Fertilization Practices for Bareroot Hardwood Seedlings

David B. South and Robert E. Cross

Emeritus Professor, School of Forestry and Wildlife Sciences, Auburn University, AL; Chief Productivity Manager, Cross Consultants, Shellman, GA.

Abstract

Large bareroot seedlings tend to be a preferred stocktype for hardwoods because they typically have larger root systems and are less expensive than seedlings grown in small containers. Fertilization can double or triple the dry mass of hardwood roots. A review of the use of fertilizers to produce bareroot hardwood seedlings revealed the total amount of nitrogen applied to seedlings depends on management objectives. The total annual rates can vary from 50 kg/ha to more than 500 kg/ha. Fertilizer regimes used to produce seedlings include a constant-rate method (i.e., each application contains similar amounts of nitrogen), a stepwise method (where initial rates are low and rates increase over the season), and formula method (where a formula is used to determine fertilizer rate). Due to a higher cost, most managers of bareroot nurseries do not use slow-release fertilizers. Some managers apply endomycorrhizal spores as insurance to prevent a phosphorus deficiency (caused by effective soil fumigation). Because micronutrient deficiencies are more likely to occur in neutral and alkaline soils, many hardwoods are grown at pH 4.5 to 5.5. Most trials in bareroot seedbeds indicate no growth benefit from K fertilization. Documented cases of Mg deficiencies in hardwood nurseries are rare and sulfur deficiencies might be overlooked in some nurseries. At nurseries with less than 1 percent organic matter, a proper fertilization regime will produce a good crop of hardwood seedlings.

Introduction

Methods used to produce hardwood seedlings have evolved over time. At one time, “shifting nurseries” were located close to reforestation sites. Once soil nutrients were depleted and weed populations increased, the temporary nurseries were abandoned. Permanent bareroot nurseries required “large needs” for fertilizer (Schenck 1907, p. 74). For example, fertilizers needed to produce 1 million seedlings might amount to 59, 7, and 36 kg of kainit (salts of potassium), superphosphate, and whale guano, respectively. Due to the cost of these fertilizers, Schenck (1907) would fertilize seedbeds using wood ashes, legumes, and compost made from street sweepings, kitchen refuse, loam, and burnt lime.

Fertilization practices today are quite different from those used 120 years ago and the species grown are different as well. In the Southern States, the demand for alder, cottonwood, and black locust (see table 1 for species’ scientific names) have declined, while demand for oaks has increased (table 1). Approximately 55 million hardwood seedlings were produced in the United States in 2016 (Hernández et al. 2018), with about 80 percent produced in bareroot nurseries in the South and Northeast (Enebak 2018, Pike et al. 2018). Demand for bareroot hardwoods in the South has doubled since 1966, but production has been declining since about 2004. In 2017, only about 39 million hardwood seedlings were produced in the United States (Haase et al. 2019), mostly in bareroot nurseries. For hardwood seedlings, the ratio of container seedlings to bareroot seedlings is about 1:8 in the Northeast (Pike et al. 2018) and about 1:142 in the South (figure 1). In the South, about 87 percent of bareroot hardwood seedlings are produced in five States (Alabama, Arkansas, Florida, Georgia, and Tennessee).

There are two primary reasons why bareroot hardwoods are the preferred stock type. First, bareroot hardwoods typically have larger roots than container-grown stock. Oak seedlings with larger root systems tend to survive better than those with smaller root systems (Alkire 2011, Kormanik et al. 1998, Schempf 2018). Oak seedlings grown in 0.75 L containers may have half the roots as 1-0 bareroot seedlings (Clark and Schlarbaum 2018, Dixon et al. 1981, dos Santos 2006, Salifu et al. 2009, Wilson et al. 2007). Although root mass of hardwoods grown in 11.3 L containers is larger than bareroot seedlings (Shaw et al. 2003, Walter et al.

Table 1. Annual production of hardwood seedlings in southern bareroot nurseries has varied by species and amount over time (based on data from Boyer and South 1984, Enebak 2018, Rowan 1972).

Species	Common Name	1966	1980	2017
		Million seedlings		
Acer spp.	Maple	–	–	–
Alnus glutinosa (L.) Gaertn.	Black alder	0.065	0.410	–
Alnus rubra Bong.	Red alder	–	–	–
Betula spp.	Birch	–	–	–
Caryea illinoensis (Wangenh.) K. Koch	Pecan	–	–	3.75
Cedrela odorata L	Cerdo	–	–	–
Cornus florida L.	Dogwood	0.395	0.492	0.401
Fraxinus pennsylvanica Marsh.	Green ash	0.313	0.647	0.542
Juglans nigra L.	Black walnut	0.240	0.147	0.114
Liquidambar styraciflua L.	Sweetgum	0.721	1.722	0.992
Liriodendron tuliperfera L.	Yellow poplar	2.078	0.601	0.642
Platanus occidentalis L.	Sycamore	0.635	1.243	0.858
Populus deltoides Bartr. Ex Marsh.	Cottonwood	3.120	0.610	–
Quercus spp.	Oaks	0.193	0.814	13.880
Quercus nigra L.	Water oak	–	–	–
Quercus rubra L.	Red oak	–	–	–
Quercus texana Buckley	Nuttall oak	–	–	–
Robinia pseudoacacia L.	Black locust	3.171	3.059	–
	Others	0.934	3.568	4.663
TOTAL		11.865	13.313	22.467

2013), the production cost is higher. This cost differential is the other reason why bareroot is preferred for hardwood seedlings. The retail price of oak seedlings may range from $0.40 (bareroot), to $1 (0.15 L container) to $11 (11.3 L container). Thus, due to the higher cost of container stock and the acceptable survival of properly planted bareroot stock, most oak plantations in the Eastern United States are planted with bareroot stock (Dey et al. 2008, Gentry 2020).

One million oak seedlings harvested in November may contain 552 kg N and 96 kg P (dos Santos 2006), but these estimates depend on several factors. For example, when oaks are grown without fertilization, one hectare of seedbeds might contain less than 120 kg N and weigh half as much as fertilized seedlings (table 2). Therefore, to maintain soil productivity and to produce good-quality seedlings, nursery managers use a variety of fertilization methods. To document the variability of bareroot hardwood fertilization practices, we conducted a literature review and also provide some observations from over 40 years of personal experience working in bareroot nurseries. It is ironic that most hardwood fertilizer research in the 21st century involves growing in containers, whereas most fertilizers used to produce hardwood seedlings are applied in bareroot nurseries.

[Abbreviations: Al = aluminum. AN = ammonium nitrate. B = boron. Ca = calcium. Cl = chloride. Cu = copper. Fe = iron. GA = green ash, K = potassium, Mg = magnesium. Mn = manganese. Mo = molybdenum. N = nitrogen. Na = sodium. P = phosphorus. S = sulfur. SG = sweetgum. YP = yellow poplar. Zn = zinc. ppm = parts per million. Cation exchange capacity = CEC. OM = organic matter. UAN = urea ammonium nitrate. US = unspecified state. Soil pH was measured in water except in one study where a calcium chloride buffer (CCB) solution was used.]

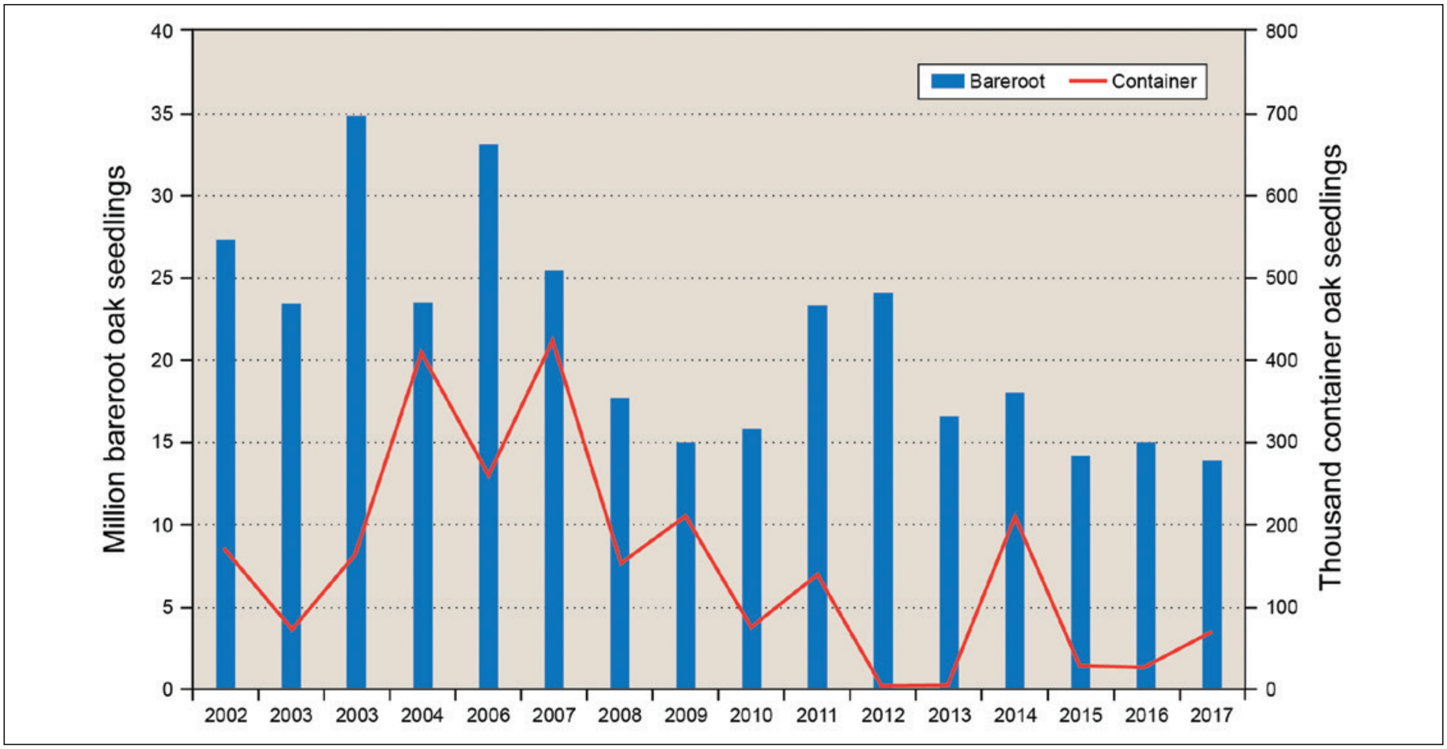

Figure 1. The trend in oak seedling production in the Southern United States (Enebak 2018). The average annual production from 2002 to 2017 was 21.3 million and 0.15 million for bareroot and container seedlings, respectively.

Fertilizer Types

Granular and Soluble Fertilizers

Common granular fertilizers applied before sowing include elemental S, KCl, gypsum (Ca-sulfate), dolomite (agricultural lime), and langbeinite (sul-po-mag). Granular AN was once commonly applied in hardwood nurseries; in fact, 1 nursery applied 14 applications over the growing season (Timmer 1985). However, due to safety reasons (Moore and Blaser 1960), AN is now applied as part of a liquid fertilizer mix (i.e., UAN).

Over time, most managers have shifted away from granular fertilizers and now apply soluble fertilizers after seedlings have formed true leaves. Some managers observe foliar burning when applying UAN (e.g., 37 kg N/ha) to young hardwood seedlings, and therefore, they switched to liquid urea (23-0-0) or urea traizone (28-0-0) to reduce phytotoxicity. Some managers apply liquid fertilizers using shielded sprayers (figure 2). Advantages to applying liquid top-dressings include: (1) greater application uniformity, (2) easier to apply with less labor (Triebwasser 2004), and (3) no need for leaves to be dry at the time of application. After application of soluble fertilizers, irrigation is used to remove fertilizer residue from foliage.

Figure 2. At some nurseries, liquid ammonium polyphosphate is applied to hardwood seedbeds in May, June, July, and August using directed sprayers. The shield reduces the amount of fertilizer applied to the tire-paths and increases the amount of phosphorus applied to the soil. (Photo by Robert Cross 2014).

Table 2. Estimates of harvested dry mass of bareroot hardwood seedlings from various nurseries (Mg/ha and #/ha are based on seedbed areas only; no unused land). Seedling dry mass at lifting depends on species, seedbed density, amount of nitrogen (N) fertilization, and seedling age at harvest. The amount of N harvested depends on the fertilization rate, fertilization method, length of time in the seedbeds and top-pruning prior to lifting. Fertilization methods include a constant rate of N per application (CON), an exponential rate of fertilization (EXP), and slow-release fertilizer application (SRF). Nitrogen use efficiency in this table was determined by dividing nitrogen harvested by nitrogen applied.

Species	Dry mass (Mg/ha)	Density (#/ha)	Dry mass (g)	Nitrogen harvested (kg/ha)	Nitrogen applied (kg/ha)	Nitrogen use efficiency (%)	Fertilization method	Lifting month	Reference
Oak	6	1,000,000	5.7	50	0	>100	NONE	September	Schmal et al. 2010
Oak	5	650,000	8.0	65	0	>100	NONE	December	Birge et al. 2006a
Oak	8	830,000	10.2	68	0	>100	NONE	December	Tilki et al. 2009
Oak	12	860,000	14.0	103	0	>100	NONE	October	Fujinuma 2009
Oak	15	860,000	18.0	120	0	>100	NONE	October	Fujinuma 2009
Oak	14	1,000,000	13.8	110*	0	>100	NONE	October	Dixon et al. 1981
Oak	7	1,000,000	7.1	85	180	47	CON	September	Schmal et al. 2010
Oak	16	860,000	18.7	96	269	40	CON	January	Williams and Stroupe 2002
Oak	12	650,000	19.0	195	273	71	EXP	December	Birge et al. 2006
Oak	23	840,000	27.5	180	287	63	CON	November	dos Santos 2006
Oak	14	650,000	21.0	286	546	52	CON	December	Birge et al. 2006
Oak	18	650,000	28.0	129	819	38	EXP	December	Birge et al. 2006
Oak	11	1,000,000	10.8	110	55	>100	CON	September	Dixon and Johnson 1992
Oak	29	860,000	33.7	158	259	61	CON	October	Fujinuma et al. 2011
Oak	25	860,000	29.0	195	157	>100	SRF	October	Fujinuma et al. 2011
Cerdo	4	4,060,000	0.9	130	660	20	CON	October	Mexal et al. 2002
Green ash	16	1,180,000	13.7	129	112	>100	CON	January	Lamar and Davey 1988
Green ash	12	920,000	13.1	86	239	36	CON	November	dos Santos 2006
Sweetgum	9	920,000	9.7	71*	140	51	CON	August	South et al. 1980
Yellow poplar	31	770,000	40.4	233	251	93	CON	November	dos Santos 2006
Walnut	20	960,000	20.9	160*	81	>100	CON	December	Brookshire et al. 2003
Walnut	18	400,000	44.7	143*	616	23	CON	November	Kormanik 1985

* Nitrogen harvested was estimated based on 0.8 percent N for seedling dry mass.

Slow-Release Fertilizers

Container nurseries use slow-release fertilizers (SRF) which can reduce waste that occurs with applying liquid fertilizers. Bareroot nurseries, however, rarely use SRF because the cost of N is 6 to 12 times more than that contained in liquid fertilizers (Timilsena et al. 2015, table 3). Applying SRF at 180 kg N/ha might cost $2,200 per ha and 484 kg N/ha (Garbaye et al. 1992) might cost $5,900.

SRF are sometimes referred to as "controlled release" but this can be misleading. Nursery managers can "control" the timing and rate of liquid fertilizer applications, but once SRF is incorporated into bareroot seedbeds, any "control" over nutrient release is gone. Greenhouse managers can control irrigation and temperature, but bareroot nursery managers do not have any control over rainfall or seedbed temperatures, which affect nutrient release rates. When SRF continue to release N in the late summer, shutting down seedling growth can be difficult (Steinfeld and Feigner 2004). Also, when soil stabilizers are not applied after sowing, some SRF pellets can work their way to the soil surface and wash away during downpours.

Table 3. Examples of nitrogen (N) fertilizers and the relative price per kg of N. Prices calculated assuming no value for Ca, K, P, and S.

Type	Fertilizer	% N	% P	% K	% S	% P_2O_5	% K_2O	Price per kg of N
Granular	Urea	46	0	0	0	0	0	$1.03
Granular	Urea + slow release coat	44	0	0	0	0	0	$1.20
Granular	Ammonium sulfate	21	0	0	24	0	0	$2.00
Granular	Diammonium phosphate	18	20	0	0	46	0	$3.00
Granular	Calcium nitrate	15.5	0	0	0	0	0	$3.65
Granular	Potassium nitrate	13	0	37	0	0	44	$10.70
Granular	Slow-release fertilizer	5	0	1.6	0	0	2	$13.20
Granular	Slow-release fertilizer	18	3	10	0	6	12	$12.30
Granular	Slow-release fertilizer	16	2	9	6	5	11	$6.80
Liquid	UAN	32	0	0	0	0	0	$1.00
Liquid	Urea	23	0	0	2	0	0	$1.20
Liquid	Ammonium thiosulfate	12	0	0	26	0	0	$2.70
Liquid	Liquid poly-phosphate	10	15	0	0	34	0	$6.00

When using SRF in bareroot seedbeds, the production of plantable seedlings is not as reliable as soluble fertilizer applications (Berenyl and Harrison 1992, van den Driessche 1988, Villarrubia 1980, Zarger 1964). In one study with bareroot pines, SRF produced 16 percent culls while liquid fertilization produced 3 percent culls (McNabb and Heser 1997). In another study, stunting occurred when seed were sown just above a band of SRF (Steinfeld and Feigner 2004). A valid economic comparison must include effects on seedbed density and cull percentages. Without a proper economic analysis, some growers may assume profits would increase after switching to SRF technology (Dobrahner et al. 2007, Timilsena et al. 2015).

Nitrogen (N)

The necessary amount of N applied to grow bareroot hardwood seedlings varies by species, year, rainfall, soil type, soil texture, and manager objectives (table 4). Slower growing species, such as water oak and pecan, may need more N than faster growing species, such as green ash and Nuttall oak. When fertilized at 434 kg N/ha, water oak may be half as tall as Nuttall oak (Kormanik et al. 1994). Typically, less N is needed when the target oak seedling height is 0.3 m, and more N will be needed when the target height is 1.2 m. Some species (e.g., alder and black locust) require little or no N in seedbeds, since they form symbionts that can utilize N from the air (Crannell et al. 1994, Hilger et al. 1991). The length of growing season affects seedling growth more than the N rate (figure 3).

Nitrogen Use Efficiency

For the purpose of this paper, nitrogen recovery efficiency and nitrogen use efficiency (NUE) are synonymous. NUE is determined by dividing N uptake (i.e., N in seedlings at harvest) by N applied as fertilizer (i.e., total N applied/seedling). When applying more than 400 kg N/ha per year, reducing the rate of N (per application) and increasing the frequency might increase NUE (Quiñones et al. 2003, South 1994).

A simple method to increase NUE is proper irrigation to reduce leaching of N. For sandy seedbeds, less N is leached at 2.5 cm water per week than at 5 cm per week (figure 4). NUE can also be increased by allowing soil acidity to gradually fall below pH 5.6. Uptake of selected nutrients in pecan was 23 to 88 percent greater when grown in pH 5.5 soil, compared with pH 6.5 soil (figure 5). Likewise, foliar N concentrations and seedling biomass were greater when oaks were

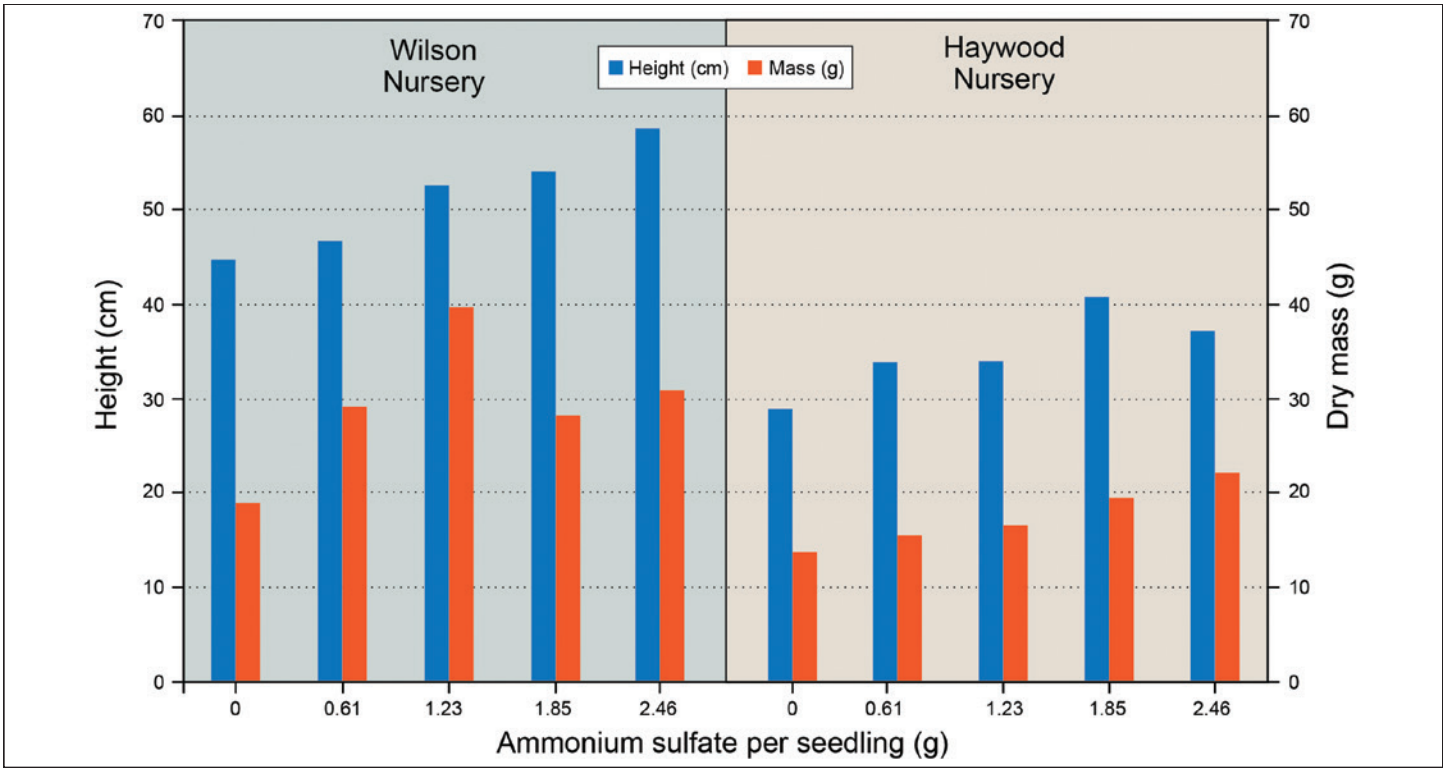

Figure 3. Effect of ammonium sulfate fertilizer and nursery location on seedling height and biomass of 2-0 northern red oak at nurseries in Wisconsin (Fujinuma 2009). The 2.46 g per seedling rate is equivalent to 445 kg N/ha and 508 kg S/ha. The growing season at the southern nursery (Wilson) is about a month longer than at the northern nursery (Haywood). The soil pH was initially 5.9 to 6.1; hardwoods tend to grow better in soils where ammonium sulfate has lowered the soil pH (Villarrubia 1980).

grown in $pH_{(CCB)}$ 4.3 soil vs. $pH_{(CCB)}$ 7.7 soil (Berger and Glatzel 2001).

Reducing soil nitrification rates can also increase NUE, especially in sandy nursery soils where rainfall leaches nitrates (Bengtson 1979, Radwan 1965). For example, fertilizing with ammonium thiosulfate can inhibit soil nitrification (Goos 2019) and will also lower soil pH. When applying nitrifying reducing products, it is important to remember that not all products work as expected (Franzen et al. 2011).

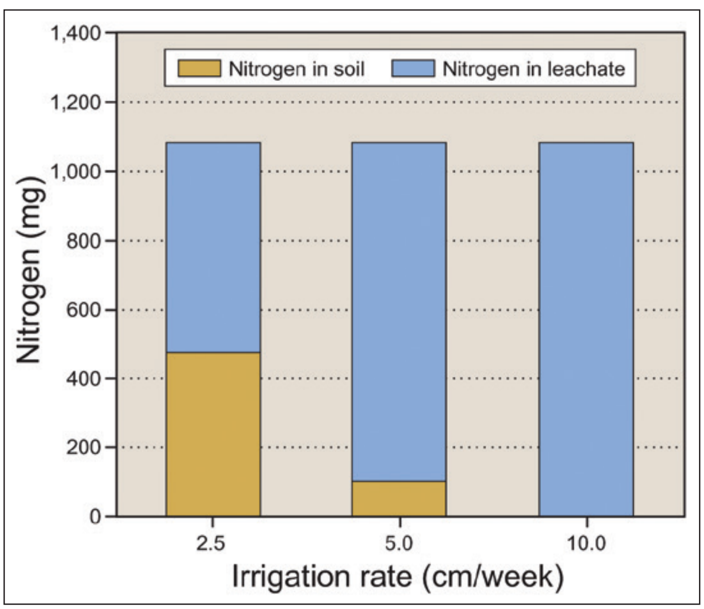

Figure 4. The effect of irrigation on the amount of nitrogen (N) leached from containers filled with sand (Bengtson and Voigt 1962). N (1,088 mg) was applied to the sand as ammonium nitrate. Although the results were presented after 17 weeks, most of the N was gone from the soil of the high irrigation rate after 4 weeks.

Seed efficiency (number of plantable seedlings produced per 100 pure live seed) can be reduced when managers lower fertilization rate in order to increase NUE. This is the main reason why NUE is not maximized at bareroot nurseries. For example, at one nursery, seed efficiency was reduced when the fertilization rate was decreased by 75 percent (O'Reilly et al. 2008).

When little or no fertilizer is applied, NUE will be above 100 percent, and when more than 200 kg N/ha is applied, NUE may average 50 percent (table 2). Therefore, when one-fourth the normal rate of N is applied to seedlings, researchers and practitioners can mistakenly attribute all the NUE increase to the use of SRF. Despite expectations that SRF applications will increase NUE, this is not true in all cases (Fujinuma et al. 2011, Fuller 1988, McNabb and Heser 1977, Villarrubia 1980, Zarger 1964).

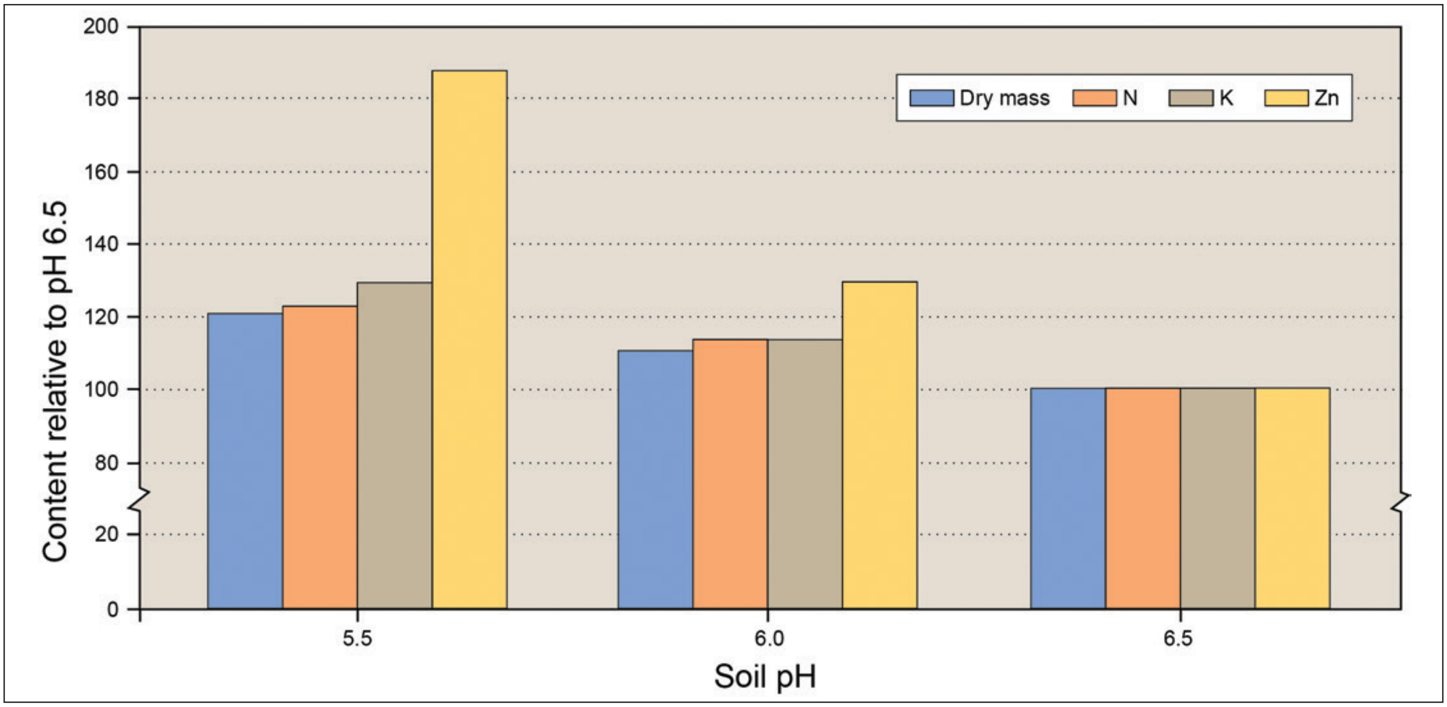

Figure 5. Nutrient use efficiency is sometimes greater when pecan seedlings are grown at soil pH 5.5 compared with soil pH 6.5. (Adapted from Sharpe and Marx 1986). Nutrient uptake of N (mg per seedling) was 23 percent greater at pH 5.5 than at pH 6.5. For pH 6.5 soil, average seedling values were 12.8 g dry mass, 145 mg N, 118 mg K, and 0.4 mg Zn.

Timing of N Application

When applied after sowing, an excessive delay in N fertilization can reduce seedling growth and NUE (Beckjord et al. 1980, Booze-Daniels et al. 1984). In some trials, a 21-week delay in N fertilization after sowing reduced seedling mass by 32 percent (Deines 1973). On the other hand, applying N too far ahead of sowing can waste resources and reduce NUE. For example, applying urea and ammonium nitrate before sowing oaks in the fall or before sowing small-seeded species in the spring is wasteful because rain can rapidly leach N, especially in sandy soils (Bengtson and Voigt 1962, Gaines and Gaines 1994). At some nurseries, AN only lasts in the soil about 6 weeks (Berenyl and Harrison 1991).

Benzian (1959, p. 639) wrote, "Nitrogen applied before sowing occasionally increased losses through 'damping off', and it has been better to apply soluble nitrogen fertilisers as top-dressings between June and September." Because soil fumigation is often used prior to sowing hardwoods, problems with damping-off and root rot are reduced. Even so, some recommend keeping N fertilization low during the first 6 weeks after emergence (Enebak 2019, Filer and Cordell 1983). For example, applying 224 kg N/ha before sowing increased sycamore seedling mortality (Berenyl et al. 1970). For this reason, many authors recommend applying N only as top-dressings to bareroot hardwood seedlings (Aldhous and Mason 1994, Landis and Davey 2009, South 2019b).

When acorns and walnuts are sown in the fall, the first application of N occurs in the spring soon after true leaves emerge. At nurseries with relatively long growing seasons, the first N application is made in April or May. At nurseries with short growing seasons, fertilization begins in June (table 4). The final N application in bareroot nurseries is typically made before mid-September.

Total Rate of N

To grow bareroot hardwoods, the total amount of N applied in a year can vary from 50 kg/ha (Hauke-Kowalska and Kasprzyk 2017) to 112 kg/ha (Grieve and Barton 1960, Hoss 2004, Lamar and Davey 1988, Thor 1965) to 295 kg/ha, (Stone 1986) to 560 kg/ha (Garbaye et al.1992, Kormanik et al. 1998, Reazin et al. 2019), and some researchers have tested rates up to 900 kg/ha (Brown et al. 1981). As a comparison, recommended rates for horticultural greenhouses can exceed 1,400 kg N/ha (Chen et al. 2001).

Table 4. Examples of nitrogen (N) fertilizer rates (kg/ha) for spring-sown (March through May) and fall-sown (October through December) bareroot hardwoods. Except for one pre-sow application (in bold), applications were top-dressings. Application dates are approximate. Asterisk (*) indicates first year of 2-0 stock. Fertilization methods are: constant rate (CON), exponential rate (EXP), and stepwise rate (STEP). Species codes are: green ash (GA), sweetgum (SG), and yellow poplar (YP).

	Location	NC	VA	VA	GA	US	TN	US	IN	WI	IN	GA	IN	MO	WI	IR	AL
	Species Code	GA	SG	SG	SG	SG	YP	YP	Oak	Oak	Oak	Oak	Oak	Oak	Oak	Oak	Oak
	Sow date	5/15 1972	5/3 1978	Spring 1986	3/15 2004	4/17 2018	4/17 2006	4/17 2018	Fall 1984	Fall 1990	Fall 2000	Fall 2003	Fall 2003	Fall 2004	Fall 2005	Fall 2007	Fall 2009
	Method	Step	Step	Step	Step	Con	Con	Step	Con	Con	Con	Step	For	Con	Con	Con	Con
1	April 24																50
2	May 1				12												
3	May 8	**112**			12		39				78	6	42				
4	May 15				20												50
5	May 22										78	6	35				
6	May 29			42	28			20	85			18		28			
7	June 5						39			37	78		37	28		36	50
8	June 12		11	41	28			20				55		28	24		
9	June 19		11			28				37	78		48	28	23	36	
10	June 26		11	41	28	2	22	35	85			55		28	24		50
11	July 3					28				37	78	55	67			36	
12	July 10		28		28	30	34	40						28	23		
13	July 17	18		65		24				37	78	55	112	28	24	36	
14	July 24	28	28	53	28	24		35							23		50
15	July 31	28	37			20	39			37	78	55	112	28		36	
16	Aug 7				28	24	61								24		
17	Aug 14	28	37	53		24		40		37		55					
18	Aug 21				20	24									23		
19	Aug 28	22	37			24				37		37					
20	Sept 11	28	7									37					
Total kg N/ha		264	207	295	232	252	234	190	170	259	546	434	453	224	188*	180*	250

In 1930, grade-1 oak seedlings might be 21 cm tall (Guillebaud 1930) and 1 million seedlings might contain a total of 18 kg N. Now a million bareroot hardwood seedlings may average 50 to 70 cm tall and contain more than 400 kg N (table 2). A driving force for increased N fertilization in nurseries over the last several decades is because growth of hardwoods after planting is affected by seedling size at planting, which increases with N application (Jacobs et al. 2005, McNabb and Vanderschaaf 2005).

N Fertilizer Regimes

Fertilizer programs can be categorized into several regimes (Park et al. 2012). The constant regime (CON) employs the same N rate for each N application, while a stepwise (STEP) regime starts with a low N application (to increase NUE and avoid phytotoxicity) and then increases the N rate in two or three "steps." A slow-release regime (SRF) may involve one or two fertilizer applications per year

(Fujinuma et al. 2011, Garbaye et al. 1992, Iyer et al. 2002, Vande Hey 2007). A formula (FOR) regime employs a mathematical equation so that each N application has a unique N rate per hectare. Thus, application rates can vary greatly among nurseries. For example, one FOR regime applied urea (46-0-0) at 112 kg N/ha on July 17 (table 4), which is about five times as great as applying 23 kg N/ha using a CON regime.

Growers who follow the CON method typically apply 28 to 85 kg N/ha at each top dressing regardless of seedling age (Hoss 2004, table 4). Managers using the STEP method who are concerned about leaching apply top dressing at low initial rates; for example, the first application may be 6 to 12 kg N/ha followed by an application of 18 to 20 kg N/ha, and then 28 to 37 kg N/ha. When growing 2-0 seedlings, one STEP manager applies 50 kg N/ha during the first year and 60 kg N/ha during the second year (Hauke-Kowalska and Kasprzyk 2017).

Some researchers use an "exponential" formula (EXP) where the first application is the lowest N rate, the rate for each subsequent application is increased by a calculated amount, and the highest N rate is applied at the end of the season. For example, in one trial, each application contained 66 percent more N than the previous application (Chen et al. 2017). With some EXP regimes, more than 70 percent of the N is applied during the last two fertilizer applications (Chen et al. 2017, Schmal et al. 2011). A danger of the EXP regime is that seedling survival can be reduced if excessive salts are applied at the last application (Salifu et al. 2008). Therefore, others use a modified exponential formula (MEX) where the initial application has more N than subsequent applications made 4 to 6 weeks later (Birge et al. 2006, Hu et al. 2015, Imo and Timmer 1992, Reazin et al. 2019). With this regime, half of the total N may be applied in the last two applications. At some locations, hardwood seedlings that receive 50 percent of the fertilizer in the last few applications are referred to as "nutrient loaded" (Salifu et al. 2008).

In one trial, the fertilization regime had little impact on yellow poplar seedling growth although the CON method resulted in quicker early growth (Park et al. 2012). Weed control is easier after canopy closure so nursery managers favor regimes that result in rapid early growth of hardwoods.

Phosphorus (P)

Growers' views vary regarding the minimum desired level for soil P in hardwood nurseries. These views also vary by the seedling species. Some growers set 15 to 22 ppm as the standard soil P level for hardwood seedbeds (Williams and Hanks 1994), while others set a target of 100 ppm (weak-Bray) (Kormanik et al. 2003) which is equivalent to 143 ppm Mehlich 3. Some growers conclude that seedbeds with more than 44 ppm P (Mehlich 3) do not need to be fertilized with P (Davey and McNabb 2019). A 300-ppm target (weak-Bray) is too high for sandy nurseries and can result in Cu and Zn deficiencies (Teng and Timmer 1990).

Endomycorrhizal hardwoods such as sweetgum, yellow poplar, green ash, and maple may become P deficient following soil fumigation. Therefore, some growers apply spores to increase the chance of endomycorrhizal formation on these hardwoods. In contrast, ectomycorrhizal species such as oak and pecan are less likely to be P deficient since windblown spores typically inoculate fumigated soil. With little or no P fertilization, mycorrhizal walnut, oak, and pecan seedlings can grow well in soil that contains as little as 8 ppm P (Marx 1979a, 1979b; Ponder 1979). Likewise, in fumigated soil with 16 ppm P, mycorrhizal plants can uptake enough P to grow well (figure 6). In contrast, non-mycorrhizal seedlings may need to be fertilized with P even when the soil has 100 ppm P. In a greenhouse trial (Yawney et al. 1982), mycorrhizal sweetgum seedlings grew taller in unlimed, fumigated soil (pH 4.5) when fertilized with enough dicalcium phosphate to raise the soil to 100 ppm P (figure 7).

For sweetgum, there is a subtle but practical difference between an unfertilized soil at 100 ppm P, and a recently fertilized soil at 100 ppm P. Growth of non-mycorrhizal sweetgum seedlings will benefit from P fertilization (figure 6), but there likely will be no growth benefit from 100 ppm in the soil if there has been no recent P fertilization because P becomes tied up and immobile in the soil. As a result, some growers apply 30 kg/ha of P (late May to early June) even when soil tests indicate 115 ppm (Mehlich 3) (South 2018). Soil P is typically high in operational hardwood seedbeds and, therefore, the difference among target values (15 ppm vs 100 ppm) may have little practical meaning.

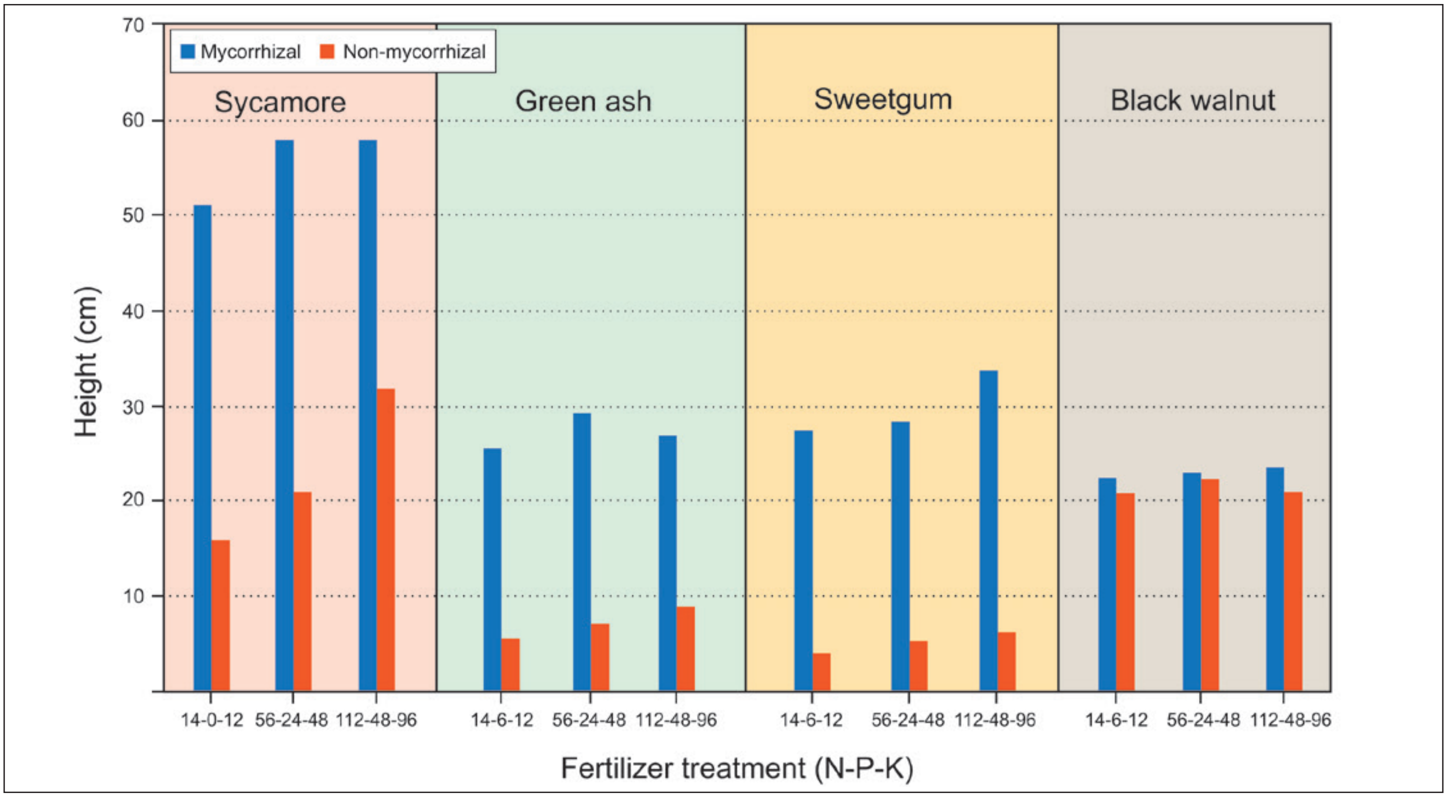

Figure 6. Effect of inoculation (about 850 Glomus spp. spores/m^2) and fertilization before sowing on height growth of bareroot hardwood seedlings (Schultz et al. 1981). Ten equal applications of $NH4NO_3$, totaling 1,680 kg/ha, (560 kg N/ha) were applied as top dressings. Pre-fertilization soil level was 12 ppm P. Fertilizer treatments did not affect heights of mycorrhizal seedlings but increased height of non-mycorrhizal sycamore, green ash, and sweetgum ($\alpha = 0.05$).

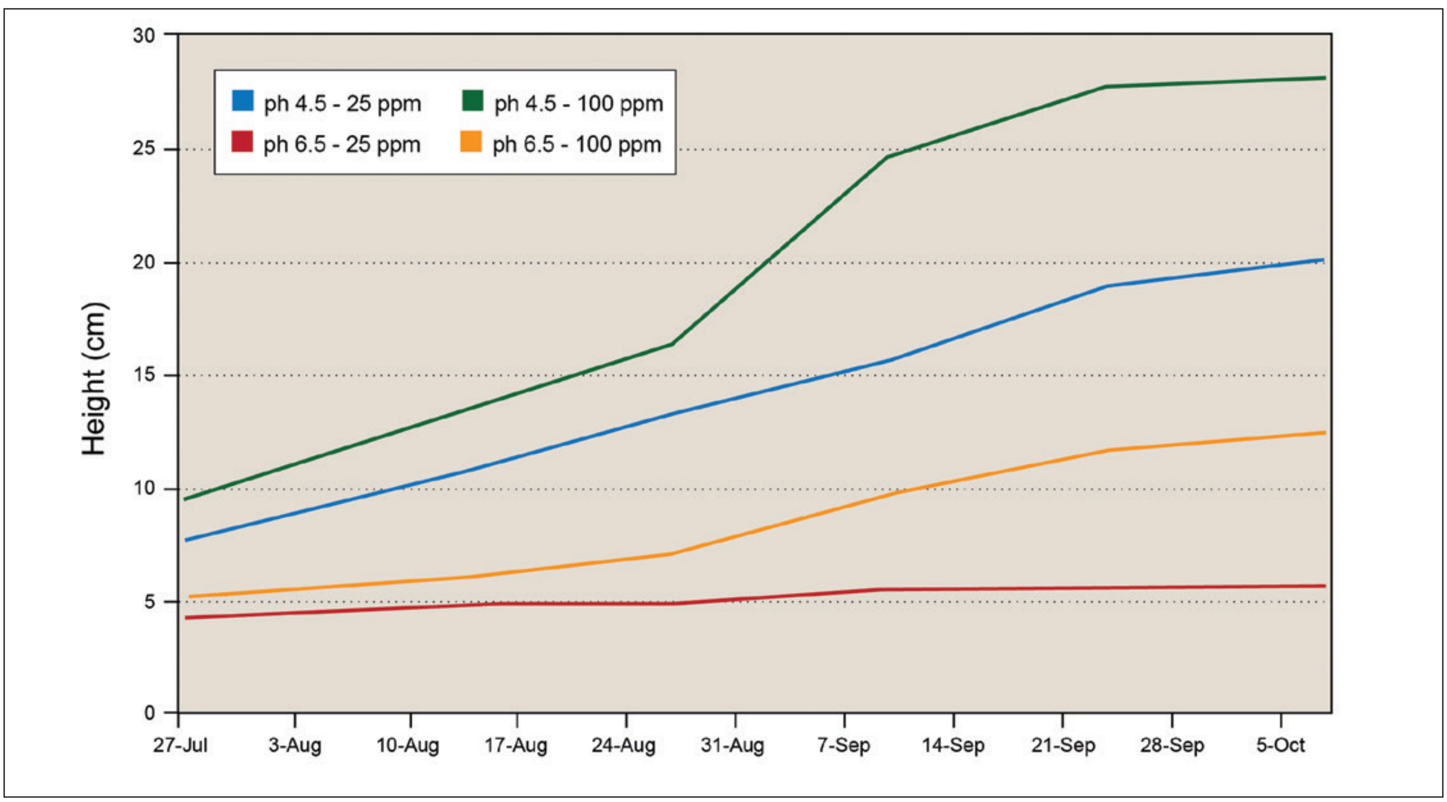

Figure 7. The beneficial effect of phosphorus fertilizer was greater for endomycorrhizal sweetgum seedlings grown without lime ($Ca(OH)_2$) compared with those with lime applied 4 weeks before sowing (soil pH 4.5 and 6.5, respectively). Dicalcium phosphate fertilization was applied at two rates (25 ppm and 100 ppm P). Seedlings were grown in a soil-perlite (4:1 v/v) medium in a greenhouse (Yawney et al. 1982).

Although research shows that a high level of soil P can reduce endomycorrhiza infection (Marx et al. 1989, Schultz et al. 1981, Yawney et al. 1982), nurseries with more than 370 ppm P have no problems growing endomycorrhizal seedlings (Han et al. 2016, Lambert 1982, Timmer 1985). In addition, fertilization with NPK can sometimes increase the percent infection with endomycorrhiza (Schultz et al. 1981). In fact, when two seedlings have an equal amount of endomycorrhizal biomass, the one with more roots will have fewer mycorrhizal biomass per m of root. Thus, larger seedlings with more roots (figure 8) can sometimes have the lowest percent infection.

Potassium (K)

There is little evidence to show that K fertilization will benefit growth of bareroot hardwood seedlings (figure 9). Soil with 21 to 40 ppm K produced 50 cm tall seedlings without any K fertilizer (Lamar and Davey 1988, South 1975). At one nursery, applying KCl (448 kg/ha) increased average sweetgum height by 6 cm (South 1975), but the same fertilizer treatment did not affect growth of sycamore and sweetgum at six other nurseries (Deines 1973, South 1975). In another trial, oak seedling growth was negatively related to foliar K (Phares 1971). Although some researchers recommend half of the K fertilizer be incorporated into the soil before sowing (Landis and Davey 2009), there is no evidence to show that hardwoods benefit from this practice. With sufficient rainfall, K can leach from irrigated sandy soil before roots can uptake nutrients. Freeze tolerance is not increased by KCl fertilization in August (Williams et al. 1974) and high levels of K can sometimes reduce freeze tolerance (Jozefek 1989, Koo 1985).

Calcium (Ca)

Most nursery soils contain more than 100 ppm Ca. Calcium deficiencies in hardwoods (Erdmann et al. 1979) are rare in bareroot nurseries (Davey 2005). There are only a few nursery studies that involve Ca treatments to hardwoods. At one nursery, a CaCl treatment temporarily lowered soil pH to 4.5, which increased yield of red alder seedlings (Crannell et al. 1994). In another trial, applying 1,121 kg/ha of Ca-carbonate after sowing (to a soil with more than 150 ppm Ca) had no effect on growth of green ash

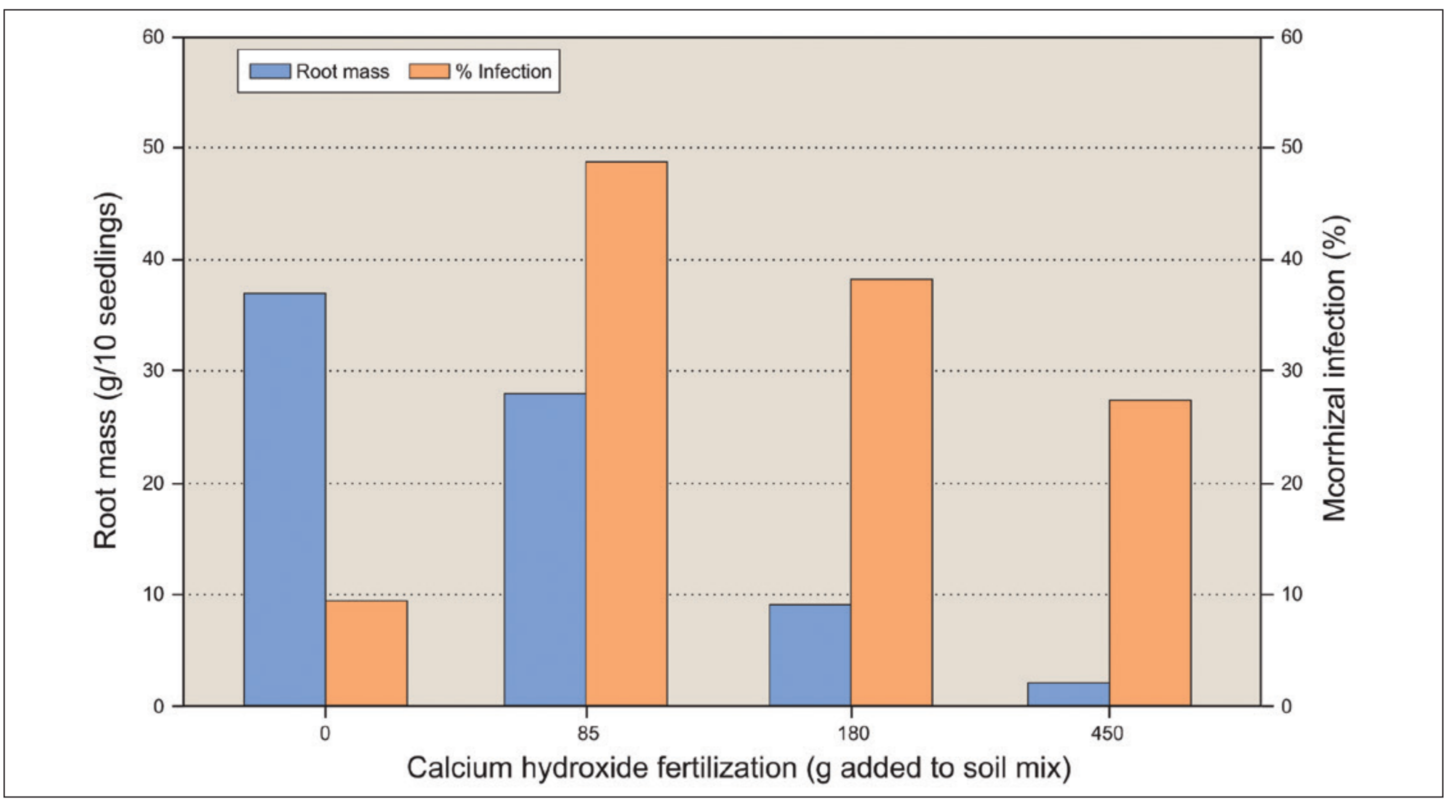

Figure 8. Fertilization with calcium hydroxide ($Ca(OH)_2$) reduced root growth of sweetgum seedlings but increased mycorrhizal infection of roots ($\alpha = 0.05$) (Yawney et al. 1982). By October, $Ca(OH)_2$ treatments resulted in pH levels of 4.6, 5.6, 6.5, and 7.8, respectively and soil calcium levels of 243, 622, 1,250, and 3,157 ppm, respectively. The largest seedlings, with the lowest percent infection of endomycorrhiza, were growing in pH 4.6 soil.

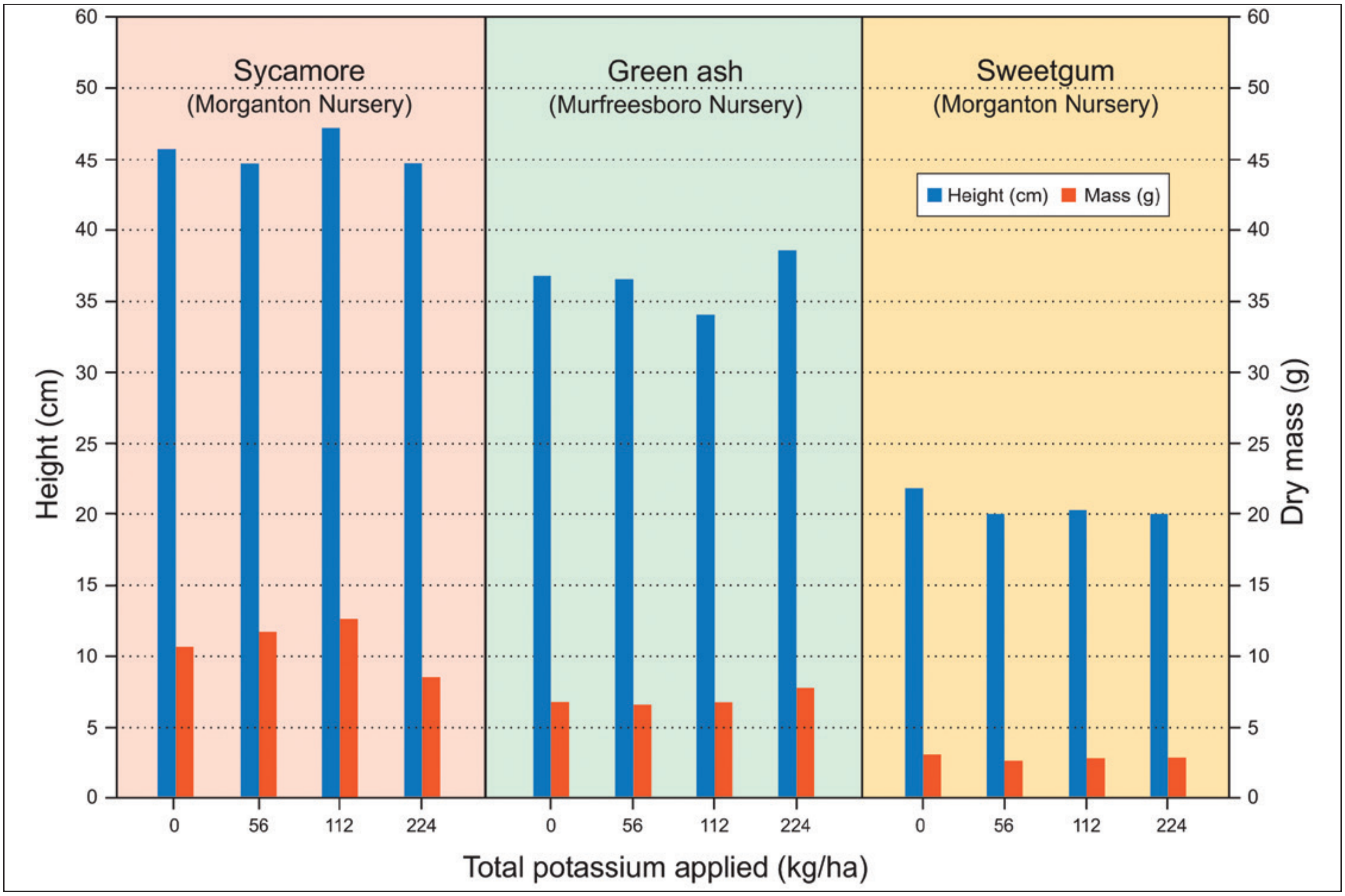

Figure 9. Four KCl fertilizer rates (divided over three equal applications) were applied to hardwood seedlings at two nurseries. At the Morganton Nursery, three applications were applied May 18 (before sowing), July 10, and August 22, 1972 on sycamore and sweetgum seedlings (Deines 1973). Similarly, three applications were made at the Murfreesboro Nursery on green ash after germination on July 17, August 14, and September 11, 1972. The KCl fertilizer had no effect (α= 0.05) on height growth at either nursery. The high rate reduced seedling dry mass (standard error = 0.8 g) of sycamore but had no effect on biomass of green ash or sweetgum. The soil K level at the Morganton Nursery was 63 ppm in October 1972 and at the Murfreesboro Nursery, soil contained 32 ppm K in April 1974 (South 1975).

seedlings (Deines 1973). At a sweetgum nursery, seedbeds contained more than 250 ppm Ca and applying 1,121 kg/ha of Ca-carbonate (before sowing) decreased shoot dry mass (Deines 1973).

For sands and loamy sands, recommended Ca levels range from 200 ppm (South and Davey 1983) to 300 ppm (Davey and McNabb 2019) to 500 ppm (Kormanik et al. 2003). For high CEC soils in Western States, 1,000 ppm Ca has been recommended for seedbeds (Engstrom and Stoeckeler 1941, Landis 1988). However, when soil Ca levels increased to 622 ppm or higher with Ca-hydroxide fertilization, growth of sweetgum seedlings was reduced (figure 8). Similarly, adding too much lime can reduce hardwood seedling growth (Phares 1964, South 2019a, Timmer 1985) and root rots are most severe in seedbeds with a pH above 5.5 (Cordell et al. 1989).

Magnesium (Mg)

Documented cases of Mg deficiencies in hardwood nurseries are rare (Davey 2005, Hüttl and Schaaf 2012). This lack of deficiency may be due to applications of dolomitic lime or sul-po-mag. Some researchers adjust soil Mg to 50 ppm before sowing hardwoods (Kormanik et al. 1998) and some agronomists recommend Mg when soils contain 60 ppm Mg (South 2019b). In contrast, others see no need to apply Mg when soil levels are above 30 ppm (Davey and McNabb 2019). Although increasing K in solution will lower the amount of Mg in foliage (Cutter and Murphey 2007), excess K fertilization in hardwood seedbeds is not likely since K fertilization is not a practice used to "harden-off" deciduous hardwood seedlings.

Sulfur (S)

Stone (1980, p. 125) raised the question, "how much sulfur is needed for adequate hardwood growth?" The answer is still unclear and therefore some researchers set no target level for soil S. Davey and McNabb (2019) suggest S fertilization when soil levels fall below 10 ppm. Most nursery soils contain less than 20 ppm sulfate-S, which is the form available to plants. S deficiencies are rarely reported in hardwood seedlings (Aldhous and Mason 1994, Knight 1981, Leaf 1968). However, this is based on: (1) no obvious color symptoms in operational seedbeds (Stone 1980); (2) operational use of fertilizers that contain S; (3) no published photos of S deficiency from hardwood seedbeds; and (4) assuming type II statistical errors do not exist in nursery trials. Variability in hardwood seedbed density can be so high that a 25-percent increase in seedling production cannot be declared statistically significant.

Sulfur deficiencies may be overlooked, especially when the amount of S in the soil and foliage is not known. Applying 385 kg S/ha at one nursery increased height growth of sweetgum and green ash seedlings by 16 to 19 percent and raised the soil level from 0 to 7 ppm S to more than 19 ppm S (Stone 1980). Adding 1,344 kg S/ha to a loamy soil reduced soil pH and increased the number of plantable sycamore seedlings (table 5), which may have occurred due to reduced damping-off or increased seed germination (Siegel and Brock 1990).

When leaves are sampled during the summer, the S sufficiency range might be 1,200 to 1,600 ppm for oak (Kramer 2008, Van Sambeek et al. 2017) and 1,500 ppm for pecan (Hu et al. 1991). In greenhouses, growth of oak seedlings can be increased by adding K-sulfate (Browder et al. 2005), Al-sulfate (Davis 2003), or S plus micronutrients (Wright et al. 1999). Growth of other species can also be increased when sulfuric acid and nitric acid are added to irrigation water (South 2019a).

Sulfur fertilization rates less than 30 kg/ha are used to correct a potential S deficiency; but when the goal is to lower soil pH, rates can exceed 400 kg/ha. Rates for sandy soils vary from 400 to 900 kg S/ha (Davey and McNabb 2019, Mullen 1969), while rates for fine-textured soils may exceed 1,000 kg/ha (table 5). Managers who apply high rates of elemental S should

Table 5. Effect of elemental sulfur on soil pH (December 1983) and hardwood seedling morphology at a nursery in Mississippi (CEC = 11; loam soil with 29 percent sand). Sulfur was mixed into the soil on March 10 (sweetgum; sow date March 12) and April 11 (sycamore; sow date May 18). There were four replications for each test (n=12) and seedlings were lifted February 10–13, 1984.

Sulfur treatment (kg/ha)	Statistics	Density (#/m²)	Height (cm)	Plantable seedlings (#/m²)	Dry mass (g)	Soil pH
Sycamore						
0		50	100	36	16	5.4
672		58	108	44	18	5.2
1344		62	103	51	15	5.2
	LSD α = 0.10	13.3	8.4	12.1	3.2	0.16
	LSD α = 0.05	16.8	10.5	15.2	4.0	0.19
	Linear P>F	0.1462	0.1405	0.0547	0.5757	0.0481
Sweetgum						
0		91	69	68	11	5.9
672		104	73	78	12	6.0
1344		82	66	61	11	5.9
	LSD α = 0.10	23.4	7.3	19.1	2.8	0.61
	LSD α = 0.05	29.4	9.3	24.1	3.5	0.77
	Linear P>F	0.4789	0.4300	0.1747	0.7033	0.5987

LSD = least significant difference.

do so at least 2 to 3 months before sowing (Armson and Sadreika 1979); applying elemental S just 2 weeks before planting can injure some hardwoods (Timmer 1985). The risk of injury decreases when sufficient rainfall occurs after application but before germination (Carey et al. 2002).

Micronutrients

There are three approaches to micronutrient fertilization: (1) wait until visual symptoms appear (Altland 2006, Benzian 1959), test foliage, and then fertilize; (2) apply low rates of chelated micronutrients to foliage as a preventive measure; and (3) apply micronutrients when soil tests indicate low levels. During the 1950s, laboratories did not routinely test soils for micronutrient levels and, as a result, many managers did not apply micronutrient fertilizers (Iyer and Love 1974). Typically, micronutrient deficiencies did not occur on hardwoods when soils were more acid than pH 6.5 but Fe, Cu, and Zn deficiencies did occur on alkaline soils (Hoch 2018, Stoeckeler and Jones 1957, Timmer and Leyden 1980). The second approach is rarely used in bareroot hardwood nurseries.

Most managers follow the third approach and apply micronutrients when soil tests indicate low levels. Minimum soil values for hardwood seedbeds are: Mn-5 ppm, Zn-1 ppm, Cu-0.8 ppm, and B-0.4 ppm (Davey and McNabb 2019). Although a 20-ppm soil level is deemed adequate for Fe, a deficiency in hardwood seedlings is rare when soil pH is below 6.5. When soil pH is near neutral, applying high rates of Cu chelates may improve growth of some hardwoods (Timmer and Leyden 1980) but low rates of Cu may have no effect on growth (figure 10). In fact, it may be difficult to induce Cu deficiencies using sandy soils (Van den Burg 1983).

Although foliar tests are used to help diagnose problems such as stunting for unknown reasons, foliar samples are not routinely used as a tool for deciding when to apply chelated micronutrients. Instead of spending money for foliar tests, money is allocated toward the purchase of micronutrients. In some cases, applying 250 g Cu/ha may cost $12 per ha for one application, while one foliar test might cost $26. In addition, interpretation of lab results is problematic for several micronutrients. A foliar test

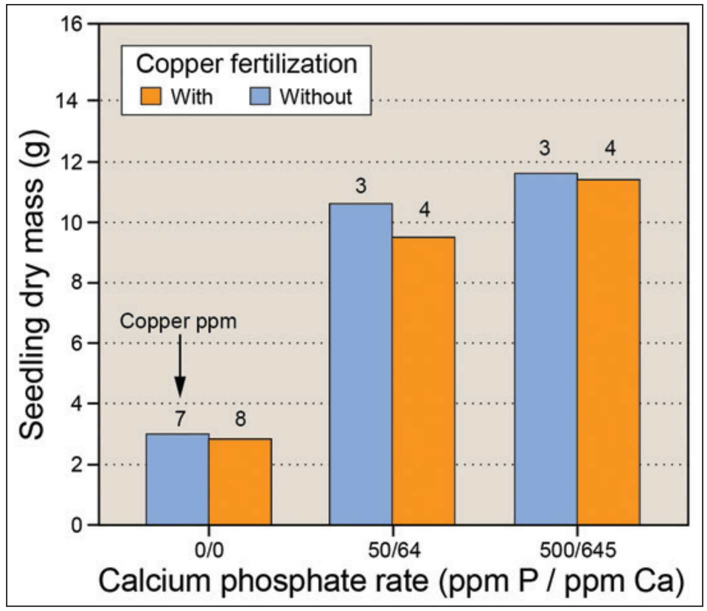

Figure 10. Copper and calcium phosphate treatments were applied to a peat:sand:sandy loam medium (pH 7.4 to 7.9; 6 ppm P). Fertilization with calcium phosphate increased growth of sweetgum seedlings (inoculated with *Glomus fasciculatus*) but fertilization with copper did not increase growth (Lambert 1982). Seedlings growing in the copper-treated treatments (soil = 5 ppm Cu) had slightly higher foliar copper (values above bars indicate foliar copper in ppm) but the 1 ppm increase was not significant (α =0.05).

result of 3 ppm Cu (figure 10) does not necessarily mean that seedlings are not growing well. Likewise, results from oak foliage are not useful in determining if chlorosis is a result of Fe deficiency (Hauer and Dawson 1996, Hoch 2018). In some cases, use of chelates may even reduce micronutrient levels in foliar tests (Kramer 2008, Wallace et al. 1983).

Organic Matter

Nurseries in Washington and Oregon may have more than 4 percent OM (Crannell et al. 1994), while nurseries in warmer environments can have less than 1 percent (South 1975, 1992). Although experienced managers typically have no nutrient-related problems growing hardwoods in low OM soils, some managers still strive to increase OM levels. In Georgia, maintaining OM at 1 percent can be accomplished by making small, frequent additions of organic materials. Small applications can reduce problems associated with too much OM (e.g., N chlorosis and stunting). A 5-cm depth of sawdust can be added prior to growing 2 years of cover-crops (Cross 1984) but, if applied just prior to sowing, sawdust might cause problems (Davey 1953, Rose et al. 1995). At $22/m^3$, a 2.5 cm depth of sawdust would cost $5,500/ha and might not increase OM by the time seed are sown a year later (Koll 2009, Munson 1982, Tran 2005). Applying more expensive compost or peat might increase soil OM by perhaps 1 percent (Brener 1971, Munson 1982) but will likely have no effect on height and diameter of red oak seedlings (Buchschacher et al. 1991).

The use of fertilizers can produce a good crop of hardwood seedlings at nurseries with less than 1 percent OM. Although much has been written about the benefits of OM to growing bareroot hardwood seedlings (Davey 1994, 1996; Davis et al. 2006), reports that show a positive economic benefit from incorporating OM before sowing hardwoods either do not exist or have not been published. Some managers have been disappointed when free or inexpensive sources of OM resulted in weed problems and high soil pH.

Additional Considerations

Statistics

Most nursery trials have only three or four replications and therefore the statistical power of the test is low (South and VanderSchaaf 2017, VanderSchaaf et al. 2003). As a result, even a 30-percent (table 5) to 100-percent increase in plantable seedlings may not be statistically significant. Also, researchers sometimes thin seedbeds to a common spacing in order to minimize the effects of variations in seedling density. Although this practice is good for research, it eliminates the ability to detect treatment effects on density. With a few exceptions (Mexal et al. 2002, O'Reilly et al. 2008, South 1977, Villarrubia 1980), most fertilizer trials in hardwood seedbeds do not report treatment effects on seedbed density. Furthermore, nursery conditions and management approaches differ from nursery to nursery. Therefore, research results from another region may have limited applicability. Managers most often adopt fertilizer regimes based on nursery records, observations from check plots, publications, assumptions, and economics.

Leave Check Plots

"In general, it is advisable to leave some nursery beds without fertilizer application to serve as controls" (Iyer and Love 1974, p. 14). Periodically, fertilizer

Figure 11. Check plots without fertilization (foreground) in a study to evaluate nitrogen source on sweetgum growth (beds on right) and green ash seedlings (beds on left) at the Capron Nursery in Virginia (Villarrubia 1980). (Photo by Chuck Davey 1978).

treatments should be reevaluated with check plots, as treatments, conditions, objectives, and managers change. For example, managers who left check plots (figure 11) learned that routine applications of K before sowing had no effect on crop production (Kahn et al. 2014, South 1975). From our experience, check plots can be installed by temporarily covering seedlings with a tarp (just prior to applying fertilizers). When applying less than 7 kg/ha of micronutrients, check plots might reveal no detectable effect on seedling color or levels of foliar nutrients.

Final comment

For more than a century, nursery managers have grown bareroot hardwood seedlings using a variety of fertilizer sources and methods of application. Since 1900, fertilizer rates have increased for hardwoods and advances in equipment have reduced labor costs. With effective cultural practices, bareroot hardwood seedlings can be grown at a cost of less than $0.20 each. From our findings, it seems fertilizer practices will continue to evolve over the next few decades. Nursery managers will have to evaluate new technologies, new techniques, and new fertilizer regimes to determine the combination that produces the best seedling quality and economic results for their facility.

Acknowledgments

The authors thanks nursery managers who shared their experiences with bareroot hardwood seedling fertilization. We thank Drs. J.B. Jett, John Mexal, Scott Enebak, Hans Williams, and Diane Haase for reviews of earlier drafts of this manuscript. The authors also thank members of the Southern Forest Nursery Management Cooperative for providing information about operational fertilizer regimes and for collecting data on sulfur fertilization trials.

Address correspondence to—

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

REFERENCES

Aldhous, J.R.; Mason, W.L., eds. 1994. Forest nursery practice. Forestry Commission Bulletin 111. London: Office of Public Sector Information, HMSO. 268 p.

Alkire, D.K. 2011. Artificial regeneration of bottomland hardwoods in southern Mississippi on lands damaged by Hurricane Katrina. Mississippi State, MS: Mississippi State University. 54 p. M.S. thesis.

Altland, J. 2006. Foliar chlorosis in field-grown red maples. HortScience. 41(5): 1347–1350.

Armson, K.A.; Sadreika, V. 1979. Forest tree nursery soil management and related practices. Toronto, ON: Ontario Ministry of Natural Resources. 179 p.

Beckjord, P.R.; Adams, R.E.; Smith, D.W. 1980. Effects of nitrogen fertilization on growth and ectomycorrhizal formation of red oak. Forest Science. 26(4): 529–536.

Bengtson, G.W. 1979. Nutrient losses from a forest soil as affected by nitrapyrin applied with granular urea. Soil Science Society of America Journal. 43(5): 1029–1033.

Bengtson, G.W.; Voigt, G.K. 1962. A greenhouse study of relations between nutrient movement and conversion in a sandy soil and the nutrition of slash pine seedlings. Soil Science Society of America Journal. 26(6): 609–612.

Benzian, B. 1959. Nutrition problems in forest nurseries. Journal of the Science of Food and Agriculture. 10(12): 637–644.

Berenyl, N.M.; Brenneman, B.B.; Owens, E.G. 1970. Sycamore fertilization on lower coastal plain soils in the greenhouse. Research Report 48. Summerville, SC: Westvaco Forest Research. 12 p

Berenyl, N.M.; Harrison, D.L. 1991. Recovery of applied nitrogen from nursery beds. Research Report 109. Summerville, SC: Westvaco Forest Research. 21 p.

Berenyl, N.M.; Harrison, D.L. 1992. Effects of slow release herbicides in the nursery. Research Report 137. Summerville, SC: Westvaco Forest Research. 28 p.

Berger, T.W.; Glatzel, G. 2001. Response of *Quercus petraea* seedlings to nitrogen fertilization. Forest Ecology and Management. 149(1-3): 1–14.

Birge, Z.K.; Francis Salifu, K.; Jacobs, D.F. 2006. Modified exponential nitrogen loading to promote morphological quality and nutrient storage of bareroot-cultured *Quercus rubra* and *Quercus alba* seedlings. Scandinavian Journal of Forest Research. 21(4): 306–316.

Booze-Daniels, J.N.; Wright, R.D.; Lyons, R.E. 1984. Effect of timed fertilizer application on *Ilex crenata* 'Helleri' cuttings during propagation. Journal of Environmental Horticulture. 2(2): 43–45.

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

Brener, W.H. 1971. Dynamics of soil fertility in the Griffith State Nursery; a record of soil management. Tree Planters' Notes. 22(2): 19–22.

Brookshire, B.L.; Garrett, H.E.; Robison, T.L. 2003. Effects of vesicular-arbuscular mycorrhizae and seed source on nursery-grown black walnut seedlings. In: Van Sambeek, J.W.; Dawson, Jeffery O.; Ponder, F.; Loewenstein, E.F.; Fralish, J.S., eds. Proceedings of the 13th central hardwood forest conference. Gen. Tech. Rep. NC-234. St. Paul, MN: U.S. Department of Agriculture, Forest Service, North Central Research Station: 468–475.

Browder, J.F.; Niemiera, A.X.; Harris, J.R.; Wright, R.D. 2005. Growth of container-grown pin oak and Japanese maple as influenced by sulfur and sulfated micronutrients. HortScience. 40(5): 1521–1523.

Brown, R.W.; Schultz, R.C.; Kormanik, P.P. 1981. Response of vesicular-arbuscular endomycorrhizal sweetgum seedlings to three nitrogen fertilizers. Forest Science. 27(2): 413–420.

Buchschacher, G.L.; Tomlinson, P.T.; Johnson, P.S.; Isebrands, J.G. 1991. Effects of seed source and cultural practices on emergence and seedling quality of northern red oak nursery stock. In: Coleman, S.S.; Neary, D.G., eds. Proceedings of the 6th biennial southern silvicultural research conference. Gen. Tech. Rep. SE-70. Asheville, NC: U.S. Department of Agriculture, Forest Service, Southern Research Station: 126–130.

Carey, W.A.; South, D.B.; Albrecht-Schmitt, T.E. 2002. Gypsum crystals on roots of nursery-grown pine seedlings. Communications in Soil Science and Plant Analysis. 33(7-8): 1131–1137.

Chen, J.; Huang, Y.; Caldwell, R.D. 2001. Best management practices for minimizing nitrate leaching from container-grown nurseries. The Scientific World Journal. 1: 96–102.

Chen, L.; Wang, C.; Dell, B.; Zhao, Z.; Guo, J.; Xu, D.; Zeng, J. 2017. Growth and nutrient dynamics of *Betula alnoides* seedlings under exponential fertilization. Journal of Forestry Research. 29(1): 111–119.

Clark, S.L.; Schlarbaum, S.E. 2018. Effects of acorn size and mass on seedling quality of northern red oak (*Quercus rubra*). New Forests. 49(4): 571–583.

Cordell, C.E.; Kelley, W.D.; Smith, R.S. 1989. Integrated nursery pest management. In: Cordell, C.E.; Anderson, R.L.; Hoffard, W.H.; Landis, T.D.; Smith, R.S.; Toko, H.V., tech. coords. Forest Nursery Pests. Agriculture Handbook 680. Washington, DC: U.S. Department of Agriculture, Forest Service. 5–13.

Crannell, W.K.; Tanaka, Y.; Myrold, D.D. 1994. Calcium and pH interaction on root nodulation of nursery-grown red alder (*Alnus rubra* Bong.) seedlings by Frankia. Soil Biology and Biochemistry. 26(5): 607–614.

Cross, R. 1984. Hardwood nursery management. In: Lantz, C.W., tech. coord. Proceedings, southern nursery conferences. Atlanta, GA: U.S. Department of Agriculture, Forest Service, State and Private Forestry: 199–203.

Cutter, B.E.; Murphey, W.K. 2007. Effects of potassium on growth and wood anatomy of a *Populus* hybrid. Wood and Fiber Science. 9(4): 282–288.

Davey, C.B. 1953. Sawdust composts: their preparation and effect on plant growth. Soil Science Society of America Journal. 17(1): 59–60.

Davey, C.B. 1994. Soil fertility and management for culturing hardwood seedlings. In: Landis, T.D.; Dumroese, R.K., tech. coords. National proceedings, forest and conservation nursery associations. RM-GTR-257. Fort Collins, CO: U.S. Department of Agriculture, Forest Service, Rocky Mountain Research Station: 38–49.

Davey, C.B. 1996. Nursery soil management – organic amendments. In: Landis, T.D.; South, D.B., tech. coords. National proceedings, forest and conservation nursery associations. RM-GTR-389. Portland OR: U.S. Department of Agriculture, Forest Service, Pacific Northwest Research Station: 6–18.

Davey, C.B. 2005. Hardwood seedling nutrition. In: Dumroese, R.K.; Riley, L.E.; Landis, T.D.; tech. coords. National proceedings, forest and conservation nursery associations - 2004. RMRS-P-35. Fort Collins, CO: U.S. Department of Agriculture, Forest Service, Rocky Mountain Research Station: 17–20.

Davey, C.B.; McNabb, K. 2019. The management of seedling nutrition. In: McNabb, K; Pike, C., eds. Nursery guide for the production of bareroot hardwood seedlings. Agriculture Handbook 733. Washington, DC: U.S. Department of Agriculture, Forest Service: 75–87.

Davis, A.S. 2003. Performance of northern red oak under adverse conditions. West Lafayette, IN: Purdue University. 112 p. Ph.D. dissertation.

Davis, A.S.; Jacobs, D.F.; Wightman, K.E.; Birge, Z.K. 2006. Organic matter added to bareroot nursery beds influences soil properties and morphology of *Fraxinus pennsylvanica* and *Quercus rubra* seedlings. New Forests. 31(2): 293–303.

Deines, J. 1973. The effects of fertilization on the growth and development of 1-0 sycamore (*Platanus occidentalis* L.), sweetgum (*Liquidambar styraciflua* L.), and green ash (*Fraxinus pennsylvanica* Marsh.) seedlings. Raleigh, NC: North Carolina State University. 80 p. Ph.D. dissertation.

Dey, D.C.; Jacobs, D.; McNabb, K.; Miller, G.; Baldwin, V.; Foster, G. 2008. Artificial regeneration of major oak (*Quercus*) species in the Eastern United States—a review of the literature. Forest Science. 54(1): 77–106.

Dixon, R.K.; Johnson, P.S. 1992. Synthesis of ectomycorrhizae on northern red oak seedlings in a Michigan Nursery. Journal of Arboriculture. 18(5): 266–272.

Dixon, R.K.; Wright, G.M.; Garrett, H.E.; Cox, G.S.; Johnson, P.S.; Sander, I.L. 1981. Container- and nursery-grown black oak seedlings inoculated with *Pisolithus tinctorius*: growth and ectomycorrhizal development during seedling production period. Canadian Journal of Forest Research. 11(3): 487–491.

Dobrahner, J.; Lowery, B.; Iyer, J.G. 2007. Slow-release fertilization reduces nitrate leaching in bareroot production of *Pinus strobus* seedlings. Soil Science. 172(3): 242–255.

dos Santos, H.Z. 2006. Morphological and nutritional development of three species of nursery-grown hardwood seedlings in Tennessee. Auburn, AL: Auburn University. 80 p. M.S. thesis.

Enebak, S.A. 2018. Personal communication. Professor, School of Forestry and Wildlife Sciences, Auburn University, Auburn University, AL.

Enebak, S.A. 2019. Pest management of bareroot hardwood seedlings. In: McNabb, K.; Pike, C. eds. Nursery guide for the production of bareroot hardwood seedlings. Agriculture Handbook 733. Washington, DC: U.S. Department of Agriculture, Forest Service: 121–133.

Engstrom, H.E.; Stoeckeler, J.H. 1941. Nursery practice for trees and shrubs suitable for planting on the prairie-plains. Agriculture Handbook 434. Washington, DC: U.S. Department of Agriculture, Forest Service, Lake States Forest Experiment Station. 159 p.

Erdmann, G.G.; Metzger, F.T.; Oberg, R.R. 1979. Macronutrient deficiency symptoms in seedlings of four northern hardwoods. Gen. Tech. Rep. NC-53. St. Paul, MN: U.S. Department of Agriculture, Forest Service, North Central Forest Experiment Station. 36 p.

Filer, T.H.; Cordell, C.E. 1983. Nursery diseases of southern hardwoods. Forest Insect and Disease Leaflet 137. U.S. Department of Agriculture, Forest Service, Southern Forest Experiment Station. 6 p.

Franzen, D.; Goos, R.J.; Norman, R.J.; Walker, T.W.; Roberts, T.L.; Slaton, N.A.; Endres, G.; Ashley, R.; Staricka, J.; Lukach, J. 2011. Field and laboratory studies comparing nutrisphere-nitrogen urea with urea in North Dakota, Arkansas, and Mississippi. Journal of Plant Nutrition. 34(8): 1198–1222.

Fujinuma, R. 2009. Improving nitrogen fertilization practices of bare-root northern red oak seedlings in Wisconsin state nurseries. Madison, WI: University of Wisconsin. 163 p. Ph.D. dissertation.

Fujinuma, R.; Balster, N.J.; Lee, H.K. 2011. Reduced rates of controlled-release fertilizer lower potential nitrogen leaching from a Wisconsin bare-root tree nursery. In: Fei, S.; Lhotka, J.M.; Stringer, J.W.; Gottschalk, K.W.; Miller, G.W., eds. Proceedings of the 17th central hardwood forest conference. Gen. Tech. Rep. NRS-P-78. Newtown Square, PA: U.S. Department of Agriculture, Forest Service, Northern Research Station: 347–357.

Fuller, D.L. 1988. Root and top growth response of five woody ornamental species to in field fabric containers, bed height, trickle irrigation, fertilizer source and fertilizer rate in Louisiana. Baton Rouge, LA: Louisiana State University. 112 p. Ph.D. dissertation.

Gaines, T.P.; Gaines, S.T. 1994. Soil texture effect on nitrate leaching in soil percolates. Communications in Soil Science and Plant Analysis. 25(13-14): 2561–2570.

Garbaye, J.; Churin, J.L.; Duponnois, R. 1992. Effects of substrate sterilization, fungicide treatment, and mycorrhization helper bacteria on ectomycorrhizal formation of pedunculate oak (*Quercus robur*) inoculated with *Laccaria laccata* in two peat bare-root nurseries. Biology and Fertility of Soils. 13(1): 55–57.

Gentry, A.S. 2020. Comparing survival and growth among three different planting stocks of water oak (*Quercus nigra*) and white oak (*Quercus alba*) on lands damaged by Hurricane Katrina. Mississippi State, MS: Mississippi State University. 88 p. M.S. thesis.

Goos, R.J. 2019. Evaluation of two products recently introduced as nitrification inhibitors. Communications in Soil Science and Plant Analysis. 50(5): 503–511.

Grieve, W.G.; Barton, J.H. 1960. Operations guide for TVA nurseries. Norris, TN: Tennessee Valley Authority: 54 p.

Guillebaud, W.H. 1930. Some experimental studies on the artificial regeneration of oak. Forestry. 4(2): 113–121.

Haase, D.L.; Pike, C., Enebak, S.; Mackey, L.; Ma, Z.; Rathjen, M. 2019. Forest nursery seedling production in the United States—fiscal year 2018. Tree Planters' Notes. 62: (1-2): 20–24.

Han, S.H.; An, J.Y.; Hwang, J.; Kim, S.B.; Park, B.B. 2016. The effects of organic manure and chemical fertilizer on the growth and nutrient concentrations of yellow poplar (*Liriodendron tulipifera* Lin.) in a nursery system. Forest Science and Technology. 12(3): 137–143.

Hauer, R.J.; Dawson, J.O. 1996. Growth and iron sequestering of pin oak (*Quercus palustris*) seedlings inoculated with soil containing ectomycorrhizal fungi. Journal of Arboriculture. 22(3): 122–130.

Hauke-Kowalska, M.; Kasprzyk, W. 2017. Influence of nitrogen fertilisation on biometric features of two-year-old seedlings of pedunculate oak subjected for root pruning. Folia Forestalia Polonica. 59(4): 281–286.

Hernández, G.; Haase, D.L.; Pike, C.; Enebak, S.; Mackey, L.; Ma, Z.; Clarke, M. 2018. Forest nursery seedling production in the United States—fiscal year 2017. Tree Planters' Notes. 61(2): 18–22.

Hilger, A.B.; Tanaka, Y.; Myrold, D.D. 1991. Inoculation of fumigated nursery soil increases nodulation and yield of bare-root red alder (*Alnus rubra* Bong.). New Forests. 5(1): 35–42.

Hoch, B.K. 2018. Assessing the tolerance of three species of *Quercus* L. and Iowa grown *Betula nigra* L. provenances to foliar chlorosis in elevated pH substrate. Manhattan, KS: Kansas State University. 152 p. M.S. thesis.

Hoss, G. 2004. Propagation protocol for growing bareroot oaks (*Quercus* L.). Native Plants Journal. 5(2): 16–170.

Hu, H.; Sparks, D.; Evans, J.J. 1991. Sulfur deficiency influences vegetative growth, chlorophyll and element concentrations, and amino acids of pecan. Journal of the American Society for Horticultural Science. 116(6): 974–980.

Hu, Y.L.; Hu, Y.; Zeng, D.H.; Tan, X.; Chang, S.X. 2015. Exponential fertilization and plant competition effects on the growth and N nutrition of trembling aspen and white spruce seedlings. Canadian Journal of Forest Research. 45(1): 78–86.

Hüttl, R.F.; Schaaf, W.W. 2012. Magnesium deficiency in forest ecosystems. Dordrecht, Netherlands: Springer Science & Business Media. 362 p.

Imo, M.; Timmer, V.R. 1992. Nitrogen uptake of mesquite seedlings at conventional and exponential fertilization schedules. Soil Science Society of America Journal. 56(3): 927–934.

Iyer, J.G.; Dobrahner, J.; Lowery, B.; Vande Hey, J. 2002. Slow release fertilizers in bareroot nurseries. In: Dumroese, R.K.; Riley, L.E.; Landis, T.D., tech. coords. National proceedings, Forest and Conservation Nursery Associations—1999, 2000, and 2001. RMRS-P-24. Ogden, UT: U.S. Department of Agriculture, Forest Service, Rocky Mountain Research Station: 112–119.

Iyer, J.G.; Love, J.R. 1974. Using micronutrient fertilizers in forest nurseries for invigorating stunted stock. Tree Planters' Notes. 25(2): 13–14.

Jacobs, D.F.; Salifu, K.F.; Seifert, J.R. 2005. Relative contribution of initial root and shoot morphology in predicting field performance of hardwood seedlings. New Forests. 30(2-3): 235–251.

Jozefek, H.J. 1989. The effect of varying levels of potassium on the frost resistance of birch seedlings. Silva Fennica. 23(1): 2–31.

Khan, S.A.; Mulvaney, R.L.; Ellsworth, T.R. 2014. The potassium paradox: implications for soil fertility, crop production and human health. Renewable Agriculture and Food Systems. 29(1): 3–27.

Knight, P.J. 1981. The maintenance of productivity in forest nurseries. In: Chavasse, C.G.R., ed. Forest nursery and establishment practice in New Zealand, FRR Symposium 22. New Zealand Forest Service, Forest Research Institute: 48–69.

Koll, P.J. 2009. Effects of conifer sawdust, hardwood sawdust, and peat on soil properties and a bareroot conifer seedling development. Houghton, MI: Michigan Technological University. 42 p. M.S. thesis.

Koo, R.C.J. 1985. Effects of nitrogen and potassium fertilization on winter injury of citrus trees. Proceedings of the Florida State Horticulture Society. 98: 53–56. https://journals.flvc.org/fshs/article/view/94991/91012

Kormanik, P.P. 1985. Effects of phosphorus and vesicular-arbuscular mycorrhizae on growth and leaf retention of black walnut seedlings. Canadian Journal of Forest Research. 15(4): 688–693.

Kormanik, P.P.; Sung, S.J.S.; Kormanik, T.L. 1994. Irrigating and fertilizing to grow better nursery seedlings. In: Landis, T.D., tech. coord. Proceedings, Northeastern and Intermountain forest and conservation nursery associations—1993. Gen. Tech. Rep. RM-243. Fort Collins, CO: U.S. Department of Agriculture, Forest Service, Rocky Mountain Research Station: 115–121.

Kormanik, P.P.; Sung, S.S.; Kass, D.J.; and Schilarbaum, S. 1998. Effect of seedling size and first order lateral roots on early development of northern red oak on mesic sites. In: Waldrop, T.A., ed. Proceedings of the 9th biennial southern silvicultural research conference. Gen. Tech. Rep. SRS-20. New Orleans, LA: U.S. Department of Agriculture, Forest Service, Southern Research Station: 247–252.

Kormanik, P.P.; Sung, S.J.S.; Kormanik, T.L.; Tibbs, T.; Zarnoch, S.J. 2003. Nutrition and irrigation regime affect size and early growth of white oak seedlings. In: Van Sambeek, J.W.; Dawson, J.O.; Ponder, F.; Loewenstein, E.F.; Fralish, J.S., eds. Proceedings of the 13th central hardwood forest conference. Gen. Tech. Rep. NC-234. St. Paul, MN: U.S. Department of Agriculture, Forest Service, North Central Research Station: 425–430.

Kramer, M.J. 2008. Fertilizer effects on soil pH, soil nutrients, and nutrient uptake in swamp white and pin oak seedlings on an alkaline Missouri River bottomland. Columbia, MO: University of Missouri. 156 p. Ph.D. dissertation.

Lamar, R.T.; Davey, C.B. 1988. Comparative effectivity of three *Fraxinus pennsylvanica* Marsh, vesicular-arbuscular mycorrhizal fungi in a high-phosphorus nursery soil. New Phytologist. 109(2): 171–181.

Lambert, D.H. 1982. Response of sweetgum to mycorrhizae, phosphorus, copper, zinc, and sewage sludge. Canadian Journal of Forest Research. 12(4): 1024–1027.

Landis, T.D. 1988. Management of forest nursery soils dominated by calcium salts. New Forests. 2(3): 173–193.

Landis, T.D.; Davey, C.B. 2009. Determining fertilizer rates and scheduling applications in bareroot nurseries. Forest Nursery Notes. 29(2): 14–21.

Leaf, A.L. 1968. K, Mg and S deficiencies in forest trees. In: Symposium proceedings, forest fertilization theory and practice. Muscle Shoals, AL: Tennessee Valley Authority: 88–122.

Marx, D.H. 1979a. Synthesis of *Pisolithus* ectomycorrhizae on white oak seedlings in fumigated nursery soil. Res. Note SE-280. Asheville, NC: U.S. Department of Agriculture, Forest Service, Southeastern Forest Experiment Station. 4 p.

Marx, D.H. 1979b. Synthesis of *Pisolithus* ectomycorrhizae on pecan seedlings in fumigated soil. Res. Note SE-283. Asheville, NC: U.S. Department of Agriculture, Forest Service, Southeastern Forest Experiment Station. 4 p.

Marx, D.H.; Cordell, C.E.; Kormanik, P. 1989. Mycorrhizae: benefits and practical application in forest tree nurseries. In: Cordell, C.E.; Anderson, R.L.; Hoffard, W.H.; Landis, T.D.; Smith, R.S.; Toko, H.V., tech. coords. Forest Nursery Pests. Agriculture Handbook 680. Washington, DC: U.S. Department of Agriculture, Forest Service: 18–21.

McNabb, K.; Heser, B. 1997. The potential use of slow release fertilizers for forest tree nursery production in the southeast U.S. In: Haase, D.L.; Rose, R., tech. coords. Symposium proceedings, forest seedling nutrition from the nursery to the field. Corvallis, OR: Oregon State University, Nursery Technology Cooperative: 50–57.

McNabb, K.; VanderSchaaf, C. 2005. Growth of graded sweetgum 3 years after root and shoot pruning. New Forests. 29(3): 313–320.

Mexal, J.G.; Rangel, R.C.; Negreros-Castillo, P.; Lezama, C.P. 2002. Nursery production practices affect survival and growth of tropical hardwoods in Quintana Roo, Mexico. Forest Ecology and Management. 168(1-3): 125–133.

Moore, O.W.; Blaser, E. 1960. Ammonium nitrate fertilizer can explode. Tree Planters' Notes. 41: 3–4.

Mullen, R.E. 1969. Acidification of a forest tree nursery soil. Soil Science Society of America Journal. 28(3): 441–444.

Munson, K.R. 1982. Decomposition, function, and maintenance of organic matter in a sandy nursery. Gainesville, FL: University of Florida: 98 p. Ph.D. dissertation.

O'Reilly, C.; De Atrip, N.; Doody, C.; O'Reilly, D.; Doody, P.; Thompson, B. 2008. Increasing the yield and quality of broadleaf planting stock through higher N fertilisation in the nursery. Irish Forestry. 65(1-2): 5–16.

Park, B.B.; Cho, M.S.; Lee, S.W.; Yanai, R.D.; Lee, D.K. 2012. Minimizing nutrient leaching and improving nutrient use efficiency of *Liriodendron tulipifera* and *Larix leptolepis* in a container nursery system. New Forests. 43(1): 57–68.

Phares, R.E. 1964. Mineral nutrition of forest tree seedlings. Ames, IA: Iowa State University. 168 p. Ph.D. dissertation.

Phares, R.E. 1971. Fertilization tests with potted red oak seedlings. Research Note NC-114. St. Paul, WI: U.S. Department of Agriculture, Forest Service, North Central Forest Experiment Station: 4 p.

Pike, C.; Warren, J.; Coggeshall, M. 2018. Trends in production of hardwood tree seedlings across the Northeast United States from 2008 to 2016. Tree Planters' Notes: 61(1): 18–25.

Ponder, F. 1979. Soil structure and mycorrhizae encourage black walnut growth in old fields. Res. Note NC-249. St. Paul, MN: U.S. Department of Agriculture, Forest Service, North Central Forest Experiment Station. 4 p.

Quiñones, A.; Bañuls, J.; Millo, E.P.; Legaz, F. 2003. Effects of 15N application frequency on nitrogen uptake efficiency in Citrus trees. Journal of Plant Physiology. 160(12): 1429–1434.

Radwan, M.A. 1965. Persistence and effect of TMTD on soil respiration and nitrification in two nursery soils. Forest Science. 11(2): 152–159.

Reazin, C.; Baird, R.; Clark, S.; Jumpponen, A. 2019. Chestnuts bred for blight resistance depart nursery with distinct fungal rhizobiomes. Mycorrhiza. 29(4): 313–324.

Rose, R.; Haase, D.L.; Boyer, D. 1995. Organic matter management in forest tree nurseries: theory and practice. Corvallis, OR: Oregon State University, Nursery Technology Cooperative. 68 p.

Rowan, S.J. 1972. Hardwood seedling production trends in southern nurseries, 1965–1970. Journal of Forestry. 70(3): 162–163.

Salifu, K.F.; Jacobs, D.F.; Birge, Z.K. 2008. Performance of nutrient-loaded red oak and white oak seedlings on mine lands in southern Indiana. In: Dumroese, R.K.; Riley, L.E., tech. coords. National proceedings, forest and conservation nursery associations—2007. Proceedings RMRS-P-57. Fort Collins, CO: U.S. Department of Agriculture, Forest Service, Rocky Mountain Research Station: 65–71.

Salifu, K.F.; Jacobs, D.F.; Birge, Z.K. 2009. Nursery nitrogen loading improves field performance of bareroot oak seedlings planted on abandoned mine lands. Restoration Ecology. 17(3): 339–349.

Schenck, C.A. 1907. Biltmore lectures on silviculture. Albany, NY: Brandow Printing Company. 184 p.

Schempf, W.M. 2018. Hardwood reforestation on reclaimed minelands in the Eastern Interior Region: interactions of nursery stocktype, herbicide, and tree shelters on reclamation success West Lafayette, IN: Purdue University. 78 p. Ph.D. dissertation.

Schmal, J.L.; Jacobs, D.F.; O'Reilly, C. 2011. Nitrogen budgeting and quality of exponentially fertilized *Quercus robur* seedlings in Ireland. European Journal of Forest Research. 130(4): 557–567.

Schultz, R.C.; Kormanik, P.P.; Bryan, W.C. 1981. Effects of fertilization and vesicular-arbuscular mycorrhizal inoculation on growth of hardwood seedlings. Soil Science Society of America Journal. 45(5): 961–965.

Sharpe, R.R.; Marx, D.H. 1986. Influence of soil pH and *Pisolithus tinctorius* ectomycorrhizae on growth and nutrient uptake of pecan seedlings. HortScience. 21(6): 1388–1390.

Shaw, G.W.; Dey, D.C.; Kabrick, J.; Grabner, J.; Muzika, R.M. 2003. Comparison of site preparation methods and stock types for artificial regeneration of oaks in bottomlands. In: Van Sambeek, J.W.; Dawson, J.O.; Ponder, F.; Loewenstein, E.F.; Fralish, J.S., eds. Proceedings of the 13th central hardwood forest conference. Gen. Tech. Rep. NC-234. St. Paul, MN: U.S. Department of Agriculture, Forest Service, North Central Research Station: 186–198.

Siegel, R.S.; Brock, J.H. 1990. Germination requirements of key southwestern woody riparian species. Desert Plants. 10(1): 3–9.

South, D. 1975. The determination of nursery practices for the production of quality sweetgum (*Liquidambar styraciflua* L.) and sycamore (*Plantanus occidentalis* L.) planting stock. Raleigh, NC: North Carolina State University. 91 p. M.S. thesis

South, D. 1977. Artificial inoculation of fumigated nursery beds with endomycorrhizae. Tree Planters' Notes. 28(3): 3–6.

South, D.B. 1994. Managing pesticides and nitrogen in southern pine nurseries and some ways to reduce the potential for groundwater contamination. Forestry School Series No. 14. Auburn, AL: Alabama Agricultural Experiment Station. 18 p.

South, D.B. 2018. Fertilizer trials for bareroot nurseries in North America. Reforesta. 5: 54–76.

South, D.B. 2019a. Is the recommended pH for growing hardwood seedlings wrong? Reforesta. 7: 81–108.

South, D.B. 2019b. Questions and considerations for the next generation of seedling fertilization researchers. Tree Planters' Notes: 62(2): 67–87.

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

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

South, D.B.; VanderSchaaf, C.L. 2017. Should forest regeneration studies have more replications? Reforesta. (3): 19–30.

Steinfeld, D.; Feigner, S. 2004. Subsurface banding of phosphorus, potassium, and controlled release nitrogen fertilizers in the 1+ 0 year at J Herbert Stone Nursery. In: Riley, L.E.; Dumroese, R.K.; Landis, T.D., tech. coords. National proceedings, Forest and Conservation Nursery Associations—2003. Proceedings RMRS-P-33. Fort Collins, CO: U.S. Department of Agriculture, Forest Service, Rocky Mountain Research Station: 33–37.

Stoeckeler, J.H.; Jones, G.W. 1957. Forest nursery practice in the Lake States. Agriculture Handbook 110. Washington, DC: U.S. Department of Agriculture, Forest Service. 124 p.

Stone, E.L. 1990. Boron deficiency and excess in forest trees: a review. Forest Ecology and Management. 37(1-3): 49–75.

Stone, J.M. 1980. Hardwood seedling production: what are the fertility requirements? In: Abrahamson, L.P.; Bickelhaupt, D.H., eds. Proceedings, North American forest tree nursery soils workshop. Syracuse, NY: State University of New York, College of Environmental Science and Forestry: 121–128.

Stone, J.M. 1986. Topdress fertilization. In: Schroeder, R.A., tech. coord. Proceedings, Southern Forest Nursery Association. Atlanta, GA: U.S. Department of Agriculture, Forest Service, State and Private Forestry: 86–91.

Teng, Y.; Timmer, V.R. 1990. Phosphorus-induced micronutrient disorders in hybrid poplar: I. preliminary diagnosis. Plant and Soil. 126(1): 19–29.

Thor, E. 1965. Effects of eight nursery treatments on yellow-poplar seedling characteristics and field performance. Tree Planters' Notes. 72: 16–18.

Tilki, F.; Yuksek, F.T.; Guner, S. 2009. The effect of undercutting on growth and morphology of 1+0 bareroot sessile oak seedlings in relation to acorn size. Australian Journal of Basic and Applied Sciences. 3(4): 3900–3905.

Timilsena, Y.P.; Adhikari, R.; Casey, P.; Muster, T.; Gill, H.; Adhikari, B. 2015. Enhanced efficiency fertilisers: a review of formulation and nutrient release patterns. Journal of the Science of Food and Agriculture. 95(6): 1131–1142.

Timmer, L.W.; Leyden, R.F. 1980. The relationship of mycorrhizal infection to phosphorus-induced copper deficiency in sour orange seedlings. New Phytologist. 85(1): 15–23.

Timmer, V.R. 1985. Response of a hybrid poplar clone to soil acidification and liming. Canadian Journal of Soil Science. 65(4): 727-735.

Timmer, V.R.; Teng, Y. 1990. Phosphorus-induced micronutrient disorders in hybrid poplar: III. Prevention and correction in nursery culture. Plant and Soil. 126(1): 41–51.

Tran, H.M. 2005. Quantifying the effects of sawdust application on soil chemical and physical properties and corn yield. Knoxville, TN: University of Tennessee. 112 p. M.S. thesis.

Triebwasser, M.E. 2004. Fertilizer application: balancing precision, efficacy, and cost In: Riley, L.E.; Dumroese, R.K.; Landis, T.D., tech coords. National proceedings, Forest and Conservation Nursery Associations—2003. Proceedings RMRS-P-33. Fort Collins, CO: U.S. Department of Agriculture, Forest Service, Rocky Mountain Research Station: 38–41.

Van Sambeek, J.W.; Kabrick, J.M.; Dey, D.C. 2017. Foliar nutrient responses of oak saplings to nitrogen treatments on alkaline soils within the Missouri River Floodplain. In: Kabrick, J.M.; Dey, D.C.; Knapp, B.O.; Larsen, D.R.; Shifley, S.R.; Stelzer, H.E., eds. Proceedings of the 20th Central Hardwood Forest Conference. Gen. Tech. Rep. NRS-P-167. Newtown Square, PA: U.S. Department of Agriculture, Forest Service, Northern Research Station: 58–71.

Van den Burg, J. 1983. Copper uptake by some forest tree species from an acid sandy soil. Plant and Soil. 75(2): 213–219.

van den Driessche, R. 1988. Nursery growth of conifer seedlings using fertilizers of different solubilities and application time, and their forest growth. Canadian Journal of Forest Research. 18(2): 172–180.

Vande Hey, J.M. 2007. Production of conifer bareroot seedling using controlled release fertilizer. Native Plants Journal. 8(3): 288–293.

VanderSchaaf, C.L.; South, D.B.; Doruska, P.F. 2003. The power of statistical tests of herbicide trials in forest nurseries. Southern Weed Science Society. 56: 202–211.

Villarrubia, J.M. 1980. Effect of nitrogen rate and source on growth and performance of *Liquidambar styraciflua* (sweetgum) and *Fraxinus pennsylvanica* (green ash) in a Virginia nursery. Raleigh, NC: North Carolina State University. 91 p. Ph.D. dissertation.

Wallace, A.; Wallace, G.A.; Samman, Y. 1983. Zinc and manganese chelate toxicity on nursery and seedling peach trees. Journal of Plant Nutrition. 6(6): 473–489.

Walter, W.D.; Godsey, L.D.; Garrett, H.E.; Dwyer, J.P.; Van Sambeek, J.W.; Ellersieck, M.R.; 2013. Survival and 14-year growth of black, white, and swamp white oaks established as bareroot and RPM®-containerized planting stock. Northern Journal of Applied Forestry. 30(1): 43–46.

Williams, H.M.; Stroupe, M. 2002. First-year survival and growth of bareroot and container water oak and willow oak seedlings grown at different levels of mineral nutrition. In: Stanturf, J.A., ed. Proceedings of the 11th biennial Southern Silvicultural Research Conference. Gen. Tech. Rep. SRS–48. Asheville, NC: U.S. Department of Agriculture, Forest Service, Southern Research Station: 338–341.

Williams, R.D.; Hanks, S.H. 1994. Hardwood nursery guide. Agriculture Handbook 473. Washington, DC: U.S. Department of Agriculture, Forest Service, State and Private Forestry. 78 p.

Williams, R.D.; Funk, D.T.; Phares, R.E.; Lemmien, W.; Russell, T.E. 1974. Apparent freeze damage to black walnut seedlings related to seed source and fertilizer treatment. Tree Planters' Notes. 25(3): 6–8.

Wilson, E.R.; Vitols, K.C.; Park, A. 2007. Root characteristics and growth potential of container and bare-root seedlings of red oak (*Quercus rubra* L.) in Ontario, Canada. New Forests. 34(2): 163–176.

Wright, A.N.; Niemiera, A.X.; Harris, J.R.; Wright, R.D. 1999. Preplant lime and micronutrient amendments to pine bark affect growth of seedlings of nine container-grown tree species. HortScience. 34(4): 669–673.

Yawney, W.J.; Schultz, R.C.; Kormanik, P.P. 1982. Soil phosphorus and pH influence the growth of mycorrhizal sweetgum. Soil Science Society of America Journal. 46(6): 1315–1320.

Zarger, T.G. 1964. Comparison of slowly and rapidly available nitrogen fertilizers for nursery production of pine seedlings. Tree Planters' Notes. 66: 8–10.