Is the recommended pH for growing hardwood seedlings wrong?

David B South

Emeritus Professor, School of Forestry and Wildlife Science, Auburn University, AL

✉ southdb@auburn.edu

ARTICLE INFO

Citation:
South DB (2019) Is the recommended pH for growing hardwood seedlings wrong? Reforesta 7: 81-108.
DOI: http://dx.doi.org/10.21750/REFOR.7.07.69

Editor: Arnulfo Aldrete, Mexico
Received: 2019-01-17
Accepted: 2019-05-20
Published: 2019-06-28

Abstract

Two schools of thought address the optimum soil pH (measured in water) for growing hardwood seedlings in bareroot nurseries. One school uses nutrient surveys in non-fertilized forests to determine the best pH range for growing seedlings in fertilized nurseries. Some students of this school believe hardwood seedlings grow best at pH 6.0 to 7.5. In contrast, another school relies on research from pH trials to conclude that fertilized hardwoods can grow well in soils that range from pH 4.5 to 6.0. This article compiles some of the findings from seedbed and greenhouse trials and attempts to use data to dispel a few myths about the “optimum pH” for growing hardwood seedlings. Greenhouse trials suggest many fertilized hardwoods grow better in acid soils (pH 4-6) than in nearly neutral soils (pH 6.0-7.5). The optimal pH for growth differs among species and, therefore, it is a myth that all hardwood seedlings grow best at pH 6 to 7.5. Most nursery managers in the southern United States grow bareroot hardwoods between pH 4.8 and 6.0.

Keywords

Acidity; Bareroot; Micronutrient; Nursery: Nutrient deficiency

Contents

1 Introduction

There is no consensus on the recommended pH range (measured in water) for growing hardwood seedlings in nurseries. In some cases, recommended ranges do not even overlap (Table 1). Although many recommendations involve a minimum pH of 5.5 or 6.0, some managers ignore this recommendation and grow bareroot hardwood seedlings in soils at pH 4.8 (Table 2). A pH range of 4.5 to 6.0 is also suitable for establishing plantations of various species (see Table 3 for scientific names). Sometimes hardwoods are established on acid strip-mined sites to restore these areas.

Table 1. The recommended soil pH for bareroot and container-grown hardwoods varies considerably. Several authors suggest seedbeds have a minimum pH (water) of 5.5 or greater.

Crop	Nursery	pH range	Reference
hardwoods	bareroot	6.5-7.5	Youngberg 1984
hardwoods	bareroot	6.5-7.0	Leaf et al. 1978
Fraxinus	bareroot	6.2	Wilde and Patzer 1940
hardwoods	bareroot	6.0-8.0	Laurie and Chadwick 1931
hardwoods	bareroot	6.0-8.0	Engstrom and Stoeckler 1941
hardwoods	bareroot	6.0-7.0	Solan et al. 1979
hardwoods	bareroot	6.0-7.0	Edwards 1986
hardwoods	container	6.0-7.0	Landis 1989
hardwoods	bareroot	6.0-8.0	Meyer 1993
hardwoods	bareroot	6.0-7.0	Briggs 2008
hardwoods	bareroot	6.0	Bonner and Broadfoot 1964
hardwoods	bareroot	6.0	Peevy 1976
hardwoods	bareroot	6.0	Williams and Hanks 1976
hardwoods	bareroot	6.0	Cordell and Filer 1984
hardwoods	bareroot	5.8-6.5	Steinbeck and May 1977
hardwoods	bareroot	5.8-6.2	Pritchett and Fisher 1987
Acer, Tilia, Ulmus	bareroot	5.8	Wilde and Patzer 1940
hardwoods	bareroot	5.6-6.8	Davey 1973
hardwoods	bareroot	5.6-6.8	Stone 1980
Acer, Carya, Juglans	bareroot	5.5-7.3	Wilde 1958
hardwoods	bareroot	5.5-6.5	Stoeckeler and Jones 1957
hardwoods	bareroot	5.5-6.5	Turner 1970
most hardwoods	container	5.5-6.5	Dumroese et al. 2012
hardwoods	container	5.5-6.5	Wilkinson et al. 2014
hardwoods and pines	bareroot	5.5-6.5	Landis 2008
Populus and Fraxinus	bareroot	5.5-6.5	Aldhous and Mason 1994
hardwoods	container	5.4-6.0	Mathers et al. 2007
Betula	bareroot	5.3	Wilde and Patzer 1940
Populus	bareroot	5.0-6.5	Jobling 1990
Prunus, *Quercus*	bareroot	5.0-6.0	Wilde 1958
Quercus	bareroot	5.0-6.0	Storandt 2002
most tree species	bareroot	5.0-6.0	Morby 1984
hardwoods	bareroot	5.0-6.0	Davey and McNabb 2019
Acer	bareroot	5.0-5.6	Altland 2006
hardwoods	bareroot	5.0-5.5	Aldhous and Mason 1994
Ilex, Magnolia	Bareroot	4.5-6.0	Laurie and Chadwick 1931
woody species	container	4.5-5.5	Whitcomb 2009
acid loving hardwoods	container	4.0-5.0	Dumroese et al. 2012

One might ask why strip-mined soils (with pH <5) are suitable for planting various hardwood species (Davis et al. 2012) while others warn against growing hardwoods in a fertilized nursery soil with a pH less than 5.5. Although seedling survival is low when strip-mined soils have a pH less than 3.5 (Davidson 1979; Hensley and Carpenter 1986), many planted hardwoods grow well in non-fertilized soils with pH 4 to 7.5 (Table 3, Ashby et al. 1989). Unlike most reclamation sites, fertilizers and irrigation are applied to increase growth of hardwoods in nurseries and several authorities indicate that fertilized hardwoods can grow well over a wide pH range. For example, yellow poplar and sycamore grow well on both alkaline (pH 7.3-8.0) and acid (pH 4.6) soils (Wilde 1954). This agrees with Peevy (1976) who said that hardwood seedlings "may be grown over a wide range [of] pH [if] the proper concentrations of essential mineral elements are maintained." In contrast, pines have a narrower pH range than hardwoods (Benzian 1965; Mizell 1980; South 2017).

After reviewing the literature (Table 1), it became apparent that the pH 5.0-5.5 recommendations by Aldhous and Mason (1994) were based on empirical nursery trials (Benzian 1965) while none of the higher recommendations (minimum = pH 6.0 or 6.5) were based on pH trials from hardwood seedbeds. Instead, they were based on various assumptions about pH ranges observed in forests (e.g. Burns and Honkala 1990; DeVall 1943; Spurway 1941) and on assumptions about nutrient availabilities in non-fertilized agronomic soils (Brady 1974).

Table 2. The pH (water) of operational 1-0 hardwood seedbeds at time of sowing.

State	Year	Lowest pH	Highest pH
Alabama	2018	5.5	5.8
Arkansas 1	2015	5.2	5.8
Arkansas 2	2018	4.7	5.0
Georgia	2014	4.8	5.8
Indiana	2017	5.6	6.4
Mississippi	1981	4.9	4.9
North Carolina 1	1984	5.5	5.5
North Carolina 2	2016	4.8	4.8
South Carolina	2017	5.6	5.6
Tennessee	2017	4.9	5.5
Virginia 1	1999	5.2	6.2
Virginia 2	2016	5.2	5.7

Table 3. Estimates of "preferred" and "acceptable" soil pH (water) for plantations of selected hardwoods.

Common name	Species	"Preferred" pH range	Acceptable pH range	Reference
Black walnut	*Juglans nigra* L.	6.0-8.0	--	Spurway 1941
Fremont cottonwood	*Populus fremontii* S. Watson	6.0-8.0	--	
Choke cherry	*Prunus virginiana* L.	6.0-8.0	--	
Basswood	*Tilia glabra* L.	6.0-7.5	--	
American elm	*Ulmus americana* L.	6.0-7.5	--	
Black locust	*Robinia pseudoacacia* L.	6.0-7.5	--	
Sweetgum	*Liquidambar styraciflua* L.	6.0-7.0	--	
Yellow poplar	*Liriodendron tulipifera* L.	6.0-7.0	--	
Eastern redbud	*Cercis canadensis* L.	5.5-6.5	--	
Dogwood	*Cornus florida* L.	5.0-7.0	--	

Continuation of Table 3.

Common name	**Species**	**"Preferred" pH range**	**Acceptable pH range**	**Reference**
White oak	*Quercus alba* L.	5.0-6.5	--	
Japanese holly	*Ilex crenata* Thunb.	5.0-6.0	--	
Sweet birch	*Betula lenta* L.	4.5-7.0	--	
Sweetbay magnolia	*Magnolia virginiana* L.	4.0-5.0	--	
Quaking aspen	*Populus tremuloides* Michx.	3.8-5.5	--	
Cottonwood	*Populus deltoides* Bartr. ex Marsh.	5.5-7.5	4.5-8.5	Baker and Broadfoot 1979
Pecan	*Carya illinoensis* (Wangenh.) K. Koch	5.5-7.5	4.5-8.5	
Green ash	*Fraxinus pennsylvanica* Marsh.	5.5-7.5	4.5-8.5	
Sweetgum	*Liquidambar styraciflua* L.	5.5-7.5	4.5-8.5	
Sycamore	*Platanus occidentalis* L.	5.5-7.5	4.5-8.5	
Yellow poplar	*Liriodendron tulipifera* L.	4.5-7.5	4.5-8.5	
Cherrybark oak	*Quercus falcata var. pagodaefolia* Ell.	4.5-5.5	4.0-7.5	
Nuttall oak	*Quercus nuttallii* Palmer	4.5-5.5	4.0-7.5	
Shumard oak	*Quercus shumardii* Buckl.	4.5-5.5	4.0-7.5	
Swamp chestnut	*Quercus michauxii* Nutt.	4.5-5.5	4.0-7.5	
Water oak	*Quercus nigra* L.	4.5-5.5	4.0-7.5	
Willow oak	*Quercus phellos* (Wangenh.) K. Koch	4.5-5.5	4.0-7.5	
Hackberry	*Celtis occidentalis* L.	4.0-8.5	4.0-8.5	
Sugarberry	*Celtis laevigata* Wild.	4.0-8.5	4.0-8.5	
Princess tree	*Paulownia tomentosa* Siebold & Zucc.	6.0-8.0	--	Londo et al. 2006
Live oak	*Quercus virginiana* Mill.	6.0-7.0	--	
Dogwood	*Cornus florida* L.	5.0-8.0	--	
Black walnut	*Juglans nigra* L.	5.0-7.5	--	
American beech	*Fagus grandifolia* Ehrh.	5.0-7.5	--	
Yellow poplar	*Liriodendron tulipifera* L.	5.0-7.0	--	
Yellow birch	*Betula alleghaniensis* Britton	5.0-6.5	--	
Pecan	*Carya illinoensis* (Wangenh.) K. Koch	4.8-7.5	--	
Blackgum	*Nyssa sylvatica* Marshall	4.6-7.0	--	
Black locust	*Robinia pseudoacacia* L	4.6-8.2	--	
White oak	*Quercus alba* L	4.5-6.2	--	
Northern red oak	*Quercus rubra* L	4.5-6.0	--	
Sycamore	*Platanus occidentalis* L	4.4-7.5	--	
Red maple	*Acer rubrum* L.	4.4-7.5	--	
Green ash	*Fraxinus pennsylvanica* Marsh.	3.6-7.5	--	
Cottonwood	*Populus deltoides* Bartr. ex Marsh.	3.6-7.5	--	
Sweetgum	*Liquidambar styraciflua* L.	3.6-7.5	--	
Nuttall oak	*Quercus nuttallii* Palmer	3.6-6.8	--	
Willow oak	*Quercus phellos* L.	3.6-6.3	--	
Water oak	*Quercus nigra* L.	3.6-6.3	--	
Black cherry	*Prunus serotine* Ehrh.	3.0-5.0	--	
Red alder	*Alnus rubra* L.	--	--	
Balsam poplar	*Populus balsamifera* L.	--	--	
Sawtooth oak	*Quercus acutissima* Carruth.	--	--	

2 Bareroot nurseries

Blanche Benzian (1965) conducted 16 pH trials with hardwoods at UK Forestry Commission nurseries (1948-1954). When lime ($CaCO_3$) was added to pH 4.2 seedbeds at the Wareham Nursery, some species grew taller while other were shorter (Table 4). Soon after, Aldhous (1972) summarized Benzian's research: "There has been little research into the pH responses of hardwoods. However, practical experience and limited research show that most hardwoods, e.g. oak, alder, beech, birch and [*Acer*] grow well on acid soils, but there are some important exceptions, namely poplars and ash which require slightly acid or neutral soils..."

Table 4. The effect of adding lime ($CaCO_3$) and aluminum sulfate (335 kg ha^{-1}) on soil pH (water) and on seedling height (mm) at the Wareham Nursery in the UK (Benzian 1965).

Species	Year	Untreated	Lime	Additional lime	Aluminum sulfate
	1948	pH 4.2	pH 5.3	pH 5.8	pH 3.8
Betula lutea L.	1948	164	121	87	61
Fagus sylvatica L.	1948	86	113	120	60
Quercus robur L.	1948	75	96	81	65
	1949	pH 4.0	pH 5.7	pH 6.5	pH 4.0
Betula spp.	1949	680	313	246	crop failed*
Fraxinus excelsior L.	1949	20	29	26	crop failed*

***** Whitcomb (2018) recommends that aluminum sulfate not be used to lower soil pH.

Only a few trials have been conducted with lime in hardwood seedbeds in the United States. Lime was applied before sowing hardwood seedbeds at the Edwards Nursery (Morganton, NC) and Union Camp Nursery at Murfreesboro, NC (Deines 1973). At the Edwards Nursery in October, check plots and the high-lime plots (1,121 kg ha^{-1}) averaged pH 5.9 and 6.8, respectively. The high lime treatment reduced growth of sweetgum (Figure 1) and a northern seed source of sycamore.

Crannell et al. (1994) conducted trials at bareroot nurseries in Oregon (pH 5.6) and Washington (pH 6.6). At the nursery in Washington, temporarily increasing acidity to pH 5.9 increased the production of red alder which increased nursery profits. In contrast, increasing soil pH to 7.2 with CaO had no effect on seedling biomass at the Oregon nursery.

While lime increases soil pH, some fertilizers (e.g. ammonium nitrate and ammonium sulfate) will lower soil pH. Trials at the Union Camp Nursery in Virginia indicated that sweetgum and green ash grew best when fertilized with ammonium sulfate which reduced soil pH to 4.5 (Figure 2; Davey 1996; Stone 1980; Villarrubia 1980). Perhaps due to these data, Davey (1996) did not mention what pH range was "optimum" for growing bareroot seedlings. Once the word spread that hardwood seedlings could be produced in soils with pH less than 5.0, several nursery managers abandoned the practice of using different soil pH targets for pines and hardwoods. In nurseries, both pines and hardwoods can be grown at the same pH range (Landis 2008; Morby 1984; Tinus 1979; Williams 1972). Good quality sweetgum, sycamore, green ash, yellow poplar, white oak and Nuttall oak have been grown in seedbeds that range from pH 4.8 to 6.0 (dos Santos 2006; Lamar and Davey 1988; Marx 1979; Rentz 1996). Whitcomb (2009) says that most woody plants grow best at soil pH 4.5 to 5.5.

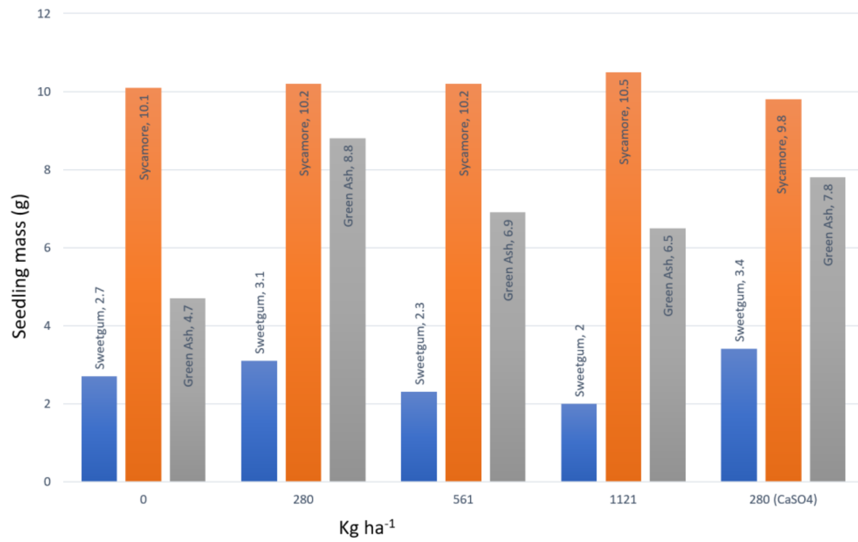

Figure 1. Data from North Carolina (Deines 1973) illustrate the effect of lime ($CaCO_3$) on dry mass of sweetgum, sycamore (Edwards Nursery at Morganton) and green ash (Union Camp Nursery at Murfreesboro) seedlings. Standard errors are 0.2, 0.8 and 1.5 g for sweetgum, sycamore and green ash respectively. Although the high rate of lime (pH 6.8 at lifting) reduced shoot mass and root-collar diameter of sweetgum seedlings, a significant increase occurred when 280 kg of gypsum ($CaSO_4$; pH 5.7) was applied to sweetgum seedbeds. Neither the lime nor $CaSO_4$ treatments had a significant effect (α=0.05) on green ash seedlings. For sycamore, adding lime increased growth of a southern seed source but decreased growth of a northern seed source (data not shown).

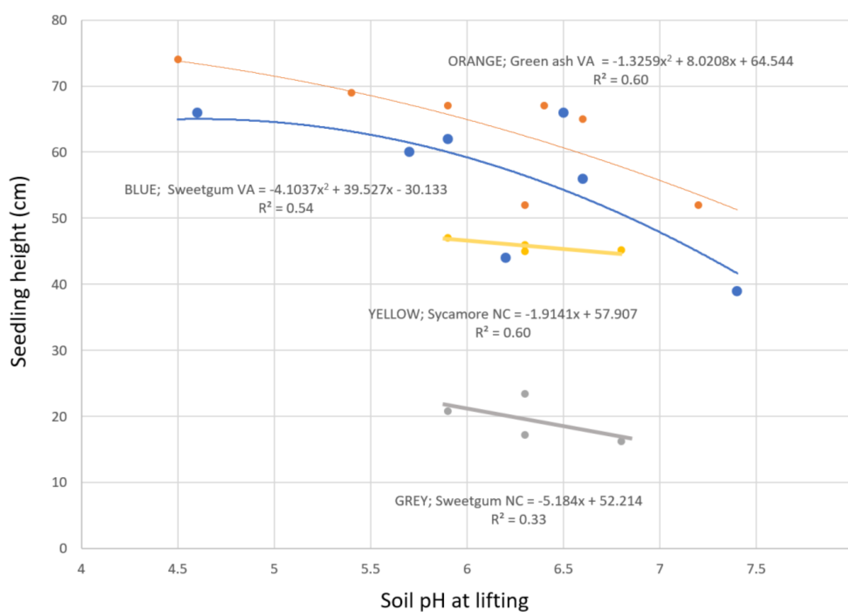

Figure 2. The correlations between soil pH (water) and height growth of bareroot hardwood seedlings. Data are from trials at the Edwards Nursery in North Carolina (Deines 1973) and from the Union Camp Nursery at Capron, Virginia (Villarrubia 1980).

3 Container nurseries

Sometimes problems with disease and nutrition occur when seedlings are grown in containers filled with 100% soil (Böhlenius et al. 2016; Chen et al. 2006; Hendrickson and Veihmeyer 1941; Wilkinson et al. 2014). Therefore, most hardwood seedlings are grown in containers using media composed of peat, perlite and vermiculite (Dumroese et al. 2012; Enebak 2011; Landis 1989). It appears that when compared to inorganic soil, the optimum pH range is greater when hardwoods are grown in a soil-less potting-mix. For example, height growth of birch grown in containers was not related to pH that ranged from pH 3.8 to 7 (Rikala and Jozefek 1990), while heights of bareroot birch seedlings were negatively related to soil pH (Table 4).

In Oklahoma, container-grown, woody ornamentals grew well at pH 3.0 when seedlings were fertilized with calcium (Ca) and magnesium (Mg), (Whitcomb 1983). "Only under conditions of high concentration of calcium, magnesium, sodium or bicarbonates of these elements does pH begin to influence micronutrient nutrition of plants in containers." After years of "frustration with pH and what it means or doesn't mean" Whitcomb (1988) now believes pH has little to do with the nutrition of growing seedlings in containers.

While media pH may not be a major factor affecting growth of properly fertilized seedlings in containers (Whitcomb 1988), various studies indicate biomass of several hardwoods is greater when media pH ranges from pH 4 to pH 5.5 (Table 5, Handreck 1989). Results from these trials can be used to reject the hypothesis that container-grown hardwoods grow best at pH 6-8. In one study (Beyer et al. 2013), oak seedlings grown at pH 7.4 were slightly chlorotic and were smaller than seedlings grown in pH 3.3 soil (Figure 3).

Figure 3. The effect of lime (reagent grade powdered amorphous $CaCO_3$ plus $MgCO_3$) on growth (11-weeks) of northern red oak seedlings in a greenhouse. Soil on the left was not limed (pH 3.3, Ca= 42 µg g^{-1}, Mg= 11 µg g^{-1}, Al= 44 µg g^{-1}) and was not fertilized while the pot on the right (pH 7.4, Ca= 590 µg g^{-1}, Mg= 150 µg g^{-1}, Al= 0.2 µg g^{-1}) contained soil that was treated with 50 g of lime per liter (Beyer et al. 2013). The lime treatment had no significant effect on root mass (left = 9.4 g; right = 9.6 g) but leaf mass (left = 8 g; right = 6 g) was reduced by the lime treatment. Better growth in acid soil (pH 3.3 – 5.4) casts doubt on the belief that the optimum pH range for growing hardwood seedlings is pH 6.0 to 8.0 (Engstrom and Stoeckler 1941, Laurie and Chadwick 1931, Meyer 1993). The soil was from the Hazleton series: loamy-skeletal, siliceous, active, mesic Typic Dystrudept. Foliar concentrations were: unfertilized = Ca 0.5%, Mn 690 µg g^{-1}, Cu 7.5 µg g^{-1}, Zn 110 µg g^{-1}; limed = Ca 1.8%, Mn 32 µg g^{-1}, Cu 2.8 µg g^{-1}, Zn 19 µg g^{-1}. (Photo by Nelson Beyer, United States Geological Survey 2009).

Table 5. Examples of greenhouse trials demonstrating the change (%) in plant mass (mg) or foliage (f) mass when hardwoods are grown at varying pH (water) levels. In most cases, mass increased when plants were grown at pH 4 to 5.5.

Genus	Comment	pH #1	pH #2	Mass for pH#1 (mg)	Mass for pH#2 (mg)	Change in mass with decreased pH (%)	Reference
Liquidambar	GM endo	6.7	5.1	2,550	610	-76	Davis et al. 1993
Carya		6.1	4.9	108,000	35,000	-67	Johnson and Hagler 1955
Paulownia		6.0	5.0	2,600	1,280	-51	Melhuish et al. 1990
Quercus		6.8	4.8	14,400	7,700	-46	Crews and Dick 1998
Trichilia		6.3	4.5	310	210	-32	Ramlall et al. 2015
Betula		7.0	5.0	30,800	23,500	-24	Zhang et al. 2016
Leucaena	GA endo	6.0	5.0	8,400	6,900	-18	Soedarjo and Habte 1995
Eucalyptus		5.2	4.0	18,400	16,200	-12	Gabriel et al. 2018
Populus	family 1	6.0	5.0	9,100	8,500	-7	DesRochers et al. 2003
Alnus		5.4	4.7	1,810	1,730	-4	Granhall et al. 1983
Populus	hybrid	7.2	5.8	9,000	8,800	-2 (f)	Timmer 1985
Cornus		7.0	5.0	12,400	12,500	+1	Zhang et al. 2016
Alnus		5.4	4.7	980	1000	+2	Granhall et al. 1983
Populus		5.7	4.6	14,500	14,800	+2	Hjelm and Rytter 2016
Betula		6.0	4.0	2,232	2,308	+3	Rikala and Jozefek 1990
Paulownia		6.5	5.5	16.3	17.6	+8	Turner et al. 1988
Carya		7.2	6.0	17,200	18,700	+9	Stafne and Carroll 2008
Betula		7.4	4.6	5,710	6,450	+13 (f)	Hoch 2018
Koelreuteria		6.0	5.0	1,200	1,400	+16	Wright et al. 1999a
Carya		6.5	5.5	13,380	15,990	+19	Sharpe and Marx 1986
Quercus	media	6.5	5.4	12,300	16,000	+30	Salifu et al. 2006
Liquidambar	GF endo	6.7	5.1	1,450	1,970	+36	Davis et al. 1993
Quercus	MM	6.1	4.5	2,600	3,600	+38	Browder et al. 2005
Populus	hybrid	6.5	4.0	3,800	5,400	+42 (f)	Böhlenius et al. 2016
Robinia		6.9	4.3	11,800	17,660	+49	McComb and Kapel 1942
Fraxinus		6.9	4.3	1,910	2,950	+54	McComb and Kapel 1942
Populus	1004	7.0	5.0	6,240	10,000	+60	DesRochers et al. 2003
Salix	GM endo	7.0	4.0	3,000	5,000	+66	Van der Heijden and Kuyper 2001
Quercus		7.4	4.0	6,000	10,000	+66 (f)	Beyer et al. 2013
Quercus		5.7	4.2	6,250	10,610	+69 (f)	Davis 2003
Eucalyptus	H495	6.6	4.6	3,000	5,300	+76	Aggangan and Malajczuk 1996
Chestnut	PT ecto	5.7	3.5	20,000	40,000	+100	Herendeen 2007
Quercus		7.4	4.6	2,810	6,510	+131 (f)	Hoch 2018
Liquidambar	GV endo	6.5	4.8	1,750	11,500	+557	Yawney et al. 1982

Supplemental fertilization [with nitrogen (N), phosphorus (P), and potassium (K)] was held constant in most of these trials, regardless of pH treatment. Better growth with increasing acidity to below pH 5.0 apparently results from higher nutrient use efficiency (e.g. uptake of N). For several species, the lower pH values increased biomass (and associated nutrients) by 15 percent or more.

In containers, the pH of the potting-mix will vary in both time and space. In some containers, the saturated area at the bottom of the container may be near at pH 7 while the top could be near pH 4 (Bumgarner et al. 2008). Also, the pH will change over time. In a yellow poplar study, pH declined from pH 5.3 to pH 4.1 in just 11 weeks

(Park et al. 2012). The amount of pH decline depends in part on how long the medium remains saturated (Ferrarezi and Testezlaf 2017).

4 Irrigation pH

In 2017, rain water in the eastern United States ranged from pH 4.9 to 5.7 while the range for irrigation water at bareroot nurseries is pH 4.5 to 10.1 (Figure 4). Although the pH reveals little about the quality of irrigation water, too much bicarbonates or too much sodium (Na) cause problems. For example, the Aliceville Nursery in Alabama closed due to irrigation water with high Na. The alkalinity of irrigation water can also affect the growth of container grown seedlings (Whitcomb 1988) as well as plants growing in sandy soils (Valdez-Aguilar et al. 2009). Iron (Fe) deficiency can occur when irrigation water contains high levels of bicarbonates (De LaGuardia and Alcántara 2002) and acidifying the water with phosphoric or sulfuric acid may improve growth. Even when bicarbonate levels are low, acidifying irrigation water with sulfuric acid (Miyamoto et al. 1975) can sometimes increase seedling growth. The growth response of 13 hardwood species to acidified water (pH 4 to pH 5) was positive (Table 6).

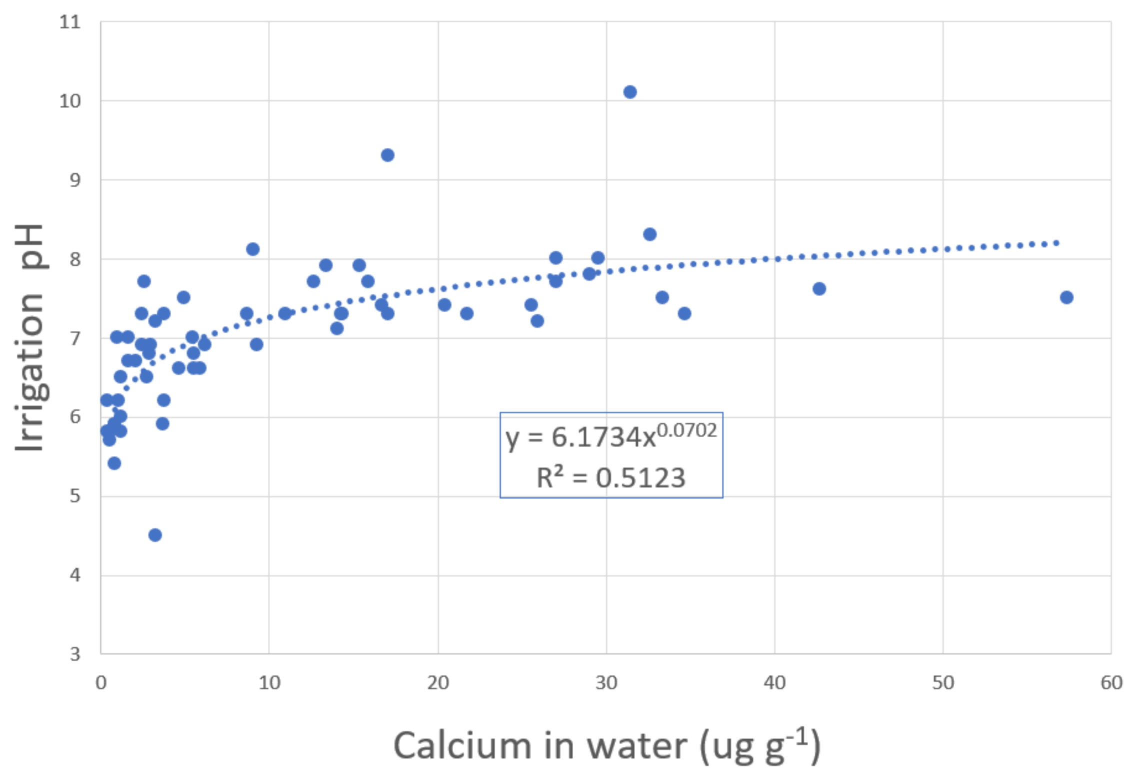

Figure 4. In general, the pH of irrigation water from nurseries in the South will be alkaline when it contains more than 10 $\mu g\ g^{-1}$ calcium. In contrast, water with less than 10 $\mu g\ g^{-1}$ calcium may range in pH from 4.5 to 8.1. Data from McNabb and Heidbreder-Olson (1998).

Some caution is recommended when making soil pH conclusions based on acid irrigation trials. Rainfall (less acidic than pH 4.0) typically does not injure foliage of hardwoods (Davis and Skelly 1992). In contrast, very acidic irrigation water (i.e. pH 3.0 to 3.5) can reduce growth due to foliar injury (Fan et al. 2000; Lee and Weber 1979; Lee et al. 1993; Miyamoto et al. 1975; Ramlall et al. 2015). One should not assume water that is artificially adjusted to pH 3.5 would produce similar results to growing seedlings in a soil at pH 3.5 (where foliar injury from acids does not occur). Likewise, one cannot assume that applying diluted hydrochloric acid to foliage (Hermle 2006; Long et al. 2017; Wingett 2005) will not injure hardwood seedlings. Although sulfuric acid can stimulate growth, acidifying irrigation water with hydrochloric acid may have no effect on growth (Browder 2004).

Table 6. Relative effects of acidifying irrigation water (nitric acid and/or sulfuric acid) on dry mass (mg) of plants or foliage (f). Mass #1 and mass #2 correspond to the dry mass of plants irrigated with water pH #1 or water pH #2, respectively.

Genus	Water pH #1	Water pH #2	Mass #1 (mg)	Mass #2 (mg)	Change in mass with decreased pH (%)	Reference
Trichilia	6.3	4.5	300	200	-33	Ramlall et al. 2015
Koelreuteria	6.0	3.5	8,170	7,090	-13	Fan et al. 2000
Melia	6.0	5.0	4,438	4,287	-3	Houbao and Chuanrong 1999
Koelreuteria	6.0	5.0	7,651	7,569	-1	Houbao and Chuanrong 1999
Liriodendron	5.5	3.0	9,220	9,220	0	Jensen and Patton 1990
Betula	5.6	3.5	1,090	1,120	+2	Kean and Manning 1988
Quercus	4.8	4.2	5,260	5,400	+3	Walker and McLaughlin 1991
Acer	6.0	4.5	108,000	111,000	+3	Medeiros et al. 2016
Liriodendron	5.6	4.3	2,590	2,670	+3	Chappelka et al. 1985
Acer	5.6	4.0	11,290	11,680	+3	Reich et al. 1986
Betula	5.6	3.5	760	790	+4	Keane and Manning 1988
Quercus	5.6	4.0	41,900	43,700	+4	Reich et al. 1986
Acer	5.2	4.0	429	460	+7	Raynal et al. 1982b
Cinnamomum	6.0	5.0	7,967	8,518	+7	Houbao and Chuanrong 1999
Quercus	6.0	4.5	40,000	45,000	+12	Medeiros et al. 2016
Acer	5.6	3.2	19,980	22,520	+13 (f)	Dixon and Kuja 1995
Acer	5.5	3.5	350	400	+14 (f)	Hogan 1998
Fraxinus	5.6	4.3	950	1,100	+15	Chappelka et al. 1986
Michelia	6.6	4.5	979	1,135	+16	Zongwei and Yunfeng 1991
Cinnamomum	6.0	3.5	7,990	9,610	+20	Fan et al. 2000
Carya	5.7	3.5	1,174	1,437	+22	Lee and Weber1979
Melia	6.0	3.5	4,450	5,730	+28	Fan et al. 2000
Ligustrum	6.0	5.0	2,285	3,342	+46	Houbao and Chuanrong 1999
Shorea	6.6	4.5	1,288	1,932	+50	Zongwei and Yunfeng 1991
Castanopsis	6.0	5.0	1,211	2,536	+109	Houbao and Chuanrong 1999

5 Genetic differences

In the absence of properly designed nursery studies, people resort to speculating about the “optimum” pH range for growing hardwoods in bareroot nurseries. When experts resort to guessing, then it is likely that some pH ranges will conflict (Table 3). It is risky to make generic claims about the “optimum” soil pH range when using data from hydroponic studies or when evaluating just one genotype growing in one soil type. Likewise, when comparing correlations between pH and seedling growth, presence of different mycorrhizal species may produce opposite results. The following examples illustrate some of the variability that exists among and within hardwood genotypes.

5.1 *Carya*

Wilde (1958) said pecan was an "exacting hardwood" that required a high level of nursery soil fertility with a pH range of 5.5 to 7.3. Although productive orchards are established on pH 8 soils (Sibbett 1995), Fe and zinc (Zn) may need to be applied to avoid a micronutrient deficiency. This indicates that when proper fertilizer management is used, the range of acceptable pH values can be increased. Sharpe and Marx (1986) grew pecan seedlings in pots and altered soil pH using $Ca(OH)_2$. Although pH 6.5 was recommended, their single test indicated seedlings grew better at pH 5.5 (Table 5). When grown at pH 5.5, Zn fertilization was not required. In contrast, other researchers found that pecan grew better when soil pH was above 7.0 (Johnson and Hagler 1955; Sparks 1977). Could it be that ectomycorrhiza species (i.e. *Pisolithus tinctorius* vs. others) affect the direction of lime response in the same way as different endomycorrhiza affect sweetgum's response to lime?

5.2 *Ilex*

Several varieties of Japanese holly are produced at bareroot ornamental nurseries. In one trial three varieties were grown in a sandy loam soil that was amended with dolomitic lime (Gilliam et al. 1985). One variety grew well at both pH 4.1 and 6.2 while two other varieties grew best at pH 4.1. The authors concluded: "these data show that in general, *Ilex* can be successfully grown at pH levels lower than the 5.5-6.5 range usually recommended."

5.3 *Liquidambar*

Sweetgum can grow well at pH 4.5 (Ashby et al. 1989; Villarrubia 1980) and a few trials indicate that lime can reduce the growth of sweetgum (Figure 1; Yawney et al. 1982). Liming also reduced height growth when sterilized soil in a greenhouse was inoculated with *Glomus fasciculatum* (Davis et al. 1993). However, opposite results occurred when seedlings were inoculated with *Glomus mosseae* where the high rate of lime increased height growth by 3.6 cm. This suggests that soil biology is as important as tree species when determining the direction of response to lime.

5.4 *Paulownia*

Princess tree reportedly grows well in both acid and alkaline soils (pH 5-8.9) (Londo et al. 2006; Icka et al. 2016). Seedling growth in containers can be increased by adding NaOH to pearlite (Melhuish et al. 1990). In Virginia, seedlings planted in pH 5.4-5.7 soil were over 1.2 m tall after two years in the field (Johnson et al. 2003). In greenhouse trials, the use of sulfuric acid on filter paper can reduce the germination of paulownia (Turner et al. 1988).

5.5 *Populus*

With proper fertilization, nursery managers can grow *Populus* in a wide range of soil pH, even in soils with a pH below 5 (Benzian 1965; Böhlenius et al. 2016; Hjelm and Rytter 2016). In fact, several researchers see no need to report pH values for either nursery or field trials with this species. This is likely due to the ease of growing stock in both acid (Davis et al. 2012; Hermle et al. 2006; Roberts and Gilliam 1995) and slightly alkaline soils (Carter 1981; Lombard et al. 2011; Puri et al. 2002; Shock et al. 2002). Although pH generalizations are often made for this genus (Table 3), variability exists among hybrids and species. Species like balsam poplar may not do well in "markedly" alkaline soils because Fe deficiencies may occur (Carter 1981; Jobling 1990; Lombard et al. 2010) while quaking aspen may die at pH 4.0 (Böhlenius et al. 2016). When certain hybrids were grown at low pH at a sandy nursery in the UK, growth was improved with copper (Cu) fertilization (Benzian 1965).

Although the pH range recommended for nurseries is pH 5.0 to 6.5 (Jobling 1990), the range for plantations can include alkaline soils (Baker and Broadfoot 1979; Shock et al. 2002). The belief that well-fertilized cuttings do not grow well at in plantations at pH 3.5 to 4.0 might be due to greenhouse trials where cuttings died (Böhlenius et al. 2016). Regardless of soil acidity, proper fertilization is important. Growth of cuttings can be reduced when too much P is applied to nursery soil at pH 6.2 (Teng and Timmer 1990).

5.6 *Quercus*

Several liming studies with northern red oak have been conducted in greenhouses. Phares (1964) added lime ($CaCO_3$) to two soil types and repeated the study over two years. He detected a year x lime x soil type interaction. For one soil type, adding lime reduced growth in both years but for another soil type, liming increased growth in one year and decreased growth in another. The three-way interaction points out the danger of making too broad a generalization based on a single pH trial. In some cases, applying lime may correct a deficiency in Ca while in other cases, it might induce a P deficiency. Overall, adding 1,120 kg ha^{-1} of lime to soil (pH 5.8) reduced heights and biomass by 10 and 4 percent, respectively. Phares concluded that increasing soil pH with lime caused problems with the uptake of P.

When northern red oak seedlings were grown in pots in a greenhouse, lime ($Ca(OH)_2$) did not improve growth in six trials but growth was reduced in one trial (Joslin and Wolfe 1989). Beyer et al. (2013) also found that too much lime ($CaCO_3$) reduced growth of northern red oak growth (Figure 3; Table 5). Although Fe chlorosis may occur when oak is planted in alkaline soils (Hacskaylo and Struthers 1959; Thomas et al. 1998), not all chlorotic oaks are Fe deficient (Watson and Himelick 2004).

Fertilized oak seedlings grow well in soils below pH 4 (Beyer et al. 2013; Davis 2003) and in media at pH 4.5 (Olchowik et al. 2017). Likewise, oak plantations also perform well at pH 4.5 (Emerson et al. 2009). Fertilized oak seedlings can grow well at pH 3.7 (Hanson et al. 1986), pH 5.8 (Hart and Sharp 1997) or at pH 7.2 (Schmal et al. 2011). In contrast, some believe that sawtooth oak should not be planted on strip mine sites with soil pH <4.0 (Kennedy and Krinard 1985).

6 Warnings about low soil pH

Experiences with growing tree seedlings (Tables 4 and 5) lend support to "the fact that the toxicity of hydrogen ions has been grossly exaggerated" (Wilde 1954). The exaggerated claims originated from "artificially prepared cultures," not soil studies (Kidd 2001; Wilde 1954). In most acid soils aluminum (Al) and manganese (Mn) toxicities are probably more important than the amount of hydrogen ions (Adams and Foy 1984; Pope 1984). Although some claim soil lower than pH 5.5 is not optimum for growth of fertilized hardwoods (Table 1), most provide no data to show their warnings have merit. Some admit they do not know what problems might result when adequate fertilizers are applied to low pH soils (Stone 1965). Others believe that Al toxicity "may" occur when soil pH is low (Sparkes 1977). Although Al toxicity symptoms can occur when soil contains 101 $\mu g\ g^{-1}$ (Pope 1984), no "toxicity" occurred at pH 3.3 when soil contained 44 $\mu g\ g^{-1}$ of Al (Figure 3). There are no reports from sandy nursery trials to show Al levels are high enough to cause any problems with hardwoods. Although northern red oak is supposed to be sensitive to Al (DeWald et al. 1990, Kelly et al. 1990), seedlings grew well in soil with more than 700 $\mu g\ g^{-1}$ (Lesko and Jacobs 2018). In one greenhouse trial, oak seedlings grew better when the potting-mix was pre-treated with aluminum sulfate (Davis 2003).

At bareroot hardwood nurseries (Table 2), micronutrient toxicities are rare in very acid soils (pH 4.0-5.0). Some wonder if poor growth of hardwoods might occur on low pH soils (with low cation exchange capacity) due to deficiencies of K, Ca and Mg. Regardless of soil pH, poor growth can occur in sandy soils when fertilization is not adequate. In sandy soils, seedling growth is positively related to the amount of soil cations (Ouimet et al. 1996; South et al. 2018). For this reason, managers typically apply fertilizers to increase growth of hardwoods in low pH soils.

Zn toxicity can occur at locations where Zn has contaminated the soil (Denny and Wilkins 1987; Shi et al. 2016) but at nurseries it is unlikely since sandy soils typically contain less than 12 $\mu g\ g^{-1}$ Zn (South and Davey 1983). Although Zn levels of 50 $\mu g\ g^{-1}$ (Mehlich III) might reduce growth of sensitive species like northern red oak (Beyer et al. 2013), other oaks are tolerant of soil levels as high as 1,600 $\mu g\ g^{-1}$ (Shi et al. 2016).

High levels of Mn in fine-textured nursery soils (pH<5) can reduce growth of hardwood (Child and Smith 1960; Wong 2005) and pine seedlings (South 2017). Growth can be negatively related to Mn levels when seedlings are grown in water (Kitao and Koike 1999; Thomas and Sprenger 2008) or soil (Böhlenius et al. 2016; Lei et al. 2007). Although high levels of Mn in irrigation water can reduce growth of sugar maple (Schier and McQuattie 2000; St.Clair and Lynch 2005), Mn is not considered a problem in most irrigation waters (Landis 1989). Even runoff containment basins at container nurseries typically contains less than 0.4 mg l^{-1}(Copes et al. 2017). In fact, there are no reports of cases where Mn toxicity has occurred in bareroot hardwood nurseries where soil contains less than 300 $\mu g\ g^{-1}$ Mn. Most sandy nursery soils contain less than 200 $\mu g\ g^{-1}$ Mn.

7 Advantages of low pH

In the past, lowering soil pH with sulfuric acid was an effective pest management practice (Bickelhaupt 1987; Hartley 1921; Jackson 1933; Wilde 1937). When soil acidity increases, beneficial fungi like *Trichoderma* and *Penicillium* may also increase (Huang and Kuhlman 1991). Populations of damping-off fungi, *Fusarium*, *Phytophthora*, nematodes, and certain weeds (Aldhous 1972; Buchanan et al. 1975; Goswami et al. 2011; Huang and Kuhlman 1991; James 1997; Khilare and Ahmed 2012; Shareef et al. 2016; Stoeckeler and Jones 1957) may all be lower when nonfumigated seedbeds have pH values less than 5.0. Damping-off of hardwoods may be less when soil pH is below 6.0 (Enebak 2019). It has been suspected for some time that nematode populations are lower in acid soils (Wilde 1934) and several studies support this view (Burns 1971; Korthals et al. 1996; Willis 1972).

Although data on the relationship between soil pH and damping-off of hardwoods are limited, some researchers recommend pH be kept below 6.1 (Hodges 1962; Hooper and Curtin 1983; Lamichhane et al. 2017). For example, when soil pH was 6.0-7.8, damping-off of hardwoods was high at three silty-clay-loam nurseries (Wright 1944). Fortunately, a few greenhouse trials report the effects of irrigation acidification on seed germination. When compared to pH 5.6-5.7, germination of yellow birch was as good or better when seeds were irrigated with pH 3.5-3.6 water (Lee and Weber 1979; Percy 1986). This is not unexpected since pre-treating seed with sulfuric acid can increase germination of some hardwoods (Li et al. 2013; Peacock and Hummer 1996). In contrast, the germination rate of ten other hardwood species was not affected by pH 4 water (Fan et al. 2000; Lee and Weber 1979) while germination of red maple was 3 percent lower (Raynal et al. 1982a).

8 Sulfur

Sulfur (S) is used to lower soil pH in bareroot nurseries (South 2017) and when growing maple, some apply elemental S when soil pH is greater than 5.6 (Altland 2006). For other hardwoods, S is applied when soil values exceed pH 6.0-6.2 (Davey and McNabb 2019; Messenger 1984). For example, at one nursery with pH 6.0 soil, adding 374 kg ha^{-1} of S increased height and diameter growth of sweetgum and green ash (Stone 1980; Villarrubia 1980).

Although peat media are typically acidic, S or sulfuric acid is sometimes added to reduce media pH (Wightman et al. 2001; Will and Faust 1999). In one study, applying sulfuric acid doubled the size of oak seedlings (Browder 2004). Sometimes S can improve growth even when a change in pH is not needed. Applying solutions (containing KCl and K_2SO_4) to pH 4.1 pine bark medium demonstrated that growth of oak and maple in containers was related to the amount of sulfur added (Browder et al. 2005). Likewise, 100 kg $ha^{-1}$of S increased the growth of container-grown quaking aspen growing in pH 5.5 soil (Liang and Chang 2004).

Applying S just before sowing can reduce growth under certain weather conditions (Aldhous 1972; South 2017). Therefore, to reduce the risk of root injury, sulfur should be applied at least two to three months before sowing (Armson and Sadreika 1979). Applying too much S just before transplanting can reduce root growth of poplar cuttings (Timmer 1985), and applying too much aluminum sulfate before sowing can reduce germination of different species (Table 4), especially when seedbeds are not kept moist (Russell 1990). Some experts do not recommend applying aluminum sulfate due to potential toxic effects (Iyer et al. 1969; Pope 1982; Voigt 1954; Whitcomb 2009). Except for maple, there is typically no need to add S when hardwood nursery soils range from pH 4.5 to 6.5 (unless there is a risk of a S deficiency which limits growth).

9 Lime

"The old concept concerning lime was that of a *cure-all* - that it was almost certain to be beneficial, no matter what the problem. Such an opinion should now be discarded since it may lead to a waste of money and in some cases to over liming. The use of lime must be based on measured soil acidity and on crop requirements" (Brady 1974).

Adding lime to soil (Table 4; Crews and Dick 1998; Gabriel et al. 2018; Wilde 1958) or potting media (Altland and Jeong 2016; Hjelm and Rytter 2016) will sometimes increase growth of hardwoods. However, it can be a waste of money when there is no effect on growth (Figure 1; Böhlenius et al. 2016; Crannell et al. 1994; Hannah 1973) or when growth is reduced. In greenhouse studies, adding lime had negative effects on choke cherry, river birch (Dumroese et al. 1990), eucalyptus (Handreck 1989; Symonds et al. 2001), oak (Browder et al. 2005; Denig et al. 2014; Hoch 2018; Wright et al. 1999b), blackgum (Wright et al. 1999b), *Prosopis* (Cline et al. 1986), and *Populus* (Timmer 1985). Some believe a reduction in growth is not due to an increase in alkalinity but to an increase in demand for nitrogen by saprophytic bacteria (Wilde 1946). In addition, root injury may occur when calcium hydroxide (slacked lime) is applied before sowing (Wilde 1958). As a precaution, Turner (1970) recommends applying lime prior to sowing a cover crop (i.e. a year before sowing hardwoods). Adding too much lime will sometimes induce deficiencies in Cu (Anderssen 1932), Fe (Hacskaylo and Struthers 1959; Handreck 1989; Hoch 2018), P (Cline et al. 1986) and Mn (Altland 2006; Messenger and Hruby 1990). For these reasons, nursery managers in the southern United States typically do not lime seedbeds until the pH falls below pH 4.8.

10 Problems with some conclusions

With few exceptions, there is always some confounding when conducting studies with S, lime, sulfuric acid and hydrochloric acid. As a result, conclusions about the "optimum" pH for most trials should be considered "tentative". For example, if species do not grow well in the presence of chloride ions, then adding hydrochloric acid to perlite may explain why pH was positively related to seedling growth (Melhuish et al. 1990). Is it possible the hydrogen ion concentration was not the primary reason for poor root growth (Whitcomb 1983; Wilde 1954)? When positive responses are observed after applications of dolomitic lime (e.g. Crews and Dick 1998; Voigt et al. 1958), could this be due to correcting deficiencies in soil Ca, or Mg, or micronutrients?

Some researchers study pH effects by comparing different types of soils (Davidson 1979; Hjelm and Rytter 2016). In one trial, soil from two strip-mined sites (pH 4.5 and 5.5) was compared to a commercial loam soil at pH 6.5 (Turner et al. 1988). Was the better growth on the 6.5 pH loam due to less acidity or was it due to beneficial variables associated with the commercial product?

Some trials are designed to have a minimum amount of confounding. One well designed study examined the effects of S on seedling growth (Browder 2004). Instead of applying S to the potting-mix (which affects pH), the authors applied various rates of K_2SO_4 and kept K levels constant by adding KCl. Although this added confounding with Cl, their approach removed pH as a confounding factor.

To improve interpretation of results, gypsum treatments should be included with lime ($CaCO_3$) treatments (Figure 5). That will allow researchers to compare the relative growth responses to equal rates of Ca (Bakker et al. 1999; Deines 1973; Fuller and Meadows 1983; Gabriel et al. 2018; Marx 1990). As a result, conclusions (about the reasons for pH related growth responses) can be made with greater confidence.

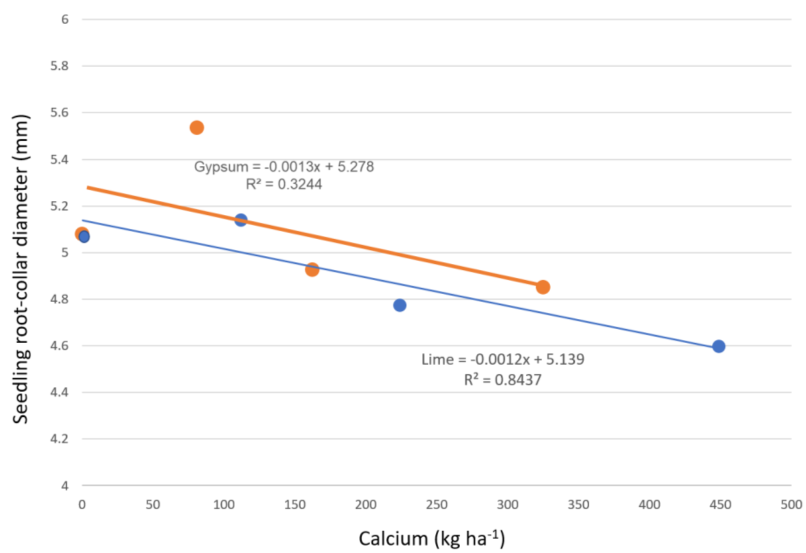

Figure 5. The effect of adding calcium on diameter growth of sweetgum seedlings at the Edwards Nursery in North Carolina (Deines 1973). The linear relationship between calcium rate and diameter growth is approximately the same for both lime ($CaCO_3$) and gypsum ($CaSO_4$). At this nursery, soil pH is apparently not the driving factor behind a significant reduction in diameter growth.

11 Future research

Greenhouse and nursery researchers should question traditional liming and pH recommendations (Gilliam et al. 1985; Ruter and van der Werken 1986; Whitcomb 1983) and should target pH values that are near optimum for the species under investigation. Unfortunately, for many tree species well-designed "optimal pH" trials have not been published. Therefore, "Assessment of a desirable pH range of a given species" should be one of the first factors investigated (Bryan et al. 1989). For a given environment, researchers should determine a peak pH value where seedling growth is maximized (Figure 2). There could be several ways to identify this peak, but one method might involve adding eight rates of lime to a low pH soil (e.g. Handreck 1989) and comparing the results from a "twin" study where the same pH levels were achieved by applying sulfuric acid (several months before sowing) to a high pH soil.

Researchers conducting bareroot trials can test several pH related hypotheses. One testable hypothesis is that micronutrient deficiencies do not occur when growing fertilized 1-0 hardwood seedlings at pH 4.5. Although micronutrient deficiencies can occur in alkaline nursery soils, there are only a few published photos of bareroot hardwoods, with micronutrient deficiencies, in seedbeds at pH 4.5 (e.g. Benzian 1965). Most micronutrient deficiency photos are taken after hardwood seedlings are grown in hydroponics or nutrient-deficient sand (e.g. Erdmann et al. 1979; Hacskaylo et al. 1969; Whittier 2018).

Several greenhouse trials suggest that nutrient use efficiency is increased when soil acidity increases (Table 5). Although the reason is not clear, some studies indicate that acidification could increase the uptake of nitrate (Paez-Valencia et al. 2013). Research aimed at a better understanding of why low pH increases uptake of nutrients should be initiated. One testable hypothesis is: for nutrient use efficiency (N), there is no species by pH interaction.

Too much elemental S applied immediately before sowing (e.g. 900 kg ha^{-1}) can sometimes reduce seedling growth (but not always). To reduce the risk of injury from the formation of sulfuric acid, elemental S should not be applied one or two months before sowing. Future research should be conducted to better quantify the factors that contribute to injury from exposure to sulfuric acid that forms after fertilization with elemental S.

12 Conclusions

Field observations and greenhouse trials confirm that pH 6.0 to 8.0 is not optimum for growing most hardwoods in either bareroot or container nurseries. Therefore, managers of sandy, bareroot nurseries grow both hardwoods and pines in soils that range from pH 4.8 to 6.0. Based on published data, the desired range for growing oak seedlings at bareroot nurseries (with more than 75 percent sand) is likely pH 4.5 to 6.0.

13 Acknowledgments

The author thanks Jake Stone who was the first to inform me that “very strongly acid” soils (pH 4.5) were not harmful when growing green ash and sweetgum seedlings at his nursery. The author thanks J.B. Jett (North Carolina State University), John Mexal (New Mexico State University), Robert Cross (Cross Consultants), Chase Weatherly (Arborgen), Carl Whitcomb (Lacebark Research) and Nicky Jones (Sappi) for providing helpful comments on the manuscript.

14 References

Adams F, Foy CD (1984) Physiological effects of hydrogen, aluminum, and manganese toxicities in acid soil. In: Adams F (ed) Soil acidity and liming. Agronomy Monograph 12: 57-97. https://doi.org/10.2134/agronmonogr12.2ed.c2

Aggangan NS, Bernard D, Malajczuk N (1996) Effects of soil pH on the ectomycorrhizal response of *Eucalyptus urophylla* seedlings. New Phytol 134(3): 539-546. https://doi.org/10.1111/j.1469-8137.1996.tb04372.x

Aldhous JR (1972) Nursery Practice. London, UK: Her Majesty’s Stationery Office. Forestry Commission Bulletin 43, 184 p.

Aldhous JR, Mason WL (1994) Forest Nursery Practice. London, UK: Her Majesty’s Stationery Office. Forestry Commission Bulletin 111, 268 p.

Altland JE (2006) Managing manganese deficiency in nursery production of red maple. Eugene, OR: Oregon State University, Extension Service. EM 8905-E. 8 p. https://ir.library.oregonstate.edu/downloads/wp988k21z

Altland JE, Jeong KY (2016) Dolomitic lime amendment affects pine bark substrate pH, nutrient availability, and plant growth: a review. Horttechnology 26(5): 565-573. https://doi.org/10.21273/HORTTECH03465-16

Anderssen FG (1932) Chlorosis of deciduous fruit trees due to a copper deficiency. Journal of Pomology and Horticultural Science 10(2): 130-146. https://doi.org/10.1080/03683621.1932.11513396

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

Ashby WC, Davidson WH, Vogel WG (1989) Soil pH guidelines for reclamation tree plantings. In: Healthy forests, healthy world: Proceedings of the 1988 Society of American Foresters national convention; 1988 October 16-19; Rochester, NY. SAF Publ. 88-01. Bethesda, MD: Society of American Foresters: 210-213.

Baker JB, Broadfoot WM (1979) A practical field method of site evaluation for commercially important southern hardwoods. Gen. Tech. Rep. SO-26. New Orleans, LA: U.S. Department of Agriculture, Forest Service, Southern Forest Experiment Station, 51 p.

Bakker MR, Kerisit R, Verbist K, Nys C (1999) Effects of liming on rhizosphere chemistry and growth of fine roots and of shoots of sessile oak (*Quercus petraea*). Plant Soil 217(1-2): 243-255. https://doi.org/10.1023/A:1004518116551

Benzian B (1965) Experiments on nutrition problems in forest nurseries. Forestry Commission Bulletin 37. London, UK: Her Majesty's Stationery Office, 251 p.

Beyer WN, Green CE, Beyer M, Chaney RL (2013) Phytotoxicity of zinc and manganese to seedlings grown in soil contaminated by zinc smelting. Environ Pollut 179: 167-176. https://doi.org/10.1016/j.envpol.2013.04.013

Bickelhaupt DH (1987) The use of sulfur to correct soil pH. In: Landis TD (ed) Proceedings, intermountain forest nursery association. Gen. Tech. Rep. RM-151. Fort Collins, CO: U.S. Department of Agriculture, Forest Service, Rocky Mountain Forest and Range Experiment Station: 58-65.

Böhlenius H, Övergaard R, Asp H (2016) Growth response of hybrid aspen (*Populus* × *wettsteinii*) and *Populus trichocarpa* to different pH levels and nutrient availabilities. Can J Forest Res 46(11): 1367-1374. https://doi.org/10.1139/cjfr-2016-0146

Bonner FT, Broadfoot WM (1964) Soil nutrients and pH in southern hardwood nurseries. In: Proceedings, region 8 forest nurserymen's conferences. U.S. Department of Agriculture, Forest Service, Southern Region: 125-127.

Brady NC (1974) The nature and properties of soils. 8th ed. New York, NY: MacMillan Publishing, 639 p.

Briggs RD (2008) Soils and nutrition: A forest nursery perspective. In: Dumroese RK, Riley LE (technical coordinators) Proceedings, forest and conservation nursery associations-2007. RMRS-P-57. Fort Collins, CO: U.S. Department of Agriculture, Forest Service, Rocky Mountain Research Station: 55-64.

Browder JF (2004) Sulfur requirements of container-grown pin oak and Japanese maple. MS thesis, Virginia Polytechnic Institute and State University, Blacksburg, Virginia. 38 p.

Browder JF, Niemiera AX, Harris JR, Wright RD (2005) Growth response of container-grown pin oak and Japanese maple seedlings to sulfur fertilization. Hortscience 40(5): 1524-1528. https://doi.org/10.21273/HORTSCI.40.5.1524

Bryan JA, Seiler JR, Wright RD (1989) Influence of growth medium pH on the growth of container-grown Fraser fir seedlings. Journal of Environmental Horticulture 7(2): 62-64.

Buchanan GA, Hoveland CS, Harris MC (1975) Response of weeds to soil pH. Weed Sci 23(6): 473-477. https://doi.org/10.1017/S004317450006505X

Bumgarner ML, Salifu KF, Jacobs DF (2008) Subirrigation of *Quercus rubra* seedlings: nursery stock quality, media chemistry, and early field performance. Hortscience 43(7): 2179-2185. https://doi.org/10.21273/HORTSCI.43.7.2179

Burns NC (1971) Soil pH effects on nematode populations associated with soybeans. Journal of Nematology 3(3): 238-245.

Burns RM, Honkala BH (1990) Silvics of North America: Volume 2. Hardwoods. Agricultural Handbook 654. Washington, DC: U.S. Department of Agriculture, Forest Service, 877 p.

Carter MR (1981) Association of total $CaCO_3$ and active $CaCO_3$ with growth of five tree species on chernozemic soils. Can J Soil Sci 61(1): 173-175. https://doi.org/10.4141/cjss81-020

Chappelka AH, Chevone BI (1986) White ash seedling growth response to ozone and simulated acid rain. Canadian Journal of Forestry Research 16(4): 786-790. https://doi.org/10.1139/x86-139

Chappelka AH, Chevone BI, Burk TE (1985) Growth response of yellow-poplar (*Liriodendron tulipifera* L.)

seedlings to ozone, sulfur dioxide, and simulated acidic precipitation, alone and in combination. Environ Exp Bot 25(3): 233-244. https://doi.org/10.1016/0098-8472(85)90007-3

Chen YL, Kang LH, Dell B (2006) Inoculation of *Eucalyptus urophylla* with spores of *Scleroderma* in a nursery in south China: comparison of field soil and potting mix. Forest Ecol Manag 222(1-3): 439-449. https://doi.org/10.1016/j.foreco.2005.10.050

Child R, Smith AN (1960) Manganese toxicity in *Grevillea robusta*. Nature 186(4730): 1067-1067. https://doi.org/10.1038/1861067a0

Cline G, Rhodes D, Felker P (1986) Micronutrient, phosphorus and pH influences on growth and leaf tissue nutrient levels of *Prosopis alba* and *Prosopis glandulosa*. Forest Ecol Manag 16(1-4): 81-93. https://doi.org/10.1016/0378-1127(86)90010-1

Copes WE, Zhang H, Richardson PA, Belayneh BE, Ristvey A, Lea-Cox J, Hong C (2017) Nutrient, pH, alkalinity, and ionic property levels in runoff containment basins in Alabama, Louisiana, Maryland, Mississippi, and Virginia ornamental plant nurseries. Hortscience 52(4): 641-648. https://doi.org/10.21273/HORTSCI11647-16

Cordell CE, Filer TH (1984) Integrated nursery pest management. In: Lantz CW (technical coordinators), Southern pine nursery handbook. Asheville, NC: U.S. Department of Agriculture, Forest Service, State and Private Forestry: Chapter 13.

Crannell WK, Tanaka Y, Myrold DD (1994) Calcium and pH interaction on root nodulation of nursery-grown red alder (*Alnus rubra* bong.) seedlings by *Frankia*. Soil Biol Biochem 26(5): 607-614. https://doi.org/10.1016/0038-0717(94)90249-6

Crews J, Dick W (1998) Liming acid forest soils with flue gas desulfurization by-product: growth of northern red oak and leachate water quality. Environ Pollut 103(1): 55-61. https://doi.org/10.1016/S0269-7491(98)00137-7

Davey CB (1973) Artificial regeneration – nursery practice. In: Proceedings, hardwood short course. Raleigh, NC: North Carolina State University: 53-59.

Davey CB (1996) Soil fertility and management for culturing hardwood seedlings. In: Landis TD, Dumroese RK (technical coordinators): Proceedings, forest and conservation nursery associations. Gen Tech Rep RM-257, Fort Collins, CO: U.S. Department of Agriculture, Forest Service, Rocky Mountain Forest and Range Experiment Station: 38-49.

Davey CB, McNabb K (2019) The management of seedling nutrition. In: McNabb K, Pike C (eds) A nursery guide for the production of bareroot hardwood seedlings. Agricultural Handbook no. 733. Washington, DC: U.S. Department of Agriculture, Forest Service.

Davidson WH (1979) Results of tree and shrub plantings on low pH strip-mine banks. Research Note NE-285. Broomhall, PA: U.S. Department of Agriculture, Forest Service, Northeast Forest Experiment Station, 5 p.

Davis AS (2003) Performance of northern red oak under adverse conditions. MS thesis, Purdue University, West Lafayette. 112 p.

Davis V, Burger JA, Rathfon R, Zipper CE, Miller CR (2012) Selecting tree species for reclamation of Appalachian mined land. Forest Reclamation Advisory No. 9. Pittsburgh, PA: The Appalachian Regional Reforestation Initiative (ARRI). 8 p. https://arri.osmre.gov/FRA/Advisories/FRA_No.9_TreeSpeciesSelection.pdf

Davis DD, Skelly JM (1992) Growth response of four species of eastern hardwood tree seedlings exposed to ozone, acidic precipitation, and sulfur dioxide. Journal of the Air & Waste Management Association 42(3): 309-311. https://doi.org/10.1080/10473289.1992.10466995

Davis EA, Young JL, Lindermann RG (1993) Soil lime level, pH level and vesicular arbuscular mycorrhizal effects on growth responses of sweet gum, *Liquidamber styraciflua* seedlings. Soil Sci Soc Am J 47(2): 251-256. https://doi.org/10.2136/sssaj1983.03615995004700020015x

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

De laGuardia MD, Alcántara E (2002) Bicarbonate and low iron level increase root to total plant weight in olive and peach rootstock. J Plant Nutr 25(5): 1021-1032. https://doi.org/10.1081/PLN-120003936

Denig BR, Macrae JrPF, Gao X, Bassuk NL (2014) Screening oak hybrids for tolerance to alkaline soils. Journal of Environmental Horticulture 32(2): 71-76.

Denny HJ, Wilkins DA (1987) Zinc tolerance in *Betula* spp. I. Effect of external concentration of zinc on growth and uptake. New Phytol 106(3): 517-524. https://doi.org/10.1111/j.1469-8137.1987.tb00156.x

DesRochers A, van den Driessche R, Thomas BR (2003) Nitrogen fertilization of aspen seedlings grown on soils of different pH. Can J Forest Res 33(4): 552-560. https://doi.org/10.1139/x02-191

DeVall WB (1943) The correlation of soil pH with distribution of woody plants in the Gainesville area. Proceedings of the Florida Academy of Sciences 6(1): 9-24.

DeWald LE, Sucoff EI, Ohno T, Buschena CA (1990) Response of northern red oak (*Quercus rubra*) seedlings to soil solution aluminum. Can J Forest Res 20(3): 331-336. https://doi.org/10.1139/x90-048

Dixon MJ, Kuja AL (1995) Effects of simulated acid rain on the growth, nutrition, foliar pigments and photosynthetic rates of sugar maple and white spruce seedlings. Water Air & Soil Pollution 83(3-4): 219-236. https://doi.org/10.1007/BF00477354

dos Santos H (2006) Morphological and nutritional development of three species of nursery-grown hardwood seedlings in Tennessee. Auburn University, AL: Auburn University, 100 p. Ph.D. dissertation.

Dumroese RK, Landis TD, Luna T (2012) Raising native plants in nurseries: basic concepts. Gen. Tech. Rep. RMRS-GTR-274. Fort Collins, CO: U.S. Department of Agriculture, Forest Service, Rocky Mountain Research Station, 84 p. https://doi.org/10.2737/RMRS-GTR-274

Dumroese RK, Thompson G, Wenny DL (1990) Lime-amended growing medium causes seedling growth distortions. Tree Planters' Notes 41(3): 12-17.

Edwards IK (1986) How to maximize efficiency of fertilizers in a forest tree nursery. In: Landis TD, Fischer JW (technical coordinators) Proceedings, intermountain nurseryman's association—1985. GTR-125. Fort Collins, CO: U.S. Department of Agriculture, Forest Service, Rocky Mountain Forest and Range Experiment Station: 99-103.

Emerson P, Skousen J, Ziemkiewicz P (2009) Survival and growth of hardwoods in brown versus gray sandstone on a surface mine in West Virginia. J Environ Qual 38(5): 1821-1829. https://doi.org/10.2134/jeq2008.0479

Enebak SA (2011) Historical forest seedling production in the southern United States: 2008 to 2009 planting season. In: Riley LE, Haase DL, Pinto JR (technical coordinators): Proceedings, forest and conservation nursery associations—2010. Proc. RMRS-P-65. Fort Collins, CO: U.S. Department of Agriculture, Forest Service, Rocky Mountain Research Station: 19-34.

Enebak SA (2019) Pest management of bareroot hardwood seedlings. In: McNabb K, Pike C (eds) A nursery guide for the production of bareroot hardwood seedlings. Agricultural Handbook no. 733. Washington, DC: U.S. Department of Agriculture, Forest Service.

Engstrom HE, Stoeckeler JH (1941) Nursery practice for trees and shrubs suitable for planting on the Prairie-Plains. Misc. Publ. 434. Washington, DC: U.S. Department of Agriculture, 159 p. https://doi.org/10.5962/bhl.title.65705

Erdmann GG, Metzger FT, Oberg RR (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.

Fan HB, Wang YH (2000) Effects of simulated acid rain on germination, foliar damage, chlorophyll contents and seedling growth of five hardwood species growing in China. Forest Ecol Manag 126(3): 321-329. https://doi.org/10.1016/S0378-1127(99)00103-6

Ferrarezi RS, Testezlaf R (2017) Automated ebb-and-flow subirrigation for citrus liners production. II. Pests, diseases and nutrient concentration. Agr Water Manage 192: 21-32. https://doi.org/10.1016/j.agwat.2017.06.017

Fuller DL, Meadows WA (1983) Effects of powdered vs. pelletized dolomite and two fertilizer regimes on pH of growth medium and quality of eight woody species in containers. Southern Nursery Association Research Journal 9(1): 1-7.

Gabriel CA, Cassol PC, Simonete MA, Moro L, Pfleger P, Mumbach GL (2018) Lime and gypsum applications on soil chemical attributes and initial growth of Eucalyptus. Floresta 48(4): 573-582.

https://doi.org/10.5380/rf.v48i4.57455
Gilliam CD, Eason JT, Evans CE (1985) Effects of soil pH on four field-grown nursery crops. Journal of Environmental Horticulture 3(3): 136-139.
Goswami BK, Rahaman MM, Hoque AKMA, Bhuiyan K, Mian IH (2011) Variations in different isolates of *Rhizoctonia solani* based on temperature and pH. Bangladesh Journal of Agricultural Research 36(3): 389-396. https://doi.org/10.3329/bjar.v36i3.9267
Hacskaylo J, Finn RF, Vimmerstedt JP (1969) Deficiency symptoms of some forest trees. Research Bulletin 1015, Wooster, OH: Ohio Agricultural Research and Development Center, 68 p.
Hacskaylo J, Struthers P (1959) Correction of lime induced chlorosis in pin oak. Research Circular 71, Wooster, OH: Ohio Agricultural Experiment Station, 5 p.
Handreck KA (1989) Assessment of iron availability in soilless potting media. Commun Soil Plan 20(13-14): 1297-1320. https://doi.org/10.1080/00103628909368152
Hannah PR (1973) Phosphorus stimulates growth of yellow birch seedlings. Tree Planters' Notes 24(1): 1-2.
Hanson PJ, Dickson RE, Isebrands JG, Crow TR, Dixon RK (1986) A morphological index of *Quercus* seedling ontogeny for use in studies of physiology and growth. Tree Physiol 2(1-2-3): 273-281. https://doi.org/10.1093/treephys/2.1-2-3.273
Hart DH, Sharpe WE (1997) Response of potted northern red oak and hay-scented fern to additions of calcium, magnesium, potassium, and phosphorus. In: Pallardy SG, Cecich RA, Garrett HG, Johnson PS (eds) Proceedings of the 11th Central Hardwood Forest Conference; Gen. Tech. Rep. NC-188. St. Paul, MN: U.S. Department of Agriculture, Forest Service, North Central Forest Experiment Station: 304-312.
Hartley CP (1921) Damping-off in forest nurseries. Bulletin 934, Washington, DC: U.S. Department of Agriculture. 79 p. https://doi.org/10.5962/bhl.title.108260
Hendrickson AH, Veihmeyer FJ (1941) Moisture distribution in soil in containers. Plant Physiol 16(4): 821. https://doi.org/10.1104/pp.16.4.821
Hensley DL, Carpenter PL (1986) Survival and coverage by several N_2-fixing trees and shrubs on lime-amended acid mine spoil. Tree Planters' Notes 37(4): 27-31.
Herendeen RV (2007) Two-year performance of hybrid and pure American chestnut *Castanea dentata* (Fagaceae) seedlings and benefit of *Pisolithus tinctorius* (Sclerodermataceae) on Eastern Ohio mine spoil. Athens, OH: Ohio University, 70 p. Ph.D. dissertation.
Hermle S, Günthardt-Goerg, MS, Schulin R (2006) Effects of metal-contaminated soil on the performance of young trees growing in model ecosystems under field conditions. Environ Pollut 144(2): 703-714. https://doi.org/10.1016/j.envpol.2005.12.040
Hjelm K, Rytter L (2016) The influence of soil conditions, with focus on soil acidity, on the establishment of poplar (*Populus* spp.). New Forest 47(5): 731-750. https://doi.org/10.1007/s11056-016-9541-9
Hoch BK (2018) Assessing the tolerance of three species of *Quercus* L. and Iowa grown *Betula nigra* L. provenances to foliar chlorosis in elevated pH substrate. MS thesis, Kansas State University Manhattan, KS. 152 p.
Hodges CS (1962) Diseases in southeastern forest nurseries and their control. Station Paper 142. Asheville, NC: U.S. Department of Agriculture, Forest Service, Southeastern Research Station. 16 p.
Hogan GD (1998) Effect of simulated acid rain on physiology, growth and foliar nutrient concentrations of sugar maple. Chemosphere 36(4-5): 633-638. https://doi.org/10.1016/S0045-6535(97)10099-6
Hooper CA, Curtin TW (1983) Growing Illinois trees from seed. Circular 1219. Urbana: IL: University of Illinois at Urbana-Champaign, Cooperative Extension Service, 32 p.
Houbao F, Chuanrong L (1999) Effects of simulated acid rain on seedling emergence and growth of five broad-leaved species. J Forestry Res 10(2): 83-86. https://doi.org/10.1007/BF02855532
Huang, J.W.; Kuhlman, E.G. 1991. Mechanisms inhibiting damping-off pathogens of slash pine seedlings with a formulated soil amendment. Phytopathology. 81(2): 171-177. https://doi.org/10.1094/Phyto-81-171
Icka P, Damo R, Icka E (2016) *Paulownia tomentosa*, a fast growing timber. Annals of Valahia University of Targoviste - Agriculture 10(1): 14-19. https://doi.org/10.1515/agr-2016-0003

Iyer JG, Chesters G, Wilde SA (1969) Recovery of growth potential of nursery stock produced on biocide-treated soils. Silva Fenn 3(4): 226-233. https://doi.org/10.14214/sf.a14595

Jackson LWR (1933) Effect of sulfuric acid and aluminum sulfate as used for the control of damping-off of conifers on soil pH. Phytopathology 23: 18.

James RL (1997) Effects of fertilizer on selected potential plant pathogens in bareroot forest nurseries. In: Haase DL, Rose R (eds) Proceedings, forest seedling nutrition from the nursery to the field. Corvallis, OR: Oregon State University, Nursery Tech. Coop, 27-39.

Jensen KF, Patton RL (1990) Response of yellow-poplar (*Liriodendron tulipifera* L.) seedlings to simulated acid rain and ozone. Growth modifications. Environ Exp Bot 30(1): 59-66. https://doi.org/10.1016/0098-8472(90)90009-S

Jobling J (1990) Poplars for wood production and amenity. Bulletin 92. Famham, Surrey: UK Forestry Commission, Forest Research Station: 84 p.

Johnson JE, Mitchem DO, Kreh RE (2003) Establishing royal paulownia on the Virginia Piedmont. New Forest 25(1): 11-23. https://doi.org/10.1023/A:1022349231557

Johnson WA, Hagler TB (1955) Response of pecans to application of lime and zinc. Proceedings, Southeast Pecan Growers' Association 48: 78-82.

Joslin JD, Wolfe MH (1989) Aluminum effects on northern red oak seedling growth in six forest soil horizons. Soil Sci Soc Am J 53(1): 274-281. https://doi.org/10.2136/sssaj1989.03615995005300010050x

Keane KD, Manning WJ (1988) Effects of ozone and simulated acid rain on birch seedling growth and formation of ectomycorrhizae. Environ Pollut 52(1): 55-65. https://doi.org/10.1016/0269-7491(88)90107-8

Kelly JM, Schaedle M, Thornton FC, Joslin JD (1990) Sensitivity of tree seedlings to aluminum: II. red oak, sugar maple, and European beech. J Environ Qual 19(2): 172-179. https://doi.org/10.2134/jeq1990.00472425001900020002x

Kennedy HE, Krinard RM (1985) Shumard oaks successfully planted on high pH soils. Res. Note SO-321. New Orleans, LA: U.S. Department of Agriculture, Forest Service, Southern Forest Experiment Station: 3 p. https://doi.org/10.2737/SO-RN-321

Khilare VC, Ahmed R (2012) Effect of different media, pH and temperature on the growth of *Fusarium oxysporum* f. sp. *ciceri* causing chickpea wilt. International Journal of Advanced Biological Research 2(1): 99-102.

Kidd PS, Proctor J (2001) Why plants grow poorly on very acid soils: are ecologists missing the obvious? J Exp Bot 52(357): 791-799. https://doi.org/10.1093/jexbot/52.357.791

Kitao M, Lei TT, Koike T (1999) Effects of manganese in solution culture on the growth of five deciduous broad-leaved tree species with different successional characters from northern Japan. Photosynthetica 36(1-2): 31-40. https://doi.org/10.1023/A:1007058418199

Korthals GW, Alexiev AD, Lexmond TM, Kammenga JE, Bongers T (1996) Long-term effects of copper and pH on the nematode community in an agroecosystem. Environ Toxicol Chem 15(6): 979-985. https://doi.org/10.1002/etc.5620150621

Lamar RT, Davey CB (1988) Comparative effectivity of three *Fraxinus pennsylvanica* Marsh, vesicular-arbuscular mycorrhizal fungi in a high-phosphorus nursery soil. New Phytol 109(2): 171-181. https://doi.org/10.1111/j.1469-8137.1988.tb03706.x

Lamichhane JR, Dürr C, Schwanck AA, Robin MH, Sarthou JP, Cellier V, Messéan A, Aubertot JN (2017) Integrated management of damping-off diseases. a review. Agron Sustain Dev 37(10):1-25. https://doi.org/10.1007/s13593-017-0417-y

Landis TD (1989) Irrigation and water management. In: Landis TD, Tinus RW, McDonald SE, Barnett JP (eds) The container tree nursery manual. Agricultural Handbook 674. Washington, DC: U.S. Department of Agriculture, Forest Service. Chapter 2. Vol. 4: 69-119.

Landis TD (2008) Nursery Practices. In: Bonner FT, Karrfalt RP (eds) The woody plant seed manual. Agricultural Handbook 727. Washington, DC: U.S. Department of Agriculture, Forest Service, Chapter 7.

Laurie A, Chadwick LC (1931) The modern nursery: a guide to plant propagation, culture and handling. New York, NY: The Macmillan Company, 494 p.

Leaf AL, Rathakatte P, Solan FM (1978) Nursery seedling quality in relation to plantation performance. In: van Eerden E, Kinghorn JM (eds) Proceedings of the root form of planted trees symposium. Joint Report #8. Victoria, BC: British Columbia Ministry of Forests: 45-51.

Lee JJ, Weber DE (1979) The effect of simulated acid rain on seedling emergence and growth of eleven woody species. Forest Science 25(3): 393-398.

Lee DK, Yun CH, Choi MI (1994) Effects of simulated acidic precipitation and aluminum on the growth of *Alnus glutinosa* and *Alnus hirsuta* seedlings and their nitrogen fixation. J Sustain Forest 1(3): 71-92. https://doi.org/10.1300/J091v01n03_06

Lei Y, Korpelainen H, Li C (2007) Physiological and biochemical responses to high Mn concentrations in two contrasting *Populus cathayana* populations. Chemosphere 68(4): 686-694. https://doi.org/10.1016/j.chemosphere.2007.01.066

Lesko J, Jacobs DF (2018) Conversion of conifer plantations to native hardwoods: influences of overstory and fertilization on artificial regeneration. New Forest 49(6): 829-849. https://doi.org/10.1007/s11056-018-9683-z

Li S, Shi T, Kong F, Ma Q, Mao Y, Yin T (2013) Methods for breaking the dormancy of eastern redbud (*Cercis canadensis*) seeds. Seed Sci Technol 41(1): 27-35. https://doi.org/10.15258/sst.2013.41.1.03

Liang H, Chang SX (2004) Response of trembling and hybrid aspens to phosphorus and sulfur fertilization in a Gray Luvisol: growth and nutrient uptake. Can J Forest Res 34(7): 1391-1399. https://doi.org/10.1139/x04-022

Lombard K, O'Neill M, Mexal J, Ulery A, Onken B, Bettmann G, Heyduck R (2010) Can soil plant analysis development values predict chlorophyll and total Fe in hybrid poplar? Agroforest Syst 78(1): 1-11. https://doi.org/10.1007/s10457-009-9214-1

Lombard K, O'Neill M, Heyduck R, Onken B, Ulery A, Mexal J, Unc A (2011) Composted biosolids as a source of iron for hybrid poplars (*Populus* sp.) grown in northwest New Mexico. Agroforest Syst 81(1): 45-56. https://doi.org/10.1007/s10457-010-9334-7

Londo AJ, Kushla JD, Carter RC (2006) Soil pH and tree species suitability in the South. SREF-FM-002 Southern Regional Extension Forestry, 5 p. https://sref.info/resources/publications/soil-ph-and-tree-species-suitability-in-the-south-1

Long A, Zhang J, Yang LT, Ye X, Lai NW, Tan LL, Lin D, Chen LS (2017) Effects of low pH on photosynthesis, related physiological parameters, and nutrient profiles of citrus. Frontiers in Plant Science 8(185): 1-22. https://doi.org/10.3389/fpls.2017.00185

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

Marx DH (1990) Soil pH and nitrogen influence *Pisolithus* ectomycorrhizal development and growth of loblolly pine seedlings. Forest Science 36(2): 224-245.

Mathers HM, Lowe SB, Scagel C, Struve DK, Case LT (2007) Abiotic factors influencing root growth of woody nursery plants in containers. Horttechnology 17(2): 151-162. https://doi.org/10.21273/HORTTECH.17.2.151

McComb AL, Kapel FJ (1942) Effect of subsoil acidity and fertility on the growth of seedling black locust and green ash. Plant Physiol 17(1): 7-15. https://doi.org/10.1104/pp.17.1.7

McNabb K, Heidbreder-Olson E (1998) Results of 1996 irrigation water quality survey. Research Report 98-05. Auburn University, AL: Auburn University Southern Forest Nursery Management Cooperative, 7 p.

Medeiros JS, Tomeo NJ, Hewins CR, Rosenthal DM (2016) Fast-growing *Acer rubrum* differs from slow-growing *Quercus alba* in leaf, xylem and hydraulic trait coordination responses to simulated acid rain. Tree Physiol 36(8): 1032-1044. https://doi.org/10.1093/treephys/tpw045

Melhuish JH, Gentry CE, Beckjord PR (1990) *Paulownia tomentosa* seedling growth at differing levels of pH, nitrogen and phosphorus. Journal of Environmental Horticulture 8(4): 205-207.

Messenger S (1984) Treatment of chlorotic oaks and red maples by soil acidification. Journal of Arboriculture 10(4): 122-128.

Messenger AS, Hruby BA (1990) Response of interveinally chlorotic red maple trees treated with medicaps or by soil acidification. Journal of Environmental Horticulture 8(1): 5-9.

Meyer DA (1993) Growing Wisconsin trees from seed. Forestry Facts No. 66. Madison, WI: University of Wisconsin, Department of Forestry, Cooperative Extension, 5 p.

Miyamoto S, Ryan J, Stroehlein JL (1975) Potentially beneficial uses of sulfuric acid in southwestern agriculture. J Environ Qual 4(4): 431-437. https://doi.org/10.2134/jeq1975.00472425000400040002x

Mizell L (1980) Maintaining optimum soil pH in sandy forest tree nurseries. In: Abrahamson LP, Bickelhaupt DH (eds) Proceedings, North American forest tree nursery soils workshop. Syracuse, NY: State University of New York: 285-298.

Morby FE (1984) Nursery site-selection, layout, and development. In: Duryea ML, Landis TD (eds) Forest Nursery Manual. The Hague, Netherlands: Martinus Nijhoff/Junk Publishers, Chapter 2: 9-15. https://doi.org/10.1007/978-94-009-6110-4_2

Olchowik J, Bzdyk RM, Studnicki M, Bederska-Błaszczyk M, Urban A, Aleksandrowicz-Trzcińska M (2017) The effect of silver and copper nanoparticles on the condition of English oak (*Quercus robur* L.) seedlings in a container nursery experiment. Forests 8(310): 1-19. https://doi.org/10.3390/f8090310

Ouimet R, Camiré C, Furlan V (1996) Effect of soil base saturation and endomycorrhization on growth and nutrient status of sugar maple seedlings. Can J Soil Sci 76(2): 109-115. https://doi.org/10.4141/cjss96-017

Paez-Valencia J, Sanchez-Lares J, Marsh E, Dorneles LT, Santos MP, Sanchez D, Winter A, Murphy S, Cox J, Trzaska M, Metler J, Kozic A, Facanha AR, Schachtman D, Sanchez C, Gaxiola RA (2013) Enhanced proton translocating pyrophosphatase activity improves nitrogen use efficiency in romaine lettuce. Plant Physiol 161: 1557-1569. https://doi.org/10.1104/pp.112.212852

Park BB, Cho MS, Lee SW, Yanai RD, Lee DK (2012) Minimizing nutrient leaching and improving nutrient use efficiency of *Liriodendron tulipifera* and *Larix leptolepis* in a container nursery system. New Forest 43(1): 57-68. https://doi.org/10.1007/s11056-011-9266-8

Peacock DN, Hummer KE (1996) Pregermination studies with liquid nitrogen and sulfuric acid on several *Rubus* species. Hortscience 31(2): 238-239. https://doi.org/10.21273/HORTSCI.31.2.238

Peevy CE (1976) Hardwood nursey management – problems that can and do occur in the nursery and how these problems can be avoided and solved. In: Lantz CW (ed) Proceedings, southeastern area forest nurserymen conferences -1976. Atlanta, GA: U.S. Department of Agriculture, Forest Service, State and Private Forestry: 4-7.

Percy K (1986) The effects of simulated acid rain on germinative capacity, growth, and morphology of forest tree seedlings. New Phytol 104(3): 473-484. https://doi.org/10.1111/j.1469-8137.1986.tb02914.x

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

Pope PE (1982) Interaction of soil pH and genotype on growth and nutrient uptake of sycamore seedlings. Can J Forest Res 12(3): 627-631. https://doi.org/10.1139/x82-095

Pritchett WL, Fisher RF (1987) Properties and management of forest soils. 2nd ed. New York, NY: John Wiley & Sons, 494 p.

Puri SL, Swamy SL, Jaiswal AK (2002) Evaluation of *Populus deltoides* clones under nursery, field and agrisilviculture system in subhumid tropics of Central India. New Forest 23(1): 45-61. https://doi.org/10.1023/A:1015620915654

Ramlall C, Varghese B, Ramdhani S, Pammenter NW, Bhatt A, Berjak P (2015) Effects of simulated acid rain on germination, seedling growth and oxidative metabolism of recalcitrant-seeded *Trichilia dregeana* grown in its natural seed bank. Physiologia Plantarum 153(1): 149-160. https://doi.org/10.1111/ppl.12230

Raynal DJ, Roman JR, Eichenlaub WM (1982a) Response of tree seedlings to acid precipitation— I. Effect of substrate acidity on seed germination. Environ Exp Bot22(3): 377-383. https://doi.org/10.1016/0098-8472(82)90030-2

Raynal DJ, Roman JR, Eichenlaub WM (1982b) Response of tree seedlings to acid precipitation—II. Effect of simulated acidified canopy throughfall on sugar maple seedling growth. Environ Exp Bot22(3): 385-392. https://doi.org/10.1016/0098-8472(82)90031-4

Reich PB, Schoettle AW, Amundson RG (1986) Effects of O_3 and acidic rain on photosynthesis and growth in sugar maple and northern red oak seedlings. Environ Pollut, Series A, Ecological and Biological 40(1): 1-15. https://doi.org/10.1016/0143-1471(86)90054-1

Rentz R (1996) Bottom-land hardwoods for today's market. In: Landis TD, South DB (tech cords): Proceedings, forest and conservation nursery associations. Gen. Tech. Rep. PNW-GTR-389. Portland, OR: U.S. Department of Agriculture, Forest Service, Pacific Northwest Research Station: 38-40.

Rikala R, Jozefek HJ (1990) Effect of dolomite lime and wood ash on peat substrate and development of tree seedlings. Silva Fenn 24(4): 323-334. https://doi.org/10.14214/sf.a15586

Roberts MR, Gilliam FS (1995) Disturbance effects on herbaceous layer vegetation and soil nutrients in *Populus* forests of northern lower Michigan. J Veg Sci 6(6): 903-912. https://doi.org/10.2307/3236405

Russell K (1990) Damping-off. In: Hamm PB, Campbell SJ, Hansen EM (eds) Growing healthy seedlings. Special publication 19. Corvallis, OR: Oregon State University, Forest Research Laboratory: 2-5.

Ruter JM, van de Werken H (1986) Is dolomitic limestone overused in container media. American Nurseryman 163(12): 49-51.

Salifu KF, Nicodemus MA, Jacobs DF, Davis AS (2006) Evaluating chemical indices of growing media for nursery production of Quercus rubra seedlings. Hort Science. 41(5): 1342-1346. https://doi.org/10.21273/HORTSCI.41.5.1342

Schier GA, McQuattie CJ (2000) Effect of water stress on aluminum toxicity in pitch pine seedlings. J Plant Nutr 23(5): 637-647. https://doi.org/10.1080/01904160009382046

Schmal JL, Jacobs DF, 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. https://doi.org/10.1007/s10342-010-0443-7

Shareef BS, Haleem RA, Saedo KA (2016) Fungi colonized the roots of seedlings in forest nurseries. Mycopathologia 14(1-2): 9-13.

Sharpe RR, Marx DH (1986) Influence of soil pH and *Pisolithus tinctorius* ectomycorrhizae on growth and nutrient uptake of pecan seedlings. Hortscience 21: 1388-1390

Shi X, Wang S, Sun H, Chen Y, Wang D, Pan H, Zou Y, Liu J, Zheng L, Zhao X, Jiang Z (2016) Comparative of *Quercus* spp. and *Salix* spp. for phytoremediation of Pb/Zn mine tailings. Environ Sci Pollut R 24(4): 3400-3411. https://doi.org/10.1007/s11356-016-7979-0

Shock CC, Feibert EB, Seddigh M, Saunders LD (2002) Water requirements and growth of irrigated hybrid poplar in a semi-arid environment in eastern Oregon. Western Journal of Applied Forestry 17(1): 46-53.

Sibbett GS (1995) Managing high pH, calcareous, saline, and sodic soils of the western pecan-growing region. Hort Technology 5(3): 222-225. https://doi.org/10.21273/HORTTECH.5.3.222

Soedarjo M, Habte M (1995) Mycorrhizal and nonmycorrhizal host growth in response to changes in pH and P concentration in a manganiferous oxisol. Mycorrhiza 5(5): 337-345. https://doi.org/10.1007/BF00207406

Solan FM, Bickelhaupt DH, Leaf AL (1979) Soil and plant analytical services for tree nurseries. In: Proceedings, Northeastern Area Nurserymen's Conference - 1979. Broomall, PA: U.S. Department of Agriculture, Forest Service, Northeastern Area State & Private Forestry: 35-42.

South DB (2017) Optimum pH for growing pine seedlings. Tree Planters' Notes 60(2): 49-62.

South DB, Davey CB (1983) Circular 265., Auburn University, AL: Auburn University, Alabama Agricultural Experiment Station, 38 p.

South DB, Nadel RL, Enebak SA, Bickerstaff G (2018) The nutrition of loblolly pine seedlings exhibits both positive (soil) and negative (foliage) correlations with seedling mass. Tree Planters' Notes 61(2): 5-17.

Sparks D (1977) Soil pH and the pecan: a review. Pecan South 4(1): 16-21.

Spurway CH (1941) Soil reaction (pH) preferences of plants. Spec. Bull 306. East Lancing, MI: Michigan State College, Agricultural Experiment Station, 36 p.

Stafne ET, Carroll BL (2008) Pot production of pecan seedlings with 'Cynthiana' grape pomace. Journal of Food, Agriculture & Environment 6(1): 89-91.

St.Clair SB, Lynch JP (2005) Element accumulation patters of deciduous and evergreen tree seedlings on acid soils: implications for sensitivity to manganese toxicity. Tree Physiol 25 (1): 85-92. https://doi.org/10.1093/treephys/25.1.85

Steinbeck K, May JT (1977) Artificial hardwood regeneration in the Southeast - some aspects of planting stock quality. In: Wilcox HE, Hamer AF (eds) Proceeding: of fourth North America forest biology workshop. State Univ. New York Coll. Environ. Sci. and Forestry. Syracuse: 1-7.

Stoeckeler JH, Jones GW (1957) Forest nursery practice in the Lake States. Agriculture Handbook 110. Washington, DC: U.S. Department of Agriculture, 124 p.

Stone EL (1965) Nursery soil fertility. In: Leaf AL (ed) Proceedings, nursery soil improvement sessions. Syracuse, NY: State University of New York, College of Forestry: 16-27.

Stone JM (1980) Hardwood seedling production: what are the fertility requirements? In: Abrahamson LP, Bickelhaupt DH (eds) Proceedings: North American forest tree nursery soils workshop. State Univ. New York Coll. Environ Sci and Forestry Syracuse: 121-128.

Storandt J (2002) Red oak propagation at the Griffith State Nursery, Wisconsin Rapids, WI. In: Dumroese RK, Riley LE, Landis TD (technical coordinators) 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: 120-121.

Symonds WL, Campbell LC, Clemens J (2001) Response of ornamental Eucalyptus from acidic and alkaline habitats to potting medium pH. Sci Hortic-Amsterdam 88(2): 121-131. https://doi.org/10.1016/S0304-4238(00)00202-8

Teng Y, Timmer VR (1990) Phosphorus-induced micronutrient disorders in hybrid poplar. Plant and Soil 126(1): 19-29. https://doi.org/10.1007/BF00041365

Thomas FM, Brandt T, Hartmann G (1998) Leaf chlorosis in pedunculate oaks (*Quercus robur* L) on calcareous soils resulting from lime-induced manganese/iron-deficiency: Soil conditions and physiological reactions. Angewandte Botanik 72: 28-36.

Thomas FM, Sprenger S (2008) Responses of two closely related oak species, *Quercus robur* and *Q. petraea*, to excess manganese concentrations in the rooting medium. Tree physiology 28(3): 343-353. https://doi.org/10.1093/treephys/28.3.343

Timmer VR (1985) Response of a hybrid poplar clone to soil acidification and liming. Can J Soil Sci 65(4): 727-735. https://doi.org/10.4141/cjss85-078

Tinus RW (1979) Production of container-grown hardwoods. Tree Planters' Notes 29(4): 3-9.

Turner EE (1970) Nursery production of hardwood seedlings. In: Hansbrough T (ed) Silviculture and management of southern hardwoods. 19th Annual Forestry Symposium. Baton Rouge, LA: Louisiana State University Press: 64-79.

Turner GD, Lau RR, Young DR (1988) Effect of acidity on germination and seedling growth of *Paulownia tomentosa*. Journal of Applied Ecology 25(2): 561-567. https://doi.org/10.2307/2403844

Valdez-Aguilar LA, Grieve CM, Poss J, Mellano MA (2009) Hypersensitivity of *Ranunculus asiaticus* to salinity and alkaline pH in irrigation water in sand cultures. Hortscience 44(1): 138-144. https://doi.org/10.21273/HORTSCI.44.1.138

Van der Heijden EW, Kuyper TW (2001) Laboratory experiments imply the conditionality of mycorrhizal benefits for *Salix repens*: role of pH and nitrogen to phosphorus ratios. Plant Soil 228(2): 275-290. https://doi.org/10.1023/A:1004850423794

Villarrubia JM (1980) Effect of nitrogen rate and sources 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.

Voigt GK (1954) The effect of fungicides, herbicides, and insecticides on the accumulation of phosphorus by Pinus radiata as determined by the use of P32. Agron J 46(11): 511-513. https://doi.org/10.2134/agronj1954.00021962004600110009x

Voigt GK, Stoeckeler JH, Wilde SA (1958) Response of coniferous seedlings to soil applications of calcium and magnesium fertilizers. Soil Sci Soc Am J 22(4): 343-345. https://doi.org/10.2136/sssaj1958.03615995002200040022x

Walker RF, McLaughlin SB (1991) Growth and root system development of white oak and loblolly pine as affected by simulated acidic precipitation and ectomycorrhizal inoculation. Forest Ecol Manag 46(1-2): 123-133. https://doi.org/10.1016/0378-1127(91)90247-S

Watson GW, Hemelick EB (2004) Effects of soil pH, root density, and tree growth regulator treatments on pine oak chlorosis. Journal of Arboriculture 30(3): 172-177.

Whitcomb CE (1983) Does pH really have an effect on nutrition of container-grown plants? The American Nurseryman 158(9): 33-34.

Whitcomb CE (1988) Plant production in containers. Revised, Stillwater OK (ed), Lacebark Publications, 633 p.

Whitcomb CE (2009) The pH factor: beneficial or bologna - Part 1: In field soils, pH provides beneficial information. Stillwater, OK: Lacebark Research. https://rootmaker.com/sites/default/files/pdf/pHFactorFieldSoilsE.pdf (November 2018)

Wightman KE, Shear T, Goldfarb B, Haggar J (2001) Nursery and field establishment techniques to improve seedling growth of three Costa Rican hardwoods. New Forest 22(1-2): 75-96. https://doi.org/10.1023/A:1012020023446

Whittier WA (2018) Nutrient disorder foliar symptoms, foliar nutrient levels and predictive near-infrared spectroscopy nutrient models of teak (*Tectona grandis* L.f.). MS thesis, North Carolina State University, Raleigh, NC. 199 p.

Wilde SA (1934) Soil reaction in relation to forestry and its determination by simple tests. J Forest 32(4): 411-418.

Wilde SA (1937) Recent findings pertaining to the use of sulfuric acid for the control of damping-off disease. J Forest 35(12): 1106-1110.

Wilde SA (1946) Difficulty soluble sources of nutrients: their use in forest nurseries. J Forest 44(12): 1082-1086.

Wilde SA (1954) Reaction of soils: facts and fallacies. Ecology 35(1): 89-92. https://doi.org/10.2307/1931409

Wilde SA (1958) Forest Soils. New York, NY: Ronald Press, 537 p.

Wilde SA, Patzer WE (1940) Soil fertility standards for growing northern hardwoods in forest nurseries. Journal of Agriculture Research 61(3): 215-222.

Wilkinson KM, Landis TD, Haase DL, Daley BF, Dumroese RK (2014) Tropical Nursery Manual. Agricultural Handbook 732, Washington, DC: U.S. Department of Agriculture, Forest Service, 376 p.

Will E, Faust JE (1999) Irrigation water quality for greenhouse production. PB 1617, Knoxville, TN: The University of Tennessee, Agricultural Extension Service, 12 p.

Williams RD (1972) Hardwood nursery management. In: Hitt BG (ed) Proceedings, southeastern area forest nurserymen conferences -1972, Atlanta, GA: U.S. Department of Agriculture, Forest Service, State and Private Forestry: 87-93.

Williams RD, Hanks SH (1976) Hardwood nurseryman's guide. Agriculture Handbook 473, Washington, DC: U.S. Department of Agriculture, Forest Service, 78 p.

Willis CB (1972) Effects of soil pH on reproduction of *Pratylenchus penetrans* and forage yield of alfalfa. J Nematol 4(4): 291-295.

Wingett MC (2005) Effects of pH on biomass allocation in *Acer rubrum* seedlings. MS thesis, Old Dominion University, Norfolk, VA. 33 p.

Wong M (2005) Visual symptoms of plant nutrient deficiencies in nursery and landscape plants. Soil and Crop Management Report-10, Mānoa, HI: University of Hawaii, Cooperative Extension Service, 4 p.

Wright E (1944) Damping-off in broadleaf nurseries of the Great Plains region. Journal of Agricultural Research 69(2): 77-92.

Wright AN, Niemiera AX, Harris JR, Wright RD (1999a) Micronutrient fertilization of woody seedlings essential regardless of pine bark pH. Journal of Environmental Horticulture 17(2): 69-72.

Wright AN, Niemiera AX, Harris JR, Wright RD (1999b) Preplant lime and micronutrient amendments to pine bark affect growth of seedlings of nine container-grown tree species. Hortscience 34(4): 669-673. https://doi.org/10.21273/HORTSCI.34.4.669

Yawney WJ, Schultz RC, Kormanik PP (1982) Soil phosphorus and pH influence the growth of mycorrhizal sweetgum. Soil Sci Soc Am J 46(6): 1315-1320. https://doi.org/10.2136/sssaj1982.03615995004600060038x

Youngberg CT (1984) Soil tissue analysis: tools for maintaining soil fertility. In: Duryea ML, Landis TD (eds) Forest Nursery Manual. The Hague, Netherlands: Martinus Nijhoff/Junk Publishers, Chapter 8: 75-80. https://doi.org/10.1007/978-94-009-6110-4_8

Zhang W, Zwiazek JJ (2016) Effects of root medium pH on root water transport and apoplastic pH in red-osier dogwood (*Cornus sericea*) and paper birch (*Betula papyrifera*) seedlings. Plant Biology 18(6): 1001–1007. https://doi.org/10.1111/plb.12483

Zongwei F, Yunfeng S (1991) Relative sensitivities of woody plants to acid deposition in south areas of China. J Environ Sci-China 3(2): 61-68.