Questions and Considerations for the Next Generation of Seedling Fertilization Researchers

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Abstract

Although 20th century researchers published numerous fertility trials, only a few bareroot nursery studies have been installed since 2000. Most seedling nutrition publications during the past 5 decades have involved either container-grown stock or stock grown in greenhouses. The next generation of researchers might consider testing old theories about bareroot nursery fertilization. Some long-held claims about nursery fertilizers were apparently based on faulty logic, while others were based solely on hydroponic research. This paper provides some questions that should be addressed by the next generation of researchers who choose to follow the scientific method. This paper was presented at the Joint Meeting of the Northeast Forest and Conservation Nursery Association and Southern Forest Nursery Association (Pensacola, FL, July 17–19, 2018)

Introduction

My first experiences with nursery fertilization trials began in 1973 as a graduate student at North Carolina State University. After I published a few papers (South and Davey 1983, Boyer and South 1985), I was confident that I knew something about fertilizers. The more I talked with nursery managers, however, the more I realized there was a lot I didn't know. I began to question some of the assumptions found in textbooks. The more I learned about problems with soil test interpretation and growing seedlings, the more questions I asked. For example, why do we rely so much on assumptions and opinions instead of relying on the scientific method? Why did we assume some nitrogen (N) and potassium (K) should be applied before sowing seed? Why did some say the optimum pH for growing hardwoods is pH 6 to 7? Why were these theories taken as facts? Why didn't anyone question some of the unfounded claims? After listening closely to first-hand experience provided by wise nursery managers, I realized there is a big difference between "book learning" and a "real world" nursery experience.

When questions about fertilizer practices are not answered, myths, mistakes, and stagnation will prevail. As a result, some 50-year old practices are still used because of tradition (figure 1). For example, it was

Figure 1. After sowing, some managers apply granular fertilizers (left) using equipment similar to that used during the first half of the 20th century. In contrast, about 87 percent now prefer to apply nutrient solutions using soluble fertilizers (right). As a result, some managers use granular diammonium phosphate (18-46-0) to stimulate seedling growth while others spray liquid polyphosphate (10-34-0). Due to a lack of solid scientific evidence, it is not known which method produces a more rapid growth response. (Photos by Warren Bryant and Michael Neel, 2018)

Table 1. A selected list of 52 reforestation nurseries in the Southern United States (2018) including location and initial year of production. Nurseries with an asterisk are members of the Southern Forest Nursery Management Cooperative.

State	Nursery	City	Stock type	Year	Ownership
Alabama	Selma*	Selma	Bareroot	1974	ArborGen
	White City	Verbena	Bareroot	1980	Summit
	Pine Hill*	Camden	Bareroot	1980	IFCO
	Elberta*	Elberta	Both	1991	Rayonier
	Westervelt*	Tuscaloosa	Container	1981	Westervelt
	Atmore	Atmore	Container	2017	PRT
Arkansas	Baucum*	North Little Rock	Bareroot	1958	State of AR
	Bluff City*	Bluff City	Bareroot	1980	ArborGen
	Magnolia*	Magnolia	Bareroot	1972	Weyerhaeuser
Florida	Buckeye	Perry	Bareroot	1956	Private
	Dwight Stansel	Wellborn	Bareroot	1986	Private
	Andrews*	Chiefland	Both	1956	State of FL
	Central Florida	Mayo	Both	1984	Private
	Superior Trees	Lee	Both	1953	Private
	Labelle*	Labelle	Container	2009	IFCO
	Blanton	Madison	Container	2001	Private
Georgia	Flint River*	Byromville	Bareroot	1987	State of GA
	Shellman*	Shellman	Bareroot	1996	ArborGen
	Jesup*	Jesup	Bareroot	1956	IFCO
	Native Forest	Chatsworth	Bareroot	1978	Private
	K&L Forest*	Buena Vista	Bareroot	1999	Private
	Pinecrest	Buena Vista	Bareroot	2007	Private
	Bell Farms	Bellville	Bareroot	1988	Private
	Rutland Forest	Lenox	Bareroot	1986	Private
	Bellville*	Claxton	Both	1957	ArborGen
	Moultrie*	Moultrie	Container	2003	IFCO
	Meeks' Farms	Kite	Container	1996	Private
	Forestate Growers	Douglas	Container	2001	Private
	Lewis Taylor	Tifton	Container	1997	Private
	Whitfield	Twin City	Container	1996	Private
	Zellner Farms	Culloden	Container	2010	Private
Kentucky	John Rhody	Kentucky Dam	Bareroot	1956	State of KY
	Morgan	West Liberty	Bareroot	1961	State of KY
Louisiana	Evans*	Deridder	Container	2014	IFCO
Mississippi	Shubuta*	Shubuta	Bareroot	1981	IFCO
	Delta View	Leland	Bareroot	1987	Private
	Pearl River*	Hazlehurst	Both	1998	Weyerhaeuser
North Carolina	Claridge*	Goldsboro	Both	1954	State of NC
	Washington*	Washington	Both	1970	IFCO
	Linville River*	Linville	Container	1970	State of NC
	Bodenhamer	Rowland	Container	2000	Private
Oklahoma	Engstrom*	Goldsby	Both	1947	State of OK
South Carolina	Blenheim*	Blenheim	Bareroot	1983	ArborGen
	Quail Ridge*	Aiken	Bareroot	1985	Weyerhaeuser
	Taylor*	Trenton	Both	1959	State of SC

Table 1 ***(continued)***

State	Nursery	City	Stock type	Year	Ownership
Tennessee	East Tennessee*	Delano	Bareroot	1989	State of TN
Texas	Bullard*	Bullard	Bareroot	1982	ArborGen
	Caddo*	Jasper	Bareroot	1976	TX Timber
	West Texas	Idalou	Container	1978	State of TX
Virginia	Augusta*	Crimora	Bareroot	1967	State of VA
	Garland Gray*	Courtland	Both	1986	State of VA

once believed that K applied in September would "promote pine seedling dormancy" (Sweetland 1978). In fact, out of the 37 bareroot nurseries in the Southern United States (table 1), about 29 still apply K in the fall to "harden off" seedlings (Starkey et al. 2015). This practice continues even though it does not "harden off" seedlings (Andivia et al. 2012, Benzian et al. 1974, Birchler et al. 2001, Bryan 1954, Dierauf 1982, Gleason et al. 1990, Hinesley and Maki 1980, Jokela et al. 1998, Rowan 1987, South and Donald 2002, South et al. 1993, Stone 1986). Unfortunately, research is of little use when it is ignored.

I have seen the origin of several other myths (Khan et al. 2014, South 1987, 2015, 2016, 2018), and I even assisted in keeping one alive for years (South 2013). It is easy to start myths, especially when applying precautionary principles to fertilization regimes and seedling quality and publishing it. Misinformation and myths can be stopped simply by asking the right questions and generating credible, scientific data. This article encourages the next generation of researchers to ask questions and test hypotheses to reevaluate unsubstantiated practices that have persisted for decades.

[Note: Except for years prior to 2000, nutrient levels mentioned in this paper were determined using the Mehlich 3 procedure. B = boron. Ca = calcium. Cu = copper. Fe = iron. kPa = kilopascal. Mg = magnesium. Mn = manganese. Mo = molybdenum. Na = sodium. P = phosphorus. S = sulfur. Zn = zinc. ppm = parts per million. CEC = cation exchange capacity. OM = organic matter.]

Researchable Questions

How Much N Is Really Needed?

Research has shown that N fertilization in the nursery affects tree growth after transplanting (Grossnickle and South 2017, van den Driessche 1991), which may explain why the application of N has increased over time (table 2). Even so, opinions can influence the rate of N fertilization. For example, some who want to avoid labor required for top-pruning believe that they can achieve this by limiting N fertilization. In contrast, those who practice top-pruning (South 1998) may apply additional N to increase wood production, perhaps as much as 14 percent at age 9 years (Jackson 2016).

N fertilizer regimes vary among nursery managers. For example, total amounts applied to pine seedbeds (over the growing season) can range from 56 kg N/ha (Kormanik et al. 1994, McNabb 1985) to 218 kg N/ha (Stone 1986) to more than 300 kg N/ha (Dierauf and Chandler 1995, Rodríguez-Trejo et al. 2003). Total amounts applied by researchers to grow pine seedlings in containers may vary by more than 700 kg N/ha (table 3). In addition, a few researchers recommend managers apply higher rates of N at the first spring fertilization than at applications made 4 to 6 weeks later (Birge et al. 2006, Timmer 1997). As a result, foliar N concentration of different genotypes and stock types vary during summer and early winter (figure 2). Although foliar N of longleaf pine (*Pinus palustris* Mill.) seedlings may be less than 1 percent when measured after September (Dumroese et al. 2005, Jackson et al. 2012, Rodríguez-Trejo and Duryea 2003, South et al. 2005), freeze tolerance is greater when levels are above 1.4 percent N (Davis et al. 2011, Dumroese et al. 2013). Growth after outplanting is also reduced when foliar N levels are

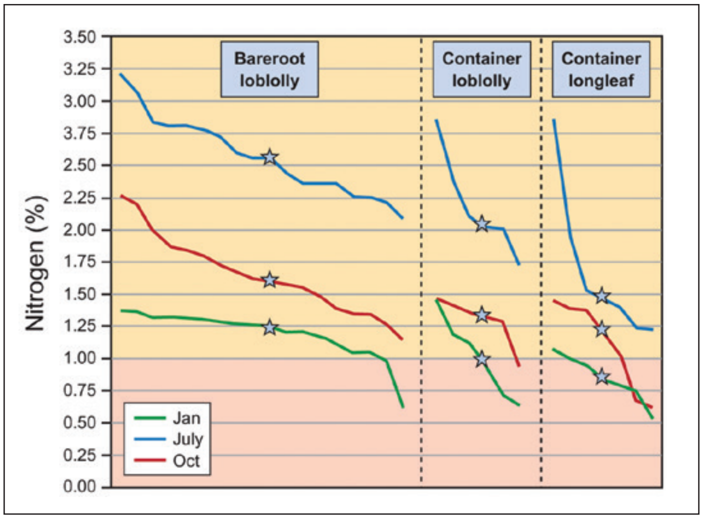

Figure 2. Foliar nitrogen (N) of pine seedlings declines over time, in part, due to carbohydrate dilution. It also varies by species, stocktype, and nursery. These data represent a range of N values in July, October, and January for 20 bareroot nurseries and 7 container nurseries, with the median value for each line marked by a star (adapted from Starkey and Enebak 2012).

below 1 percent (figure 3, Barker 2010, Jackson et al. 2012, Larsen et al. 1988). Excess N application can contribute to groundwater pollution (South 1994), while inadequate amounts can reduce seedling performance. These wide-ranging N application rates can occur due to species, soil conditions, growth stage, and target seedling specifications but can also be driven by unsubstantiated ideas about formulations, freeze tolerance, growth responses, and nutrient loading. Future research is needed to better define optimum N rates needed under varying circumstances.

Do Pines Really Need More K Than N?

Although most mineral soils contain 3,000 to 100,000 kg of K/ha (Sparks 2001), a sandy slash pine (*Pinus elliottii* Engelm.) nursery (20 cm deep) usually contains less than 200 kg/ha of available K. When soil tests indicate less than 60 kg K/ha, many managers in the Southern United States fertilize pine seedlings with more K than N (224 kg K/ha and less than 200 kg N/ha). The high use of K originated from Wilde (1958), who said a nursery soil should contain 4 times more K than N. There are no data, however, to show that pines need to be fertilized with more K than N. In fact, "some nursery researchers report that K fertilization is not needed in forest tree nurseries" (May 1984: 12-22) and others suggest K fertilization will likely not increase cover-crop yields (Khan et al. 2014).

At the time of lifting, 1-0 loblolly pine (*Pinus taeda* L) seedlings may contain 17 to 55 percent more N than K (Boyer and South 1985, Nelson and Switzer 1985). It is not clear, however, that pine seedlings need this much K to function effectively. The amount of K present in seedlings at lifting depends on how much K fertilizer is applied during the growing season and not on how much K is required for growth (Switzer and Nelson 1956). Therefore, when little or no K is applied during the growing season, seedlings lifted in January contain 100 to 300 percent more N than K (Danielson 1966, Miller et al. 1985, Sung et al. 1997, Switzer and Nelson 1956, Wall 1994). There is insufficient data to show that reducing K fertilization in the

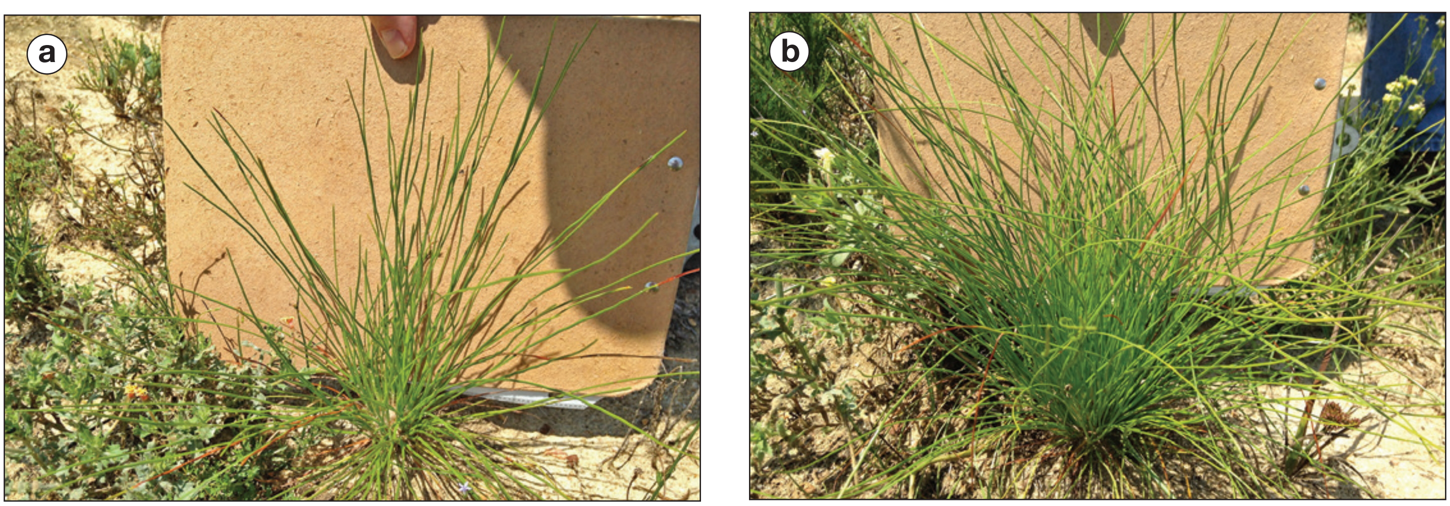

Figure 3. Both longleaf pine seedlings in these photos (June 26, 2016; 6 months after planting) were well fertilized and top-pruned multiple times in the nursery. The seedling on the right was grown with slow-release fertilizer in the container plug and therefore had about 119 percent more foliar nitrogen (N) applied than the seedling on the left (Starkey and Nadel 2017). At outplanting, the average root-collar diameter was the same (6.3 mm) for both seedlings but foliar N concentration of the seedling on the right was higher (1.5 percent) compared with the one on the left (1.2 percent). As a comparison, container-grown longleaf pine seedlings that are managed to produce short needles (that do not need to be top pruned) typically have foliar N levels in October (before outplanting) that are less than 1.0 percent. (Photos by Ryan Nadel, 2016)

Table 2. Examples of how nursery fertilizer practices for bareroot loblolly and slash pine seedlings have changed over time.

		Year:	**1935**	**1958**	**1978**	**1998**	**2018**	**2018**
		Sowing Date:	**April 28**	**May 5**	**April 25**	**April 15**	**April 20**	**Cost**
Fertilizer	**Application Month**		kg/ha	kg/ha	kg/ha	kg/ha	kg/ha	$/ha
6-10-7 (cover crop)	April		224					
4-10-7	April			896				
$MgSO_4$	March				112			
10-20-10	March				336			
$(NH_4)_2SO_4$	June				112			
$(NH_4)_2SO_4$	July				112			
$(NH_4)_2SO_4$	Aug				112			
KCl	Sept				112	112	112	77
$Ca(H_2PO_4)_2\ H_2O$	March					168		
$K_2Mg_2(SO_4)_3$	March					224	280	231
$(NH_4)_2NO_3$	June			56		56		
$(NH_4)_2NO_3$	July			56		56		
$(NH_4)_2NO_3$	July			56		56		
$(NH_4)_2NO_3$	Aug					100		
$(NH_4)_2NO_3$	Aug					100		
UAN 10-0-4 (4 percent S)	June-Aug						210 (10 sprays)	594
B	March					2.7	3.1	68
KCl	March						112	77
Gypsum	March						785	115
Fe - chelated	June			4.5			5	250
Cu - chelated	March						2.2	100
Zn - chelated	March						8	211
20-20-20 + micros	Summer						8 (5 sprays)	99
TOTAL N/ha			13	96	103	165	218	1,822

UAN = 50 percent urea and 50 percent ammonium nitrate

nursery has a negative effect on subsequent seedling field performance. Most reforestation sites have adequate K.

When soil K is low at time of sowing, can nursery managers fertilize conifer seedlings using an N/K ratio of 3? For loblolly pine, seedlings grew well when fertilized with a N/K ratio of 2.3 (figure 4), and a ratio of 4 resulted in maximum shoot growth in a greenhouse (Blackmon 1969). Ratios greater than 4 are sometimes used in bareroot seedbeds (table 4). Applying extra K (which decreased the N/K ratio to 1) had no effect on growth of Douglas-fir (*Pseudotsuga menziesii* [Mirb.] Franco) seedlings (Shaw et al. 1998). Would applying only 70 kg/ha of K during the growing season (with 210 kg/ha of N) affect performance of pine seedlings? At one sandy loam nursery that contained 68 ppm exchangeable K at sowing, adding 300 kg/ha of K before sowing had no effect on seedling growth (Switzer and Nelson 1956). In another trial, irrigation leached K from the soil and yet seedling growth increased (figure 5). Early studies suggested that applying too much K to sandy nurseries "may result in a considerable loss by

Figure 4. Loblolly pine seedlings in this photo (July 25, 2018) were fertilized with 64 kg/ha of potassium (K) before sowing and received no additional K fertilization. Soil contained 24 ppm extractable K in May and 9 ppm K in October (Mehlich 3). These seedlings were fertilized with an N/K ratio of 2.3, and by October, needles contained 1.8 percent nitrogen (N) and 0.8 percent K. Assuming 10,000 kg/ha of seedlings were harvested (at 0.7 percent K for the total seedling), the amount of K removed at harvest would equal 70 kg/ha. (Photo by David South, 2018)

leaching, especially if heavy rains or excessive irrigation follow the application" (Wilde and Kopitke 1940: p. 331).

It may be that tradition, without sufficient scientific evidence, is the reason that growers apply more K than N. This practice needs to be investigated by the next generation to determine the appropriate levels of K to apply.

When Should We Apply Mg?

With the exceptions of N, Cl, Fe, Mo, and Na, soil tests may help determine when there is a need to fertilize seedbeds. "Trigger values" are used to determine when to apply P, K, Ca and Mg, but there is no consensus as to what these values should be (table 5) or how much of each element should be applied once the soil test value drops below the trigger value. For example, when a soil contains 34 ppm Mg (table 5), some experts may add Mg while others would delay fertilization until the value drops below 25 ppm. The cost of applying 35 kg of Mg (e.g., 350 kg/ha of Epsom salts) might exceed $150 per ha and, at some nurseries, this rate may result in no growth advantage (figure 6). A top-dressing rate this high might even reduce growth of some conifers (Ruter 1999). At the 25-ppm soil level, researchers have yet to report a response that justifies spending the extra time and money to apply Mg to pine seedbeds. At

Table 3. Nitrogen (N) fertilizer rates for several longleaf pine container studies. Rates assume all N applied enters the cell.

Cells/m²	Container volume	N/cell	N/m²	N/ha	Reference
#	cm³	mg	g	kg	
530	95	40	21.2	212	Sung and Dumroese 2013
936	60	24	22.4	224	Dumroese et al. 2013
364	125	80	29.1	291	Davis et al. 2011
441	98	66	29.1	291	Jackson et al. 2012
581	98	63	>36.5	>365	South et al. 2005
441	98	66	38.3	383	Dumroese et al. 2005
441	98	88	38.8	388	Jackson et al. 2007
366	164	116	>42.5	>425	Sword Sayer et al. 2009
581	113	79	45.7	457	Figure 3- smaller seedling
364	164	112	59.0	590	Haywood et al. 2012
213	336	274	58.4	584	Dumroese et al. 2013
441	144	159	84.0	840	McGuire and Williams 1998
581	113	164	95.5	955	Figure 3 – larger seedling

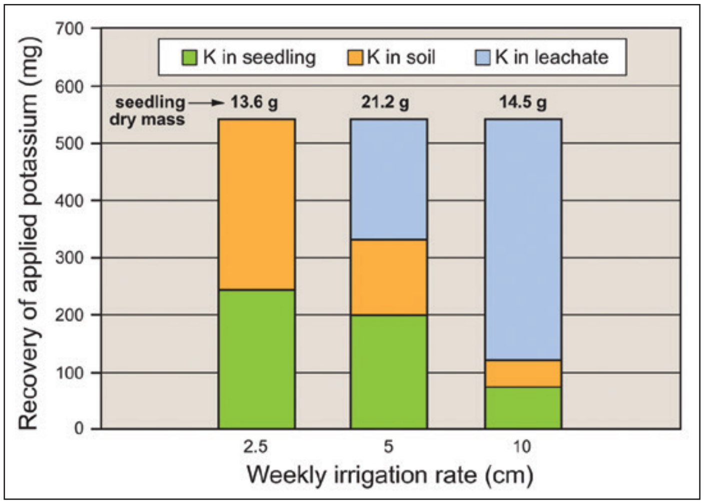

Figure 5. Irrigation rate influenced the amount of potassium (K) leached from containers filled with sand in a greenhouse. The slash pine seedlings grown with the low irrigation rate contained more K but seedlings grown with the middle irrigation rate had more growth (values above bars indicate seedling dry mass). (Adapted from Bengtson and Voigt 1962).

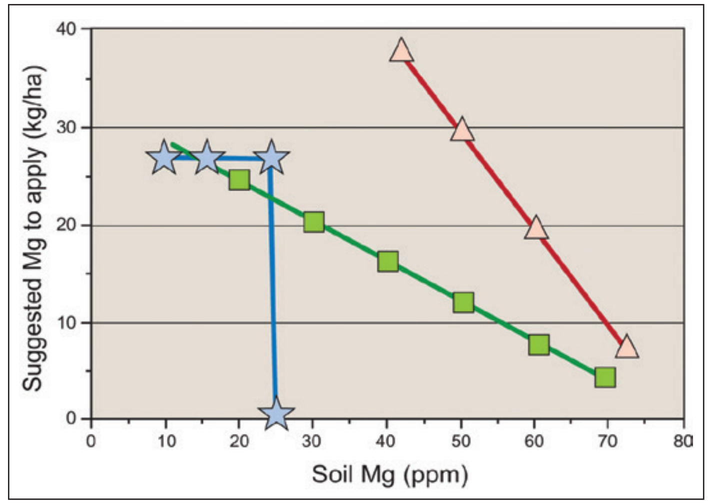

Figure 7. This figure compares three opinions as to how much magnesium (Mg – Mehlich 3) should be applied to the soil before sowing pine seed. Growth of pine seedlings is sometimes unaffected by increasing soil available Mg above 15 to 31 ppm (Edwards et al. 1991, Wall 1994). One professor (stars) recommends applying Mg only when soil tests indicate less than 25 ppm available Mg. In contrast, when soil contains more than 25 ppm available Mg, two agronomists recommend various rates of Mg. For example, when the soil Mg is 50 ppm, one agronomist (squares) recommends applying 12 kg/ha and another (triangles) recommends 30 kg/ha.

some sandy nurseries, pines have been grown in soil that contains only 8 ppm Mg (Munson 1982). Even so, some agronomists recommend adding Mg to pine seedlings when tests indicate the soil contains 50 ppm (figure 7). Clearly, there is a wide range of recommendations and there is a need for more science-based input regarding Mg fertilization.

What Is the Optimum pH for Growing Hardwood Seedlings?

In the past, bareroot hardwood seedlings were thought to grow best in soil ranging from pH 6 to pH 7 (Briggs 2008, Tinus 1980). I, however, reject that theory, since seedling mass of several species can increase when the pH drops below 5.0 compared with higher pH values (Wright et al. 1999, figure 8). Although some species grow well at pH 6 (DesRochers et al. 2003, Melhuish et al. 1990, Sparks 1977), several hardwood species grow well between pH 4 and pH 5.5 (Han et al. 2016, Hauer and Dawson 1996, Herendeen 2007, Lee and Weber 1979, Lutter et al. 2015, Ouimet et al. 1996, Rikala and Jozefek 1990, Salifu et al. 2006, South 1992, South 2019, Villarrubia 1980). “Assessment of a desirable pH range of a given species is quicker and easier than many growth factors often investigated for improving plant growth and should be one of the first factors investigated” (Bryan et al. 1989: p. 64). Hopefully, the next generation will establish empirical, species-specific trials to determine optimum nursery pH for hardwoods.

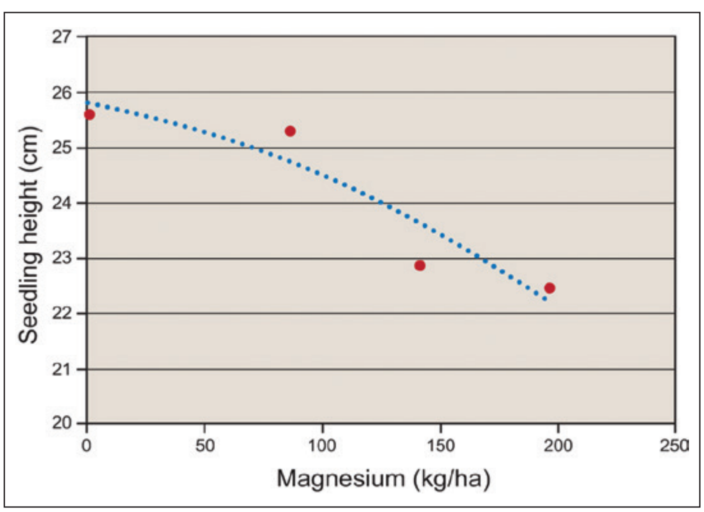

Figure 6. Effect of top-dressing of Epsom salts on height of pine seedlings at the Indian Mound Nursery in Texas (Wall 1994). A traditional F-test indicated no treatment effect ($\alpha = 0.05$).

How Much Irrigation Is Really Needed?

Insufficient irrigation can reduce seedling growth (Dierauf and Chandler 1991, Haase and Rose 1994, May et al. 1961, Pessin 1938, Shi et al. 2018, Williams et al. 1988). Likewise, excessive soil moisture for too long reduces seedling growth (Bengtson and Voigt 1962, Retzlaff and South 1985, South and Carey 1999, South and Starkey 2010). When managers use the precautionary principle, overirrigation can occur

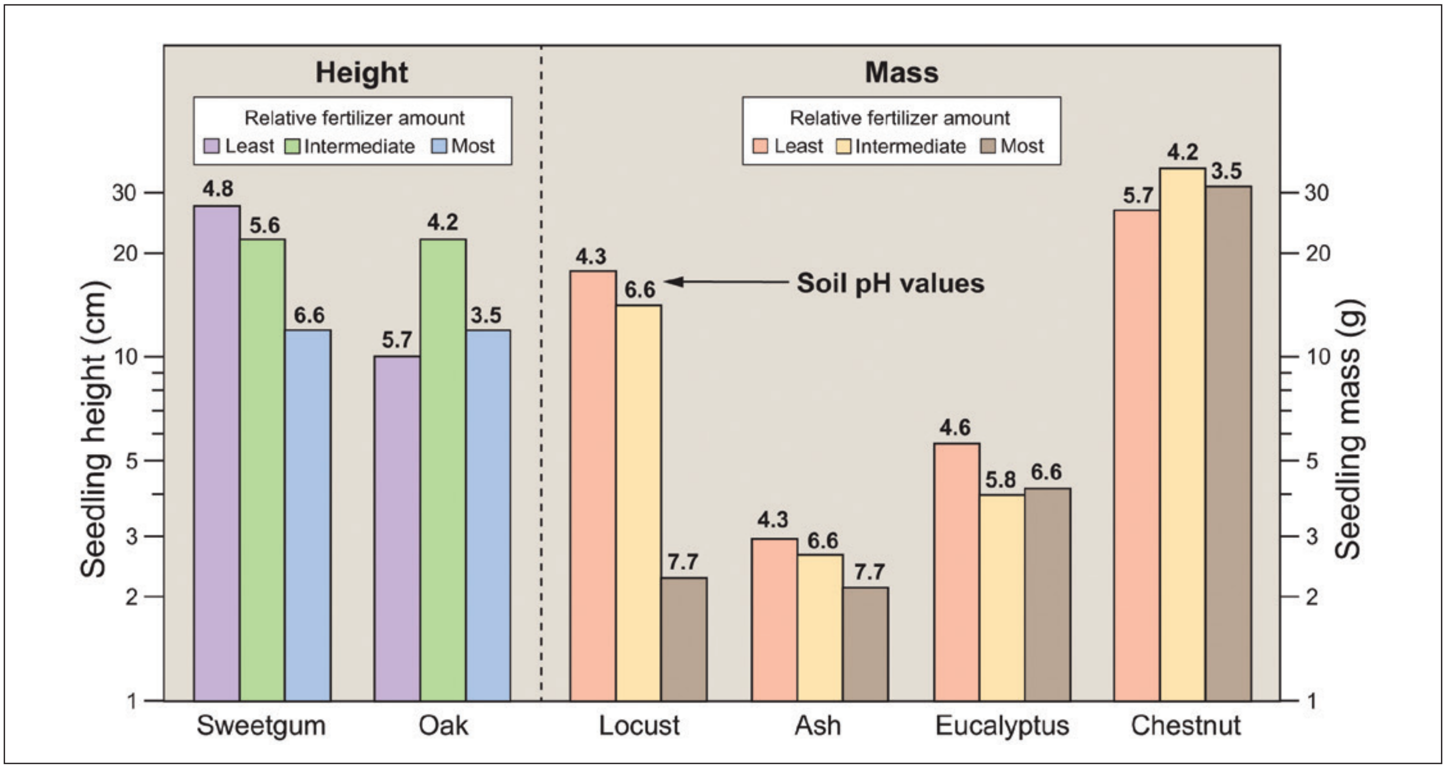

Figure 8. Growth of oak (*Quercus rubra* L.) and chestnut (*Castaneta dentata* Mill.) can be reduced by adding too much aluminum sulfate (see bars with pH < 3.6) while too much lime (see bars with pH > 6.0) can reduce growth of sweetgum (*Liquidambar styraciflua* L.), black locust (*Robinia pseudoacacia* L.), green ash (*Fraxinus pennsylvanica* Marshall) and *Eucalyptus urophylla* S. T. Blake). Absolute amounts of aluminum sulfate (for studies with oak and chestnut) and lime were reported by Yawney et al. 1982 (sweetgum), Davis 2003 (oak), McComb and Kapel 1942 (locust and green ash), Aggangan and Malajczuk 1996 (Eucalyptus), and Herendeen 2007 (chestnut).

in both container nurseries (Dumroese and Haase 2018) and bareroot nurseries (Johnson 1986, Retzlaff and South 1984). For example, applying more than 51 mm of irrigation after June reduced shoot mass of pine seedlings at nurseries in Alabama and Georgia (May et al. 1961). When compared to no irrigation, shoot mass at the Alabama nursery was 11 percent less when seedbeds were irrigated with 6.7 mm/week. Although several managers of pine nurseries in the Southern United States target about 25 mm/week (irrigation plus rainfall), some may apply three times that rate during hot periods in the summer. Future research may find that managers who fertilize with more N (table 2) do so because they apply more irrigation than needed.

The optimum combination of N and irrigation varies with soil texture (Pham et al. 1978, Sloan 1992), nursery location, mulch type, rainfall, and target seedling size. In addition, there likely is an interaction between irrigation rate and N rate (Bumgarner et al. 2008, Cabello et al. 2009, Dierauf and Chandler 1991, Gagnon and Girard 2018, Shi et al. 2018). Applying too much irrigation can leach N (Bengtson and Voigt 1962) and produce needles that are not as green (figure 9). If this interaction affects seedling performance (Dierauf and Chandler 1991), then it will be important for the next generation of researchers to provide details of N rates, irrigation rates, and rainfall rates.

Do Organic Matter Additions Improve Economic Returns?

Sandy nursery soils in the Southern United States average about 1.6 percent OM (South and Davey 1983, Starkey et al. 2015), though some nursery soils produce large seedlings with less than 0.8 percent OM (South et al. 2017). The amount of organic amendments applied to fallow or cover-crop fields is about 115 m^3/ha (Starkey et al. 2015) applied once every 3 to 5 years. In the past, OM was also added as a mulch to seedbeds, but since about 78 percent of managers now use soil stabilizers, only a few still apply sawdust or bark mulch after sowing.

Although there are several biological benefits from increasing soil OM, few studies provide the

Table 4. Selected examples of the ratio of nitrogen (N) and potassium (K) used to grow pines in research trials.

Species	Units	N	K	N/K ratio	Reference
Container					
Pinus taeda L.	ppm	250	40	6.2	Marx et al. 1989
Pinus taeda L.	ppm	100	30	3.3	Woessner et al. 1975
Pinus elliottii Engelm.	ppm	264	86	3.0	Samuelson 2000
Pinus palustris Mill.	mg	80	33	2.4	Davis et al. 2011
Pinus taeda L.	ppm	575	353	1.6	Ruehle and Marx 1977
Pinus tabuliformis Carr.	mg	150	100	1.5	Shi et al. 2018
Pinus palustris Mill.	mg	66	50	1.3	Jackson et al. 2012
Pinus palustris Mill.	g	684	538	1.3	Haywood et al. 2012
Pinus taeda L.	ppm	20	17	1.2	Marx and Barnett 1974
Pinus taeda L.	mg	155	129	1.2	Williams and South 1995
Pinus palustris Mill.	ppm	350	329	1.1	Barnett and McGilvery 1997
Pinus rigida Mill.	g	812	939	0.9	Helm and Kuser 1991
Pinus palustris Mill.	mg	78	120	0.6	Dumroese et al. 2013
Pinus elliottii Engelm.	ppm	80	132	0.6	DeWald et al. 1992
Bareroot					
Pinus taeda L.	kg/ha	185	24	7.7	Greene and Britt 1998
Pinus taeda L.	kg/ha	218	39	5.6	Stone 1986
Pinus taeda L.	kg/ha	205	46	4.4	Marx 1990
Pinus palustris Mill.	kg/ha	392	90	4.4	Hinesley and Maki 1980
Pinus palustris Mill.	kg/ha	250	66	3.8	Hatchell 1985
Pinus strobus L.	kg/ha	125	48	2.6	Bickelhaupt et al. 1987
Pinus elliottii Engelm.	kg/ha	106	41	2.6	Marx et al. 1989
Pinus taeda L.	kg/ha	143	88	1.6	Leach and Gresham 1983
Pinus taeda L.	kg/ha	110	60	1.8	VanderSchaaf and McNabb 2004
Pinus taeda L.	kg/ha	179	108	1.7	South et al. 2017
Pinus elliottii Engelm.	kg/ha	215	123	1.7	Simpson 1985
Pinus strobus L.	kg/ha	180	112	1.6	Dobrahner et al. 2004
Pinus palustris Mill.	kg/ha	352	227	1.6	Rodríguez-Trejo et al. 2003
Pinus caribaea Morelet	kg/ha	188	120	1.6	Ward and Johnson 1985
Pinus taeda L.	kg/ha	171	112	1.5	South and Donald 2002
Pinus elliottii Engelm.	kg/ha	67	51	1.3	Marx et al. 1986
Pinus taeda L.	kg/ha	157	156	1.0	South et al. 2015
Pinus elliottii Engelm.	kg/ha	101	167	0.6	Munson 1982
Pinus elliottii Engelm.	kg/ha	50	88	0.6	McNabb 1985

Figure 9. Loblolly pine seedlings were irrigated when soil tension (6 cm depth) reached either 8 kPa (left) or 30 kPa (right) at the New Kent Nursery (Dierauf and Chandler 1991). Over a 19-week period, the average weekly irrigation applied was 9.9 mm (left) and 2.8 mm (right). By October, the plots receiving less irrigation were a deeper green color. (photo by David South, 1985)

economics of adding OM (Blumenthal and Boyer 1982, Low and Sharpe 1973, Muntz 1944, Rose et al. 1995). Adding too much OM before sowing can be expensive and might reduce seed germination (which might appear to increase seedling mass). In some cases, applying too much OM may reduce seedling growth (Bickelhaupt et al. 1987, Davey 1953, Dierauf 1991, Koll 2009). Application costs are easy to determine (e.g., compost ranges from \$30 to \$200/m^3), but the economic gains from increasing OM by 1 percent (e.g., 13,000 dry kg/10 cm/ha) have not been well documented. Economic returns may not occur when OM has no effect (α=0.05) on conifer seedling size (Barnard et al. 1997, Dierauf 1991, Jacobs et al. 2003, Koll 2009, Mexal and Fisher 1987, Munson 1982, Sloan 1992) or when the amendment reduces subsequent plantation survival (Coleman et al. 1987). At one hardwood nursery in Indiana, applying 200 m^3/ha of compost increased both OM (+0.9 percent) and seedling size (α=0.1) (Davis et al. 2006). Unfortunately, it is not known if the increase in seedling size was caused by a reduction in density (e.g., Mañas et al. 2008). If a reduction in seedling production did occur, the cost of applying compost (e.g., \$10,000/ha) would have resulted in a reduction in profits. Economic analyses on short- and long-term effects of soil OM amendment are needed to determine whether the benefit/cost ratio is greater than 1.

Does Calcium Actually Harden Seedlings?

Some researchers claim that applying Ca nitrate helps bareroot seedlings develop strong cell walls and leaf waxes to protect seedlings during freezer storage (Jacobs and Landis 2009). There appears to be a lack of scientific evidence, however, to support this claim. Although Ca nitrate ($Ca(NO_3)_2$) and Ca ammonium

Table 5. Fertilizer regimes for bareroot loblolly pine seedbeds (> 80 percent sand) differ among individuals who prescribe fertility ranges (Davey 1991, Kormanik et al. 1994, May 1984, Steinbeck et al. 1966) and among individuals who prescribe fertilizers based on Mehlich 3 soil test results. Phosphorus values in bold are for the Brey II method of extraction.

	Desired fertility ranges				Soil test	Fertilizer rates prescribed by		
	Steinbeck	May	Davey	Kormanik	pH 5.7	Professor	Agronomist	Nursery manager
Element	ppm	ppm	ppm	ppm	ppm	kg/ha	kg/ha	kg/ha
Nitrogen		700				168	112	218
Phosphorus	25-38	25-50	**25-200**	**80**	100	0	0	0
Potassium	75-100	37-63	80-	80-90	39	196	93	162
Calcium	300-600	200-300	200-	350-400	150	112	0	173
Magnesium		25-30	25-	50-	34	0	20	31
Boron			0.3-	0.5-1.2	0.3	2.2	1.1	3.1
Zinc			1-30	3-8	1.4	0	2.2	8
Copper			0.8-8	0.3-3	0.7	3.3	1.1	2.2
Manganese			5-200		8	0	6.7	0
Sulfur					12	0	10	84
Iron					100	0	0	5

nitrate ($5Ca(NO_3)_2 \cdot NH_4NO_3 \cdot 10H_2O$) are sometimes used to increase shoot growth of container-grown seedlings (Dumroese and Wenny 1997, Holopainen et al. 1995), Ca nitrate does not increase freeze tolerance of pine seedlings (Christersson 1973, 1975, Montville et al. 1996) and may decrease freeze tolerance of some agronomic crops (Dexter 1935). In Washington, 2-0 seedlings fertilized with urea survived the winter better than seedlings fertilized with Ca nitrate (Radwan et al. 1971). This should not have happened if Ca nitrate really does produce stronger cell walls. More research is needed to define any relationship between calcium and cold hardiness.

Other Questions

Will Researchers Test "Snake-Oil" Products?

Several "snake-oil" products have been sold to farmers and nursery managers; the industry is "plagued" by such products (Cóndor Golec et al. 2007, Underwood 2000, Wagner-Döbler 2003). Promoters for these products boast of their amazing benefits to soil and plants. Most of these products purportedly have profound effects at low dosages. For example, one product (which costs about $62 to apply 0.14 kg/ha) is supposed to aid in the breakdown of OM and enhance micronutrient uptake while improving soil moisture. However, many view such treatments equivalent to a snake-oil remedy (Lazarovits 2001). The more benefits listed, the more likely the product does not work as promised. "Something about high fertilizer prices brings the snake oil salesmen crawling out from the woodwork looking for a quick dollar from folks trying to reduce the cost of raising crops" (Smith 2010: p. 1).

Alleged miracle products typically contain more than 90 percent inert ingredients, with the price of the active ingredients often greater than $150/kg. The benefit/cost ratio is low and the implied activity is very high. The recommended rates are miniscule and yet they supposedly will affect seedling physiology. Before purchasing a product that contains more than 90 percent water, one should search the web for independent publications with valid scientific testing to show the product works as intended. Unfortunately, many products have not been adequately tested (McFarland et al. 2002). One reason is because many researchers (like me) read the product label, calculate the math, and then see no need to test products that are applied at such minuscule rates. Also, some journal editors are prone to reject papers that do not demonstrate a significant treatment effect (Fanelli 2012). Fortunately, some researchers (with other funds) will test and expose products that do not work as advertised (Dumroese et al. 1996, Elegba and Rennie 1984, Miller et al. 1991, Starkey and Enebak 2009, Wolkowski et al. 1985).

Will We Learn Anything Useful from Hydroponic Studies?

Sometimes researchers conduct nutrient trials in hydroponics, since travel is not required and they do not have to deal with "real-world" variables such as rain, hail, irrigation irregularities, and interactions with soil organisms. Unfortunately, conclusions drawn from hydroponic studies often do not apply to bareroot seedbeds (Crannell et al. 1994). For example, the concept of exponential fertigation arose as a hydroponic method for maintaining the relative growth rate (South 1991) of seedlings that were less than 6 weeks old (Ingestad 1982). A constant mean relative growth rate, however, is not an objective of nursery managers and it may not work for older, bareroot seedlings (Birge et al. 2006, McAlister and Timmer 1998, Salifu et al. 2008, Wall 1994). Although researchers have conducted many exponential fertilization trials in pots and containers (where the highest dose of N is applied on the last day of fertilization), this fertilization method is not used in nurseries in Finland (Juntunen and Rikala 2001) nor at the nurseries listed in table 1. Most managers see no disadvantage of achieving sigmoidal seedling growth using conventional fertilization/top-pruning regimes.

Sometimes hydroponic trials have been used to determine which N fertilizers are best for growing conifers in nursery seedbeds. For example, some say that nitrate is not a good source of N and yet some trials cast doubt on that assumption (figure 10). Results from hydroponic trials may favor ammonium sulfate, but after correcting for the beneficial effect of lowering pH in soils, there may be no difference in seedling mass when comparing Ca nitrate with ammonium sulfate (van den Driessche 1971).

Why Do Lab Tests Vary So Much?

Different methods will result in different estimates of both foliar nutrients (Colbert and Allen 1996)

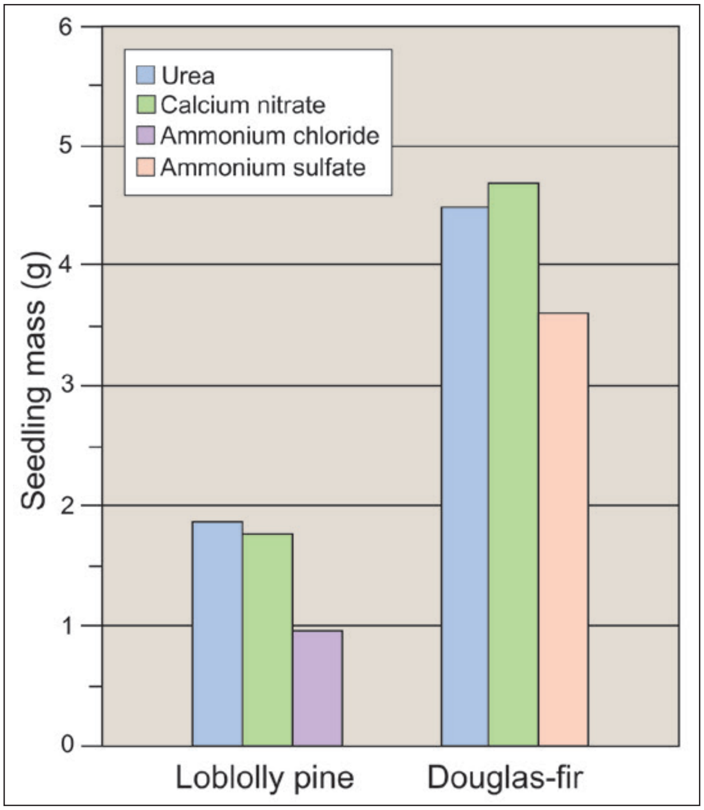

Figure 10. Nitrate fertilizers can produce acceptable growth for conifer seedlings. Loblolly pine seedlings were grown in sand in a greenhouse (Pharis et al. 1964) and fertilized with 75 ppm nitrogen (N) and 200 ppm calcium, then measured 4.5 months after sowing. In a different study, Douglas-fir seedlings were fertilized in a bareroot nursery in May and September with 56 kg N/ha for each application then measured in November (Radwan et al. 1971).

Table 6. Soil test results from the Mehlich 3 extraction procedure vary by laboratory.

Description	Laboratory A	Laboratory B	Laboratory C
pH (water)	5.2	5.1	-
pH (calcium chloride)	-	-	4.2
Buffer pH	7.9	6.9	-
CEC (meq/100g)	2.7	1.0	-
Organic matter (%)	0.48	0.7	-
	ppm	ppm	ppm
Phosphorus	65	44	22
Potassium	34	20	22
Calcium	308	93	63
Magnesium	29	8	34
Sulfur	6	2	-
Boron	0.16	0.5	0.7
Zinc	2	1.6	1.0
Manganese	32	11	3.5
Copper	1.5	0.7	0.5
Iron	120	97	34
Sodium	-	6	343

and soil nutrients (Davey 2002). Furthermore, when using the same soil extraction procedure (table 6), different labs will produce different results (Cools et al. 2004, Jacobsen et al. 2002). For this reason, the "Southern Forest Nursery Soil Testing Program" uses a single laboratory so that soil test results can be compared among different years and different nurseries (South and Davey 1983).

Which Fertilization Philosophy Will the Next Generation Adopt?

Currently, there are three fertilization philosophies: low, medium, and progressive. Some in the "low" group do not apply fertilizers (Hubbel et al. 2018), while others advocate reducing use of chemical fertilizers by 50 percent or more in hopes of benefiting mycorrhiza. Those in the "medium" group fertilize with the goal of producing seedlings that are easy to plant by hand (i.e., more than 80 percent Grade 2 seedlings [Boyer and South 1988]). Those in the "progressive" group adopt regimes to increase seedling growth after transplanting to the reforestation site. Stoeckeler and Arneman (1960: p. 132) said that "With a crop of such high value per acre, the progressive nurseryman also does not hesitate to provide whatever fertilizers or soil amendments are necessary to keep the trees in a state of active growth, high vigor, and good color. As a general rule, fertilized trees are larger and sturdier and have better survival than do unfertilized ones." Progressive growers produce "optimum" seedlings, which meets survival and growth goals (Grossnickle and South 2017) at the minimum cost of reforestation (South and Mitchell 1999). Based on field studies (Autry 1972, Irwin et al. 1998, Jackson et al. 2012, Kabrick et al. 2015, Larsen et al. 1988, South et al. 2015), seedlings (South et al. 2016) produced with the progressive approach can outperform those produced with the low or medium approach.

Recommendations

I have some recommendations for the next generation of researchers. First, be aware of the most common statistical errors (Fowler 1990, Haase 2014, South and VanderSchaaf 2017) and then consult with an experienced statistician before designing your fertilizer trial. Ask for an experimental design with enough statistical power to detect an 8-percent difference in seedbed density and a 7-percent first-year height increase. The statistical power of some fertilizer trials is sometimes low (e.g., figure 6) and therefore variability might not be able to reject a null hypothesis even when a treatment caused a 100-percent increase in a seedling trait. If you do not already know, ask how to use contrast tests to examine linear and quadratic effects because these tests should be used for fertilizer rate trials. In toxicity trials, where the primary question is whether the treatment reduces growth, use a one-sided t-test (South and VanderSchaaf 2017).

When writing a study proposal, state the null hypotheses you wish to test. This might avoid embarrassment if the assumed outcome (i.e., alternative hypothesis) does not occur. Finally, when writing a thesis or dissertation, provide all the data (i.e., individual seedling measurements) in appendices (e.g., Olanin 2017) or in a digital data bank (South and Duke 2010). This will allow others the opportunity to collaborate by asking different questions that may produce additional insights.

Fertilizers typically represent a small percentage of the total growing costs in a nursery. When fertilizers cost $1,800 per ha (table 2), the cost per seedling is less than 0.1 cent, which equates to a small percentage (e.g., 2 percent) of the retail price. Even so, researchers should be aware of fertilizer costs before designing fertilizer trials. In some cases, a chelated fertilizer can cost 90 times more than a non-chelated formulation. It will be a waste of time to conduct research on products that are cost prohibitive (e.g., benefit/cost ratio less than 0.5). Although nursery costs certainly impact profits, the next generation should include the economic effects of fertilizers on short- and long-term outplanting performance. In some cases, spending money for fall-applied fertilizers will reduce the cost per living seedling at the reforestation site (Hinesley et al. 1980, Irwin et al. 1998, Puértolas et al. 2012).

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