southern pine seedlings with greater RGP exhibit greater survival (Larsen et al. 1986, South and Loewenstein 1994, Feret and Kreh 1985) (figure 6) and early growth (Feret and Kreh 1985, South and Mitchell 1999, Williams and South 1995).

A number of reviews found RGP forecasted seedling survival 70 to 80 percent of the time (Ritchie and Dunlap 1980, Ritchie and Tanaka 1990, Joustra et al. 2000). The lack of a consistent relationship between RGP (measured before seedlings were lifted) and field performance of southern pines led to questions about the usefulness of this test to determine when to lift seedlings (South and Hallgren 1997). Simpson and Ritchie (1997) maintained that RGP was strongly related to field performance when seedlings have an inherently low level of stress resistance and/or when site environmental conditions become more severe. Root egress into the surrounding soil (i.e. good RGP) establishes

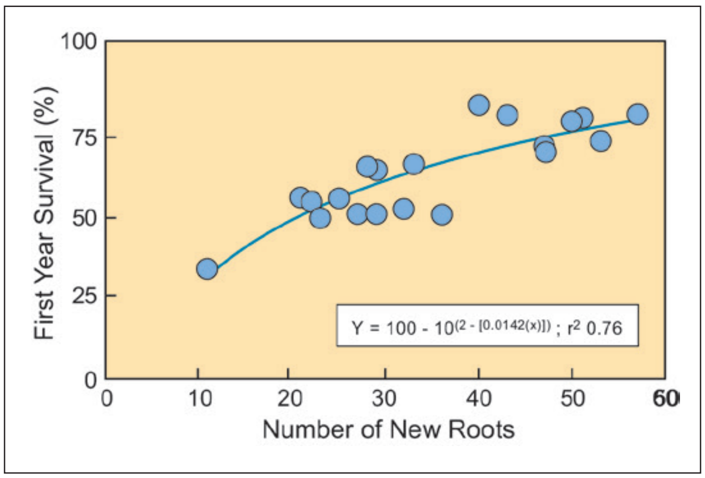

Figure 6. Relationship between root growth potential (number of new roots >0.5 cm) and seedling survival 11 months after planting for bareroot loblolly pine (*Pinus taeda* L.) seedlings. (Larsen et al. 1988)

a favorable morphological balance for water and nutrient uptake, which reduces planting stress (Grossnickle 2005a). If seedlings are not exposed to planting stress, then initial root growth is not essential for good field performance (Simpson and Ritchie 1997). This view is illustrated by Stone et al. (2003), where critical RGP (i.e., minimum root growth required for seedling survival on a given planting site) was twice as high for harsh sites compared with low-stress sites. Thus, site conditions dictate the amount of root growth required to overcome planting stress and ensure good seedling performance. Site conditions must be taken into account when using RGP to forecast seedling survival.

Conclusion

Nursery cultural practices used to produce southern pine seedlings affect seedling morphological and physiological attributes and—along with handling, weather, and field site conditions—affect their field performance. An adequate understanding of the previously discussed material and performance attributes helps managers produce good quality seedlings. When nursery cultural practices that improve seedling quality are applied, chances are good that these practices can optimize seedling field performance after outplanting.

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Subsoiling as Site Preparation on Ponderosa Pine Plantations of the Yakama Nation Forest

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Abstract

Early logging efforts on the Yakama Nation Indian Reservation in Washington State featured 100 percent piling of logging slash, with minimal concern for soil compaction. Observations of regeneration growth and development indicate that soil compaction may play a role in reducing tree growth on timbered land that was harvested in the era before logging practices were modified to minimize compaction. This article describes a project to document soil compaction on Yakama Nation forest land, compare the operations of two separate machines in subsoiling to break up soil compaction, and examine the growth of seedlings in response to subsoiling.

Introduction

The Yakama Nation Indian Reservation was formally established upon signing of a treaty with the United States Government on June 9, 1855. The Yakama Reservation consists of more than 1.1 million ac (445,155 ha) on the east side of the Cascade Mountains in south-central Washington State and is bounded by the Cascade crest (including Mount Adams) to the west, Ahtanum Creek to the north, and the Yakima River to the east. Over one-half of the reservation is classified as forest, with forest zones ranging from lower to upper timberlines.

The Yakama Nation began commercial timber harvest of its large holdings in the late 1940s. The early timber sales were large expanses concentrated on the drier eastern portion of the Yakama forest, salvaging ponderosa pine (*Pinus ponderosa* Lawson & C. Lawson) damaged by bark beetles (Schutter and Charmichael 1993). The extensive nature of the harvesting, combined with low stumpage prices and the Tribe's preference to harvest the forest selectively, resulted in widespread logging impacts on the soil. Handfelled trees were bucked to length, leaving large, unsightly piles of logging slash. The slash was 100 percent machine-piled using bulldozers, and piles were burned in the winter. No records can be found of any timing restrictions regarding slash piling. These practices continued into at least the 1970s.

Over the last 30 years, soil compaction has become recognized as an important issue on forest lands, as numerous studies showed that compacted soils have characteristics unfavorable for plant growth (Cambi et al. 2015). Layers of compacted soil restrict the movement of water, air, and roots, reducing the survival and growth of trees and other plants. Froehlich et al. (1986) found that total growth and the last 5 years of growth in ponderosa pine in south-central Washington on or near compacted skid trails were significantly related to the percent increase in soil bulk density caused by skidding. After that study, completed on the Yakama Reservation in 1983, the Yakama Nation's Forest Management Plan was adjusted to include policies to protect forest soils from heavy-equipment impacts.

Despite these belated preventative measures, soil compaction can persist for decades, depending on a number of factors. Although the soil surface can be de-compacted through natural frost heaving, a compacted layer tends to persist about 30 to 60 cm (1 to 2 ft) deep that the frost cannot reach. Overall, the moderate climate and soil types common to the Pacific Northwest seem to produce very slow rates of recovery from compaction (Adams and Froelich 1981).

Most of the compacting impact on soil usually occurs in the first few machine passes (Han et al. 2006, Wallbrink et al. 2002, Wang, 1997). Williamson and Neilsen (2000) found that, on average, 62 percent of the compaction experienced by the top 10 cm (4 in) of soil occurred after a single machine pass. In the 10-to-20 and 20-to-30 cm layers (4-to-8 in and 8-to-12 in, respectively), compaction increased up to the third pass, when it reached 80 to 95 percent of the final compaction. Therefore, we can logically surmise that the possibility of widespread soil compaction is high in those areas of early harvest on the Yakama forest during which multiple machine passes were common.

The Yakama Nation Tribal Forestry Program has anecdotal evidence of soil compaction having a detrimental effect on its reforestation efforts, especially in the early-harvested drier zone dominated by ponderosa pine. A more recent round of harvesting began in 2005 and focused on regenerating pine stands with extensive Western dwarf mistletoe (*Arceuthobium campylopodum* Engel.) infection. Many of the subsequent reforestation units had seedling survival and growth much less than expected. Planting crews complained that it was extremely hard to dig a planting hole to the appropriate depth in some spots because they hit an impenetrable layer with their shovels. A test project using an excavator revealed sheets of compacted soil several inches below the soil surface which younger tree roots could not penetrate (figure 1). Excavations of seedlings in the area confirmed root issues due to soil compaction (figure 2).

Figure 1. Compacted sheets of soil revealed by excavator work result in difficult growing conditions for planted seedlings. (Photo by Jack Riggin, 2011)

Figure 2. Excavation of a natural seedling shows negative influences on root development due to the compacted soil layer. (Photo by Jack Riggin, 2011)

Conventional agricultural cultivators have difficulty reaching below 30 cm (12 in). Hence, treatment of deep compaction in forest soils requires special equipment called subsoilers, sometimes known as rippers, to fracture them. Subsoiling fractures compacted soil without adversely disturbing plant life, topsoil, and surface residue. Fracturing compacted soil promotes root penetration by reducing soil density, improving moisture infiltration and retention, and increasing air spaces (Kees 2008). Since effectiveness of subsoiling in actually fracturing the compaction layer depends on various factors (soil moisture, structure, texture, type, clay content, etc.), the landowner may need to try different equipment or configurations to find out which is most effective for his or her specific situation.

In 2012, the Tribal Forestry Program received a Conservation Innovation Grant from the USDA Natural Resources Conservation Service (NRCS) to evaluate pine plantation development after subsoiling. Conservation Innovation Grants are used by the NRCS to assess different conservation practices that can, if successful, then justify their inclusion as a sponsored larger conservation practice in their larger programs, such as the Environmental Quality Incentive Program. The grant project goals were to:

- Assess different subsoiling techniques;
- Evaluate the effectiveness of subsoiling in reducing soil compaction;
- Evaluate tree seedling growth response to subsoiling.

Materials and Methods

The project consisted of selecting typical regeneration units, documenting the presence of preexisting soil compaction, implementing compaction-fracturing work (subsoiling), planting with seedlings in a typical manner, and then measuring seedling growth and development as influenced by the subsoiling. Each of these components is described in the following sections.

Forest Regeneration Units

Two units in the White Creek sub-basin were included in this project. The first unit, known as East Hopper's, is located on the east side of Vessey Springs Road, with an elevation of 1,065 m (3,500 ft). The second unit, known as West Hopper's, is located on the south side of the Ixl Crossing Road, with an elevation of about 1,005 m (3,300 ft). Both sites have an average precipitation of 68 cm (27 in), with a fine, sandy loam soil texture. The soils are rated as severe risk for compaction, with a low bearing capacity and poor drainage. The site index (base age 100) is about 30 m (99 ft) for ponderosa pine (USDI 2008).

Evidence exists (old burned logs and snags) that a stand-replacement fire occurred on the units about 100 years ago. The units were logged four times using selective harvesting and/or thinning from 1952 to 1995. In 2010, the areas where both units exist were regenerated due to the presence of dwarf mistletoe in the overstory.

Soil Density Assessment

Soil density was measured using a soil densiometer in the fall of 2012 (figure 3) both before and after the subsoiling work was carried out. Plots in both units revealed a clay layer lying just below the ash-cap layer of surface soil, thus confirming the compacted status of the soil (figure 4).

Figure 3. Soil density was measured on both units using a soil densiometer. (Photo by Jack Riggin, 2017)

Figure 4. A clay layer below the soil surface reveals signs of compaction. (Photo by Jack Riggin, 2017)

Figure 5. This triple-winged shank was used behind a bulldozer for subsoiling treatments on the West Hopper's site. (Photo by Jack Riggin, 2017)

Subsoiling

Subsoiling was carried out on both sites in the fall of 2012. The East Hopper's site was done by dragging a winged shank behind a tractor. The West Hopper's site was done by dragging a triple-winged shank behind a bulldozer (figure 5). The tractor contract was done for $480 per ha ($195 per acre), whereas the inhouse bulldozer work cost an estimated $430 per ha ($174 per acre).

Figure 7. Satellite imagery shows subsoiling work and areas where access was limited due to rocks, debris, or other obstacles. (Google Earth 2017)

The bulldozer was able to cover the ground more extensively than the tractor, and subsoiling work was still evident 3 years after treatment (figure 6). In some areas within the planting units, it was not possible to carry out the subsoiling. Rocky outcrops, areas of many stumps close together, heavy slash areas, and unburned landings were typical problem areas (figure 7). The tractor setup was rather lightweight for the intended job, at times tending to ride up out of the ground. The work shut down a few times due to soggy soils on both units.

Tree Planting

Ponderosa pine seedlings (styro-15) were grown under operational conditions at the Silvaseed Nursery (Roy, WA) during 2012 for planting in both units using local seed. The same seed lot was used in planting units. Seedlings were planted in spring 2013 at about 3.5 by 3.5 m (12 by 12 ft) spacing, or 740 seedlings per ha (300 per acre) (figure 8).

Figure 6. The West Hopper's site 3 years after planting still shows signs of subsoiling work using the bulldozer method. (Photo by Jack Riggin, 2017)

Figure 8. Seedlings were planted on both units after subsoiling. Some were planted directly in the subsoiling slot, as shown in this photo, and others were planted farther from the slot. (Photo by Jack Riggin, 2013)

Monitoring Plots

After planting, monitoring plots (81 m [871 ft²]) were installed on a grid on each planting unit (10 plots on East Hopper's; 11 plots on West Hopper's). Seedlings inside each plot were tallied for initial height and distance from the soil fracture slot. Several plots landed where no subsoiling was done.

Plots were revisited after the end of the first, second, and third growing seasons, during which height and survival were measured on seedlings within each plot.

Results and Discussion

Subsoiling Equipment

The bulldozer was cheaper, covered the ground better, and was easier on the site compared with the tractor. The tractor could only pull one shank through the ground at a time. That shank was in the middle center of the tractor and was light enough that it tended to pop out of the ground when encountering greater resistance. Furthermore, the tractor tires carried the potential of having a negative influence on soil density without being mitigated by additional fracturing behind the wheels.

The bulldozer was heavy enough to drag three shanks at a time, including behind its tracks, and was able to drag continuously below the ground unless it encountered rock. The tracked nature of the bulldozer distributed the weight of the machine over a wide area, reducing negative impacts associated with running heavy equipment over the ground.

Subsoiling Effects on Soil Compaction

Before subsoiling, the West Hopper's unit appeared to have a wider and denser compaction layer than the East Hopper's unit, though both areas showed signs of compaction (figure 9). Soil densiometer plots on both units showed that soil density was reduced in the zones from 7 to 23 cm (3 to 9 in) below the soil surface for both sites (figure 9). The East Hopper's site showed good soil density reduction near the surface, with limited impact after about 23 cm (9 in) (figure 9). This corresponds to the observations that the setup was not heavy enough to remain in the ground sufficiently to accomplish the task. The West Hopper's site, which featured great increases in soil density beginning just 7 cm (3 in) below the surface, showed great reductions in soil density after the subsoiling was completed, with slight declines farther below the surface (figure 9).

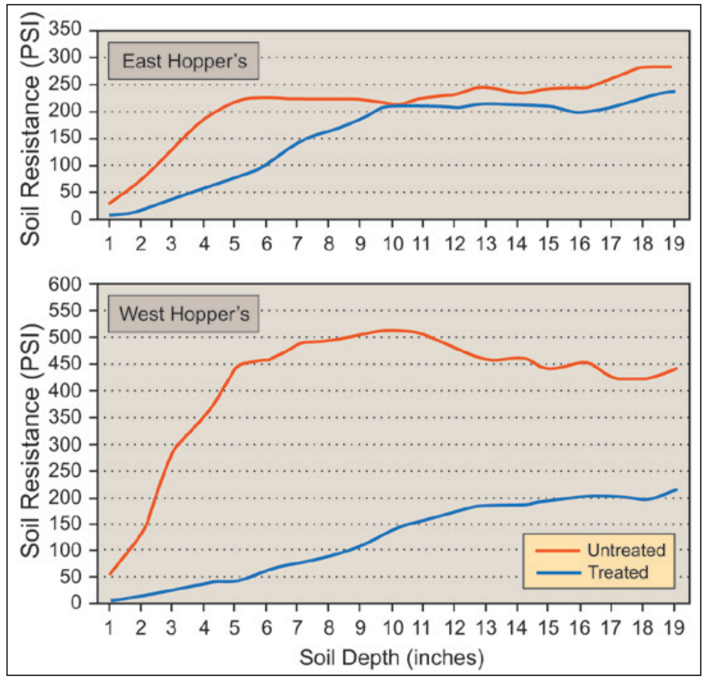

Figure 9. Soil density readings prior to subsoiling shows compaction beginning around 10 cm (4 in) below the surface. After subsoiling, density declined, especially for the West Hopper's site.

Subsoiling Effects on Seedling Growth and Survival

Seedling survival was similar among plots, regardless of distance from the subsoiling slot. The survival results are not unexpected because soil compaction is a long-term impact affecting growth and development and not something that immediately affects a seedling's ability to survive in its first few years.

At the end of the first growing season, no clear patterns in height growth emerged based on distance from the subsoiling (figure 10). It was not unexpected to see no subsoiling effects during the first season because initial root egress is much more directly influenced by available ground moisture in the immediate vicinity of the roots. Planting quality, precipitation patterns, and immediate vegetative competition all affect ground moisture availability to the seedling roots during the first year. After the second and third seasons, however, height growth on both units tended to be greater for trees that were planted closer to the soil fracture slot (figure 10).

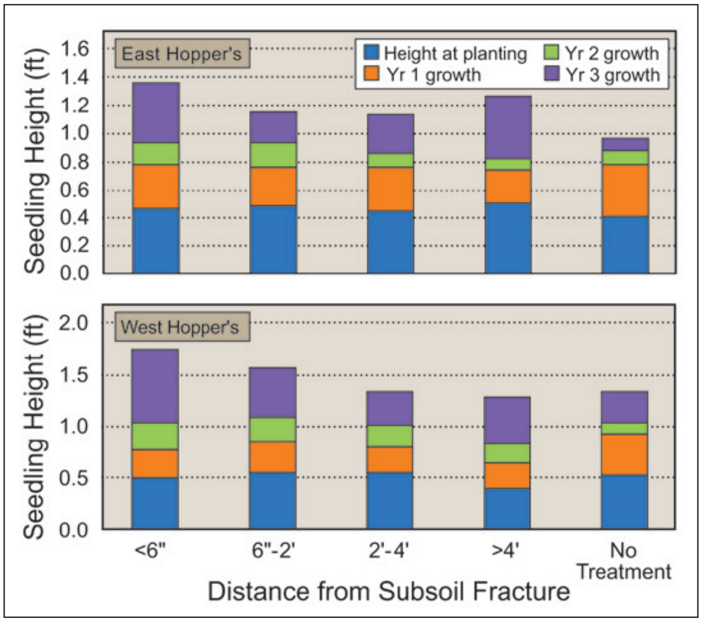

Figure 10. Seedling height growth did not differ greatly during the first year but showed increased growth in years 2 and 3 for seedlings planted closer to subsoiling compared to those that were planted further from the treated areas.

In a similar study, Gwaze et.al. (2006) found that ripping (subsoiling) increased height growth, basal diameter, volume, and crown spread in shortleaf pine (*Pinus echinata* Mill.) in Missouri from the first year. That study found continued increases in most measures through the third year, but revisiting the study after 16 years found slight decreases in diameter and volume compared with the control.

The bulldozer work not only broke up soil compaction below the soil, but also provided the additional benefit of breaking up the grass that had developed into a turf after logging. Grass is a formidable competitor to tree seedlings, especially during the first two seasons after planting. The tractor work, on the other hand, covered less area and was less effective in breaking up grass.

One might conclude that grass control was a more influential factor than subsoiling in improved seedling growth. The data show, however, that growth improved in years 2 and 3, when the impact of the grass control would be diminishing, as grass expands naturally into unoccupied ground. Instead, macro-site characteristics may be improved by subsoiling, something that would logically become more influential as the seedling roots extend further down into the soil profile. Further root egress in years 2 and 3 was perhaps enough to access the fractured layer and the additional volume of moisture and nutrients available there.

Although the current study shows seedling growth trends positively correlated with subsoiling, the literature's perspective on subsoiling is more ambivalent, or worse, when one takes a financial look into the additional preplanting costs that need to be accounted for at harvest time. Blazier and Dunn (2008) compared stock-type (container and bareroot), subsoiling (with or without) and planting densities (746 or 1493 trees per ha) on loblolly pine (*Pinus taeda* L.) in Louisiana. They found the container plus no subsoil plus low density (similar to the standard practice on the Yakama Nation) produced the highest stand volume after 13 years. The container plus subsoil plus low density alternative produced lower heights, tree volumes, and stand volumes. On the other hand, Berry (1986) found subsoiling benefited growth of loblolly and shortleaf pine seedlings in Georgia.

Closer to home, much of the work regarding soil compaction and seedling growth has concentrated on skid trails. In coastal Washington, Miller et al. (1996) found that change in soil bulk density due to logging was not a reliable predictor of growth and yield losses on silt loam soils. Meanwhile, Helms et al. (1986), working in a 16-year-old ponderosa pine plantation in the Sierra Nevada of California, found that tree height in the areas of the highest soil bulk density was 43 percent less at age 1 and 13 percent less at age 15 than those in areas of lowest bulk density. Helms and Hipkin (1986) found that mean tree volume in a landing, a skid trail, and areas adjacent to skid trails showed volume reductions of 69, 55, and 13 percent, respectively, when compared to areas of the same plantation that showed the lowest bulk density.

Peculiarities of the Yakama Situation

The history of timber harvest on the Yakama reservation differs from its neighbors in that multiple entries were made prior to regenerating the stand, including 3 entries prior to the implementation of changes to minimize soil compaction. It is unclear how many acres of compacted soils this early harvesting created. Regardless, an underlying susceptibility to compaction is based on soil properties on the forest. The Yakama forest soils GIS (geographic information system) layer estimates that 34 percent of the Yakama forest's soils are at severe risk to compaction and 35 percent are estimated to be at moderate risk.

Although soil compaction is addressed routinely in the Southeast United States, the economic return of forestry in that region is inherently higher and thus has an easier time supporting the extra cost of subsoiling. The ability to incur the cost of addressing this underlying forest productivity issue is much more questionable for the Yakama forest.

Additional Environmental Benefits to Subsoiling

In addition to the potential for improved seedling growth, subsoiling has other conservation benefits, such as improved runoff absorption and improved stream recharge. Smidt and Kolka (2001) found that subsoiling reduced surface runoff and sediment yield when compared to standard practices for skid trail retirement in Central Kentucky.

Although income from stumpage, raw materials for the Tribal sawmill, and local employment are important to the Yakama people, the protection of natural resource conditions for their use by future generations is also important. Clean water, for both drinking and salmon habitat, is of extreme importance to the Yakama Nation. Anything that can enhance the quantity and quality of water coming off the forest is of great value. As the trustee for the Yakama Nation and the agency in charge of the timber sales program, the Federal Government, via the Bureau of Indian Affairs—Yakama Agency, likewise has a stake in the long-term productivity of the Yakama forest.

Future Needs

Our understanding of the impact of previous timber harvesting on Yakama soils and their productivity is mostly anecdotal. To develop a better understanding of the state of the soil resource, documentation is needed on the extent of actual compaction on the Yakama forest, initially targeting the sites of early timber harvest. We also don't really understand how variable this compaction is or how severe it is by location. By building that information into a map layer, we could integrate those locations into silvicultural prescriptions for timber sales to trigger compaction amelioration work, such as subsoiling at a practical time (i.e., regeneration) in the life cycle of the affected stands.

More work is needed on the operational aspects of subsoiling at the local level. How can this remediation work be done most efficiently? When is the best time in the stand's rotation to carry this out? Are there sites that may suffer from this logging-generated soil compaction that are not worth treating?

Given not only the forest health benefits, but also the benefits to the soil/water profile, subsoiling in these situations may be something to consider for a broader conservation portfolio.

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Optimum pH for Growing Pine Seedlings

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Abstract

Two schools of thought address the optimum soil pH (measured in water) for growing pine seedlings (*Pinus* spp.) in bareroot nurseries. One school uses nutrient availability charts to determine the best pH range for growing conifers. Students of this school believe pine seedlings grow best at pH 5.5 to 6.5. In contrast, another school uses research from nursery trials to conclude that pines grow best in "very strong acid" soils (pH 4.5 to 5.0). This article compiles some of the findings from seedbed and greenhouse trials and attempts to use data to dispel a few myths about growing pine seedlings in soils with pH less than 5.0. This paper was presented at the Joint Meeting of the Northeast Forest and Conservation Nursery Association and Southern Forest Nursery Association (Lake Charles, LA, July 18–21, 2016).

Introduction

It may be surprising, but there is no consensus on the pH (measured in water) range for growing pine seedlings (table 1). In some cases, the "optimum" ranges do not even overlap. Recommendations from the United States typically involve a minimum of pH 5.0 to 5.5. In contrast, some recommendations from other countries set pH 5.0 as the maximum value (table 1). I agree with Bryan et al. (1989: p. 64) that "some of the pH ranges suggested for conifers result in slow growth and unhealthy seedlings..." Not only is the pH 5.5 to 6.5 range too high for Fraser fir (*Abies fraseri* [Pursh] Poir.) (Bryan et al. 1989), but this range is also too high for loblolly pine (*Pinus taeda* L.) (Marx 1990). Indeed, sowing loblolly pine seed at pH greater than 5.5 resulted in smaller seedlings (requiring extra nitrogen [N] fertilization), and in some cases, chlorotic seedlings (figure 1). One might ask why some recommend a pH range of 4.5 to 5.0 (Aldhous 1972, Brix and van den Driessche 1974, Januszek and Barczyk 2003) or 4.2 to 4.5 (Bryan et al. 1989), while others recommend a range of 5.5 to 6.5 (table 1).

Table 1. The recommended pH range for bareroot pine seedbeds varies considerably. Most U.S. authors suggest a minimum pH of 5.0 or greater.

Recommended pH range	Country	Reference
5.5–6.5	USA	Steinbeck et al. (1966)
5.5–6.5	USA	Solan et al. (1979)
5.5–6.5	USA	Youngberg (1984)
5.5–6.5	USA	Landis (1988)
5.5–6.5	USA	Bueno et al. (2012)
5.5–6.0	USA	Leaf et al. (1978)
5.5–6.0	USA	May (1966)
5.3–5.6	USA	Stoeckeler (1949)
5.2–6.2	USA	Davey (1984)
5.2–5.8	USA	Stoeckeler and Jones (1957)
5.2–5.8	USA	Stone (1965)
5.0–6.0	USA	Wilde (1934)
5.0–6.0	USA	Wakeley (1954)
5.0–6.0	USA	Switzer and Nelson (1967)
5.0–6.0	Canada	Armson and Sadrika (1979)
5.0–6.0	USA	Tinus (1980)
5.0–5.5	USA	Wilde (1958)
5.0–5.5	USA	Barnett (1974)
5.0–5.5	Canada	Carlson (1979)
5.0–5.5	USA	South and Davey (1983)
4.5–6.5	USA	Wakeley (1935)
4.5–6.0	Canada	Van den Driessche (1980)
4.5–5.5	Latvia	Mangalis (in Donald 1991)
4.5–5.5	USA	South (this article)
4.5–5.0	UK	Aldhous (1972)
4.5–5.0	Canada	Brix and van den Driessche (1974)
4.4–4.6	Poland	Januszek and Barczyk (2003)
4.0–5.0	Germany	Rehfuess in Donald (1991)

After reviewing the literature, it became apparent that the lower pH recommendations were based on empirical nursery trials (Benzian 1965, Januszek and Barczyk 2003, van den Driessche 1971) while the higher pH recommendations were based primarily

Figure 1. Applying too much lime 2 weeks prior to sowing slash pine (*Pinus elliottii*) seed can result in chlorosis. (Photo by Jack May, University of Georgia, 1961)

on nutrient availability charts that suggest pH 5.5 to 6.5 is optimal for the growth of agronomic species; these species include ryegrass (*Lolium* spp.) and velvet beans (*Mucuna pruriens* (L.) DC.) (Ankerman and Large 2001). In one survey, the average pH for 43 loblolly pine plantations was about 4.8, and the researchers reported a positive correlation (r = 0.4) between soil exchangeable acidity (meq per 100 g of soil) and volume growth (NCSFNC 1991). Likewise, when compared to pH 5.8, loblolly pine sown in soil at pH 4.8 required less N fertilization to reach the target shoot mass (Marx 1990). The purpose of this paper is to review pH research in conifer nurseries and to dispel a few myths about growing pine seedlings on "very strong acid" soils.

Bareroot Nurseries

Liming trials in the United Kingdom determined the optimum pH range for several pines to be 4.5 to 5.0 (Benzian 1965). In contrast, only a few liming trials in bareroot nurseries have been published in the United States. A few trials were conducted at nurseries where soil calcium (Ca) and/or magnesium (Mg) were likely deficient, and as a result, liming reduced needle chlorosis (Stoeckeler and Jones 1957, Voigt et al. 1958, Will 1961). At nurseries where Ca and/or Mg are not deficient, however, applying lime can induce chlorosis and reduce growth. For example, applying 2,240 kg/ha of dolomitic lime 2 weeks before sowing pine seed increased chlorosis at two nurseries in Georgia (Steinbeck et al. 1966). In Louisiana, applying lime (4,480 kg/ha) and fertilizer in April caused seedling chlorosis in May (Shoulders and Czabator 1965).

Studies have demonstrated a correlation between nursery soil pH and seedling growth. In Poland, a sulfur trial with Scots pine (*Pinus sylvestris* L.) showed optimal growth at pH 4.4 to 4.6 (Januszek and Barczyk 2003). Results from a liming trial at a nursery at the University of Georgia (Marx 1990) showed that five genotypes of loblolly pine seedlings grew best at pH 4.8 (figure 2). Armson and Sadreika (1979) examined seedling mass for four nurseries in Ontario and found that red pine (*Pinus resinosus* Aiton.) mass increased about 50 percent (0.6 g) when pH was 5.4 (vs. pH 6.4). Marx et al. (1984) measured soil pH at the time of sowing over a 4-year period, 1977 to 1980, at 30 operational pine nurseries in the United States. These data indicate that pH 4.5 might increase the fresh weight of seedlings by about 33 percent compared with seedlings grown in soils at pH 5.5 (figure 3).

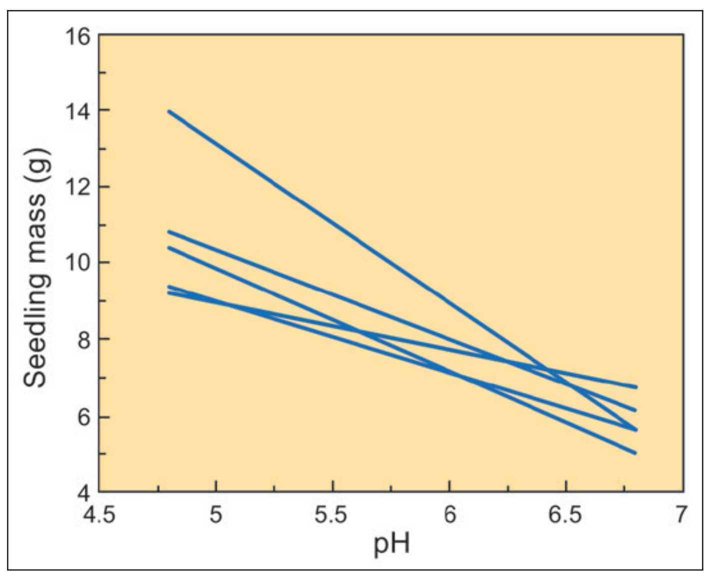

Figure 2. Relationship between seedling mass and soil pH (at time of sowing) for five genotypes of bareroot loblolly pine (*Pinus taeda*) seedlings (adapted from Marx 1990). Prior to adding lime, the soil pH averaged 4.8. After adding 2,850 or 5,700 kg/ha of slacked lime, the soil pH (at sowing) averaged 5.8 and 6.8, respectively. For one genotype (top line), seedling mass was 77 and 130 percent greater on plots with no lime (pH 4.8) versus plots that averaged pH of 5.8 and 6.8, respectively.

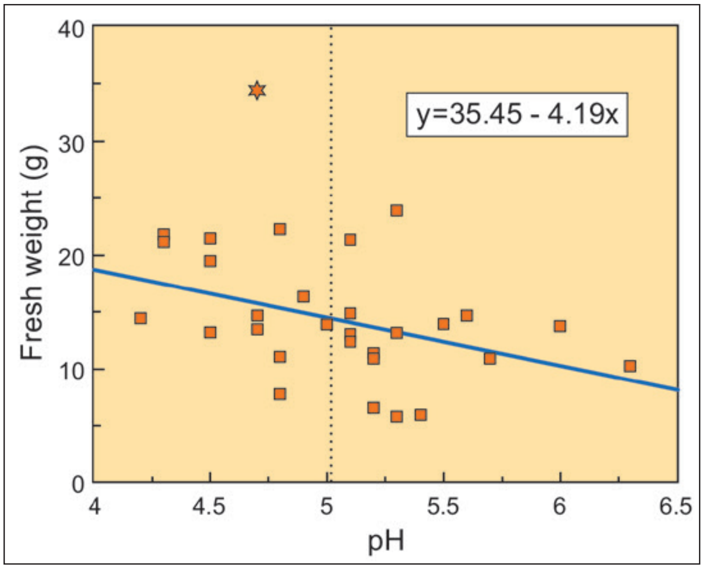

Figure 3. Operational data (control plots) from seedlings grown in 31 different nursery soils indicate a general relationship between soil pH at sowing and fresh weight of pine seedlings at lifting (adapted from Marx et al. 1984). Data include loblolly pine (*Pinus taeda*; n=20), slash pine (*Pinus elliottii*; n=4), Virginia pine (*Pinus virginiana*; n=4), and shortleaf pine (*Pinus echinata*; n=3). The statistical equation (n = 30) does not include the star data point (Westvaco Nursery) since the large seedlings (34.4 g) were grown at a low seedbed density of 150 seedlings per m2. The average fresh weight of seedlings to the left of the dashed line (below 5.05 pH) was 16.1 g (n=14), and the average fresh weight of seedling to the right of the line (above 5.0 pH) was 12.7 g (n = 16). The linear regression indicates lowering pH from 5.5 to 4.5 might increase seedling fresh weight by about 33 percent.

Greenhouse Trials

A number of greenhouse studies indicate pine seedling mass increases as soil acidity increases (i.e. pH decreases) (table 2, Ivanov et al. 2013). Results from these trials can be used to reject the hypothesis that pines grow best at pH 5.2 to pH 6.6. In most of these trials, supplemental fertilization (with N, potassium [K], and phosphorus [P]) was held constant, regardless of pH treatment indicating that increasing acidity to below pH 5.0 can increase nutrient use efficiency (e.g. uptake of N mass in foliage) (Kakei and Clifford 2000). In many cases (table 2), the overall uptake of biomass (and associated nutrients) is increased by 20 percent or more.

Concerns over harmful effects of acid rain helped fund studies (table 3) that examined the effects of acidification of irrigation water with nitric acid and/or sulfuric acid. Typically, the acidified water gradually decreased soil pH as the number of irrigations increased. In most studies with pine, the growth response was positive when small amounts of nitric acid (and other acids) were added to irrigation water (table 3).

Some caution is recommended, however, when making conclusions based on acid rain trials. Natural rainfall (greater than pH 4.0) typically does not injure pine needles. Acid irrigation trials in which pH is lowered by adding nitric acid or sulfuric acid to distilled water to create a high acid treatment (i.e., pH 3.3), however, can result in a negative growth effect (McLaughlin et al. 1994). One should not simply assume irrigation with water at pH 3.3 would produce similar results to growing seedlings in a soil at pH 3.3 (where foliar injury from acids does not occur). Likewise, one should also not assume that applying sulfuric acid just prior to transplanting pines will not injure roots (Shan et al. 1997, van den Driessche 1972).

When To Add Lime

Stoeckeler and Jones (1957) reported that finely ground limestone should not be applied before sowing conifer seed; Steinbeck et al. (1966) said limestone normally should be applied preceding a cover crop; and Wakeley (1954) said that application of lime to increase soil pH should be avoided unless definite evidence of a need exists. The fear of liming prior to sowing pines may have originated from concern over seedling losses, as the rate of damping-off increases with the rate of liming (Chapman 1941, Stoeckeler 1949, Voigt et al. 1958). This concern, however, decreased after soil fumigation with methyl bromide became a common practice. Therefore, some now say pine seed may be sown about 3 weeks after liming. Without methyl bromide, damping-off can increase when alkaline water is used to irrigate pine seedbeds (Januszek et al. 2014).

Because of the high genetic value of pine seedlings today, most nursery managers do not wait until evidence of a low pH problem appears. Therefore, most managers add lime prophylactically according to general guidelines found in nursery manuals (Stoeckeler and Jones 1957; van den Driessche 1969, 1984). In the past, some growers applied lime when soil acidity reached pH 5.4 (Solan et al. 1979: figures 4, 5), while others limed at pH 4.0 to 4.2 (Stoeckeler 1949, Stoeckeler and Arneman 1960). In British Columbia, several bareroot nurseries produced conifers at pH 4.4 (Maxwell 1988). In contrast, when one loblolly pine seedbed (which has a cation exchange capacity [CEC] of 3.4) reached pH 6.1 in 2016, one agronomist suggested applying 1,120 kg/ha of lime to raise the pH to 6.5.

Table 2. Examples of greenhouse trials demonstrating the change (%) in seedling mass (mg) when seedlings are grown at different pH levels. In most cases, mass increased with decreasing pH.

Species	pH #1	pH #2	Mass #1 (mg)	Mass #2 (mg)	Change in mass with decreased pH (%)	Reference
Pinus. radiata D. Don	6.2	4.5	1,610	1,160	– 28	Theodorou and Bowen (1969)
P. sylvestris L.	6.2	4.0	~150	~125	– 17	Erland and Söderström (1990)
P. elliottii Engelm.	6.8	5.8	1,900	1,610*	– 15	van den Driessche (1972)
P. elliottii Engelm.	5.6	4.0	217	242	11	Marx and Zak (1965)
P. elliottii Engelm.	6.8	5.5	580	660	14	van den Driessche (1972)
P. resinosa Aiton	6.0	5.0	7,630	8,980	18	Mullin (1964)
P. radiata D. Don	6.1	4.2	2,170	2,660	22	Theodorou and Bowen (1969)
P. contorta Douglas ex Loudon	6.1	4.2	131	161	23	Griffin (1958)
P. rigida Mill.	5.6	4.6	590	730	24	Helm and Kuser (1991)
P. strobus L.	5.6.	4.3	330	410	24	Sundling et al. (1932)
P. banksiana Lamb.	5.6	4.3	310	390	25	Sundling et al. (1932)
P. resinosa Aiton.	5.6	4.3	310	400	29	Sundling et al. (1932)
P. taeda L.	6.5	4.5	1,060	1,411	33	Harbin (1985)
P. elliottii Engelm.	7.0	5.8	1,140	1,610	41	van den Driessche (1972)
P. ponderosa Law.	6.0	4.0	2,950	4,350	47	Howell (1932)
P. sylvestris L.	5.8	4.4	72	107	49	Wallander et al. (1997)
P. radiata D. Don	6.1	4.5	205	310	51	de Vires (1963)
P. sylvestris L.	6.0	4.5	380	600	58	Rikala and Jozefek (1990)
P. sylvestris L.	6.2	5.5	63	100	59	Carter (1987)
P. elliottii Engelm.	6.9	5.8	4,680	8,090	73	Richards and Wilson (1963)
P. banksiana Lamb.	8.2	6.1	357	669	87	Dale et al. (1955)
P.contorta Douglas ex Loudon	4.9	4.0	80	165	106	Danielson and Visser (1989)
P. radiata D. Don	7.5	6.7	670	2,810	319	Richards (1965)
Larix kaempferi (Lamb.) Carr.	4.9	4.5	~217	~272	25	Choi et al. (2008)
Pseudotsuga menziesii (Mirb.) Franco	5.4	4.0	4,220	5,390	28	van den Driessche (1971)
Abies fraseri (Pursh) Poir.	5.0	4.5	1,896	2,438	29	Bryan et al. (1989)
Taxodium distichum (L.) Rich.	6.0**	4.5	4,100	7,200	75	Hinesley et al. (2001)

~ = approximately. mg = milligrams.

* Sand-vermiculite media treated with 28,062 L/ha of 1N sulfuric acid.

** Estimated from Wright et al. 1999.

Several managers prefer dolomitic lime because it contains Mg (Altland and Jeong 2016, Davey 2002). The rate applied varies with initial soil pH, soil texture, organic matter, and desired pH. From a survey of 11 nurseries (Marx et al. 1984), one manager applied lime at 560 kg/ha, seven applied lime at 1,120 kg/ha, and three applied lime at 1,680 to 2,240 kg/ha. Examples of increasing soil pH with dolomitic lime are provided in figure 4.

When soil is at pH 5.2, less lime will be required to raise pH to 5.5 than to raise the pH to 6.5. For example, at one nursery, two applications of dolomitic lime raised the pH to 6.5 (figure 5). At the time of sowing the pine seed (spring of 1995), the soil was at pH 6.3. Pines growing in soils with pH greater than 6.0 often exhibit "summer chlorosis" in June and July soon after the first N application. Over time, several nursery managers realized that iron (Fe) chlorosis seldom occurs at pH 5.5 (Mizell 1980). Adding lime at pH 5.2 can reduce pine seedling growth (Coultas et al. 1991, Marx 1990), increase the risk of damping-off (Bickelhaupt 1989, Griffin 1958, Helm and Kuser 1991, Pawuk 1981, Voigt et al. 1958) (figure 6), reduce uptake of N (Carter

Table 3. The effect of acidifying irrigation water on pine seedling mass (mg). Mass #1 and mass #2 correspond to the dry mass of seedlings irrigated with water pH #1 or water pH #2, respectively.

Genus/species	Water pH #1	Water pH #2	Mass #1 (mg)	Mass #2 (mg)	Change in mass with decreased pH (%)	Reference
Pinus taeda L.	4.5	3.0	750	680	– 9	Seiler and Paganelli (1987)
P. elliottii Engelm.	5.5	3.5	2,390	2,170	– 9	Hart et al. (1986)
P. ponderosa Law.	5.6	2.0	1,780	1,770	– 1	McColl and Johnson (1983)
P. strobus L.	5.6	3.0	436	435	0	Reich et al. (1987)
P. taeda L.	4.8	3.6	503	501	0	Walker and McLaughlin (1993)
P. strobus L.	5.7	3.0	68	69	+1	Lee and Weber (1979)
P. rigida Mill.	5.6	4.0	49	51	+4	Schier (1986)
P. taeda L.	5.6	2.4	930	970	+4	Shafer et al. (1985)
P. strobus L.	5.6	3.0	631	693	+10	Reich et al. (1987)
P. banksiana Lamb.	4.7	2.5	83	93	+12	MacDonald et al. (1986)
P. echinata Mill.	5.6	4.0	48	54	+12	Schier (1987)
P. strobus L.	6.0	4.0	490	600	+22	Wood and Bormann (1977)
P. strobus L.	5.6	3.0	424	644	+52	Reich et al. (1987)

mg = milligrams.

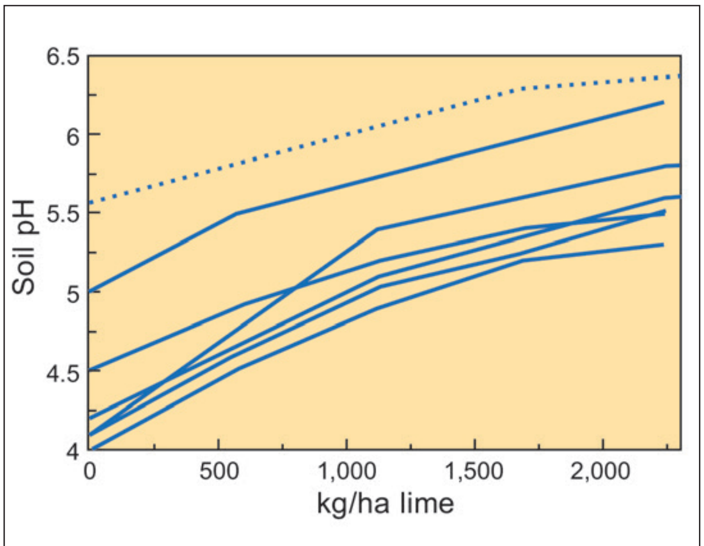

Figure 4. Examples from research trials illustrate the effect of slacked lime (dashed line) or dolomitic lime (solid lines) on soil pH in nurseries. Data are from trials in Wisconsin (Stoeckeler and Jones 1957, Voigt et al. 1958), Louisiana (Shoulders and Czabator 1965), and British Columbia (van den Driessche 1969).

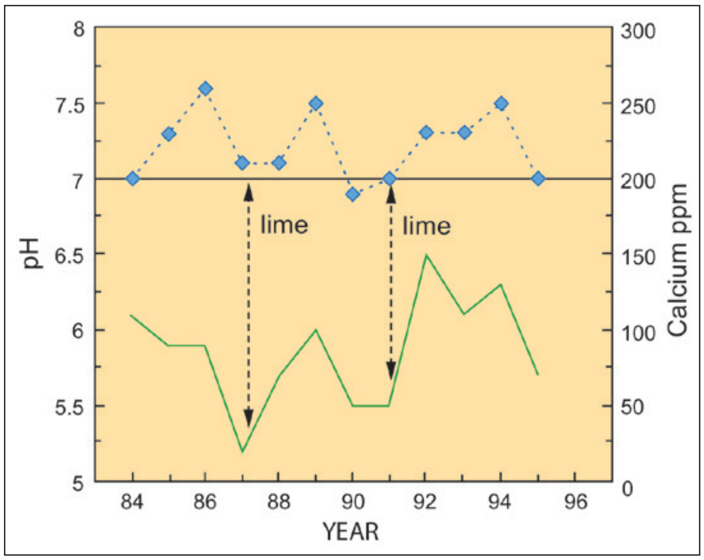

Figure 5. Operational data are from field i3 at the Westvaco Nursery in South Carolina. Dolomitic lime was added to the soil in the spring of 1987 (2,240 kg/ha) and again in the spring of 1991 (1,450 kg/ha). Both applications increased the availability of calcium (dotted line), and the second application increased soil pH to 6.5 (solid line). For each year, soil samples were collected in November.

1987, Kakei and Clifford 2000), and increase chlorosis (Richards 1965, Shoulders and Czabator 1965) (figure 1).

Gypsum, not lime, is recommended when soil pH is in the desirable range but Ca levels are low. In sandy nurseries, chlorosis and resin exudation may occur when available soil Ca is less than 100 ppm. When this happens, adding Ca will produce green needles and may increase foliar Ca levels to greater than 29 ppm (Voigt et al. 1958). Since the median level of Ca in sandy nurseries is 200 ppm (South and Davey

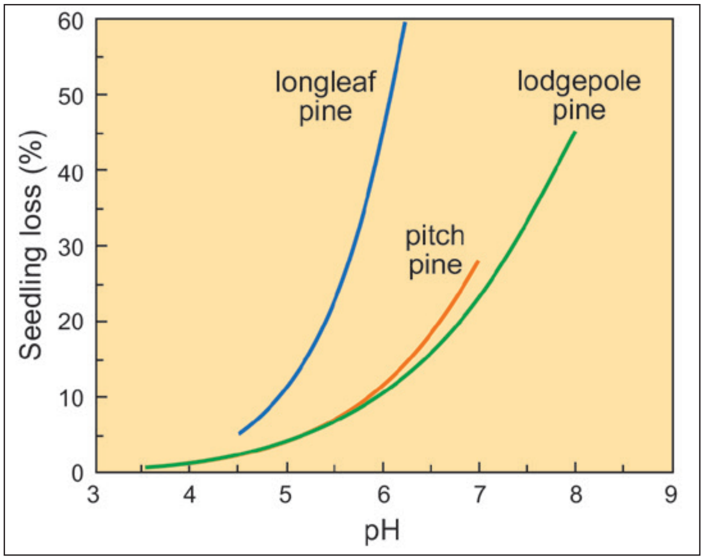

Figure 6. The relationship between pH and damping-off of pine seedlings in greenhouses. Data are for longleaf pine (*Pinus palustris*) (Pawuk 1981), pitch pine (*Pinus rigida*) (Helm and Kuser 1991), and lodgepole pine *(Pinus contorta*) (Griffin 1958).

1983), most managers add Ca when soil tests show levels below 200 ppm (e.g. figure 5).

When should lime be applied to bareroot pine beds to increase pH? Operational data show good growth of pine seedlings when soil pH is less than 4.5. In 2016, fertilized loblolly pine seedlings (in one experimental plot) grew well at pH 3.5 at a nursery in Texas (figure 7). In 1977–78, pine seedlings performed well at pH 4.2 (Griffith Nursery, NC and Nepco Lake Nursery, WI) and pH 4.3 (Ashe Nursery, MS and Vallonia Nursery, IN) (Marx et al. 1984). Other studies have shown that some pines grow well at pH 3.6 to 3.8 in the field (Marx et al. 1995, NCSFNC 1991, Woodwell 1958). On the other hand, stunted pines have been observed at pH 3.6 (Carey et al. 2002) and pH 2.9 (Sundling et al. 1932), and stunted Larix seedlings have been observed at pH 3.8 (Choi et al. 2008). Since poor soil sampling can yield variable results, a tentative trigger point for liming nursery soil might be pH 4.4. This is 0.3 units lower than the current trigger value for southern pines and 0.7 units lower than the value used in the past. In contrast, where manganese (Mn) toxicity is possible, it would be wise to lime when soil pH reaches 4.9. Lowering the trigger value for lime to pH 4.4 might save money. First, the frequency of liming would likely be reduced, since it will take longer for soil to reach this level of acidity. Second, the cost per kg of lime applied would be lower, since the biggest cost of liming is the application. Thirdly, for some soils, the nutrient use efficiency may increase when pine seedlings are grown in soil at pH 4.5 to 5.0. As a result, less N would be required (versus pH 6.0 to 6.5) to produce the desired "target seedling" (Marx 1990).

Figure 7. This photo shows loblolly pine (*Pinus taeda*) seedlings (average 32 cm height and 8.2 mm root-collar diameter; measured in February) in pH 3.5 to 3.6 soil. Soil in this plot was treated with 2,440 kg/ha of elemental sulfur on April 9, and seed were sown on April 16, 2016. Rainfall during the 2 weeks following sowing was above average (330 mm total). The topsoil in this plot contained 96 ppm of sulfur in July. If rainfall had been low, however, gypsum crystals (figure 8) might have formed and stunted the seedlings. (Photo by Gene Bickerstaff, Arborgen, 2017).

When To Add Sulfur

Sulfur has been beneficial at several nurseries. At a nursery in New York (80 to 90 percent sand; CEC 8 to 11), adding 2,000 kg/ha of sulfur (as sulfuric acid) increased soil acidity, from pH 6.5 to 6.2, and doubled seedling production (Bickelhaupt 1987). At a pine nursery in North Dakota (silt loam, organic matter 4.6 percent, pH 7.9), applying 1,525 kg/ha of sulfur at the time of sowing increased acidity (to pH 6.8) and doubled seedling mass (Stoeckler and Arneman 1960). At a nursery in Ontario (83 percent sand; CEC 4 to 8), 840 kg/ha of elemental sulfur lowered soil pH, from 6.5 to 6.0, and increased seedling production by 8 percent (Mullin 1964). In Poland, adding 1,200 kg/ha of sulfur increased root-collar diameter of Scots pine (Januszek and Barczyk 2003).

Operational timing of sulfur applications to lower soil pH varies widely. Some nursery managers apply ammonium sulfate or elemental sulfur when the soil pH is at 6.6, while others apply sulfur at pH 6.0 (Mizell 1980). In the Southern United States, 900 kg/ha of elemental sulfur is a common rate applied at sandy nurseries (Davey 2002). Of course, when a sulfur deficiency exists, it is wise to apply a lower rate of sulfur (e.g. gypsum; ammonium sulfate) even to strongly acidic soils (Bolton and Benzian 1970, Lyle and Pearce 1968).

Armson and Sadreika (1979) suggest sowing seed at least 2 months after soil incorporation of sulfur, and van den Driessche (1969) said this interval should be as long as possible. When rainfall is limited, however, applying sulfur a few months prior to sowing can result in gypsum crystals forming on roots (figure 8). Although chlorosis and stunted growth were observed after a sulfur application at two nurseries (Carey et al. 2002), stunting was attributed to the formation of gypsum crystals on roots. In years with normal rainfall, no stunting has been noted after applying 900 kg/ha of sulfur. To reduce the risk of gypsum crystals forming on pine roots, sulfur application should be applied before sowing a cover crop. This will allow a year for sufficient rainfall to convert the sulfur to sulfuric acid.

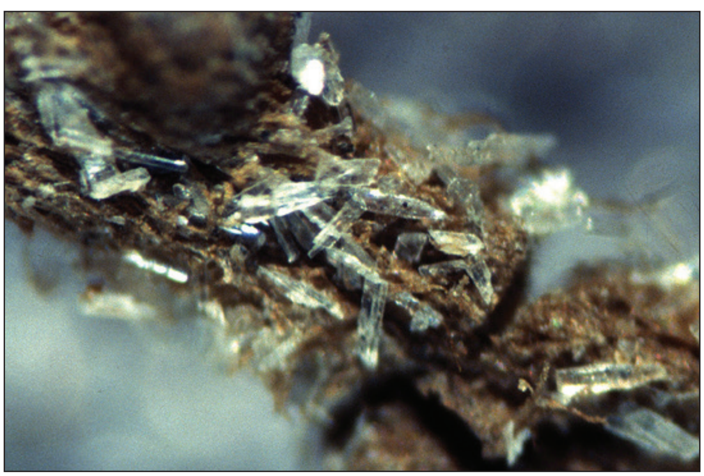

Figure 8. Applying too much sulfur prior to sowing can cause gypsum crystals to form on roots of pine seedlings when rainfall is low. These loblolly pine (*Pinus taeda*) roots were growing in pH 3.6 soil at the Verbena Nursery in Alabama. To reduce the chance of crystals forming on conifer roots, sulfur can be applied prior to sowing cover crops. (Photo by Bill Carey, Auburn University, 1998)

Figure 9. Loblolly pine (*Pinus taeda*) seedlings were grown in a sandy soil where an accidental overdose of elemental sulfur resulted in stunted root development. Soil acidity in July (same time as the photo) was pH 3.3, and the topsoil contained 94 ppm sulfur. Foliar nutrients were: 2.0 percent nitrogen, 0.24 percent phosphorus, 1.04 percent potassium, 0.08 percent magnesium, 0.19 percent sulfur, 0.2 percent calcium, and 77 ppm boron, 8 ppm copper, 949 ppm manganese, and 236 ppm aluminum. (Photo by Chase Weatherly, Arborgen, 2014)

It is important for managers to sample soil in cover crop fields to avoid applying sulfur only a few months before sowing pines. Toxic oxidation products are produced soon after sulfur applications (van den Driessche 1969), which may explain why phototoxic symptoms on roots occurred when too much sulfur was applied a few weeks prior to sowing pine (Mullin 1964). Sundling (1932) applied an unknown amount of sulfur to a Morrison sand, and roots in the most acid pots (pH 1.5) were dark brown with black root tips. An accidental overdose of sulfur at one nursery resulted in a pH 3.3, and by July, stunted roots had the appearance of nematode injury (figure 9). To reduce the risk to young pine germinates, Mizell (1980) applied sulfur at 450 kg/ha before sowing a cover crop and then checked soil pH in the following winter. If the pH had still been above pH 5.9 in March, he would apply another 450 kg/ha before sowing pine seed.

Problems With Low pH on High Manganese Soils

Mn toxicity can occur on fine-textured soils (less than 75 percent sand) with low soil pH (Adams and Wear 1957), and this can be exacerbated by flooding. High levels of Mn may have induced a Ca deficiency at a nursery in Alabama and an Fe deficiency at a nursery in Louisiana (Shoulders and Czabator 1965). When combined with high soil moisture (resulting in low soil oxygen), high levels of Mn can injure pine seedlings (Slaton and Iyer 1974). In a greenhouse study, adding 45 kg/ha of Mn (as Epsom salt) killed red pine seedlings when the water table was 15 cm below the surface. In contrast, when soils were not flooded, applying manganese sulfate did not affect white pine (*Pinus strobus* L.) or loblolly pine seedlings (Shoulders and Czabator 1965, St. Clair and Lynch 2005).

Lowering pH tends to increase the availability of Mn (figure 10). At one nursery in Alabama, in 2008, loblolly pine seedlings were chlorotic when foliage contained 990 ppm Mn, but those with 688 ppm Mn were green. The median level of Mn for loblolly pine seedlings at harvest is about 485 to 520 ppm (Boyer and South 1985, Starkey and Enebak 2012), and the maximum reported level of Mn for loblolly pine foliage in plantations was 916 ppm (Albaugh et al. 2010). In greenhouse trials with pines, growth was reduced when foliar levels exceeded 855 ppm of Mn (Kavvadias and Miller 1999, Morrison and Armson 1968). Some nursery managers apply a mixture of micronutrients to loblolly pine seedlings during the summer, which may explain why one foliage sample in January contained 1,677 ppm of Mn (Starkey and Enebak 2012). Sandy soils have a low reserve of Mn, and therefore are less likely to experience toxic levels of Mn. If the nursery soil has a high reserve of Mn, it may be wise to maintain the pH above 5.0.

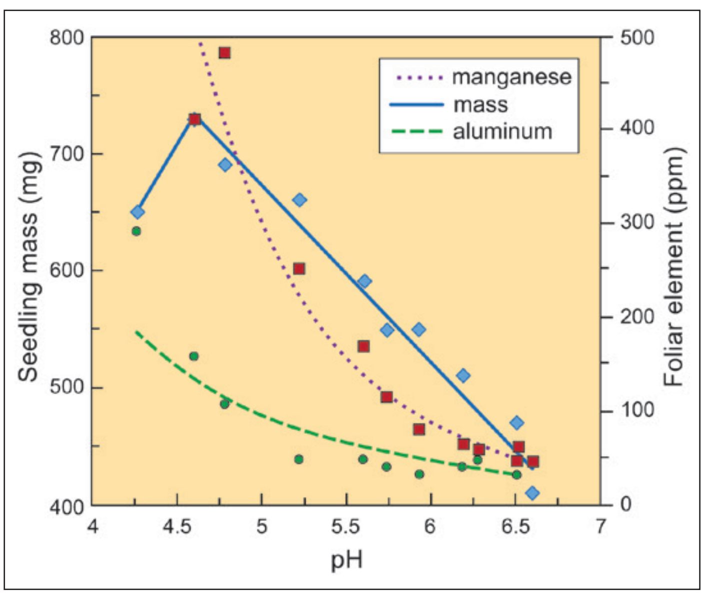

Figure 10. The effect of media pH on seedling mass and foliar aluminum and magnesium on container-grown pitch pine (*Pinus rigida*) seedlings (Helm and Kuser 1991). Seedlings grown with no dolomitic lime (pH 4.3) contained 58 percent more mass than seedlings grown with 40 g of lime per kg of medium (pH 6.6). In this trial, decreasing foliar aluminum concentrations by applying dolomitic lime was not beneficial to seedling growth.

Advantages of Low pH in Conifer Seedbeds

In the past, lowering soil pH with sulfuric acid was an effective pest management practice (Bickelhaupt 1987, Hartley 1921, Jackson 1933, Wilde 1954). Beneficial fungi (*Trichoderma* and *Penicillium*) may increase as acidity increases (Huang and Kuhlman 1991). Populations of damping-off fungi, nematodes, and certain weeds (Aldhous 1972, Buchanan et al. 1975, Huang and Kuhlman 1991, Stoeckeler and Slabaugh 1965) may all be lower when nonfumigated seedbeds have pH values less than 5.0. It has been suspected for some time that nematode populations are lower in acid soils (Wilde 1934), and numbers of some species of nematodes decrease as soil acidity increases to pH 4.0 (Burns 1971, Korthals et al. 1996, Willis 1972).

Seed efficiency may be greater when the soil pH is less than 5.0. In some trials, more than 40 percent of longleaf pine seedlings (*Pinus palustrius* Mill.) died when container media exhibited pH greater than 6.0 (Pawuk 1981). Helm and Kuser (1991) found that pitch pine damping-off mostly occurred at pH greater than 6.0 (figure 6). When pH was 3.5, mortality of lodgepole pine (*Pinus contorta* Douglas ex Loudon) did not exist, but at pH 6.1, about 20 percent of seedlings died due to damping-off (Griffin 1958). In a simulated acid rain study with white pine, seedling emergence was 17 percent greater at pH 4.0 when compared to pH 5.7 (Lee and Weber 1979). Typically, damping-off of pines in containers is lower when pH values are less than 5.0 (figure 6).

Several researchers report that the percent N concentration in conifer needles increases as soil pH decreases (Coultas et al. 1991, Helm and Kuser 1991, Kraus et al. 2004, Marx 1990, Schiler 1986, van den Driessche 1971). When both seedling mass and N concentration increase, it follows that nutrient use efficiency increases. Possible reasons for greater uptake of N on more acidic soils include (1) lower consumption of N by soil microorganisms, (2) reduced leaching of nitrate (NO_3^-), and (3) less activity by nematodes. The belief that N use efficiency is low when pines are grown on "very strong acid" soils appears to be poorly supported.

Warnings About Low Soil pH

Wilde (1954: p. 89) said concerns about the toxicity of hydrogen ions to roots have been "grossly exaggerated." The exaggerated claims originated from "artificially prepared cultures," not soil studies (Wilde 1954). Although some experts claim growing pine seedlings in soil that is below pH 5.2 is not optimum, most provide no data to show their warnings have merit. Some admit they do not know what problems might result when adequate fertilizers are applied to low pH soils (Stone 1965). In contrast, Davey (1991) said that poor growth of pines might occur on low pH soils (with low CEC) due to deficiencies of K, Ca, Mg, and possibly due to toxicity from Mn, Fe, copper (Cu), and zinc. Some (Davey 1991, Landis 1989) warn against high levels of available aluminum (Al), although pines seem to be very tolerant of Al (Cronan et al. 1989), and most sandy soils contain low levels of Al. Al toxicity was not observed in a greenhouse when pines were grown in soil at pH 3.0 (Coultas et al. 1991), or when 740 kg/ha of aluminum sulfate was applied to bareroot seedbeds (Januszek et al. 2014). Naturally high levels of Al are not known to have undesirable effects on conifers (Stone 1965). In fact, seedling growth may increase, up to a point, when both soil acidity and foliar Al increase (Marx 1990, figure 10).

Some authors warn about Ca, Mg, and K deficiencies when seedlings are grown on soils with a pH less than 5.0 (Bueno et al. 2012, Davey 1991, Krause 1965, Voigt et al. 1958). Decreasing soil pH by adding sulfur will increase leaching of Ca, Mg, and K from the soil (figure 11). Increasing soil pH by adding dolomitic lime will increase Ca and Mg levels, and this explains why the correlation between soil pH and the amount of these elements in nursery soils is positive (South and Davey 1983). Increasing soil pH, however, does not prevent Ca leaching in sandy soils (figure 5), and the pH of forest soils is not significantly related to the level of these three elements (NCSFNC 1991, Wytienbach et al. 1991). When soil levels of these cations are low, many nursery managers add fertilizers. For example, when a Ca deficiency occurred in Georgia, an application of gypsum greened up pine seedlings within a month (Haugabook 2017). Cu deficiencies have occurred in pH 3.9 soils in pine plantations (South et al. 2004) and at a peat nursery with pH 4.2 soil in New Zealand (Knight 1975). Cu deficiency for pines, however, has not occurred in nurseries in the 13 Southern States that have sandy soil comprised of low amounts of organic matter with low pH. Several nursery managers apply Cu prior to sowing, when levels in the topsoil fall below 0.7 ppm. Even in low pH soils, the Cu level in loblolly pine foliage was above average (Albaugh et al. 2010, Boyer and South 1985) (figure 9).

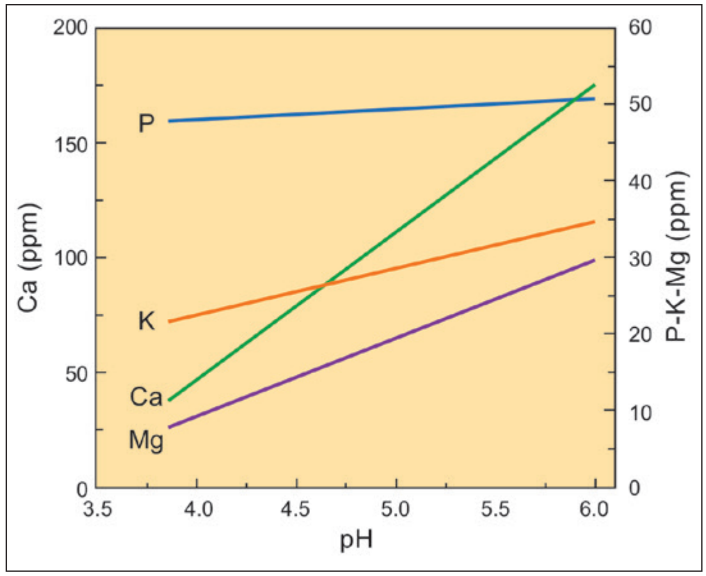

Figure 11. Adding sulfur to a sandy loblolly pine (*Pinus taeda*) nursery (pH 5.0 to 5.3) lowered pH to 4.6 to 3.9, and this lowered available calcium, magnesium, and potassium (soil nutrients measured in the following winter). In contrast, adding dolomitic lime increased soil pH to 5.4 to 6.0 and, as expected, it increased the levels of soil calcium and magnesium.

Future Research

"Assessment of a desirable pH range of a given species is quicker and easier than many growth factors often investigated for improving plant growth and should be one of the first factors investigated" (Bryan et al. 1989: p. 64). For a given pine species and environment, researchers can determine a peak pH value where seedling growth is maximized (e.g. Howell 1932). Future research might determine (1) the shape of the pH-growth curve and (2), exactly why growth increases as hydrogen ion concentrations increase.

There appears to be an interaction between soil texture and optimal pH range. For some fine-textured soils, low soil pH may result in Mn toxicity, but no toxicity occurs when the CEC is low (e.g., sandy soils with less than 2 percent organic matter). Future research is needed to better understand the relationship among soil pH, soil CEC, and Mn toxicity.

An interaction also exists between rainfall and formation of gypsum crystals on pine roots (after applying sulfur to pine seedbeds) (figure 8). For example, applying 1,500 to 2,000 kg/ha of elemental sulfur a few months prior to sowing pines may increase seedling production for years with normal rainfall (Bickelhaupt 1987, Mullin 1964). In a dry year, however, even 900 kg/ha of sulfur might cause problems (Bueno et al. 2012, Carey et al. 2002). Future research could provide more information about this interaction.

One trait common to almost all pH trials is the confounding of certain elements with pH treatments. Most researchers will either start with a high pH soil and lower it with sulfur or an acid treatment, or will start with a low pH soil and then add some type of lime. A classic example of confounding involved overcoming a foliar deficiency of Ca and Mg (Voigt et al. 1958) by applying dolomitic lime over the top of Jack pine seedlings (*Pinus banksiana* Lamb.). Not surprisingly, chlorosis was reduced by one-half, but this could lead to the erroneous conclusion that growth of pine is optimum at pH 5.0 to 6.0 (instead of pH 4.5 to 5.0).

An alternative approach to a single amendment trial would be to conduct a paired trial in which one trial evaluates acidifying an alkaline soil and another evaluates liming an acid soil. Establishing paired trials might result in fewer confounding risks and stronger conclusions about the direct effects of soil pH on seedling growth.

Conclusions

Field observations and greenhouse trials confirm that a range of pH 5.5 to 6.5 is not optimum for growing most pines in nurseries. When based on data, the desired range for growing pine seedlings at sandy bare-root nurseries (more than 75 percent sand) is likely pH 4.5 to 5.0 (Aldhous 1972, Benzian 1965, Brix and van den Driessche 1974, Januszek and Barczyk 2003, Marx 1990). A range of pH 5.0 to 5.5 would be appropriate for fine-textured soils containing high levels of Mn.

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Seed Moisture Content, Relative Humidity, and Better Storage of Longleaf Pine Seed

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Abstract

The science for preserving the germination of longleaf pine (*Pinus palustris* Mill.) has long been known. In practice, however, the germination of longleaf pine seeds after 1 to 5 years of storage is disappointingly low, resulting in significant financial losses and threatening an already precarious seed supply that is needed for restoration and reforestation. This article discusses the relationship between seed moisture and relative humidity and how that relationship indicates ways to improve the handling of longleaf pine seeds so that germination is maintained in storage. Emphasis is placed on using equilibrium relative humidity testing as a way to improve seed longevity. This paper was presented at the Joint Meeting of the Northeast Forest and Conservation Nursery Association and Southern Forest Nursery Association (Lake Charles, LA, July 18–21, 2016).

Introduction

Trees produce seeds in cycles and, therefore, seeds are commonly preserved during bumper crops for use in years with poor seed crops. For at least 50 years, foresters have understood that the viability of desiccation-tolerant (also called orthodox) tree seeds is preserved by drying the seeds to a moisture content of 6 to 9 percent and then freezing them in sealed, moisture-proof containers (Jones 1966). These moisture and temperature conditions lower the metabolic rate of seeds, thereby putting them in a resting stage where they can remain alive for many years. Of these two storage variables, moisture is the most critical factor (Bonner 2008, Justice and Bass 1978). Barnett (1969) and Barnett and Pesacreta (1993) recommended drying longleaf pine (*Pinus palustris* Mill.) seeds to 10 percent moisture content or lower; they also found the seeds could be stored for up to 7 years at -4 °C (25 °F) and at least 20 years at -18 °C (0 °F). Unfortunately, however, many clients of the USDA Forest Service's National Seed Laboratory (NSL; Dry Branch, GA) have reported unacceptable germination losses after 1 to 5 years of storage, in spite of adhering to these storage recommendations. Thus, some improvement is needed in the operational handling of the seeds to produce a better storage result. To give a good framework for discussing the problem and possible solutions, we will first discuss the concept of seed vigor and moisture relations for longleaf pine seed.

Longleaf Pine Seed Vigor

Germination is the emergence from the seed of a seedling with all essential plant parts. For a particular seed lot, it is expressed as the number of individual seeds out of 100 seeds that germinate. Seed vigor is a concept for determining the relative value of seed lots of comparable germination. It is typically defined using either the speed of germination, the ability to germinate under adverse conditions, or the ability to not lose germination while stored. Understanding vigor as the ability to withstand the loss of germination during storage is the definition most appropriate to the issue with longleaf pine longevity addressed in this article. Therefore, we can think of longleaf seed lots that decrease in germination during storage as not sufficiently vigorous to remain alive. When a seed dies, the switch from living to dead is not immediate. A period of aging and loss of vigor precedes the loss of the ability to germinate. Vigor initially declines at a faster rate than germination does (figure 1). When the vigor loss line in figure 1 is more horizontal, the seeds survive for longer periods of storage. When the vigor line has a steeper slope, the seeds do not survive as well and a drop in germination will be realized sooner.

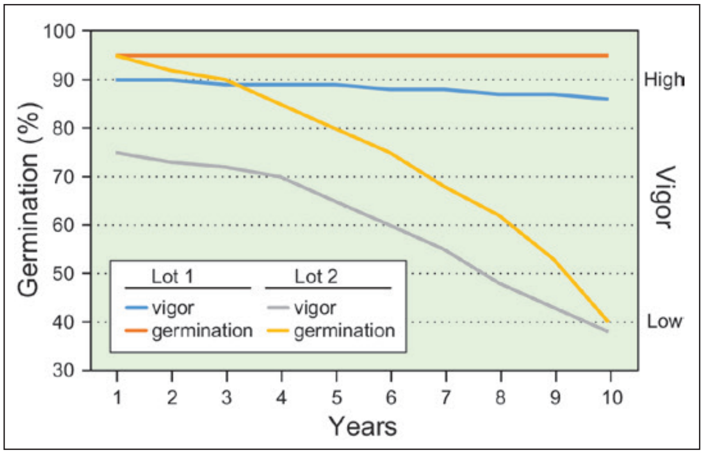

Figure 1. Illustrative graph of seed vigor decrease and germination loss over time. Seed lot 1 is high vigor. Seed lot 2 is lower vigor.

McLemore (1961) reported that longleaf pine seeds must be extracted from the cones within 30 days of harvest for best germination, and that seeds extracted at 60 days postharvest had lower germination. By contrast, high-quality seeds can be extracted from most other conifers, including all other southern pines, for 60 to 90 days postharvest. Therefore, at the very beginning of the process, longleaf pine seeds are demonstrating low seed vigor and a low capacity to remain viable in storage. Interpreting McLemore's findings in light of the vigor graph (figure 1), we can say that at some point between the date of cone collection and 30 days later, vigor begins to decline but not so much that it causes a measureable decline in germination. At some point between 30 and 60 days of cone storage, however, the seeds decline sufficiently in vigor so that germination also declines. The seeds are not dying from a sudden trauma, but from a series of small, cumulative, and increasing losses of vigor over time. Vigor losses initiated during cone storage are likely to increase with time. This process occurs with all pine species, but is more an issue with longleaf pine seeds because they have little or no dormancy. That means they are more physiologically active at harvest time compared with other species of pine seeds. Without internal mechanisms to arrest biological activity, only the control of seed moisture and storage temperature can retard the deterioration process. Another factor influencing the loss of vigor is that longleaf seeds are shed from kiln-dried cones at high moisture levels, which is not the case with other southern pines. To expand on these concepts and improve the preservation of longleaf pine seed quality, three trials were conducted on the relationship between seed moisture content and relative humidity (RH).

Materials and Methods

Two methods were used in these trials to assess seed moisture. The first method was the constant temperature oven method (ISTA 2017) in which seeds are weighed, dried for 16 hours at 103 °C (217 °F), and then reweighed. The weight loss (assumed to be the weight of water originally in the seed) is divided by the original weight of the sample, and the answer is multiplied by 100 to give the moisture percentage on a wet-weight basis. The second method is equilibrium relative humidity (eRH). Testing eRH has been discussed elsewhere (Baldet et al. 2009, Karrfalt 2014) and will be reviewed again here with specific reference to longleaf pine. Figure 2 shows hygrometers (VWR International catalog number 35519-020) attached to test chambers (50 ml Erlenmeyer flasks) containing seeds. Any quality hygrometer can be used, and any vessel can be used to hold the seeds, as long as it can be sealed securely enough to isolate the air inside the vessel from the outside air. Just as seeds adjust their moisture content to changes in RH, air in a closed vessel adequately filled with seeds will adjust to the moisture of the seeds. For example, when seeds are equilibrated at a RH of 30 percent, the air around them in a closed vessel will adjust to RH of 30 percent. The test chamber must be at least one-quarter full; more seed gives more buffer against moist ambient air (50 percent or more RH).

A quality hygrometer costs between $300 and $600. Less expensive hygrometers have not provided reliable service at the NSL. The Rotronic water activity meter (figure 3) (HygroPalm - HP23-AW-A—portable

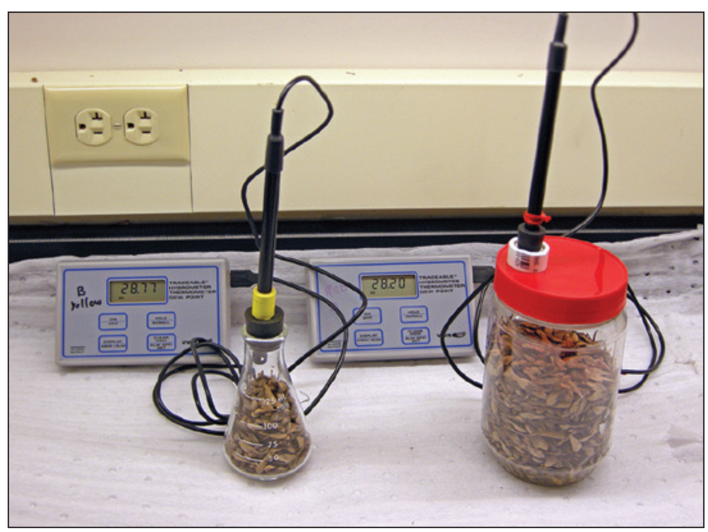

Figure 2. Hygrometers are attached to test chambers to measure seed equilibrium relative humidity. (Photo by R.P. Karrfalt 2017)

Figure 3. Rotronic water activity meter used to measure seed equilibrium relative humidity on small seed samples. (Photo by R.P. Karrfalt 2017)

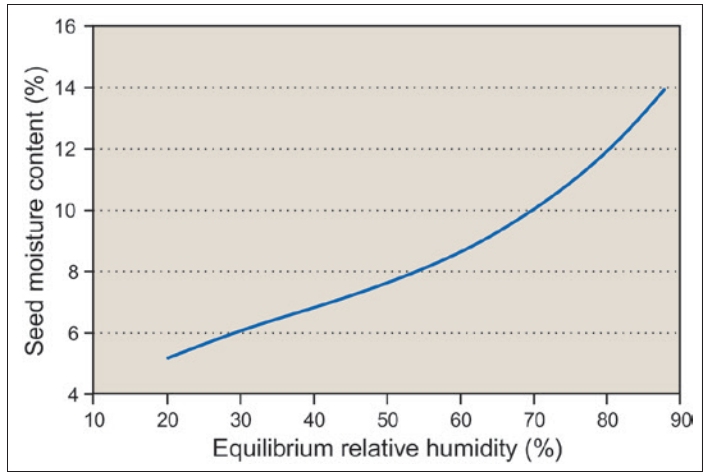

Figure 4. Moisture content of longleaf pine seeds plotted against equilibrium relative humidity.

analyzer, Rotronic USA) is much higher priced ($3,000 or more) than the VWR hygrometer. It was designed for use in the food industry and expresses the RH as water activity which, from a practical point of view in testing seeds, is really only the RH expressed as a decimal rather than as percent. For example, 30-percent RH is equal to 0.30 water activity. The concept of water activity has value in understanding the physiology of the seeds, but for the purpose of determining if seeds are sufficiently dry for storage, it only adds confusion. The Rotronic meter has the advantage of accommodating small samples.

All seed lots used in these trials were samples submitted to the NSL for routine germination tests for nursery sowing and had been in storage for 1 or 2 years.

Trial 1

eRH and seed moisture content are closely related. To describe this relationship, five longleaf pine seed lots were subjected to eight constant RHs, ranging from 20 to 87 percent. Each humidity level was regulated in a closed plastic box by a saturated solution of an appropriate inorganic salt. Seeds were placed in small containers designed for use with the Rotronic water activity meter (figure 3). One open container of each seed lot was then suspended over the salt solution on a fine-screen rack until the weight of the sample had stabilized, and seeds were judged to be at equilibrium with the respective RH. Upon reaching equilibrium, each sample was tested for its eRH with the Rotronic water activity meter and then for moisture content using the constant temperature method. Moisture contents were then plotted against eRH to produce an isotherm (figure 4).

Trial 2

Following a drying period, the initial eRH values were not the same as values taken some time later. To clarify what was happening, a drying trial was done. Seven longleaf pine seed lots, ranging from approximately 33- to 58-percent eRH, were dried on a pressurized dryer (Karrfalt 2014) for 2 hours at 26-percent RH. The seeds were then transferred to test vessels, and the hygrometer was attached and left connected and undisturbed until all readings were complete. The eRH of each seed lot was recorded 10 minutes after drying was stopped and then at 11 additional intervals over the next 120 hours. These eRH values were then plotted against time (figure 5).

Trial 3

To measure how much and how fast seed moisture content might increase with the ambient RH, samples from seven longleaf seed lots were placed into six RH treatments (42 combinations total). The eRH of all lots initially ranged from 30 to 35 percent. The same saturated salt technique described in trial 1 was used to establish the six different RHs. All samples were weighed at the start of the trial and again after 48, 72, and 96 hours to detect moisture increases. From these weights, the moisture content of each sample-humidity combination was calculated.

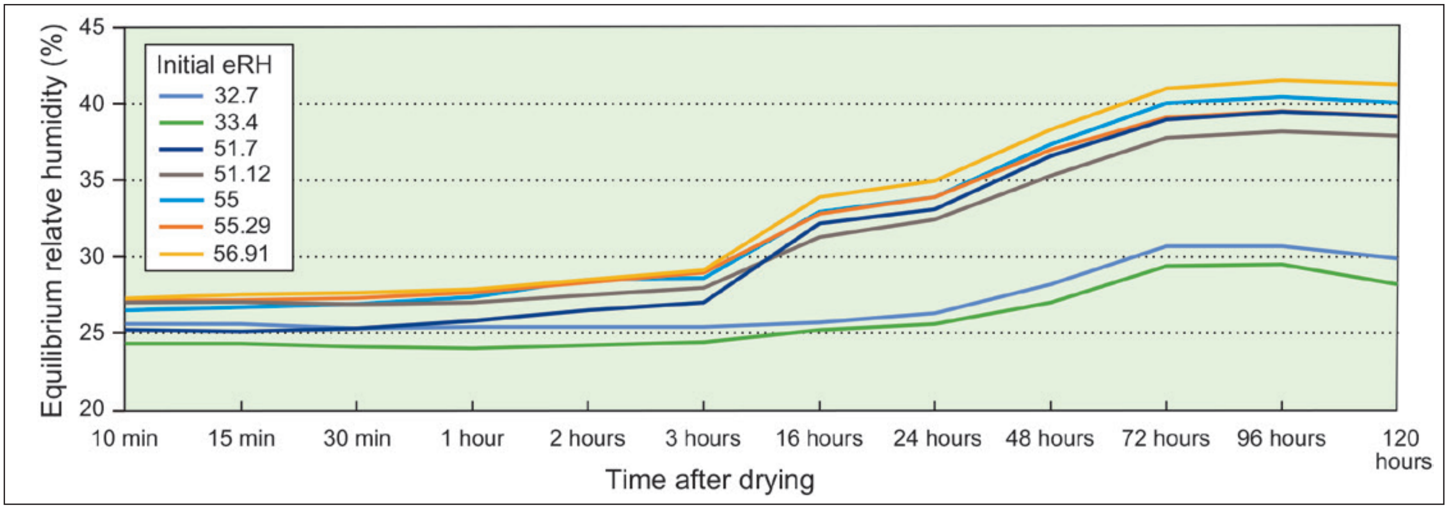

Figure 5. Equilibrium relative humidity readings change until seeds obtain internal moisture equilibrium. Water moves from the inside of the seed to the outer layers until all layers of the seed are in moisture equilibrium.

Results and Discussion

Trial 1

The isotherm shown in figure 4 is typical for seeds of many species. It indicates that 30-percent eRH corresponds to 6-percent moisture content and approximately 60-percent RH corresponds to 9-percent moisture content. In other words, seeds equilibrated at RHs between 30 percent and 60 percent would be in the moisture-content range that Barnett recommended for maintaining longleaf seed germination for 20 years. Equilibrating seeds at RH ≤ 30 percent is not a good idea, because the water removed at those lower RHs is structurally important to the cells, and removal will damage the cell membranes. On the other hand, enzyme activity increases as eRH increases above 30 percent. Therefore, 30 percent should be the best humidity at which to equilibrate longleaf pine seeds for storage because the rate of seed metabolism is as minimal as possible, without damaging the cells by overdrying. This optimal humidity was also apparently the case with sagebrush (*Artemesia tridentate* var *wyomingensis* Beetle & Young) (Karrfalt and Shaw 2013), another desiccation-tolerant species that is frequently short-lived in storage. At storage temperature of -8 °C (17.6 °F), sagebrush seeds at 40-percent eRH did not survive as well as seed equilibrated at 30-percent eRH. Because 30-percent eRH appears to be an optimal seed moisture level for storage, it is logical to use eRH as a moisture test. As will be explained later, moisture content can be less precise for indicating that the optimal moisture status has been achieved.

Trial 2

After drying longleaf pine seed for 2 hours with air at 26-percent RH, all seed lots in trial 2 had the same eRH, of 26 percent, for at least 1 hour. Those seed lots, which were initially the driest (predry eRH of 32.7 and 33.4 percent), continued to test at 26 percent for 3 hours and changed very little, even at 24 hours. All seed lots took until 72 hours to present their true eRH, one that did not change during the next 24 hours. These results imply two things. The first implication is that recently dried seeds may give a false reading lower than the true eRH, requiring subsequent readings to be sure the values are correct. If the readings are not verified, seeds might be put into storage at moistures higher than optimal to preserve germination and vigor. The second implication is it can take up to 3 days for water deep inside the seed to work its way to the surface of the seed coat and evaporate (figure 6). In other words, it can take 3 days, perhaps longer, to dry longleaf seeds to a moisture content that is safe for storage. This finding is especially important on the initial dry of seeds just freshly extracted from the cone, as they are known to be 10-percent moisture content or higher, or in terms of eRH, above 70 (figure 4). Because it is the first time seeds are being dried, they will likely have moisture in the layers of gametophyte furthest from the seed coat and the embryo. Meters that estimate moisture content will be discussed in the following but are mentioned here to say that they, too, can produce false readings because the surface layers of the seed can be drier than the interior portions.

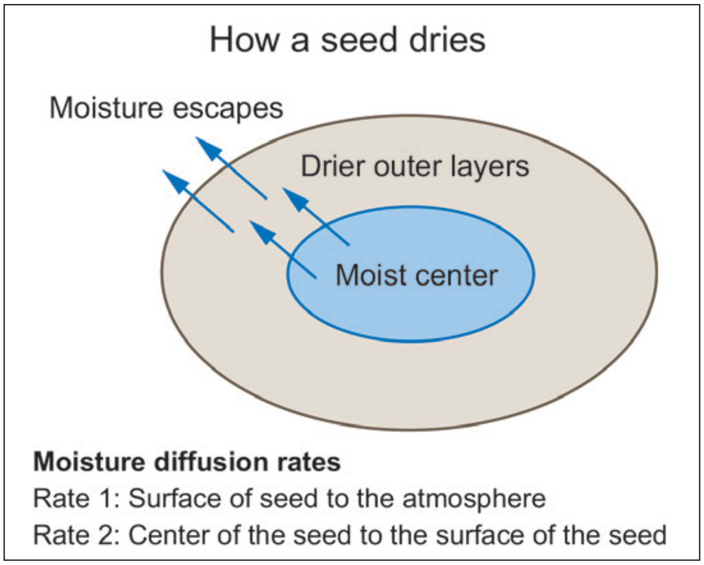

Figure 6. Moisture moves within the seed from areas of higher moisture to areas of lower moisture until the seed is internally at moisture equilibrium.

Trial 3

From trial 3, we see how much and how fast seed moisture content increases under different ambient RHs (table 1). When ambient conditions are near 30 percent, the seeds remain near their ideal moisture content to remain vigorous and able to germinate. As RH increases, seed moisture content also increases. When ambient conditions are damp and RH exceeds 70 percent, seeds can become borderline or even reach dangerous moisture contents in as little as 48 hours. Therefore, it is very important not to leave seeds exposed to humid air unless necessary to work with the seeds for short periods of time. Ideally, seed moisture should be monitored frequently each day the seeds are exposed to ambient conditions. Drying should be done as soon as possible when eRH values are 40 percent or above to bring the seeds back to the optimal eRH of 30 percent. Never make the assumption that once the seeds are dry they will remain dry. Seeds are continually adjusting their moisture level to the humidity around them.

Table 1. Mean moisture content of seven longleaf pine seed lots over time when exposed to air of six different relative humidity levels.

	Mean moisture contents		
RH (%)	48 hours	72 hours	96 hours
33	6.4	6.4	6.5
43	7.1	7.2	7.3
53	8.0	8.5	8.6
76	9.0	9.6	10.2
84	9.7	10.3	11.3
100	13.8	15.3	18.2

RH = relative humidity.

Moisture Meters and Longleaf Pine Seed

Moisture meters (figure 7) have been used to test longleaf pine seed moisture content. To use a moisture meter, the seeds are poured into a chamber between two electrodes. Then the electrodes are energized and either the conductance or resistance between them is measured. The meter reading is converted to moisture content using a previously constructed conversion chart. Accurate readings from these meters require that the seeds make solid contact with the electrodes. Therefore, only well-cleaned seeds can be tested in moisture meters. Monitoring moisture in unfinished raw seeds with a moisture meter is not possible without first cleaning the test sample to the same degree as the finished product. In addition, raw seeds will still contain empty seeds that will bias the moisture meter reading toward moisture contents lower than is true for the full seeds. Although moisture meters are available, a hygrometer testing eRH is more reliable because it is able to accurately test the seeds without bias, regardless of the state of cleaning, thereby enabling frequent, if not nearly continuous, seed-moisture measurements.

Figure 7. Seed moisture meter that has been used to estimate seed moisture content. (Photo by R.P. Karrfalt 2016)

Quality Control for eRH Testing

In addition to regular checks of seed eRH, checks on the hygrometer need to be made on a regular schedule. During the seed-cleaning season, the hygrometer should be checked daily and before use at other times of the year. The check is made by filling a test vessel about halfway with a saturated solution of magnesium chloride and then measuring eRH. Magnesium chloride is used because it will create an RH very close to 33 percent between the temperatures of 20 and 30 °C (68 and 86 °F). Choosing the 33-percent test value insures the meter is reading correctly for measuring the target value of 30-percent eRH with the seeds. Care needs to be taken not to get the solution on the hygrometer probe, as salt on the probe could create a bias when measuring seed eRH or damage the sensors. The hygrometer should read between 31 and 35 percent at the check; if the hygrometer fails it should be replaced or recalibrated.

Conclusion

eRH testing offers a new opportunity to increase the storage life of longleaf pine seeds. First, the understanding of seed moisture relations provided by eRH suggests that operationally produced seed lots might maintain better germination if moisture is reduced to the driest moisture condition recommended by Barnett. Theoretically, 30 percent eRH (6 percent moisture content) should be superior to 60 percent eRH (9 percent moisture content). Second, eRH testing can provide accurate moisture evaluations on raw seeds, which facilitates early detection of high seed moisture through frequent evaluations throughout the cleaning process, and subsequently the immediate drying of any seeds that are not at optimal moisture levels.

Key points for using eRH to improve longleaf pine seed storability are as follows:

1. Longleaf pine seeds are reduced in storability the longer they are held in the cone.

2. Seeds just extracted from the cone will be at high moisture content and will require immediate drying.

3. Germination is anticipated to be best-preserved by drying seeds to 30-percent eRH and maintaining seeds at that level.

4. Above 30-percent eRH, seeds are slowly and silently dying (losing vigor), which later shows up as an unexpected loss of germination, even in seeds between 6- and 9-percent moisture content.

5. eRH can be accurately measured on raw, uncleaned seeds as well as finished seeds.

6. Hygrometer accuracy should be checked every day of use with a saturated solution of magnesium chloride.

7. Freshly dried seeds might test as being drier than they actually are. You should repeat measurements in 16 to 24 hours to verify the accuracy of eRH test.

8. You shoud never assume dry seeds are staying dry. Test the eRH frequently and dry as needed.

9. Figure 8 provides a flow chart to guide the management of moisture in longleaf pine seeds.

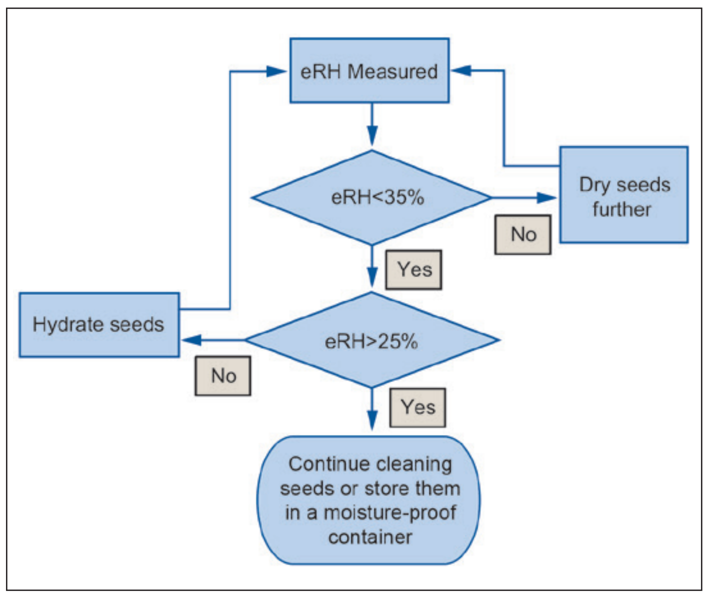

Figure 8. Flow chart of actions and decisions needed to maintain longleaf pine seeds at optimal moisture status to preserve germination.

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Regeneration Insect Pests: Protecting Southern Pine Seedlings After Outplanting

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Abstract

The intensively managed plantations of genetically improved pine (*Pinus* sp.) in the Southern United States have a low threshold for insect damage. Research has refined integrated pest management options for these insect pests of young pines. Timing of foliar applications to control the Nantucket pine tip moth (*Rhyacionia frustrana* [Scudder in Comstock]) is simplified by published optimal spray period predictions for all Southern States. Pales weevil (*Hylobius pales* [Herbst]) and pitch-eating weevil (*Pachylobius picivorus* [Germar]) are managed by adjusting planting schedules. New pesticides and application technologies are also available, such as synthetic pyrethroids for tip moth, weevils, and sawflies. Alternatives for tip moth management include a tablet formulation of imidacloprid and the biorational spinosad. Systemic neonicotinoids are labeled for white grubs, aphids, and scale insects, as are the biorational avermectins for spider mites. Fipronil can be applied to containerized seedlings in the nursery, as well as at planting. This paper was presented at the Joint Meeting of the Northeast Forest and Conservation Nursery Association and Southern Forest Nursery Association (Lake Charles, LA, July 18–21, 2016).

Figure 1. A healthy first-season progeny test of loblolly pine in South Carolina, an example of intensive forestry in the South. (Photo by Steve McKeand, North Carolina State University, Tree Improvement Cooperative, 2006)

Introduction

The large industrial forest plantations of the South produce more timber than any other region of the world. Virtually all of the intensively managed pine plantations in the Southern United States are comprised of genetically improved planting stock from tree improvement programs (figure 1); more than 95 percent are genetically improved loblolly pine (*Pinus taeda* L.) and slash pine (*P. elliottii* Engelm.) (McKeand et al. 2003). Seedling costs range from $25 to $200 per ac ($62 to $494 per ha), although elite, genetically improved loblolly pine seedlings are typically under $100 per ac ($247 per ha) (McKeand et al. 2010). When site preparation and other management costs are added, these plantations represent a major investment on a per-ac basis, thereby resulting in a great incentive to optimize survival and growth.

Insects can directly damage young pines or cause unthrifty growth. Fortunately, in the last 20 years, integrated pest management (IPM) programs have provided effective management options. This article describes some of the most important insect pests of southern pine seedlings and the effective management options to address them.

Southern Pine Insect Pests

Nantucket Pine Tip Moth

Nantucket pine tip moth (*Rhyacionia frustrana* [Scudder in Comstock]; Lepidoptera: Tortricidae) is the major insect pest of pine regeneration in the South (Asaro and Creighton 2011). This pest infests young pine plantations, tree improvement progeny tests, and Christmas tree plantations throughout the Eastern and Southern United States. Loblolly pine, shortleaf pine (*Pinus echinata* Mill.), and Virginia pine (*P. virginiana* Mill.) are the most commonly infested, whereas longleaf pine (*Pinus palustris* Mill.) and slash pine are only occasionally affected (Fettig et al. 2000, Nowak et al. 2010).

The Nantucket pine tip moth is primarily a pest of seedlings and young trees; attacks on older trees are not numerous, and the pests have little impact on trees older than 6 years of age. Infestations are most common and severe in the first or second year of plantation establishment. Larval feeding kills the terminal buds and tips of shoots, and the attached needles turn reddish brown (figure 2). Attacks are most common on the terminal leader (figure 3) and upper branches but all shoots can be infested (Nowak et al. 2010).

Stunting and deformation of trees occurs with resulting growth reduction. The height and volume growth lag delays rotation periods, which impedes the ability of managers to grow merchantable trees in the shortest time through intensive management (Nowak et al. 2010).

Adult moths are 4 to 7 mm (0.2 to 0.3 in) long and have forewings of red scales scattered among bands of gray scales (figure 4). Mated females deposit clusters of eggs on needles and shoots. Of the five larval instars, the first instar larvae enter needles and feed within, as do the second and third instars. The later instars are 9 to 10 mm (0.35 to 0.40 in) long yellow-red larvae and feed within the buds and shoots, consuming the vascular cambium and killing the bud or shoot. Pupation occurs in the damaged tip. Pupae are brown in color, about 6 mm (0.25 in) long, and overwinter in shoot tips (Asaro et al. 2003, Nowak et al. 2010).

Figure 2. A pine seedling severely infested with Nantucket pine tip moth (*Rhyacionia frustrana* [Scudder in Comstock]). (Photo by R. Scott Cameron, Advanced Forest Protection, Inc., Bugwood.org)

Figure 3. Damage to growing pine branch caused by larvae of the Nantucket pine tip moth (*Rhyacionia frustrana* [Scudder in Comstock]). (Photo by Ronald F. Billings, Texas A&M Forest Service, Bugwood.org)

The Nantucket pine tip moth has 2 to 5 generations per year depending on climate and location. The life cycle is synchronized roughly with host phenology so that a new generation of adults emerges with each new growth flush of the young trees (Asaro et al. 2003, Fettig et al. 2000). In spring, first-generation adults emerge in large numbers within a definite interval;

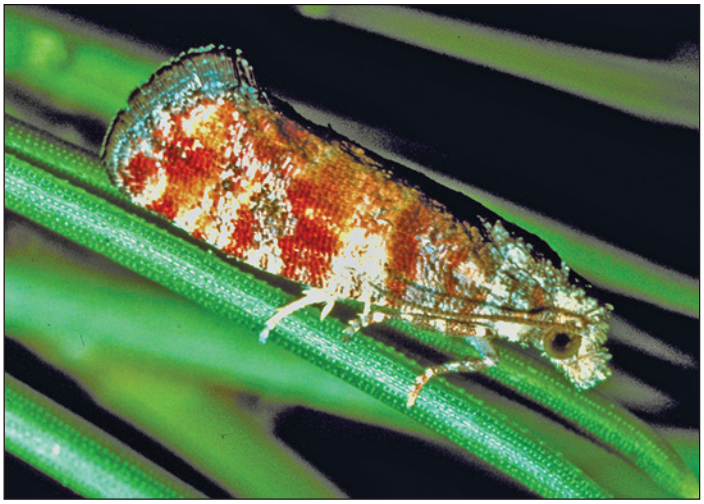

Figure 4. An adult Nantucket pine tip moth (*Rhyacionia frustrana* [Scudder in Comstock]) on pine needles. (Photo by James A. Richmond, USDA Forest Service, Bugwood.org)

later generations are smaller and less discrete, as life stages tend to overlap as the season progresses (Asaro and Berisford 2001, Asaro and Creighton 2011).

Tip moth infestations have become more prevalent since the adoption of intensive plantation forestry and genetically improved planting stock. Since the 1990s, researchers have investigated new techniques for hazard-rating and management (Asaro et al. 2003). One technique is to use degree-day models (Berisford et al. 1984; Gargiullo et al. 1984; Richmond 1992) to schedule foliar applications to coincide with the presence of exposed early-instar larvae as they move among the needles (Asaro et al. 2003). These models, however, are labor-intensive; proper use requires monitoring of traps, collection of daily maximum and minimum temperature data, and calculation of degree-days. Mistakes in predictions often occur due to improper model use (Fettig et al. 2000).

An alternative to the degree-day models is to use predicted optimal spray periods. A manager can locate the nearest weather station to the plantation site and use the optimal spray periods in the appropriate publication to time insecticide applications (Fettig et al. 2000—Southeastern States, Fettig et al. 2003—Western Gulf States). Control of the large, synchronous first generation has the greatest impact; timing this application is critical for effective management (Fettig and Berisford 2002). These field-validated predictions work for synthetic pyrethroids (bifenthrin, esfenvalerate, lambda-cyhalothrin, and permethrin) currently registered for tip moth control (Dalusky and Berisford 2002, Fettig et al. 2000). These products have largely replaced the organophosphate products still registered for tip moth control (Nowak et al. 2000).

Biorational pesticides registered for tip moth control include diflubenzuron and tebufenozide, both growth regulators; spinosad, a biopesticide derived from bacterial fermentation; and the microbial *Bacillus thuringiensis* variety *kurstaki* Berliner (Btk). Nowak et al. (2000) demonstrated the efficacy of spinosad and Btk and established spray-timing intervals for the Georgia Piedmont area. These biorationals are less harmful to parasitoids and other beneficial insects than the pyrethroids. Spinosad, with its very low worker-exposure risk, is a valuable addition to tip moth IPM (Nowak et al. 2000).

Systemic insecticides eliminate the problem of timing applications (Berisford et al. 2013). Two systemics are registered for tip moth control, CoreTect™ Tree and Shrub Tablets (formerly SilvaShield™ Forestry Tablets; Bayer Environmental Science) and PTM™ Insecticide (BASF Corporation). The CoreTect™ Tablet is a formulation of 20 percent imidacloprid plus a small amount of fertilizer (12-9-4). The tablet can be placed into the planting hole when the seedling is planted or pushed into the ground near the seedling after planting. PTM™ Insecticide is a 9.1-percent formulation of fipronil that must be diluted and applied using a commercially available soil injector. Application can be made into the planting hole or below ground within the root zone of each seedling. This product can also be applied to containerized seedlings in the nursery.

Both PTM™ and CoreTect™ reduce tip moth numbers during the first 36 months after planting—the critical period in which tip moth impact can be the greatest (Asaro and Creighton 2011, Grosman 2010). Both products have relatively low toxicity and are labeled as general use pesticides. They can be applied at any time when the soil is not frozen (Grosman 2010). Labels restrict the amount of product per ac per year to 21 fl oz (0.6 L) of PTM™ formulation and 450 CoreTect™ tablets; managers must account for the number of seedlings per ac. Cost is perhaps the major disadvantage to systemics. At roughly $100 per ac for either product, plus the added application costs, systemics are a substantial addition to already costly intensive silvicultural practices (Asaro and Creighton 2011).

Figure 5. Pales weevil (*Hylobius pales* [Herbst]), feeding damage on the stem of a young pine seedling. (Photo by Lacy L. Hyche, Auburn University, Bugwood.org)

Reproduction Weevils

The pales weevil (*Hylobius pales* [Herbst]) and the pitch-eating weevil (*Pachylobius picivorus* [Germar]) (Coleoptera: Curculionidae), commonly known as reproduction weevils, are important pine regeneration pests in the South (Cade et al. 1981, Grosman et al. 1999), especially in recently cutover stands that are replanted to pine. Volatile chemicals released by cut pine stumps and slash attract weevils. The weevils breed and emerge in large numbers then move to the pine seedlings to feed on the bark. This feeding girdles the stem and kills the seedling. Maturation feeding by brood beetles causes the most damage (Cade et al. 1981) (figure 5). First-year seedling mortality is often 30 to 60 percent but can reach 90 percent (Grosman et al. 1999); this loss is unacceptable in modern intensive plantation forestry.

Similar in appearance, adults of both species have broad snouts and clubbed elbowed antennae (figure

Figure 6. A pitch-eating weevil (*Pachylobius picivorus* [Germar]), feeding on a pine stem. (Photo by Robert L. Anderson, USDA Forest Service, Bugwood.org)

6). The pales weevil and the pitch-eating weevil are both robust, dark-brown to black with irregular patches of yellow scales on the thorax and elytra; the pitch-eating weevil is typically slightly darker (Antonelli 2012b, Nord et al. 1984). Females lay eggs on underground parts of stumps, roots, and slash. Larvae, legless white grubs with a brown head capsule, feed between phloem and wood. There are five larval instars. The mature larva, about 12 mm (0.5 in) in length, excavates a chamber, packs the excavated wood fragments around itself, and pupates in this "chip cocoon" (Nord et al. 1984).

In the Piedmont and Coastal Plain of the South, adult weevils are active throughout the year. Except for the coldest winter months, adults quickly find freshly logged areas and begin to reproduce. The life cycle varies from 3 to 12 months in this area, depending on when the logged areas are colonized. In the southern Appalachians, the life cycle cannot be completed in a year; larvae overwinter, and adults emerge the following spring (Nord et al. 1984).

Weevils are managed by silvicultural practice. Planting dates are adjusted to exploit the life cycle of the insects. In the Piedmont and Coastal Plain, stands logged and site-prepared before July can be planted during the following winter without weevil damage because the emerging brood weevils will disperse before the planting time. Planting should be delayed 1 year for stands logged in July or later (Cade et al. 1981, Grosman et al. 1999, Nord et al. 1984). In the southern Appalachians, planting must be delayed by 1 or 2 years (Nord et al. 1984).

High-value sites, such as breeding program progeny tests and Christmas tree plantations, need careful monitoring and merit additional care, such as grinding stumps and removing slash.

Stands logged late in the year must, on occasion, be planted in the same year due to financial or management constraints. In the Appalachians, where weevils take longer to disperse, waiting more than a year to regenerate may be impractical (Nord et al. 1984). These plantings need monitoring and, if necessary, chemical control. Stumps can be treated prior to planting seedlings. Insecticide application to seedlings can be done if weevil damage is evident. Registered insecticides include bifenthrin, esfenvalerate, and permethrin (synthetic pyrethroids); and phosmet (organophosphate).

Managers should assess the potential for weevil damage. Former old-field and hardwood sites are low hazard; they will not attract weevils when cut. Extensive clearcuts of pine, especially adjacent to cuts made the year before, are high hazard; they will likely have high weevil numbers (Nord et al. 1984).

Pine Sawflies

In the South, the redheaded pine sawfly (*Neodiprion lecontei* [Fitch]; Hymenoptera: Diprionidae) is often a major pest of young pine plantations. Shortleaf, loblolly, slash, and longleaf pines are all prone to being attacked (Wilson and Averill 1978).

The redheaded pine sawfly overwinters as a prepupa in a silken cocoon in litter under the trees. Adults emerge in the spring, and larvae feed gregariously on needles before dropping to the ground. In the South, several generations per year occur, and generations may overlap. Larvae feed together, stripping the needles off a branch before moving to another (figure 7). When a tree is defoliated, larvae move to adjacent trees to feed until they are fully grown. Young larvae have a brown, transparent head, and older larvae have a characteristic shiny red head and two to four rows of black spots on a yellow body (figure 8) (Wilson and Averill 1978).

Controlling sawflies is usually unnecessary in large plantations. Outbreaks typically subside after a year or so due to parasitoids and diseases. Small mammals consume cocoons on the ground (Wilson and Averill 1978). Control may be needed in progeny tests, young orchards, and other high-value sites where the damage threshold is low. In those cases, diligent monitoring in early spring will reveal populations before damage is extensive. Contact insecticides labeled for sawfly

Figure 7. A young plantation of longleaf pine (*Pinus palustris* Mill.) defoliated by the redheaded pine sawfly (*Neodiprion lecontei* [Fitch]). (Photo by Andrew J. Boone, South Carolina Forestry Commission, Bugwood.org)

Figure 8. Larvae of the redheaded pine sawfly (*Neodiprion lecontei* [Fitch]), feeding on pine needles. (Photo by Gerald J. Lenhard, Louisiana State University, Bugwood.org)

control include acephate and malathion (organophosphates); carbaryl (carbamate); bifenthrin, cyfluthrin, lambda-cyhalothrin (synthetic pyrethroids); diflubenzuron and spinosad (biorationals). The systemic imidacloprid, as CoreTect™ Tree and Shrub Tablets, is also labeled for sawfly control and is an IPM option.

White Grubs

The beetle genus *Phyllophaga* (Coleoptera: Scarabaeidae), known as May or June beetles, have soil-inhabiting larvae called white grubs (figure 9). The larvae feed on organic matter and plant roots as they develop (Mayfield 2012); however, they can also feed on the roots of young trees in nursery and plantation settings. They are abundant in grassy, old field sites that have been fallow for some time. Coniferous plantations established on or near these habitats are the most severely impacted (Speers and Schmiege 1971).

Symptoms are similar to drought damage; in late summer and early fall, pine seedlings turn red or brown and may die (figure 10). Seedlings are easily uprooted with a gentle pull and reveal clipped or girdled roots. Excavation exposes large (up to 4.5 cm [1.8 in]), white, C-shaped larvae with brown heads and a translucent, swollen terminal abdominal segment. Pupae resemble adult beetles. (Mayfield 2012, Speers and Schmiege 1971).

Figure 9. White grub (*Phyllophaga* spp.) larvae exposed after feeding on pine roots. (Photo by Steven Katovich, USDA Forest Service, Bugwood.org)

Figure 10. A pine seedling killed by larvae of *Phyllophaga* spp. feeding on roots. (Photo by Steven Katovich, USDA Forest Service, Bugwood.org)

Management includes preplanting excavation to sample for larvae, particularly for sites being converted from agricultural use. Site preparation should include disking several times from late spring through fall when larvae are near the surface. Fumigation is problematic; larvae deeply imbedded in cold months may escape (Mayfield 2012). If damage is observed post-planting, insecticides may be applied. Several brands of the systemic imidacloprid are registered for white grubs, including CoreTect™ Tree and Shrub Tablets.

Aphids and Scale Insects

Aphids and scale insects, both in the order Homoptera, are occasional pests on young pine seedlings. Both groups feed by sucking plant juices with piercing-sucking mouthparts (Antonelli 2012a).

Aphids in the genus *Cinara* (Homoptera: Aphididae) are the most common aphids on pines. They are large, long-legged, darkly colored, pear-shaped aphids found on the stems of terminal and lateral branches (figure 11). Infestations rarely kill trees; large numbers of aphids may reduce vigor. When feeding, aphids secrete sweet, sticky honeydew that accumulates on needles and stems (Brooks and Warren 1964) and attracts bothersome bees and ants (Clarke 2010). Sooty mold fungi grows on honeydew; it gives trees an unthrifty appearance and

Figure 11. Giant conifer aphids (*Cinara* spp.) feeding on pine branches in the "candle" stage in spring. (Photo by Jim Baker, North Carolina State University, Bugwood.org)

interferes with photosynthesis. Natural enemies usually keep aphids in check (Antonelli 2012a) Severe infestations can be treated with imidacloprid or thiamethoxam (neonicotinoids), pymetrozine (avermectin), or acephate (organophosphate).

Scale insect (Homoptera) (table 1) infestations reduce growth and vigor of young trees; severe infestations can kill young seedlings (figure 12) (Clarke 2010, 2013). As with aphids, scale insects produce honeydew; infestations are accompanied by the resulting sooty mold, bees, and ants (figure 13).

Table 1. Common scale insect (Homoptera) species on southern pines.

Soft Scales—Coccidae	
	Wooly Pine Scale—*Pseudophilippia quaintancii*
	Pine Tortoise Scale—*Toumeyella parvicornis*
	Virginia Pine Scale—*Toumeyella virginiana*
Mealybugs—Pseudococcidae	
	Loblolly Pine Scale—*Oracella acuta*
Armored scales—Diaspididae	
	Pine Needle Scale—*Chionaspis pinifoliae*
	Pine Scale—*Chionaspis heterophyllae*

Figure 12. Pine tortoise scale (*Toumeyella parvicornis* [Cockerell]) feeding on the stem of a pine tree. (Photo by USDA Forest Service, Northeastern Area Archives, Bugwood.org)

Figure 13. A young pine infested with pine tortoise scale (*Toumeyella parvicornis* [Cockerell]) and covered with sooty mold growing on honeydew produced by the scale insects. (Photo by Lacy L. Hyche, Auburn University, Bugwood.org)

Scale insects often occur as secondary pests after insecticide applications for other pests also kill off natural enemies; pyrethroid products are notable for causing outbreaks (Clarke 2010). When outbreaks occur, managers should adjust management and, if feasible, pesticide use should be avoided to enable natural enemies to build up (Clarke 2010). Severe infestations can be treated with acephate or malathion (organophosphates); or acetamiprid (neonicotinoid). For efficacy, foliar applications must be timed when the crawler stage is present and be applied as drenching sprays rather than aerosols. Dormant oils are also effective (Clarke 2010, 2013).

Mites

The spider mites (*Oligonychus* spp.; Acari: Tetranychidae) infest young pines (figure 14). Spider mites use their needle-like mouthparts to pierce plant cells and suck out the cell contents, resulting in a mottled appearance of the needles. Eventually, needles turn yellow or brown (figure 15). Associated with the discolored needles is a dense webbing made by the mites (Mangini 2012).

Spider mites and rust mites have natural enemies that keep their populations in check; the most important biological control agents are the phytoseiid mites (family Phytoseiidae). Chemical control is usually not needed. Miticides available for severe infestations are abamectin and spiromesifen (avermectins). Insecticidal soaps and dormant oils are also effective (Mangini 2012).

Figure 14. Spruce spider mite (*Oligonychus ununguis* [Jacobi]) adult and egg on conifer needle. (Photo by USDA Forest Service, Northeastern Area Archives, Bugwood.org)

Figure 15. Fir tree with discolored needles caused by spruce spider mite *(Oligonychus ununguis* [Jacobi]) feeding. (Photo by USDA Forest Service, Northeastern Area Archives, Bugwood.org)

Southern Pine Seedling IPM

Intensively managed pine plantations, progeny tests, and young seed orchards are major investments. A solid IPM program for regeneration insects will protect these investments by planning for problems before the trees are planted. Managers must consider the array of potential pests and their biology, site-specific conditions, damage thresholds, and logistic and financial constraints to develop an optimal management plan.

Some pests, such as Nantucket pine tip moth, are widespread and can be expected at any plantation site in the South. Sawflies, in contrast, occur sporadically in space and time. An IPM plan must be flexible enough to handle both. In all cases, monitoring is crucial—this is the heart of regeneration IPM. Finding an infestation early, before damage is extensive, is the goal. Early detection usually results in better control efficacy and efficiency; early-instar larvae are more easily controlled than large larvae or adults.

Effective IPM includes the judicious use of pesticides. Managers should use a product that is labeled for the site and/or pest species involved. Label directions must be followed—a central tenet of IPM is to avoid mistakes when handling pesticides and making applications. Managers should insist that contractors make pesticide applications correctly.

Insect pest management can be a useful part of intensive forestry in the South. With this discussion and the abundant resources available online (table 2), regeneration insect IPM for southern pine seedlings can be done effectively and efficiently.

Table 2. Online resources for regeneration insect biology, management, and pesticide information.

Resource	Website	Comments
General references		
Forest Nursery Pests—USDA Ag. Hdbk. 680	http://www.rngr.net/publications/forest-nursery-pests	General reference on nursery insects and diseases of conifers and hardwoods—each chapter can be downloaded as individual document
Link to Forest Insect and Disease leaflets	https://www.na.fs.fed.us/pubs/	Leaflets provide biological and management information on various forest insect and diseases
Tip moth references		
Fettig et al. (2000)	http://www.srs.fs.usda.gov/pubs/rp/rp_srs018.pdf	Optimal spray predictions for AL, FL, GA, MS, NC, SC, and VA—foliar applications for tip moth control
Fettig et al. (2003)	http://www.srs.fs.usda.gov/pubs/rp/rp_srs032.pdf	Optimal spray predictions for AR, LA, and TX—foliar applications for tip moth control
Asaro et al. (2003)	http://www.srs.fs.usda.gov/pubs/ja/ja_asaro005.pdf	Comprehensive literature review of publications on Nantucket pine tip moth—through 2002
Nowak et al. (2000)	http://www.bioone.org/doi/pdf/10.1603/0022-0493-93.6.1708	Optimal spray timing for applications of lambda-cyhalothrin, spinosad and Bacillus thuringiensis variety kurstaki Berliner (Btk) in southern Piedmont, NC and coastal VA
Nantucket pine tip moth Forest Insect and Disease leaflet	http://www.fs.usda.gov/Internet/FSE_DOCUMENTS/fsbdev2_042974.pdf	Biology and management information for Nantucket pine tip moth
Pesticide label information		
Crop Data Management Systems, Inc. (CDMS®)	http://www.cdms.net/Home.aspx	Listings of pesticide manufacturers, labels, and Safety Data Sheets (SDS)
Environmental Protection Agency (EPA) Pesticide Product and Label System	http://iaspub.epa.gov/apex/pesticides/f?p=PPLS:1	Listings of past and current registrations for pesticides
Greenbook®	http://www.greenbook.net/	Listings of pesticide manufacturers, labels, and SDS
Kelly Solutions®	http://www.kellysolutions.com/	Web portal for State Department of Agriculture Registrants and Licensees
National Pesticide Information Retrieval System (NPIRS)	http://ppis.ceris.purdue.edu/	Web listings of Federal pesticide registrations
National Pesticide Information Center	http://npic.orst.edu/index.html	Pesticide information and links to resources

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Pathology Smorgasbord: Biocontrol, Pathogen Movement, and Recent Fumigation Results

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Abstract

This article summarizes recent research on soilborne pathogens, disease control, and new forest diseases including reduced-rate soil fumigation, *Pythium* diversity and biocontrol, pathogen movement among nurseries, and a new incense-cedar disease. Results from the fumigation study indicate that reduced-rate soil fumigation is effective for soilborne disease and weed control. Results from the biocontrol study provide a partial explanation for why biocontrol may sometimes fail in forest nurseries, and results from the population genetics study show that *Pythium* species are being moved in the forest nursery industry. Our latest forest tree research found a new incense-cedar canker disease in Oregon. This paper was presented at the joint annual meeting of the Western Forest and Conservation Nursery Association and the Intermountain Container Seedling Growers' Association (Troutdale, OR, September 14–15, 2016).

Introduction

Soilborne pathogens and weeds are important production constraints for the forest nursery industry. Some of the most common soilborne pathogens are species of *Pythium*, *Fusarium*, and *Cylindrocarpon*. Together, these pathogens cause damping-off (figure 1) and root rot (figure 2) of seedlings, resulting in chlorosis, stunting, and seedling death. The variety of soilborne pathogens affecting forest nurseries makes it difficult to achieve adequate disease control in the absence of soil fumigation. For example, the fungicides used to control *Pythium* are mostly ineffective against *Fusarium* and *Trichoderma*. Species diversity within each of the three pathogen genera may also affect disease control. Nineteen *Pythium* species have been found in the forest nurseries of Washington and Oregon. Not only do these species differ in their ability to cause disease, but also in how they respond to fungicides and biocontrol agents. New evidence shows that *Pythium* species and fungicide-resistant *Pythium* isolates have been moved among nurseries, which further complicates disease control decisions. This highlights the risk for accidentally introducing new pathogens and diseases into locations where they previously did not occur.

Figure 1. Damping-off of a young Douglas-fir seedling caused by *Pythium* species. (Photo by Jerry Weiland, 2010)

Figure 2. Root rot of 1-year-old Douglas-fir seedlings in nursery beds where water collects at the end of a row. (Photo by Jerry Weiland, 2010)

Figure 3. Soil fumigation at a forest nursery. The fumigant is injected into the soil and then covered with totally impermeable film (TIF) to keep the fumigant in place. (Photo by Jerry Weiland, 2010)

Traditionally, control of soilborne pathogens and weeds is achieved in forest nurseries through soil fumigation with methyl bromide and chloropicrin (figure 3). The benefit of soil fumigation is that fumigants have broad-spectrum activity against most pathogen species compared with the more targeted effects of fungicides and biocontrol agents. Methyl bromide is being phased out through the Montreal Protocol, however, and it is uncertain how much longer the industry will have access to this fumigant. In addition, current Environmental Protection Agency (EPA) regulations require a buffer zone (nonfumigated area between fumigated fields and neighboring properties) that can be reduced based on certain conditions, including tarping and the amount of fumigant applied. In general, the more impermeable the tarp (e.g., totally impermeable film, or TIF), and the less fumigant that is applied, the smaller the buffer zone. It is unknown, however, whether reduced-rate fumigant applications (fumigants applied below the label rate) will be effective for disease and weed control. Therefore, forest nursery managers are interested in fumigant alternatives to methyl bromide and in the efficacy of reduced-rate fumigants against soilborne pathogens and weeds.

Reduced-Rate Soil Fumigation

In 2010 to 2012, a reduced-rate soil fumigation study (Weiland et al. 2016a) was established to evaluate the effects of three fumigant treatments: (1) MBC, 50/50 methyl bromide/chloropicrin at 250 lb/ac (280 kg/ha); (2) MSC, metam sodium plus chloropicrin at 27 gal/ac (253 l/ha) plus 150 lb/ac (168 kg/ha); and (3) DPC, 40/60 1,3-dichloropropene/chloropicrin at 285 lb/ac (319 kg/ha), as well as a nonfumigated (NF) control. The three fumigant treatments were applied in August 2010 at a rate requiring a 25-ft (7.6-m) buffer zone, according to 2010 EPA guidelines. Each treatment was replicated four times, and the experiment was repeated at two nurseries. One-year-old, bareroot 1 + 0 Douglas-fir seedlings were transplanted into each nursery, in May of the following year. Approximately 10 months after fumigation, four biocontrol treatments were applied to seedlings within the MSC, DPC, and NF treatments to see if disease control could be improved after fumigation. The four treatments were: (1) *Streptomyces lydicus* (6 oz/100 gal [47 ml/100 L]) plus *Bacillus subtilis* (64 oz/100 gal [500 ml/100 L]); (2) *Trichoderma harzianum* (5 oz/100 gal [39 ml/100 L]) plus *Gliocladium virens* (2 lb/100 gal [2400 g/100 L]); (3) All four biocontrol agents applied in combination; and (4) no biocontrol treatment (water only). The biocontrol treatments were applied three times during the growing season in June, July, and October 2011.

Results showed that all three fumigant treatments were effective in reducing soilborne pathogen populations (*Pythium* and *Fusarium*) in the soil (data not shown) and on seedling roots (figure 4 for *Pythium*), in comparison to the NF plots. None of the biocontrol treatments were effective, however (data not shown). Weeds were also controlled by all three fumigant treatments (figure 5) relative to the NF plots. Seedlings were largest and healthiest from the MBC and MSC treatments, and were the smallest and least healthy in the NF plots (data not shown). Seedlings in NF plots were on average 3 to 5 in (7 to 13 cm) shorter than those in fumigated plots. Results from this study show that reduced

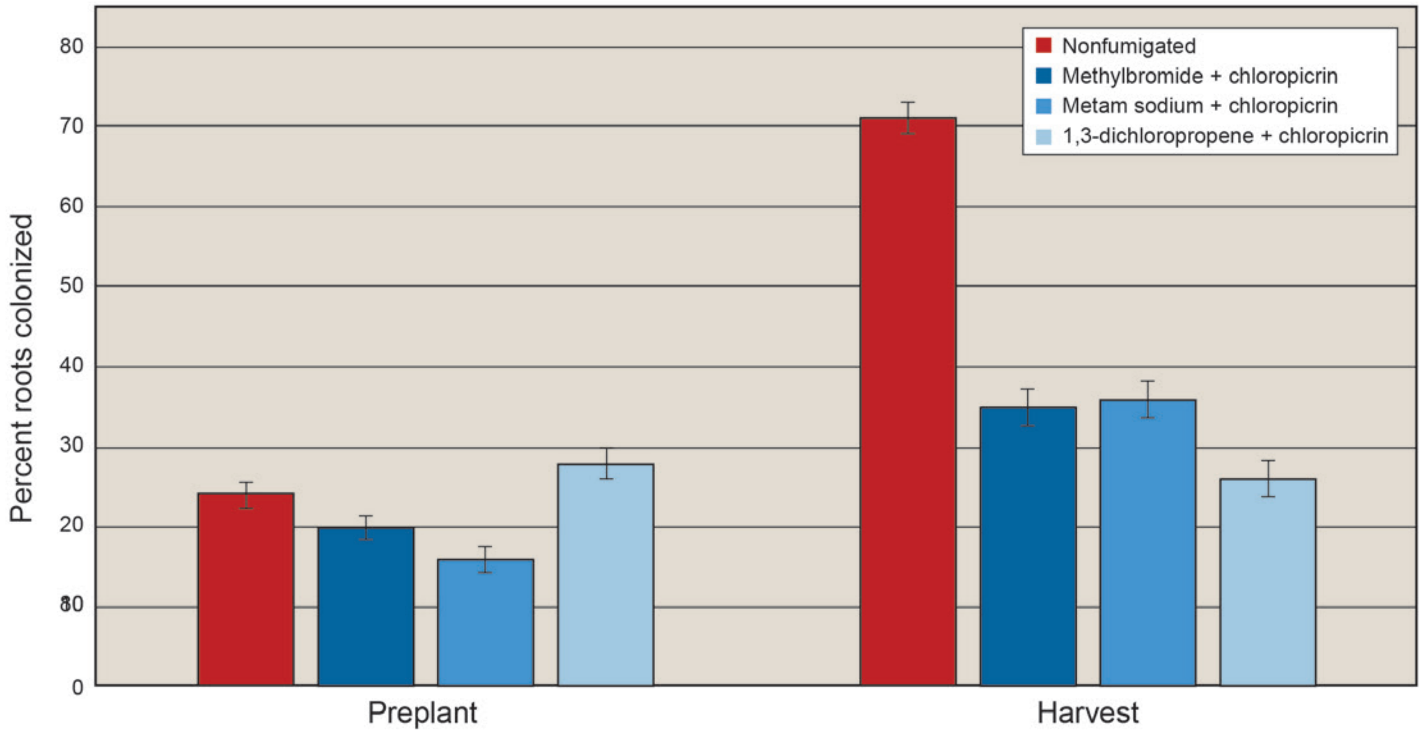

Figure 4. Average percent root colonization by *Pythium* species of 1-0 Douglas-fir seedlings before planting into treatment plots in mid-May 2011 (preplant) and at harvest in December 2011 (harvest) across two nurseries. Results were similar for *Fusarium* species (not shown). Error bars = standard error.

rates of these fumigants help produce healthy seedlings and are effective for managing soilborne diseases and weeds in forest nurseries.

Pythium Species Diversity and Biocontrol

In 2008, a study was conducted to describe the diversity of *Pythium* species in forest nurseries of Oregon and Washington (Weiland 2011). Soil at three forest nurseries (two in Oregon and one in Washington) was surveyed, and 300 individuals of *Pythium* were identified from each nursery. The results showed that each nursery had a different set of *Pythium* species. For example, the most commonly identified species at each nursery was different (table 1): *P. irregulare* was the most common at nursery A, whereas *P. 'vipa'* and *P. dissotocum* were more common at nursery B and C, respectively. Additionally, although *P. irregulare* occurred at all three nurseries, it made up a different percentage of the population at each nursery (65 percent at nursery A, 10 percent at nursery B, and 6 percent at nursery C). Finally, some species were only present at a single nursery. For example, *P. 'vipa'* was only found at nursery B.

This *Pythium* species diversity makes a difference in terms of disease (Weiland et al., 2013). In a greenhouse pathogenicity study with Douglas-fir seedlings (figure 6), eight *Pythium* species were found to be weak pathogens causing root lesions and less than 25

Table 1. Percentage occurrence of the five most common *Pythium* species at three forest nurseries.

Nursery A (WA)		Nursery B (OR)		Nursery C (OR)	
%	**Species**	**%**	**Species**	**%**	**Species**
65	*P. irregulare*	53	*P. 'vipa'*	47	*P. dissotocum*
10	*P. torulosum*	15	*P. aff. macrosporum*	14	*P. ultimum*
6	*P. aff. macrosporum*	10	*P. irregulare*	11	*P. aff. spiculum*
6	*P. irregulare* type III	9	*P. sylvaticum*	8	*P. sylvaticum*
5	*P. aff. spiculum*	8	*P. ultimum*	6	*P. irregulare*
92% of total population		**95% of total population**		**86% of total population**	

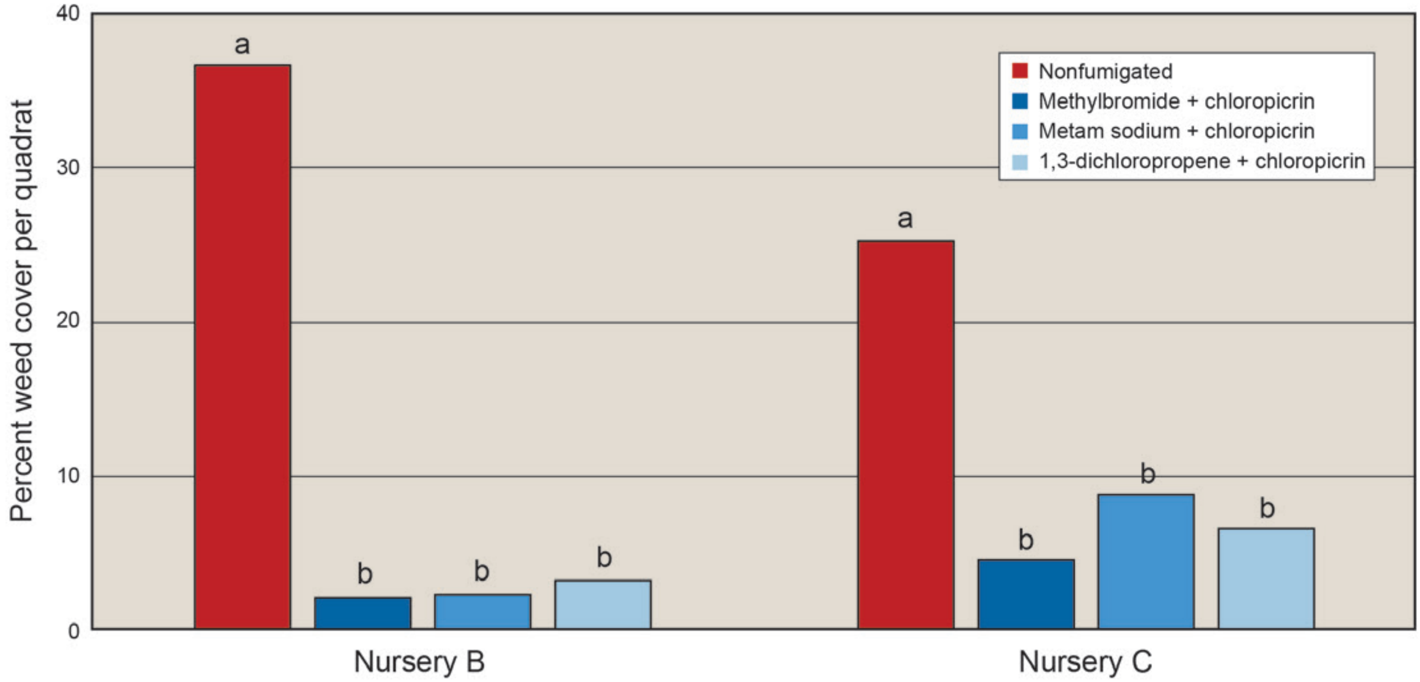

Figure 5. Effect of treatment on average weed cover (percent) at both nurseries in January 2012.

percent seedling mortality, compared to noninoculated control plants (figure 7). Eight other *Pythium* species were considered aggressive pathogens, however, and caused greater than 25 percent seedling mortality (figure 8). Revisiting the *Pythium* species diversity research from Weiland 2011, the percentage of aggressively pathogenic *Pythium* species can now be identified at each of the three forest nurseries (table 2). These results show that 76 percent of the *Pythium* population at nursery A and 85 percent of the population at nursery C are aggressive pathogens compared to only 43 percent at nursery B. Although direct evidence is not yet available, this might be an indication that the disease pressure due to *Pythium* may be almost one-half at nursery B, compared with the other two nurseries. Given the diversity of *Pythium* species in the soil at each nursery, is it reasonable to expect that a single biocontrol agent will work equally well against all *Pythium* species? To test this, we evaluated 16 *Pythium* species against a commercial Streptomyces lydicus strain in a Petri plate assay (figure 8, Weiland 2014).

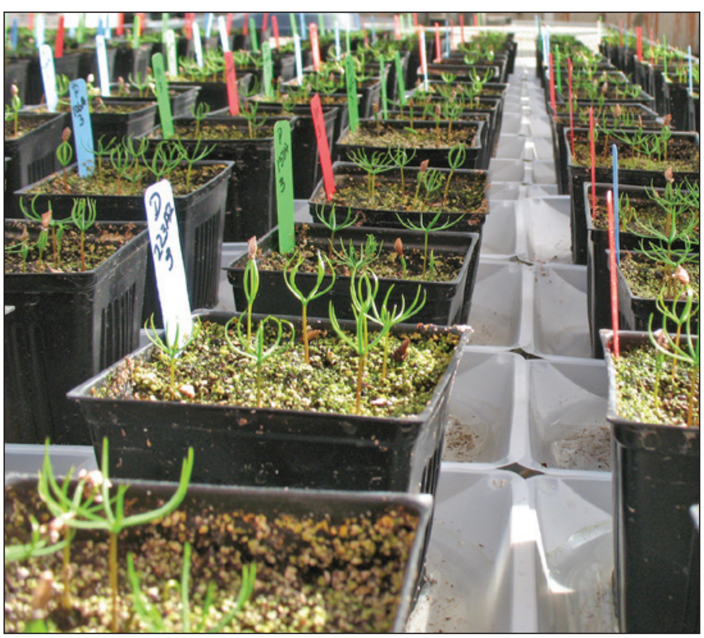

Figure 6. Douglas-fir seedlings inoculated with 16 different *Pythium* species in a greenhouse pathogenicity assay. (Photo by Jerry Weiland, 2011)

Table 2. Percentage occurrence of eight aggressively pathogenic Pythium species at three forest nurseries.

Pythium species	Nursery A (%)	Nursery B (%)	Nursery C (%)
P. dissotocum	2	0	47
P. irregulare	65	10	6
P. aff. macrosporum	6	15	7
P. mamillatum	1	0	2
P. aff. oopapillum	0	0	1
P. rostratifingens	1	1	0
P. sylvaticum	0	9	8
P. ultimum	1	8	14
Total	76	43	85

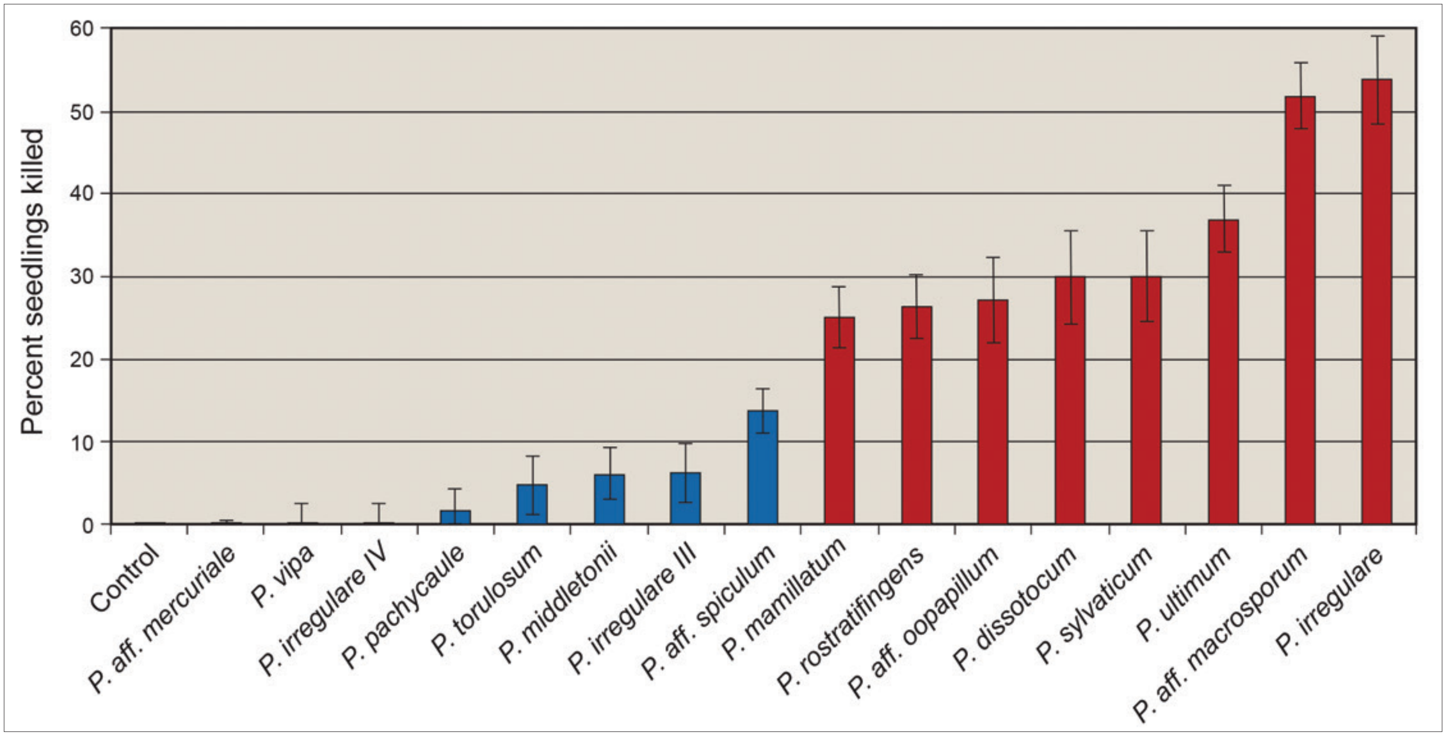

Figure 7. Percent Douglas-fir seedlings killed by eight weakly pathogenic *Pythium* species (less than 25 percent mortality, on left in blue) and eight aggressively pathogenic *Pythium* species (more than 25 percent mortality, on right in red) compared to noninoculated seedlings (control, far left).

Results indicated that the biocontrol agent inhibits each *Pythium* species to a different degree; some species, like *P. torulosum*, were inhibited more by *S. lydicus* than other species, like *P. ultimum* (figure 9). In addition, we found that the nursery from which the *Pythium* species were isolated affected the results. For example, individuals of *P. irregulare* from nursery A were inhibited more than individuals of the same species from nursery B (data not shown). These results show that *S. lydicus* does not work equally against all *Pythium* species and may partially explain why applications of biocontrol in forest nurseries may sometimes fail against soilborne pathogens. Poor biocontrol establishment, poor environmental conditions, and improper application, however, are among the explanations for why a biocontrol can fail. Nevertheless, these results suggest it may be too much to expect that a single biocontrol agent will be effective against the diversity of *Pythium* species in the soil, not to mention the diversity of soilborne *Fusarium* and *Cylindrocarpon* species that were not even tested in our study.

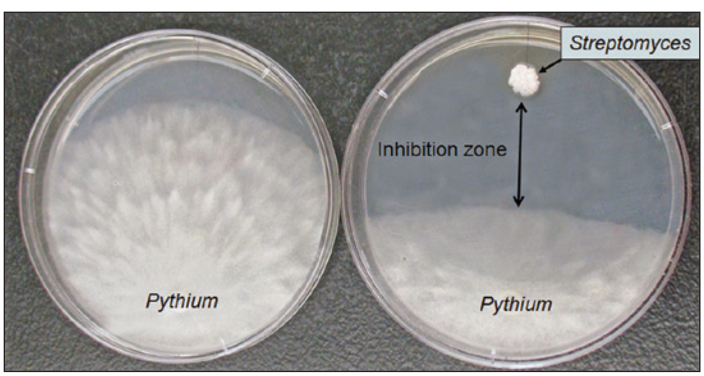

Figure 8. Petri plate assay to evaluate *Pythium* species inhibition by the biocontrol agent *Streptomyces lydicus*. No inhibition was observed in plates only containing a *Pythium* isolate (left). Plates containing *S. lydicus* inhibited the growth of *Pythium* toward the other side of the plate, creating an inhibition zone (right). (Photo by Jerry Weiland, 2013)

Pathogen Movement Among Nurseries

In 2015, a study evaluating the genetic relatedness of *Pythium* species (*P. irregulare*, *P. ultimum*, and *P. sylvaticum*) from three forest nurseries was conducted to find out if these pathogens are being moved among nurseries (Weiland et al. 2015). For *P. irregulare*, individuals at nursery A were genetically identical or very similar to those from nursery B and C, indicating that this species had been moved among the three nurseries. Similar results were found with *P. ultimum* and *P. sylvaticum* from nurseries B and C. In addition, two fungicide-resistant (mefenoxam) individuals of *P. ultimum* were found, one each at nursery B and C. These two resistant individuals were genetically related, which provided evidence that fungicide-resistant species are also being moved among nurseries. It

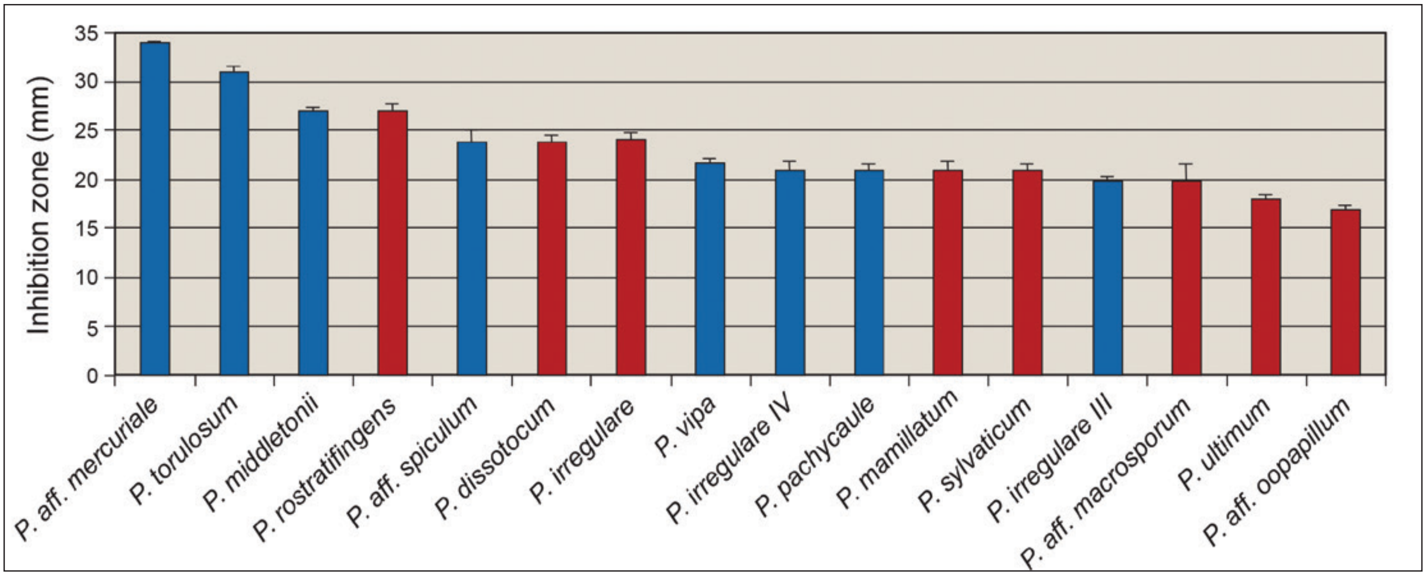

Figure 9. Inhibition of 16 *Pythium* species by Streptomyces lydicus strain WYEC108, a commercial biocontrol agent. Species on the left are inhibited more by the *S. lydicus* than those on the right. Species in blue are considered weakly pathogenic (less than 25 percent mortality) and those in red are considered aggressive pathogens (more than 25 percent mortality).

is unknown whether *Pythium* is being moved from nursery to nursery on nursery stock or on equipment, but moving new species or fungicide-resistant individuals to nurseries where they did not occur previously is risky. For example, *P. dissotocum* was not found at nursery B (table 2), therefore, this nursery would be at risk of importing this pathogen if it received nursery stock or shared equipment from nurseries A or C. Likewise, nursery A would be at risk of accidentally importing fungicide-resistant isolates of *P. ultimum* from nurseries B and C. Nursery managers could help reduce this risk by designating specific fields for seedlings imported from other nurseries and then reserving the remaining field space for inhouse seedling production. Although difficult, shared equipment should also be cleaned whenever possible. Future research directions might focus on whether fungicides or fumigation can be used to limit the spread and establishment of soilborne pathogens in the industry.

New Incense-Cedar Disease

A new incense-cedar (*Calocedrus decurrens* [Torr.] Florin) disease was recently discovered in the Willamette Valley of Oregon (Weiland et al. 2016b). The pathogen, *Phaeobotryon cupressi*, causes branch cankers that are scattered throughout the crown of the tree. Infected branches die, thereby destroying the tree's ornamental value (figure 10). Interestingly, the pathogen was first discovered causing branch cankers of Italian cypress in Iran in 2009. Prior to its discovery in Oregon in 2015, it was described only once from a healthy juniper in Kansas. Similar symptoms have been reported on native populations of incense-cedar in the Cascade Mountains, but the pathogen has not been confirmed as causing disease at those locations. We have not heard of similar symptoms occurring in forest nurseries, but this disease may be something to keep in mind for anyone producing this native tree species.

Figure 10. Incense-cedar with branch cankers caused by *Phaeobotryon cupressi.* (Photo by Jerry Weiland, 2014)

Conclusions

In the short term, soil fumigation with methyl bromide will continue to play a large role in producing healthy forest seedlings. As methyl bromide stocks are depleted, however, the industry will need to switch to other fumigant chemistries. Current studies show that reduced-rate fumigant treatments can be effective for controlling soilborne pathogens and weeds. What remains unknown is how long control will last after application, in comparison to the standard application of methyl bromide:chloropicrin (67:33) at 350 lb/ac (392 kg/ha). Studies are needed to see how many crop cycles can profitably be produced, following newer alternative soil fumigation treatments, without compromising seedling quality. Fungicides will continue to play an important role in providing supplemental disease control. The development of fungicide resistance is a concern, however, and growers must alternate fungicide chemistries to prevent the further spread of resistance in the industry. Biocontrol options for soilborne pathogens remain limited and inconsistent. It is unlikely that a single biocontrol agent will provide adequate disease control, given the diversity of soilborne pathogens that are present in forest nurseries. Further research on combining biocontrol agents may be useful, but it will probably take many years before effective formulations become available. Finally, growers must be wary of accidental pathogen introductions. The awareness of pathogen movement is growing in all nursery industries, particularly when new diseases and insects are introduced that devastate our native tree species.

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Testing Herbicides for Tree Safety and Efficacy in Conifer Nurseries

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Abstract

Weeds are a significant challenge in forest tree nurseries. Few herbicides are currently registered in conifer nurseries, with none providing complete weed control. Two trials were therefore conducted to generate data to support future herbicide registrations. In the first trial, 22 herbicide treatments were applied to freshly transplanted Douglas-fir (*Pseudotsuga menziesii* Mirb. Franco) seedlings. Weed control was initially excellent, but waned with some treatments 3 to 4 months after treatment. Douglas-fir foliar injury was excessively high with several treatments though seedlings had largely recovered by harvest, with most growth measurements not differing from nontreated Douglas-fir. In the second trial, 13 herbicide treatments were applied in July to yellow fieldcress (*Rorippa sylvestris* [L.] Besser), a particularly difficult perennial species to control in conifer nurseries, then all plots were late-winter fumigated followed by transplanting to Fraser fir (*Abies fraseri* [Pursh] Poir.) or noble for (*A. procera* Rehder) seedlings the following May. Only imazapyr gave acceptable initial control of yellow fieldcress, reducing weed cover from an average of 20 percent to 2 percent 2 months after treatment. Four months after planting (14 months after application), however, seedlings exhibited significant injury from soil-residual imazapyr. This paper was presented at the joint annual meeting of the Western Forest and Conservation Nursery Association and the Intermountain Container Seedling Growers' Association (Troutdale, OR, September 14–15, 2016).

Introduction

Weeds are a significant challenge in forest tree nurseries. Reduced growth due to weed competition results in tree seedlings of lower vigor and quality, and may result in an inability to meet customer expectations and thus the loss of business in future years. In addition, tree seedlings contaminated with certain weed species (such as yellow nutsedge [*Cyperus esculentus* L.]) may result in a quarantine that prevents certain lots from being sold at all. Many forest nurseries fumigate with methyl bromide to control soilborne disease pathogens, but fumigation provides only partial weed control and thus is usually augmented with herbicides followed by periodic hand weeding (Weiland et al. 2016).

Several herbicides are registered for use in conifer nursery plantations, including oxyfluorfen (Goal® and GoalTender®), napropamide (Devrinol®), s-metolachlor (Pennant Magnum®), dimethenamid-p (Tower®), prodiamine (Endurance®), and oxadiazon (Ronstar®) for preemergence control of broadleaf weeds, whereas fluazifop (Fusilade II®), sethoxydim (Segment™), and clethodim (Envoy Plus™) are postemergence herbicides for grass weed control (Peachey 2016). Additionally, glyphosate (Roundup®) is available for use prior to tree seedling germination or for postemergence wiper/spot treatment. Of the broadleaf control products, most provide only limited control of certain weed species; in particular, members of Caryophyllaceae and Brassicaceae tend to increase in regional forest tree nurseries. Testing of new herbicides, particularly those with differing modes of action, may successfully identify products suitable for future registration while delaying the onset of herbicide resistance.

A particular weed of concern is yellow fieldcress (*Rorippa sylvestris* [L.] Besser), a species described as being difficult to control in Swedish conifer nurseries (Barring 1986) (figure 1). It is a rhizomatous perennial weed known to be allelopathic to lettuce (Yamane et al. 1992), and probably other crops as

Figure 1. Yellow fieldcress in flower. This weed is particularly damaging problematic in forest tree nurseries. (Photo by Tim Miller, 2011)

Figure 2. Yellow fieldcress infesting a bed of Douglas-fir seedlings. (Photo by Tim Miller, 2011)

well. Herbicides have been tested in the United States to help manage the weed with only moderate success (Elmore 2000, Koster et al. 1997, Kuhns and Harpster 1998). This species exists in forest tree nurseries in Oregon (figure 2), as well as sites in Washington and southern British Columbia, and although it is not yet abundant in the region, obtaining control data is a wise course of action. Herbicide application timing and combination treatments may assist in managing this weed, particularly if used prior to seedbed fumigation.

Two trials were conducted to generate data to support future herbicide registrations in forest tree nurseries. The first trial evaluated several nonregistered herbicides for weed-control efficacy and Douglas-fir safety. The second trial examined control of yellow fieldcress during the fallow year prior to fumigation and the potential for injury of subsequently transplanted tree seedlings.

Materials and Methods

Herbicide Screening Trial

This trial was conducted at Weyerhaeuser's Aurora Forest Nursery near Aurora, OR (figure 3). Twenty-two herbicide treatments were applied at varying rates preemergence (PRE to weeds, but after tree transplanting) or postemergence (POST to weeds), as appropriate, to freshly transplanted Douglas-fir seedlings. Oxyfluorfen was included in the trial as the industry standard, as well as a nontreated control. PRE herbicides were applied to dormant tree seedlings on May 15, 2015 (4 days after transplanting, prior to onset of new growth), and POST herbicides were applied on June 15, 2015. A CO2-pressurized backpack sprayer equipped with a three-nozzle boom was used for all applications. Treatments were applied to 4-by-8 ft (1.2-by-2.4 m) plots (four per treatment).

Visual estimates of weed control and tree injury percentages were made on June 15, July 1, and September 9, 2015. Trees were lifted January 20, 2016, for growth analyses. Three trees in each plot were measured for fresh weight of shoots and roots, stem height, and stem diameter at the lowest branch. Trees were additionally checked for abnormalities (crooked stems, swellings at the soil line, etc.). The experimental design was a randomized complete block with four replicates. Analysis of variation (ANOVA) was performed using SAS 9.2, and means were separated using Tukey's Honestly Significant Difference (HSD) test ($P \leq 0.05$).

Yellow Fieldcress Trial

This trial was also conducted at Weyerhaeuser's Aurora Forest Nursery in an area infested with yellow fieldcress. Thirteen herbicide treatments, including a nontreated control, were applied in 8-by-8 ft (2.4-by-2.4 m) plots (four per treatment) on July 1, 2015, to 3-to-6 in (1.2-to-2.4 cm) tall yellow fieldcress. Imazapyr and sulfometuron treatments were mixed with methylated seed oil (MSO) at 0.25 percent (volume/volume) prior to application. Percent visual

Figure 3. Herbicide trial to evaluate several potential products for us in forest tree nurseries. (Photo by Tim Miller, 2011)

yellow fieldcress cover was estimated at the time of herbicide application and again on September 2, 2015.

Plots were tilled in fall 2015 and fumigated in spring 2016. In May 2016, two beds (consisting of two of the four replicates) were then transplanted with Fraser fir (*Abies fraseri* [Pursh] Poir.) seedlings, and two beds were transplanted with noble fir (*A. procera* Rehder) seedlings. Fraser and noble fir seedlings were evaluated for herbicide injury on September 7, 2016. Since plots contained no appreciable growth of yellow fieldcress on the date of evaluation, plots were only rated for common groundsel (*Senecio vulgaris* L.) control. The experimental design was a randomized complete block design with four replicates. ANOVA was performed using SAS 9.2, and means were separated using Tukey's HSD test ($P \leq 0.05$).

Results and Discussion

Herbicide Screening Trial

Douglas-fir injury due to PRE treatments was excessively high by June 15 (4 weeks after PRE treatment) for both rates of flazasulfuron, both rates of saflufenacil, the 9 pt/ac rate of oxyfluorfen plus penoxsulam, and pyroxasulfone at 1.25 oz/ac (table 1). Injury from these PRE products was still high through September 9 (12 weeks after PRE treatment), although seedlings in plots treated with flazasulfuron or pyroxasulfone showed substantial recovery compared with June observations. POST treatments with triclopyr caused up to 74 percent injury by July 1 (2 weeks after POST treatment), and seedlings did not appreciably recover by September 9 (8 weeks after POST treatment). All other PRE and POST treatments had relatively low damage and did not differ significantly from the nontreated control.

Primary weeds in the plots were common groundsel and annual bluegrass (*Poa annua* L.); some plots contained white clover (*Trifolium repens* L.) and annual sowthistle (*Sonchus oleraceus* L.). Weed control was good to excellent for most treatments, generally 85 percent or more through September 9 (table 1). Exceptions to good weed control were triclopyr at either rate, pyroxasulfone at 1.25 oz/ac, saflufenacil at either rate, or flazasulfuron at either rate.

Douglas-fir seedling biomass in most herbicide-treated plots was similar to trees in nontreated plots (table 2). Saflufenacil at 2 oz/ac (PRE) reduced stem diameter significantly, and other parameters nonsignificantly, compared to nontreated trees. Though not statistically significant, triclopyr at 5 pt/ac (POST) and isoxaben at 11 oz/ac (PRE) tended to reduce all measured parameters; oxyfluorfen plus penoxsulam at 9 pt/ac reduced root and shoot biomass; and saflufenacil at 1 oz/ac (PRE), triclopyr at 3 pt/ac (POST), and oxyfluorfen plus penoxsulam at 6 pt/ac (PRE) reduced shoot biomass.

Based on these data, herbicides offering excellent weed control and low injury potential to Douglas-fir seedlings include indaziflam at 5 oz/ac, dithiopyr at 12 fl oz/ac, isoxaben at 11 oz/ac, mesotrione at 7 fl

Table 1. Douglas-fir injury and weed control in a forest tree nursery after treatment with several herbicides (2015).

Chemical name	Trade name	Manufacturer	Rate (product/ac)	Timing[b]	Douglas-fir injury (%)			Weed control (%)		
					Jun 15	Jul 1	Sep 9	Jun 15	Jul 1	Sep 9
Dithiopyr	Dimension®	Dow	8 fl oz	PRE	0 d	0 f	1 f	95 b	88 abc	88 ab
Dithiopyr	Dimension®	Dow	12 fl oz	PRE	0 d	4 f	3 f	98 ab	85 bc	89 ab
Flazasulfuron[a]	Mission®	ISK	1 oz	PRE	63 ab	36 de	14 ef	99 ab	98 abc	79 abc
Flazasulfuron[a]	Mission®	ISK	2 oz	PRE	79 a	66 abc	29 def	99 ab	99 ab	80 abc
Indaziflam	Alion®	Bayer	3 fl oz	PRE	0 d	3 f	1 f	100 a	100 a	100 a
Indaziflam	Alion®	Bayer	5 fl oz	PRE	1 d	3 f	0 f	99 ab	98 abc	98 a
Isoxaben	Gallery®	Dow	8 oz	PRE	1 d	1 f	0 f	99 ab	95 abc	94 ab
Isoxaben	Gallery®	Dow	11 oz	PRE	3 d	3 f	0 f	98 ab	89 abc	91 ab
Oxyfluorfen	GoalTender®	Dow	3 pt	PRE	0 d	1 f	0 f	100 a	100 a	98 a
Oxyfluorfen	GoalTender®	Dow	6 pt	PRE	1 d	2 f	0 f	100 a	100 a	99 a
Oxyfluorfen + penoxsulam	Pindar™ GT	Dow	3 pt	PRE	1 d	0 f	3 f	100 a	100 a	99 a
Oxyfluorfen + penoxsulam	Pindar™ GT	Dow	4.5 pt	PRE	9 d	10 f	18 def	100 a	100 a	88 ab
Oxyfluorfen + penoxsulam	Pindar™ GT	Dow	6 pt	PRE	11 d	10 f	11 ef	100 a	100 a	96 a
Oxyfluorfen + penoxsulam	Pindar™ GT	Dow	9 pt	PRE	40 c	35 e	39 cde	100 a	100 a	85 abc
Pyroxasulfone	Zidua®	BASF	1.25 oz	PRE	71 a	50 cde	20 def	100 a	95 abc	84 abc
Saflufenacil	Treevix®	BASF	1 oz	PRE	51 bc	58 bcd	60 abc	99 ab	95 abc	68 bc
Saflufenacil	Treevix®	BASF	2 oz	PRE	66 ab	80 a	83 a	98 ab	89 abc	60 c
Mesotrione	Tenacity®	Syngenta	5 fl oz	POST	—	8 f	0 f	—	86 abc	94 ab
Mesotrione	Tenacity®	Syngenta	7 fl oz	POST	—	10 f	1 f	—	95 abc	91 ab
Triclopyr	Garlon 3A®	Dow	3 pt	POST	—	45 cde	44 bcd	—	84 c	75 abc
Triclopyr	Garlon 3A®	Dow	5 pt	POST	—	74 ab	70 ab	—	91 abc	83 abc
Nontreated	—	—	—	—	0 d	0 f	0 f	0 c	0 d	0 d

[a] Flazasulfuron treatments were mixed with nonionic surfactant at 0.25%, volume/volume prior to application.

[b] PRE = preemergence, applied May 15, 2015 (4 days after transplanting); POST = postemergence, applied June 15, 2015.

Notes: Means within a column followed by the same letter or with no letters are not statistically different ($P \leq 0.05$). 1 fl oz = 29.6 ml; 1 pint = 0.47 L.

oz/ac, and oxyfluorfen plus penoxsulam at 4.5 pt/ac. The industry-standard product oxyfluorfen at 6 pt/ac also provided excellent weed control with low crop injury. Flazasulfuron, saflufenacil, triclopyr, and pyroxasulfone may have potential for use in conifer nursery production for other tree species, or if applied prior to transplanting Douglas-fir seedlings.

Yellow Fieldcress Trial

Initial injury to yellow fieldcress was greatest with imazapyr alone or in tank mixtures (table 3). Weed cover was reduced from an average of 20 percent to 2 percent by September 9 (2 months after treatment) in plots treated with that herbicide. No other plots differed significantly from the nontreated control, although sulfometuron and triclopyr treatments showed a trend of reduced yellow fieldcress cover (table 3). Plots were tilled shortly after the September 2015 evaluation and were observed to be essentially weed-free on January 20, 2016 (data not shown).

Fraser and noble fir seedlings were sensitive to soil residuals of imazapyr at 14 months after treatment and 4 months after outplanting (table 3). Fraser fir was more sensitive (25 to 40 percent injury) than noble fir (15 to 26 percent injury), although both species sustained unacceptably high injury. Common groundsel was

Table 2. Douglas-fir tree measurements at time of lifting after treatment with several herbicides (2016).

Treatment	Trade name	Manufacturer	Rate (product/ac)	Timing [b]	Tree height[c] (cm)	Stem diameter[c] (mm)	Root biomass[c] (g)	Shoot biomass[c] (g)
Dithiopyr	Dimension®	Dow	8 fl oz	PRE	43.1 a	8 ab	34 abc	35 ab
Dithiopyr	Dimension®	Dow	12 fl oz	PRE	38.0 abc	8 ab	36 ab	31 abc
Flazasulfuron[a]	Mission®	ISK	1 oz	PRE	38.3 abc	8 ab	40 ab	24 a–f
Flazasulfuron[a]	Mission®	ISK	2 oz	PRE	31.8 abc	8 ab	20 abc	18 b–f
Indaziflam	Alion®	Bayer	3 fl oz	PRE	43.9 a	9 ab	42 a	39 a
Indaziflam	Alion®	Bayer	5 fl oz	PRE	41.0 abc	9 a	33 abc	31 a–d
Isoxaben	Gallery®	Dow	8 oz	PRE	39.9 abc	9 ab	28 abc	28 a–e
Isoxaben	Gallery®	Dow	11 oz	PRE	42.8 a	8 ab	19 abc	26 a–e
Oxyfluorfen	GoalTender®	Dow	3 pt	PRE	42.3 ab	8 ab	36 ab	33 abc
Oxyfluorfen	GoalTender®	Dow	6 pt	PRE	41.8 abc	8 ab	24 abc	27 a–e
Oxyfluorfen + penoxulam	Pindar™ GT	Dow	3 pt	PRE	37.7 abc	9 ab	26 abc	28 a–e
Oxyfluorfen + penoxulam	Pindar™ GT	Dow	4.5 pt	PRE	33.9 abc	8 ab	22 abc	26 a–e
Oxyfluorfen + penoxulam	Pindar™ GT	Dow	6 pt	PRE	31.0 abc	7 ab	17 abc	17 b–f
Oxyfluorfen + penoxulam	Pindar™ GT	Dow	9 pt	PRE	28.8 abc	7 ab	11 bc	17 b–f
Pyroxasulfone	Zidua®	BASF	1.25 oz	PRE	40.6 abc	8 ab	34 abc	26 a–e
Saflufenacil	Treevix®	BASF	1 oz	PRE	42.7 a	6 abc	13 abc	12 ef
Saflufenacil	Treevix®	BASF	2 oz	PRE	20.8 c	4 c	5 c	6 f
Mesotrione	Tenacity®	Syngenta	5 fl oz	POST	40.4 abc	8 ab	24 abc	26 a–e
Mesotrione	Tenacity®	Syngenta	7 fl oz	POST	44.3 a	8 ab	27 abc	30 a–e
Triclopyr	Garlon 3A®	Dow	3 pt	POST	24.9 abc	6 abc	16 abc	16 c–f
Triclopyr	Garlon 3A®	Dow	5 pt	POST	20.9 bc	6 bc	11 bc	12 def
Nontreated	—	—	—	—	36.0 abc	8 ab	25 abc	23 a–f

[a] Flazasulfuron treatments were mixed with nonionic surfactant at 0.25%, volume/volume prior to application.

[b] PRE = preemergence, applied May 15, 2015 (4 days after transplanting); POST = postemergence, applied June 15, 2015.

[c] Trees lifted January 20, 2016.

Notes: Means within a column followed by the same letter or with no letters are not statistically different ($P \leq 0.05$). 1 fl oz = 29.6 ml; 1 pint = 0.47 L.

found in most plots in September 2016, and control did not differ among treatments (data not shown). Because yellow fieldcress had been removed by hand-weeding crews, ultimate control of this species from herbicide treatment followed by fumigation was not estimable.

Based on these data, sulfometuron alone or in combination with glyphosate applied in the summer prior to soil fumigation is recommended for control of yellow fieldcress in forest tree nurseries. Although it provided excellent initial control of yellow fieldcress, imazapyr persisted in the soil and injured fir seedlings transplanted into treated soil. It is not known if other conifer species would be less sensitive to residual imazapyr.

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Table 3. Yellow fieldcress control in a forest tree nursery before and after application of several herbicides and percent injury to noble fir and Fraser fir (4 months after planting and 14 months after herbicide application).

Treatment[a]	Trade name	Manufacturer	Rate (product/ac)	Yellow fieldcress cover		Noble fir injury[b]	Fraser fir injury[b]
				Pre-treat (Jul 1) (%)	Sep 9, 2015 (%)	(%)	(%)
Glyphosate	Roundup Pro®	Monsanto	1 qt	25	70 a	0 c	0 c
Glyphosate	Roundup Pro®	Monsanto	2 qt	20	60 ab	0 c	0 c
Glyphosate	Roundup Pro®	Monsanto	3 qt	19	64 ab	0 c	0 c
Imazapyr	Arsenal®	BASF	3 pt	18	3 c	19 ab	20 b
Imazapyr	Arsenal®	BASF	6 pt	20	0 c	15 b	40 a
Sulfometuron	Oust® XP	Bayer	2 oz	18	23 bc	1 c	0 c
Sulfometuron	Oust® XP	Bayer	4 oz	15	14 c	0 c	0 c
Triclopyr	Garlon 3A®	Dow	1 gal	23	39 abc	1 c	0 c
Triclopyr	Garlon 3A®	Dow	2 gal	25	29 abc	0 c	0 c
Glyphosate + imazapyr	Roundup + Arsenal	—	1 qt + 6 pt	24	4 c	26 a	40 a
Glyphosate + imazapyr	Roundup + Arsenal	—	2 qt + 3 pt	18	0 c	19 ab	25 ab
Glyphosate + sulfometuron	Roundup + Oust	—	2 qt + 2 oz	21	26 bc	0 c	0 c
Nontreated	—		—	20	58 ab	0 c	0 c

[a] Treatments were applied July 1, 2015; Imazapyr and Sulfometuron treatments were mixed with methylated seed oil at 1%, volume/volume prior to application.

[b] Tree injury evaluated September 7, 2016.

Notes: Means within a column followed by the same letter or with no letters are not statistically different ($P \leq 0.05$). 1 fl oz = 29.6 ml; 1 pint = 0.47 L; 1 qt = 0.95 L.

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An Update on New and Emerging Pests in the Pacific Northwest

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Abstract

Foresters and horticulturists should be aware of the risks of invasive species and should be updated on a regular basis regarding emerging pest threats. In the Pacific Northwest, many new potential threats to natural landscapes and forests have emerged. Recent detections include new species of whiteflies, lace bugs, sawflies, beetles, and earthworms. In addition to detections of new species, some are concerned about the expansion of host associations from prior-established exotic species. This article covers several emerging pest threats to forests, landscapes, and crops grown in the Pacific Northwest. This paper was presented at the joint annual meeting of the Western Forest and Conservation Nursery Association and the Intermountain Container Seedling Growers' Association (Troutdale, OR, September 14–15, 2016).

Introduction

Foresters and horticulturists responsible for the introduction of plants into natural landscapes play a vital role to reduce the risk of invasive species by awareness, prevention, and early detection of potentially damaging species. Invasive species awareness is a dynamic process, requiring frequent updates to keep current. Predictably, several new detections of exotic arthropods happen on an annual basis in the Pacific Northwest. In recent years, several emerging pests have caused concern given their potential to damage Pacific Northwest forests and natural landscapes. Among the recent detections are new species of whiteflies, lace bugs, sawflies, beetles, and earthworms. In addition to detections of new species, some are concerned about expansion of host associations from prior-established exotic species. In some cases, efforts are under way to mitigate establishment of these pests, and for those exotic species that have already become established, to reduce the damage from them. This article discusses several emerging pest issues of concern for landscapes, forests, and crops grown in the Pacific Northwest.

Ash Whitefly

Ash whitefly (*Siphoninus phillyreae* Haliday) was first detected in 2014 in southern Oregon near Medford, and later in Forest Grove, OR in the northern Willamette Valley. Ash whitefly is a small sucking insect that can cause excess honeydew and black-sooty mold on infested leaves and premature defoliation of host trees. Ash whitefly reached nuisance levels in the Portland metropolitan area in 2014 and 2015 when numerous, blizzard-like swarms of whitefly were seen at dusk searching for overwintering host plants in the late summer and fall. Evidence of feeding and reproduction of ash whitefly was found on several common host plants, including Oregon ash (*Fraxinus latifolia* Benth.), ornamental pears (*Pyrus calleryana* Decne.), hawthorn (*Crateagus* sp.), and flowering quince (*Chaenomeles* sp.). In Oregon, ash whitefly has been found to overwinter on the evergreen plant firethorn (*Pyracantha* sp.).

Ash whitefly adults have light yellow bodies and white wings. Their eggs are pale waxy yellow and usually surrounded by white powdery deposits. Young nymphs are nearly translucent but become more opaque as they age and increasingly covered with white waxy secretions. The pupae, or puparia, are very distinct (figure 1a). They are covered with tufts of white wax and have tubercules or long tubes formed around the edge of their bodies topped with clear waxy droplets (Rosetta 2016).

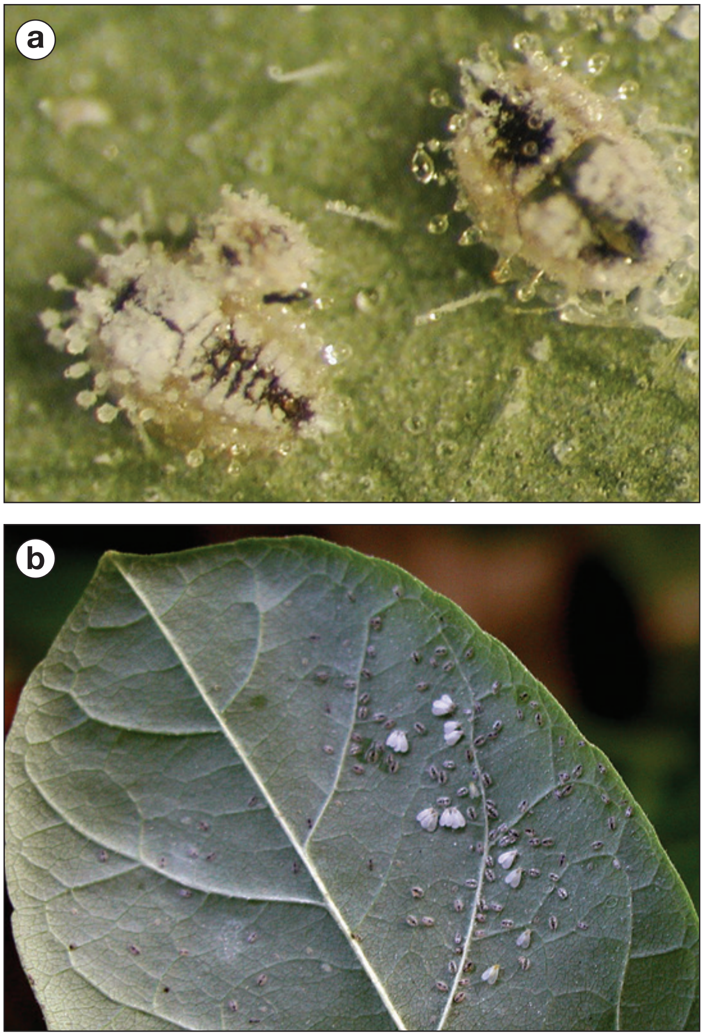

Figure 1. (a) Ash whitefly (*Siphoninus phillyreae* Haliday) puparia are covered with tufts of white wax and have tubercules or long tubes formed around the edge of their bodies topped with clear waxy droplets. (b) Oregon ash (*Fraxinus latifolia* Benth.) is a common host tree species for ash whitefly. (Photos by Robin Rosetta, 2015)

The adult female lives for about 30-60 days. They lay eggs on the undersides of the leaves on host plants. Nymphs emerge from the eggs, and that first "crawler" stage moves to a new site and settles onto the leaves where they remain and feed on the plant sap. They then pupate and later emerge as winged adults (figure 1b). Both the nymphs and adults can feed. The whiteflies can develop from egg to adult stage in 25 days at 25 °C (77 °F) (Bellows et al. 1990). Ash whitefly can develop continuously during the year with several generations per year; development slows with cooler temperatures. The whiteflies emigrate from preferred deciduous summer hosts, such as ash, pear, and hawthorn, to evergreen overwintering hosts in the fall. All stages of the whitefly can overwinter on evergreen host plants.

A classical biological control program was developed by the University of California, Riverside, soon after ash whitefly first appeared in California in 1988 (Bellows et al. 1992). That program was very successful and relied on activity of an imported parasitic wasp (*Encarsia inaron* Walker) and a lady beetle (*Clitostethus arcuatus* Rossi). The parasitic wasp, in particular, is credited with reducing populations of ash whitefly and thus their damage, from 98 percent of ash leaves infested in 1991 to less than 1 percent after establishment in 1992 (Driestadt and Flint 1995). Oregon Department of Agriculture staff detected both the parasitic wasp and the lady beetle in the fall of 2015. By the late summer of 2016, ash whitefly populations were noticeably diminished, and the parasitic wasp was found throughout the Willamette Valley (Hedstrom 2016).

Cabbage Whitefly

An Oregon State University (OSU) Master Gardener first detected cabbage whitefly (*Aleyrodes proletella* Linnaeus) in 2014 from a plant sample submitted from a Portland home garden that was confirmed by the Oregon Department of Agriculture. Named cabbage whitefly due to its preference for Brassicaceous plant hosts (*Brassica oleracea* L.), cabbage whitefly is more of a pest of curly kale (*Brassica oleracea* L. var. *sabellica* L.) (figure 2a) and Brussels sprouts (*Brassica oleracea* L var. *gemmifera* [DC.] Zenker), but less so of cabbage (*Brassica oleracea* L. var. *capitata*) (Trdan et al. 2003). Although it is best known as a pest of crucifers, it does have a wide host range, including sow thistle (*Sonchus* sp.) and other composite species, spurge (*Euphorbia* sp.) plants in the family Euphorbiaceae, columbine (*Aquilegia* sp.) in the family Ranunculaceae, greater celandine (*Chelidonium majus*) in the family Papaveraceae, greenhouse grown gerbera (*Gerbera jamesonii*) in the family Asteraceae (Loomans et al. 2002), and plants in the family Apiaceae (Martin 2015).

Cabbage whitefly is not known to transmit plant viruses. Most damage occurs directly from large numbers of adult and juvenile whitefly sucking on plant sap, producing copious honeydew, and the development of black sooty mold fungus, which feeds on the honeydew. Observations of populations on kale in the Portland metropolitan area have shown very high densities of these whiteflies with relatively little natural enemy suppression.

Adult cabbage whiteflies are small and white with two faint gray marks on their wings, which are held tent-like as they rest (figure 2b). Eggs are laid on

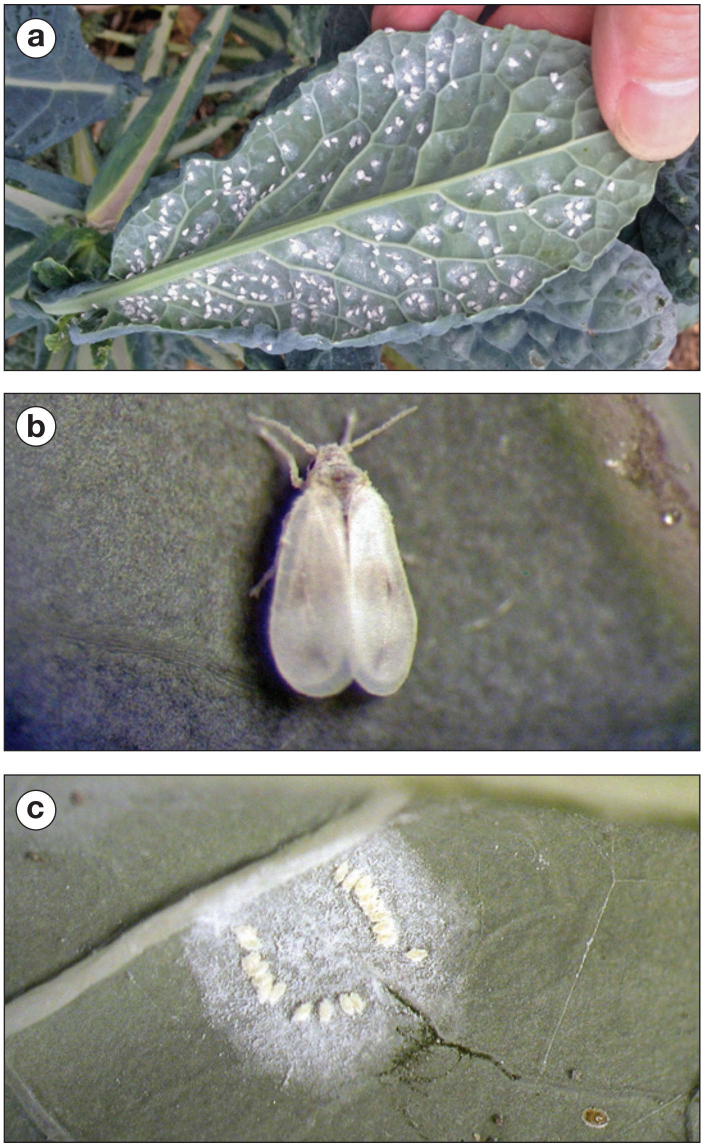

Figure 2. (a) Cabbage whitefly (*Aleyrodes proletella* Linnaeus) populations on kale in Oregon have shown very high densities. (b) Adults are small and white with two faint gray marks on their wings, which are held tent-like as they rest. (c) Eggs are laid on the leaf underside and often in a circle or semi-circle. (Photos by Robin Rosetta, 2016)

the underside of host leaves and often in a circle or semi-circle with noticeable white powdery deposits (figure 2c). The three nymphal stages are flat and oval. Depending on climate, there may be 2 to 6 generations per year depending on climate. Cabbage whiteflies overwinter on plant hosts (ODA 2015).

Cabbage whitefly has been found to be significantly resistant to pyrethroid insecticides in Great Britain, but no cross-resistance to neonicotinoid insecticides has been detected (Springate and Colvin 2011). At least nine species of parasitic wasps have been reared from cabbage whitefly, including commonly used biocontrol species such as *Encarsia formosa*, *E. inaron*, E. *perganiella*, and *Eretmocerus mundus*, but attempts to control cabbage whitefly with augmentative releases have been unsuccessful (Loomans et al. 2002).

Bandedwinged Whitefly

Bandedwinged whitefly (*Trialeurodes abutilonea* Haldeman; BWWF) was detected on sunflowers (*Helianthus* sp.) along Highway 84 near Biggs, OR, in 2015 (Vlach 2017). Limited information is available on the extent and damage so far from BWWF in Oregon. A reference from the University of Kentucky refers to BWWF as an "occasional pest" of greenhouse crops (White 2013), and Sanderson (2017) seems to concur stating that BWWF, "… is relatively rare; it is sometimes found on yellow sticky traps, though rarely on the crop."

In addition to its namesake host, flowering maple (*Abutilon* sp.), a number of other economic hosts exist: that is, approximately 140 host species in 33 plant families (Malumphy et al. 2011). Malumphy et al. (2011) list numerous commercially important ornamental hosts: *Acacia* sp., *Aster* sp., *Bidens* sp., *Brugmansia* sp., *Citrus* sp., *Eucalyptus* sp., *Euphorbia* sp., *Fuchsia* sp., *Hibiscus* sp., *Impatiens* sp., *Pelargonium* sp., *Petunia* sp., *Solidago* sp., and *Veronica* sp. In addition, they report finding BWWF on *Acacia* sp., *Banisteriopsis caapi*, and *Brugmansia* sp. plants imported to England from the United States. BWWF had previously been intercepted on *Hibiscus rosa-sinensis* var. 'Kopper King' plants imported from the United States in 2005. Their list of field and orchard hosts include: *Brassica* sp., *Citrus* sp., *Lactuca* sp., *Phaseolus* sp., and *Solanum* sp. They mention that BWWF has a "preference for feeding on plants belonging to the families Malvaceae and Solanaceae."

BWWF nymphs resemble greenhouse whitefly and are initially translucent but gradually show faint yellow markings (figure 3a). The pupal stage is helpful to distinguish this species from greenhouse whitefly, as it often has a dark longitudinal band down the center. The adult has white wings with two dark zigzag markings on the forewings (figure 3b).

Like most whiteflies, BWWF can damage plants through feeding, honeydew production, and the accompanying growth of black sooty mold. Malumphy et al. (2011) note the adults can vector four viruses: abutilon yellows virus, diodia vein chlorosis virus, sweet potato chlorotic stunt virus, and tomato chlorosis virus.

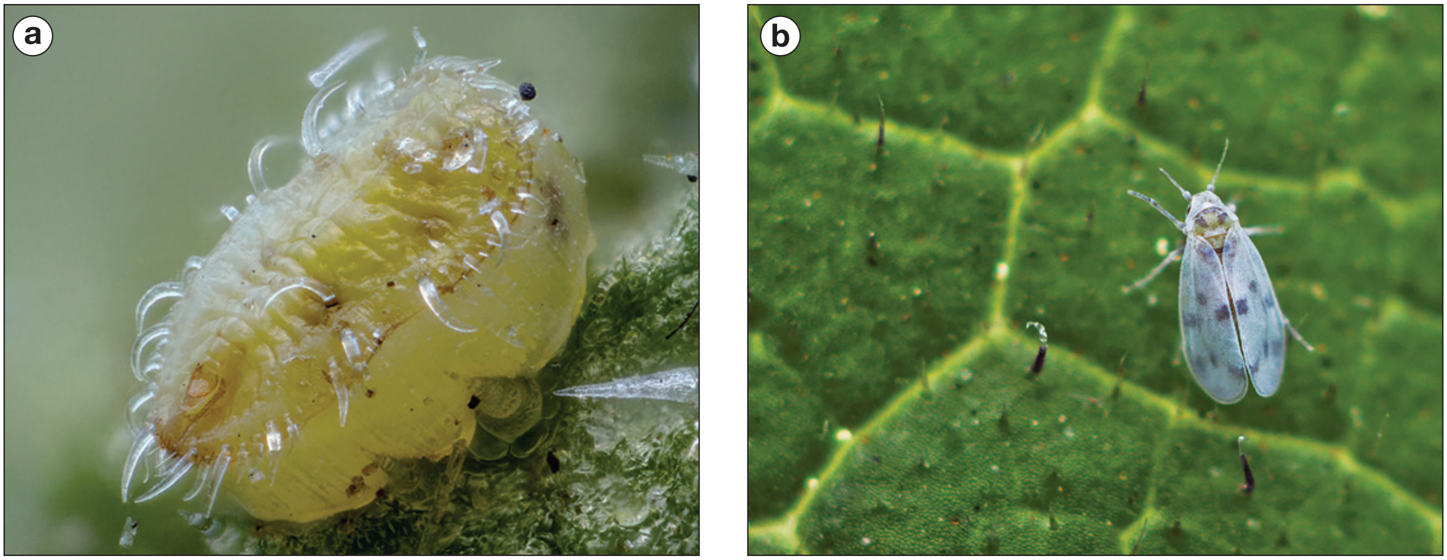

Figure 3. (a) Bandedwinged whitefly (*Trialeurodes abutilonea* Haldeman) pupae have a dark longitudinal band down the center. (b) Adults have white wings with two dark zigzag markings on the forewings. (Photos courtesy of Oregon Department of Agriculture, 2015)

Azalea Lace Bug

Azalea lace bug (*Stephanitis pyrioides* Scott) was officially confirmed in 2009 in Oregon. Since then, azalea lace bug distribution has expanded, and reports of damage are widespread, sometimes severe, to rhododendrons (*Rhododendron* sp.) and azaleas (*Azalea* sp.) in the North Willamette Valley. Soon after establishment, it became clear that azalea lace bug was damaging additional important plant genera, including evergreen huckleberry (*Vaccinium ovatum* Pursh) and salal (*Gaultheria shallon* Pursh) (figure 4a). The known host plants of this pest have expanded by over 20 plant species and three new plant families, based on natural observations and plant trials in Oregon (LaBonte and Valente 2014).

Azalea lace bug generally overwinters in the egg stage although adults can be found as well. The eggs are embedded in the leaf stem or tissue and covered over by a varnish-like coating of fecal material (figure 4b). Upon emergence, the immature lace bugs, or nymphs, are nearly translucent, changing to a light yellowish-green with early feeding. They darken with later molts and become spiny. Adult lace bugs are around 0.635 cm (0.25 in) long. Their wings are held flat and are covered with a network of veins. The wings are lightly colored with white and black patterns, creating a windowpane effect (figure 4c). Adults have a large, bulbous head capsule.

Visible damage from azalea lace bug feeding begins with yellow stippling on the upper surface of the leaves as these piercing-sucking insects feed on the lower surface. Continued feeding causes the stipples to coalesce, turning leaves of rhododendron completely yellow (figure 4d) with green veins, and turning leaves of azaleas white (figure 4e). Heavily damaged leaves turn brown, and affected plants may experience defoliation. Azalea lace bug reduces chlorophyll content, photosynthesis, and transpiration (Rosetta 2013).

Phenological surveys found 3.5 generations a year occur in the Willamette Valley (Flores 2016). Management with green lacewing (*Chysoperla rufilabris* Burmeister) releases and with water sprays targeting the nymphal stage show promise (Flores et al. 2016). A large container nursery has already adopted these tactics, and further industry adoption is expected. Flores (2016) also surveyed which cultivated varieties were infested or not, in order to find more resistant cultivars, and the results were passed to interested stakeholders. Nurseries, public parks, and colleagues have made numerous requests for this information, and they continue these assessments.

Oak Lace Bug

Another new lace bug, tentatively identified as oak lace bug (*Corythucha arcuata* Say), was detected from a public park in Portland on Oregon white oak (*Quercus garryana* Douglas ex Hook.). We still await

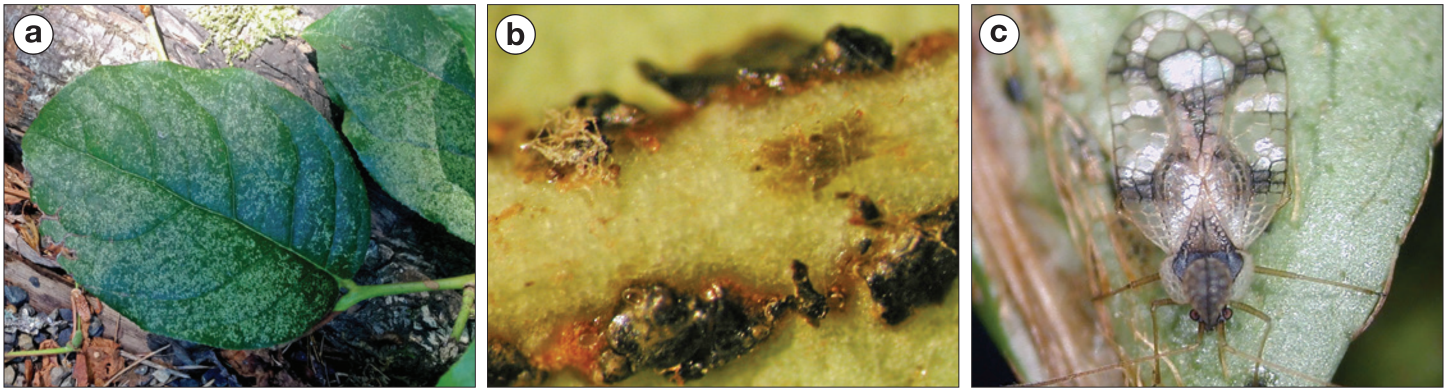

Figure 4. (a) Feeding by azalea lace bug *(Stephanitis pyrioides* Scott) causes stippling on leaves such as this salal leaf. (b) The eggs are embedded in the leaf stem or tissue and covered over by a varnish-like coating of fecal material. (c) Adult azalea lace bug holds its wings flat at rest. The wings are translucent and lightly colored with white and black patterns, creating a windowpane effect. Adults have a large, bulbous head capsule. (d and e) Heavy feeding causes leaves of rhododendron to turn completely yellow and leaves of azaleas to turn white. (Photos by Robin Rosetta, 2009)

official confirmation by USDA for this species but its appearance and key characters are consistent with oak lace bug. If confirmed, this would be the first record of oak lace bug west of the Rockies. Currently, no information exists on the extent of the distribution of oak lace bug in Oregon.

According to a Rutgers Cooperative Extension Advisory (Rettke 2013), oak lace bug has three to four generations per year, with the final generation laying eggs in late summer. Five nymphal stages occur prior to the adult stage. Unlike azalea lace bug, which embeds its eggs in plant tissue, oak lace bug lays its eggs on the surface of the leaf underside in characteristic rows of black eggs (figure 5a). Lace bugs in the genus *Corythucha* are associated with deciduous hosts and overwinter as adults under the bark of host trees. Similar to other lace bugs, oak lace bugs hold their wings flat and have parts of their wings that are translucent, giving a windowpane effect (figure 5b). Oak lace bug adults can be distinguished from azalea lace bug, as their wings have a more rectangular shape compared to the oval shape characteristic of lace bug species in the genus *Stephanitis*.

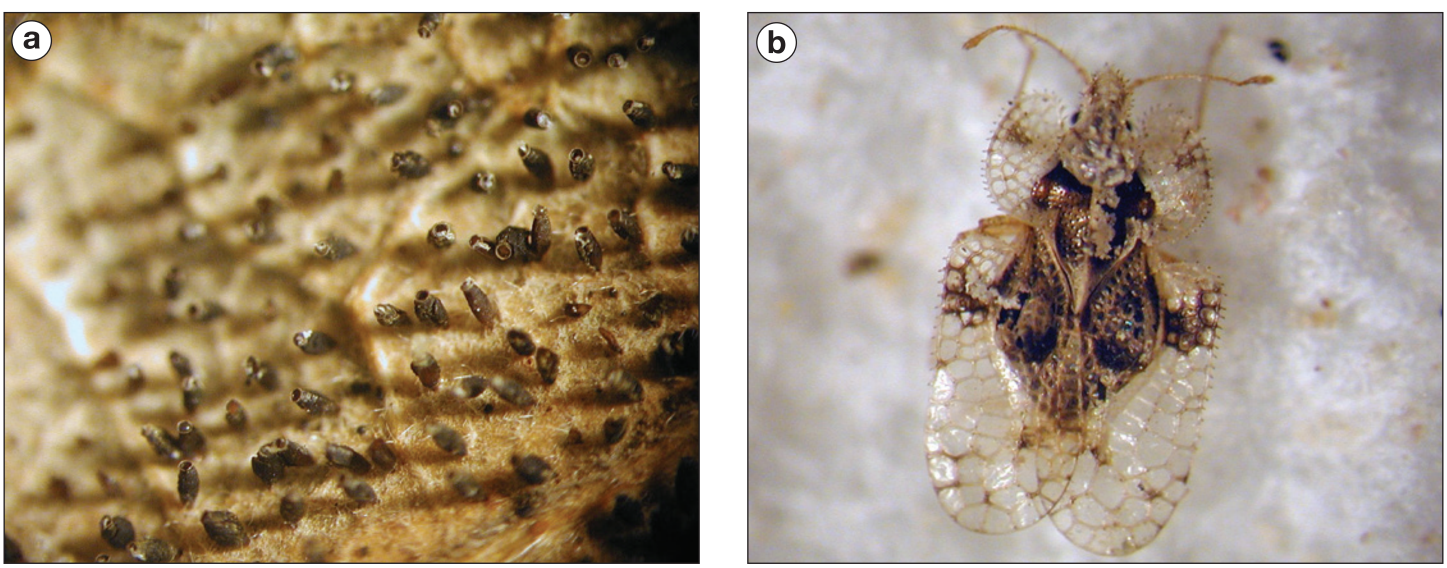

Figure 5. a) Oak lace bug (Corythucha arcuata Say) lays its eggs on the surface of the leaf underside in characteristic rows of black eggs. (b) The wings of oak lace bug adults have a rectangular shape with dark markings on their translucent wings. (Photos by Robin Rosetta, 2015)

Damage from oak lace bug is similar to that of other lace bug feeding, first exhibited as stippling on the top of leaves. Continued feeding can cause leaf discoloration and scorch-like symptoms. Oak trees can tolerate significant oak lace bug damage without plant health consequences, and the damage is mainly cosmetic. If management is required, it is suggested to target the nymphal stage early in the season.

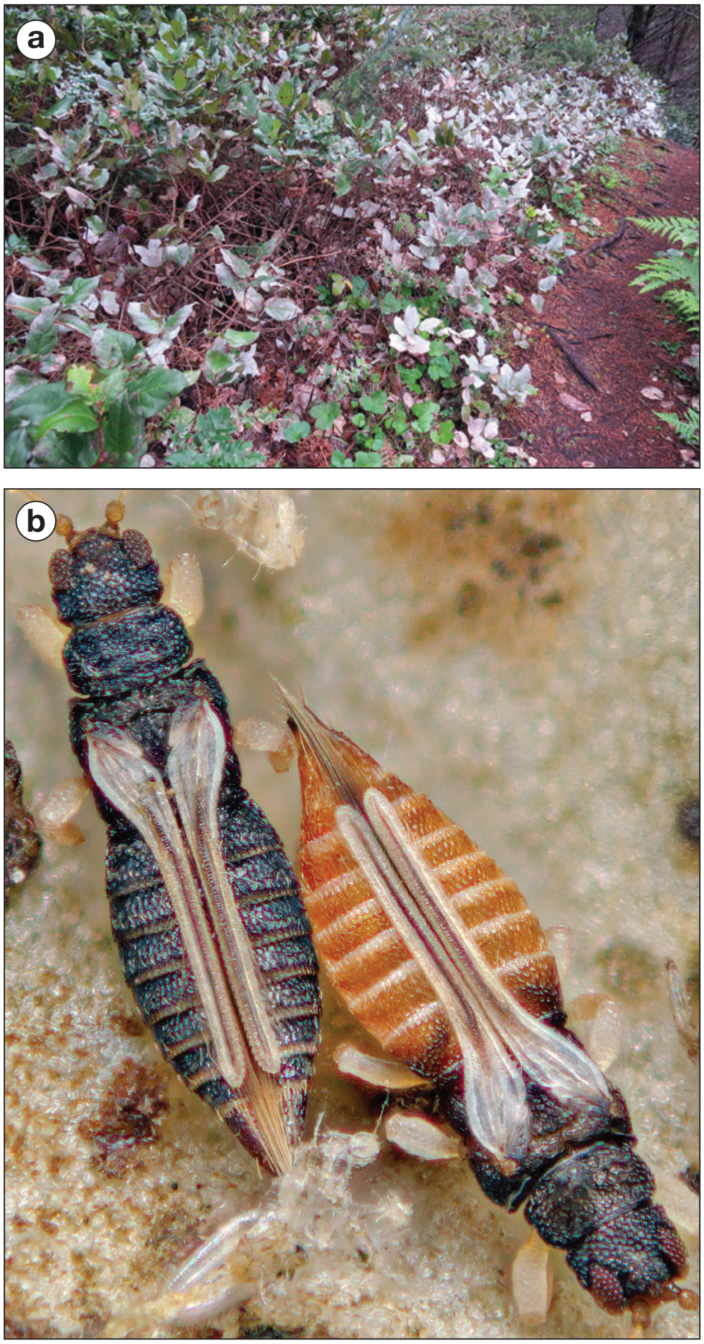

Figure 6. (a) Greenhouse thrips (*Heliothrips haemerroidalis* Bouché) feeding causes salal leaves to turn white, and the damage superficially resembles azalea lace bug injury (figure 4a). (b) Adult greenhouse thrips have a black head and thorax and either a black or orange abdomen with prominent bands. They hold their wings over their abdomen when not in flight. (Photo A by Neil Bell, Oregon State University, 2016; Photo B courtesy of Oregon Department of Agriculture, 2016.)

Greenhouse Thrips

In September 2015, OSU Extension Ask an Expert received a question about damage to salal on the southern coast of Oregon. The salal leaves were turning white or "silvering," and damaged plants were defoliating (figure 6a). The initial concern was that azalea lace bug was causing the damage, as it has been found damaging salal in Oregon, and the damage superficially resembles azalea lace bug injury (figure 4a). Direct observation and sampling by the Oregon Department of Agriculture, however, determined the damage was caused by greenhouse thrips (*Heliothrips haemerroidalis* Bouché). In 2016, greenhouse thrips were detected feeding on salal and Pacific wax myrtle (*Myrica californica* Cham. & Schltdl.) in natural landscapes near Florence on the Oregon Coast (LaBonte 2016). Though prior reports have been made of greenhouse thrips damage on salal, and on Viburnum plants near Seattle, the outbreak in Oregon appears to be more extensive, with reports of damage to salal from Benton, Coos, Curry, Douglas, and Lane Counties (Edmunds 2016a, 2016b; Pscheidt 2015; Young 2017). A search through OSU Insect ID Clinic records revealed entries of thrips damage on wax myrtle in 2004 and on rhododendron in 2005 from Coos County. In addition, the OSU Insect Identification Clinic has images of plant specimens of greenhouse thrips damage on salal, rhododendron, and native fern (*Polystichum imbricans imbricans*) collected from a courtyard on the OSU campus in 2007 (Young 2007). The collector/identifier wrote, "These specimens were brought in as an example of damage that has been observed for the last 3 years on salal growing south of Newport on US 101." Those entries and images suggest greenhouse thrips has been a pest on the southern Oregon coast since as early as 2004.

Greenhouse thrips generally remain on the leaf underside where they pierce plant cell walls and feed on cell contents, removing the green chloroplasts. With extensive feeding, the leaves turn a silver color, nearly devoid of green. Black fecal spotting is also present in areas where they have fed, making the underside of the leaf look "dirty." Larval thrips are light colored with red eyespots. Adult greenhouse thrips have a black head and thorax and either a black or orange abdomen with prominent bands (figure 6b). They hold their wings over their abdomen when not in flight. Additional host plants are reported for greenhouse thrips,

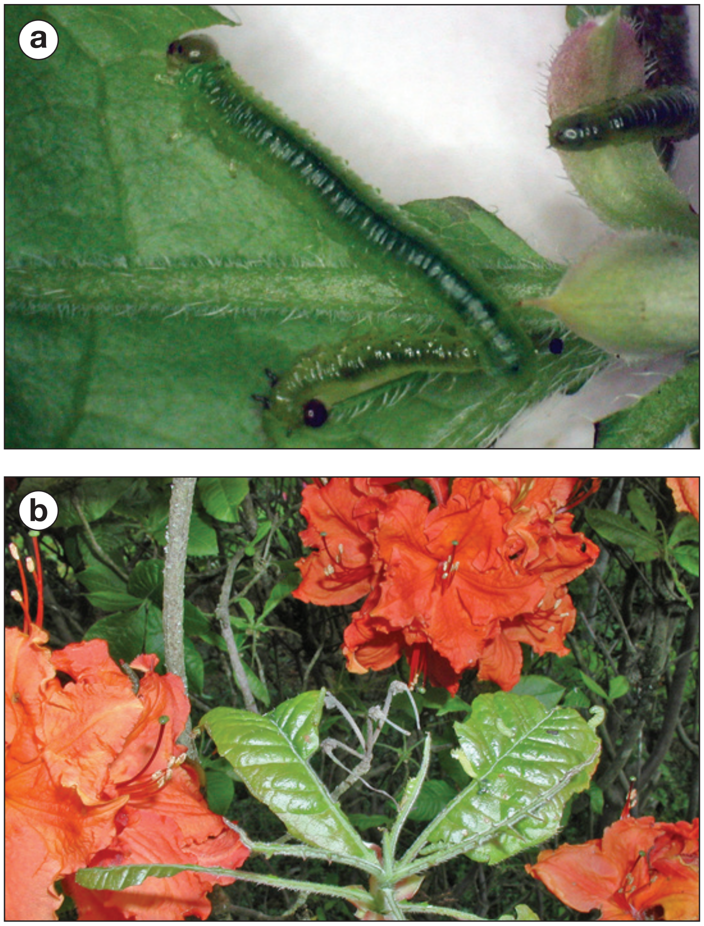

Figure 7. (a) Azalea sawfly (*Nematus lipovskyi* Smith) larvae are light green with a yellow head capsule. They closely match the green color of the azalea leaves. (b) Azalea plant showing defoliation from azalea sawfly. (Photos by Robin Rosetta, 2016)

including woody plants such as azalea, Oregon grape (*Mahonia* sp.), and maples (*Acer* sp.), as well as other evergreen and herbaceous plants like fuchsia (*Fuchsia* sp.) (Collman 2017, LaBonte 2016).

Azalea Sawfly

The azalea sawfly (*Nematus lipovskyi* Smith) may have been present in the Pacific Northwest for some time based on anecdotal reports, but has only been officially determined to be present in Oregon in 2016. Azalea sawfly was documented as present in Washington State in 1996 (Looney et al. 2016). Azalea sawfly is native to the eastern United States, originally described from *Rhododendron molle* Blume (Smith 1974). In addition to *R. molle*, host plants include flame azalea (*R. calendulaceum* Michx.), swamp azalea (*R. viscosum* L.), honeysuckle azalea (*R. luteum* Sweet), and clammy azalea (R. × *obtusum* 'Ledikanense') (Macek and Sipek 2015). Distribution information is limited but the author has noted populations in several locations in the northern part of the Willamette Valley extending south to Corvallis and also found at an Oregon Department of Transportation rest stop on Highway 26 in the coastal mountains.

Azalea sawfly has a single generation per year. The adults are stout-bodied wasps. Macek and Sipek (2015) observed swarming of the females around azaleas prior to oviposition. The female sawflies lay their eggs along the central vein of young developing leaves. Larvae hatch in 7 to 10 days. The larvae are light green with a yellow head capsule (figure 7a). They closely match the green color of the azalea leaves and generally escape detection until severe damage is noticed (figure 7b). The sawflies are gregarious, and numerous larvae can rapidly defoliate individual plants; they consume both leaves and flowers. The larvae eventually drop to the soil to pupate.

European Pine Sawfly

European pine sawfly (*Neodiprion sertifer* Geoff.) was first collected in North America in Somerset County, New Jersey in 1925 (Schaffner 1939). The sawfly was detected in Washington State in 2008 (Looney et al. 2016). In 2015, this sawfly was confirmed from a landscape in Albany, OR.

European pine sawfly larvae resemble caterpillars but have three thoracic legs and seven prolegs. They are grayish-green with two prominent dark lateral stripes as well as several lighter stripes alongside. Adult female sawflies are stout, brownish-black wasps that insert their eggs within slits in rows on pine needles in September through October. They overwinter in the egg stage, and larvae emerge in late April to May. The young larvae feed on the previous year's needles (Hoover and Barr 2002). They reach maturity in late May or early in June, then drop to the ground and spin cocoons in the needle litter. They have one generation per year. Severe defoliation can occur when these gregarious larvae are around (figure 8), and outbreaks can reach epidemic levels. Observations in New Jersey (Schaffner 1939) indicate that European pine sawfly preferentially feeds on red pine (*Pinus resinosa* Aiton), Scots pine (*P. sylvestris* L.), Japanese red pine (*P. densiflora* Siebold & Zucc.), jack pine (*P. banksiana* Lamb.), table mountain pine (*P. pungens* Lamb.), and mugo pine (*P. mugo* Turra). It has also been found feeding on eastern white pine (*P. strobus* L.), Austrian pine (*P. nigra* Arnold), ponderosa pine (*P. ponderosa* Lawson & C. Lawson), shortleaf pine (*P. echinata* Mill.), and more rarely, pitch pine (*P. rigida* Mill.) when they are growing near preferred host pines.

Crazy Snake Worms

A new species of earthworm has been detected in Oregon, and it may have ecological implications. Crazy snake worms (*Amynthas gracilis* Kinberg), also known as Asian jumping worms, were first detected in the Pacific Northwest in Grants Pass, OR, in 2016 and have since been confirmed from landscapes in McMinnville and southwest Portland (ODA 2016a). Originally from Asia, these exotic earthworms have been implicated in ecological damage in the Northeastern United States where they have been for many decades. In these areas, free of native species of earthworms, they harm the understory habitat due to their rapid turnover of leaf mulch, depriving native plants of sufficient seedbed in which to germinate and thrive and enabling excessive erosion. In Oregon, where native species of earthworms are found, the ecological damage from this introduced exotic species has yet to be determined.

Figure 8. European pine sawfly (*Neodiprion sertifer* Geoff.) damage from a landscape in Albany, Oregon. (Photo courtesy of Oregon Department of Agriculture, 2015)

Figure 9. Crazy snake worms (*Amynthas gracilis* Kinberg) are a pale burgundy color with a light white band separating the front third of their body from the rear. They have a ring of stout bristles on each segment. (Photo courtesy of Oregon Department of Agriculture, 2016)

The earthworms are a pale burgundy color with a light white band separating the front third of their body from the rear (figure 9). They have a ring of stout bristles on each segment, which is a reliable diagnostic character. They are noted for vigorously wiggling when disturbed and having movement similar to a snake across the soil surface.

Japanese Beetle

Japanese beetle (*Popillia japonica* Newman) is a high-priority exotic beetle of concern in the Pacific Northwest. It has a wide host range of over 300 species of plants, including many economic field crops as well as valuable landscape plants. First detected in the United States in 1916 in New Jersey, Japanese beetles have expanded their distribution throughout the Eastern United States. In order to remain free of Japanese beetles, Western States have begun eradication procedures when Japanese beetles have been caught in traps or found through surveys. During 2016, 369 Japanese beetles were trapped in one area of northwest Portland, prompting plans for one of the Oregon Department of Agriculture's largest eradication programs in recent years. Current eradication procedures in Oregon will rely on a newer chemical, Acelepryn® (Chlorantraniliprole), along with the use of entomopathogenic nematodes in sensitive sites (ODA 2016b).

The adult beetles resemble typical scarab or June beetles. They are large and thick with bright metallic green heads and tan-brown elytra or hindwings (figure 10). Small tufts of white hair line the sides and posterior of the beetles. Larvae are C-shaped beetle grubs with tan head capsules and stout bristles on their posterior. Both adults and beetle grubs feed and damage plants. The adult beetles feed on a wide range of host plants causing chewing damage and defoliation. They are particularly attracted to roses (*Rosa* sp.). The beetle grubs are strongly associated with turf feeding damage and are one of the key turf pests in the Eastern United States.

Figure 10. Japanese beetles (*Popillia japonica* Newman) are large and thick with bright metallic green heads and tan-brown elytra or hindwings. (Photo by Robin Rosetta, 2012)

Figure 11. (a) European chafer (*Amphimallon majalis* Razoumowsky) adults are brown with a typical scarab beetle shape. (b) Larvae are large, white, C-shaped grubs with tan head capsules and darkened posteriors. (Photo A by Chris Looney, Washington Department of Agriculture, 2015; Photo B by Todd Murray, Washington State University, 2015)

European Chafer

An additional catch of concern is the detection of European chafer (*Amphimallon majalis* Razoumowsky) in a Japanese beetle trap in the Portland metro area in 2015 (LaBonte 2015). The European chafer was first detected on the west coast in New Westminster, British Columbia, in 2011. It was confirmed from a homeowner sample from SeaTac in the State of Washington in 2015. European chafer is a damaging beetle pest of turf and other cereal and grass plants. A Washington State University Extension Fact Sheet contains a report that they have also been found feeding on the roots of broadleaf plants and conifers (Murray et al. 2012).

These beetles are large and robust with a typical scarab beetle shape. The adults are brown and about 1.27 cm (0.5 in) long (figure 11a). The larva is a large, white, C-shaped grub with a tan head capsule and darkened posterior (figure 11b). The adult beetles mate in the early evening. Females lay eggs in the soil shortly after mating. When the eggs hatch (in about 2 weeks), the young grubs feed on plant roots. European chafer overwinters in the larval stage and pupates in May. Adults emerge in 2 to 3 weeks, in June (Murray et al. 2012). Feeding damage on turf can be severe and may be mistaken for damage from crane flies or cutworms.

Rose Stem Girdler

Rose stem girdler (*Agrilus cuprescens* Ménétriés) has been captured in the Portland area (2015) and in southwest Washington (2014), as well as east of the Cascade Mountains. This beetle borer has the potential to cause damage to important plants in the Northwest, including caneberries (*Rubus* sp.), currants and gooseberries (*Ribes* sp.), and its namesake, roses. A buprestid beetle, it feeds in the cambium and girdles the plants.

Adult rose stem girdler beetles are narrow and flattened, with a coppery red or green color. The larvae are white, long, narrow, and segmented with an enlarged pronotal segment next to the small dark head capsule (figure 12). The rose stem girdler overwinters as a fourth-instar larva within the pith of the canes. Only one generation of rose stem girdler occurs each year. Pupation occurs when temperatures average 12.8 °C (55 °F). Adults emerge from canes in May and June in Utah. Beetles can often be found mating in June and lay their eggs on the stems. Larvae chew through the bottom of the eggs and into the canes. The larvae feed

Figure 12. Rose stem girdler (*Agrilus cuprescens* Ménétriés) larvae are white, long, narrow, and segmented with a small dark head capsule. (Photo by Tom Peerbolt, Peerbolt Crop Management, 2015.)

in a shallow, spiral gallery that may cause ripples on the bark of the cane. They attack both vegetative and fruiting canes on caneberries, and severe infestations can kill plants in 2 to 3 years (Alston 2015).

Viburnum Leaf Beetle

Viburnum leaf beetle (*Pyrrhalta viburni* Paykull) is a chrysomelid beetle, aptly named, as it feeds on leaves of viburnum (*Viburnum* sp.). The damage potential from this beetle is quite extensive if not managed. Viburnum leaf beetle, first introduced from Europe to Ontario, Canada, in 1947, spread to the United States and was first reported in Maine (1994). It has since spread to Connecticut, Massachusetts, New Hampshire, New Jersey, New York (1996), Pennsylvania, Ohio (2002), and Vermont (Weston et al. 2007). Viburnum leaf beetle was first detected in the Pacific Northwest in 2001 in southern Victoria Island in British Columbia. Beetle presence in Washington was confirmed in 2004 from a homeowner sample from Bellingham, WA, in Whatcom County. It has since been found in a number of sites in King, Skagit, Snohomish, and Whatcom Counties in Washington State (Murray et al. 2016).

Viburnum leaf beetle overwinters in the egg stage. Eggs are inserted into pits chewed into the stems, generally in a straight line (figure 13a). Larvae hatch from the eggs in the spring, by mid- to late April, closely synchronized with leaf bud development of arrowwood viburnum (*Viburnum dentatum* L.), a very susceptible host species (Weston et al. 2007). Three larval stages (instars) feed on the upper surface of the leaves. Larvae eventually crawl down the trunk of the plant to pupate in the soil. Pupae remain in the soil for about 10 days. The adults are found in the summer in July. Both larvae

Figure 13. (a) Viburnum leaf beetle (*Pyrrhalta viburni* Paykull) eggs are inserted into pits chewed into the stems. (b) Larger larvae are light-to-dark green with black spots. (Todd Murray, Washington State University, 2004)

and adults feed on leaves. Adult females begin laying eggs in the late summer and fall. She can lay up to 500 eggs during her lifetime; the viburnum leaf beetle has only one generation per year.

Monitoring should begin by looking for egg-laying or oviposition scars on the current year's growth. Early feeding by the larvae will be evident as holes in leaves in the spring. They usually feed on the leaf undersides. Like many leaf beetle larvae, they superficially resemble a caterpillar but lack crochets (hooked appendages) on the prolegs (the fleshy, leglike protuberances in addition to the three pair of true legs). The newly hatched larvae are very small, around 1/8 in long, and are light yellow to tan. Their feeding damage is described as leaf skeletonization. Larger larvae are light to dark green with black spots (figure 13b). The adult beetles are a bronze-brown color and are similar in size to an elm leaf beetle. Feeding by the adults tends to show up as larger holes in the leaves. Damage from egg-laying can also lead to terminal dieback on stems.

Management for this beetle relies on several tactics, including pruning out stems with eggs, use of sticky material (Tanglefoot™) to trap larvae as they crawl down to pupate, chemical management, and plant resistance. Current recommendations are to plant resistant varieties. Dr. Paul Weston developed a very successful citizen science program to compile a list of susceptible and resistant varieties; that information is available at Cornell University's Viburnum Leaf Beetle Citizen Science website (Weston 2016).

Conclusion

Although some of the pests mentioned in this article have potential to be quite disruptive, the impact of others may be minimized with eradication programs, classical biological control, or may even escape notice due to relative obscurity. Recent exotic insect introductions have focused attention on both the potential of whiteflies for crop damage (e.g., cabbage whitefly on kale) but also on the success of classical biological control programs to diminish these exotic populations, such as the establishment of the parasitic wasps, *Encarsia inaron* (Walker) and *Clitostethus arcuatus* (Rossi) ladybeetles for ash whitefly. Some pests have likely been established for years before official detection, such as greenhouse thrips or azalea sawfly in Oregon, but natural spread and certain weather conditions conducive to pest population growth eventually make their damage more noticeable. Devastating pests such as Japanese beetles have constant monitoring programs, but funding for these programs are often at risk due to variations in State and Federal funding. Given the precarious budgets for pest survey and the sometimes fortuitous detections of pests from the public, a focus on invasive species awareness for growers, landscapers, and forestry personnel is definitely warranted.

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Preparing Seeds To Minimize the Risk of Seedlings Damping Off

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Abstract

Damping off is a disease of newly germinated seedlings prior to their development of woody tissues. High-quality seeds invigorated with moist, cold stratification will germinate rapidly under suboptimal conditions, and therefore reduce the time a seedling is vulnerable to damping off. An optimal invigoration of the seeds requires stratification times that will result in sprouted seeds, unless moisture levels are properly balanced to be high enough for stratification to be effective, yet low enough to prevent premature radicle emergence. A four-step process for adjusting seed moisture and conducting cold moist stratification can reduce damping off risks. This paper was presented at the joint annual meeting of the Western Forest and Conservation Nursery Association and the Intermountain Container Seedling Growers' Association (Troutdale, OR, September 14–15, 2016).

Introduction

Cram (2003) gave a thorough review of damping off in forest and conservation nurseries in which she noted that seeds are sometimes the source of the disease, but environmental and soil factors are more significant in determining whether the disease organisms are present and if the disease develops. Applying fungicides and sterilants to the seeds is sometimes helpful but must be used with caution because of potential phytotoxicity. Cram also noted that damping off is a disease of very young seedlings that have not yet developed woody tissue, and that rapid seed germination is an important defense because it minimizes the time the seedlings are vulnerable. This article focuses on using quality seeds and cold, moist stratification to speed germination and reduce the number of days a seedling is at risk for damping off. The discussion predominately relates to desiccation-tolerant seeds, although some of the principles also apply to seeds that are desiccation intolerant, such as oaks (*Quercus* sp. L.).

Seed Vigor is Key

To understand seed vigor, we must first understand seed germination. Germination is the emergence of a seedling, from a seed, with all the essential parts necessary to produce a normal plant. Germination also refers to the number or percent of individual seeds germinating out of 100 seeds. In considering an entire seed lot, the terms "germination," "germination percentage," and "percent germination" are used interchangeably. Seed vigor is a relative measure comparing the performance among seed lots, within one species of plant, of similar germination. Vigor is expressed in three ways. One of these is how long a seed remains alive in storage. A seed lot that maintains high germination for 50 years is more vigorous than one that only maintains high germination for 10 years. A second measure is how fast germination occurs. Seed lots that complete germination in 7 days are considered to be more vigorous than those taking 14 days to complete germination. The final measure of seed vigor is how much germination occurs under sub-optimal conditions. A seed lot is more vigorous when, under environmental conditions less favorable to germination, it has higher germination than other lots. From the standpoint of protecting a seedling crop from damping off, it is the speed of germination and the ability to germinate under stress conditions that are the most important expressions of vigor. Both of these types of seed vigor can be enhanced through seed management. To realize high seed vigor in the nursery, seeds of highest quality are used, and they are stratified in a way that will produce a rapid and complete germination.

Producing Seeds of Highest Quality

As a general rule, a seed has its maximum vigor when it reaches physiological maturity on the mother plant, just before it is shed to the environment. With some species, this maturation process can be completed after the seeds are harvested, but generally it is best to delay harvest until seeds reach maturity on the mother plant. Vigor continually decreases over time, from harvest through all the seed-processing steps. Species can vary considerably in their rate of vigor loss during the extraction and cleaning periods, but all are susceptible to loss. Therefore, seeds should be processed as promptly as possible and with no or minimal mechanical injury or other stress. Keeping the seeds dry during this process is also very important because higher moistures favor higher enzyme activity, which reduces seed vigor. Seeds are very hygroscopic and will readily take up moisture from the air if they are left exposed in open seed containers or machine hoppers. Therefore, keep seeds in moisture proof containers or covered with a moisture barrier unless they are actively being worked with. For some species, it could be necessary to monitor seed moisture while seeds are exposed to ambient conditions. The equilibrium relative humidity test (Karrfalt 2014) is a good way to test seeds that have not yet been finished as well as finished seeds. Seeds should not be left at high moistures for long, as vigor loss will be the result. The definition of "long" is somewhat relative to the amount of dormancy the seeds have and exactly how moist they are. High-moisture seeds can deteriorate even within 24 hours.

Although the period from harvest to optimal storage should be as short as possible, compromising care of the seeds for speed should never occur. Hasty seed cleaning leads to mechanical damage or an unfinished product. I have observed both a large western conifer and a southern pine seed cleaning facility that destroyed a large portion of a pine seed crop because the seeds were pushed too rapidly through the dewinging step. Enough time needs to also be invested in the removal of empty, insect- and fungal-damaged, and poorly developed seeds. These types of seeds are potential vectors of microorganisms, some of which can be pathogenic but can be removed with the right procedure Karrfalt (1983). A more complete discussion on seed cleaning can be found in Chapter 3 of the *Woody Plant Seed Manual* (Karrfalt 2008).

Rapid and Complete Germination

Obtaining high-quality seeds is one part to realizing a vigorous germination and lowering the susceptibility to damping off. Another part is to provide an optimal environment, including proper drainage, adequate and timely moisture, optimal temperature and light, and correct sowing depth (generally close or at the surface with a 0.25-in [6-mm] deep or less covering). The final part is to optimize seed imbibition and stratification to bring the first two parts together, especially for species that have seeds with dormancy. Dormancy is most frequently defined as the failure of a live seed to germinate when placed in environmental conditions favorable for germination. Another manifestation of dormancy is a slow and protracted germination. Therefore, optimized stratification will prepare a seed not only to germinate, but germinate promptly. Optimization usually involves extending the stratification period beyond what is needed to simply obtain germination with favorable environmental conditions.

Stratification is obligatory for dormant seeds, but can also improve the vigor of nondormant seeds. In one example of this improved vigor, Gosling and Rigg (1990) demonstrated that Sitka spruce (*Picea sitchensis* [Bong.] Carrière) seeds can be induced to germinate at suboptimal temperatures following cold stratification (figure 1). This benefit has also been observed with longleaf pine (*Pinus palustris* Mill.) and slash pine (*Pinus elliottii* Engelm.), two other species considered to be nondormant. Several nurseries now routinely stratify these two southern pines. Bonner et al. (1974) presented data that showed that loblolly pine (*Pinus taeda* L.) seeds cold-stratified for 60 days completed germination in 14 days, whereas seeds stratified for 30 days did not complete germination until approximately 21 days. Therefore, all other factors being equal, the longer stratification potentially reduced the time for damping off to develop by 7 days.

The challenge in stratifying nondormant species, or in stratifying dormant species for extended periods, is

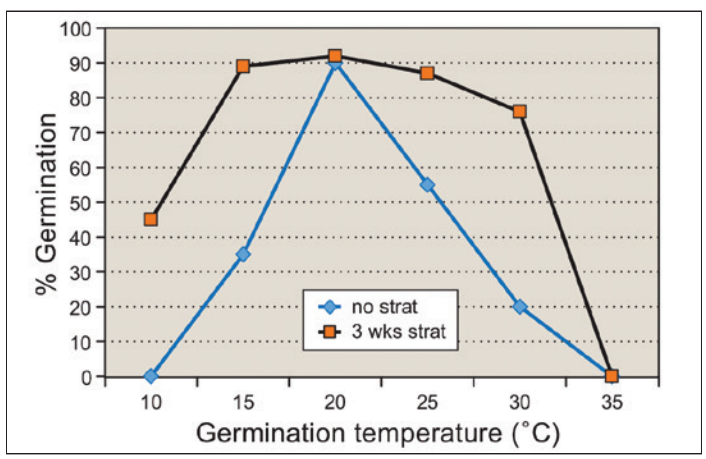

Figure 1. Cold stratification can invigorate Sitka spruce (*Picea sitchensis* [Bong.] Carrière) seeds, enabling them to germinate at suboptimal temperatures. (Adapted from Gosling and Rigg 1990)

to prevent sprouting, which precludes mechanical sowing. Seed moisture control is key in meeting this challenge. Seeds must have sufficient water to stratify, yet insufficient water to germinate. Traditional stratification procedures focused on providing sufficient moisture levels for stratification. Bonner et al. (1974) gave the instruction that, "Full imbibition is essential for stratification in plastic bags without moisture-holding media." Therefore, they recommended soaking the seeds in water overnight or even for 3 to 4 days. Although the water was drained off the seeds at the end of the soak period, some liquid water usually remained in the stratification bag. This extra moisture kept the seeds moist for breaking dormancy and provided the water needed to initiate radicle emergence, an undesirable condition that interfered with mechanical sowing. Keeping temperatures as low as possible without freezing helped restrain radicle emergence but not sufficiently for extended stratification periods. Therefore, the practice at nurseries has mostly been to shorten the stratification period to avoid radicle emergence and forfeit the advantage of invigorating the seeds for a faster germination. In more recent studies, however, lengthening stratification periods and mixing warm and cold periods have been found possible without radicle emergence if moisture contents were properly regulated (Edwards 1981, Gosling and Rigg 1990, Suszka et al. 1996).

Controlled Moisture During Stratification

To better understand the role of restricting moisture during stratification, we need to understand the three phases of water uptake by a seed, as it moves from the resting desiccated and dormant condition to active germination (figure 2). The first phase is a relatively rapid imbibition. During the second phase, very little water is absorbed, and the seed goes through preparatory metabolic steps to germinate. The third phase is again rapid, and a large uptake of water occurs as the embryo emerges from the seed. Therefore, to effectively stratify and avoid sprouting, water uptake must be arrested in the second phase. The following four-step process gives specific directions on how keep seeds at this second phase of water uptake.

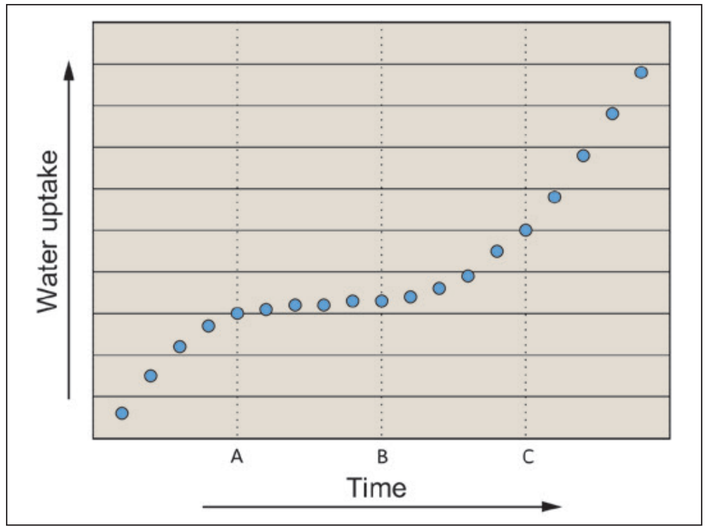

Figure 2. The three phases of water uptake as a seed germinates. Water uptake begins rapidly, then plateaus at point A when the seed is fully imbibed. Between point A and B, the water uptake is minimal as the seed prepares to germinate. From point B to point C and beyond, water uptake is again rapid as the seedling emerges from the seed.

Step 1—Imbibition

The first step in the process is to soak the seeds in water until they are fully imbibed. To determine how long this water soak must be, a series of weighing-soaking-reweighing cycles is followed. First, weigh a sample of seeds. Next, place the seeds in a water soak for approximately 24 hours, then drain off the water, surface dry the seeds, and weigh them again. Repeat this cycle until the weight stops increasing. Because very small increases can continue to occur for a long number of cycles, it is often difficult to decide when to stop the process. To give some perspective on when to end the process, I find it helpful to express the weight gain as a percentage of the original dry weight. Then full imbibition is considered the point when the weight increase is close to zero. For example, imbibition for whitebark pine (*Pinus albicaulis* Engelm.) is completed in 4 days, because the percent increase in seed weight is nearly zero by day 4 (figure 3). If possible, this process needs to be conducted on five separate samples, one from each of five seed lots. As a general guide, each individual sample should contain at least 300 to 500 seeds but not less than 1 oz (28 g). A two-place balance is sufficient for weighing. Determining the length of the water soak can be done at the nursery, or assistance can be obtained from the National Seed Laboratory (NSL; Dry Branch, GA) or other qualified laboratory.

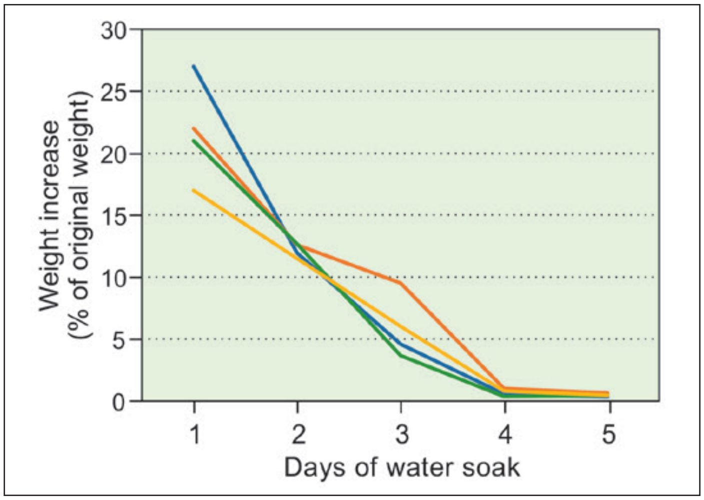

Figure 3. Whitebark pine becomes fully imbibed after 4 days of water soak.

Step 2—Water Rinse

Rinsing seeds with water is frequently practiced as an effective method to remove fungal spores from the seed coats. The imbibition phase is an ideal time to conduct this rinse. Soaking the seeds loose enables a daily stirring of the seeds to rinse their surfaces (figure 4). The water should be changed daily by pouring the seeds into a paint strainer, such as the E-Z Strainer™ (U.S. Plastic Corp., Lima, OH) (figure 5), from which they can easily be poured and rinsed back into a bucket for another day of soaking.

Step 3—Removal of Excess Water

At the end of the water soak, the excess water is removed in a two-stage process. The majority of water is first drained off in the strainer (figure 5). Then, the strainer is placed on a bucket connected to a wet-dry vacuum (figure 6). This connection can be made by simply inserting the vacuum hose into a hole cut into the side of the bucket or by attaching an electrical

Figure 4. Seeds are soaked in water until they are fully imbibed. (Photo by Robert Karrfalt)

Figure 5. The water is drained from the seeds using a paint strainer. (Photo by Robert Karrfalt)

connector to the bucket and an elbow (figure 7). The elbow can deflect the vacuumed water to the bottom of the bucket. The open strainer enables easy monitoring of the water removal process. Usually about 15 seconds of vacuuming is sufficient to remove the capillary water. Next, the surface film of water must be removed because, as demonstrated with Sitka spruce (Gosling and Rigg 1990), this surface film of water can lead to sprouting in stratification. Removing this film can be done by putting the seeds into a tumbler and passing a flow of dry air over the seeds as the tumbler rotates. A small concrete mixer is an easily acquired and low-cost tumbler. A pedestal fan is a good way to deliver the airflow because the height of the fan is usually adjustable to the height of the tumbler and can be positioned far enough from the tumbler so that no seeds are blown away. Removal of the paddles in the concrete mixer makes removing the seeds easier. When adequately dry, the seeds will look damp but no longer shiny (figure 8). The more humid the ambient conditions, the longer it will take to dry the seeds.

Step 4—Stratification

The final step in the process is to pour the seeds out of the tumbler and back into the strainer. Place the strainer into a polyethylene bag to keep the seeds moist and then into the stratification cooler, maintained at 2 to 3 °C for a time appropriate for the species or seed lot being grown. Appropriate stratification times for many species can be found in the *Woody Plant Seed Manual* (Bonner and Karrfalt 2008) or a laboratory seed test report on the specific seed lot. The former resource would give a general place to start, and the latter source would be more precise for the specific seed lot. Assistance in determining an appropriate time can also

Figure 6. A wet-dry vacuum is used to pull capillary water from the seeds. (Photo by Robert Karrfalt)

Figure 7. The disassembled base used to hold the paint strainer of seeds during the vacuuming of capillary water. The elbow should point to the bottom of the bucket. (Photo by Robert Karrfalt)

Figure 8. Seeds on left have a surface film of water. Seeds in center are properly surface-dried for stratification. Seeds at right are totally dry. (Photo by Robert Karrfalt)

be had by contacting the NSL. The bag should be 4 ml or less in thickness to facilitate gas exchange. Keeping the seeds in the strainer facilitates easy inspection for mold growth. If mold is detected, the rinsing and surface drying process should immediately be repeated. With the mold removed, the cleaned and re-dried seeds are returned to stratification. As a quality control measure, some strainers of seeds should be weighed upon entry into stratification and periodically reweighed to be sure the seeds are not drying any further. If much weight loss has occurred, return to the soak step for a period appropriate for the weight loss. The final weight of the surface-dried seeds following this second soak should be close to the weight at which the seeds were when originally placed into stratification.

Conclusion

The use of high-quality seeds that are adequately invigorated is one tool to prevent damping off in the nursery. The four-step process for adjusting seed moisture and conducting cold moist stratification allows for maximized invigoration while preventing premature radicle emergence that would make sowing the seeds difficult.

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Evaluating Dominus® Soil Biofumigant as a Substitute for Methyl Bromide in Pacific Northwest Forest Nurseries

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Abstract

Dominus® is a new soil biofumigant that is registered for use in bareroot forest nurseries with minimal buffer zone requirements. The active ingredient is allyl isothiocyanate (AITC), a compound found in certain mustard family plants (Brassicaceae). Washington Department of Natural Resources Webster Nursery (Tumwater, WA) tested five treatments applied in September 2015: (1) Dominus® alone; (2) Dominus® plus chloropicrin; (3) chloropicrin alone; (4) an operational control of methyl bromide plus chloropicrin; and (5) a nontreated control. All treatments were immediately tarped with totally impermeable film (TIF). In May 2016, Douglas-fir (*Pseudotsuga menziesii* [Mirb.] Franco) seedlings were transplanted into the treatment plots. Height and stem diameter differences throughout the trial were minimal and nonsignificant among treatments. Dominus®, with or without chloropicrin, significantly lowered soil *Fusarium* populations one month after treatment to levels similar to the standard methyl bromide plus chloropicrin fumigation. All fumigation treatments maintained lower soil and root *Fusarium* populations than the nontreated control through the trial. Dominus® reduced initial (winter) weed presence similarly to the operational standard, but low weed pressure during the growing season limited meaningful evaluation of the fumigant treatments' herbicidal effects. This paper was presented at the joint annual meeting of the Western Forest and Conservation Nursery Association and the Intermountain Container Seedling Growers' Association (Troutdale, OR, September 14–15, 2016).

Introduction

The standard practice in the Pacific Northwest (PNW) forest nursery industry to address soilborne insects, weeds, and pathogens is to fumigate with a mixture of methyl bromide plus chloropicrin. Recent changes to fumigant application regulations and pesticide labels, however, have significantly limited the use of methyl bromide and other fumigants in forest nurseries (EPA 2017, Enebak 2007, Masters 2005). Buffer zone requirements have increased fumigation costs, and, in some cases, restricted the use of fumigation entirely in increasingly suburban situations (Weiland et al. 2013). Many nurseries, to reduce buffer-zone limits, pay an extra expense for the contract fumigator to split applications to the same field on different dates.

Methyl bromide alternatives in the PNW have been examined for decades (Littke et al. 2002, Hansen et al. 1990). Chemical alternatives such as dimethyl disulfide or methyl iodide, both in combination with chloropicrin, have compared favorably to methyl bromide fumigation at nurseries in the PNW, but neither is currently registered due to environmental concerns. Methyl isothiocyanate (MITC)-producing agents (dazomet and metam sodium) have also been studied. Although dazomet, a granular product, can be inconsistent in conversion and performance, metam sodium, a liquid, in combination with chloropicrin, performed similarly to methyl bromide in a recent study (Weiland et al. 2011).

Brassica (Mustard) Biofumigation as an Alternative to Methyl Bromide

One line of research in alternatives to methyl bromide studies has examined the use of Brassica spp. (Brassicaceae; mustard family) cover crops; Brassica is crushed and immediately incorporated in to soil as a biofumigant, to reduce pathogen pressure. Glucosinolates in these crops hydrolyze in the presence of the enzyme myrosinase into AITC, a compound with pesticidal properties (Mazzola et al. 2007). AITC shares some similarities to the active ingredient MITC mentioned previously.

In studies at the U.S. Department of Agriculture, Forest Service's nursery in Coeur d'Alene, ID, and Weyerhaeuser Company's Washington and Oregon nurseries in the late 1990s and early 2000s, Brassica cover-crop biofumigation in Douglas-fir (*Pseudotsuga menziesii* [Mirb.] Franco) bareroot seedling beds failed to adequately control pathogen and weed populations, and in many cases, exacerbated soil pathogen levels post-fumigation (Hildebrand et al. 2004, Stevens 1996). Trials from 2009–2011 at Washington Department of Natural Resource's (WADNR) Webster nursery (Tumwater, WA), and the IFA Nurseries, Inc. Toledo nursery (Toledo, WA), in cooperation with Washington State University (Pullman, WA), examined the latest brassica cultivars bred for high glucosinolate (AITC precursor) cover crops as well as seed meals with relatively high glucosinolate content. Incorporated brassica material was immediately tarped with HDPE (high-density polyethylene) in an attempt to maximize treatment effect. Again, these trials produced inconsistent results in Douglas-fir transplant beds, with occasional exacerbation of pathogen levels and failure to produce effective weed control (Paudel et al. 2016). James et al. (2004) explained similar results by theorizing that insufficient toxicity levels in combination with increased organic matter can result in an unintended favorable environment for pathogens.

A challenge for both cover crop and seed meal applications of biofumigation is quantity. In the case of cover-crop application, as much as 22 tons/ac (50 metric tons/ha) has been estimated for adequate disease control (Clarkson et al. 2013). Seed meal applications up to 2 tons/ac (4.5 metric tons/ha), which in theory would have a more concentrated effect than green manure, have failed to consistently control soil pathogens even to the level of cover-crop incorporation (Mazzola and Gu 2002, Paudel et al. 2016). Combinations of seed-meal species mixtures appear to have more promise than single seed-meal applications, but the effects are species-dependent and pathogen-dependent (Mazzola and Brown 2010).

For brassica cover crop incorporation, Morra and Kirkegaard (2002) found that efficient isothiocyanate production from brassica is dependent on the species and variety, amount of tissue incorporated, growth stage when macerated and incorporated, thoroughness of tissue cell disruption, and climate and tillage system. One study showed that no more than 1 percent of AITC predicted from glucosinolate precursor concentrations was actually measured in soil amended with mustard leaf tissue (Kirkegaard 2009). Increases in crop performance observed in particular areas may have more to do with improving soil health parameters rather than direct pathogen reduction (Handiseni et al. 2013).

Ultimately, biofumigation through cover crop or seed meal incorporation is unlikely to be accepted by growers as a sustainable disease management alternative due to operational challenges and inconsistent results experienced to date. The best use of these biofumigation tools may be in conjunction with other integrated pest management practices in a holistic disease management approach (Bolda 2015).

Dominus®, a Concentrated Brassica-Based Biofumigant

In 2014, Isagro USA, Inc. (Morrisville, NC) received labeling in the State of Washington for the new soil biofumigant Dominus®. This product, applied through conventional nursery fumigation equipment, is a very close mimic of the naturally occurring AITC compound and is produced at 96-percent concentration active ingredient. The concentrated product increases the potential for consistent pathogen reduction, compared with incorporated cover crop or seed meal applications, due to its ability to achieve higher AITC levels in the soil.

The Environmental Protection Agency (EPA) fast tracked the registration of Dominus® under its biopesticide division (Rusnak 2013). No fumigation management plan is required, and the label requires a maximum buffer zone of 25 ft (7.6 m) from the edge of application, regardless of soil type, field size, etc. Also, the EPA did not limit the number of acres that can be treated in a day (Isagro 2016).

Fennimore (2014) evaluated Dominus® in a drip-irrigation, standard polyethylene-tarped strawberry (Fragaria x anannasa 'Monterey') row system in two trials. In the first trial, Dominus® was tested at rates of 340, 225, and 170 lb/ac (381, 252, and 191 kg/ha) against an operational standard of 350 lb/ac (392 kg/ha) PicClor60 (57:37 chloropicrin:1,3 dichloropropene) and a nontreated control. Yields were 95, 89, and 62 percent of the operational standard. In a second trial, 67:33 mixtures of Dominus®:chloropicrin were tested at 360, 270, and 180 lb/ac (404, 303, and 202 kg/ha), compared with Dominus alone at 340 lb/ac (381 kg/ha), a chloropicrin alone application of 300 lb/ac (336 kg/ha), the PicClor60 operational standard detailed previously, and a nontreated control. Across all treatments, harvest weights were highest for the 340 lb/ac (381 kg/ha) Dominus®:chloropicrin and 300 lb/ac (336 kg/ha) chloropicrin alone treatments. The medium rate of 270 lb/ac (303 kg/ha) Dominus®:chloropicrin yielded similar harvest weights to the operational standard. The Dominus® alone and all Dominus®:chloropicrin treatments outperformed the nontreated control, with the high rate of 340 lb/ac (381 kg/ha) Dominus®:chloropicrin more than doubling the control yield. In both trials, satisfactory weed control, particularly for yellow nutsedge (*Cyperus esculentus* [L.]), was only achieved at the high-end rates of 340 lb/ac (381 kg/ha) Dominus® alone or the 360 lb/ac (404 kg/ha) Dominus®:chloropicrin mixture.

Bolda (2015) found that a 360 lb/ac (404 kg/ha) Dominus®:chloropicrin 67:33 combination under a polyethylene tarp resulted in strawberry yields that were not significantly different from a 300 lb/ac (336 kg/ha) methyl bromide:chloropicrin 67:33 application.

Due to the immobile nature of AITC gas, Dominus® is best suited to lighter soil types in warm conditions to enhance its ability to move through the soil profile (Isagro 2016). Nearly all forest nurseries are located on light soils due to the need for good drainage and ease of winter lifting operations, but the requirement for warm soil temperatures to aid in gas mobility makes Dominus® a better fit for late summer fumigation, compared with spring fumigation.

Despite this limitation to warm-soil application, the early results from the strawberry industry are encouraging for Dominus application in conifer systems. Conifers share a relatively similar soil-disease complex to that found in strawberry production, particularly the prevalence of *Fusarium oxysporum* as a major pathogen (James 2004, Fennimore 2014, Bolda 2015). The objective of our study was to examine Dominus® as a potential substitute for current use of methyl bromide soil fumigation in conifer nurseries.

Materials and Methods

Nursery

Field trials were established at the WADNR Webster nursery. The soil is classified as a Cagey loamy sand (USDA NRCS 1987). The last crop of seedlings in the trial field was harvested in March 2015. In April 2015, the trial field was sown with a *Brassica juncea* (L.) Czern. 'Caliente 199' cover crop then mowed and tilled in July (one month before fumigation treatments).

Fumigation Treatments and Experimental Design

Working with Trident Agricultural Products (Woodland, WA), five fumigation treatments (table 1) were applied in early September 2015 in a randomized complete block design with four replicate blocks. All treatment plots, including the nontreated control, were immediately tarped with totally impermeable film (TIF) (Raven Industries; Sioux Falls, SD) (figure 1). Treatment plots were approximately 15 by 35 ft (5.0 by 11.5 m). TIF tarp was cut 20 days post-fumigation to enable venting and was removed the following day (22 hours post-cutting).

Thirty bed feet (approximately 700 seedlings) of 1-year-old, coastal Douglas-firs were transplanted into each treatment-replication plot in May 2016.

Sample Collection

Nursery soil was sampled five times during the experiment: on September 8, 2015 just before fumigation

Table 1. Fumigation treatments applied to bareroot nursery soil in September 2015 in a randomized complete block design with four replicate blocks.

Fumigation treatment	Rate
Nontreated control	n/a
Dominus® (AITC)	340 lb/ac (381 kg/ha)
Pic	250 lb/ac (280 kg/ha)
Dominus® (AITC) + Pic	340 lb/ac (381 kg/ha) + 125 lb/ac (140 kg/ha)
MB + Pic (operational control)	167.5 lb/ac (188 kg/ha) + 82.5 lb/ac (92 kg/ha)

AITC = allyl isothiocyanate. Pic = chloropicrin. MB = methyl bromide. N/a = no fumigant.

Figure 1. Fumigation plots were installed at Washington Department of Natural Resources Webster Nursery on September 9, 2016 to evaluate Dominus® biofumigant as an alternative to methyl bromide. (Photo by Nabil Khadduri)

(prefumigation); three weeks after fumigation on September 30, 2015 (post-fumigation); one week before planting on May 3, 2016 (preplant); on July 23, 2016 (mid-season); and February 6, 2017 (harvest). Soil samples were collected by taking twenty 1-in (2.5-cm) diameter cores in a randomized pattern to a depth of 12 in (30 cm) from each treatment plot. Samples were bulked by plot and mixed thoroughly to generate 20 composite samples. Each composite sample was then divided to provide separate samples for *Fusarium* and *Pythium* analyses. Samples were stored at 38 °F (4 °C) until assays were completed.

Douglas-fir seedlings were sampled prior to planting (preplant), in July 2016 (mid-season), and in February 2017 (harvest). Ten seedlings per time period were selected at random from within the center 10 ft (3 m) of the plot, for assays of *Fusarium* and *Pythium* root colonization. Seedlings were stored at 38 °F (4 °C) until assays were completed.

Fusarium Populations

Soil *Fusarium* colonies from soil samples were enumerated on Komada's medium (Komada 1975), and colony-forming units (CFU/g) were determined on a dry-mass basis. From each composite sample, 0.04 oz (1 g) of soil was diluted in 2.7 oz (80 ml) of 0.1 percent agar, and a 0.014 oz (0.40 ml) aliquot of the soil-water agar slurry was placed in each of the three replicate Petri plates. Prepared Komada's medium was cooled to 38 °C, poured into plates containing the slurry, and then mixed by gently stirring the plates. Plates were then placed in an incubator at 25 °C with 16 hours per day of fluorescent light for one week, at which point *Fusarium* colonies were counted using morphological traits (Leslie and Summerell 2006) (figure 2a).

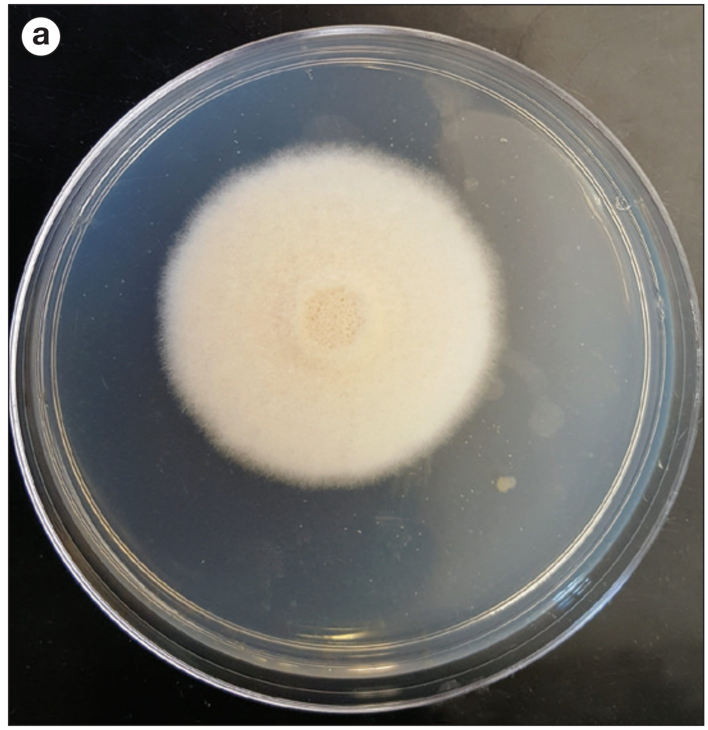

Figure 2. *Fusarium* colonies were quantified on soil and root samples. These photos show (a) a well-developed *Fusarium* colony from soil plate and (b) Fusarium infection of seedling root segments. Both photos are from July 23, 2016 sampling. (Photos by Anna Leon)

Roots of each seedling were washed free of soil, cut into ten 0.4-in (1-cm) long segments, sanitized in 10-percent bleach for 10 min, and rinsed in distilled water. Ten root segments per sample were then plated on Komada's medium and incubated as described previously (figure 2b). Following incubation, the percentage-root segments colonized by *Fusarium* in each plate for each seedling were calculated.

Pythium Populations

Pythium colonies were counted through plating Rhododendron spp. baits on clarified V8 juice-based agar (Stevens 1974) with the following post-autoclave amendments to reduce competing microbial activity: 0.15 g pentochloronitrobenzene, 0.20 g streptomycin sulfate, and 1.5 ml rose bengal. From each composite sample, 0.04 oz (1 g) of soil was diluted in 2.7 oz (80 ml) of 0.1-percent agar. Ten 0.015 oz (0.40 ml) aliquots of the soil-water agar slurry were then placed in a sterile, empty 100-mm diameter Petri plate. A sterile 8-mm round piece of rhododendron leaf was placed in each of the 10 aliquots. Rhododendron leaves were allowed to rest in the soil-water agar slurry for 48 hours before being plated onto V8 media and incubated in the dark for 48 hours. Colony morphology was checked after 24 and 48 hours. The percentage of *Pythium*-positive rhododendron disks was calculated.

Roots of each seedling were washed free of soil, cut into ten 0.4-in (1-cm) long segments, sanitized in 10-percent bleach for 10 min, and rinsed in distilled water. Ten root segments per sample were then plated on V8 media and incubated as described previously. The percentage of roots segments colonized by *Pythium* for each seedling was calculated.

Weed Evaluation

Weed sampling was conducted in November 2015 and February 2016 prior to any herbicide application and in July 2016, after seedling planting and the application of preemergent herbicides had occurred. Three 1-x-4 ft (30-x-121 cm) frames were placed at random within the inner 15 ft (5 m) of each plot. At each sampling date, weed species were identified, and total weeds were tallied. For the July 2016 evaluation, the amount of weeding time necessary was also recorded for each plot.

Seedling Morphology

Twenty-five Douglas-fir seedlings per treatment plot were measured for height and stem diameter just after planting in May 2016, in late August, and at the end of active growth in November (figure 3). At final harvest, ten seedlings per treatment plot were measured for root and shoot volume.

Statistical Analyses

All data were analyzed by sample date for treatment effects using analysis of variance, or ANOVA. Differences among treatment means were determined using a protected Fisher's least significant difference test and Tukey's Honestly Significant Difference test for multiple comparisons at $p < 0.05$. Analyses were performed using the R statistical package (R Core Team 2016).

Results

Fusarium Populations

Prefumigation (September 2015) *Fusarium* population means were similar among treatments (figure 4). Three weeks after fumigation, soil *Fusarium* populations were reduced by all treatments to low levels compared with the nontreated control plots. In May of 2016, the week before transplanting (preplant), *Fusarium* levels had declined in the nontreated control and increased in the Dominus® (AITC) alone treatment, although the Dominus®-treated soils still averaged one-half the *Fusarium* level of the nontreated control soils. All other treatments remained significantly lower than the nontreated control (figure 4). By mid-July 2016, all soil *Fusarium* levels were low, with no significant differences among treatments. At harvest in February 2017, soil *Fusarium* levels had risen in the control plots and were again significantly higher than all other treatments (figure 4).

Seedling root infection at preplant was low across all treatments (figure 5). By late July, seedlings in the nontreated control plots had significantly higher levels of *Fusarium* root disease than all fumigation treatments. This pattern maintained through sampling at harvest (figure 5).

Figure 3. Seedling plots at Washington Department of Natural Resources Webster Nursery to evaluate fumigation treatments: (a) May 2016 at transplanting; (b) August 2016; and (c) February 2017 at harvest. (Photos by Nabil Khadduri)

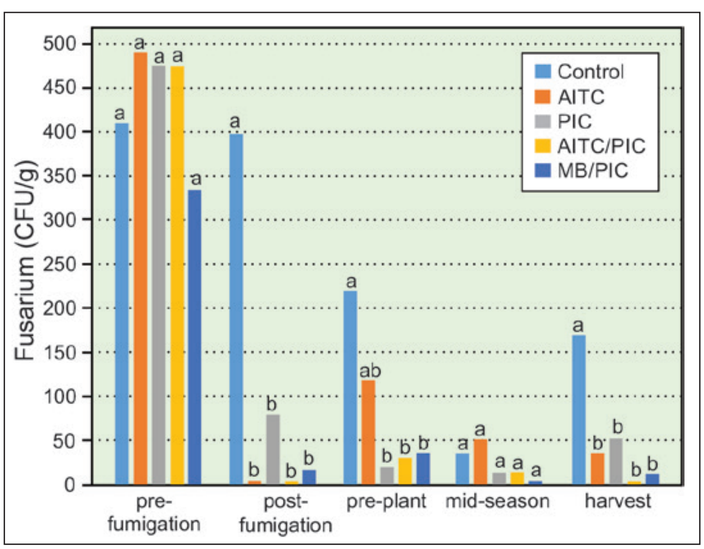

Figure 4. Soil *Fusarium* population means were similar among treatments prior to fumigation. Three weeks after fumigation (September 30, 2015), soil *Fusarium* populations had declined significantly in all fumigation treatments compared with the nontreated control plots. Although soil *Fusarium* levels in nontreated control plots declined to nonsignificant levels by mid-season (July 23, 2016), levels rose again and were significantly higher than all other treatments at harvest (February 6, 2017). For each sampling date, means with the same letter are not significantly different at the $\alpha \leq 0.05$ level.

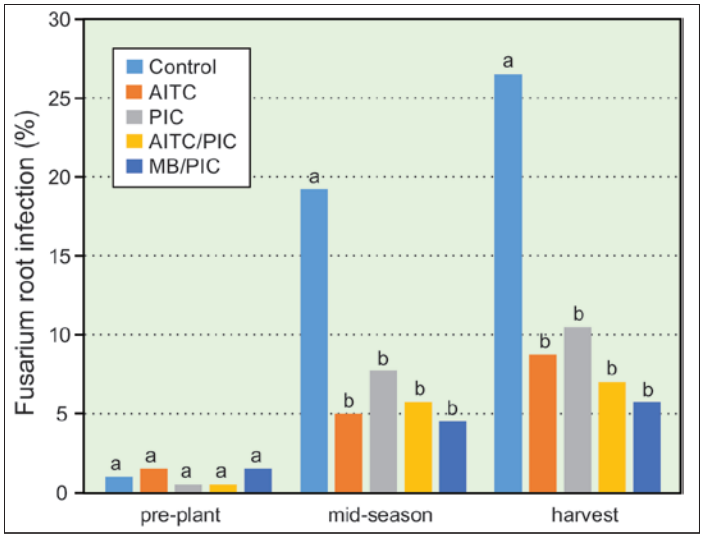

Figure 5. Soil *Fusarium* seedling root infection levels were low across all treatments prior to planting (May 2016). By late July, *Fusarium* root disease on seedlings transplanted into the nontreated control plots was significantly higher than all fumigation treatments. This pattern continued through sampling at harvest (February 2017). For each sampling date, means with the same letter are not significantly different at the $\alpha \leq 0.05$ level.

Pythium Populations

Soil *Pythium* was only observed at the preplant sampling in May 2016, during which all fumigation treatments significantly reduced soil *Pythium*, compared to the nontreated control (figure 6).

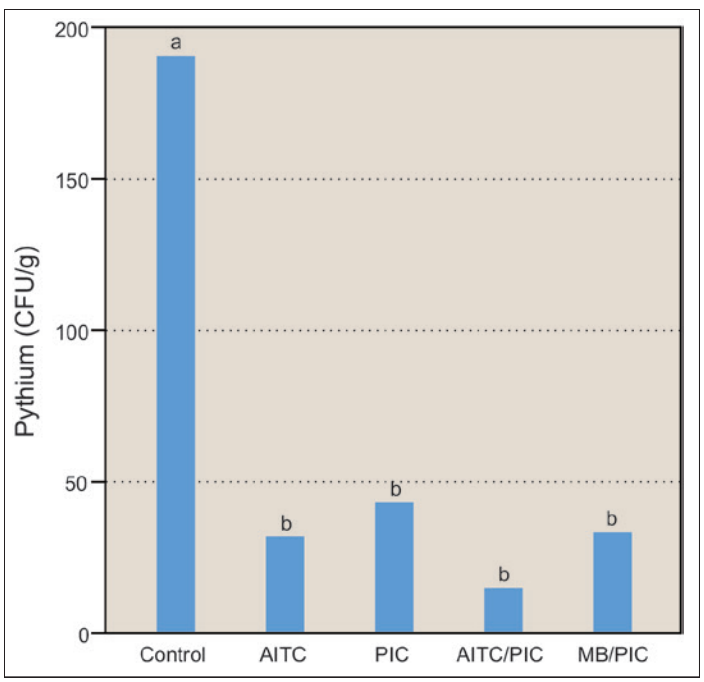

Figure 6. Soil *Pythium* was only observed at the preplant sampling (May 2016), when all fumigation treatments had significantly lower levels compared with the nontreated control. Thereafter, soil *Pythium* levels were minimal in all treatments (data not shown). Means with the same letter are not significantly different at the $\alpha \leq 0.05$ level.

Very little to no *Pythium* seedling root infection occurred during the trial for any of the treatments (data not shown).

Weeds

Treatment differences in winter annual weeds were evident soon after tarps were removed following fumigation, with treated plots showing no germination relative to nontreated areas (figure 7). The most frequent weeds recorded were *Brassica juncea* (L.) Czern. (from the cover crop) and annual bluegrass (*Poa annua* L.). In November 2015, nontreated control plots had higher weed counts than all fumigated plots (figure 8). By February 2016, weed counts in the chloropicrin alone treatment had increased to a nonsignificant difference compared with the nontreated control, but still averaged fewer weeds. All other fumigation treatments had significantly lower weed counts. Weed pressure following transplant was low throughout the growing season, and no treatment effects were observed during the July assessment (data not shown).

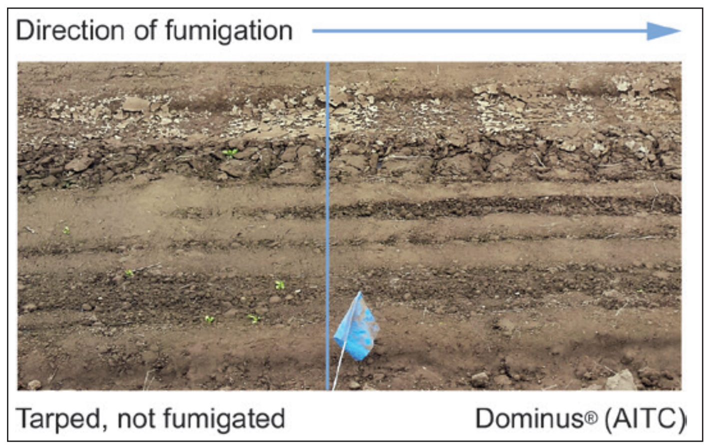

Figure 7. This photo illustrates weed germination differences within 2 weeks of removing the tarp. The area to the left was tarped, but not fumigated, and the area to the right received Dominus® (AITC) fumigation. (Photo by Nabil Khadduri)

Seedling Morphology

At planting, average seedling morphology did not differ among treatments (data not shown). At the July and November sampling, seedling height and stem diameter averaged largest in methyl bromide/chloropicrin plots, but differences in morphology throughout the trial were nonsignificant among treatments. At harvest, the root or shoot volumes among treatments had no significant differences (data not shown).

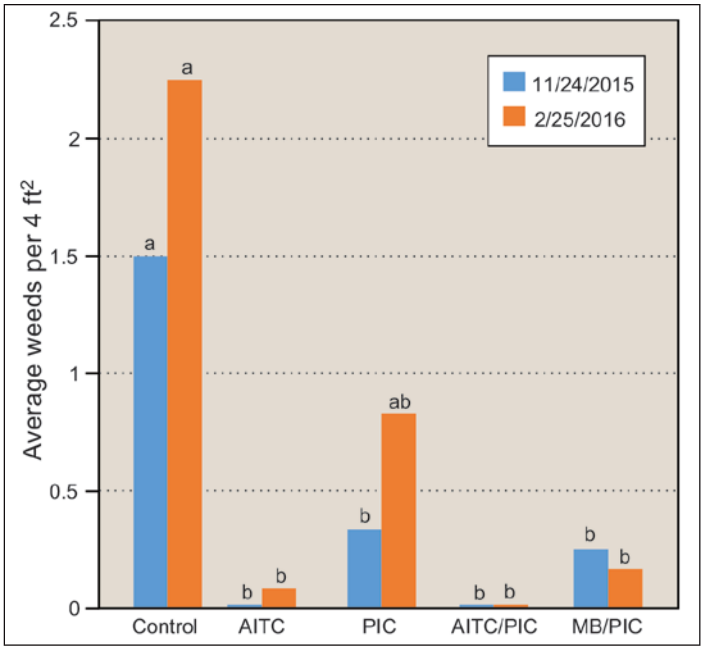

Figure 8. In November 2015 (2 months after fumigation), nontreated control plots had higher weed counts than all fumigation treatments. By February 2016, weed counts remained low for all fumigated plots, although the chloropicrin-alone treatment, while still averaging lower, was no longer significantly different than the nontreated control. For each sampling date, means with the same letter are not significantly different at the $\alpha \leq 0.05$ level.

Discussion

To our knowledge, this is the first trial with Dominus® in a conifer nursery in the Pacific Northwest and in the United States. The efficacy of the Dominus®-alone and Dominus® plus chloropicrin treatments in reducing soil *Fusarium* (and soil *Pythium* when it occurred) is encouraging. Perhaps more importantly, Dominus®, either alone or in combination with chloropicrin, maintained low levels of *Fusarium* seedling root infection. This control is on par with what would be expected with a standard methyl bromide plus chloropicrin fumigation. The results are encouraging but not entirely unexpected, as commercial isothiocyanate-based fumigants, such as metam sodium, are currently in wide use in agriculture. Weiland et al. (2011) found that a metam-sodium:chloropicrin mixture compared favorably with an operational methyl bromide:chloropicrin mixture at three forest nurseries in the Pacific Northwest. Unlike metam sodium, however, Dominus® is not subject to a fumigation management plan, restricted buffer zones, or the threat of reduced use due to commercial fumigant reregistration decisions (Isagro 2016, EPA 2017).

A concurrent study examining the use of Dominus® was conducted at a Weyerhaeuser forest seedling nursery south of Olympia, WA. This trial examined the same rates of Dominus®, with and without chloropicrin, as did the WADNR Webster study described in this article. Treatments were compared against an operational methyl bromide plus chloropicrin control. As in the WADNR Webster trial, Dominus®, both with and without chloropicrin, successfully lowered initial *Fusarium* populations to minimal levels (unpublished data). The *Fusarium* or *Pythium* populations within the soils or seedlings at any time post-fumigation had no significant differences, nor any differences among treatments for seedling height or stem diameter throughout the growing season or at harvest.

Although morphology differences were absent at both nursery studies, seedling root infection by *Fusarium* was over 25 percent at harvest in the nontreated control of this trial—several times higher than the fumigation treatments. This study did not attempt to separate either soil or seedling *Fusarium* populations into pathogenic vs. nonpathogenic categories. James et al. (2002) were the first to identify pathogenic species of *Fusarium* from forest nursery soils. For example, genetic markers can distinguish between generally pathogenic isolates of *Fusarium* commune vs. generally nonpathogenic isolates of *Fusarium* oxysporum (Stewart et al. 2006). Proportions between these pathogenic vs. nonpathogenic isolates can indicate greater or lesser risk of disease (Leon 2013). Since morphology differences were absent, it is possible that the *Fusarium* populations in this study were largely nonpathogenic. Had they been pathogenic, perhaps greater differences in morphology would have been expressed.

AITC gas is relatively immobile in the soil (Isagro 2016). Weed germination suppression following tarp removal, however, was an initial indication that the gas, at least in the loamy sand and relatively warm, late-summer conditions at application, was able to move from injection ports at 8-in (20-cm) depth to the soil surface. Nevertheless, concerns remain as to how adaptable Dominus® will be to the inevitable range of soil moisture and temperature conditions encountered in general practice. Bolda (2015) emphasizes vapor pressure of AITC gas is considerably lower than even the slower moving fumigants, such as chloropicrin or MITC agents, and the manufacturer classifies it as a "passive fumigant" (Isagro 2016).

Although this initial trial has shown promise, more testing needs to be done to demonstrate the efficacy of the product across a number of preexisting soil pathogen loads, baseline weed populations, and growing season conditions.

Future Directions

Despite these encouraging results to date, Dominus® faces two main challenges for widespread nursery use as a substitute for methyl bromide. Along with the aforementioned lack of gas mobility, which particularly limits its use in cool soil conditions, the cost of Dominus® is relatively high. Product costs in 2016 at the rates tested were 43 percent higher for the Dominus® alone application (which was applied at the maximum rate), and 69 percent higher for the Dominus® plus chloropicrin treatment, compared with the cost of the standard methyl bromide plus chloropicrin treatment ($1,860, $2,200, and $1,300, respectively). Methyl bromide and other fumigants, however, can incur increased costs, due to the necessity of having the contract fumigator visit a nursery more than once to reduce buffer zone sizes. These product costs do not include installation and TIF plastic costs of $1,200, which are the same regardless of treatment.

We plan to establish an outplant study with seedlings from this trial to evaluate whether documented pathology differences, with morphology being equal, lead to subsequent differences in outplanting performance. Ideally, baseline data on pathogenic vs. nonpathogenic proportions of the *Fusarium* populations will be determined prior to the outplant trial.

An identical trial was established in September 2016 at WADNR Webster Nursery in a higher pathogen-load field. Initial *Fusarium* reduction by Dominus® has again been dramatic, although not as low as methyl bromide plots. It will be interesting to see how trees growing in Dominus®-treated plots fare morphologically in this higher-pressure field.

A third trial is planned for late summer 2017 to address the issues of gas mobility and product cost. This trial will use a new formulation of Dominus® that has a new emulsifier adjuvant to help with gas diffusion. Perhaps more importantly, the trial will also use a tighter spacing of injection shanks, with two ports instead of one on the shanks. In theory, two shank ports will compensate for low gas mobility through improved product placement in the soil, both vertically and horizontally (Allan 2017).

The 2017 trial will also include testing at 75-percent strength rates and under cheaper tarps (HDPE vs. TIF plastics) to reduce treatment cost while maintaining efficacy through the improved emulsifier and product placement.

At some point, methyl bromide, chloropicrin, and other commercial fumigants may no longer be available to nurseries due to buffer zone restrictions or other regulations. Dominus® is a promising alternative, but must be further examined for efficacy and cost reduction before it gains widespread acceptance in the bareroot forest nursery industry.

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