Tree Planters' Notes

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***Tree Planters' Notes* (TPN) is dedicated to technology transfer and publication of information relating to nursery production and outplanting of trees and shrubs for reforestation, restoration, and conservation.**

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Editor: Diane L. Haase

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Dear TPN Reader

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Once again, I'm pleased to bring you another issue of *Tree Planters' Notes*, packed with useful information to all of you who grow and plant trees for reforestation and restoration.

This issue includes an article by Topper about current and past tree planting activities in Delaware (page 4). Delaware is the 19th State to be profiled so far for TPN's ongoing State-by-State series. In another article, Karrfalt describes simple and effective methods and materials for assembling seed testing and drying equipment using supplies from any hardware store (page 11). This issue also includes results from several studies developed to improve outplanted tree performance: Carlson and colleagues describe a study to compare tillage treatments on subsequent loblolly pine seedling performance (page 18). Overton presents a case study for measuring irrigation uniformity in a bareroot nursery in Indiana with a discussion on implications for irrigation design and management (page 23), and Bainbridge summarizes results from a study to evaluate irrigation systems and inoculation treatments to aid in establishing mesquite trees on a degraded surface mine site (page 44). Gagnon and DeBlois describe their study to evaluate foliar urea fertilization treatments along with the effects of subsequent washing treatments for accurately measuring foliar nitrogen concentration (page 53). This issue also includes an article from me with some important considerations and easy tips for designing studies so that they yield meaningful and valid results (page 32). Finally, this issue contains a report on forest nursery seedling production in the United States during the previous fiscal year (page 62). The report provides quantitative estimates of hardwood and conifer as well as bareroot and container seedlings produced and planted in each State and each region.

I'm always looking for more articles to fill future issues of TPN. Please consider submitting your paper for publication. You can also send suggestions for topics or authors you would like to see included in TPN. Guidelines for authors can be found at the end of this issue as well as online at http://www.rngr.net/publications/tpn.

May you all enjoy the fall and winter seasons!

Diane L. Haase

Trees are poems that the earth writes upon the sky…Kahlil Gibran

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The Forests of the First State

Samual L. Topper

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Abstract

More than 400 years after European explorers first discovered Delaware, one-third of the State remains forested. Delaware has a long and rich history of timber production that has seen many changes since its initial settlement. A formal forest management policy for Delaware evolved around the turn of the 20th century, culminating with the formation of the State Forestry Department in 1927, driven in large part by a need for wildfire management. Delaware has a unique geographical position, resulting in a unique mix of forest types. Because of its shape, orientation, and location, the State enjoys the benefits of the southernmost range of the eastern hardwood forest type and the northernmost range of the southern pine and hardwood type. Because of the timber type variation in Delaware, a few different management regimes are practiced, each with its own silviculture concerns and management activities. The Delaware Forest Service (DFS) offers financial and technical assistance programs for private landowners, including the regulation of forest activities such as timber harvests and reforestation. The DFS also maintains a robust and ongoing forest health monitoring and management program to deal with potential outbreaks from environmental and human-caused factors. With an eye to the future, the DFS has plans under way for a periodic review and assessment to measure statewide progress in meeting forest management goals and to chart a pathway to healthier and sustainable forests for the 21st century.

Delaware's Forests and Forest History

The total land area of Delaware is roughly 1.25 million ac (506,000 ha) and is approximately one-third forested (figure 1) (DFS 2010a). Like many other States, Delaware experienced a sharp decline in forest land associated with the wave of European settlement that began around 1610. It is believed that 90 percent of Delaware was forested before settlement. The low point of forest cover in Delaware occurred in the early 1900s at approximately 350,000 ac (142,000 ha), followed by an increase to roughly 450,000 ac (182,000 ha) after the Great Depression. Another reduction in forest acreage during the early 2000s was associated with the housing boom.

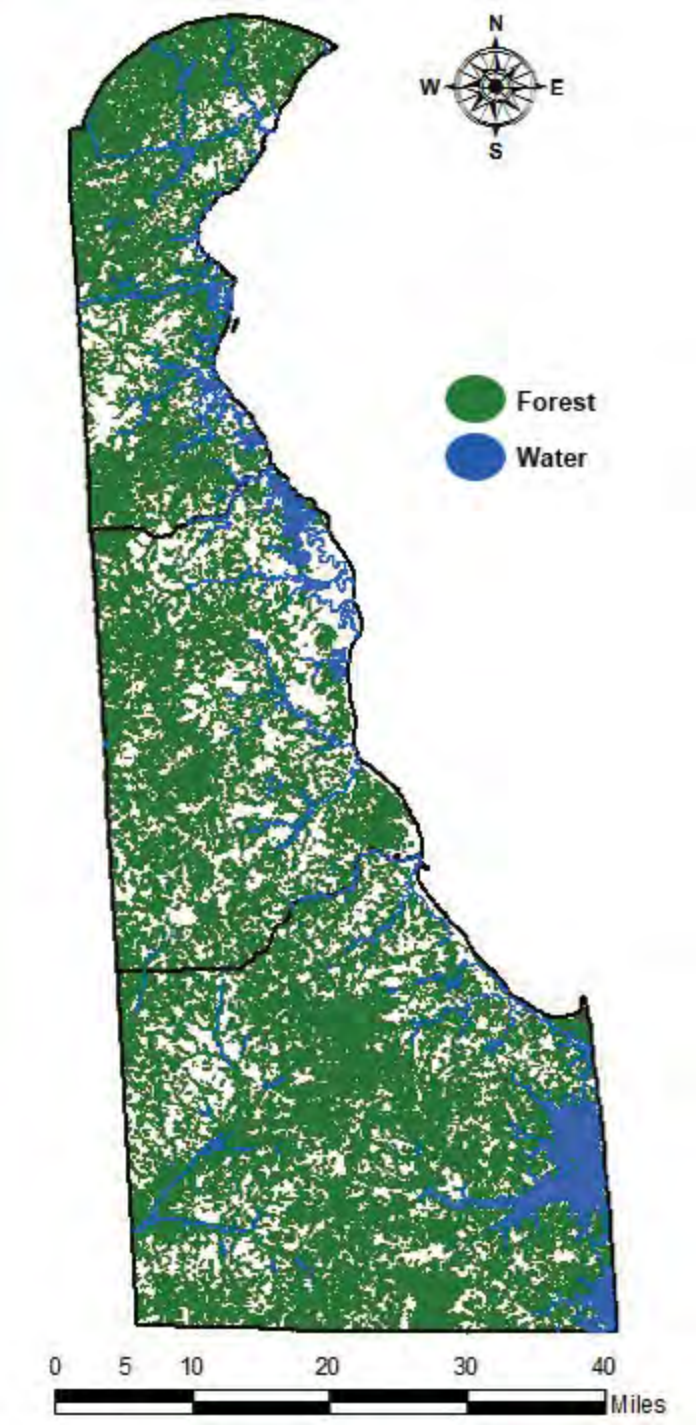

Figure 1. Approximately 30 percent of Delaware is forested. (Source: Delaware Forest Service 2012)

Forest land in Delaware has since stabilized at approximately 370,000 ac (150,000 ha), with only minor annual fluctuations (table 1). Delaware loses approximately 2,000 ac (809 ha) per year of forest land because of agriculture and development; some of this loss is offset by afforestation.

Table 1. Delaware forest acreage, 1907–2007.

Year	Acres of forest (thousands)
1907	350
1938	423
1953	454
1963	392
1977	392
1987	398
1997	389
2002	383
2007	371

Source: Delaware Forest Service (2010a)
Metric conversion: 1 ac = 0.404 ha

Delaware has a long and rich history of timber production that has seen many changes since the initial European exploration and settlement. The earliest uses for Delaware's timber resources were building ships and settlements. As the area became more settled, trade was established with Europe and included ship-building materials, barrel staves, cedar shingles, charcoal, and tanning bark. It was not long before numerous sawmills were established along the streams and rivers, producing all sorts of wood products for local use and trade. Numerous sawmills produced lumber for wagons and wheels, crates, and many other uses. From the mid-1800s to mid-1900s, charcoal and railroad ties were major products. The 1950s saw a boom in machine-made wood products, such as "spoon wood" and "basket wood." Wood production in Delaware rose to a high of 55 million board feet (130,000 m^3) in 1909 and dropped to a low of 5.2 million board feet (12,300 m^3) in 1918, but has since stabilized at approximately 14.4 million board feet (34,000 m^3) annually (DFS 2010a).

Current wood production in Delaware is roughly 46 percent softwood and 54 percent mixed hardwood (DFS 2010a). The main products are hardwood and softwood sawtimber, mixed pine pulpwood, pilings, and some hardwood veneer. The current growing stock volume in Delaware is 810 million ft^3 (22.9 million m^3), a 17-percent increase since 1999 (Lister et al. 2012). Approximately 2.9 billion board feet (6.8 million m^3) of sawtimber are in Delaware, a nearly 30-percent increase since 1999 (Lister et al. 2012). Hardwoods account for most of this volume and have been responsible for most of the increases (table 2).

Table 2. Volume of forest growing stock in Delaware, 1957–2009.

	Volume (million cubic feet)				
	1957	1972	1986	1999	2009
Softwoods	230	184	164	115	120
Hardwoods	273	403	496	581	690
Total	503	587	660	696	810

Source: Delaware Forest Service (2010a)
Metric conversion: 1 million ft^3 = 28,317 m^3

A formal forest management policy for Delaware evolved around the turn of the 20th century. In 1906, Professor Hayward, Director of Delaware Agriculture Experiment Station, applied to the U.S. Forest Service (now the Forest Service, an agency of the U.S. Department of Agriculture [USDA]) for a cooperative study of Delaware's forests. This led to the publication of Sterrett's *Report on Forest Conditions in Delaware and a Forest Policy for the State* (1908). In 1909, Delaware's General Assembly passed legislation to create a forestry advisory board; however, no funds were allocated and a board was never appointed. In the late 1920s, a series of large fires in the Great Cypress Swamp reignited concern about forest management in the State. In 1927, the General Assembly established the State Forestry Department (Senate Bill 16). Its original responsibilities included fire control, a State nursery, and State forests. William S. Taber was appointed the first State forester and served for 43 years.

State forest management areas began with the establishment of a tree nursery north of Ellendale in 1928. In 1936, the State purchased the 844-ac (342-ha) gun club property north of Georgetown, including the historic Redden Lodge—the centerpiece of Redden State Forest. Acquisition of the 672-ac (272-ha) Tybout Tract was complete in 1941, representing the first property of what would become Blackbird State Forest. Today, State forest land totals more than 19,200 ac (7,770 ha).

In 1948, the first farm (service) forester was appointed to help private landowners. Today, financial and technical assistance to nonindustrial private landowners is one of the core programs of the Delaware Forest Service (DFS), a section within the State's Department of Agriculture. In 1995, the DFS began regulating forestry activities by issuing permits for compliance with its best management practices (BMP) program and instituting the State's Seed Tree Law, designed to protect commercially important native species.

Forest Composition

Delaware has a unique geographical position in the United States, resulting in an interesting mix of forest types. Because of its shape, orientation, and location, the State enjoys the benefits of the southernmost range of the eastern hardwood forest type and the northernmost range of the southern pine/hardwood type. Situated on the Peninsula south of Pennsylvania, known as the Delmarva Peninsula, Delaware is mostly lowland, coastal area. Most of Delaware is part of what is known as the "coastal plains" of the Southeast United States. Soils in this region consist of mostly sandy loam with some clay. Important timber species common to the coastal plain include loblolly pine (*Pinus taeda* L.), Virginia pine (*P. virginiana* Mill.), Atlantic white cedar (*Chamaecyparis thyoides* L.), bald cypress (*Taxodium distichum* L.), white oak (*Quercus alba* L.), southern red oak (*Q. falcata* Michx.), black oak (*Q. velutina* Lam.), yellow poplar (*Liriodendron tulipifera* L.), red maple (*Acer rubrum* L.), American holly (*Ilex opaca* Aiton), and sweetgum (*Liquidambar styraciflua* L.). Some of these species, such as loblolly pine, bald cypress, and Atlantic white cedar, are at the northernmost portion of their native range.

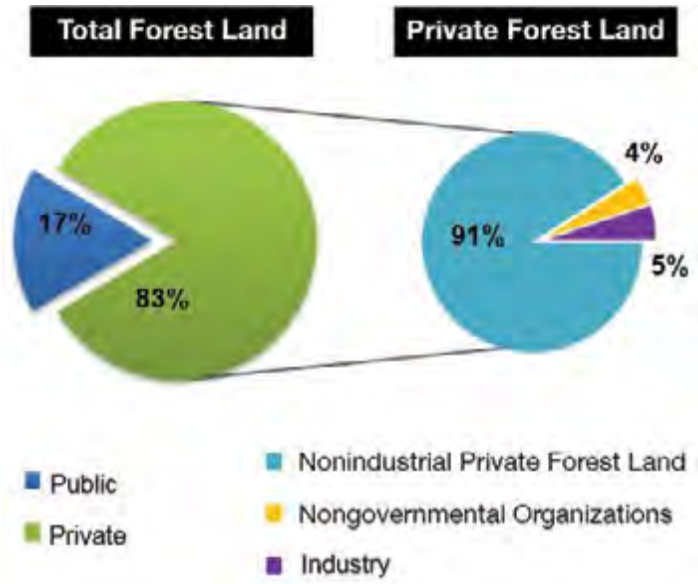

Figure 2. Delaware forest land ownership, 2009. (Source: Delaware Forest Service 2010a)

The northernmost part of Delaware lies within the eastern Piedmont geographic region. This region is characterized by a rocky parent material and clay soils. Important timber species common to this region include northern red oak (*Quercus rubra* L.), yellow poplar, white oak, red maple, black oak, and American beech (*Fagus grandifolia* Ehrh.).

Forest Ownership

Of the forest land in Delaware, 83 percent is privately owned, and 91 percent of that land is owned by nonindustrial private owners (figure 2). Public ownership includes the U.S. Fish and Wildlife Service and several State agencies, such as the DFS, State parks, and State wildlife areas (figure 3) (DFS 2010a).

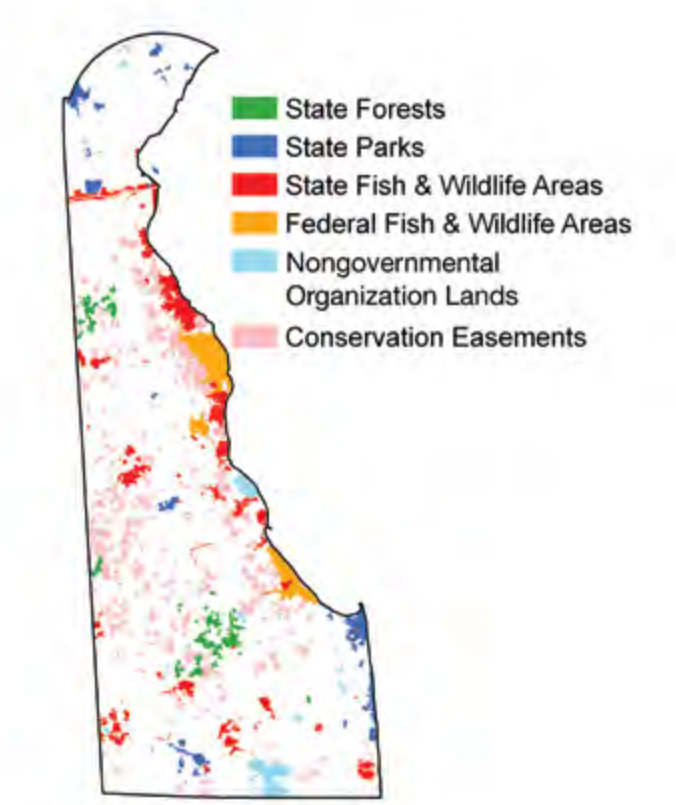

Figure 3. Delaware's publicly owned lands. (Source: Delaware Forest Service 2010a)

Forest Management in Delaware

Because of the variation of timber types in Delaware, a few different management regimes are practiced, each with its own silviculture concerns and management activities. In southern Delaware, the primary management regime is southern pines (figure 4). Loblolly pine is grown naturally and in plantations. Management for southern pines includes stand establishment (natural or artificial) followed by aerial chemical application to control woody competition. A precommercial thinning is sometimes conducted to reduce stocking and speed growth (figure 5). One or more commercial thinnings are conducted during the rotation, followed by one or more controlled burns to reduce fuel loads and clear understory competition. Prescribed fire is also used to maintain and improve wildlife habitat. A clearcut harvest is conducted around age 50. Stand establishment is a common obstacle to this type of silviculture. Variations in weather and soil conditions make survival of young seedlings difficult at times. Other management concerns are wildfire, insects, and disease.

Figure 4. Pine forest in southern Delaware. (Photo by John Petersen, Delaware Forest Service, 2012)

Figure 5. Young pine stand after precommercial thinning. (Photo by Samual Topper, 2014)

Management is less intense in the southern hardwood forest types. Stand establishment is done naturally using three methods: selection harvest, shelterwood harvest, and seed-tree harvest. Manual timber stand improvement work is sometimes done to manipulate species composition. Most landowners harvest timber periodically using the selection harvest method. This approach continues until the land is depleted of suitable sawtimber and then is left to recover on its own. The issue of most concern in these forest types is high-grading. The DFS works to educate landowners about the dangers of high-grading and how to avoid it.

In Delaware's Piedmont region, northern hardwoods are grown in rotations of 80 to 100 years (figure 6). Usually only one intermediate selection harvest is conducted before the natural regeneration sequence is initiated. Regeneration occurs naturally through shelterwood or seed-tree harvests.

Figure 6. Hardwood stand in northern Delaware. (Stock photo by Delaware Forest Service, 2014)

Delaware tracks all timber harvests of more than 1 ac (0.4 ha) in size through a State permitting and BMP program administered by DFS. In 2013, 4,203 ac (1,700 ha) were permitted statewide (table 3). This system tracks only acres permitted, not acres harvested (figure 7). Although DFS foresters conduct periodic inspections on all timber sales, no data are available for how many of the permitted acres are harvested each year or harvested at all.

Table 3. Timber harvest permits in Delaware, by type and year.

Year	Clearcut		Selection		Thinning	
	Permits	Acres	Permits	Acres	Permits	Acres
1997	83	3,553	43	973	11	447
1998	56	2,870	54	1,564	14	398
1999	54	1,904	42	1,095	8	439
2000	81	3,888	51	1,530	8	717
2001	62	2,344	47	2,301	2	37
2002	74	2,609	59	1,488	1	9
2003	87	3,208	48	1,428	11	637
2004	59	2,181	49	1,453	15	1,157
2005	74	2,446	46	1,209	14	1,286
2006	73	1,979	47	1,373	17	1,109
2007	58	1,690	56	1,254	20	1,111
2008	41	1,232	58	1,457	17	2,557
2009	40	1,211	45	918	20	908
2010	47	2,323	36	972	32	3,161
2011	39	876	49	1,422	13	561
2012	43	1,259	41	1,556	23	1,657
2013	51	1,698	35	1,237	9	1,268

Source: Delaware Forest Service (2013)
Metric conversion: 1 ac = 0.404 ha

Figure 7. Clearcut harvest of loblolly pine forest in southern Delaware. (Photo by Samual Topper, 2014)

Delaware has a unique law affecting timber harvests—the Delaware Seed Tree Law (Delaware Code 2014). The Seed Tree Law is intended to guard against the loss of two commercially important timber types—the loblolly pine type and the yellow poplar type. The law states that if the harvest area is 10 ac (4 ha) or more, contains at least 25 percent loblolly pine and yellow poplar, and the land will remain forest land, then the landowner is responsible for successfully regenerating the stand back to a loblolly pine and yellow poplar stand within 2 years of the completion of harvest. This regeneration can be natural or artificial.

Most of the reforestation is conducted in the southern portion of the State. Most planting done in Delaware is reforestation of loblolly pine plantations (figure 8). Planting is conducted in the spring of each year. Between 2008 and 2013, nearly 1.5 million seedlings were planted. In 2014, 128,000 trees were planted in Delaware on about 250 ac (101 ha) (table 4). Approximately 100 ac (40 ha) are planted annually under the Conservation Reserve Enhancement Program, administered by the USDA Natural Resources Conservation Service. The trees used for Delaware's planting program are obtained from the Maryland State Forest Service Nursery, because Delaware no longer has a State nursery. Delaware does have a seed orchard that the DFS maintains to provide seed to the Maryland nursery when needed.

Cost-share funding available to Delaware landowners takes the form of the USDA Environmental Quality Incentives Program and a State cost-share program.

Figure 8. A worker reforests a 60-acre (24.3-ha) clearcut harvest site in Kent County, DE, with loblolly pine seedlings. (Photo by John Petersen, Delaware Forest Service, 2014)

Table 4. Acres and number of trees planted in Delaware, 2008–2014.

Year	Acres planted	Number of trees planted
2008	982.0	481,250
2009	428.0	230,100
2010	273.5	123,000
2011	373.0	175,500
2012	384.5	220,500
2013	412.0	246,875
2014	255.0	128,000

Source: Delaware Forest Service (2014)
Metric conversion: 1 ac = 0.404 ha

Forest Industry in Delaware

For landowners, Delaware has a wide range of options regarding forest management assistance. The DFS, the primary source of forestry assistance in the State, employs five service foresters who serve forest landowners and offer technical assistance in all aspects of forest management. They write stewardship plans, assist with harvest and reforestation planning, conduct insect and disease diagnoses and recommendations, plan and conduct prescribed burning, provide education and outreach, and conduct many other resource management activities. The services of DFS service foresters are free of charge to Delaware landowners.

Consulting foresters are another source of forestry information in Delaware. No certification or license is required in Delaware, other than a commercial business license. Despite this fact, all the consulting foresters who operate in Delaware have forestry or related degrees and a high level of experience. Delaware participates in the Master Logger program that encourages loggers and timber buyers to participate in this program. Because no regulation is in place regarding the review of timber harvests and forest management activities from a silvicultural perspective, many Delaware landowners still receive timber management advice from loggers and timber buyers.

DFS has a staff of 23 full-time positions, including 10 foresters, plus 1 casual-seasonal employee. The overall timber industry in Delaware employs more than 2,600 people, with a total payroll of roughly $92 million (DFS 2010a) (table 5). Most of this employment is in the secondary timber industry.

Table 5. Employment in Delaware's forest industries over time.

Year	Employed
1954	1,800
1967	2,200
2002	2,600

Source: Delaware Forest Service (2010a)

Threats to Delaware's Forests

The threats to Delaware's forests are similar to those in many other States and can be categorized into two major groups—environmental and human-caused.

Environmental threats include native and nonnative insects and disease, deer browse, and wildfire. Delaware has not had any known occurrences of the most well-known invasive insects such as emerald ash borer (*Agrilus planipennis* Fairmaire) and Asian longhorned beetle (*Anoplophora glabripennis* Motschulsky). Monitoring programs, however, are in place for detecting these pests. Forest managers also monitor for sirex woodwasp (*Sirex noctilio* Fabricius) and sudden oak death (*Phytophthora ramorum*). Gypsy moth (*Lymantria dispar*) is a recurring problem but has not reached critical mass for many years. Delaware has not sprayed for the gypsy moth since the late 1990s. The State, however, is struggling with some invasive plants, namely Norway maple (*Acer platanoides* L.), mile-a-minute weed (*Ipomoea cairica* [L.] Sweet), and phragmities (*Phragmites australis* Cav.).

Uncontrolled native species include bacterial leaf scorch (*Xylella fastidiosa*), southern pine beetle (*Dendroctonus frontalis* Zimmermann), and whitetail deer (*Odocoileus virginianus*). Populations of southern pine beetle have been on the increase for the past 3 years, but so far have not reached epidemic levels. Whitetail deer continue to pose a challenge to forest management. DFS is currently conducting a long-term study of deer browse on plant species composition and prevalence.

Although wildland fire is not a substantial threat in Delaware, it is a concern in the wildland urban interface and in the coastal areas. Volunteer fire departments are the primary responder for wildfires in Delaware; the DFS is available to assist upon request and responds to approximately 50 wildfires per year, most in the southern portion of the State.

Delaware's main human-caused forest threats are forest fragmentation and parcelization, as well as urban sprawl and wildland urban interface issues. Both of these issues cause problems for implementing traditional forest management concepts. Today's average forest ownership size is less than 10 ac (4 ha), down by roughly one-third in three decades.

More information about the threats to Delaware's forests and its plans for addressing them is in the Delaware Statewide Forest Strategy, which is available for review on the DFS Web site (DFS 2010b).

The Future

Delaware continues to face the challenges associated with being a small State with little in-State industry and some challenges that all States face, such as changing climate, exotic and invasive plants and animals, and changing public perceptions and expectations of forest land. One bright spot on the horizon is the increased use and value of low-quality and small-diameter wood. Delaware is in a good position to expand its traditional forest markets as these new utilization trends continue. DFS is looking ahead to 2015 when the agency will update its statewide assessment and strategy. DFS met many of the goals set out in the original documents (DFS 2010a, 2010b) and looks forward to identifying new challenges and opportunities in the near future. More information about the challenges and opportunities facing Delaware and its plans for addressing them is in the Statewide Assessment and Strategy, which is available for review on the DFS Web site (DFS 2010b).

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Acknowledgments

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ADDITIONAL INFORMATION

Delaware Forest Service Web site: http://www.dda.delaware.gov/forestry/

Delaware Forest Service FY 2013 Annual Report: http://www.delawaretrees.com/2013_dfs_annual_report.pdf

Delaware Forest Service Resource Assessment: http://www.dda.delaware.gov/forestry/061810_DFS_ResourceAssessment.pdf

Delaware Forest Service Statewide Strategy: http://www.dda.delaware.gov/forestry/061810_DFS_Strategy.pdf

Delaware Forest Service BMP Manual/Harvest Regulations: http://www.dda.delaware.gov/forestry/forms/2007/2007_BMP.pdf

Delaware Forest Service Timber Industry Directory: http://www.dda.delaware.gov/forestry/forms/2009/2009_DFSWood%20Directory.pdf

Delaware Forest Service Big Trees Of Delaware Book: http://www.dda.delaware.gov/images/forestry/BigTreesOfDelawareThirdEdition.pdf

Delaware Forest Service Timber Harvest Permit/Harvest Regulations: http://www.dda.delaware.gov/forestry/forms/2011_ESPermit_withRegs.pdf

Delaware Forest Service Forest Use Regulations: http://regulations.delaware.gov/AdminCode/title3/400/402.shtml

Delaware Forestry Association: http://delawareforest.com

Delaware Urban Forestry: http://delawaretrees.com

Maryland/Delaware Master Logger Program: https://www.extension.umd.edu/masterlogger

Assembling Seed Moisture Testers, Seed Dryers, and Cone Dryers From Repurposed Components

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Abstract

Accurately determining seed moisture and efficiently drying seeds, cones, and fruits is a critically needed capacity for seed management. In this article, instructions are provided to make a moisture test chamber for easily assessing seed moisture content with a handheld hygrometer. In addition, instructions are given for assembling pressurized dryers for seeds, cones, and fruits. By using repurposed materials, cost and assembly time are minimized and assembly requires only basic mechanical skills and simple tools. Because of the size of the components used, the dryer is best suited to small seed lots weighing less than 100 lb (45 kg). Basic instructions for using the hygrometer, test chamber, and dryer are also provided. Portions of this article were published previously in Karrfalt (2013).

Seeds and Moisture

Moisture is the single, most important factor affecting the viability of seeds in short- and long-term storage (Justice and Bass 1978, Bonner 2008) because high moisture leads to a higher respiration rate, increased microorganism growth, and, in extreme cases, premature germination. These negative effects are further aggravated by higher temperature. Low moisture, on the other hand, lowers respiration and inhibits microorganism growth. When seeds have low-moisture contents, they can even endure short periods of elevated temperature with little measurable loss to viability.

Recalcitrant and orthodox are the two basic types of seeds in regards to moisture relations (Roberts 1973). Recalcitrant seeds are those that must maintain moisture contents in the range of 25 to 45 percent, depending on species and genotype, to maintain viability. Recalcitrant seeds are common with tropical species and retain viability for only a few days, weeks, or months (Luna and Wilkinson 2014). By contrast, orthodox seeds are those that can sustain drying to moisture contents less than 10 percent and not lose viability. Orthodox seeds can maintain viability for long periods of time when stored under low-moisture content. Therefore, it is necessary to understand how to control seed moisture at all stages of seed handling from harvest to sowing. A complete discussion of seed moisture and seed storage is found in Bonner (2008). The methods and equipment described in this article are for reducing and measuring seed and fruit moisture for orthodox-seeded species.

Orthodox seeds are dynamic in relation to the moisture in their environment. That is, when more moisture is in the environment than inside the seeds, moisture will move into the seeds. Conversely, when seeds have more moisture than the surrounding environment, moisture will move out of the seeds. This gain and loss of seed moisture goes on constantly until the environment becomes stable and seeds equilibrate. In a stable high humidity, seeds will equilibrate to that high-moisture content, and at a stable lower relative humidity, the seeds will equilibrate to the lower moisture content. When seeds have reached this stable state with the environment, they have achieved equilibrium moisture content (Bonner 2008). This equilibrium moisture content corresponds to a specific relative humidity that is called the equilibrium relative humidity, or ERH, when moisture is neither gained nor lost. The general relationship of ERH to seed moisture content is shown in figure 1. The use of ERH to manage tree seed moisture has been described by Baldet et al. (2009) and Karrfalt (2010).

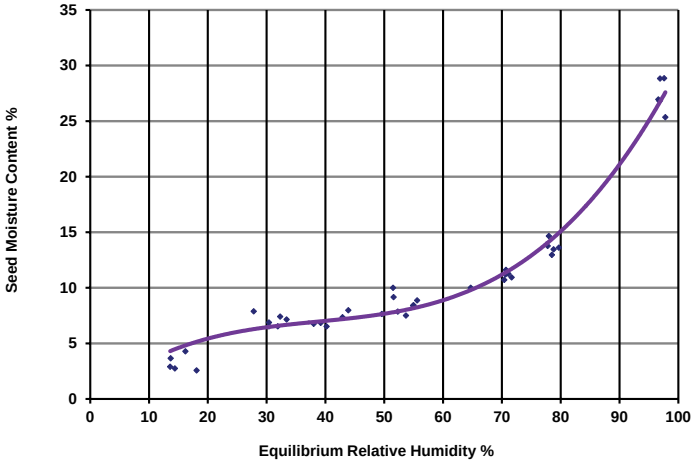

Figure 1. The relationship of seed moisture content with equilibrium relative humidity.

Determining Seed Moisture Using a Hygrometer

Because of the strong relationship between seed moisture content and ERH, it is possible to accurately assess seed moisture status using a hygrometer. Optimal moisture content for storing orthodox seeds is between 5 and 10 percent, which corresponds to an ERH of 30 to 50 percent (Bonner 2008). To allow for errors in measurement and accidental increases in seed moisture, it would be safe to use 30 percent ERH (equivalent to about 6 percent moisture content) as a target to which seeds should be dried to preserve maximum viability. With a compact electronic hygrometer (figure 2), it is possible to rapidly, accurately, and nondestructively determine the ERH of any orthodox seeds. Reliable digital hygrometers range in price from $200 to $600 and are available from various suppliers.

The environment is generally the greater determinant of ERH of seeds. In a small, confined space, however, the situation can reverse and the seeds can dominate the relative humidity of the air. Such is the situation in a sealed jar that is at least half full of seeds. With this quantity of seeds, the loss or gain of moisture with the air will be too small to measurably change the seed ERH. Seeds having a high-moisture content will create high humidity in the jar, and seeds with a low-moisture content will create low humidity in the jar. Thus, ERH in the jar will equal the ERH of the seeds. The sensor of the hygrometer inserted into the jar can measure the ERH.

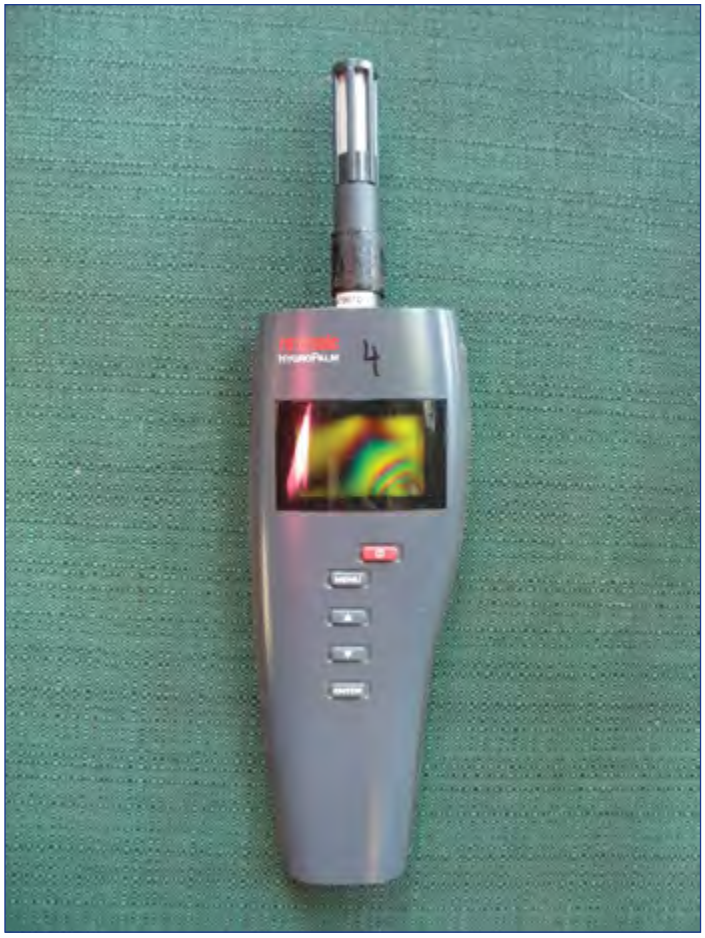

Figure 2. Hand-held hygrometer for measuring relative humidity in drying area and equilibrium relative humidity of seed samples. (Photo by Robert Karrfalt)

Any recycled plastic jar with a tight lid can be used for this test (figure 3A). Simply make an opening in the jar lid that closely matches the diameter of the hygrometer probe to create an airtight seal between the lid and the probe. Figure 3B shows how to assemble the hygrometer and test chamber.

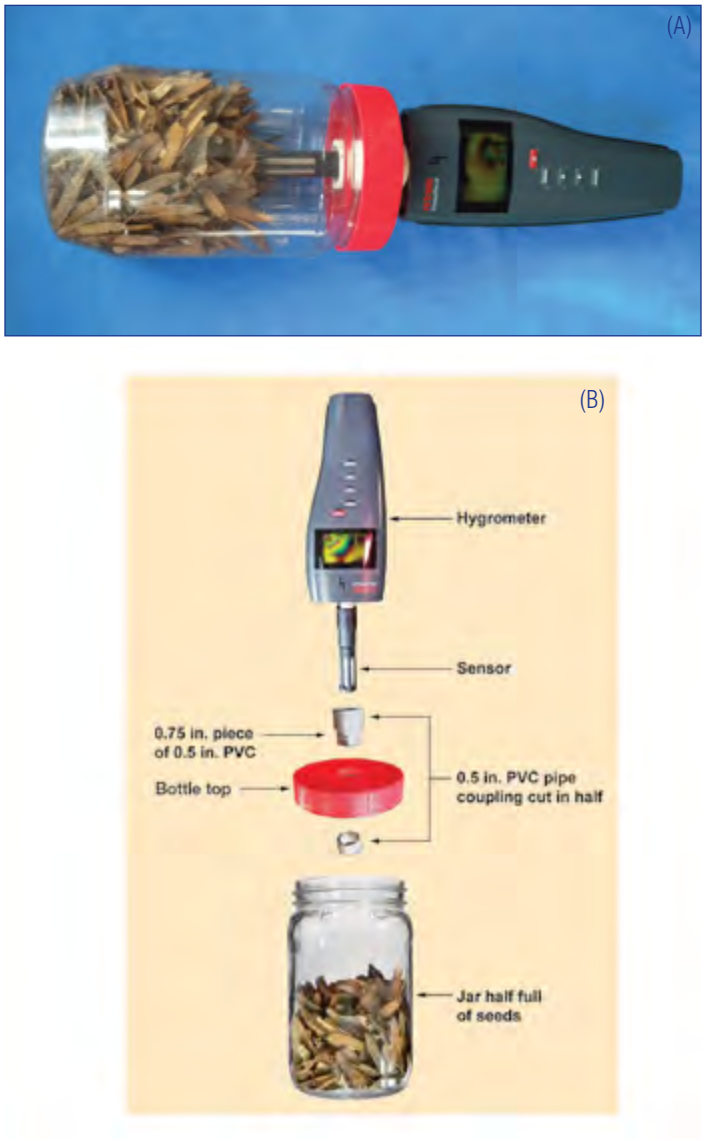

Figure 3. (A) Hygrometer inserted into closed jar to measure the equilibrium relative humidity of a seed sample. (B) Schematic representation of the hygrometer, insertion port, and sample jar. (Photo by Robert Karrfat and illustration by Jim Marin)

The parts include a 0.75-in (1.9-cm) long piece of 0.5-in (1.3-cm) polyvinyl chloride (PVC) pipe and a 0.5-in (1.3-cm) PVC pipe coupling, cut in half. The exact size of the fittings chosen must match the particular hygrometer used. In this example, the probe of the meter shown had to be shimmed out using a few wraps of electrical tape to make a secure fit with the pipe fitting (figure 2). After it is assembled, fill the jar half full of seeds, screw on the lid, and allow the sample to come to equilibrium (a steady reading on the hygrometer). If in doubt about whether or not the sample is at ERH, leave the jar closed and retake a reading in a few hours. If the second reading is different than the first, repeat the process until two consecutive observations are equal. When the reading remains unchanged, the seeds are at equilibrium. The hygrometer should be periodically compared with traceable standards that are usually available from the meter vendor.

Drying Seeds in a Pressurized Dryer

Seeds, cones, or fruits kept in a mass, such as contained within a mesh bag, will dry only at the surface. Therefore, these materials are frequently spread in very thin layers or stirred often so that all the material spends some time exposed to the air and can dry. The seeds are spread in thin layers by placing them on sheets or in screen bottom trays. This approach requires relatively large drying areas. To reduce the work area needed, one variation is to put the trays in a rack and blow air across the trays. Food dehydrators or egg incubators have been used to dry seeds also, but their use usually means the seeds have to be stirred periodically by hand. If air is forced up through the seed mass from the bottom, however, all seeds can be dried without any stirring, in a compact space, and often more rapidly. The apparatus for drying seeds in this manner is called a pressurized dryer.

Pressurized dryers have been made in various configurations and capacities, but all use the same principle of placing seeds in a container with air-tight sides in which dry air is forced upward through the seeds. In larger forest tree seed extractories in the United States, a version of the pressurized dryer consisted of stacks of trays 4-ft (1.2-m) wide, 8-ft (2.4-m) long, and 1-ft (0.6-m) deep. These trays are handled by forklifts and are very efficient for very large volumes of cones. For smaller volumes of material, a pressurized drier can easily be constructed (figure 4) using off-the-shelf components (table 1). The main parts are a 5-gal (19-L) bucket, paint strainers, and a small electric fan. The mesh bottoms of the paint strainers used as trays come in different sizes, described in more detail in the following section.

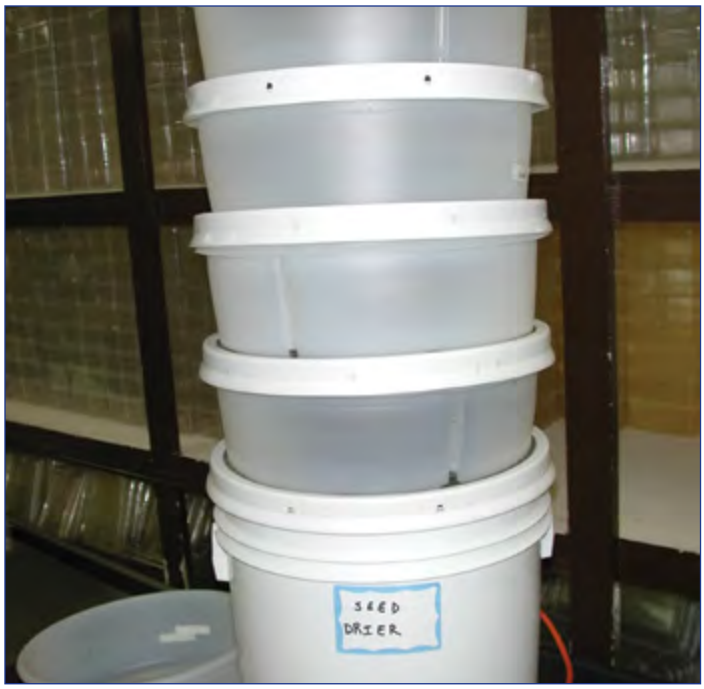

Figure 4. Pressurized seed dryer made from a 5-gal (19-L) bucket, paint strainers, a furnace motor, and other readily available parts. (Photo by Robert Karrfalt)

Table 1. Specifications and possible sources for parts needed to make the pressurized seed dryer.

Item	Specifications	Approximate cost	Possible source(s)
Paint strainer	EZ Strainer 600, 400, 100 mesh (larger number is larger opening)		Internet vendors and local paint supply company
	5-gal (19-L) bucket size 55-gal (208-L) barrel size	$5 ea $12 ea	
5-gal (19-L) bucket	New or used, clean	$0 to $5	Hardware store and recycle bin
5-gal (19-L) pail lid	New or used, clean	$0 to $2	Hardware store and recycle bin
Blower motor	Induced draft, operates at 1.5 to 2.0 in (3.8 to 5.0 cm) of water column (wc) minimum (e.g., Dayton 4C723)	$125	Grainger.com Heating and air conditioning supply store
Extension cord	6 to 10 ft (1.8 to 3.0 m) long, 16 wire minimum	$5	Local hardware
Nonmetallic cable connector	3/8 in (0.95 cm)	< $1	Local hardware
Two wire nuts	For number 16 wire	$2	Local hardware
Weather stripping	0.25-in (0.64 cm) foam tape	< $3	Local hardware
Pan head screws	Number 10 by 0.75 in (1.9 cm)	< $3	Local hardware
2 by 2 in (5 by 5 cm) wood blocks	2- to 3-in (5.0- to 7.5-cm) long		Wood scrap pile

Assembling the Seed Dryer

The dryer can be easily assembled by following six steps.

1. Place a piece of paper on the side of the blower opposite the motor and make a pattern by tracing the blower inlet and mounting tabs and holes.
2. Cut out the pattern and place it on the bottom of the 5-gal (19-L) bucket (figures 5 and 6). Mark the location of the mounting holes and the inlet of the fan. Be certain the pattern is oriented correctly so that the holes on the pattern match the holes on the fan.
3. Drill out the mounting holes with a 0.25-in (0.63-cm) twist drill and carefully cut out the fan inlet opening using a sharp utility knife.
4. Use #10 by 0.75-in (1.9-cm) pan head screws to mount the fan motor by driving them into 2- by 2-in (5- by 5-cm) wooden blocks that will be the legs of the dryer. The type of fan is an induced draft blower for high-efficiency furnaces. It was chosen because it will operate at a high static pressure. A high static pressure in this case is approximately 1.5 to 2.0 in (3.8 to 5.0 cm) of water column that is usually shown in blower specifications as "wc." Trays full of seeds will create a strong static pressure, and if the fan is not built to operate at high static pressure, it will burn out. We have used these fans in seed dryers continuously for several weeks at a time and none have burned out.
5. The drying trays are tapered and will not form a tight seal between trays unless a collar is put between them. This collar is made from the bucket lid. Cut out the center of the lid leaving about 2 to 3 in (5.0 to 7.5 cm) of the lid around the edges. Installing 0.25-in (0.64-cm) foam weather stripping around the lid (figure 6) makes the seal complete.

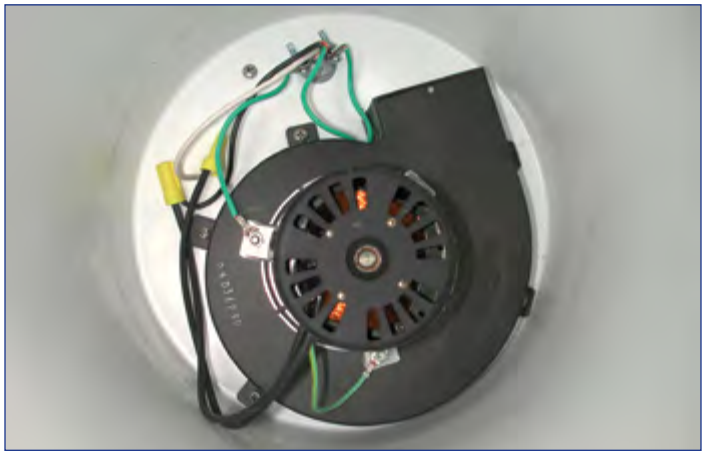

Figure 5. Placement of the induced draft blower and wiring in the bottom of the 5-gal (19-L) bucket. (Photo by Robert Karrfalt)

6. The power cord to the fan is a 6- to 10-ft (1.8- to 3.0-m) long, 16-gauge wire extension cord. Drill a 0.5-in (1.3-cm) hole in the bottom of the bucket and put a nonmetallic cable connector in it to secure the power cord to the dryer bottom (figure 5). Cut off the female end of the power cord, feed it through the connector, and attach the exposed wires to the wires of the blower motor with wire nuts. Obtain assistance in wiring the dryer if you are unfamiliar with electrical wiring.

Using the Dryer

The smallest seeds require trays with 100-mesh bottoms, while larger seeds can be dried on two larger sizes, 400- and 600-mesh bottoms. Using the largest sized mesh that does not let seeds fall through minimizes the resistance of the air movement and allows more seeds to be placed on the dryer at one time. The strainer mesh size needs to be adapted to each seed processor's needs.

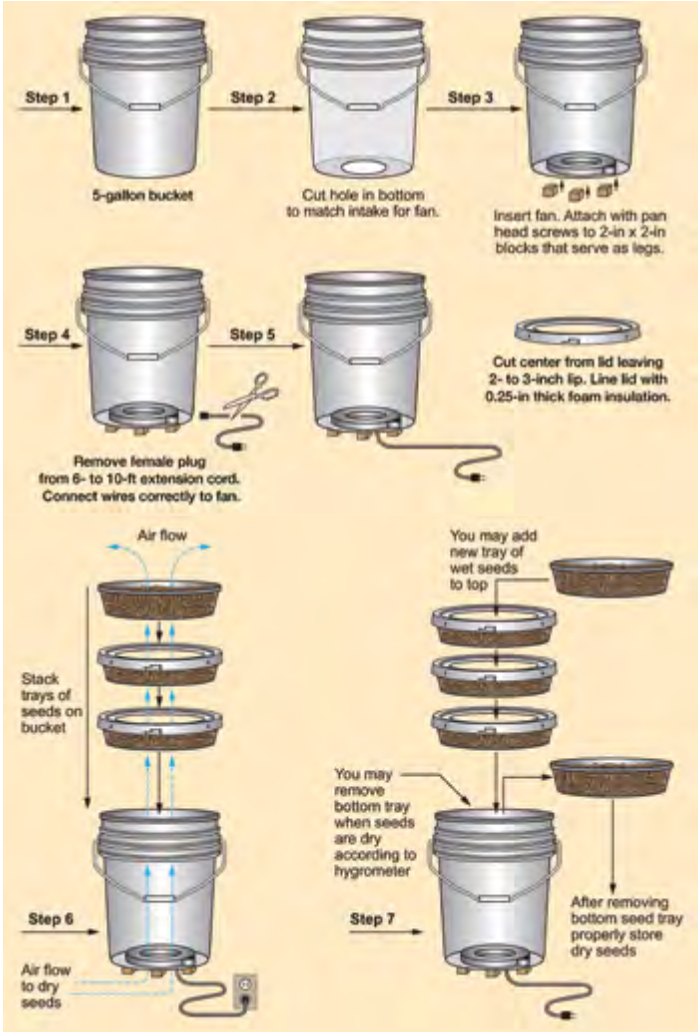

Figure 6. Steps for building and operating a seed dryer. (Illustration by Jim Marin)

The trays can be either completely or partially filled with seeds. When a small amount of seeds are dried in a single tray, it is usually necessary to place another tray over top of the one holding the seeds to keep them from blowing out. Small quantities of seeds, or extremely small seeds, could also be kept in bags with fine mesh and placed inside the tray. Additional weight might also be needed to keep this cover tray in place, but in doing so, do not block the airflow completely. When drying large quantities of seeds, trays may be stacked five or six high before the pile becomes unstable. As long as a gentle airflow is felt coming out the top of the stack, the stack is not too tall.

When stacked, the seeds in the bottom tray will dry first, then the seeds in the middle trays, and finally the seeds in the top tray. The position at which the seeds have come to equilibrium with the dry air is called the drying front. Seeds beneath that front (closer to the fan) are dry, but seeds farther away (over top of it) are still drying. Use your hygrometer to test whether the seeds are at the desired ERH. After seeds in the bottom tray are completely dry (that is, the drying front has passed the top of the first tray), the tray can be removed from the dryer and another tray of seeds added to the top of the stack (figure 6). Do not place the dry tray at the top of the stack, because moisture will be put back into these finished seeds slowing down the whole process. Removing the bottom tray of dry seeds is only an option, and whether it is removed or left in place does not affect the rate of drying in the other trays. Under good conditions, the full stack of trays will dry overnight (or similar period), and the full stack can be changed out all at once. Because the seeds do not require any stirring during this process, as is the case when air-drying a mass of seeds on a table or the ground, pressurized drying saves labor.

The dryer must operate in a closed room or closet where the air is approximately 30 percent relative humidity. This humidity level is achieved by adding heat when outdoor ambient temperatures are less than 60 °F (15 °C). When temperatures are higher, a dehumidifier (or dehumidifier in combination with an air conditioner) will dry the air. Some ambient conditions are naturally dry and then a closed, conditioned space is not needed. The same hygrometer used to test the ERH of the seeds is used to test the dryness of the air in the drying area.

Larger Dryers

If your situation requires a larger dryer, the paint strainers also come in a 55-gal (208-L) barrel size (figure 7). The plenum in this figure was made of plywood. A whole barrel, or one cut in half, would also work. Note the hole on the side of the plenum to allow air to be pulled in by the blower fan. The blower motor described in the previous section will also work for these larger drying trays. The larger paint strainers usually have less taper than the smaller ones, so a collar may not be necessary to seal the stack.

Figure 7. Pressurized dryer made with 55-gal (208-L) barrel paint strainers. (Photo by Robert Karrfalt)

Drying Time and Storage

Using these dryers, seeds should be dried to safe storage ERH within 1 to 16 hours, depending on the amount of moisture that needs to be removed from the seeds. After the seeds are dry, they must be kept in a dry environment or sealed in moisture-proof containers to maintain their low ERH and their viability (Bonner 2008).

Drying Conifer Cones and Expanding Fruits in a Pressurized Dryer

Pine cones and chestnut burrs are examples of plant materials that expand as they dry. These materials are best dried using the larger strainers. Because these materials are relatively heavy, however, they might cause the large paint strainers to nest too tightly for expansion of the cones or fruits, necessitating a collar like those on the smaller strainers (figure 8). Barrel covers are available that work well as collars, just as the 5-gal (19-L) pail lid worked for the small strainers. Barrel covers are relatively expensive, however. Straight-walled pallet containers are another excellent option. The straight-walled containers come in various sizes. A 24.0 by 15.0 by 9.5 in (61 by 38 by 24 cm) container accommodates 0.25 to 0.50 bushels (8.8 to 17.6 L) of cones or one bushel (35.2 L) of seeds and is easily handled by one person.

Figure 8. The lid of the 5-gal (19-L) bucket should have the center removed, leaving a 2- to 3-in (5- to 7-cm) lip. In addition, attaching 0.25-in (0.6-cm) thick foam insulation will improve the seal between the lid and the paint tray that will sit upon it. (Photo by Robert Karrfalt)

Straight-walled containers have solid bottoms and need to be perforated. Use a 0.5-in (1.3-cm) twist drill to make 25 evenly spaced holes in the bottom of each drying container. This number of holes equals the area of the opening for the blower motor. A cardboard template (figure 9) is useful for placing the holes uniformly. A screen must be placed in the bottom of each drying container to prevent smaller seeds from falling through. Pet-proof, screen-door screen is recommended because of its durability. The screen must be secured to the

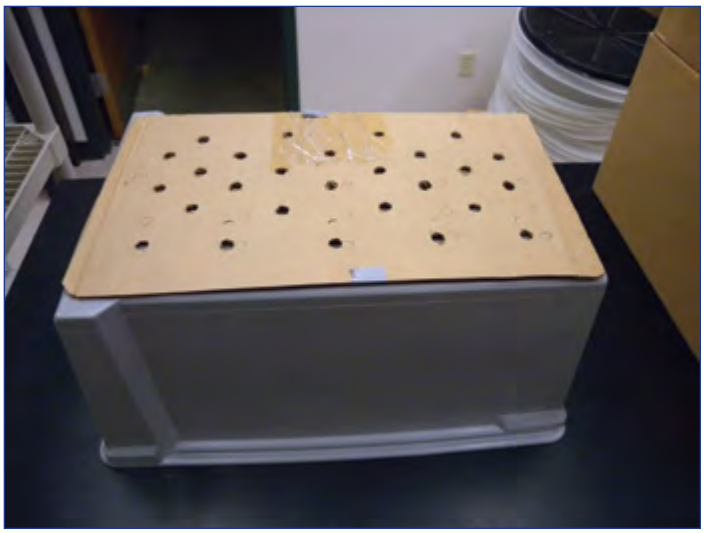

Figure 9. A cardboard template is a quick way to show where to drill the holes across the bottom of the drying boxes. (Photo by Robert Karrfalt)

container using quality packaging or duct tape (figure 10). Glues, cements, or solvent welding cannot be used because the containers are made of high-density polyethylene (HDPE). The physical and chemical nature of HDPE is such that only tape can be used to attach things to it. A fastener such as a pop rivet might also work. The same reasoning is applied when using tape to cover the waffles in the container flanges (discussed in the following paragraph).

Figure 10. Box on the left shows pet screen taped to the bottom and box on the right shows hole pattern and foam gasket. (Photo by Robert Karrfalt)

Straight-walled pallet containers have a flange at the bottom that allows two containers to stack securely together while leaving ample room for cone expansion. Although secure for stacking, the connection between containers requires a foam gasket to make an air-tight seal for the dryer (figure 11). The container's flange has a waffle design (figure 12), which requires a covering before attaching the gasket. The covering is a layer of 2-in (5.0-cm) wide tape (packaging or duct tape). To apply the tape, first place the container upside down on a level work surface. Cover one side of the flange at a time by using a piece of tape the length of the flange and attach it to the outside edge of the flange. Carefully fold the tape over the waffles to make a smooth surface and a sharp junction with the side of the container. Finally, smooth the remaining tape against the side of the container. The foam gasket can now be attached to the underside of the flange. The most suitable foam gasket seems to be the foam sealer for pick-up truck body caps. Other foam weather stripping is usually too stiff or too soft. Not having to use a collar between containers is an advantage while loading and emptying containers because only one item, the container, is handled and not two, container and collar. Fewer movements can save much time in a busy cone-processing day.

Figure 11. A foam gasket is needed on the flange on the bottom of the drying box to form an airtight seal. (Photo by Robert Karrfalt)

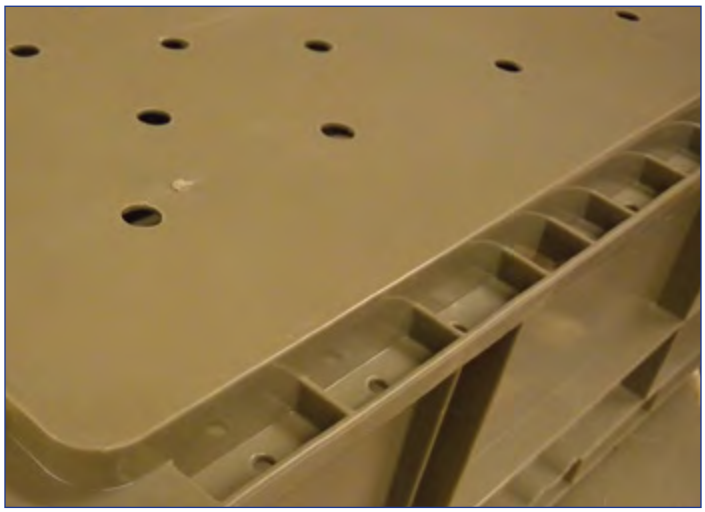

Figure 12. The flange on the bottom of the drying box has a waffle design that must be covered with tape before applying the foam gasket shown in figure 11. (Photo by Robert Karrfalt)

The blower motor can be mounted in a container at the base of the stack of drying containers in the same way as it was mounted in the 5-gal (19-L) pail. Unlike seeds, the container should be filled only half way when drying cones or fruits to allow for expansion during drying. Drying time is 1 to 16 hours depending on the amount of moisture that needs to be removed from the plant material. After the cones or fruits are dried, they are ready for seed extraction. Seed extraction and cleaning are covered in detail in Karrfalt (2008).

Conclusions

By constructing and using the equipment described in this article, it is possible to have advanced seed technology methods for drying seeds and testing their moisture status. Seeds, cones, or fruits can be dried rapidly, using minimal labor and a minimal amount of work area. By deploying repurposed components, a minimal amount of time and mechanical abilities is required to assemble the equipment. Cost is also kept low because all components are mass produced for other purposes. The end result is maximum seed quality at minimal labor and material costs.

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Effects of Combination Plowing on the Survival and Growth of Loblolly Pine

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Abstract

Six trial sites were established in the Southeast United States to investigate the effect of a combination of surface and subsurface tillage on survival and growth of loblolly pine (*Pinus taeda* L.). The tillage was conducted in a single pass using a 3-in-1 combination plow. Seedling survival 1 year after planting was significantly greater in tilled plots compared with nontilled plots at two of the six trial sites. The increase in survival at these two sites averaged 10 percent. Seedling growth after 6 years was significantly greater in tilled plots than nontilled plots at three of the six trial sites. The volume response to tillage at 6 years on the most responsive site was equivalent to an annual growth increase of 29.8 ft^3 per ac per yr (2.1 m^3 per ha per yr) more than the nontilled control. In light of the small and variable response on these well-drained upland sites, it is unlikely that this costly operation is warranted.

Introduction

Site preparation prescriptions in pine plantations in the Southeastern United States are designed to create soil conditions favorable for survival and growth of seedlings (Lowery and Gjerstad 1991). Many plantations in the Piedmont and Upper Coastal Plain in the South are established on sites that were previously used for row crop agriculture (Fox et al. 2007). Because of the severe erosion that accompanied row crop agriculture, the clayey B horizon soil, which has high bulk density, is now incorporated into the Ap horizon. Tillage treatments are frequently used on these upland sites to decrease bulk density and increase aeration porosity of the soil, thereby allowing seedling roots to proliferate through the soil (Gent et al. 1984, Morris and Lowry 1988). Tillage also soil increases water and nutrient availability to the planted seedlings because it increases rainfall infiltration and organic matter decomposition and decreases hardwood competition (Campbell et al. 1974, Morris and Lowery 1988, Wheeler et al. 2002, Schilling and Lockaby 2004). Previous trials established in the Southeast United States to examine the effect of tillage on loblolly pine (*Pinus taeda* L.) seedling growth have reported growth responses ranging from 15 to 90 percent (Wheeler et al. 2002, Carlson et al. 2006).

Tillage equipment, such as the 3-in-1 combination plow (figure 1), was developed to allow surface tillage and deep ripping to occur in a single pass in hopes of cost-effectively altering soil physical properties (figure 2) and thus more

Figure 1. Typical 3-in-1 combination plow used for tillage showing disks for surface tillage and ripping shank for subsoil tillage. (Photo by Forest Productivity Cooperative, North Carolina State University, date unknown)

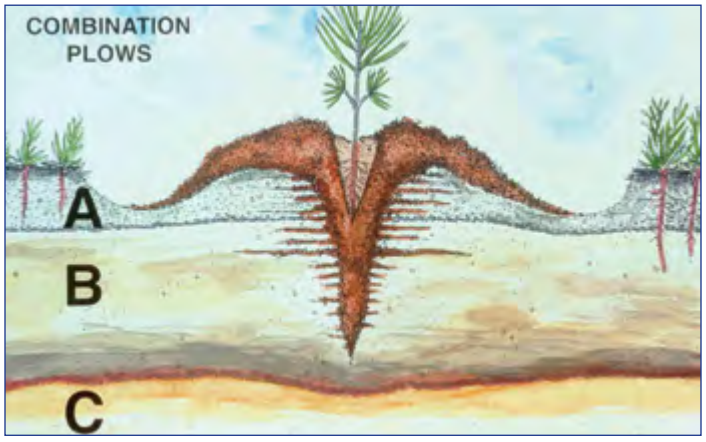

Figure 2. Effects of tillage with 3-in-1 combination plow on the A, B, and C horizons in a typical soil profile. (Illustration courtesy of Weyerhaeuser Company)

consistently increasing seedling growth. This article describes results from a trial that was established across the Southeast United States to compare seedling survival and growth between two treatments—a nontilled control and a combination of surface and subsurface tillage in a single pass using a 3-in-1 combination plow. The study was established at six locations and seedling response was monitored for 6 years.

Methods

Six trial sites were established between 1994 and 1998 in the Piedmont and Upper Coastal Plain in the Southeastern United States. Sites had well-drained soils and relatively shallow topsoils over heavy clay subsoils (tables 1 and 2). A control treatment using no tillage was compared with a tillage treatment in which subsoiling and surface tillage were done in a single pass of a 3-in-1 combination plow (figures 1 and 2). Tillage was done using either a Savannah™ Model 310 or 450 3-in-1 combination plow, which tilled the surface soil to a depth of approximately 12 in (25 cm) and the subsoil to a depth of approximately 24 in (50 cm). Each treatment was replicated twice at study 3801, three times at studies 0101 and 4501, and four times at the remaining three sites (0601, 2801, and 3201). Individual measurement plots ranged in size from 0.07 to 0.17 ac (0.03 to 0.07 ha) and averaged 0.10 ac (0.04 ha). A treated buffer of 30 to 40 ft (9 to 12 m) surrounded each measurement plot.

All trials were hand planted with 1-0 genetically improved loblolly pine seedlings. The number of trees in each treatment plot ranged from 48 to 77 and averaged 61 trees. Measurement plots in four studies (0101, 3201, 3801, and 4501) were double planted (i.e., two seedlings were planted approximately 6 in [15 cm] apart at each planting spot within the planted row) and were thinned to a single seedling 12 months after planting. The aim of the double planting was to minimize the effects that variation in stocking may have on long-term growth measurements. A prolonged drought in the spring of 1995 resulted in extremely poor survival at site 3801, which was subsequently replanted the following winter.

Because our goal was to isolate the tillage effects on soil properties and seedling survival and growth, we applied weed control and fertilization to the control and the tilled plots. All trials were fertilized the first year after planting with 200 lb per ac (224 kg per ha) diammonium phosphate (DAP), which added 36 lb per ac N + 40 lb per ac P (40 kg per ha N + 45 kg per ha P) except trial 0101, which received 142 lb per ac DAP (160 kg per ha), which added 26 lb per ac N + 28 lb per ac P (29 kg per ha N + 31 kg per ha P). Competing vegetation was controlled during the first two growing seasons using repeated applications of herbicide at labeled rates. The number of herbicide applications, chemicals used, application rates, and application methods varied across study sites. The vegetation control achieved during the first two growing seasons, however, exceeded typical operational control levels at the time. Although the sites were qualitatively assessed to ensure that the standard of vegetation control was suficient to meet the goals of the trial, no quantitative assessments of vegetative cover were made at any of the sites.

After the first growing season, seedling survival was assessed. In the four trials that were double planted, survival of both seedlings was determined. If both seedlings survived, survival was 100 percent; if only one seedling survived, survival was 50 percent. Survival data were transformed before analysis using an arcsine transformation to normalize the data.

Table 1. Site and soil characteristics for each study site. The subsoil depth represents the depth of the transition to an argillic horizon (Bt). Soil texture was determined at a soil depth of 20 in (50 cm).

Study	Year trial established	Physiographic provence	County, State	Principal soil series	Drainage class[1]	Mineralogy	Depth to subsoil (cm)	Subsoil texture[2]
0101	1994	Piedmont	Laurens, SC	Cecil, Pacolet, and Appling	w	kaolinitic	19	scl and cl
0601	1997	Piedmont	Halifax, NC	Tatum	w	mixed	18	c
2801	1998	Upper Coastal Plain	Little River, AR	Smithton	w	siliceous	38	sl
3201	1996	Upper Coastal Plain	Santa Rosa, FL	Bama and Norfolk	w	siliceous	28	sl and scl
3801	1995	Piedmont	Saluda, SC	Appling	mw and w	kaolinitic	31	sc
4501	1998	Upper Coastal Plain	Wilcox, AL	Izagora	mw	siliceous	28	l and cl

[1]Drainage Class: mw = moderately well; p = poor; w = well.
[2]Texture: c = clay; l = loam; s = sand; si = silt.

Table 2. Pretillage soil texture, bulk density, total carbon, soil strength, and aeration porosity for surface (A) and subsurface (Bt) horizons on each study site.

Site	Horizon	Depth (cm)	Texture[1]	Bulk density (g per cm^3)	Soil strength[2] (MPa)	Aeration porosity (%)	Total carbon (g per kg)
0101	A	0–19	ls	1.54	1.5	16	9.6
	Bt		scl	1.52	5.5	8	5.0
0601	A	0–18	sl	1.44	1.2	14	12.6
	Bt		cl	1.45	3.1	9	4.4
2801	A	0–38	sl	1.60	1.4	5	6.1
	Bt		l	1.65	3.2	5	2.1
3201	A	0–28	ls	1.56	1.6	9	10.3
	Bt		scl	1.61	3.9	8	3.0
3801	A	0–31	sl	1.58	3.9	9	7.9
	Bt		cl	1.52	5.6	6	3.4
4501	A	0–28	sl	1.57	1.7	5	8.5
	Bt		l	1.60	2.7	3	2.3

[1]Texture: c = clay; l = loam; s = sand; si = silt.
[2]Soil strength was predicted for soil moisture at field capacity (0.03 MPa) using equations from da Silva and Kay (1997).

Total height and diameter at breast height (dbh) of surviving trees was measured in December or January after the second, fourth, and sixth years following planting (with the exception of site 3801, which was not measured during the fourth year). Individual tree volume was calculated using the equation for inside bark volume developed by Smalley and Bower (1968): inside bark volume (ft^3) = 0.002 by dbh (in^2) by height (ft). Summing individual tree volumes in each plot and scaling to per acre values based on the area of each plot determined volume per acre.

For each site, survival, cumulative height, diameter, and volume at age 6 were analyzed using paired sample t-tests in SAS (SAS Institute, Cary, NC). Trends in volume growth over time were determined using data from ages 2, 4, and 6 analyzed using repeated measures procedures in PROC MIXED (SAS Institute, Cary, NC) to determine whether the treatments affected tree growth rates during their first 6 years. A first-order autoregressive covariance structure was used in these analyses.

Results and Discussion

Differences in first-year survival between seedlings planted in plots tilled using the 3-in-1 combination plow and those planted in the nontilled control plots ranged from small and statistically insignificant at sites 0601, 2801, 3801, and 4501 to a significant ($p = 0.058$) increase of 14 percent at site 3210 (table 3). Because all the trials had good weed control and were fertilized to ensure adequate nutrition, the improved survival is most likely attributable to improved soil tilth. Improved soil physical properties following tillage can increase root growth and allow seedlings to more quickly explore deeper soil horizons, which allows them to access more soil water than seedlings in the nontilled plots (Campbell et al. 1974, Morris and Lowery 1988, Wheeler et al. 2002). This method reduces the likelihood of water stress during dry periods.

The results from this study, however, suggest that the effect of improved soil physical properties on seedling survival on these cutover sites is relatively small when good weed control is obtained using herbicides.

After 6 years, there were significant treatment effects at only two trial sites. Seedlings in trial 3210 were significantly greater in height, dbh, and volume in the tilled treatment compared with the control (table 3). At this site, volume of seedlings in the 3-in-1 combination plow treatment averaged 179 ft^3 per ac (12.6 m^3 per ha) more than in the control treatment. Seedlings in the tillage treatment at trial 0101 tended to have larger dbh than those in the control treatment (table 3). Seedling growth showed no significant differences among treatments at the other four locations.

Volume growth rate through time of seedlings planted in the 3-in-1 combination plow treatment was more than for those planted in the nontilled control treatment at three of the installations: 0101, 2801, and 3201 (figure 3). On site 3201, where the greatest response to tillage using the 3-in-1 combination plow occurred, the volume growth rate was 29.8 ft^3 per ac per yr (2.1 m^3 per ha per yr) more per year

Table 3. One-year mean survival, and six-year mean height, dbh, and volume for each treatment at each site. The p values are the results of paired t-tests between comparable replicates of nontilled and 3-in-1 combination plow treatments at each site. The analysis with the survival data used arcsine transformed means.

Sites	Number of repetitions	Survival (%)			Height ft (m)			dbh in (cm)			Volume ft³ per ac (m³ per ha)		
		Nontilled	3-in-1 plow	P value	Nontilled	3-in-1 plow	P value	Nontilled	3-in-1 plow	P value	Nontilled	3-in-1 plow	P value
0101	3	91	97	0.061	22.0 (6.7)	23.3 (7.1)	0.960	4.5 (11.5)	4.9 (12.5)	0.072	629 (44)	778 (54)	0.221
0601	4	75	85	0.637	14.4 (4.4)	14.4 (4.4)	0.997	3.0 (7.5)	2.9 (7.4)	0.291	154 (10)	157 (11)	0.795
2801	4	95	98	0.914	19.4 (5.9)	21.3 (6.5)	0.131	3.8 (9.6)	4.2 (10.7)	0.141	240 (16)	341 (24)	0.544
3201	4	82	96	0.058	23.3 (7.1)	26.3 (8.0)	0.032	4.1 (10.5)	4.5 (11.5)	0.041	410 (28)	589 (41)	0.035
3801	2	68	77	0.379	19.0 (5.8)	19.4 (5.9)	0.254	3.9 (9.8)	3.8 (9.7)	0.889	344 (24)	374 (26)	0.611
4501	3	95	96	0.915	30.2 (9.2)	30.5 (9.3)	0.361	5.1 (12.9)	5.2 (13.1)	0.153	1,106 (77)	1,158 (81)	0.531

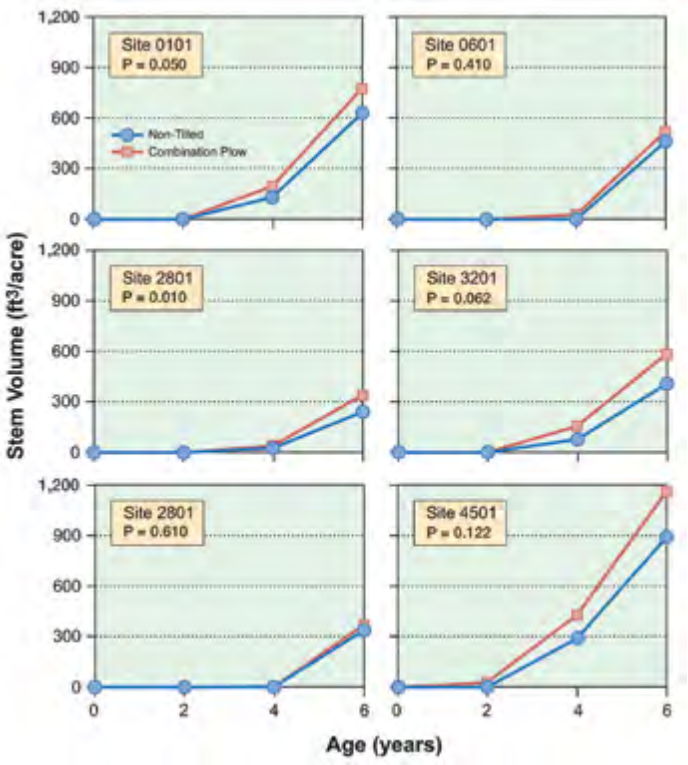

Figure 3. Cumulative volume at the different sites for the nontilled plots and the combination plow treatment. P-values on the individual graphs are the results of the repeated measures analysis for the Time by Treatment interaction.

than the untilled control. The growth response was much lower, however, on the other sites. Across all six trials, the average volume growth gain following tillage using the 3-in-1 combination plow was only 15.6 ft^3 per ac per yr (1.1 m^3 per ha per yr) relative to the control. This gain is relatively small compared with those reported for other silvicultural treatments applied in young loblolly pine plantations. For example, the average growth response during the 6 years after nitrogen and phosphorus fertilization was 62.4 ft^3 per ac per yr (4.4 m^3 per ha per yr) (NCSFNC 1997). The cost of this tillage operation is considerable, averaging $185 per ac ($457 per ha) in 2012 (Dooley and Barlow 2013). The growth responses we observed in these trials are unlikely to be large enough to pay for such an expensive treatment, particularly when the costs must be carried for 20 to 25 years until the end of the rotation.

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Measuring Irrigation Uniformity in Bareroot Nurseries: A Case Study

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Abstract

A cup test was conducted to measure irrigation uniformity in a bareroot nursery field on a semipermanent, solid-set irrigation system with lateral irrigation lines 60 ft (18.3 m) apart and 60 ft (18.3 m) between sprinklers in the lines, with sprinklers arranged in a triangular pattern. Irrigation uniformity was good in the middle of the field, with Christian's Coefficient of Uniformity (CU) of 86 percent, and the irrigation precipitation rate was 0.29 in per hr (0.74 cm per hr). Uniformity was considerably lower at the south end of the field (CU = 69 percent), mainly because of a different sprinkler layout designed to compensate for prevailing south and west winds. Precipitation rate at the end of the field was 150 percent more (0.43 in per hr [1.1 cm per hr]) than the interior of the field. Matching precipitation rates on sprinklers at the end of the field may reduce the higher precipitation rate, although the uneven spacing of sprinklers in the area will still reduce uniformity. Other irrigation management factors are discussed in relation to the soil conditions in the field and the results of the irrigation uniformity test.

Introduction

Irrigation uniformity is a key factor in producing high-quality nursery stock. Uniform irrigation allows for better control of seedling growth, more efficient use of fertilizer and other agricultural chemicals, and mitigation of water pollution by reducing runoff and leaching of nutrients and pesticides from nursery fields (Solomon 1990). Measuring irrigation system uniformity is one part of an irrigation audit, which is the process used to determine how effectively the system is applying water at a given point in time (Setson and Mecham 2011). Results of uniformity assessments include Christian's Coefficient of Uniformity (CU) and Lower Quarter Distribution Uniformity (DU_{LQ}) and also the precipitation rate for a particular group of sprinklers operating in the field at a point in time (Zoldoske et al. 1994). These measures are obtained by measuring the amount of water deposited into catch devices placed at specific intervals within the irrigated area. Information gathered during the assessment also helps determine the reasons for the uniformity numbers and can be used to make repair, maintenance, and scheduling decisions.

A number of papers have described methods for measuring and improving irrigation uniformity in forest and conservation nurseries (Shearer 1981, Scholtes 2001, Fernandez 2010). Few examples of results from actual tests conducted in bareroot nurseries, however, are available. This article presents the results of a uniformity test conducted at the Indiana Department of Natural Resources Vallonia State Nursery (Vallonia, IN) in July 2013. The purpose of the test was to characterize the uniformity of irrigation of a production field at the Vallonia Nursery and to examine the difference between the irrigation patterns over the main (interior) part of the field and the pattern at the south end of the field, where the sprinkler pattern was different from the main part of the field.

Methods

Tests were conducted in Vallonia Nursery's Block 3, Section 1, Units 1 and 2 on July 12, 2013. The soil in this field is a sandy loam.

Test Procedure

The four western lateral irrigation lines in the field (figure 1) were operating during the test. Each lateral line contained 11 impact sprinklers on ¾-in (19-mm) diameter risers 18 in (46 cm) in height. Lateral irrigation lines were 60 ft (18.3 m) apart, and sprinklers were 60 ft apart on the laterals (figure 2). Sprinklers were arranged in a triangular pattern, i.e., sprinklers on one lateral were offset 30 ft (9.1 m) from sprinklers on adjacent laterals. Offset sprinklers in adjacent laterals were 67.0 ft (20.4 m) apart. Lateral lines consisted of 3.0-in (7.6-cm) diameter aluminum tubing 30.0-ft (9.1-m) long connected with quick couplers.

Full-circle sprinkler heads were used on the risers in the middle of the field. On the south end of the field, a half-circle sprinkler was located at the end of each irrigation line where

Figure 1. Satellite imagery of test site showing location of irrigation lines (in red) operating during the test. (Source: "Vallonia Nursery" 38°48'06.99"N 86°05'30.91"W, Google Earth, April 4, 2013; accessed May 2014)

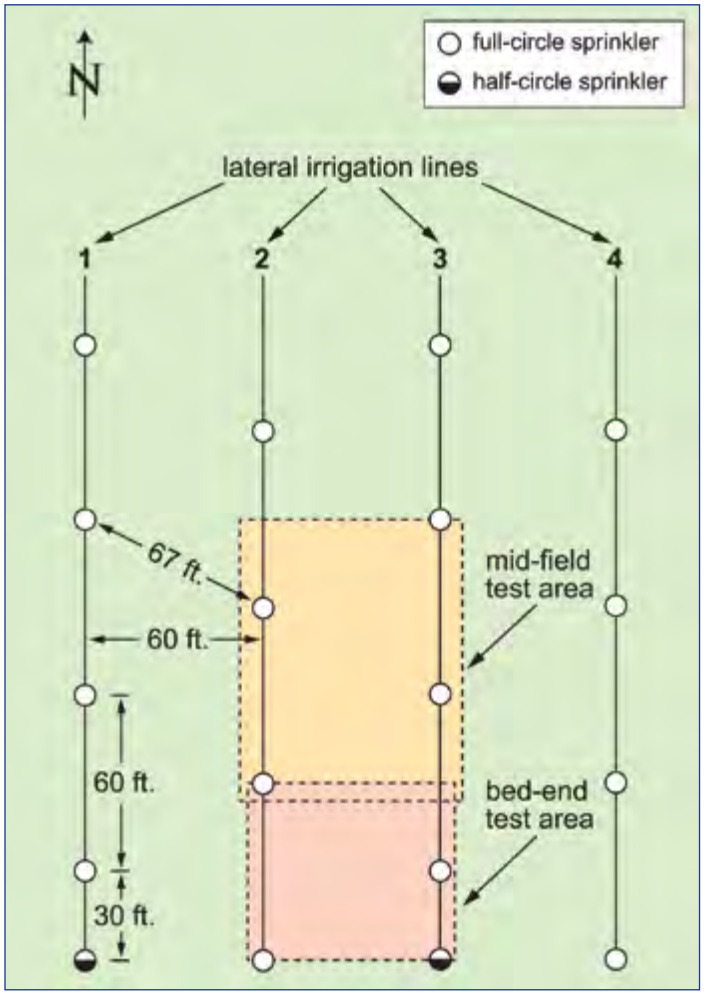

Figure 2. Diagram showing spacing of risers and sprinklers in test areas.

the first full-circle sprinkler was inset 30 ft (9.1 m) from the beginning of the field (figure 2). The purpose of these half-circle sprinklers was to provide more water at the end of the bed to compensate for the lower irrigation rates in these areas resulting from the prevailing south and west summer winds. The full-circle sprinkler heads were Rain Bird® Model 30WH with a 3/16-in (4.8-mm), straight-bore nozzle and a 1/8-in (3.2-mm), 20-degree spreader nozzle. The half-circle sprinklers were Rain Bird® Model 35A-TNT with a 3/16-in (4.8-mm), straight-bore nozzle. Manufacturer's performance data for these sprinklers are shown in tables 1 and 2.

Table 1. Performance data for Rainbird™ 30WH full circle impact sprinkler with a 3/16-in straight bore nozzle and a 1/8-in–20 degree spreader nozzle based on manufacturer's specifications.

Pressure at nozzle (psi)	Sprinkler throw radius (ft)	Flow rate (gpm)
50	50	10.4
55	50	10.9
60	51	11.4
65	51	11.8
70	52	12.3
75	52	12.7

Source: Rainbird (2014a)

Conversions: 100 psi = 6.9 bar; 10 ft = 3.05 m; 10 gpm = 2.27 m^3/hr

Table 2. Performance data for Rainbird™ 35A TNT full or part circle sprinkler.

Pressure at nozzle (psi)	Nozzle size (in)					
	5/32		11/64		3/16	
	Sprinkler radius (ft)	Flow rate (gpm)	Sprinkler radius (ft)	Flow rate (gpm)	Sprinkler radius (ft)	Flow rate (gpm)
50	45	5.0	47	6.0	49	7.2
55	45	5.2	48	6.3	50	7.5
60	46	5.4	48	6.6	51	7.8

Source: Rainbird (2014a)

Conversions: 100 psi = 6.9 bar; 10 ft = 3.05 m; 10 gpm = 2.27 m^3/hr

Collection cups were placed at a 5- by 5-ft (1.5- by 1.5-m) square spacing between the second and third riser lines from the west side of the field (figure 3), starting at the south end of the field and extending north to the fourth riser on the third lateral from the west side of the field (figure 2). A total of 403 cups were used in this test. The cups were 32 oz (0.95 L) round plastic paint-mixing cups with a top opening 4.5 in (11.3 cm) in diameter and 15.6 in^2 (100.6 cm^2) in area.

Figure 3. Cup layout and sprinkler operation during test. (Photo by Ronald Overton 2013)

Water pressure was measured at the first riser in the set by attaching a pressure gauge beneath the sprinkler (figure 4) and by measuring pressure in several sprinklers in each line with a pressure gauge attached to a pitot tube (figure 5). Water pressure at the first riser was 68 psi (4.7 bars) during the test, but fluctuated slightly (1 to 2 psi) (0.07 to 0.14 bars) as a second pump in the system cycled on and off. Pressures measured with the pitot tube gauge at other sprinklers in the set were slightly lower than that of the pressure gauge attached beneath the sprinkler but were within 2 to 3 psi (0.14 to 0.21 bars) of each other. Pressure measured at the end of the nozzle with a pitot tube should not be compared directly with pressure measured with a gauge just beneath the sprinkler, but it is important that pressure differences between sprinklers not vary more than 10 percent of operating pressure or irrigation uniformity will be affected (Irrigation Association 2010).

Figure 4. Measuring water pressure with a pressure gauge installed on a riser. (Photo by Ronald Overton 2014)

The water was turned on at 7:45 a.m. and applied for a total of 69 min. Winds were calm during the test.

Figure 5. Measuring water pressure with a pressure gauge attached to a pitot tube. (Photo by Ronald Overton 2013)

Measurements and Calculations

After the test was complete, the catch (volume of water) in each container was measured using a 250-ml graduated cylinder. Uniformity measures and precipitation rates were calculated for two separate areas of the field: a midfield area farther into the field where only the full-circle sprinklers were depositing water and a bed-end area where the half-circle sprinklers were located (figure 2). Using the cup collection data for the midfield area and bed-end areas (tables 3 and 4, respectively), the following values were calculated from these data using Microsoft Excel software:

1. The average cup catch.
2. The deviations of the individual cup catch from the average cup catch (individual cup catch minus average cup catch). These values for the midfield area are shown in table 5.
3. The absolute deviations of the individual cup catch from the average cup catch, which is calculated by dropping the minus sign from negative deviations in table 5.
4. The average of the absolute deviations of the individual cup catches.
5. The average of the lowest 25 percent of cup catches.

Table 3. Diagram showing position of cups and risers and amount collected (ml) in each cup for midfield area. Lowest 25 percent of cups (65 cups) highlighted in yellow or orange. The upper value (72 ml) of the lowest 25 percent of cups (shown in orange) was shared by 6 cups, 4 of which were included in the 65 cups used to calculate the average catch of the lowest 25 percent of cups. Position of riser = ☐.

Cup number	A	B	C	D	E	F	Cup line G	North ☐ H	I	J	K	L	M	
1	97	92	85	82	76	70	64	79	89	96	76	90	93	☐
2	98	93	86	86	82	76	68	76	84	92	64	80	96	
3	93	88	88	86	80	79	72	72	80	88	64	56	64	
4	89	88	84	86	82	78	72	70	78	82	74	60	59	
5	82	84	78	73	76	76	72	70	76	83	84	80	77	
6	80	86	70	68	70	76	76	78	78	87	90	90	90	
☐7	78	60	58	65	64	66	77	80	80	87	92	104	102	
8	76	54	62	64	60	70	76	83	86	90	98	107	110	
9	50	52	60	59	60	70	76	84	88	92	102	116	113	
10	55	58	58	60	66	71	76	84	84	94	102	112	114	
11	66	56	64	68	68	73	76	86	86	90	100	108	100	
12	80	66	74	76	76	76	78	85	82	90	86	86	92	
13	80	88	84	80	82	82	80	87	84	90	76	87	118	☐
14	97	94	86	86	86	83	84	88	82	87	68	84	85	
15	106	104	96	87	84	32	83	93	88	83	68	62	68	
16	108	110	100	88	80	80	80	90	98	84	70	62	66	
17	102	104	100	85	80	76	64	86	90	89	82	74	70	
18	90	80	86	85	72	74	60	78	86	96	94	90	87	
☐19	89	70	78	85	64	60	62	76	86	102	108	110	118	
20	72	60	80	81	64	52	58	76	92	110	118	125	130	

Table 4. Diagram showing position of cups and risers and amount collected (ml) in each cup for bed-end area. Lowest 25 percent of cups (39 cups) highlighted in yellow or orange. Upper value (86 ml) of the lowest 25 percent of cups (shown in orange) was shared by 4 cups, only 1 of which was included in the 39 cups used to calculate the average catch of the lowest 25 percent of cups. Position of riser = ☐.

Cup number	A	B	C	D	E	F	Cup line G	North ☐ H	I	J	K	L	M	
20	72	60	80	81	64	52	58	76	92	110	118	125	130	
21	66	68	86	80	60	52	54	80	102	122	134	139	140	
22	82	88	86	77	64	57	64	93	110	134	139	141	143	
23	96	94	88	80	64	63	78	114	130	140	136	140	134	
24	109	108	97	86	75	79	98	130	146	151	144	146	130	
25	112	110	96	88	84	96	124	150	158	163	154	148	160	☐
26	114	104	98	94	90	103	129	170	180	180	168	176	190	
27	108	102	96	96	89	100	130	168	184	198	180	174	172	
28	106	94	92	86	84	96	128	172	206	213	196	184	180	
29	99	90	84	78	74	90	128	169	204	218	194	190	192	
30	104	94	80	72	74	94	122	162	194	204	182	171	228	
☐31	116	74	66	63	76	98	121	142	158	158	158	210	219	☐
							South end of block							

Table 5. Deviation of amount collected in individual cups (ml) in midfield test area from average catch of 81.7 ml for all cups in test area. Position of riser = ☐. Cells highlighted with yellow or orange represent the lowest 25 percent of collected volume.

Cup number	Cup line							North ☐						
	A	B	C	D	E	F	G	H	I	J	K	L	M	
1	15.3	10.3	3.3	0.3	– 5.7	– 11.7	– 17.7	– 2.7	7.3	14.3	– 5.7	8.3	11.3	☐
2	16.3	11.3	4.3	4.3	0.3	– 5.7	– 13.7	– 5.7	2.3	10.3	– 17.7	– 1.7	14.3	
3	11.3	6.3	6.3	4.3	– 1.7	– 2.7	– 9.7	– 9.7	– 1.7	6.3	– 17.7	– 25.7	– 17.7	
4	7.3	6.3	2.3	4.3	0.3	– 3.7	– 9.7	– 11.7	– 3.7	0.3	– 7.7	– 21.7	– 22.7	
5	0.3	2.3	– 3.7	– 8.7	– 5.7	– 5.7	– 9.7	– 11.7	– 5.7	1.3	2.3	– 1.7	– 4.7	
6	– 1.7	4.3	– 11.7	– 13.7	– 11.7	– 5.7	– 5.7	– 3.7	– 3.7	5.3	8.3	8.3	8.3	
☐7	– 3.7	– 21.7	– 23.7	– 16.7	– 17.7	– 15.7	– 4.7	– 1.7	– 1.7	5.3	10.3	22.3	20.3	
8	– 5.7	– 27.7	– 19.7	– 17.7	– 21.7	– 11.7	– 5.7	1.3	4.3	8.3	16.3	25.3	28.3	
9	– 31.7	– 29.7	– 21.7	– 22.7	– 21.7	– 11.7	– 5.7	2.3	6.3	10.3	20.3	34.3	31.3	
10	– 26.7	– 23.7	– 23.7	– 21.7	– 15.7	– 10.7	– 5.7	2.3	2.3	12.3	20.3	30.3	32.3	
11	– 15.7	– 25.7	– 17.7	– 13.7	– 13.7	– 8.7	– 5.7	4.3	4.3	8.3	18.3	26.3	18.3	
12	– 1.7	– 15.7	– 7.7	– 5.7	– 5.7	– 5.7	– 3.7	3.3	0.3	8.3	4.3	4.3	10.3	
13	– 1.7	6.3	2.3	– 1.7	0.3	0.3	– 1.7	5.3	2.3	8.3	– 5.7	5.3	36.3	☐
14	15.3	12.3	4.3	4.3	4.3	1.3	2.3	6.3	0.3	5.3	– 13.7	2.3	3.3	
15	24.3	22.3	14.3	5.3	2.3	– 49.7	1.3	11.3	6.3	1.3	– 13.7	– 19.7	– 13.7	
16	26.3	28.3	18.3	6.3	– 1.7	– 1.7	– 1.7	8.3	16.3	2.3	– 11.7	– 19.7	– 15.7	
17	20.3	22.3	18.3	3.3	– 1.7	– 5.7	– 17.7	4.3	8.3	7.3	0.3	– 7.7	– 11.7	
18	8.3	– 1.7	4.3	3.3	– 9.7	– 7.7	– 21.7	– 3.7	4.3	14.3	12.3	8.3	5.3	
☐19	7.3	– 11.7	– 3.7	3.3	– 17.7	– 21.7	– 19.7	– 5.7	4.3	20.3	26.3	28.3	36.3	
20	– 9.7	– 21.7	– 1.7	– 0.7	– 17.7	– 29.7	– 23.7	– 5.7	10.3	28.3	36.3	43.3	48.3	

These values were used to calculate precipitation rate DU_{LQ} and CU using the following formulas (Stetson and Mecham 2011).

- Precipitation rate (in per hr) = [3.66 by average cup catch (ml)]/[run time (min) by area of collection cup opening (in^2).
- Where—
  - 3.66 = conversion factor to convert cup catch volume from ml to in^3 and run time from min to hr.
  - Run time = 69 min.
  - Area of collection cup opening = 15.6 in^2 (100 cm^2)
- DU_{LQ} = average of the lowest 25 percent of cup catches/average cup catch.
- CU = 100 by [1-(average of the absolute deviations of cup catches/average cup catch)].

Results and Discussion

Values for average cup catch, average of the absolute deviations of cup catches, average of lowest 25 percent of cup catches, precipitation rate, lower quarter distribution uniformity (DU_{LQ}), and coefficient of uniformity (CU) statistics for both areas are given in table 6.

Table 6. Average cup catch, average absolute deviation from average cup catch, and average of lowest 25 percent of cup volumes, precipitation rates, lower quarter distribution uniformity (DU_{LQ}), and coefficient of uniformity (CU) for midfield and bed-end areas.

	Midfield area	Bed-end area
Average cup catch (ml)	81.7	120.2
Average deviation from average cup catch (ml)	11.2	37.4
Average of lowest 25 percent of cup volumes (ml)	63.3	71.3
Precipitation rate (in per hr)	0.28	0.41
DU_{LQ}	0.78	0.59
CU (percent)	86.3	68.9

Conversions: 100 ml = 3.4 oz; 1 in per hr = 2.5 cm per hr

Midfield Area

The values for DU_{LQ} (0.78) and CU (86 percent) for the midfield area indicate good uniformity for this type of irrigation system under the conditions of this test, i.e., no wind and sprinklers operating at 68 psi. CU considers deviations above and below the average precipitation rate in determining uniformity and is usually used in agricultural situations. Shearer (1981) recommended a minimum CU of 85 percent for nursery crops. CU values between 80 and 90 percent are usually the best that can be obtained, however, for solid-set systems with impact sprinklers (Stetson and Mecham 2011).

DU_{LQ} is more commonly applied to turf or landscape irrigation situations in which the emphasis is on applying enough water to the driest portion of the area for optimum growth, even if it means overwatering much of the rest of the area (Zoldoske et al. 1994). The DU_{LQ} value can be used to calculate a Scheduling Multiplier (SM) to help judge how much additional water should be applied to compensate for not having a perfect DU_{LQ} of 1.0. The SM provides an upper irrigation run time to consider compared with the lower boundary, or ideal run time, if perfect uniformity existed (Stetson and Mecham 2011). The SM can be calculated from the DU_{LQ} using the following equation (Stetson and Mecham 2011):

$SM = 1/(0.4 + [0.6 \text{ by } DU_{LQ}])$

The SM calculated using the values for the midfield area in this study would be—

$SM = 1/(0.4 + [0.6 \text{ by } 0.78]) = 1.15$

Therefore, if it takes 1 hour to apply an average of 0.28 in (0.71 cm) of water over the midfield area in a system with a DU_{LQ} of 1.0, then a time of 1.15 hours (69 minutes) should be considered an upper run time to actually fulfill this requirement given a DU_{LQ} of 0.78 for this area. The actual run time can be adjusted between the upper and lower run time boundaries based on operator experiences and observations specific to the site (Stetson and Mecham 2011).

The precipitation rate of 0.28 in per hr (0.71 cm per hr) in the midfield area is well matched with the infiltration rates for the sandy loam soil in this field. The basic infiltration rate (the rate which is nearly stable over time) for a sandy loam soil is 0.5 in per hr (1.27 cm per hr), although this rate can vary considerably over time depending on soil cover, organic matter, compaction, and tillage (von Bernuth 2012). Infiltration is higher in drier soil and decreases as water is added. The actual infiltration rate for this field was not determined, but based on the basic infiltration rate for this soil, surface runoff should be minimal at the precipitation rates found in this test.

Bed-End Area

Water distribution uniformity in the bed-end area was poorer than at the midfield area under the conditions of this test, with a DU_{LQ} of 0.59 (versus 0.78 at midfield), and a CU of 69 percent (versus 86 percent at midfield). The precipitation rate at the end of the bed was 0.41 in per hr (1.04 cm per hr), or about 150 percent more than the precipitation rate at midfield. This rate is close to the base infiltration rate for sandy loam of 0.5 in per hr (1.27 cm per hr), noted in the previous section, and, in fact, surface runoff was observed in the bed-end area before the end of the test.

The main reason for the lower uniformity in the bed-end area was the increased precipitation rate in the area covered by the supplemental half-circle nozzle at the end of the lateral located only 30 ft (9.1 m) from a full-circle sprinkler (figure 2). These supplemental sprinkler nozzles were placed at the south end of the field to improve irrigation uniformity at the bed ends during windy periods, because the prevailing wind is from the south and west at this nursery. Because this test was run under calm conditions, it was not possible to determine how well this approach might work.

Increased uniformity of water distribution could be achieved in the bed-end area by better matching the precipitation rates of the full- and half-circle sprinklers. Half-circle sprinklers should have one-half the flow rate of full-circle sprinklers operating in the same zone to provide similar precipitation rates (von Bernuth 2012). The full-circle sprinklers in this system have a flow rate of about 12 gpm (2.73 m^3 per hr) at 68 psi (4.7 bars) (table 1), and the half-circle sprinklers have a flow rate of more than 8 gpm (1.82 m^3 per hr) (estimated, because no data exist for this sprinkler at more than 60 psi [4.14 bars] [table 2]), which is more than 75 percent of the rate of the full-circle sprinklers. The flow rate of the half-circle sprinkler could be reduced to approximately 6 gpm (1.36 m^3 per hr) (estimated based on information in table 2) by using a 5/32-in (4.0-mm) nozzle instead of a 3/16-in (4.8-mm) nozzle. This flow rate would more closely match the precipitation rate for the full-circle sprinklers while still providing coverage of the ends of the fields under windy conditions, although the throw radius of the half-circle sprinkler would be reduced from about 52 ft (15.8 m) to about 46 ft (14.0 m) (table 2).

The uneven spacing of sprinklers will still reduce irrigation uniformity in the bed-end area compared with the midfield area. In addition, the half-circle sprinklers may be operating at more than the manufacturer's recommended water pressure, because no performance data are available for more than 60 psi (4.14 bars). Exceeding recommended water pressure will result in less uniform distribution patterns for these sprinklers (von Bernuth 2012). Beds in this field are about 630-ft (192-m) long, so about 6 percent of the area (the first 40 ft [12.2 m]) is affected by the poorer uniformity.

Irrigation Design Considerations

Watering patterns of irrigation systems are susceptible to distortion by wind speed, wind direction, and changes in wind patterns over time (Solomon 1990). Wind speeds as low as 5 mph can result in considerable changes in water distribution patterns and irrigation uniformity. To improve uniformity during windy conditions, the distance between sprinklers must be reduced, or sprinkler throw diameter increased, as wind speed increases. In the Vallonia Nursery irrigation system, increasing water pressure and using larger nozzles would slightly increase sprinkler throw diameter, but probably not enough to greatly improve uniformity. The main effect of increasing water pressure or nozzle diameter would be to increase precipitation rate.

Solomon (1990) recommends maximum sprinkler spacing of 60 to 65 percent, 50 percent, or 30 to 50 percent of wetted diameter for low (0 to 4 mph [0.0 to 6.4 kph]), medium (4 to 9 mph [6.4 to 14.5 kph]), or high (more than 9 mph) wind conditions, respectively. Full-circle sprinklers in the Vallonia irrigation system have a throw radius of about 52 ft (15.8 m) at 68 psi (4.7 bars) (table 1). Based on Solomon's recommendations, the Vallonia sprinklers should have a maximum spacing of 62 to 67 ft (18.9 to 20.4 m), 52 ft (15.8 m), or 33 to 52 ft (10.1 to 15.8 m) in low, medium, or high wind conditions, respectively. The current spacing of 60.0 ft (18.3 m) between sprinklers on the same lateral and 67.0 ft (20.4 m) between offset sprinklers on adjacent laterals should deliver reasonable uniformity under low wind conditions. Irrigating at higher wind speeds will result in less uniformity. Variable wind patterns during irrigation events may result in more uniform irrigation patterns than steady wind conditions, because the resulting changes in areas of high- and low-precipitation average out (Solomon 1990). Therefore, if irrigation cannot be done under low wind conditions, it may be possible to improve uniformity under variable wind conditions by applying the required amount of water in multiple events. Irrigation under high (> 9.0 mph [14.5 kph]), steady winds should be avoided if possible, because poor uniformity will likely result.

Changing the operating pressure of the sprinklers will affect flow rate and throw, with the larger effect on flow rate (tables 1 and 2) and, hence, precipitation rate. A pressure difference of 10 percent between sprinklers in the same set is considered the maximum allowable for good irrigation uniformity (von Bernuth 2012). Therefore, the total numbers of sprinklers that can be operated and still maintain uniform pressure across a set should be determined for the irrigation system. Open the laterals until pressure differences occur within sets and note the number of sprinkler heads in operation. Irrigation uniformity should be checked under normal operating pressure.

Systematic maintenance of the irrigation system is a key factor in irrigation uniformity (Scholtes 2001, Fernandez 2010). This maintenance includes repairing leaks, keeping risers plumb and sprinkler heads level with the ground, and checking for worn or plugged nozzles and proper sprinkler rotation. Check sprinklers during each watering cycle to make sure they are operating properly.

Irrigation should be scheduled to maintain optimum soil moisture in the rooting zone while reducing surface runoff and percolation beneath the root zone. Although soil moisture availability curves were not determined for this field, sandy loam has an approximate moisture holding capacity of 1.1 in of water per ft (9.2 cm per m) of soil at field capacity (von Bernuth 2012). As a rule of thumb, irrigation is usually scheduled to begin when soil moisture reaches about 50 percent of available water (approximately 1.5 bars of soil matrix potential), because this level is about the point at which growing conditions become less than optimum (von Bernuth 2012). Assuming a rooting depth of about 1 ft (0.3 m), about 1.1 in (2.8 cm) of water is available to plants at field capacity. Irrigation should begin when one-half or 0.55 in (1.4 cm) of water has been removed from the rooting zone by plant evapotranspiration and surface evaporation. The rate of water depletion depends on several factors including temperature, wind speed, and plant size.

The operational irrigation schedule for the Vallonia Nursery is to apply about 2 in (5.1 cm) of water per week. One inch (2.5 cm) of rainfall per week is also considered adequate to meet plant water requirements. Irrigation is increased if temperature or wind is more than normal and rainfall is less than normal. This schedule appears to be sufficient to produce high-quality nursery stock at this site. Some system of more

accurately assessing soil moisture levels may improve the irrigation efficiency (i.e., may do a better job of adjusting irrigation rates to apply only enough water to maintain optimum moisture levels in the root zone). Because rainfall is fairly well distributed during the growing season at this nursery, however, increased irrigation efficiency may not affect plant quality here as much as in nurseries where irrigation supplies a larger proportion of plant water needs. Increasing efficiency will reduce operating expenses, such as pumping and fertilizer costs, to the extent that present irrigation practices are overwatering (and leaching fertilizer or other chemicals from the root zone) or poor irrigation system maintenance is affecting irrigation uniformity. Increased efficiency will also reduce runoff and water pollution to the extent the current practice is overwatering.

Lessons Learned

Cup spacing could be reduced when assessing irrigation uniformity. Calculations of CU, DU_{LQ}, and precipitation rate based on cups spaced 10 by 10 ft (3 by 3 m) and 15 by 15 ft (4.6 by 4.6 m) were similar (table 7), although differences were slightly greater in the less-uniform bed-end area. A minimum grid spacing of one-third to one-fourth of the average sprinkler spacing is recommended for impact sprinkler systems in which sprinklers are 40 ft (12.2 m) or more apart (Setson and Mecham 2011). Based on this recommendation, a spacing of 15 by 15 ft is the greatest that should be used in this nursery. A spacing of 10 by 10 ft may provide a more accurate estimate than the 15 by 15 ft spacing if irrigation uniformity is poor.

For the area in this test, 5 by 5 ft, 10 by 10 ft, and 15 by 15 ft spacing required a total of 403, 112, and 55 cups, respectively. A good strategy for future tests would be to use cups at wider spacing distributed in subgroups in several areas of the field. The number of cups in the test, and in the subgroups, should be divisible by four to make it easy to calculate DU_{LQ}.

Table 7. Comparison of coefficient of uniformity (CU), lower quarter distribution uniformity (DU_{LQ}), and precipitation rate calculated from different cup spacings.

Cup spacing (ft)	Midfield			Bed-end area		
	CU (%)	DU	Rate (in per hr)	CU (%)	DU	Rate (in per hr)
5 by 5	86.3	0.78	0.28	68.9	0.59	0.41
10 by 10	86.0	0.78	0.28	70.3	0.58	0.41
15 by 15	85.2	0.76	0.29	71.9	0.59	0.43

Conversions: 5 ft = 1.5 m; 1 in per hr = 2.5 cm per hr

At the end of the cup test, cups near sprinklers should be covered directly before turning off the water to prevent collecting excess water draining from sprinklers.

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ADDITIONAL RESOURCES

The Irrigation Association offers a variety of online and traditional face-to-face classes on various irrigation subjects and a number of technical references on irrigation. More information is available at the Irrigation Association Web site at https://www.irrigation.org.

Beyond Cowboy Science: Simple Methods for Conducting Credible and Valid Research

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Abstract

Many nursery and field trials are conducted every year to test new products and techniques. Some of these trials, however, can produce data that are too variable or confounded to accurately assess the question(s) of interest. A "cowboy science" approach can yield results that are statistically invalid and biologically untrue; using such data can lead to erroneous conclusions. By incorporating a few basic principles of study design and data collection, anyone can yield credible data that can be used to answer questions or make decisions. Despite beliefs to the contrary, using a valid experimental design usually requires little or no additional input of time and resources, nor does it require an in depth understanding of statistics. Good study design also ensures that the time and resources invested in research yields meaningful results. This article describes the "Three Rs" of study design—representation, replication, and randomization—along with examples of pitfalls and successes. It also describes how to create a study plan to guide effective research in the nursery or the field. An earlier version of this article was published in the 2013 *National Proceedings: Forest and Conservation Nursery Associations* (Haase 2014).

What Is Cowboy Science?

The term "Cowboy Science" was coined many years ago by northwest foresters to refer to "quick and dirty" trials or "demo plots" established operationally to evaluate a technique or treatment (Rose 2000). In no way is this term meant to be derogatory to cowboys—quite to the contrary. This term is a nod to the stereotypical cowboy's independence and resourcefulness in solving problems. Many foresters and other field professionals lack the background or confidence to set up a research project based on statistical theory and design, but most have the intelligence, professional curiosity, and creativity to practice Cowboy Science on occasion. Over the decades, an enormous amount of time, land, and resources has been dedicated to investigating seedling growth in the nursery and after outplanting in response to new products or techniques.

Cowboy Science can be helpful for generating some preliminary observational data used for initial exploration of simple research questions. Such data, however, are considered "anecdotal" and insufficient to adequately or accurately assess the question at hand. Drawing conclusions from such data can be risky.

Risks Associated With Cowboy Science

The inherent characteristic of Cowboy Science is its disregard for experimental methods designed to generate valid data for addressing study objectives. This approach can yield results that are statistically invalid or biologically untrue. Using such data can lead to erroneous conclusions. Using flawed results is especially problematic (and costly) when making management decisions.

Example 1

Cowgirl Jane set up a nursery study to test two products that the manufacturer claims will increase root growth. She applied the products to two nursery beds in an out-of-the-way area of the nursery. Each nursery bed had seedlings from a different low-demand seed lot. She chose these seed lots because she did not want to take the chance of having a negative effect on one of the seed lots she regularly grows in the nursery. She applied Product A to one nursery bed and Product B to the adjacent nursery bed. After several months, she measured 50 of the largest seedlings in each bed and found that those treated with Product B grew more than those treated with Product A. Based on this result, she decided to order Product B for her entire crop. So, what is the problem with Cowgirl Jane's study?

Cowgirl Jane's study design has several problems. To begin with, conditions in the study area were not uniform. Each nursery bed has a different seed lot, and the irrigation patterns result in one bed receiving more water than the other (figure 1). The growth differences she observed could have been due to differences in seed lot or water availability and therefore have nothing to do with the products she was testing. In addition,

because the treatments were applied to seed lots that are infrequently grown and the study was carried out in an infrequently used area of the nursery, it would be unwise to assume that other seed lots in other areas of the nursery will respond similarly to the treatments. Another issue is that she did not include a control treatment, which leaves no way to determine if using either of the products results in better or worse root growth than what she does already. Furthermore, data were collected only on the largest seedlings, so it is difficult to conclude that the treatment difference is likely to occur throughout the group of seedlings.

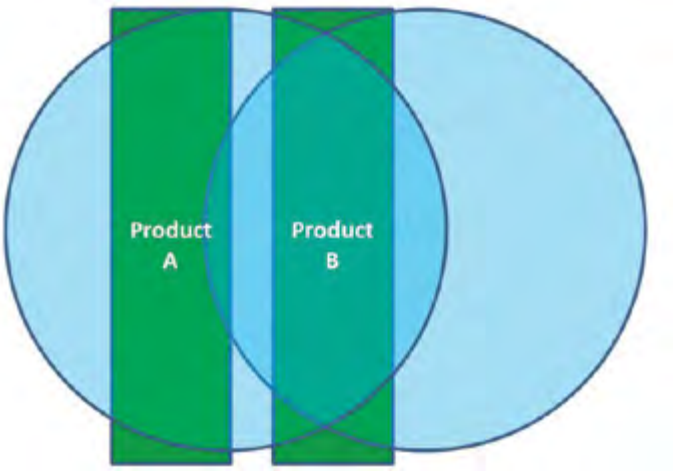

Figure 1. In this Cowboy Science example, a study was installed to compare effects on seedling development of Products A and B applied to two nursery beds. Irrigation patterns, different seed lots, and the lack of a control treatment, however, resulted in confounding and an inability to accurately assess responses to the two products.

Example 2

Cowboy Joe set up a study to compare growth of seedlings from five different nurseries.

He established five plots (one per nursery), each with 100 seedlings, on his site. He chose a typical reforestation site to ensure that the study simulated his operational practices. From the onset, he was confident that seedlings from Nursery C or Nursery E would outperform the others. After 3 years, he found that seedlings from nursery C grew the most and decided to sign a large contract with that nursery. So, what is the problem with Cowboy Joe's study?

The problem with the study design that Cowboy Joe used is similar to the problem with Cowgirl Jane's study design in Example 1—conditions in the study area were not uniform. Because of the variability on the site, conditions in some of Cowboy Joe's plots were more favorable for seedling growth compared with conditions in other plots. Part of the study area was covered with a berry thicket, another part was where a burn pile had been located, and another part was adjacent to a mature forest resulting in increased browsing and shading (figure 2).

This study design is akin to the adage of having all of one's eggs in one basket—if something goes wrong in one plot, then the study is irreparably compromised. For example, if most of the seedlings in the plot adjacent to the mature forest are severely browsed, then that plot, containing all the seedlings from one of the nurseries, is effectively eliminated from the study. In addition to the site having observable variation, it could also have hidden factors such as gradients in soil depth, moisture, fertility, texture, and drainage.

Given the variability on the site, it would be risky for Cowboy Joe to conclude that seedling performance from one nursery is superior to seedlings from other nurseries when, in fact, site conditions may be the primary factor influencing differences in growth and survival among the plots. Furthermore, Cowboy Joe's prejudice in favor of two of the nurseries may have inadvertently swayed the study setup and data collection.

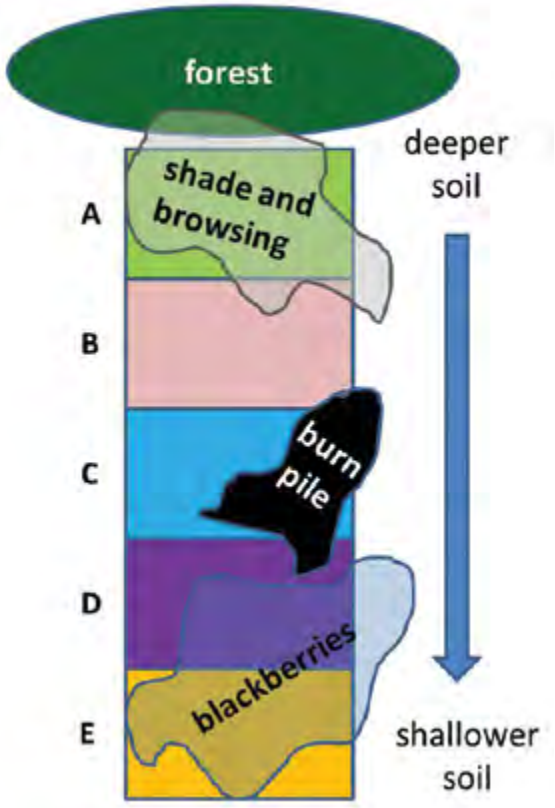

Figure 2. In this Cowboy Science example, five plots were established on a field site to compare seedling growth from five different nurseries (A, B, C, D, and E), but variation in site conditions likely had a greater influence on field performance than the originating nursery. Data from this study design can lead to incorrect conclusions and faulty management decisions.

Confounding and Bias

Regarding study design, confounding and bias can be defined as follows (Dictionary.com 2013a, 2013b).

Confounding—

- To throw into confusion or disorder.
- To treat or regard erroneously as identical.
- To mix or associate by mistake.
- To mingle so that the elements cannot be distinguished or separated.

Bias—

- A tendency or inclination, especially one that prevents unprejudiced consideration of a question.
- A systematic distortion of a statistic as a result of sampling procedure.
- To cause partiality or favoritism in.
- To influence, especially unfairly.
- Selectivity in a sample that influences its distribution and so renders it unable to reflect the desired population parameters.

In Cowboy Science, confounding and bias can result in differences among treatments that are not actually due to the treatment. In Example 1, it is impossible to isolate the influences of irrigation pattern, seed lot, and treatment application because those factors are confounded with each other. Furthermore, data in Example 1, collected only from the largest seedlings, resulted in a biased dataset. In example 2, the effects of nursery source were confounded with the site conditions and the researcher's bias toward the study's outcome may have influenced its design and outcome.

Other Pitfalls of Cowboy Science

In addition to confounding, the Cowboy Science approach often has other aspects that can result in misleading, erroneous, or limiting conclusions. Some of these aspects are—

- **No control treatment**—any study should include a control treatment that enables one to determine how much better (or worse) the new method is compared with the usual way.
- **No study plan**—any study, small or large, needs to have a written plan regarding the objectives, methods, measurements, etc. This plan is important to stay on track and to keep others informed, especially if the person who set up the study is unable to continue it to completion.
- **No labeling or mapping**—the study needs to be clearly labeled and mapped so that it can be revisited for future measurements without any questions regarding plot and treatment identification.
- **No follow-through or maintenance**—it is a waste of time and effort to set up a study only to abandon it later because of changes in personnel, poor time management, lack of documentation, or inadequate maintenance of the plots.
- **Too many treatments**—trying to compare too many treatments or treatment combinations (e.g., several species treated with different fertilizer types applied at different rates) can lead to data from which making any meaningful conclusions is challenging.
- **Too few trees per treatment**—the study needs to have enough trees (or other study subjects) in each treatment to generate an adequate amount of data from which averages and differences among averages can be calculated with confidence.
- **An emphasis on being "operational"**—although the study objective is to generate results that can be applied to operational practices, using an operational approach when conducting the study can result in excess variation. Any variation not attributable to the treatments or subjects being studied makes it difficult to isolate treatment effects and determine the maximum response potential.

Variation Is the Key

Setting up a study of any kind is all about controlling sources of variation. In fact, variation is the basis of most statistical calculations—analyzing variation within and among different groups to determine whether or not the groups differ from one another. For example, if you wish to compare heights for two groups of seedlings (such as groups by species, treatment, or some other factor) and the average height is 22 in (56 cm) for one group and 17 in (43 cm) for the other group, you would then examine the variation to determine if those two groups truly differ in height. If very little variation exists in the data (e.g., most height measurements within each group fall within 1 to 2 in [2 to 5 cm] of their respective group's average), then the conclusion would likely be that the two groups are different. If the data vary quite a bit (e.g., some height measurements are much higher and some are much lower than the average), then a lot of overlap is likely between the two groups and you cannot conclude that the two groups truly differ in height.

To generate valid and useful data, it is essential to maximize its accuracy and precision (figure 3), both of which can be significantly affected by how the study is designed and implemented. Variation created by bias, confounding, or outside influences can generate data that is inaccurate or inconclusive. Ultimately, the only desired source of variation is the variation resulting from the treatments or other factors being studied; everything else is "noise."

Because variation plays a fundamental role in the ability to compare different treatments or other factors, proper study design is critical. Understanding and controlling the causes and magnitude of variability are the keys to generating data that can be used to make valid conclusions about the treatments or other factors being studied.

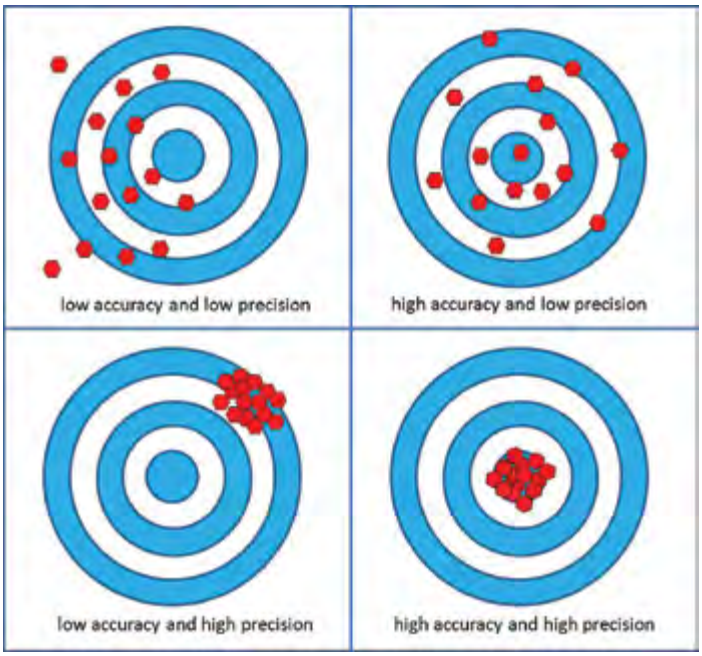

Figure 3. A good study design strives to eliminate bias, confounding, and other sources of variation to isolate treatment effects with accuracy and precision.

Treatments

The treatment is the one factor that is intentionally changed for the sake of the experiment. It is the factor that is expected to create a response. For example, a treatment could be fertilizer rates, fertilizer formulations, growing media components, species, seedling stock types, seed lot, planting method, or other treatments. All other factors must stay the same to be able to isolate responses to the treatment in question. So, unless the intent is to compare seed lots, species, planting dates, etc., all other factors must be the same throughout the study.

Control Treatment

Including a control treatment is an essential component of experimentation. The control treatment is the usual method of doing something. It is important to have a control treatment so responses to the modified method can be compared with the usual method.

Some studies may include two control treatments: (1) the "do-nothing control" (in which no product is applied) and (2) the "operational control" (in which the usual product or treatment is applied). Having an operational control is most common with pesticide trials in which new pesticide treatments are compared with the currently used pesticide and with a control treatment in which no pesticides are used.

Factorial Treatments

Studies can also be designed to evaluate two treatments (factors) at the same time. For example, fertilizer would be factor A and stock type would be factor B. Factorial study designs enable you to determine if interactions occur between the two factors: Is the response to fertilizer the same for every stock type? For the design to be valid, all combinations of the two factors must be included. For instance, if three fertilizer rates (factor A) and three seedling stock types (factor B) are used, then a total of nine treatment combinations need to be included in the study (three rates by three stock types). A control level for each factor must be included as well.

Number of Treatments

Although it may be tempting, including more than two factors or more than 10 treatment combinations will not increase the usefulness of a study. Keep it simple—do not include too many treatments and do not go beyond two factors. In fact, increasing the number of treatment comparisons in a study increases the odds of finding a difference when one does not exist. Furthermore, three-way (or more) interactions are very challenging to quantify and interpret. It is better to establish additional studies rather than try to answer too many questions in a single study.

The Three "Rs" of Study Design

After the objectives have been defined for a study, details about the experimental design need to be established. A good study design does not have to be complicated, but all study designs need to incorporate the "Three Rs"—randomization, replication, and representation. These Three Rs are important tools to control variation and generate valid data that can help answer the questions posed by the study.

Randomization

Randomization is the circumstance in which each experimental unit in the study has the same chance of being assigned to any of the treatments. The experimental unit is the basic unit to which the treatments are applied. This unit must be clearly defined (e.g., individual trees, rows of trees, a pallet of seedlings, a field plot, a greenhouse bench, a nursery bed, a greenhouse). Individual trees are good for short-term studies in small areas with relatively uniform conditions. Plots are usually best for forest or nursery studies. The most common plot configurations are row, square, or rectangle plots. Square and rectangular plots are usually better for longer term studies because they create a very small depiction of how the area would be if it were all treated in the same manner, whereas row plots will have a greater influence from adjacent rows.

Randomization prevents bias, which can be defined as any process that tends to produce results or conclusions that differ systematically from the truth. For instance, if treatments A, B, and C are assigned from left to right to a series of plots, then B is always left of A, and C is always left of B. When a gradient in the soil exists or sunlight moves from left to right, then the trees might respond systematically different because of factors other than the treatment in question.

The following examples are some other approaches that result in a biased study.

- "This plot looks weedy; let's put the vegetation control treatment here."
- "This area is close to the road; let's install the fertilizer treatments here so we don't have to carry it up that hill."
- "These seedlings are smaller than the others; let's put them in the plot with the highest irrigation treatment."
- "These seedlings have nice foliage; let's choose them for foliar sampling."

To implement randomization, assign treatments to trees or plots using a random, nonbiased method. Randomization can be accomplished by rolling a die, drawing a playing card, using a random-number generator, drawing treatment names or numbers out of a hat, or other methods. To save time and avoid on-the-ground bias, it is best to plan randomization in the office before implementing the study in the nursery or field.

Replication

Replication is the most often neglected, yet most important, component of study design. Replication provides the ability to measure variation whether it is due to the treatments, the study subjects, or the physical conditions on the site. Failure to replicate renders it impossible to make valid comparisons between treatments. Without replication, all you have is a one-time event that may or may not be repeatable. For instance, if a cowboy successfully rides a bucking bull one time, how confident can we be that she or he will do so from now on? Making management decisions on unreplicated data is as risky as gambling on the rodeo cowboy who has ridden the bull only once.

Replication is achieved by applying each treatment to more than one experimental unit. As described in the previous section, experimental units can be individual trees but are more often field plots, nursery benches, or other units composed of several seedlings. It is important to distinguish that the trees within a plot (or other multitree unit) are the sampling units, whereas the plot itself is the experimental unit. The most common mistake regarding replication occurs when the sampling units are regarded as replicates when, in fact, they are not. This error results in pseudo-replication.

Statistical procedures exist for determining the ideal number of replicates for a given study based on how much variance is expected. Statistical calculations are beyond the scope of this article, however, and mathematical determinations of study size are not often used for field studies. The most important thing to know is that more replicates are always better than less. Having more replicates (while still keeping the study at a manageable size) increases the study's ability to detect any significant differences among groups. When determining the number of replicates and plot size (number of sampling units), various factors, such as expected survival, duration of the study, and type of measurements (nondestructive versus destructive), need to be considered. When individual trees are used as replicates, I recommend a minimum of 25 trees in each treatment (50 or more if possible). When plots are used, I recommend a minimum of four plots per treatment, each with a minimum of 10 trees. As stated previously, however, more is better; the study design I have used most often is five plots of 25 trees per treatment.

Representation

Common sense tells us to compare apples with apples rather than apples with oranges. This approach is also a basic tenet of good study design. When designing a study, be aware of its "scope of inference"—the population and circumstances to which the results can be applied. The study should be conducted such that the results are applicable to the specific trees or situations of interest. For instance, if the objective is to apply the study results to pine trees on high-elevation sites, then it would be imprudent to conduct the study with oak trees or on low-elevation sites because oak trees and low-elevation sites do not represent the situation defined in the study objectives.

To ensure that the study design is adequately representative, select treatments, experimental materials, sites, timing, and situations that best represent the desired scope of inference. By ensuring representation, you can confidently apply the results to specific populations and circumstances.

Incorporating the Three "Rs" Into Study Design

There are numerous study designs. For purposes of this article, however, I will describe the two most common designs used in reforestation and nursery studies.

Completely Randomized Design

The completely randomized design (CRD) is one of the simplest study designs. A representative population of trees (or other study subjects) and site(s) are designated for the study. Within the representative population, trees are randomly selected to be included in the study. These trees are then replicated by individual trees or in plots and randomly assigned to a treatment (figure 4).

CRD should be used only in situations in which conditions on the study site are expected to be homogenous (e.g., inside one area of a greenhouse, in a bareroot nursery field, on a flat outplanting site with consistent ground cover). Although CRD is simple and efficient, it is not often used, because researchers are often uncomfortable assuming that conditions in their study area are truly uniform.

Randomized Complete Block Design

The randomized complete block (RCB) design is the most common design used in nursery and reforestation studies. This

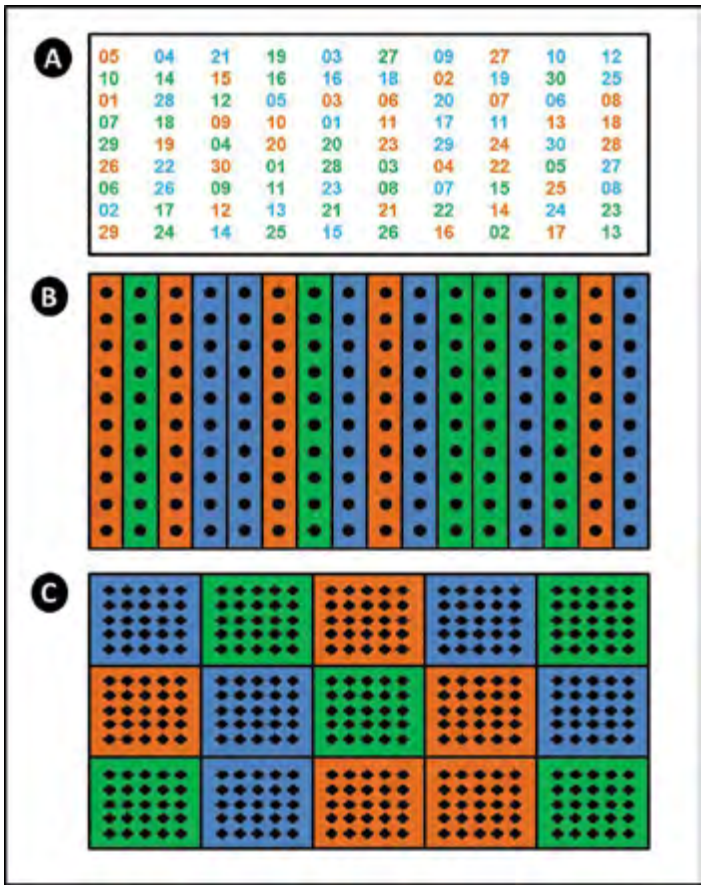

Figure 4. Examples of completely randomized designs to assess three treatments (illustrated here with three colors) using single tree replicates (A), row plots (B), or square plots (C).

study design can be used under variable conditions (e.g., typical outplanting sites, different soil types in a nursery, a series of greenhouses). As with the CRD, representative study site(s) are chosen and trees (or other study subjects) are randomly selected from a representative population to be included in the study. These trees are then replicated into treatment plots. One plot of each treatment is then grouped into a block. Trees are randomly assigned to each treatment plot and treatment plots are randomly assigned within each block (figure 5).

Each block in a RCB design is a replicate. For this design to be effective, conditions within each block should be as homogenous as possible but conditions among blocks can vary significantly. Blocks can be located adjacent to one another, spread throughout the site (figure 5), or even established on different sites. Blocking should be based on any condition or gradient that could affect treatment responses (e.g., slope, drainage, soil type, aspect, vegetation).

The great advantage of blocking is the ability to perform simple statistical analyses that can isolate the variation due to the treatments in question from the variation due to differences in

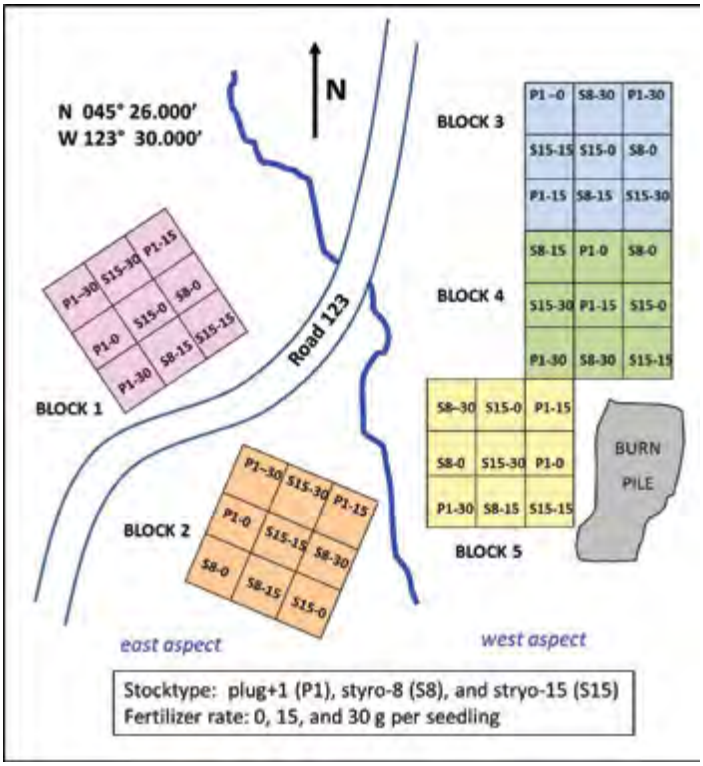

Figure 5. An example of a randomized complete block design with five blocks, each containing nine treatment plots. Note that this example shows three-by-three factorial treatments: three stock types (P1, S15, and S8) and three fertilizer rates (0, 15, and 30g [0.0, 0.5, and 1.0 oz]). This illustration is also a good example of mapping the site location and layout.

conditions among blocks (i.e., it can separate treatment effects from block effects). The RCB is actually a stronger design than the CRD because the treatments can be compared under a wider range of circumstances; if relative treatment responses are similar in all blocks, even though the rate or magnitude of response may vary due to block conditions, conclusions about treatment effects can be made with even greater confidence.

Example 1 Revisited

In Example 1, Cowgirl Jane's study to test two products in her nursery had a variety of issues (figure 1). First, her treatments were confounded with seed lot and with the irrigation pattern in the two nursery beds. Second, the seed lots and test location were not representative of the crop to which she would like to apply the treatments operationally. Third, she did not include a control treatment to allow for determination of whether either of the treatments truly is better (or worse) than her existing practices. Last, data were collected only on the largest seedlings.

By incorporating the Three Rs into the study design, Cowgirl Jane's study can be improved greatly. The treatments need to be applied to one representative seed lot in a representative location of the nursery. She can plan ahead to ensure that excess stock will be available for the study. If she expects seed lots to respond differently to the treatments and wants to include more than one seed lot in the study, then seed lot will need to be a second factor included in the study design (see section describing factorial treatments). She needs to add a control treatment to the study design and she needs to replicate the treatment plots. If she chooses an area that is relatively uniform (same irrigation pattern, cultural regime, etc., throughout), then she could set up the study in a CRD (figure 6A). Because variation in soil or other factors can be hidden, however, she may prefer to set up the study in a RCB (figure 6B). Regardless of the study design she uses, the treatments need to be randomly assigned to each plot. These changes to her study design will result in a valid dataset that can isolate the seedling responses to the applied products and determine if they improve crop performance relative to the control. When it is time to collect data, she must randomly select seedlings for measurement from each treatment plot to avoid bias (see later section on Data Collection).

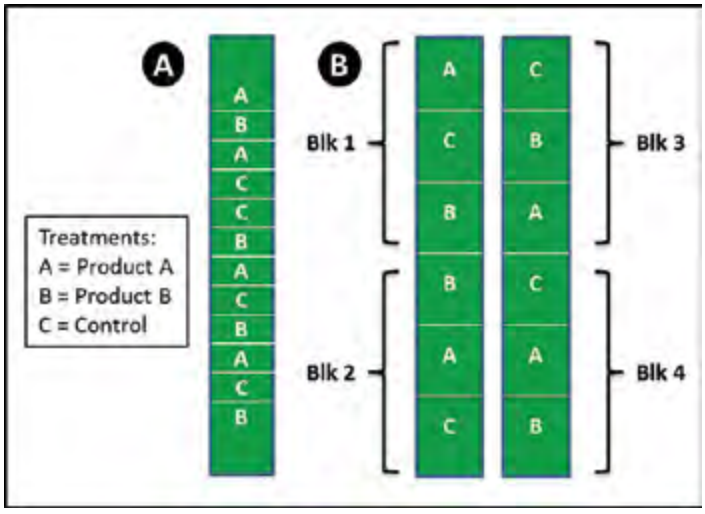

Figure 6. The study design shown in figure 1 can be modified to incorporate representation, randomization, and replication in a completely randomized design (A) or in a randomized complete block design (B) to compare seedling responses to applications of Product A and Product B, thereby eliminating excess variation and confounding. In addition, a control treatment has been added to determine if either of the treatments is better or worse than the existing method.

Example 2 Revisited

How can Cowboy Joe incorporate the Three Rs to improve his study design (figure 2)? Because a great deal of variation exists on his site, a good start would be to take steps to reduce variation as much as possible in the study area. He can establish the study plots away from the mature forest to reduce browsing and shading influences. He can also exclude the burn pile from the study area. In addition, he can take measures to control the blackberries. These extra efforts are above and beyond operational practices but are necessary to eliminate excess variation, thereby increasing the data's accuracy and precision. Cowboy Joe cannot rid the site of all variation (such as soil depth) but, by using an RCB design with five replications (blocks) and 20 seedlings in each treatment plot, he can better isolate seedling growth differences due to nursery of origin from growth differences due to site conditions (figure 7). He can also eliminate his own bias about the study outcome by randomly assigning seedlings to plots ahead of time.

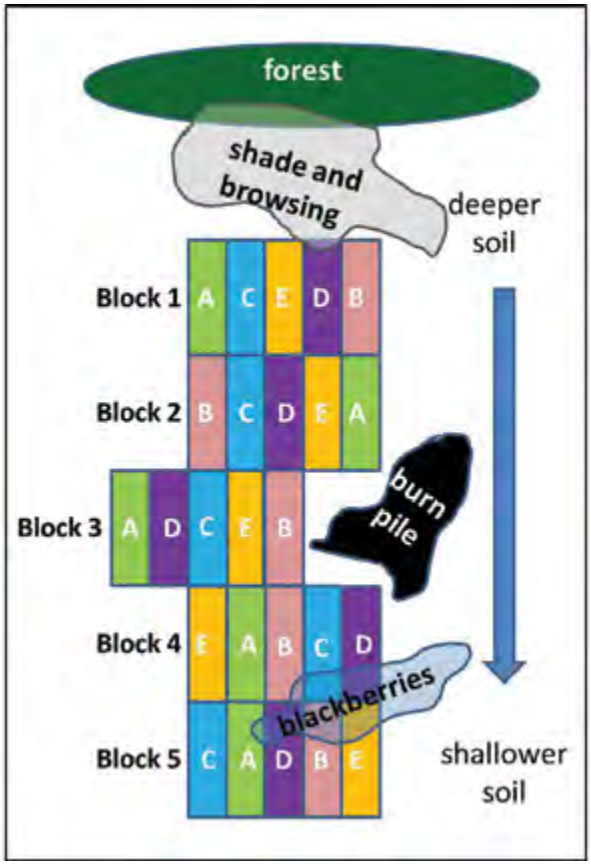

Figure 7. The study shown in figure 2 can be redesigned so that any field performance differences due to nursery of origin (A, B, C, D, and E) can be isolated from variation in site conditions. A randomized complete block design positioned away from known sources of variation or damage along with some vegetation control can improve the quality of the data generated. Note that the revised study design requires the same amount of space and seedlings as the original design.

Note that Cowboy Joe's revised study design requires the same amount of space and seedlings as his original design. The assumption that proper study design is costly and time consuming is a misconception and is usually not true. The reality is that poorly designed studies can waste 100 percent of the time and resources invested and can lead to additional unnecessary costs if management decisions are predicated on flawed data.

Elements of a Study Plan

Any study should start with a study plan. This document should read like a recipe that anyone can follow from start to finish. The plan needs to be clear, concise, and specific. It does not have to be lengthy, but it should contain sufficient detail so the purpose and methods are clearly understood. The study plan enables you to think ahead and plan all aspects of the study. Important elements of a study plan are described in the following sections.

Define the Problem and State the Objectives

The first step is to describe the issue at hand and the purpose of the study. If the problem cannot be defined, it will be difficult to solve. A paragraph or two about the problem (history, symptoms, magnitude, consequences, etc.) and the proposed solution will provide the necessary background and justification for the study. With that information, the study objective statement can be formed. For example, "The objective of this study is to determine the effect of four fertilizer treatments on first- and second-season growth and survival of Douglas-fir plug+1 seedlings outplanted on a coastal site."

Describe the Experimental Material and Study Site

The material selected must be representative of the population in question. For example, "Plug+1 Douglas-fir seedlings (seed lot 123-456, seed zone 071), sown in 2014 at the WeGrow Nursery (Trees, OR), and grown under standard nursery procedures will be used for this study." Likewise, the site should be representative of the environment associated with the problem and objectives. For example, "Seedlings will be outplanted to a site 5 miles NW of Research City, OR, at an elevation of 1,300 feet. The site was harvested in 2011 and prepped in 2012 by broadcast burning."

Describe the Treatments

Treatments included in the study should be specific to the problem and objectives. Details about each treatment need to be given. For example, "Four fertilizer treatments will be included in the study: (1) unfertilized control, (2) 10-25-4 (N-P-K), (3) 17-17-17, and (4) 15-9-12. Fertilizers are controlled-release (16-month rate) and manufactured by NPK Company (Nutrientville, CA). Fertilizers will be applied once at the time of outplanting, at a rate of 12 g (0.42 oz) per seedling."

Define the Experimental Design

It is best to use the simplest design that will yield data that can be used to meet the study objectives. Randomization and replication must be outlined. For example, "Seedlings will be outplanted in a completely randomized block design. Six blocks, consisting of four treatment plots with 25 seedlings each, will total 600 seedlings for the study."

Describe the Installation

A good description of study installation specifies dates, labor, equipment, supplies, and any other details associated with establishing the study site. For example, "The study will be planted in February 2014. Color-coded pin flags will mark each planting spot and each seedling will be tagged with block and treatment. Four planters will be needed to install the study and will be monitored for quality. A detailed map of block and plot layout on the site will be prepared."

List the Desired Data and How They Will Be Collected

Describe the data that are to be collected on the study including the procedures, timeline, and tools. For example, "Within one week of planting, all seedlings will be measured for initial height and stem diameter. Foliar samples will be collected in July 2014 from a branch in the upper half of three randomly selected seedlings in each treatment plot and analyzed for concentrations of N, P, K, Mg, and B. Nutrient analyses will be conducted at Ion Lab, Ltd. (Bunson, ID). At the end of each growing season from 2014 to 2017, all seedlings will be measured for height (groundline to base of terminal bud), stem diameter (0.4 in [1 cm] above groundline), and survival."

Describe How the Data Will Be Analyzed

The sources of variation and method of analysis should be determined ahead of time to ensure that the experimental procedures will generate the answers sought. For details, see the Data Analyses subsection of this article that follows in the Conducting the Study section.

Describe Study Maintenance and Duration

Consider all resources and tasks necessary for the entire study duration. Include necessary annual activities other than data collection. For example, "Competing vegetation will be controlled with herbicide for the first three seasons after planting. Plastic mesh tubing and seedling tags will be checked on each measurement date and moved as needed to avoid damage and growth restriction."

List the Expected Outcomes

Explain how the study results will be used to address the objective, make management decisions, and determine future research needs. For example, "Results of this study will be used to determine if fertilization at the time of planting yields growth increases sufficient to warrant widespread use of fertilizer on Douglas-fir seedlings. A report of this study will be presented at the 2016 Company Board meeting and an article will be prepared and submitted to *Tree Planters' Notes* for publication."

Conducting the Study

Good study design and a detailed study plan can be rendered meaningless if a study is not set up or measured carefully. Use the study plan to guide every step of the study; if anything must be changed, record it in detail. Avoid introducing bias, confounding, or excess variation during study installation or measurement.

Study Installation

After a study site is selected, the plots should be laid out ahead of time. For an outplanting study, all seedlings should be handled and planted very carefully using experienced planters. As much as possible, the study site should be protected from outside influences that can create more variation and mask potential treatment responses. If browse is anticipated, then the site should be fenced or seedlings protected with mesh tubing. If adjacent treatments have the potential to influence each other, minimize this effect by installing border rows or buffer strips between treatment plots.

The following example illustrates how confounding was inadvertently created during a study installation: A study plan was developed to compare seedling responses to two different fertilizer treatments and an untreated control using a CRD. The relatively uniform site was laid out ahead of time in a random arrangement of 100 white, blue, and yellow pin flags. In an effort to simplify the planting process, one planter was given a bag of seedlings and a bucket of one fertilizer type to plant at each blue pin flag, another planter was given a bag of seedlings and a bucket of the other fertilizer type to plant at each yellow pin flag, and the third planter was given a bag of seedlings and no fertilizer to plant at each white pin flag. This idea seemed good until the forester measured initial height and stem diameter 1 week later and discovered that seedlings in one treatment had a shorter average height than the other two treatments. Because all the seedlings were from the same seedlot and nursery, and because the sample size was sufficient, this result was unlikely at the onset of the study because treatments could not yet have an influence on seedling size. It turned out that one planter tended to plant deeper than the other two planters, resulting in shorter measured heights. To prevent this confounding, the planting could have been done using a single planter or by having each planter plant one-third of the seedlings within each treatment.

Data Collection

As with all other aspects of planning and conducting the study, taking measurements must be done carefully to ensure accuracy and ease of interpretation. Be consistent when taking measurements (tool used, time of year, and so on). It is best to measure under ideal conditions if possible; avoid worker fatigue or severe weather conditions to help ensure data quality. Do not introduce any confounding or bias during measurement (some examples—one person measures all of one treatment, some treatments are measured earlier than others, or stem diameter is measured higher up on the stem of trees growing in prickly vegetation).

Initial tree size (or other characteristics of interest) should be measured as soon as possible after the study is installed. These initial data are the benchmark for calculating subsequent changes during the study. Be careful not to damage trees during measurement; broken tops from handling or girdled stems from calipers will result in negative effects on those trees that are not due to the treatment.

If possible, enter data into a spreadsheet on a handheld field device as it is collected. If a handheld device is not available, then carefully enter the data into a computer as soon as possible after it is collected. All data for a single study need to be in the same spreadsheet so they can be easily analyzed (table 1). Too often, people make multiple spreadsheets for different treatments, different measurements, different dates, and so on. Data in multiple spreadsheets, however, cannot be imported into statistical software programs and can be unnecessarily confusing.

In addition to collecting measurement data on the study subjects, record anything else, such as weather events, unusual observations, and annual precipitation that may have an influence on the study. Also, take numerous photos during the study setup and on each measurement date.

Data Analyses

A well-designed study that has been carefully conducted will generate quality data for analyses. Most data for simple field studies as described in this article are analyzed using Analysis of Variance (ANOVA). Many field and nursery personnel, however, do not have the time or inclination to learn statistical methods nor do they have access to statistical software. Consequently, data sets can sometimes languish or are analyzed using only simple calculations in a spreadsheet. When developing the study plan, it is wise to partner with another person within the agency or company who has a statistical background, with someone outside the company or agency who has statistical experience and would like to collaborate on the study, or with someone in academics (professor, student, or extension agent) who can assist with data analyses.

Study Longevity

Accessibility to the site should be available for the duration of the study. A detailed map of the study layout including global positioning system coordinates, roads, and other major site features is indispensable (figure 5). Also, lasting identification of plot boundaries and individual trees is essential. Pin flags are useful for study layout but can fade over time or be hard to locate after vegetation establishes on the site. Labeled wooden or metal fence stakes can be used to mark the corners or centers of plots. Aluminum tags are useful for tagging individual trees with block, plot, and tree numbers (if placed on the main stem, these tags will need to be moved after a year or two to prevent girdling).

Table 1. A spreadsheet of all data in the study is useful to calculate averages, growth, and ratios and can be imported into software programs to determine if there are statistical differences among treatments. This sample spreadsheet shows data for two plots from a study with two treatment factors (fertilizer by stock type). The spreadsheet includes the identifying information for each tree (block, fertilizer, stock type, and tree number) and the height, diameter, and survival data measured soon after planting (2/2012) and on two subsequent dates (9/2012, and 9/2013), along with comments ("comm") for unusual observations (chlor = chlorotic; mt = multitop; dt = dead top). The full data set continues in subsequent rows for all trees in all treatment plots from all blocks. Columns can be added to the right for additional dates.

Block	Fert	Stock type	Tree number	Ht212 (cm)	Dia212 (cm)	Comm 212	Ht912 (cm)	Dia912 (cm)	Surv 912	Comm 912	Ht913 (cm)	Dia913 (cm)	Comm 913	Surv 912
1	con	P1	1	64	9	–	76	11	1	–	107	18	–	1
1	con	P1	2	48	12	–	63	15	1	–	111	29	–	1
1	con	P1	3	56	10	–	66	12	1	–	87	16	–	1
1	con	P1	4	37	7	–	46	7	1	–	70	15	–	1
1	con	P1	5	52	8	–	62	10	1	–	75	17	–	1
1	con	P1	6	57	6	–	–	–	0	dead	–	–	dead	0
1	con	P1	7	51	8	–	59	9	1	–	71	14	–	1
1	con	P1	8	58	9	–	68	9	1	–	82	15	–	1
1	con	P1	9	57	9	–	62	10	1	browse	88	19	–	1
1	con	P1	10	46	7	–	55	7	1	–	67	12	–	1
1	con	P1	11	58	9	–	63	10	1	–	49	18	dt	1
1	con	P1	12	68	11	–	71	12	1	–	83	15	–	1
1	con	P1	13	40	7	–	–	–	0	dead	–	–	dead	0
1	con	P1	14	53	10	–	–	–	0	dead	–	–	dead	0
1	con	P1	15	58	9	–	64	9	1	–	–	–	dead	0
1	con	P1	16	43	6	–	44	7	1	–	43	8	dt	1
1	F1	s15	1	31	5	–	50	10	1	–	66	13	–	1
1	F1	s15	2	23	4	–	43	9	1	–	76	15	–	1
1	F1	s15	3	38	6	–	65	10	1	–	120	21	–	1
1	F1	s15	4	33	5	–	57	10	1	–	93	20	–	1
1	F1	s15	5	33	7	–	52	13	1	–	86	20	–	1
1	F1	s15	6	40	5	–	62	10	1	–	89	17	–	1
1	F1	s15	7	43	7	–	59	10	1	–	73	16	–	1
1	F1	s15	8	43	6	–	75	11	1	–	133	44	–	1
1	F1	s15	9	33	7	–	38	11	1	brown	61	17	–	1
1	F1	s15	10	37	7	–	57	10	1	–	86	17	–	1
1	F1	s15	11	48	7	–	65	11	1	–	80	17	–	1
1	F1	s15	12	35	6	–	37	8	1	chlor	59	14	–	1
1	F1	s15	13	40	5	–	47	10	1	–	88	23	–	1
1	F1	s15	14	37	5	mt	48	6	1	–	54	11	browse	1
1	F1	s15	15	42	6	–	68	10	1	–	74	13	–	1
1	F1	s15	16	41	5	–	53	7	1	–	78	14	–	1

and so on...

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Inoculation Response by Irrigation System Type for Desert Tree Establishment

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Abstract

Revegetation research offers the opportunity to test theories under difficult field conditions. These tests can help improve guidelines for establishing trees on arid and degraded sites. The borrow pit (surface mine) used for this study reflects the most difficult challenges of low fertility, extreme water stress, and harsh microclimate conditions. This set of conditions made it an ideal site to test interactions between irrigation system type and inoculation with rhizobial bacteria and mycorrhizal fungi. The tree chosen for the study, *Prosopis glandulosa* var. *torreyana* (L.D. Benson, M.C. Johnston), (mesquite, honey mesquite), is a small- to medium-sized leguminous tree with considerable value for ecosystem structure and function. It was once much more common in the low desert of California and was widely used as a food by indigenous people. The destruction of mesquite woodlands for fuel wood and agricultural and urban development has reduced once vast stands to isolated remnants. The California Department of Transportation supported research to mitigate mesquite habitat loss caused by ongoing highway construction. It was also expected this research would help nursery managers better prepare plants for difficult sites and assist restoration specialists and foresters in developing better techniques for restoration and agroforestry projects. The soil analyses showed that soil fertility was greatly reduced and inoculation potential was nearly absent in the borrow pit. Deep-pipe and buried-clay-pot irrigation each enhanced survival and growth. The steady moisture of buried clay pots appears to be more favorable for rhizobial inoculation, and deep-pipe irrigation with deeper wetting and greater aeration is better for mycorrhizal inoculation. Double inoculation provided increased survival and growth in the short term, but long-term effects were minimal.

Introduction

The establishment events for many perennial desert plants are poorly understood but often appear to be confined to pulses linked to unique climatic patterns that may occur only a few times a century. Most of the time, plant establishment is limited by very low and variable precipitation, extreme evaporation, wind desiccation and abrasion, low soil fertility, excessive salinity and sodicity, and herbivory by insects and small mammals (McAulliffe 1986, Allen 1989a). Human activities, such as construction and agriculture, can compound these problems by radically altering ecosystem structure and function, limiting or eliminating beneficial microsymbiont propagules, increasing moisture stress, adding soil salinity from irrigation, adversely affecting soil structure, and changing nutrient levels (Bainbridge et al. 1993, Lovich and Bainbridge 1999, Bainbridge 2007). Revegetation research under rigorous field conditions can help develop guidelines for restoring this type of desert ecosystem. The most extreme condition possible is a borrow pit where excavation of a large volume of soil will typically remove microsymbionts, nutrients, seeds, and propagules.

Mesquite (*Prosopis glandulosa* var. *torreyana* [L.D. Benson, M.C. Johnston]), a small- to medium-sized leguminous tree (Burkart and Simpson 1977), once occurred in extensive woodlands in the low deserts of southern California. Its distribution and occurrence has been greatly restricted during the past century by harvesting for fuel wood, intensive agriculture, groundwater overdraft, off-road vehicle activity, and urban development. Only isolated stands now remain. In the Colorado Desert, mesquite is found in washes, along the edges of playas, and in other areas where groundwater reserves are available. Mesquite usually has a fibrous root system near the surface, exploiting moisture from infrequent rains, and a fast-growing tap root that can reach great depths in its search for water (Phillips 1963, Bainbridge et al. 1990).

Mesquite is a good multipurpose tree crop for dry land agroforestry (Meyer 1984, Bainbridge et al. 1990) and was once a critical food resource for indigenous populations who planted, transplanted, and managed this species (Bean and Saubel 1972). Mesquite trees can be a major nitrogen source for desert ecosystems and may play an important role in long-term productivity of desert plant communities through their effect on soil chemical and physical properties (Virginia 1986,

1990). Indigenous people utilized this trait by transferring mesquite soils to gardens to improve fertility (Nabhan 1982). Mesquite also provides valuable habitat for many desert wildlife species.

Mesquite commonly forms symbiotic root associations with nitrogen-fixing rhizobial bacteria (Virginia and Jarrell 1983, Virginia et al. 1984). Research showed that a mesquite stand near Harper's Well (in the Colorado Desert west of the Salton Sea) was fixing approximately 60 percent of its nitrogen supply (Shearer et al. 1983). Mesquite was the most effective N fixer in a comparative study in Riverside, CA (Abrams et al. 1990). Fast-growing *Rhizobium* and slow-growing *Bradyrhizobium* were found associated with mesquite (Jenkins et al.1987, 1989; Waldon et al. 1989). Nodules were found at depths of up to 26 ft (8 m) (Virginia et al. 1986, Jenkins et al. 1988).

Rhizobial associations have nutrient requirements and limitations. High nitrogen levels in soil can inhibit root-hair infection and nodule development (Gibson and Jordan 1983), but added phosphorus may increase nodulation and nitrogen fixation in phosphorus-limited soils (Louis and Lim 1988). Nodules are commonly found in the moist soils of the phreatic zone with limited oxygen exchange.

Mesquite is also mycotrophic and forms a symbiotic association with vesicular-arbuscular mycorrhiza (VAM) fungi (Bethlenfalvay et al. 1984). VAM can enhance plant growth by improving uptake of phosphorus, water, and other nutrients (Allen 1988). Mycorrhizal plants may be more capable of accessing water in dry soil than nonmycorrhizal plants (Allen and Allen 1986). To perform well, the VAM fungi and plant symbiosis require nitrogen (Allen 1992, Azcón-Aguilar and Barea 1992) and benefit from higher oxygen levels and well-aerated soil. High phosphorus levels can inhibit symbiotic formation and persistence (Menge 1984, Louis and Lim 1988).

Dual inoculation with VAM fungi and rhizobia may increase plant survival and growth (Barea et al. 1987, Carpenter and Allen 1988). Rhizobia and VAM fungi may influence each other directly, at the preinfection and early colonization stages, or indirectly, through their effects on plant nutrition (Azcón-Aguilar and Barea 1992). VAM causes changes in plant water relations, hormonal balance, photosynthetic rate, and carbon allocation that can improve the development of the rhizobial symbiosis.

Reestablishing mesquite trees in disturbed and degraded environments may require careful attention to microsymbiont associations through preplant preparation, field inoculation, and irrigation strategies, especially during establishment in infertile soils without symbionts, such as found in borrow pits. The objective of this study was to explore the effects of irrigation type and inoculation strategies with VAM fungi and rhizobia to develop best practices for desert revegetation with mesquite. Plants were established into resource islands intended to act as islands of fertility to improve soil conditions and provide a source of seeds, microsymbionts, and other propagules to speed recovery of the denuded site.

Materials and Methods

Site Description

The borrow pit site for this experiment is located on the western edge of the Sonoran Desert, northwest of the Salton Sea at 66 ft (20 m) elevation in the Coachella Valley of California (33°25.52 N, 116°05.48 W). The ecosystem is a creosote (*Larrea tridentata* [DC.] Coville) desert scrub bajada intercut with washes having palo verde (*Parkinsonia florida* [Benth. ex A. Gray] S. Watson), smoketree (*Psorothamnus spinosus* [A. Gray] Barneby), and a few ocotillo (*Fouquieria splendens* Engelm.). Mesquite was not found in the immediate area but was growing within 1 km (0.6 mi).

At the start of the experiment, the borrow pit was a bit more than 2.5 ac (1.0 ha) in area and was still in use (figure 1). The borrow pit was used as a source of material for highway construction. Up to 26 ft (8 m) of soil had been removed, leaving a compacted, barren gravel and rock alluvium. The borrow pit was also aerial seeded with a mix of 12 native plant species after the resource islands for the study were fenced. Seeds were then worked into the soil by dragging the site with a section of chain link fence between the fenced resource island plots with transplants.

Figure 1. The borrow pit and one of the resource islands where seedlings were planted for this study. (Photo by David A. Bainbridge 1990)

The annual rainfall at Indio, the closest recording station, averages 3.3 in (83.0 mm) (Western Regional Climate Center 2012). Tropical storms that move north from the Gulf of California every 30 to 40 years result in rain equal to the yearly average in a few minutes, however, causing extensive sheet and stream flow and flash floods. These floods recharge the wash soils for as much as a year after a flow event (Virginia and Bainbridge 1987). Winter storms can also bring ecologically significant rain events every 15 to 20 years, with 4 in (10 cm) of rain or more in a month or two. These large rain events are minor, however, compared with evaporation rates, with annual mean evaporation from a class A pan of 105 in (268 cm), more than 32 times the mean annual precipitation (figure 2).

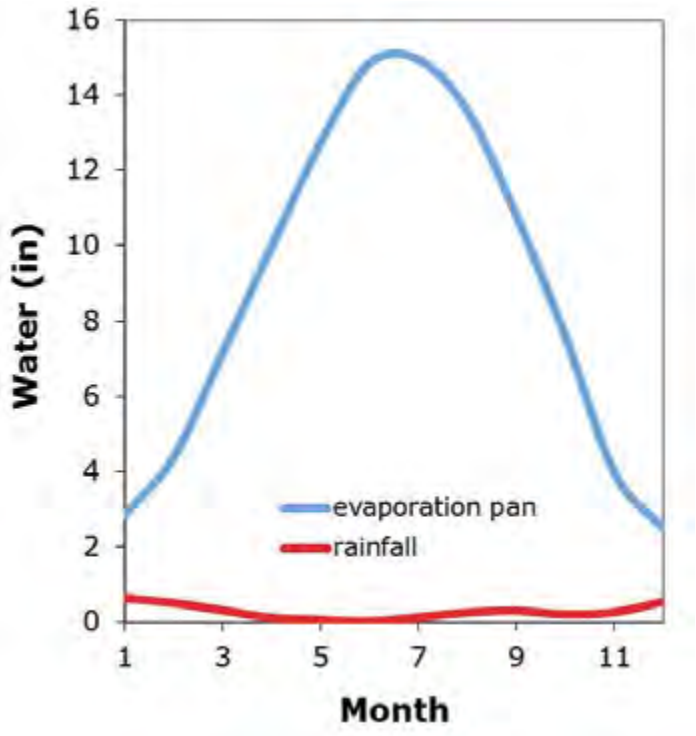

Figure 2. This site water balance graph demonstrates the extremely dry climate as this site by showing evaporation and precipitation. Even in the rainy season, evaporation far exceeds rainfall. Irrigation is essential for initial survival of outplanted seedlings.

Seedlings and Inoculant

Surface sterilized mesquite seeds were sown in 10 in^3 (164 cm^3) Ray Leach SuperCells™ filled with 16-grit silica in the greenhouse at the University of California, Riverside. They were irrigated with tap water as needed for 2 months. No fertilizer was added. Four inoculation treatments were applied: (1) a control (no treatment), (2) rhizobial inoculum, (3) VAM inoculum, and (4) a dual (rhizobia + VAM) inoculation. Seedlings for the rhizobial and dual inoculation treatments were inoculated 1 week before planting by adding a teaspoon of mesquite rhizobia on a peat carrier from Nitragin, Inc. (Milwaukee, WI), to the container surface and watering it in.

Before planting, the site was ripped by a tractor pulling a scarifier. Seedlings were planted as resource islands within the borrow pit site in late March 1990. The seedlings were uniform in size and appearance at the time of planting with roots 4- to 6-in (10- to 15-cm) long and shoots ~1-in (2- to 3-cm) tall with the first pair of true leaves. The seedlings were gently removed from the containers and barerooted into a planting hole made with a KBC tree-planting bar (Ben Meadows™, Janesville, WI) (figure 3). A tablespoon (15 g) of VAM inoculum (*Glomus intraradices* [Nutrilink, NPI, Salt Lake City, UT]) was placed at the bottom of the planting hole. A 3.0-in (7.5-cm) tall section of 3.0-in (7.5-cm) diameter PVC pipe collar was placed around each seedling to protect from sand blast and reduce desiccation. Each plant received 1 qt (0.94 L) of water immediately after planting.

Each resource island started out with a 24-in (60-cm) tall wire mesh fence to limit herbivory, but the fence material was stolen after the second year.

Figure 3. The mesquite seedlings were quite small at outplanting. Also shown is the KBC planting bar. (Photo by David A. Bainbridge 1990)

Irrigation

Three irrigation methods were compared: clay pot, deep pipe, and surface.

Buried-clay-pot irrigation uses an unglazed earthenware pot filled with water to provide controlled irrigation to plants growing adjacent to it. The water moves out of the buried clay pot by capillary action at a rate that is influenced by the adjacent plant's evapotranspiration. This traditional irrigation method is very efficient and effective (Sheik and Shaw 1983, Bainbridge 2001). The clay pots used for this trial were standard 8-in (20-cm) diameter terra cotta nursery pots with the hole in the bottom sealed with silicone caulk. Each pot was covered with an aluminum lid (with holes punched in it to allow rainfall to enter the pot) weighted with a glued-on small rock (figure 4). Four seedlings were planted per pot.

Figure 4. Buried-clay-pot irrigation showing the plant collar, plant protector, and arrangement of seedlings. (Photo by David A. Bainbridge 1990)

Deep-pipe irrigation uses an open vertical pipe to move irrigation water to the deep-root zone (Sawaf 1980, Bainbridge 2006). Deep-pipe irrigation has provided excellent survival and growth in the low desert (Bainbridge and Virginia 1990). The deep-pipe system used in this test consisted of a 16-in (40-cm) length of 2-in (5-cm) diameter PVC pipe (figure 5). Three 0.25-in (6-mm) holes were spaced along the pipe on the sides next to the plants to improve water delivery to roots of the young seedlings. Two seedlings were planted per pipe.

Figure 5. Deep-pipe irrigation showing the plant collar and plant protector. The tall seedling on the right was inoculated and shows the benefit of nitrogen produced in root nodules by rhizobial bacteria. (Photo by David A. Bainbridge 1990)

A surface irrigation treatment with water applied to a shallow basin was used as a control. Two seedlings per basin were planted.

Plants were given 13.5 fl oz (400 ml) of water during each irrigation. This watering occurred approximately every 2 weeks in the summer and tapered off in the fall. Plants received a total of 2.6 gal (10 L) over 2 years. Rainfall in the first growing year, July to June, was 3.3 in (8.4 cm), an average year for this location, and a perfect test for the irrigation systems.

Measurements

A preliminary study of the area soils had been done to explore the effects of site disturbance on soil fertility and soil symbionts (Virginia et al. 1988). Soil samples taken from under plant canopies and barren areas between plants showed that overall soil fertility was low but improved by the presence of plants. Soil saturation percent, soil moisture, and VAM spores were also higher under plant canopies. For the pit site where this study was established, 34 samples were collected and analyzed before planting, 14 in the pit, including one ant mount, and 20 nearby with and without existing plants. Plant roots were excavated, stained, and examined for mycorrhizal infection, and an infection potential bioassay was performed with collected soils. Spores from soils at root collection spots were extracted and

counted. Soil samples were taken 5 years after planting from two depths beneath and outside six mesquite tree (from planting) and three creosote bush (from direct seeding) canopies growing in the pit were analyzed for N and P to examine the recovery of soil fertility.

Plant height and survival were recorded several times over the 2 years.

Experimental Design and Analyses

The three by four (inoculation by irrigation) factorial experiment was set up in seven resource islands (replications) within the borrow pit. Each of the 12 treatment combinations included 8 planted seedlings in each resource island. Analysis of variance was done using SuperAnova and Fisher's Least Significant Difference for soils. Duncan's new multiple range test was used to evaluate significance of irrigation and inoculation on plant development.

Results

Soil samples collected before planting revealed that the already low fertility of the desert soils was further reduced by the extensive soil removal from the borrow pit (figure 6). Nitrogen was one-half and phosphorus was about one-tenth that of undisturbed soils. The ant mound sampled at the bottom of the pit had 12 times as much phosphorus and 3 times as much nitrogen as adjacent soils. Previous bioassays of soils with similar disturbance adjacent to the planting site revealed no mycorrhizal infection potential in recently bladed areas (Virginia et al. 1988, Bainbridge and Virginia 1995). After

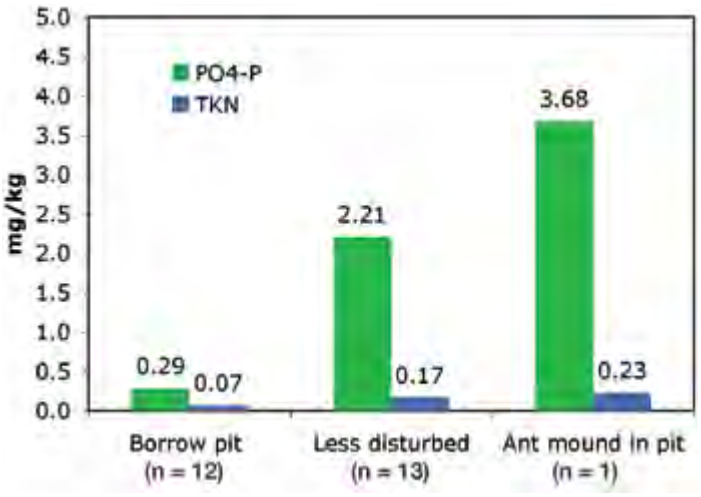

Figure 6. Soil fertility before outplanting from samples taken in the borrow pit, in adjacent less disturbed areas, and in an ant mount in the pit.

5 years, soil fertility improved under plant canopies from container plants (mesquite) or direct seeding (creosote bush). Mean total nitrogen levels doubled under mesquite and tripled under creosote bush (table 1).

Seedling responses to inoculation were minimal. Although early growth effects were observed, survival and growth differences among inoculation treatments were minor over time (table 2, figure 7). All the surface-irrigated plants died by the

Table 1. Mean organic nitrogen concentrations for surface (0.0 to 2.5 cm [0.0 to 1.0 in]) and subsurface (2.5 to 10 cm [1.0 to 4.0 in]) soils sampled beneath and outside mesquite (n = 6) and creosotebush (n = 3) canopies in 1995 increased compared with soil samples collected at the mesquite planting sites before planting in 1990. Within soil layers, means with different letters are significantly different at $p < 0.05$. (1 mg per g = 1,000 ppm).

Sample date and location	Surface layer total organic nitrogen (mg per g)	Subsurface layer total organic nitrogen (mg per g)
1990—open area	0.08 b	0.08 a
1995—beneath mesquite canopy	0.19 a	0.09 a
1995—mesquite open area	0.10 b	0.10 a
1995—beneath creosotebush canopy	0.31 c	0.15 b
1995—creosote bush open area	0.12 ab	0.09 a

Table 2. Growth and survival of mesquite seedlings from each treatment planted in the borrow pit (1.0 cm = 0.39 in).

Irrigation	Inoculation	6-week height (cm)[1]	2-year height (cm)[2]	2-year survival (%)[2]
Surface	None	3.75 A b	—	0
	Rhizobia	3.21 A c	—	0
	VAM	4.31 A c	—	0
	Dual	3.58 A b	—	0
Deep pipe	None	9.36 B a	94.2	79
	Rhizobia	8.38 B b	82.0	86
	VAM	13.32 A a	86.8	86
	Dual	13.84 A a	86	93
Clay pot	None	10.87 B a	70.6	81
	Rhizobia	10.45 B a	72.1	67
	VAM	9.38 B b	50.4	42
	Dual	14.87 A a	52.8	81

[1] For 6-week height, means within each irrigation treatment followed by uppercase letters are significantly different and within each inoculation treatment, means followed by a different lowercase letter are significantly different according to Duncan's new multiple range test.

[2] For 2-year height and survival, plants in the deep-pipe irrigation treatment were significantly greater, but inoculation treatments did not have a significant effect.

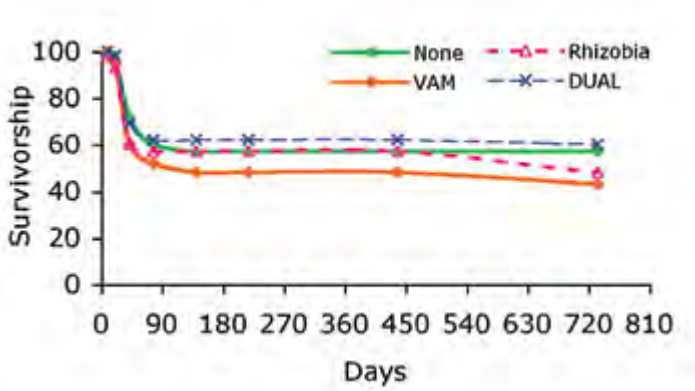

Figure 7. Inoculation treatments did not influence survival significantly over time.

end of the first 5 months, but 86 percent of seedlings irrigated using the deep-pipe method and 68 percent of those irrigated using the buried clay pots remained alive after 2 years (figure 8). Although the growth data have large standard deviations because of high variance in height, differences among the irrigation treatments were significantly different, according to Duncan's new multiple range test. Several trees were more than 3 ft (1 m), while others were only 8-to-16-in (20-to-40-cm) tall after 2 years. The three tallest plants after 2 years were all irrigated using the deep-pipe method. The tallest plant (9.5 ft [2.9 m]) was dual inoculated using deep-pipe irrigation.

Overall, the planted resource islands developed well, due in part to a rain event in spring 1993 (figure 9). This rainfall also led to establishment of a range of other annual and perennial species from the aerial seeding.

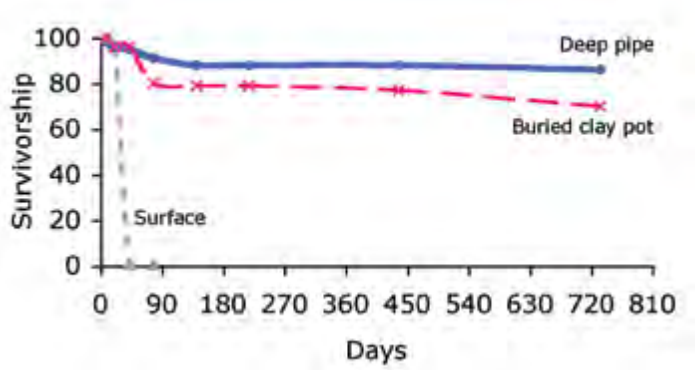

Figure 8. Irrigation method had a significant effect on seedling survival after 2 years.

Discussion

This research clearly demonstrated the changes that severe disturbance can have on site soil fertility and soil ecology. It also confirmed the beneficial effects that plants have on soil fertility and soil moisture. Although we might expect

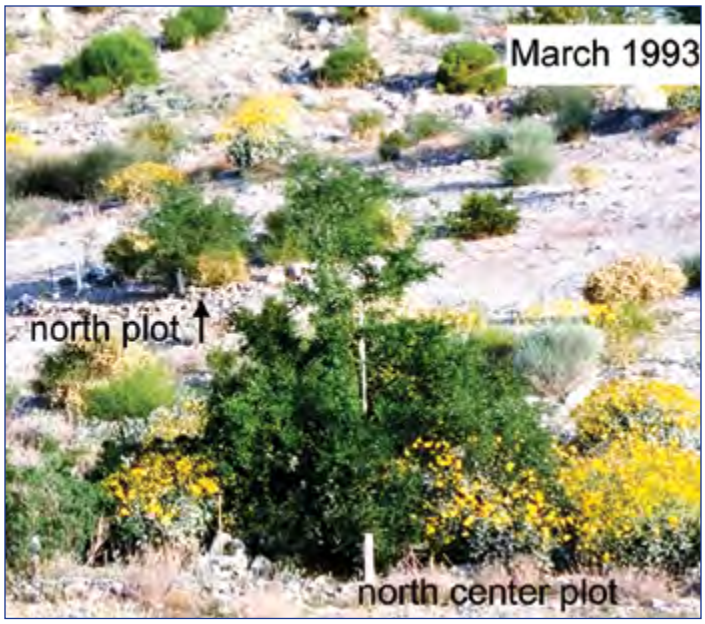

Figure 9. After 2 years, the resource islands were successfully established in the borrow pit. (Photo by David A. Bainbridge 1992)

soil moisture to be depressed under plants, it was increased. This study highlighted also the benefits of deep-pipe and buried-clay-pot irrigation for establishing small seedlings on arid sites (see also Bainbridge 2013). Nearly all the surface-irrigated plants were dead within 78 days, a result all too familiar for many project managers dealing with restoration, revegetation, or reforestation on harsh dry sites, while survival with deep-pipe and buried-clay-pot irrigation was excellent. Mortality in all treatments occurred primarily between July and September of the first year, and more frequent irrigation during this first critical summer may be advantageous. After surviving beyond the critical establishment phase, mesquite seedlings were able to persist.

The very small seedlings used in this study were probably also more vulnerable to drought stress. Larger plants from deep containers with deep-pipe irrigation might survive better and grow faster (Bainbridge 2007, 2012).

The very low soil fertility and limited inoculation potential made this borrow pit an ideal site for an inoculation test, but the benefits of commercial inoculum were modest at best. Inoculation has shown some potential for improving restoration (Allen 1989a, 1989b) but field results have been inconsistent, perhaps because soil ecosystems are complex and not well understood. The interactions between mycorrhizal fungi, rhizobia, and soil fertility are also important. For example, Barea et al. (1987) found that VAM improved nitrogen fixation and uptake. New genetic tools may make it possible to better understand these belowground communities. Koch

(2006) showed large genetic differences between individuals in a mycorrhizal population in an area of 295 by 360 ft (90 by 110 m). Production of effective inoculum for a given site may require much more sophisticated selection and testing.

The soil fertility measurement 5 years after planting and seeding confirmed that plants improve their own microsite by capturing dust and increasing soil fertility. It was surprising to see the increase in soil N under creosote growing in the pit was higher than under mesquite. This result may reflect better capture of litter and dust by creosote. High winds and extensive dust movement may have returned inoculum to these relatively small disturbance sites fairly quickly. Cross infection between treatments may also have occurred. In retrospect, it would have been helpful to sample roots of surviving plants and those that died to see if they had been colonized by symbionts.

The improvement in early performance using clay pots and deep-pipe dual inoculation is instructive. The steady moisture of buried clay pots appears to be more favorable for rhizobial inoculation, deep-pipe irrigation is more favorable with deeper wetting, and greater aeration is better for mycorrhizal inoculation. Deep-pipe plants may also benefit from dust and inoculum falling into the screened open pipe during wind events.

Conclusions

The main goal of this study was to evaluate the effects of inoculation and irrigation treatments on mesquite establishment in the degraded soil of a borrow pit. Inoculation results were mixed and not large. These results might have been different if a locally adapted, site-specific inoculum had been developed. The importance of ants and other microfauna for reestablishing desert soil fertility was also clear (Bainbridge and Virginia 1995, Cammerat et al. 2002).

The value of water-efficient irrigation methods was clearly demonstrated by the excellent survival of clay-pot- and deep-pipe-irrigated trees at the borrow pit. No plants survived using the more traditional surface irrigation.

Preinoculating seedlings is a reasonable strategy for reintroducing symbionts on severely degraded sites but managing root symbiotic associations are complex because of the interactions between soil moisture, soil ecology, and soil chemistry. The management of microsymbionts in containers is not well understood, and inoculation with commercial symbionts is still a developing art even in a controlled nursery setting (Corkidi et al. 2004). Further investigation is needed to determine the optimum inoculum populations, watering regime, irrigation system type, water application rates, nutrient concentrations, growth media, and container size and shape for developing symbiotic associations for mesquite in the greenhouse that will provide long-term benefits in the field. Inoculation of direct seeded plots can also be improved.

Deep-pipe and buried-clay-pot irrigation are each well suited for the most severe sites. Successful revegetation of heavily disturbed arid sites is feasible, but everything must be done well and on time (Allen 1989b, Bainbridge et al. 1993, Bainbridge 2007). Mesquite is a desirable plant for reconstruction because it plays an important role in desert ecosystem function and structure and can provide useful products for animals, birds, and people as well. Funding for long-term research is needed to better determine the best ways for returning mesquite and other multipurpose native trees to degraded drylands.

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Effects of Foliar Urea Fertilization on Nitrogen Status of Containerized 2+0 Black Spruce Seedlings Produced in Forest Nurseries

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Abstract

A 7-day study of foliar fertilization was carried out after fall budset of containerized 2+0 black spruce (*Picea mariana* [Mill.] B.S.P.) to assess if one application of urea (U), alone or with surfactant (US), can lead to a rapid increase of foliar nitrogen (N) concentration. Two washing treatments of seedling shoots (W: 15 sec washing [control], WS: W + 5 min soaking) were also performed to evaluate their efficiency to remove urea residues from the needle surface before foliar N concentration analysis. At day 0 (2 hours after application), fertilized seedlings already had significantly greater foliar N concentration than unfertilized seedlings (NF) and after 7 days, it had increased 7 and 12 percent for U and US seedlings, respectively. The addition of a surfactant did not significantly improve N status. Foliar N concentration of fertilized seedlings was not significantly affected by washing treatments. These results indicate that foliar urea fertilization after budset is an effective tool for rapidly increasing foliar N concentration without affecting seedling shoot height.

Introduction

Of the 128 million containerized and bareroot forest seedlings that were produced in the 19 forest nurseries (13 privately owned and 6 government owned) in Québec (Canada) in 2013, 94 percent were grown in containers, one-half of which were black spruce (*Picea mariana* [Mill.] B.S.P.) (Arsenault, pers. comm.). These nurseries follow a nutritional approach developed in the 1980s (Langlois and Gagnon 1993) and applied operationally using PLANTEC software (Girard et al. 2001). Using this approach, containerized seedlings are fertilized weekly to satisfy their nutrient demands (nitrogen [N], phosphorous [P], and potassium [K]) for growth, while taking into account their phenological phases (active or dormant). Containerized conifer seedlings in Québec nurseries must not only meet morphological quality criteria (e.g., height, diameter, height/diameter), but also must have a minimum foliar N concentration of 1.6 percent for seedlings grown in cavities with volumes smaller than 200 cm^3 (12 in^3) and 1.8 percent for seedlings grown in cavities equal to or larger than 200 cm^3 before delivery for outplanting (Veilleux et al. 2014). Québec forest nurseries assess whether seedlings have met the minimum foliar N concentration target after autumn bud formation and again before delivery for outplanting. Before this analysis, the Québec governmental laboratory washes the seedling shoots for 15 seconds to remove the fertilizer residues from the needle surface. To date, with the exception of our preliminary study (Gagnon 2011), no other study has evaluated the efficiency of this washing method to remove fertilizer residues.

During the period between fall budset and the evaluation of foliar N concentration, foliar N fertilization could be a useful tool for increasing the foliar N concentration of containerized conifer seedlings to the desired level without affecting their shoot height growth. Foliar N fertilization of containerized conifer seedlings can also be used at any time during the growing season to complement soil fertilization and rapidly increase foliar N concentration, thus permitting nursery growers to attain target foliar N levels throughout the season. Foliar sprays, which are primarily used to correct micronutrient deficiencies, such as iron chlorosis, can also be used with N to provide a quick "green-up" before seedlings are shipped to the planting site (Landis et al. 1989). According to Dumroese (2003), foliar fertilization can be used to quickly recharge nutrient-depleted containerized seedlings or to add high doses of nutrients for luxury consumption (nutrient loading). Because foliar N fertilization is applied to the foliage rather than to the soil, it can also contribute to a reduction in the quantity of nutrients leached from container-grown seedlings and, consequently, the pollution of groundwater by nitrate.

Foliar N application has been largely used in agriculture and horticulture during the past 50 years (Handreck and Black 1984, Alexander and Schroeder 1987, Gooding and Davies 1992, Wojcik 2004). Only a few studies have been carried

out, however, with conifer seedlings grown in containers under forest nursery conditions: Monterey pine (*Pinus radiata* D. Don.) (Coker et al. 1987, Coker 1991), black spruce (Gagnon 2011), ponderosa pine (*Pinus ponderosa* Laws.), and Douglas-fir (*Pseudotsuga menziesii* [Mirb.] Franco) (Montville and Wenny 1990, Montville et al. 1996). This lack of research may be explained by the small absorptive surface of conifer needles relative to leaves of broadleaved plants and by the waxy cuticular surface of the needles, which slows nutrient absorption (Landis et al. 1989, Marschner 1995, Mengel and Kirkby 2001, Lamhamedi et al. 2003). In autumn, after bud formation, the wax load on the needle surface increases (Landis et al. 2010) and the cuticle becomes thicker.

Surfactants are often used with foliar spray solutions to ensure diffusion of nutrients across the cuticle, which, because of its hydropobic nature, impedes the diffusion of hydrophylic ions (Mengel and Kirkby 2001). According to Landis et al. (1989), a surfactant is often used with foliar fertilization to ensure uniform distribution of the fertilizer solution over the needle surface. Indeed, by reducing the surface tension of water droplets, the surfactant permits a thin layer to adhere to the needle surface, thus improving nutrient absorption (Wittwer and Teubner 1959, Mengel and Kirkby 2001, Wojcik 2004).

Among the three N sources that can be used for foliar N fertilization (ammonium [NH_4^+], nitrate [NO_3^-], and urea [$CO(NH_2)_2$]), urea is the most readily absorbed by the leaves of most crops. Several studies showed that after its rapid absorption by leaves, urea is then rapidly metabolized and translocated by plants (Handreck and Black 1984, Alexander and Schroeder 1987, Gooding and Davies 1992, Wojcik 2004). Urea can also be applied at relatively high concentrations without damaging needles because of its low-phytotoxicity potential (Alexander and Schroeder 1987, Gooding and Davies 1992, Wojcik 2004). Urea is also considered to be the most suitable form of N for foliar applications because of its nonpolarity and its high solubility in water and oil (Wittwer et al. 1963, Yamada et al. 1965, Swietlik and Faust 1984). Being a neutral molecule, urea is absorbed more quickly by needles than either NH_4^+ or NO_3^- because it rapidly diffuses through the waxy cuticule (Wittwer et al. 1963). Using these three N sources in a foliar fertilization study with containerized *Pinus radiata* seedlings, Coker et al. (1987) showed that urea was absorbed 10 times more rapidly than NO_3^- and three times faster than NH_4^+. Given these advantages of urea for foliar fertilization, this N source was successfully tested in a preliminary study with containerized 2+0 black spruce seedlings (Gagnon 2011).

The objectives of this study were to evaluate (1) the effects of a single foliar application of urea after seedling budset on N concentration of containerized 2+0 black spruce seedling needles, (2) the addition of a surfactant to the urea solution on the efficiency of urea foliar fertilization, and (3) the efficiency of washing treatments of seedling shoots to remove urea residues from the needle surface for subsequent accurate determination of foliar N concentration after a foliar urea fertilization.

Materials and Methods

Seedlings

Large 2+0 black spruce seedlings (seedlot: EPN-V2-PLU-1-0) grown in 25-310 containers (25 cavities with a volume 310 cm^3 [19 in^3] each, IPL 25-310, Saint-Damien, Québec, Canada) at Normandin nursery were used for this experiment. This governmental forest nursery (ministère des Forêts, de la Faune et des Parcs, MFFP du Québec) is located in the Saguenay-Lac St. Jean region of Québec (48°48'48" N, 72°45'00" W), Canada.

In Quebec, seedlings produced in cavity volumes more than 300 cm^3 [18 in^3] are deemed large seedlings and are grown under forest nursery conditions for 2 years. During their first growing season, 1+0 seedlings are produced under white, unheated polyethylene tunnels (figure 1), the covers of which are removed in October, at the end of the season. Thereafter, seedlings are moved outside the tunnels and placed directly on the ground until spring (April). The thick snow cover and lack of air circulation under the containers protect the seedlings against frost damage during the winter. During the second growing season, 2+0 seedlings are cultivated outdoors (figure 1). All 2+0 container seedlings are irrigated by sprinklers arranged in a square pattern and fertilized using a tractor-mounted boom sprayer.

Figure 1. In Québec forest tree nurseries, containerized seedlings are grown for 2 years: 1+0 seedlings are produced in unheated white polyethylene tunnels (left) and 2+0 seedlings are grown outdoors (right). These seedlings are large 2+0 black spruce seedlings produced in 25-310 containers at Normandin nursery (Québec, Canada) in July. (Photo by Jean Gagnon 2013)

Before the experiment, seedlings were fertilized biweekly from May 18 to September 27 according to the seedlings' weekly nutritional needs (Langlois and Gagnon 1993) determined by Plantec 2 software, a new version of PLANTEC (Girard et al. 2001). Fertilization totalled 81 mg (0.0027 oz) N (41 percent NH_4^+, 49 percent NO_3^-, and 10 percent urea), 21 mg (0.0007 oz) P, and 42 mg (0.0014 oz) K. The seedlings also received small amounts of calcium and magnesium as well as micronutrients present in commercial soluble fertilizers. No fertilizer was applied between September 28 and the beginning of the foliar fertilization study on October 12. Irrigation of these seedlings was managed using IRREC irrigation software (Girard et al. 2011). Directly before application of the foliar fertilization treatments, substrate fertility was determined on one composite sample from each treatment (72 root plugs per composite sample). The average substrate concentration of mineral N was 0.4 ppm and the concentration of urea-N was 0 ppm. This analysis was performed by the laboratoire de chimie organique et inorganique (ISO/CEI 17025) de la Direction de la recherche forestière (DRF), MFFP du Québec. This laboratory carried out all other N analyses (tissue and water) described in this article.

Foliar Fertilization Treatments

A completely randomized design with two factors (foliar urea fertilization and washing of seedling shoots), each with three levels of treatments and eight replicates (2 containers per replicate), was installed at Normandin nursery on October 12, 2011. A total of 600 containers received one of the three treatments of foliar urea (46-0-0) fertilization on day 0 (October 12): (1) Urea (U), (2) Urea + surfactant (US), and (3) no fertilization (NF: control). For the US treatment, the surfactant used was Agral 90 (Norac Concepts Inc. 2009, Guelph, Ontario, Canada), a nonionic surfactant containing 90 percent of nonylyphenoxy polyethyoxy ethanol (NPE). Agral 90 was mixed with the urea solution in the following proportions: 1 ml per L (0.11 oz per gal). Because the addition of Agral 90 to urea solution leads to foam formation, a 12.5 percent antifoaming/defoaming agent (Fighter-F® 12.5 antifoaming/defoaming agent, Loveland Products, Inc. Greeley, CO) was added at a dose of 15 ml (0.51 oz) to the 32-L (8-gal) mix of urea and surfactant (US treatment).

For the two foliar urea fertilization treatments (U, US), an application of 15 mg (0.0005 oz) N per seedling or 29 kg N per ha (26 lb per ac) was applied, corresponding to a dose of 33 mg (0.0011 oz) urea per seedling or 68 kg per ha [60 lb per ac]. For each urea treatment, 7 kg (15 lb) of 46-0-0 was mixed in 48 L (13 gal) of water, producing a solution with a concentration of 145.8 g urea per L [1.2 lb per gal]. U and US treatments were applied at a rate of 518 L per ha (57 gal per ac) using a tractor-mounted boom sprayer (Model Multi 33, Timm Enterprises Inc., Oakville, Ontario, Canada) equipped with a 720-L (191-gal) reservoir and two rails of nine-nozzle irrigation (Model Teejet XR 11002, TeeJet Technologies, Spraying Systems Co., Wheaton, IL) (figure 2). At the time of fertilization, air temperature was 14°C (57°F) and relative humidity was 68 percent. No irrigation to rinse the foliage was applied either following foliar urea fertilization or during the 7-day study.

Figure 2. For the urea foliar fertilization study carried out in mid-October at Normandin nursery, urea treatments were applied using tractor-mounted booms to 2+0 black spruce seedlings grown in 25-310 containers. (Photo by Jean Gagnon 2011)

Immediately after application of the fertilization treatments, 16 containers per treatment (8 replicates of 2 containers) were randomly selected. These containers were then moved into an unheated warehouse with open doors for 7 days, thus exposing the seedlings to outside temperatures while protecting them from rainfall. A total of 72 seedlings per fertilization treatment (9 seedlings per replicate by 8 replicates) was randomly harvested on day 0 (October 12) and at 1, 3, 5, and 7 days (October 13–19) after foliar urea fertilization. On each harvest date, the seedlings were severed at the root collar and placed into 24 bags, each containing either 3 shoots or 3 roots. The shoots were then subjected to washing treatments.

Washing Treatments and Water Analyses

The harvested seedling groups (three seedlings per replicate by eight replicates) were randomly subjected to one of three shoot washing treatments before analysis of foliar N

concentration: (1) washing (W: control): washing for 15 seconds using a sink-mounted vegetable sprayer (standard washing method of the laboratoire de chimie organique et inorganique de la DRF, MFFP du Québec, for analyses of nutrients in seedling tissues); (2) washing + soaking (WS): same as the W treatment but followed by soaking for 5 minutes; or (3) no washing or soaking (NWS). These three washing treatments were done 0, 1, 3, 5, and 7 days after foliar fertilization to evaluate their efficiency in removing urea residues from the needle surfaces and their effect on foliar N concentration. Washing treatments on day 0 were carried out 1 hour after fertilization.

After washing seedling shoots, the water used for washing or for soaking (3.2 L [0.8 gal] for W, 2 L [0.5 gal] for WS) was transferred to 250 ml (10 oz) plastic bottles. The bottles from all six treatments (two washing treatments by three fertilization treatments) were frozen and sent to the laboratory for analyses. Following filtration of the water samples (PVDF filters of 0.45 μm), urea-N concentration was determined by high-performance liquid chromatography with diode array detector (model 1200, Agilent Technologies, Waldbronn, Germany) using a Sugar-Pak I column (Waters, Milford, MA). Because the two washing treatments were carried out using a composite sample of three seedling shoots for each fertilization treatment, the urea-N concentration in the washing water was then calculated for one seedling. Thereafter, the amount of urea-N in each water sample was obtained by multiplying the volume by its concentration.

Seedling Measurements

Following the washing treatments, shoot and root tissues of the nine treatments (three fertilization treatments by three washing treatments) were oven-dried for 48 hr at 65 °C (149 °F). In addition, seedlings harvested on day 7 were measured for height, root-collar diameter, shoot, root, and total dry mass (24 seedlings per treatment by 9 treatments) and a visual assessment of foliar color or burning damage. The average morphology (± standard error: SE) for all treatments at day 7 was height (26.7 ± 0.3 cm, [10.7 in]), diameter (3.43 ± 0.03 mm, [0.14 in]), shoot dry mass (3.47 ± 0.05 g, [0.12 oz]), root dry mass (1.73 ± 0.02 g, [0.06 oz]), and total dry mass (5.20 ± 0.06 g, [0.18 oz]).

Needle, stem, and root samples (n = eight composite samples of three seedlings per replicate per treatment) were analyzed for total N concentrations (N_{tot}) using a LECO Nitrogen Determinator (model TruMac N, LECO Corporation, St. Joseph, MI). On day 0, these tissues were placed in the oven 2 hours after foliar urea fertilization; therefore N_{tot} tissue concentration on day 0 corresponds to 2 hours. Nitrogen content of each seedling part (needles, stem, roots, and total) was calculated (concentration by dry mass) to accurately reflect nitrogen uptake and accumulation (Timmer and Miller 1991).

Statistical Analyses

In this experiment, the first factor (foliar urea fertilization) was applied on day 0 (October 12) while the second factor (washing of seedling shoots) was carried out 0, 1, 3, 5, and 7 days (October 12–19) after fertilization. Because the washing treatments were applied on each of the five harvest dates, their effects are confounded in part with the effects of days, so two different approaches were used to analyze the data: (1) a linear mixed-effects model for repeated measurements (days 0 to 7) and (2) a linear mixed-effects model for each day.

First, a linear mixed-effects model for repeated measurements was carried out to determine the effects, over time, of the three foliar urea fertilization treatments on several variables using a variance-covariance matrix to account for the correlation between measurements done on the same experimental units. This matrix was chosen to minimize the likelihood value of the model while using as few parameters as possible. Thus, for all the variables presented in the results section (N concentrations and contents in needles, stems, shoots, roots, and seedlings), the selected variance-covariance matrix was variance components (VC), except for root N content where heterogeneous compound symmetry (CSH) was chosen. Fertilization treatments, days, and their interaction were introduced in the model as fixed-effect factors, whereas the replicates of fertilization treatments were considered as a random-effect factors. The three washing treatments (considered as subreplicates) and their interaction with days were also considered as random-effect factors. When the interaction between the fertilization treatments and the days was significant, comparisons between the fertilization treatments were performed for each of the five harvest dates (0, 1, 3, 5, and 7 days after fertilization).

Second, a linear mixed-effects model for each day was carried out to compare the washing treatments and to determine if an interaction occurred between them and the fertilization treatments. Fertilization and washing treatments, as well as their interaction, were introduced in the model as fixed-effect factors, whereas the replicates of fertilization treatments were considered to be random-effect factors. When the interaction

between the fertilization and the washing treatments was significant, comparisons were first carried out between the fertilization treatments for each washing treatment and second between the washing treatments for each fertilization treatment.

All of the statistical analyses were performed using the MIXED procedure of SAS (version 9.2, SAS Institute, Cary, NC, United States). When required, a simulation-based approach was used to assess differences (Westfall et al. 1999). Normality of the residuals was confirmed using the Shapiro-Wilk's statistic, whereas the homogeneity of variance was validated using standard graphical methods. Differences were deemed significant when $p < 0.05$.

Results

Nitrogen Concentration and Content

The interaction between fertilization treatments and day was significant for foliar N concentration ($p = 0.0177$) and content ($p = 0.0009$). At day 0 (2 hours after fertilization), foliar N concentrations of U and US seedlings were 8 and 10 percent, respectively, higher than that of NF seedlings (figure 3a). After 3, 5, and 7 days, U and US seedlings continued to have significantly greater foliar N concentrations than NF seedlings, although no significant differences existed between U and US seedlings (figures 3a and 4a). After 7 days, N content was 23 and 27 percent higher than NF seedlings for U and US seedlings, respectively (figure 4b). Also, U and US seedlings appeared greener than the controls and had no burning damage from urea or from urea plus surfactant on their needles.

Although the interaction between the fertilization treatments and day was not significant for shoot N concentration ($p = 0.1577$), it was significant for shoot N content ($p = 0.0013$). During the 7-day study, U and US seedlings had significantly greater shoot N concentrations than NF seedlings, but these two fertilized treatments did not differ significantly (figure 3b). After 7 days, shoot N concentration of U and US seedlings were 9 and 13 percent higher, respectively, compared with unfertilized seedlings, (figures 3b and 4a), and their N contents were each increased 27 percent (figure 4b).

The interaction between the fertilization treatments and days was significant for root N concentration ($p = 0.0016$) and content ($p = 0.0028$). At day 0, root N concentration of U and US seedlings was 7 and 8 percent higher, respectively, compared with NF seedlings, (results not shown). After 1, 3, and 5 days (results not shown) and at day 7 (figure 4a), however, root N concentration did not differ significantly among the

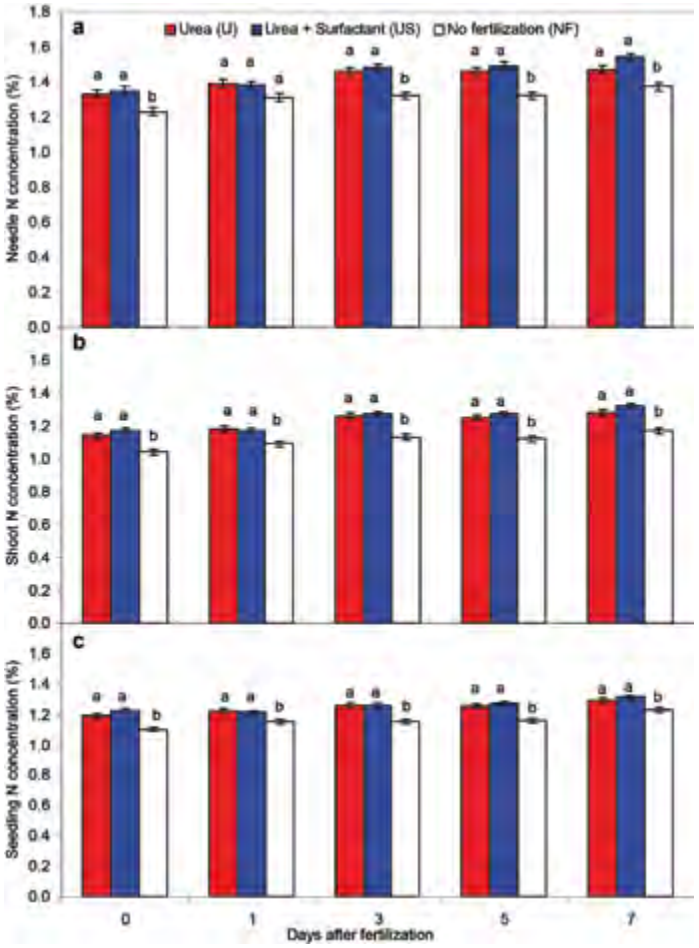

Figure 3. (a) Needle, (b) shoot, and (c) seedling nitrogen concentration (percent) of 2+0 containerized black spruce seedlings 0, 1, 3, 5, and 7 days after urea foliar fertilization. For each day, bars with different letters differ significantly at the 5-percent level (n = 8 composites samples ± SE).

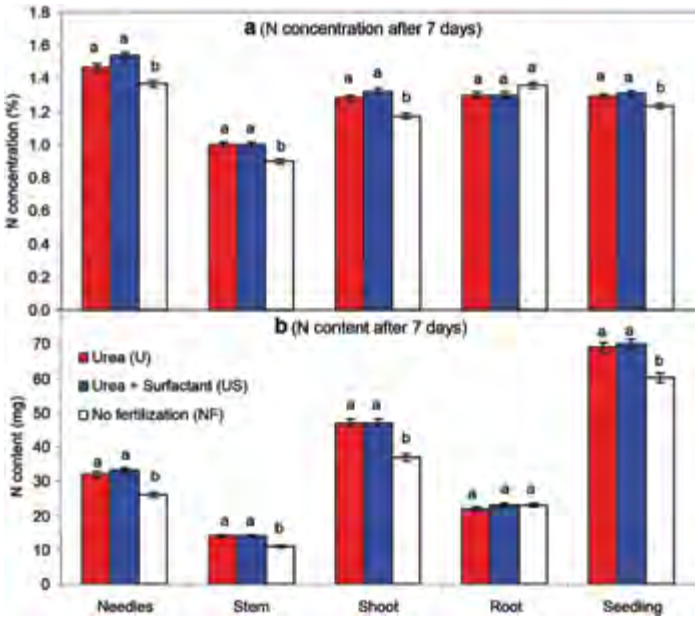

Figure 4. (a) Nitrogen concentration and (b) nitrogen content of seedling parts (needles, stems, shoots, roots, and entire seedling) 7 days after urea foliar fertilization of 2+0-containerized black spruce. For each seedling part, bars with different letters differ significantly at the 5-percent level (n = 8 composites samples ± SE).

three fertilization treatments. The root N content did not differ significantly among fertilization treatments after 0, 1, 3, and 5 days (results not shown) or at day 7 (figure 4b).

Although the interaction between the fertilization treatments and days was not significant for seedling N concentration (p = 0.1187), it was significant for seedling N content (p = 0.0059). During the 7-day study, U and US seedlings had a significantly greater seedling N concentration than NF seedlings, but these two fertilization treatments were not significantly different (figure 3c). At day 0, compared with NF seedlings, seedling N concentration of U and US seedlings had increased 8 and 11 percent, respectively (figure 3c). After 7 days, compared with NF seedlings, seedling N concentration of U and US seedlings had increased 5 and 7 percent, respectively (figures 3c and 4a), and seedling N content of U and US seedlings had increased 15 and 17 percent, respectively (figure 4b).

Effect of Seedling Shoot Washing Treatments on Foliar Nitrogen Concentration

Shoot washing treatments and fertilization treatments had significant interaction for foliar N concentration ($p \leq 0.0077$). Foliar N concentrations were significantly lower for seedlings from either washing treatment compared with the control treatment (figure 5). U and US seedlings had no significant difference in foliar N concentration between washed (W) seedlings and washed and soaked (WS) seedlings after 0, 1, and 3 days (figure 5). The same trend was also observed after 5 and 7 days (results not shown).

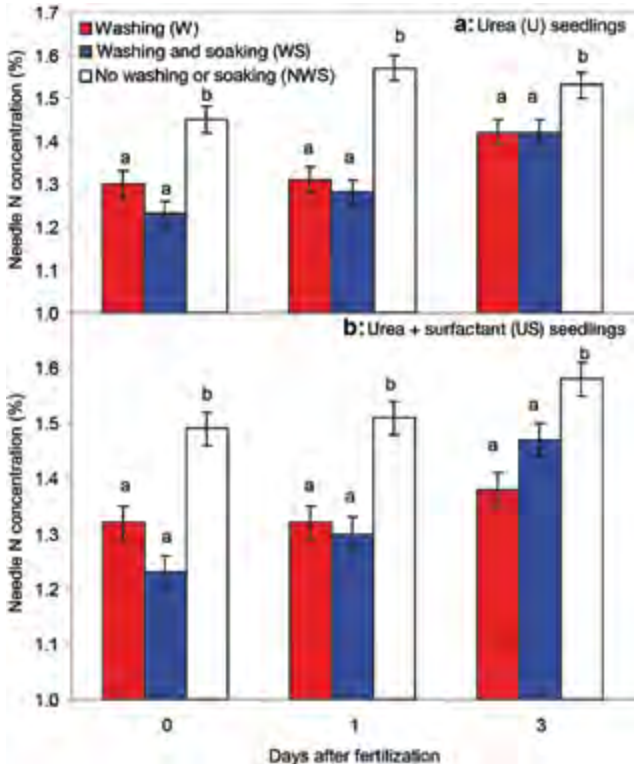

Figure 5. Effect of seedling shoot washing treatments on 2+0 black spruce seedling foliar nitrogen concentration 0, 1, and 3 days after foliar fertilization with (a) urea or (b) urea + surfactant. For each day, bars with different letters differ significantly at the 5-percent level (n = 8 composites samples ± SE).

Amount of Urea Removed by the Washing Treatments

Washing and fertilization treatments had significant interaction on days 0 (p = 0.0261), 1 (p = 0.0056), 3 (p < 0.0001), and 5 (p < 0.0001) and very close to being significant on day 7 (p = 0.0506). As expected, water used for washing treatments of unfertilized seedlings contained no urea-N (results not shown). For each fertilization treatment, however, urea-N content in the water used for washing was significantly greater (approximately 90 percent of the total) over time than that used for soaking (figure 6). In addition, more urea-N was removed by washing seedlings from the U treatment than those from the US treatment (figure 6). The urea-N content in washing water for each fertilization treatment decreased over time indicating foliar urea absorption by U and US seedlings during the 7-day study (figure 6).

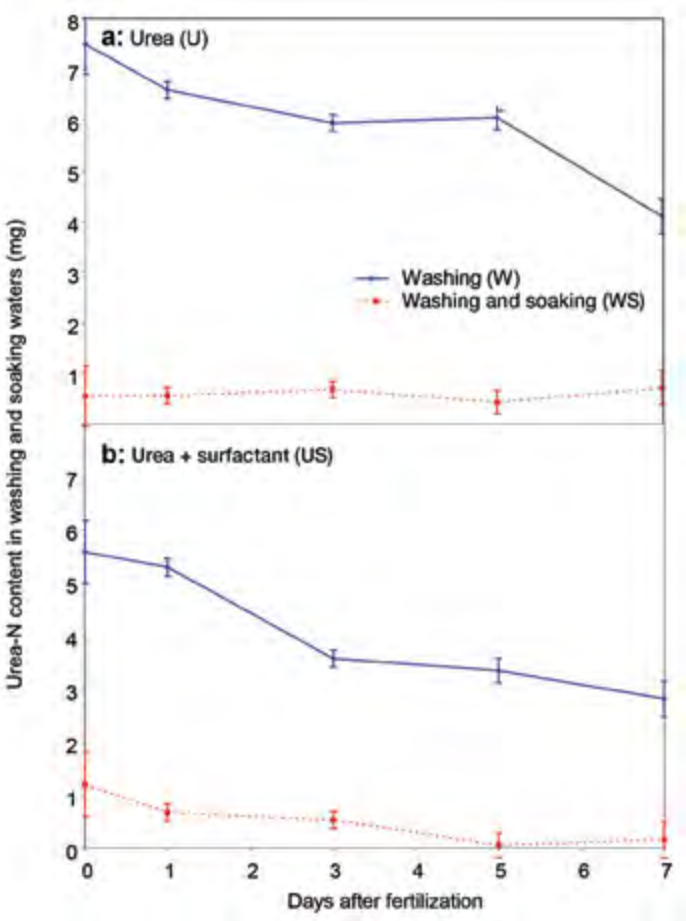

Figure 6. Urea-N content in the water used for washing or water used for soaking after washing 2+0 black spruce seedling shoots 0, 1, 3, 5, and 7 days after foliar fertilization with (a) urea or (b) urea + surfactant (n = 8 composites samples ± SE).

Discussion

The use of foliar urea fertilization after fall budset of containerized 2+0 black spruce seedlings promoted a rapid (within 2 hours) increase in foliar N concentration under forest nursery conditions compared with unfertilized seedlings. This effect was still observed after 7 days. With *Pinus radiata* seedlings, all foliar-applied ^{15}N urea was taken up within 6 hours (Coker et al. 1987, Coker 1991), and with apple (*Malus domestica* Borkh) trees, most foliar uptake of ^{15}N urea occurred within 2 days (Dong et al. 2002).

Rapid urea absorption and increased foliar N concentration following foliar urea fertilization have also been observed in agriculture and horticulture studies (Handreck and Black 1984, Alexander and Schroeder 1987, Gooding and Davies 1992, Wojcik 2004). Cain (1956) reported rapid foliar uptake of urea by a number of horticultural crops during the first few hours after application, with 80 percent absorption by cacao (*Theobroma cacao* L.) leaves within 2 hours. The concentration of urea solution used in our study (146 g per L [1.2 lb per gal]) was much higher than the level of 20 to 50 g per L (0.2 to 0.4 lb per gal) recommended by Mengel and Kirkby (2001) to avoid leaf burning. We did not, however, observe any burning damage or any leaf damage in our study, nor in a preliminary study of foliar urea fertilization with 2+0 black spruce and a urea solution of 80 g per L [0.7 lb per gal] (Gagnon 2011).

Foliar fertilization also led to significant increases in N concentration and content of other seedling parts (stems, shoots, and entire seedlings). Increased N reserves in seedlings at the end of the season should help to improve their performances after outplanting (Dumroese 2003, Landis et al. 2010). Foliar urea fertilization carried out after budset had the advantage of increasing the foliar N concentration of seedlings without affecting shoot height, thereby preventing dilution of foliar N during the seedlings' active growth phase (Dumroese 2003). Such a situation (no dilution effect of N) was also obtained when foliar urea fertilization was applied during bud initiation of containerized ponderosa pine seedlings, leading not only to higher foliar N concentration, but also to improved viability and a 45-percent increase in root collar diameter (Montville et al. 1996).

The efficiency of foliar urea fertilization is often improved by using surfactants (Alexander and Schroeder 1987, Gooding and Davies 1992, Wojcik 2004). In our experiment, however, adding a surfactant to the urea solution did not significantly improve the N status of containerized 2+0 black spruce seedlings. Although seedlings fertilized with a urea and surfactant mixture had slightly greater foliar, shoot, and seedling N concentrations than those that received only urea, these two treatments did not differ significantly. The success of surfactant use for urea foliar fertilization is variable and depends on several factors, such as the pulverisation system and the surfactant used, the dose of urea applied and concentration of urea solution, and the environmental conditions (temperature, relative humidity, wind) at the time of fertilization (Alexander 1986, Alexander and Schroeder 1987, Coker et al. 1987, Gooding and Davies 1992, Wojcik 2004).

To our knowledge, this experiment and a preliminary one conducted by Gagnon (2011) are the first to test the effects of washing treatments on foliar N concentration. Our results showed that washed seedlings had significantly reduced foliar N concentration compared with those that were not washed. Foliar N concentration of seedlings that were washed and soaked, however, was not significantly lower than those that were only washed. It is likely that most of the urea residue on the needle surface was removed by the washing treatment, which occurred before the soaking treatment, as evidenced by the significantly higher N content in water used for the washing treatment compared with water used for the soaking treatment. Because foliar N concentration of fertilized seedlings was not significantly affected by these two washing treatments, we conclude that the current method for washing seedling shoots without soaking is appropriate to remove most (90 percent) of the fertilizer residues on the needles. Urea-N content in water collected from the W treatment decreased rapidly over time indicating foliar urea absorption of U and US seedlings, which was confirmed by the rapid increase of their foliar N concentration during 7 days.

Conclusion

The results of this 7-day study with containerized 2+0 black spruce seedlings showed that foliar fertilization of urea applied after fall budset is a useful tool for rapidly increasing the foliar N concentration of conifer seedlings without affecting their shoot height growth. This tool can help Québec nursery growers to meet the physiological quality criteria (minimum of 1.6 or 1.8 percent N concentration depending on container size) for container-grown conifer seedlings.

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Forest Nursery Seedling Production in the United States—Fiscal Year 2013

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Background

This report is the second USDA, Forest Service, Forest Inventory and Analysis (FIA) and State and Private Forestry (S&PF) report of tree planting in the United States based on forest seedling production data gathered directly from forest nurseries. *Forest Nursery Seedling Production in the United States* replaces the USDA Forest Service, State and Private Forestry (S&PF) annual *Tree Planting in the United States* report that was discontinued in 2000. The original *Tree Planting in the United States* report was based on data reported each year by the 50 State forestry agencies and by Federal land management agencies.

In 2010, FIA and S&PF worked with land-grant universities located in the southern, northeast, and western regions to develop a means for collecting forest tree seedling production as a proxy for tree planting data. The data are reported in this new *Forest Nursery Seedling Production in the United States—Fiscal Year 2013* report and were developed using an empirical source and a calculated approximation.

Current Methodology

The empirical data for the *Forest Nursery Seedling Production in the United States—Fiscal Year 2013* report were produced using the same protocols that were used to generate the *Forest Nursery Seedling Production in the United States—Fiscal Year 2012* report. The Forest Service collected data in collaboration with Auburn University, the University of Idaho, and Purdue University, which are the same universities that collected data for the 2012 report. Each university was responsible for collecting forest tree seedling production data directly from the forest and conservation nurseries that grow forest tree seedlings in its region of the United States (Auburn University collected from 12 States in the Southeast, 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 a 5-, 7-, or 10-year period and compiled as an average annual estimate for the 2011 evaluation. FIA estimates of acres of trees planted by State may not correlate with the estimates produced by nursery production surveys. Assessing total acres by region provides a reasonable comparison between the two methods, however. 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).

Assumptions

The following assumptions were used in compiling this report.

1. *The number of seedlings reported by the participating forest and conservation nurseries was the number of shippable seedlings produced for distribution in the 2013 planting season (i.e., seedlings to be planted from the fall of 2012 to the spring of 2013).*

   Some species of forest seedlings require two or more growing seasons to reach accepted forest and conservation seedling size standards, so not all seedlings in production at a nursery at any given time are considered shippable (i.e., available for distribution). Therefore, only shippable seedlings were counted.

2. *All seedling production reported in this survey met the grading standards for the respective nurseries (i.e., cull seedlings were not included in the estimates).*

   Production estimates are often based on seedbed inventories of seedlings meeting grading standards. For cases in which nurseries ship seedlings by weight, as opposed to examining and counting each seedling, landowners and tree planters often plant every seedling that is shipped to them, including any cull seedlings.

3. *Seedling production data were collected from all the major nurseries that produced forest and conservation tree seedlings for the 2013 planting season.*

   Considerable effort was made to contact all producers of forest and conservation seedlings. The universities collecting the survey data reported, with few exceptions, that the major producers were included in the results.

4. *All seedlings reported in this survey were produced for reforestation and conservation projects.*

   Some of the nurseries that participated in this survey produce seedlings for ornamental use, Christmas tree production, or other horticultural purposes. Private nurseries were asked to report only seedling production destined for conservation and reforestation planting.

5. *Forest tree seedlings remain in the general area where they are produced.*

   Forest and conservation seedlings are routinely shipped across State borders and at times across international borders. It is assumed that, on average, the number of seedlings imported into a State is equal to the number of seedlings exported from that State. In the Lake States (Michigan, Minnesota, and Wisconsin), a significant amount of container seedlings produced in Canada are used for planting on State- and county-owned land and industrial forest land. Estimates of the amount of seedlings shipped from Canada to the Lake States were obtained from the State nursery programs and industrial forest landowners in these States. Similarly, seedlings produced in forest industry nurseries in Canada are planted on industrial forest land in Maine. Estimates of the amount of Canadian-grown seedlings planted in Maine were provided by the forest industry. Seedlings are also imported from Canada for planting in the Pacific Northwest, but no estimates of the amount of Canadian seedlings imported in 2013 were available for this region.

6. *Dividing the number of seedlings shipped from forest and conservation nurseries by the average number of stems planted per acre in a specific State is an appropriate proxy of the number of acres of trees planted in the 2013 planting season.*

   These estimations do not include direct seeding or natural forest regeneration activities.

7. *Respondents to the production survey reported only hardwood and conifer trees produced.*

   Nurseries were asked not to include shrubs in their production estimates. Many conservation and restoration plantings include shrubs and herbaceous plants to address wildlife, biodiversity, or other management objectives. The average number of stems planted per acre used to estimate acres planted may include shrubs in some operations. Using only tree production to estimate acres planted would result in an underestimate of planted acreage where a mixed planting of shrubs and trees occurred. For example, in the Northern United States, State-owned nurseries produced more than 4 million shrubs in addition to the more than 54 million trees reported for the 2013 planting season.

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Table 1. Hardwood and conifer tree seedling production and acres planted for each State and each region during the 2012–2013 planting year.

State	Hardwood seedlings produced	Hardwood acres planted[a]	Conifer seedlings produced	Canadian conifer imports	Conifer acres planted[a]	Total seedlings produced	Total acres planted[a]	FIA data average acres planted[l]
SOUTHEAST								
Florida[b]	239,400	435	33,785,000	–	61,427	34,024,400	61,863	140,247
Georgia[b]	8,857,438	16,104	307,267,279	–	558,668	316,124,717	574,772	196,602
North Carolina[b]	404,700	736	65,464,000	–	119,025	65,868,700	119,761	108,286
South Carolina[b]	4,966,350	9,030	117,785,935	–	214,156	122,752,285	223,186	55,479
Virginia[b]	662,000	1,204	25,410,000	–	46,200	26,072,000	47,404	92,707
Regional Totals	**15,129,888**	**27,509**	**549,712,214**	**–**	**999,477**	**564,842,102**	**1,026,986**	**593,320**
SOUTH CENTRAL								
Alabama[b]	890,944	1,620	100,388,247	–	182,524	101,279,191	184,144	263,720
Arkansas[b]	14,626,125	26,593	90,250,500	–	164,092	104,876,625	190,685	156,973
Kentucky[b]	1,966,810	3,576	234,920	–	427	2,201,730	4,003	1,479
Louisiana[b]	4,929,468	8,963	15,951,102	–	29,002	20,880,570	37,965	166,984
Mississippi[b]	1,957,058	3,558	88,125,000	–	160,227	90,082,058	163,786	192,746
Oklahoma[b]	805,400	1,464	3,168,125	–	5,760	3,973,525	7,225	25,434
Tennessee[b]	1,635,000	2,973	5,093,000	–	9,260	6,728,000	12,233	22,489
Texas[b]	54,000	98	88,226,000	–	160,411	88,280,000	160,509	113,125
Regional Totals	**26,864,805**	**48,845**	**391,436,894**	**–**	**711,703**	**418,301,699**	**760,549**	**942,949**
NORTHEAST								
Connecticut	–	–	–	–	–	–	–	–
Delaware	–	–	–	–	–	–	–	–
Massachusetts	–	–	–	–	–	–	–	–
Maryland[b]	1,102,600	2,005	1,834,450	–	3,335	2,937,050	5,340	–
Maine[b, k]	–	–	–	17,660,000	22,075	17,660,000	22,075	8,284
New Hampshire[b]	13,555	25	255,760	–	465	269,315	490	–
New Jersey[b]	658,147	1,197	214,255	–	390	872,402	1,586	–
New York[i]	154,852	172	601,435	–	668	756,287	840	203
Pennsylvania[b]	5,797,925	10,542	22,861,947	–	41,567	28,659,872	52,109	1,391
Rhode Island	–	–	–	–	–	–	–	–
Vermont	–	–	–	–	–	–	–	–
West Virginia[b]	840,720	1,529	148,805	–	271	989,525	1,799	–
Regional Totals	**8,567,799**	**15,468**	**25,916,652**	**17,660,000**	**68,771**	**52,144,451**	**84,239**	**9,878**
NORTH CENTRAL								
Iowa[e]	722,850	1,205	173,850	–	290	896,700	1,495	–
Illinois[h]	1,168,495	2,686	219,420	–	504	1,387,915	3,191	5,062
Indiana[d]	2,329,271	3,583	1,369,168	–	2,106	3,698,439	5,690	1,331
Michigan[j, k]	1,492,800	2,714	10,850,050	1,546,500	12,397	13,889,350	15,111	11,899
Minnesota[e, k]	1,127,280	2,050	8,784,830	3,000,000	19,641	12,912,110	21,691	20,059
Missouri[c]	3,750,919	8,623	797,642	–	1,834	4,548,561	10,456	–
Ohio[c]	10,000	23	–	–	–	10,000	23	3,775
Wisconsin[f, k]	1,603,283	2,004	9,045,862	1,930,000	13,720	12,579,145	15,724	9,413
Regional Totals	**12,204,898**	**22,888**	**31,240,822**	**6,476,500**	**50,492**	**49,922,220**	**73,380**	**51,540**

Table 1. Hardwood and conifer tree seedling production and acres planted for each State and each region during the 2012–2013 planting year. (continued)

GREAT PLAINS								
Kansas[b]	88,925	162	146,000	–	265	234,925	427	–
North Dakota[b]	20,500	37	1,252,000	–	2,276	1,272,500	2,314	–
Nebraska[b]	112,000	204	1,493,249	–	2,715	1,605,249	2,919	–
South Dakota[b]	661,156	1,202	351,364	–	639	1,012,520	1,841	–
Regional Totals	**882,581**	**1,605**	**3,242,613**	**–**	**5,896**	**4,125,194**	**7,500**	**0**
INTERMOUNTAIN								
Arizona[b]	43,000	78	–	–	–	43,000	78	–
Colorado[b]	41,000	75	577,000	–	1,049	618,000	1,124	–
Idaho[b]	13,000	24	1,350,000	–	2,455	1,363,000	2,478	4,287
Montana[b]	213,650	388	41,600	–	76	255,250	464	5,142
New Mexico[b]	6,900	13	86,800	–	158	93,700	170	–
Nevada[b]	9,047	16	118	–	<1	9,165	17	–
Utah	–	–	–	–	–	–	–	–
Wyoming	–	–	–	–	–	–	–	–
Regional Totals	**317,750**	**577**	**2,055,400**	**–**	**3,737**	**2,373,150**	**4,314**	**9,429**
ALASKA								
Alaska	–	–	–	–	–	–	–	806
PACIFIC NORTHWEST								
Oregon[g]	1,301,000	3,717	37,508,827	-	107,168	38,809,827	110,885	88,379
Washington[g]	1,127,374	3,221	34,264,518	-	97,899	35,391,892	101,120	54,179
Regional Totals	**2,428,374**	**6,938**	**71,773,345**	**–**	**205,067**	**74,201,719**	**212,005**	**142,558**
PACIFIC SOUTHWEST								
California[h]	–	–	15,600,000	–	34,667	15,600,000	34,667	29,535
Hawaii[h]	44,000	97.78	–	–	–	44,000	98	–
Regional Totals	**44,000**	**98**	**15,600,000**	**–**	**34,667**	**15,644,000**	**34,764**	**29,535**
TOTALS	**66,440,095**	**123,928**	**1,090,977,940**	**24,136,500**	**2,079,809**	**1,181,554,535**	**2,203,738**	**1,780,014**

[a] Acres planted were estimated assuming:

[b] 550 stems/acre.

[c] 435 stems/acre.

[d] 650 stems/acre.

[e] 600 stems/acre.

[f] 800 stems/acre.

[g] 350 stems/acre.

[h] 450 stems/acre.

[i] 900 stems/acre.

[j] 1,000 stems/acre.

[k] Totals include an estimate of conifers produced in Canada for distribution to neighboring States, bareroot imports for ME, and container for other States.

[l] Average annual acreage planted estimated for all States (2011 evaluation) on 5-year cycles, except AL, LA, MS, and NC are 7-year cycles and AZ, CA, CO, HI, ID, MT, NV, NM, OR, and WA are 10-year cycles; data generated by R. Harper.

Table 2. Bareroot and container tree seedling production for each State and each region during the 2012–2013 planting year.

State	Bareroot	Container[a]	Total seedlings produced
SOUTHEAST			
Florida	28,822,400	5,202,000	34,024,400
Georgia	169,957,219	146,167,498	316,124,717
North Carolina	49,778,700	16,090,000	65,868,700
South Carolina	121,131,535	1,620,750	122,752,285
Virginia	26,072,000	–	26,072,000
Regional Totals	**395,761,854**	**169,080,248**	**564,842,102**
SOUTH CENTRAL			
Alabama	97,305,069	3,974,122	101,279,191
Arkansas	104,876,625	–	104,876,625
Kentucky	2,201,730	–	2,201,730
Louisiana	20,300,570	580,000	20,880,570
Mississippi	82,257,058	7,825,000	90,082,058
Oklahoma	3,912,900	60,625	3,973,525
Tennessee	6,728,000	–	6,728,000
Texas	88,280,000	–	88,280,000
Regional Totals	**405,861,952**	**12,439,747**	**418,301,699**
NORTHEAST			
Connecticut	–	–	–
Delaware	–	–	–
Massachusetts	–	–	–
Maryland	2,937,050	–	2,937,050
Maine	–	–	–
New Hampshire	269,315	–	269,315
New Jersey	202,402	670,000	872,402
New York	728,550	27,737	756,287
Pennsylvania	28,305,872	354,000	28,659,872
Rhode Island	–	–	0
Vermont	–	–	0
West Virginia	989,525	–	989,525
Canada	–	17,660,000	17,660,000
Regional Totals	**33,432,714**	**18,711,737**	**52,144,451**
NORTH CENTRAL			
Iowa	896,700	–	896,700
Illinois	1,387,300	615	1,387,915
Indiana	3,556,439	142,000	3,698,439
NORTH CENTRAL (CONTINUED)			
Michigan	12,342,850	–	12,342,850
Minnesota	6,613,110	3,299,000	9,912,110
Missouri	4,177,243	371,318	4,548,561
Ohio	–	10,000	10,000
Wisconsin	10,649,145	–	10,649,145
Canada	–	6,476,500	6,476,500
Regional Totals	**39,622,787**	**10,299,433**	**49,922,220**
GREAT PLAINS			
Kansas	–	234,925	234,925
North Dakota	1,200,000	72,500	1,272,500
Nebraska	870,000	735,249	1,605,249
South Dakota	997,501	15,019	1,012,520
Regional Totals	**3,067,501**	**1,057,693**	**4,125,194**
INTERMOUNTAIN			
Arizona	–	43,000	43,000
Colorado	–	618,000	618,000
Idaho	120,000	1,243,000	1,363,000
Montana	–	255,250	255,250
New Mexico	–	93,700	93,700
Nevada	–	9,165	9,165
Utah	–	–	–
Wyoming	–	–	–
Regional Totals	**120,000**	**2,253,150**	**2,373,150**
ALASKA			
Alaska	–	–	–
PACIFIC NORTHWEST			
Oregon	15,701,046	23,108,781	38,809,827
Washington	14,351,288	21,040,604	35,391,892
Regional Totals	**30,052,334**	**44,149,385**	**74,201,719**
PACIFIC SOUTHWEST			
California	–	15,600,000	15,600,000
Hawaii	–	44,000	44,000
Regional Totals	**–**	**15,644,000**	**15,644,000**
TOTALS	**907,919,142**	**273,635,393**	**1,181,554,535**

[a] ME, MI, MN, and WI include container seedlings produced in Canada.

Guidelines for Authors

Editorial Policy

Tree Planters' Notes (TPN) is a journal dedicated to technology transfer and publication of information relating to nursery production and outplanting of trees and shrubs for reforestation, restoration, and conservation. TPN welcomes manuscripts on any subject within the scope of the journal. Examples of past issues can be viewed at the Reforestation, Nurseries, and Genetics Resources Web site: http://www.RNGR.net/publications/tpn.

Submitting Articles

Send electronic files by e-mail or traditional mail to:

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Include a cover letter with the mailing address, e-mail address, and telephone number of the corresponding author. Please label all CDs carefully with name(s) of author(s) and file(s). The editor will notify you of receipt of the manuscript. Revisions should be returned to the editor at the above address in a timely manner. Page proofs sent after acceptance and layout must be proofread carefully and returned promptly to the address that accompanies the proofs.

Format

Text: Manuscripts must be in a Microsoft Word compatible format and must be IBM-PC compatible. Refrain from special formatting. Please **do not embed** photos, maps, charts, graphs, or figures into the manuscript text.

After the manuscript title, list the complete name(s), title(s), affiliation(s), and address(es) of the author(s). Include a brief abstract (150 words or less) followed by the text, references, figure captions, and tables. Total length of the paper should not exceed 6,000 words.

Tables: Create tables using the Table feature in Word; refrain from formatting tables with tabs or the space bar. Include tables at the end of the manuscript. Tables should be logical and understandable without reading the text. Tables should be numbered consecutively (table 1, table 2, table 3, etc.), and each table should be referred to in the text.

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Style

TPN uses the spelling, capitalization, hyphenation, and other styles recommended in the U.S. Government Printing Office Style Manual, as required by the U.S. Department of Agriculture (USDA). Try to keep titles concise and descriptive; subheadings and bulleted material are useful and help readability. As a general rule of clear writing, use the active voice (e.g., write "Nursery managers know…" and not, "It is known…"). Note: modern, proportionate fonts no longer require double spacing after each sentence.

- Use numerals when referring to money, time, and measurement and for all numbers 10 and above.
- Abbreviate all units, except those with no numerical value (for example, "results are provided in parts per million" in contrast to "only 0.05 ppm was effective").
- Provide both English and metric units for all values.
- Nomenclature—Use common names of organisms, if available, in the title, abstract, and text. At first mention in the abstract and in the text, provide the scientific name in italics with authority in parentheses, e.g. white pine (*Pinus strobus* L.). The taxonomic standard for USDA publications is the Integrated Taxonomic Information System online database (http://www.itis.gov).

References

List citations in the text by date, oldest first, then alphabetically by author (for example, Roberts 1988, Garcia and Calhoun 1994, Baker 2009, Wong 2009, Smith et al. 2013). Separate citations with a comma unless citing more than one publication by the same author; when that occurs, use a semicolon (for example, Jackson 2009, 2013; Anderson 2012).

- In the references section, list references alphabetically by author, then by date, with oldest first. When there are multiple articles by the same author, list first those articles with one author only, oldest first; then list articles with two authors, and so on, alphabetically by second author, oldest first.
- For journal articles, use the full journal name, rather than the abbreviated version.

- For meeting proceedings, follow the date and location of the meeting with the city of publication and publishing body. If the proceedings are a part of a Government publication series, put that information after the publishing body.

- For online resources, provide the URL and the month accessed.

Examples

Journal article:	Graham, J.S.; Joyner, P.A. 2011. Tree planting in Alaska. Tree Planters' Notes. 54(2): 4–11.
Entire book:	Pallardy, S.G. 2008. Physiology of woody plants. 3rd ed. Burlington, MA: Academic Press. 454 p.
Chapter in book:	Goorahoo, D.; Sharma, F.C.; Adhikari, D.D.; Benes, S.E. 2011. Soil-water-plant relations. In Stetson, L.E.; Mecham, B.Q., eds. Irrigation. 6th ed. Falls Church, VA: Irrigation Association: 23–73. Chapter 3.
Article in proceedings:	Dumroese, R.K.; Jacobs, D.F.; Davis, A.S.; Pinto, J.R.; Landis, T.D. 2007. An introduction to subirrigation in forest and conservation nurseries and some preliminary results of demonstrations. In Riley, L.E.; Dumroese, R.K.; Landis, T.D., tech. coords. National proceedings, forest and conservation nursery associations—2006. Proc. RMRS-P-50. Fort Collins, CO: U.S. Department of Agriculture, Forest Service, Rocky Mountain Research Station: 20–26.
Thesis or dissertation:	Akgul, A. 2004. Performance of slash pine (*Pinus elliotti engelm*) containerized rooted cuttings and bare-root seedlings established on five planting dates in the flatlands of western Louisiana. College Station, TX: Texas A&M University. 91 p. Ph.D. dissertation.
Online resource:	Bardon, R.E.; Megalos, M.A.; New, B.; Brogan, S., eds. 2010. North Carolina's forest resources assessment: a statewide analysis of the past, current and projected future conditions of North Carolina's forest resources. Raleigh, NC: North Carolina Division of Forest Resources. 489 p. http://www.ncforestassessment.com. (January 2011).

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