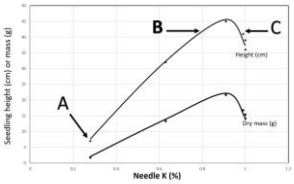
Potassium fertilization in bareroot nurseries in the southern US: a review

David B South

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

✉ southdb@auburn.edu



ARTICLE INFO

Citation:
South BD (2019) Potassium fertilization in bareroot nurseries in the southern US: a review. Reforesta 8: 25-59.
DOI: http://dx.doi.org/10.21750/REFOR.8.03.73

Editor: Vladan Ivetić, Serbia
Received: 2019-12-16
Accepted: 2019-12-25
Published: 2019-12-31

Abstract

This review covers most of the published literature on potassium (K) fertilization in bareroot seedbeds with the intent to concentrate on the southern United States. The timing and rates of K fertilization for bareroot seedlings are often based on logic and myths and, as a result, K recommendations vary considerably. Some recommend bareroot pine seedlings be fertilized with twice as much K as nitrogen (N) while others apply less than 100 kg ha^{-1}. It was determined that several long-held claims about K fertilization are invalid. Nursery seedbeds do not need to contain four times as much available K as N and the belief that extra K fertilization will increase freeze tolerance or drought resistance of non-deficient seedlings is invalid. There are no data to support the claim that K fertilization increases root growth or assists in the formation of terminal buds. For sandy seedbeds, there is no need to apply K before sowing. Adding extra K during the fall does not increase seedling morphology or seedling performance when loblolly pine seedlings, at lifting, have more than 0.5% K in needles. A reduction of K fertilization can be achieved by reviewing foliar tests prior to K top-dressings.

Keywords

Nutrition; Freeze tolerance; Seedling quality; Nutrient use efficiency: Seedling survival

Contents

1 Introduction

In some low-fertility soils, fertilization with potassium (K) will sometimes increase the growth of eucalyptus and pine plantations (Stoeckeler and Arneman 1960; Baule and Fricker 1970; Shoulders and Tiarks 1987; Almeida et al. 2010; Carlson et al. 2014; Bassaco et al. 2018). However, many soil types have adequate levels of K and adding additional K to soil at these locations does not improve plantation growth. For this reason, many loblolly pine (*Pinus taeda* L.) and slash pine (*Pinus elliottii* Engelm.) stands are fertilized only with nitrogen (N) and phosphorus (P) (Albaugh et al. 2018). In contrast, most nursery managers in southern states (United States) apply K annually to sandy seedbeds to produce more than 0.85 billion seedlings (Hernández et al. 2018). One estimate is that more than one-third of the nutrients applied to seedbeds is due to K fertilization (South and Zwolinski 1996). Although much is known about the effects of N and P fertilization on seedlings growth and development, information about positive effects of K fertilization on bareroot seedlings is limited. For this reason, a literature review was undertaken to establish what is known about K fertilization practices in bareroot nurseries in southern states. This review addresses nursery literature from the 20th century since most of the fertility research after 2000 deals with N and P applications for container nurseries.

2 Deficiency levels and zone of hidden hunger

There are two methods to determine a K deficiency in seedlings. One method is to produce visual symptoms in a greenhouse so that deficiency levels for pines can be determined (Table 1). Photographs illustrating the effects of K deficiency on various species are available (Pwrnell 1958; Murison 1960; Sucoff 1961; Baule and Fricker 1970; Erdmann et al. 1979; May 1985; Hernández and Lombardo 1987; Donald 1991; Whittier 2018). K deficient loblolly pine cotyledons can be chocolate brown or red (Sucoff 1961; Lyle 1969; May 1985) but the color can vary with other pines. Although May (1957b) said that K deficiencies have been noted in many nurseries, especially when soil pH, organic matter and cation exchange capacity (CEC) are low (Davey 1991), documented cases from the southern United States are rare. Stunted pine seedlings (4 µg g^{-1} of K in soil at time of sowing) occurred at a nursery in Florida (Leach and Gresham 1983) and a photo of slash pine seedlings shows winter discoloration of seedlings fertilized only with N and P (Brendemuehl 1968, p. 309). Although overall fertilization improved growth of stunted conifers at northern nurseries (Wilde and Wittenkamp 1939; Baule and Fricker 1970); there was no proof a K deficiency had occurred. It is also likely that some nursery managers (who do not monitor foliage nutrients) over fertilize with K in hopes of preventing a K deficiency.

The second method involves developing a growth response curve. The independent variable (x-axis) can either be soil K level (McKee 1978), foliar K concentration (Sucoff 1962; McGee 1963), or fertilizer rate (Bassaco et al. 2018). Typically, greenhouse trials (using 100% sand) are required to define the “hidden hunger" zone (Figure 1) since positive growth responses to K fertilizers are seldom detected in bareroot nurseries.

Table 1. Selected examples of the deficiency values for potassium (K) in pine foliage.

Species	Location	% K	Reference
Pinus contorta	Field	0.27	Binggeli et al. 2000
Pinus contorta	Bareroot nursery	0.37	Landis 1976
Pinus elliottii	Greenhouse	0.24	McGee 1963
Pinus elliottii	Greenhouse	0.21	Mead and Pritchett 1971
Pinus elliottii	Greenhouse	0.20	Brendemuehl 1968
Pinus radiata	Field	0.35	Raupach and Hall 1971
Pinus radiata	Bareroot nursery	0.35	Knight 1978
Pinus resinosa	Field	0.29	Heiberg et al. 1959
Pinus resinosa	Field	0.31	Madgwick 1964
Pinus resinosa	Greenhouse	0.41	Rosendahl 1943
Pinus strobus	Field	0.33	Heiberg and White 1951
Pinus strobus	Greenhouse	0.41	Schomaker 1969
Pinus strobus	Field	0.44	Walker 1956
Pinus strobus	Bareroot nursery	0.16	Gilmore and Kahler 1965
Pinus sylvestris	Under roof	0.27	Ylimartimo 1990
Pinus sylvestris	Greenhouse	0.34	Holopainen and Nygren 1989
Pinus taeda	Field	0.29	Carlson et al. 2014
Pinus taeda	Bareroot nursery	0.18	Gilmore and Kahler 1965
Pinus taeda	Greenhouse	0.26	Sucoff 1961
Pinus taeda	Field	0.34	Albaugh et al. 2010
Pinus virginiana	Greenhouse	0.28	Sucoff 1962

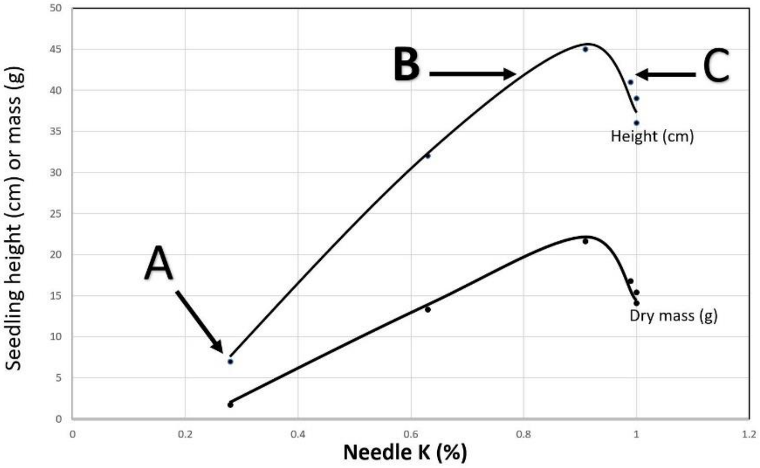


Figure 1. Response curves for pine seedlings to potassium (K). Data are for greenhouse-grown pine seedlings in sand (after Sucoff 1962). Point (A) illustrates the beginning of the hidden hunger zone and point (B) is the end. Visual deficiency symptoms occur at "A" while "B" is the critical level, defined as 90% of maximum growth. Point "C" is where toxicity levels are reducing seedling growth. Seedling age affects both the x- and y-axis of this graph and, therefore, point B will decline (along the x-axis) as seedling mass increases. It is a waste of resources to produce seedlings with needle K at point C.

Visual deficiency symptoms mark the beginning of the "hidden hunger" region and the end occurs near the peak of the response curve. Although K deficient symptoms have been produced in greenhouses (Pessin 1937; Hobbs 1944; Murison 1960; Sucoff 1961; Lyle 1969), only a few trials define "hidden hunger" ranges for pine (Sucoff 1962; Smethurst et al. 2007). Most soils contain enough K to produce seedlings with no "hidden hunger." For example, in a greenhouse trial, fertilizing with KCl+N resulted in a diameter growth response only when soil contained less than 10 µg g^{-1} K (Mead and Pritchett 1971).

Some circumstantial evidence suggests a "hidden hunger" zone exists for bareroot loblolly pine seedlings. In one trial in Texas, several soil cations (K, zinc, copper, iron) were positively correlated with seedling biomass (South et al. 2018). Steinbeck (1962) tested three rates of KCl at two Georgia nurseries but no "hidden hunger" zone could be determined since soil K levels were above 10 µg g^{-1} K and non-fertilized seedlings contained more than 0.5% K at harvest.

As pine seedlings gain biomass in the nursery, the foliar K% declines due to carbohydrate dilution (Fraysse and Crémière 1998; South et al. 2018; Table 2). Needles sampled in June may have 1.1% K while the same seedlings tested seven months later would be at 0.5% K (Figure 2). Awareness of this decline is important for those who attempt to identify points A and B of the "hidden hunger" zone. The values for these points will decline as seedling mass increases with time. Prudent managers who test the foliage for K in August should compare the values with expected values for August (not for values derived at time of lifting). If seedlings in August are at or above the target range, a manager can forgo applying a late-summer application of K. However, managers may apply K if the foliar value appears to be approaching the "hidden hunger" zone. The "hidden hunger" zone illustrated in Figure 2 is preliminary and the proposed boundaries should be refined with additional studies.

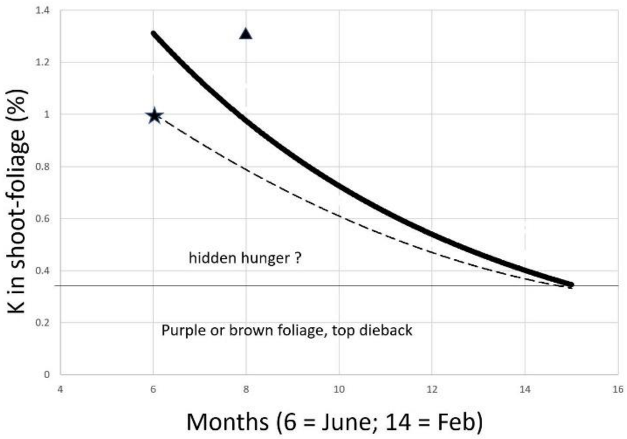


Figure 2. Foliar tests can be used to determine when to apply foliar applications of potassium (K). When foliar tests for loblolly pine needles are above the dashed line, K fertilization is not expected to affect seedling performance. Visual deficiency symptoms may occur when foliar tests are less than 0.4% K. Seedlings with foliar values below the dashed line may be in the "hidden hunger" zone. The solid line represents values that are near normal for seedlings that were sown in April. The TRIANGLE represents seedlings (sampled in June) that received an excessive amount of K while STAR seedlings will be fertilized with K.

Table 2. Selected examples of the effect of sampling month on foliar potassium (K) from research trials in bareroot seedbeds.

Species	Tissue	Month	Fertilizer K kg ha^{-1}	% K	Reference
Pinus taeda	Shoot	June	0	1.16	Switzer and Nelson 1956
Pinus taeda	Needle	July	??	1.11	Starkey and Enebak 2012
Pinus taeda	Shoot	Aug	??	1.11	Danielson 1966
Pinus taeda	Shoot	Aug	56	1.02	South et al. 1988
Pinus echinata	Needle	Aug	0	0.98	Brissette and Carlson 1987
Pinus taeda	Needle	Sept	??	0.95	Miller et al. 1985
Pinus taeda	Shoot	Oct	0	0.68	Switzer and Nelson 1956
Pinus taeda	Shoot	Oct	??	0.66	Starkey and Enebak 2012
Pinus elliottii	Shoot	Nov	167	0.92	Munson and Stone 1984
Pinus elliottii	Shoot	Dec	0	0.56	Steinbeck 1962
Pinus elliottii	Shoot	Dec	0	0.55	Steinbeck 1962
Pinus echinata	Needle	Dec	0	0.54	Brissette and Carlson 1987
Pinus taeda	Shoot	Dec	0	0.54	Rowan 1987
Pinus taeda	Needle	Jan	0	0.60	Wall 1994
Pinus taeda	Needle	Jan	0	0.52	May 1957a
Pinus taeda	Needle	Jan	0	0.54	May 1957a
Pinus taeda	Needle	Jan	??	0.57	May et al. 1962
Pinus taeda	Needle	Jan	??	0.35	Miller et al. 1985
Pinus taeda	Shoot	Jan	??	0.31	Starkey and Enebak 2012
Pinus taeda	Needle	Feb	69	0.58	Switzer and Nelson 1963
Pinus taeda	Stem	Feb	69	0.55	Switzer and Nelson 1963
Pinus taeda	Shoot	Feb	108	0.74	South et al. 2017
Pinus taeda	Seedling	Feb	??	0.49	Bryan 1954
Pinus taeda	Needle	Feb	??	0.47	Danielson 1966
Pinus taeda	Stem	Feb	??	0.46	Danielson 1966
Pinus taeda	Seedling	Feb	??	0.45	Sung et al. 1997
Pinus echinata	Needle	March	13	0.27	Gilmore and Kahler 1965
Pinus taeda	Needle	March	13	0.25	Gilmore and Kahler 1965
Pinus elliottii	Shoot	March	167	0.82	Munson and Stone 1984
Pinus palustris	Needle	March	90	0.78	Hinesley and Maki 1980

It should also be noted that many response curves are incorrectly labeled. Often authors incorrectly assume that KCl is only a potassium treatment and that chloride (Cl^-) has no effect on seedling growth, soil microbiology, or biochemistry. In addition, some researchers did not provide the source of K used (Gilmore and Kahler 1965; Bjorkbom 1973; Edwards 1989; Alt et al. 1993; Shaw et al. 1998; Jacobs et al. 2004; Cutter and Murphey 2007; Fernández et al. 2007) so readers do not know if seedlings were exposed to high levels of Cl. Although some response curves are drawn correctly (e.g. Figure 3), misleading and incorrect graphs list only K on the x-axis. In contrast, some authors assume KCl is just a “chlorine treatment” and that high rates of K have no impact on disease or plant growth (Rupe et al. 2000). Cl is biologically active (Hansen et al. 1923; Browder et al. 2005a; Nowak and Friend 2006; Heckman 2007; Geilfus 2018) and yet some editors and reviewers do not remind authors of this fact.

For simple compounds, response graphs can be improved by presenting multiple x-axes as in Figure 4. One method to reduce confounding would be to test potassium-acetate as a comparison to KCl. Another approach would be to test appropriate rates of nitric acid (HNO_3) along with various rates of potassium nitrate (KNO_3) (Brown et al. 1981; Holopainen and Nygren 1989). Likewise, it would be informative to compare a response curve for KNO_3 (Figure 4) with an equivalent response curve for HNO_3. Future researchers should not assume that only one element (in KCl or K_2SO_4) qualifies as the dependent variable.

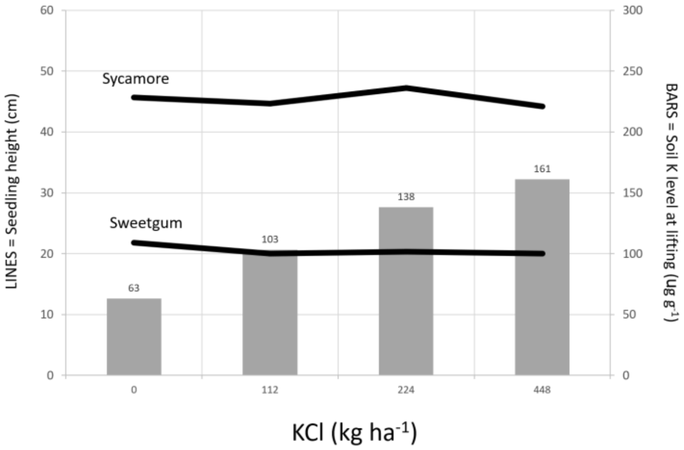


Figure 3. Response curves for hardwoods seedlings growing in bareroot seedbeds (silt loam). With no nitrogen fertilization, applying KCl at this nursery did not improve height growth of either sycamore or sweetgum but the level of K in the soil was increased. Applying 224 kg ha^{-1} of K (total of three equal applications) increased extractable soil K by 98 µg g^{-1} at lifting (adapted from Deines 1973).

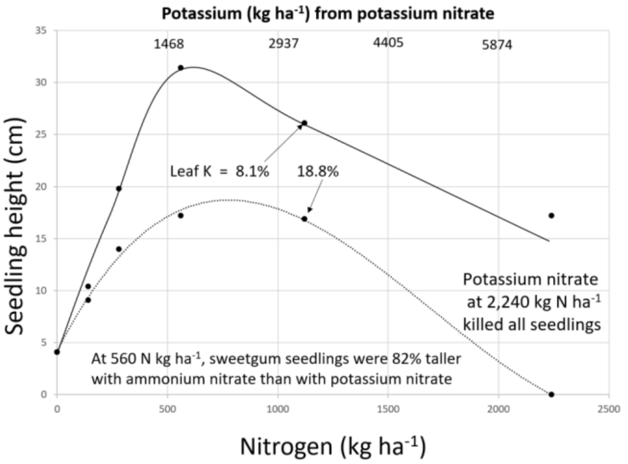


Figure 4. Response curves for 5-month-old sweetgum (*Liquidambar styraciflua* L.) seedlings. Seedlings were growing in a soil-sand-bark mix and were treated with ammonium nitrate (solid line) and KNO_3 (dotted line). Applying too much KNO_3 can increase foliar K concentration and reduce height growth (Brown et al. 1981). All nitrogen (N) treatments were applied in eight equal applications spaced about two weeks apart. Therefore, the highest KNO_3 treatment received eight applications of 2,154 kg ha^{-1} each (i.e., a total of 2,240 kg ha^{-1} of N). When the growing medium contains 72 µg g^{-1} K, sweetgum seedlings can grow well with only ammonium nitrate fertilization. Rates of K at the top of the graph apply only to KNO_3 treatments and rates this high are not used to grow sweetgum in bareroot nurseries. Applying too much KNO_3 (N/K_f ratio = 0.35) can kill seedlings. Due to the high cost per kg (as either N or K), KNO_3 is used primarily by researchers. As a comparison, 5-month-old sweetgum seedlings were 21.8 cm tall when grown without any fertilizer in a silt-loam soil (see Figure 3).

3 Will K fertilization increase growth of bareroot seedlings

Although K does not form any vital organic compounds, studies conducted in greenhouses with either washed sand or hydroponics show that insufficient K can stunt growth of pine seedlings (Pessin 1937; Shear et al. 1953; Pwrnell 1958; Goslin 1959; McGee 1963; Marx et al. 1977; Michniewicz and Stopińska 1980; Smethurst et al. 2007). At a sandy nursery, height of loblolly pine was correlated (Pearson-r = 0.77) with soil K (South et al. 2018) and in a greenhouse trial, adding KCl increased height by 1.4 cm (or 6%) (Rowan 1971). However, positive growth responses to KCl or K_2SO_4 may not occur when bareroot pine seedlings are growing in nursery soil (Flaten 1939; Auten 1945; Rosendahl and Korstian 1945; McComb and Griffith 1946; Westveld 1946; Schaedle 1959; Steinbeck 1962; Switzer 1962; Stoeckeler and Slabaugh 1965; Hodgson 1977; Manikam and Srivastava 1980; South and Donald 2002). Adequate amounts of K in bareroot seedbeds makes it difficult to define the "hidden hunger" zone for bareroot stock (Wahlenberg 1930; Will 1978; van den Driessche 1984; van den Driessche and Ponsford 1995; Landis and Davey 2009). Apparently, several nursery soils in the southern United States contain enough K to support adequate seedling growth. Even so, some managers report an increase in height growth after applying KCl to seedlings in June.

Although fertilizing with N plus K can increase root-collar diameter of slash pine (Mead and Pritchett 1971), there are no data from nurseries to show K fertilization increases the root-collar diameter of pine seedlings (Westveld 1946; Steinbeck 1962; Hodgson 1977; Hinesley and Maki 1980; South and Donald 2002). When biomass is increased with K_2SO_4 fertilization (Hodgson 1977; McKee 1978; Browder et al. 2005b), the growth increase might be due to correcting a S deficiency (Lyle and Pearce 1968; Will and Youngberg 1978; Browder et al. 2005b). Perhaps some researchers incorrectly assumed that K increased growth when a S deficiency was corrected by a K_2SO_4 treatment.

When pine seedbeds contain less than 35 $\mu g\ g^{-1}$, a growth response from KCl fertilization might occur. For example, a sterile soil with 30 $\mu g\ g^{-1}$ K was used to grow loblolly pine seedlings in containers in a greenhouse (Marx et al. 1977). When the N level (in fertigation solution) was 300 $\mu g\ g^{-1}$, adding KCl (100 $\mu g\ g^{-1}$ K) increased seedling mass by 50% (13 weeks after sowing). However, it is not known if some of the increase was due to Cl (Browder et al. 2005a; Nowak and Friend 2006; Heckman 2007) or if the response was entirely due to K.

For hardwoods, K fertilization will sometimes increase growth when roots are in water (Murphy and McAdoo 1969; Houman et al. 1990) or when seedlings are grown in pots containing sand (Rosendahl 1943; Browder et al. 2005b; Foulger et al. 2007; Whittier 2018). In contrast, K fertilization typically has no positive effect on hardwoods when soil contains some silt and clay. In a loam soil, growth of American elm (*Ulmus americana* L.) and green ash (*Fraxinus pennsylvanica* Marsh.) was not increased when seedlings were fertilized with 124 to 217 kg ha^{-1} of K (McComb 1949). Likewise, some hardwoods did not respond to K fertilization in greenhouse trials (Phares 1964; 1971; Bjorkbom 1973; Hannah 1973; Radwan and DeBell 1994; Andivia et al. 2011; Perez et al. 2016). In some trials, too much K fertilization decreased height growth of hardwoods (Martin and Bingham 1954; Phares 1964; Cutter and Murphey 1978; Brown et al. 1981 Whittier 2018). These results with container-grown seedlings support the following studies established in bareroot nursery soils.

In North Carolina, trials were conducted on a silt loam soil at the Edwards Nursery and on a sandy loam at the Murfreesboro Nursery (Deines 1973). Growth of green ash was not affected by KCl fertilization. At lifting, the foliar K mass was not significantly different, suggesting soil K levels at time of sowing were enough to "satisfy the plants' needs." Similar results occurred at the Edwards Nursery (Figure 3).

Subsequent fertilizer trials were conducted at six nurseries (224 kg ha^{-1} KCl before sowing plus 224 kg ha^{-1} of KCl as top-dressings) (South 1975). These treatments had no effect on growth of sycamore (*Platanus occidentalis* L.) at six nurseries and had no effect on sweetgum (*Liquidambar styraciflua* L.) at five nurseries. Out of fifteen tests (Deines 1973; South 1975), K fertilization increased height growth in just one test (i.e., height of sweetgum was increased by 7.5 cm). Top-dressings of K are not required to grow plantable sweetgum or sycamore when seedbeds contain more than 27 µg g^{-1} K at time of sowing (South 1975).

4 K application before sowing

It was once common to incorporate N into seedbeds several weeks before sowing pine (Table 3) and some managers continue this practice. However, when using non-fumigated soil, N fertilization can increase damping-off (Auten 1945; Tint 1945; Richards and From 1965; Rowan 1971) and therefore researchers started to recommend N be applied after sowing (Barnett and Brissette 1986; Triebwasser and Altsuler 1995; Landis and Davey 2009). Likewise, fertilizing with KCl or K_2SO_4 before sowing can be wasteful (Davey 2002), especially on sandy nursery soils. Although applying KCl before sowing will reduce risk of foliar injury from applying top-dressings without irrigation, inefficiency results due to leaching prior to seed germination. For example, at one nursery, applying K_2SO_4 before sowing resulted in only 13 µg g^{-1} of K in the sandy soil at sowing (Table 3). With no leaching and no fixation, the expected amount of K should have been at least 78 µg g^{-1}. Excessive leaching due to rain (Krause and Wilde 1960; Bengtson and Voigt 1962) is why some managers do not apply KCl before sowing pine. In contrast, potassium-magnesium sulfate (K-mag) dissolves slower because its particles are denser than KCl. Therefore, some managers apply K-mag (0-0-22% K_2O) before sowing, especially when seedbeds are low in magnesium (Mg).

Although fertilized sandy nurseries may contain about 50 µg g^{-1} of available K at time of sowing, infertile fields may contain less than 30 µg g^{-1} before fertilization (Figure 5). When seedbeds contain 12 µg g^{-1} extractable K, there is apparently no need to apply K before sowing pine seed (Mead and Pritchett 1971; Brendemuehl and Mizell 1978; Davey 2002). Nursery managers have reported no problems when sowing pine seed in peat (Hubbel et al. 2018) or soil that contains 12 to 13 µg g^{-1} K (Table 3). Most sandy nursery soils have more than this amount and "some researchers report that K fertilization is not needed in forest tree nurseries" (May 1985, p 12-22). For example, when soil is used as growing media, some researchers do not add K when applying 200 kg ha^{-1} of N (Walker et al. 2016).

It is known that adding too much KCl to soil before sowing can kill germinating seeds (Hicks 1900; Rosendahl and Korstian 1945; Richards and From 1965). Applying even low rates of KCl before sowing can delay emergence of wheat (*Triticum aestivum* L.), especially when soil moisture is low (Chapin and Smith 1960). Although soaking seed in a solution of $KN0_3$ (prior to sowing) will sometimes improve germination (Heit and Nelson 1941; Biswas et al. 1972; Pitel and Wang 1985) it can also inhibit germination of pine seed (Johnson 1946; Hare 1981) and can increase growth of fungi (Heit and Nelson 1941).

At a silt loam nursery in North Carolina, 672 kg ha^{-1} of KCl was applied two weeks before sowing loblolly pine seed (Rosendahl and Korstian 1945). This high rate reduced height growth and reduced the number of plantable seedlings. Similar results occurred when 744 kg ha^{-1} of KCl was applied before sowing (Steinbeck 1962). Most managers now apply zero to 300 kg ha^{-1} of KCl before sowing while others apply 224 to 336 kg ha^{-1} of K-mag (Leach and Gresham 1983; Irwin et al. 1998; South 2019).

Table 3. Use of potassium (K) fertilizers in pine nurseries in the southern United States prior to 1981 (Marx et al. 1984).

Nursery/State	Year	Sand %	K Fertilizer before sowing	K applied kg ha^{-1}	Soil K µg g^{-1}	K Fertilizer after sowing	K applied kg ha^{-1}	Total K kg ha^{-1}	N/K$_f$ ratio
Buckeye/FL	1977	95	5-10-15	98	26	KCl**	17	115	1.7
Andrews/FL	1977	94	K_2SO_4	153	13	K_2SO_4*	131	284	0.8
Buckeye/FL	1978	94	5-10-25	163	59	KCl**	37	200	0.4
Ft. Towson/OK	1978	91	10-20-10	46	67	-	0	46	6.0
Ft. Towson/OK	1977	89	10-20-10	46	31	KCl***	168	214	2.0
Great Southern/GA	1977	89	0	0	42	KCl*	72	72	1.6
New Kent/VA	1977	89	KCl?	130	136	-	0	130	1.4
New Kent/VA	1978	88	KCl	130	34	-	0	130	2.7
Buckeye/FL	1979	88	10-10-10	65	30	10-10-10*	9	74	2.2
Buckeye/FL	1980	88	10-10-10	65	25	KCl**	28	93	1.6
Champion/SC	1980	88	10-10-10	80	49	KCl*+ K_2SO_4*	88	168	1.2
Magnolia/AR	1977	87	10-20-20	93	41	-	0	93	3.5
Westvaco/SC	1978	86	10-10-10	93	41	KCl*	56	149	1.7
Champion/SC	1979	86	10-10-10	93	12	KCl*	56	149	2.0
Westvaco/SC	1980	86	10-10-10	74	49	KCl*	56	130	1.2
Griffith/NC	1977	84	8-8-8	37	95	-	0	37	2.9
Great Southern/GA	1978	84	10-10-10	46	61	KCl*	70	116	1.2
Westvaco/SC	1977	83	10-10-10	74	132	KCl*	56	130	3.3
Magnolia/AR	1978	83	10-20-10	28	59	KCl**	112	140	0.7
Ashe/MA	1977	81	13-13-13	6	81	-	0	6	6.2
Beauregard/LA	1977	79	KCl	167	104	-	0	167	0.4
Beauregard/LA	1978	69	0-0-22	81	87	-	0	81	1.8
Edwards/NC	1978	67	10-10-10	33	62	K_2SO_4*	70	103	1.5
Kentucky Dam/KY	1977	66	15-15-15	42	110	-	0	42	3.0
Waynesboro/MS	1978	65	KCl?	144	159	-	0	144	0.5
Kimberly Clark/AL	1977	53	10-10-10	56	160	15-10-15*	21	77	3.3
Hiwassee/GA	1979	51	20-20-20	93	55	-	0	93	2.2
Kimberly Clark/AL	1978	48	10-10-10	56	119	-	0	56	2.9
Oklahoma State/OK	1978	47	0	0	130	15-15-4*	4	4	56.4
Pinson/TN	1977	42	13-13-13	67	89	-	0	67	1.1
International/MS	1979	15	6-12-12	45	69	KCl**	68	113	3.9
Meadian values	--	84	--	65	61	--	56	113	1.8

* = one top-dressing; ** = two top-dressings; *** = three top-dressings
Fertilizer code = (N-P_2O_5-K_2O)

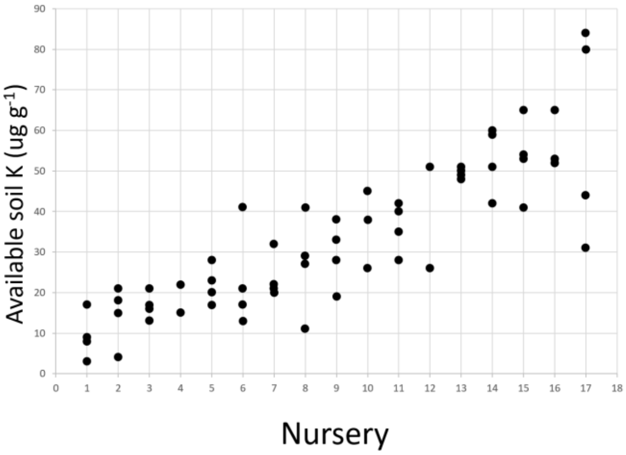


Figure 5. Pre-fertilization soil test results for available K (Mehlich 3) from 17 nurseries. Each dot represents the lowest reported value for a particular year (two, three or four years per nursery). Nurseries are ranked from the lowest soil K (#1) to highest (#17). Course textured soils have numbers below 11 while higher numbers represent finer textured soils. After fertilization (at time of sowing), the average K value for sandy nurseries is about 54 µg g^{-1} K and the average for finer-textured nurseries is 105 µg g^{-1} K.

5 K application after sowing

From a nutrient use efficiency perspective, applying K after seedlings emerge makes more sense than treatments before sowing (Andrews 1941). The rate of K applied after sowing varies and the total amount may average about 61 kg ha^{-1} (Table 3). Applications to bareroot seedbeds (12 kg ha^{-1} K) may begin six to eight weeks after sowing while at container nurseries applications start about 2 to 4 weeks after sowing (Barnett and Brissette 1986; Dumroese and Wenny 1997). Auten (1945) stated that K "should be applied only in moderate quantities and after seedling emergence" since too much K can kill seedlings (Bjorkbom 1973).

In Alabama, extra KCl (300 kg ha^{-1}) applied in October did not affect seedling growth in the nursery (South and Donald 2002) and this rate also did not affect growth in four tests in Georgia (Rowan 1987). In another trial, KCl (310 kg ha^{-1}) was applied to 3-month-old loblolly pine and seedlings were measured eight months after sowing. When N was applied, the early KCl fertilizer treatment had no effect on shoot biomass (Hodgson 1977). So far, there are no data to support the belief that K fertilization after sowing improves the growth of pine seedlings in nursery seedbeds.

K top-dressings made in late-summer or fall was a common operational practice (Table 3), but it was "not based on a proven need for seedling survival and growth" (Rowan 1987). In one trial, growth of loblolly pine was reduced when 310 kg ha^{-1} of KCl was applied eight months after sowing (Hodgson 1977). Several researchers have demonstrated that pine seedings can grow well without applying any K in the fall (May 1957a; Dierauf 1982; Rowan 1987; Wall 1994; South and Donald 2002). Brendemuehl and Mizell (1978) said that after fertilizing with 66 kg ha^{-1} of K (during June and July) there was no need to apply additional K after August 10. At some bareroot nurseries, the amount of K in pine foliage at lifting is high (e.g. 1.9% K) due to routine use of K on fertile soils (Rowan 1987).

6 K source is important

"Some researchers report that K fertilization is not needed in forest tree nurseries" (May 1985, p 12-22) since several trials indicate it does not benefit seedling growth. However, the source of K is important even when K fertilization does not benefit seedling growth. This is because fertilizer source affects growing costs at nurseries that apply K to seedbeds (Table 4). For example, applying KNO_3 is a "waste of both time and money" (Davey 2002). Growers in the western United States prefer to use K_2SO_4 (Auten 1945; Triebwasser and Altsuler 1995; Landis 2005) while those in the southern United States favor KCl simply because it costs less per kg (Edwards 1986) and is more readily available [it is said that KCl makes up 95% of the K fertilizers used annually]. From a survey of 19 nursery managers, eight applied KCl to pine seedbeds, three applied top-dressings of K_2SO_4 and one applied K-mag (Table 3). In other countries, about half of nursery managers prefer to apply K_2SO_4 (Donald 1991).

Table 4. Various potassium (K) fertilizer materials and their relative cost (2018).

Compound	Formula	Fertilizer code	K%	Form	Example $ per tonne	$/kg K
Potassium chloride	KCl	0-0-60	50	granular	435	0.87
Potassium chloride	KCl	0-0-62	51	granular	529	1.04
Potassium chloride	KCl	0-0-10	8	liquid	132	1.65
Potassium sulfate	K_2SO_4	0-0-50	41	granular	882	2.15
K magnesium sulfate	$K_2SO_4{}2MgSO_4$	0-0-22	18	granular	441	2.45
Potassium hydroxide	KOH	0-0-83	69	granular	2346	3.40
Potassium thiosulfate	$K_2S_2O_3$	0-0-25	21	liquid	735	3.50
Potassium nitrate	KNO_3	13-0-44	37	granular	1764	4.46
Potassium nitrate	KNO_3	3-0-12	10	liquid	485	4.59
Mixture	$KCl + K_2SO_4{}2MgSO_4$	10-10-10	8	granular	468	4.75
Potassium phosphate	KH_2PO_4	0-52-34	28	granular	1372	4.90
Potassium carbonate	K_2CO_3	0-0-30	25	liquid	2425	9.70
Potassium sodium nitrate	$KNa(NO_3)_2$	15-0-14	12	granular	1530	11.65
Potassium acetate	CH_3CO_2K	0-0-29	24	liquid	7172	29.80
Potassium silicate	K_2O_3Si	0-2-12	10	liquid	5070	50.70

Price per kg of K assumes no value for Cl, Mg, Na, P, S, and Si and $0.88 per kg of N. Fertilizer code = (N-P_2O_5-K_2O)

Some nursery managers apply K-mag as a top dressing at a rate of 224 kg ha^{-1} (Marx et al. 1989). An advantage of K-mag is that it supplies three nutrients (S, K, Mg) instead of only two. At some nurseries, K-mag is applied before sowing at rates as high as 448 kg ha^{-1}. If we place the value of S at $0.5/kg and Mg at $3/kg, then K-mag is the least expensive K source.

Applying an excessively high rate of KNO_3 can kill seedlings (Figure 4) and too much KCl can injure young seedlings (Rosendahl and Korstian 1945; Steinbeck 1962; Rowan 1971; Deines 1973; South 1975; Hodgson 1977). Therefore, some managers apply K_2SO_4 to avoid any potential problems with chloride ion on sensitive species (Deines 1973; Callan and Westcott 1996).

It may seem obvious but when applied at rates that are low enough, there will be no difference in seedlings between KCl and K_2SO_4 for either loblolly pine (Dierauf 1982; Rowan 1987) or hardwood seedlings (Deines 1973; South 1975). However, when applying high rates of K, hardwoods seedlings usually grow better when fertilized with K_2SO_4 (Deines 1973; Browder et al. 2005b). In situations where fumigated soil is very warm during seed germination, KCl fertilization (before sowing) might increase damping-off (Rowan 1971).

7 Liquid K fertilization

At one time, many managers applied K as concentrated granular formulations but now most K top-dressings are applied as liquid solutions. Lunt (1938) said "It is very easy to over-fertilize seedlings, particularly with concentrated, soluble materials. In the light of the experiences of Mitchell and others (1937) in seedbed work, it is quite probable that more satisfactory results can be obtained from the use of fertilizer if it is applied in frequent, light doses in soluble form. The seedlings grow so slowly that excess soluble fertilizer is either leached out before it is taken up, or, if too concentrated, it injures the seedlings." Many growers agree with Lunt and apply light doses of liquid fertilizers and irrigate seedlings soon after each application. At one nursery, ten weekly applications of KCl (24 kg ha^{-1} per application) were made starting on June 1.

Some nursery managers purchase KCl (0-0-62) in bags and dissolve the material in warm water (5 to 1 ratio) to produce a liquid solution (e.g. 0-0-10.3). This saves on the cost of shipping water to the nursery. When this solution is added to liquid N solutions, the process eliminates one or more fertilizer applications. An alternative is to purchase liquid 10-0-4 directly from the fertilizer dealer at a higher cost per kg of K (Table 4).

8 Does K fertilization increase survival of pine seedlings after planting?

In a review of the literature (van den Driessche 1991), N-P-K fertilizers increased survival of pine in half of the 12 cited studies. However, studies show that extra KCl (or KNO_3) fertilization does not increase the chance of survival of pines after planting (Bryan 1954; Ursic 1956; Switzer 1962; Hinesley and Maki 1980; Dierauf 1982; Rowan 1987; South and Donald 2002). Research in other regions with bareroot (Gleason et al. 1990) and container-grown pine seedlings also supports a no survival benefit from K fertilization (van den Driessche 1992; del Campo et al. 2011b). As a result, the level of potassium in foliage is not considered to be important attribute for seedling survival (Grossnickle 2012).

In some cases, applying K can reduce survival especially when environmental conditions do not favor high survival. In one year, applying 372 kg ha^{-1} of KCl reduced survival of stored pine seedlings by 10 to 13% (Dierauf 1982). In another trial, N (179 kg ha^{-1}) plus KCl (372 kg ha^{-1}) were applied to bareroot loblolly pine seedlings over an 8-day period in January (Ursic 1956). Seedlings were lifted a month later (February 15), were planted on February 16-23, and survival of fertilized seedlings was reduced by 12%. The high rate of Cl (186 kg ha^{-1}) in both trials might have reduced the ability of seedlings to produce new roots (Donald 1988). Several factors can affect seedling survival (Grossnickle 2012) and a few authors imply that K affects root growth, freeze tolerance, drought tolerance, etc.

8.1 Root growth potential (RGP)

In theory, if a sub-sample of pine seedlings produces more roots in a greenhouse, the chance of survival after outplanting for the entire population is increased (Larsen et al. 1988). Data with bareroot pine seedlings indicate that extra Cl in operational fertilizer (applied just prior to the winter equinox) likely reduced the RGP of seedlings lifted 14 to 42 days later (Donald 1988). When fertilized with 593 mg of superphosphate per seedling, extra K_2SO_4 also reduced RGP (Figure 6). Extra KCl fertilizer applied at other bareroot nurseries did not result in more root growth four weeks after transplanting (Bryan 1954; Switzer 1962). Therefore, when nursery soil already contains more than 200 µg g^{-1} K, adding more K is unlikely to increase RGP and foliar K concentrations (Birchler et al. 2001). Results with container-grown pines also indicate RGP is not increased when seedlings are fertilized with either extra KCl (van den Driessche 1992) or extra K_2SO_4 (Del Campo et al. 2011b). It is known that applying too much fertilizer at time of transplanting can reduce root growth (Jacobs et al. 2004) and kill pine seedlings (Wakeley 1954).

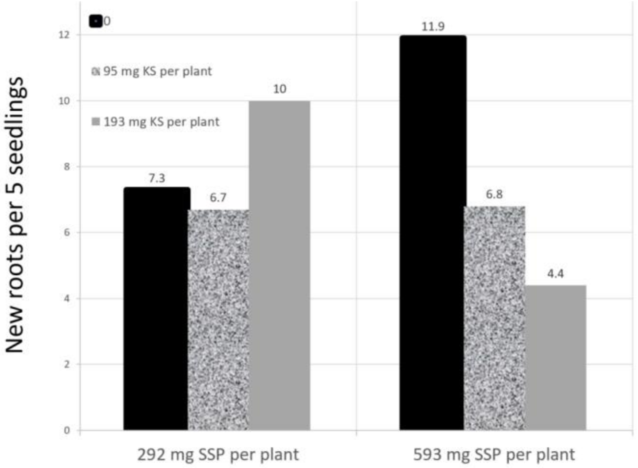


Figure 6. The effect of K_2SO_4 (KS) and single superphosphate (SSP) on root growth potential (RGP). A factorial fertilizer study tested the effects of three fertilizers on RGP of bareroot pine seedlings (Donald 1988). Fertilizers included KS, and SSP (which contains P, Ca and S) and lime ammonium nitrate (LAN) (which contains N, Ca, and Mg). Fertilizer rates are listed as mg per seedling with 100 mg equivalent to 133 kg ha^{-1}. During the 5 months after sowing, seedlings were fertilized with twice as much K as N and this was followed by wrenching and undercutting for an additional 3 months. Prior to the winter equinox, a 3x3x3 LAN-SSP-KS factorial study was installed and seedlings were tested for RGP at 2-week intervals. A statistical analysis revealed a significant SSPxKS interaction that indicated K_2SO_4 reduced RGP when seedlings were well fertilized with SSP. Least significant difference = 2.37 roots (α=0.05). There was also a significant LANxSSP interaction (data not shown).

8.2 Freeze tolerance

Although some authors claim that K plays an important role in freeze tolerance (Leaf 1968; Baule and Fricker 1970; Knight 1981), there are no data from the southern states to show fall fertilization with KCl increases freeze tolerance or survival of pines (Hinesley and Maki 1980; Dierauf 1982; Rowan 1987; van den Driessche 1992; South et al. 1993; Landis 2005). Others report that K% in shoots of pine is not related to frost hardiness (Christersson 1975; Aronsson 1980). Fall fertilization with K does not increase freeze tolerance of several other conifers (Benzian et al.1974; Gleason 1989; van den Driessche 1991; Birchler et al. 2001). Fertilization of broadleaf trees with K_2CO_3 (Jozefek 1989) or KCl (Sakai 1962; Williams et al. 1974; Fernández et al. 2007; Andivia et al. 2011) did not increase freeze tolerance but KCl reduced electrolyte leakage in young leaves of some tropical hardwoods (Gómez-Ruiz et al. 2016). Sometimes mature trees fertilized with high rates of K are less cold resistant (Koo 1985).

Those who claim that additional K fertilization in bareroot seedbeds "hardens" pines against cold temperatures (Wilde 1946; Stoeckeler and Slabaugh 1965; Baule and Fricker 1970) cite Kopitke (1941) who assumed it would be beneficial. However, Kopitke did not report any relationship between foliar K levels in pine seedlings and freeze injury. The idea that K increases freeze tolerance of southern pines is based on flawed assumptions (using data from a single, non-replicated study with two northern pines that were not statistically analyzed). In fact, when soil (containing 42 $\mu g\ g^{-1}$ K) was treated with 100 kg ha^{-1} of K (before sowing), Kopitke found no difference in the freezing value of sap (sampled in June) of eastern white pine (*Pinus strobus* L.). For some species, KCl has no preventive effect because of the toxic action of KCl upon cells (Sakai 1962).

Beattie and Flint (1973) said "Potassium levels within or below the optimum range for growth are necessary for full development of frost hardiness, but higher levels are of no benefit, and may reduce hardiness." Indeed, for some conifers there exists a negative relationship between K levels and freeze tolerance (Menzies et al. 1981; Gleason 1989; South et al. 1993; Sarjala et al.1997; Jalkanen et al. 1998; Jokela et al. 1998; Fløistad and Kohmann 2004; del Campo et al. 2011b).

It is important not to confuse the benefits of N fertilization with that from K fertilization. For example, KNO_3 can increase freeze tolerance of pine seedlings (Ramírez-Cuevas and Rodríguez-Trejo 2010) but the increased tolerance is likely due to improved N status (Taulavuori et al. 2014). Others have demonstrated that N fertilization can increase freeze tolerance (Benzian 1966; Williams et al. 1974; Dumroese 2003; Fernández et al. 2007; Islam et al. 2008; Davis et al. 2011; Andivia et al. 2012).

It is also important not to confuse the symptoms of K deficiency with symptoms of freeze injury. Simply assuming that purple and/or necrotic needles are the result of freeze injury is not sufficient evidence that freeze injury occurred. In fact, freeze injury to roots of pines can occur without any change in appearance of foliage (South 2007).

8.3 Drought tolerance

When container-grown conifer seedlings are deficient in K (< 0.4% K in needles), some authors find a relationship between drought tolerance and K in needles (Christersson 1976; Larsen 1978). However, when needles contain more than 0.4% K, there is no evidence to support the claim that additional KCl improves drought tolerance of southern pine seedlings in plantations. No increase in seedling quality was observed at a sandy field site in Alabama where seedling survival after three years was less than 75% (South and Donald 2002) and similarly, no benefit was observed at a site in Georgia where first year survival ranged from 45 to 57% (Rowan 1987). Others also report no effect of K_2SO_4 or KCl on drought tolerance of conifers (Jopson and Paul 1985; Kam et al. 1991; van den Driessche 1992; Del Campo et al. 2011b). Extra KCl reduced transpiration of mahogany (*Khaya senegalensis* A. Juss.) seedlings (Perez et al. 2016) but extra K_2SO_4 did not affect tree biomass or water use efficiency when hardwoods were subjected to drought conditions (Harvey and Van den Driessche 1999; Silva et al. 2004). Extra N is more likely to increase drought tolerance than extra K (Stoeckeler and Arneman 1960; van den Driessche 1992).

Early work suggested pine seedlings fertilized with KH_2PO_4 retained more moisture (after three days of exposure to artificial drought), but survival was not measured (Shirley and Meuli 1939). Did others assume this study proved K fertilization increased drought tolerance? A trial at a Wisconsin nursery found no improvement in drought tolerance when seedlings were treated with 134 kg ha^{-1} of K (Stoeckeler and Arneman 1960).

8.4 Disease resistance

Fertilization with K can have mixed effects on diseases of agronomic crops (Perrenoud 1990). Dordas (2008) said "Potassium decreases the susceptibility of host plants up to the optimal level for growth: beyond this point, there is no further increase in resistance which can be achieved by increasing the supply of K and its contents in plants (Huber and Graham 1999)." This trend also appears to be true for conifer seedlings. Although applying K_2SO_4 can reduce the length of fungal lesions formed on potted pine seedlings with less than 0.4% K in needles (Kam et al. 1991), extra K fertilization appear to have little effect when foliage contains more than 0.5% K.

In greenhouse studies, KCl fertilization did not affect either root-rot index (Rowan 1971) or rust infection of pine seedlings (Rowan and Steinbeck 1977). Vaartaja (1956) found that KNO_3 in Petri dishes was ineffective in suppression of disease organisms or was effective only at concentrations toxic to pine seed. Likewise, KCl was ineffective in reducing the length of fusarium cankers on pine seedlings (Fraedrick and Witcher 1982) but it did reduce needle cast of pine in pots (Chung and You 1970). KNO_3 fertilization of pines had no effect on *Fusarium circinatum* (Hans 2013) and KCl fertilization did not decrease *Anthracnose* disease of black walnut (*Juglans nigra* L.) (Neely 1981). At a site where Douglas fir (*Pseudotsuga menziesii* (Mirb) Franco var. *menziesii*) was infected with *Armillaria* root rot, K fertilization (without N) reduced diameter growth (Moore et al. 1994). Since Cl has some disease controlling properties (Russell 1978; Trolldenier 1985; Datnoff et al. 2006) and seedlings fertilized with KCl contain higher levels of Cl (Birchler 1997), it seems there is no proof that K has any disease prevention ability on bareroot seedlings. In fact, applying KCl (prior to a freeze) can increase the growth of *Botrytis* on pine seedlings (South et al. 1993).

K-iodate has some fungicidal properties (Chen 1995) and some K-fungicides have been used operationally in nurseries. K-metabisulfite has been used to treat hydromulch (once used as a packing material) to increase survival of loblolly pine seedlings (Rowan 1982). Likewise, one container nursery in Georgia used K-bicarbonate in an attempt to reduce the probability of diseases occurring in southern pines stored at 2°C (Dumroese and Barnett 2004).

At an ornamental nursery, K-bicarbonate controlled powdery mildew on dogwood (*Cornus florida* L.) seedlings (Hagan et al. 2003) but the recommended rate cost more than \$3,000 ha^{-1} (336 kg ha^{-1} of product). In a study with greenhouse-grown slash pine, KCl or K_2SO_4 (approximately 20 Mg ha^{-1}) reduced the colonization of *Rhizoctonia* (Huang and Kuhlman 1991). However, a rate of KCl this high (before sowing) would cost more than \$8,000 ha^{-1} and would produce negative effects on seedling production.

8.5 Thickness of cell walls

Some authors believe that bareroot pine seedlings (grown in soil with adequate K) will have thicker cell walls when fertilized with extra K but data to support this belief are lacking. In fact, for 5 m tall Scots pine (*Pinus sylvestris* L.), there was no effect of K fertilization on cell wall thickness of either newly formed needles or one-year old needles (Jokela et al. 1997). However, the thickness of Sclerenchyma cell walls was smaller for trees growing in K-deficient soil. Without data, researchers should not make claims about K fertilization increasing cell wall thickness of 1-0 pine seedlings (even when foliar K levels are at 0.3%).

8.6 Bud formation

Some say fall fertilization with K can assist in growth cessation and bud development (Glerum 1985) but this practice had no effect on bud formation of loblolly pine (Rowan 1987) and slash pine (South et al. 1993). In fact, applying 150 kg ha^{-1} of K to seedlings in October delayed bud formation of loblolly pine (South et al. 1993). At one slash pine nursery, 42% of the seedlings treated with K-mag (270 kg ha^{-1} in July plus 270 kg ha^{-1} in October) had unformed buds (or growing buds) in January (Irwin et al. 1998). In greenhouse trials with container-grown seedlings, increasing the amount of K_2SO_4 did not affect bud formation when shoots contained 1% K (Timmis 1974). Likewise, adding KH_2PO_4 to seedlings has no effect on bud formation (Fløistad and Eldhuset 2017). There is no scientific evidence to indicate K fertilization assists in bud development of non-deficient pine seedling.

8.7 Root growth

Although some believe K fertilization will encourage root growth, there are no data to show that K fertilization will increase root growth in bareroot nurseries. Extra fertilization with KCl did not increase root growth of loblolly and shortleaf pine seedlings (Auten 1945; Rowan 1971; Hodgson 1977; South and Donald 2002) or sweetgum, sycamore or green ash seedlings (Deines 1973). Fertilization with KNO_3 (160-320 kg ha^{-1}) in October reduced root growth of longleaf pine seedlings (Hinesley and Maki 1980). When grown in containers, extra K fertilization increased root growth of eucalyptus (Silva et al. 2004) but did not increase root growth of oak seedlings (Andivia et al. 2011, 2014) or Douglas fir seedlings (Shaw et al. 1998).

8.8 Ectomycorrhiza

Non-mycorrhizal roots can take up K (van Rees and Comerford 1990; Plassard et al. 2002). Therefore, in seedbeds, non-mycorrhizal pine seedlings typically have adequate levels of K but are deficient in P. For example, needles of non-mycorrhizal loblolly pine seedlings (sampled in July) had more than 0.9% K but were deficient in P (South et al. 1988) and similar results were observed at two other nurseries (South et al. 2018). Since extra root growth in the field can result in more uptake of K (van Rees and Comerford 1990), the uptake of K (i.e., mg K $seedling^{-1}$) can be less for smaller, non-mycorrhizal roots (Garcia and Zimmerman 2014). Although ectomycorrhiza formed in 100% sand in greenhouses can increase the concentration of K in pine foliage (Rosendahl 1943), mycorrhiza typically does not increase K concentrations in foliage when pine or hardwood seedlings are grown in soil (Mitchell et al. 1937; Rosendahl 1943; Marx et al. 1977; Schultz et al. 1979).

9 Does extra K in nursery increase growth of pine seedlings in the field?

The growth of planted pines can be correlated with nutrient status of needles (on trees 9 to 19 years old). For loblolly pine stands, the correlations coefficients (Pearson-r) between volume growth and foliar N% and P% are 0.36 and 0.29, respectively (NCSFNC 1991). In comparison, the correlation between growth and foliar K% ($r = 0.19$) was not significant ($\alpha = 0.07$). Sometimes researchers report a positive relationship ($r = 0.55$ to 0.73) between K mass (mg seedling^{-1} at planting) and field growth (Mead and Pritchett 1971; Shi et al. 2018) but this should be expected in studies where seedling size at planting is positively related to early growth in the field (Grossnickle and MacDonald 2018). Because they contain more biomass, larger bareroot pine seedlings typically have greater K mass even when K% in foliage is slightly lower in larger seedlings (South et al. 2018). Furthermore, correlation does not imply causation. No significant relationship was found for K% in needles (at planting) and early growth (Mead and Pritchett 1971; Hinesley and Maki 1980; Larsen et al. 1988; 1989; Puértolas et al. 2003, Grossnickle and MacDonald 2018).

Data from nineteen trials indicate that K fertilization, after sowing, does not increase growth of pine seedlings in the field (Bryan 1954; Switzer 1962; Autry 1972; Hinesley and Maki 1980; Dierauf 1982; Rowan 1987; South and Donald 2002). However, an October application of KCl may have increased growth of non-stored loblolly pine seedlings that were outplanted on a loamy site in Alabama (South and Donald 2002). The K fertilized seedlings had a higher foliar N% (equal to that of N fertilized seedlings) and this may explain the extra growth since N levels in pine foliage are related to additional growth after planting (Larsen et al. 1988; Irwin et al. 1998; Jackson et al. 2012). As expected, seedlings stored for six weeks before planting did not benefit from the extra K fertilization.

At a nursery in North Carolina, an increase in field growth was measured (control vs K only) but it was not biologically meaningful (Bryan 1954). After one season, the K-fertilized seedlings were 18 cm tall while operationally fertilized seedlings were 17.3 cm tall. A critical examination revealed that two of the K-fertilized treatments were confounded with N and P treatments. As a result, the conclusion that a 7 mm increase was statistically significant was due to a flaw in the method of hypothesis testing. Maki (1950) reported that “potash” fertilization in the nursery resulted in “more vigorous seedlings” in the field, but he provided no data and did not define the chemical makeup of “potash”.

10 N/K ratios

For more than 70 years experts have disagreed about the relative amounts of N and K to apply to bareroot seedlings (Westveld 1946). Since there are five types of N/K ratios, some disagreement might arise from applying different methods to calculate the ratio. The N/K_h ratio is based on amounts of nutrients harvested per ha (based on “equilibrium fertilization”). Loblolly pine and red oak have N/K_h ratios of about 1.2 and

2.1, respectively (Boyer and South 1985; Struve 1995). The N/K_p ratio is based on nutrient percentages in needles (Timmis 1974; Ylimartimo 1990) and can be about 1.5 for pine seedlings (Boyer and South 1985; Landis 2005). The N/K_s ratio is based on soil tests and therefore can vary from 0.25 to 15. Nursery managers calculate a N/K_f ratio by dividing the total amount of N applied by the total amount of K applied. Some managers grow pines using a 2 to 6 N/K_f ratio while a few managers apply less N than K (Table 5). Ideally the N/K_f should be based on fertilizer trials and should not be based on assumptions and guesses.

Table 5. Selected examples of the use of nitrogen (N) and potassium (K) to grow pines in bareroot nurseries. The N/K_f ratio is determined by dividing the total amount of N applied by the total amount of K applied. There are no data to show that bareroot pines do not grow well with a N/K_f ratio of 2 to 4 (when N = 200 kg ha^{-1}).

Species	**kg ha^{-1}**	**kg ha^{-1}**	**N/K_f Ratio**	**Reference**
	N	K		
Pinus taeda	185	24	7.7	Greene and Britt 1998
Pinus resinosa	242	36	6.7	Islam et al. 2008
Pinus taeda	218	39	5.6	Stone 1986
Pinus taeda	205	46	4.4	Marx 1990
Pinus palustris	392	90	4.4	Hinesley and Maki 1980
Pinus palustris	250	66	3.8	Hatchell 1985
Pinus strobus	125	48	2.6	Bickelhaupt et al. 1987
Pinus elliottii	106	41	2.6	Marx et al. 1989
Pinus taeda	224	93	2.4	May 1984
Pinus taeda	110	60	1.8	Vanderschaaf and McNabb 2004
Pinus taeda	179	108	1.7	South et al. 2017
Pinus elliottii	215	123	1.7	Simpson 1985
Pinus taeda	143	88	1.6	Leach and Gresham 1983
Pinus strobus	180	112	1.6	Dobrahner et al. 2007
Pinus palustris	352	227	1.6	Trejo et al. 2003
Pinus caribaea	188	120	1.6	Ward and Johnson 1985
Pinus taeda	171	112	1.5	South and Donald 2002
Pinus elliottii	67	51	1.3	Marx et al. 1986
Pinus elliottii	194	168	1.2	Irwin et al. 1998
Pinus taeda	134	112	1.2	Marx and Artman 1978
Pinus taeda	157	156	1	South et al. 2015
Pinus elliottii	128	165	0.8	Berry 1980
Pinus elliottii	101	167	0.6	Munson and Stone 1984
Pinus elliottii	50	88	0.6	McNabb 1985

The practice of applying high rates of K to seedbeds in the United States might be traced back to flawed assumptions made about N/K_s ratios calculated from virgin soils in Wisconsin and Minnesota (Wilde 1938). Professor Wilde (1946; p. 195) wrote that a nursery with an N/K_s ratio of 0.25 would produce “vigorous well-balanced stock.” Wilde published a Germen version of his textbook (Forstliche Bodenkunde) in 1962 and his graduate student (Dr. Davey) continued to recommend more K fertilizer than most other soil scientists (Figure 7).

For bareroot seedbeds with more than 80% sand, the median N/K_s ratio at sowing was 6.9 (Marx et al. 1984) and at least one sandy nursery had a N/K_s ratio of 15 (Lyle 1960). Therefore, the N/K_s ratio of 0.25 (Wilde 1938, 1946) is far from desired for sandy bareroot nurseries and there is no scientific evidence to support such a low N/K$_s$ ratio.

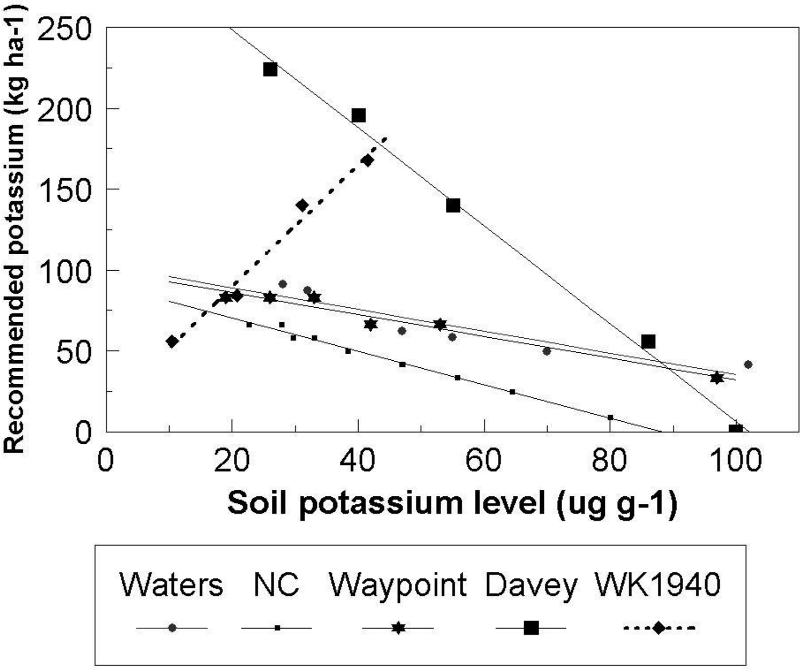


Figure 7. Soil tests (x-axis) are used as a tool for making potassium (K) recommendations (y-axis). Rates for loblolly pine seedbeds will depend on if recommendations are based on soil cation exchange capacity [dotted line - Wilde and Kopitke (1940)] or on results from soil K extraction tests (solid lines). When soil tests indicated less than 40 µg g^{-1} K, three soil laboratories (Waters, North Carolina and Waypoint) suggest applying less than 100 kg ha^{-1} of K (over the entire growing season).

In the past, 16% of nursery managers (Table 3) applied more K than N, but why? May (1985) recommend pines be treated with a N/K$_f$ ratio of 2.7 (224 kg N and 83 kg K ha^{-1}) and there is no economic reason to justify applying a N/K$_f$ ratio of 0.26 to 0.35 (Brown et al. 1981; Scarratt 1986; Dobrahner et al. 2007). In fact, there is no economic or biological reason to apply more than 100 kg ha^{-1} of K to 1-0 bareroot seedbeds. Although low N/K$_f$ ratios (<1.0) have been used to grow pine seedlings in Austria, Finland, Germany, Indonesia, Norway, South Africa and the USA (Baule and Fricker 1970; Manikam and Srivastava 1980; Young 1981; Donald 1986; Dumroese and Wenny 1997; Rikala and Repo 1997; Juntunen and Rikala 2001; Domisch et al. 2002; Fløistad and Eldhuset 2017) there are no data to support applying more K than N to pine seedlings. In fact, lowering the N/K$_f$ with K_2SO_4 will sometimes reduce the growth of container-grown pines (Srivastava et al. 1979; Del Campo et al. 2011a). Fertilizers with a N/K$_f$ ratio of 0.6 will cost more (vs N/K$_f$ ratio = 2.0) to achieve equal-sized seedlings (Oliet et al. 2004). As a result, some researchers do not even test N/K$_f$ ratios that are lower than 1.0 (Struve 1995; van den Driessche 1997). Although data indicate no benefit to low N/K$_f$ ratios, some managers continue to rely on tradition and over-fertilize with K. This tradition may have started 70 years ago when Wilde (1946) said that fertilizers with a N/K$_f$ ratio of 0.35 "frequently fills exactly the needs of nursery practice".

11 Nursery recommendations

For bareroot nurseries, several methods have been used to determine how much K fertilizer to apply (Landis and Davey 2009). The method is known as "equilibrium fertilization" or "replacement input" has been used in nurseries for over a century. This method adds enough nutrients (or slightly more) to replace the nutrients removed when seedlings are harvested (Lyle 1960; Stoeckeler and Arneman 1960; Baule and Fricker 1970; Simpson 1985; Pritchett and Fisher 1987; Janssen and De Willigen 2006).

A second method involves soil testing which became popular after soils laboratories provided tests for free or at low cost. Although soil K (Mehlich 3) can sometimes account for 49% of the variability in seedling mass (South et al. 2018), others found no relationship between soil-K and seedling mass (Switzer and Nelson 1956; Brendemuehl 1968). As a result, recommendations as to the minimum amount of extractable K required for pines vary from a low of 38 µg g^{-1} to more than 160 µg g^{-1} (Table 6). Deficiencies have been reported when sandy soils contain less than 20 µg g^{-1} K (Mead and Pritchett 1971; Leach and Gresham 1983; Alt et al. 1993).

Table 6. The recommended amount of soil K for growing pine seedlings varies by soil texture, individual and soil extraction method.

Soil texture	Minimum µg g^{-1}	Upper value µg g^{-1}	Reference
Sandy loam; CEC =3	31	-	Wilde and Kopitke 1940
Loamy sand	40	60	May 1984
Loam	40	65	May 1984
Loamy sand; sandy loam	41	83	Stoeckeler and Jones 1957
Sandy loam; CEC =5	42	-	Wilde 1946
Sand; loamy sand	75	-	Davey 1972
Loam	75	125	May 1984
Sand; sandy loam	75	100	Steinbeck et al. 1966
Sand; loamy sand	80	-	Davey 1991
Sandy loam	80	-	Kormanik et al. 1994
Loam; CEC =10	83	-	Wilde 1946
Sand; sandy loam	83	-	Youngberg 1952
Loam; CEC =8	100	-	Briggs 2008
Coarse textured	100	140	Knight 1978
Loam; sandy loam, CEC>10	100	150	Martian 1989
Sand; sandy loam	100	200	Youngberg 1984
Loamy sand; sandy loam	104	-	Stoeckeler and Slabaugh 1965
Sandy clay loam	120	-	Nelson and Switzer 1985

A third, rarely used, method bases the rate of K on the CEC of the soil. Originally, Wilde and Kopitki (1940) stated that less K fertilizer would be needed for low CEC soils because the soil could not retain as many cations as fine-textured soils with higher CEC. As a result, a sandy soil (CEC =1) with 10 µg g^{-1} K would receive perhaps 56 kg ha^{-1} of K while a loam soil (CEC = 8) with 42 µg g^{-1} K would receive about 168 kg ha^{-1} of K. This approach resulted in over-fertilization of K at nurseries with fine-textured soils. In contrast, soil agronomists today recommend less K fertilizer for high CEC soils (Figure 7).

The fourth method utilizes response curves based on foliar tests. Some researchers report that soil tests are ineffective for determining K needs (Khan et al.

2014) and that foliar tests are the only real way to determine nutrient needs (Landis and Davey 2009). For example, soil at lifting may be low in K (< 25 µg g^{-1}) while foliar tests indicate pine needles contain more than 0.7% K (South et al. 2018). Even with no K fertilizers (Table 3), foliage in December may have more than 0.5% K (which is not considered to be deficient). Some managers sample foliage in August and compare the results with expected K levels. K fertilization is applied when the foliar values approach the “hidden hunger” zone. The use of foliar tests should eliminate the production of seedlings with less than 0.4% K in needles in January (Table 3).

Foliar tests can be used to determine the need for late season applications of K (Landis and Davey 2009) and this practice has reduced the overuse of K. At one nursery, fertilized loblolly needles in July 2010 exceed 2% K which is very high (Starkey and Enebak 2012). With no K fertilization a low value in July can be 1.1% and the average July value might be 1.4% K (Figure 5). Without foliar tests, the manager would likely have applied an additional 112 kg ha^{-1} of KCl in August. There are no data to show any benefit to very high K in loblolly pine foliage. In fact, applying too much KCl can retard bud development (South et al. 1993) and may induce a Mg deficiency (Shear et al 1953; Will 1961; Knight 1978).

The scientific method is the best method to determine how much K fertilizer to apply to seedbeds (Landis and Davey 2009). Research trials involving liquid K-acetate (Table 4) could be installed to determine the effect of K fertilization on growth of bareroot seedlings. However, since these tests are relatively expensive and have not been installed (or have not been published), nursey managers have to rely mainly on guesses, assumptions and experience when deciding how much K bareroot seedlings require for optimal economics and growth.

12 Conclusions

A review of the literature results in the following conclusions.

1) For bareroot seedbeds, there is no need for the soil to contain four times as much K as N.
2) There is no need to apply KCl or K_2SO_4 before sowing pines or hardwoods.
3) KCl is commonly used in bareroot nurseries because it is readily available and costs less than K_2SO_4.
4) Use of foliar tests (in August) can reduce routine use of KCl in bareroot nurseries.
5) There are no data to suggest that 1-0 bareroot seedlings need to be fertilized with more than 100 kg ha^{-1} of K.
6) Applying KCl in the fall does not increase freeze tolerance of non-deficient pines.
7) Applying K after the fall equinox does not increase the root growth of pine seedlings and does not increase the ability of seedlings to survive or grow after transplanting.
8) Except for preventing a nutrient deficiency (e.g. foliar K < 0.5%), the benefit/cost ratio is less than 1.0 when applying extra K to soils with adequate K.
9) Applying K does not assist in growth cessation and bud development in bareroot seedbeds.
10) “Hidden hunger” zones are easy to demonstrate using containers filled with 100% sand but hard to demonstrate in seedbeds that contain more than 10 µg g^{-1} available K.

11) Many nursery nutrition papers published this century do not discuss possible K effects and usually do not report K concentrations in foliage.
12) Non-mycorrhizal pines can easily obtain sufficient K from the soil solution.
13) There is much we do not understand about K fertilization in bareroot seedbeds and much of what we do know was discovered during the 20th century.

13 Acknowledgments

I thank Drs. Scott Enebak, Steven Grossnickle, J.B. Jett, Nicky Jones, John Mexal, Risto Rikala and Pedro Villar-Salvador for reviews of draft versions of this manuscript. I also thank Tom Dierauf, Jim Rowan and Derek Donald for using the scientific method to address prevailing myths about K and southern pine seedlings. I also thank Doug Shelburne, Warren Bryant, Trent Miller and Chase Weatherly regarding discussions involving operational use of K in pine nurseries.

14 References

Albaugh JM, Blevins L, Allen HL, Albaugh TJ, Fox TR, Stape JL, Rubilar RA (2010) Characterization of foliar macro-and micronutrient concentrations and ratios in loblolly pine plantations in the southeastern United States. South J Appl For 34(2): 53-64. https://doi:10.1093/sjaf/34.2.53

Albaugh TJ, Fox TR, Cook RL, Raymond JE, Rubilar RA, Campoe OC (2018) Forest fertilizer applications in the southeastern United States from 1969 to 2016. Forest Sci 65(3): 355-362. https://doi:10.1093/forsci/fxy058

Almeida JCR, Laclau JP, de Moraes Goncalves JL, Ranger J, Saint-André L (2010) A positive growth response to NaCl applications in Eucalyptus plantations established on K-deficient soils. Forest Ecol Manag 259(9): 1786-1795. https://doi.org/10.1016/j.foreco.2009.08.032

Alt D, Jacob S, Rau N, Wirth R (1993) Potassium deficiency causes injuries to *Picea pungens glauca* in nurseries. Plant Soil 155(1): 472-429. https://doi:10.1007/BF00025074

Andivia E, Márquez-García B, Vázquez-Piqué J, Córdoba F, Fernandez M (2012) Autumn fertilization with nitrogen improves nutritional status, cold hardiness and oxidative stress response of Holm oak (*Quercus ilex* ssp. *ballota* [Desf.] Samp) nursery seedlings. Trees 26(2): 311-320. https://doi:10.1007/s00468-011-0593-3

Andivia E, Fernández M, Vázquez-Piqué J (2011) Autumn fertilization of *Quercus ilex* ssp. ballota (Desf.) Samp. nursery seedlings: effects on morpho-physiology and field performance. Ann Forest Sci 68(3): 543-553. https://https://doi:10.1007/s13595-011-0048-4

Andivia E, Fernández M, Vázquez-Piqué J (2014) Assessing the effect of late-season fertilization on Holm oak plant quality: insights from morpho-nutritional characterizations and water relations parameters. New Forests 45(2): 149-163. https://https://doi:10.1007/s11056-013-9397-1

Andrews LK (1941) Effects of certain soil treatments on the development of loblolly pine nursery stock. J Forest 39(11): 918-921. https://https://doi:10.1093/jof/39.11.918

Aronsson A (1980) Frost hardiness in Scots pine (*Pinus sylvestris* L.) II. hardiness during winter and spring in young trees of different mineral nutrient status. Studia Forestalia Suecica 155: 1-27.

Auten JT (1945) Response of shortleaf and pitch pines to soil amendments and fertilizers in newly established nurseries in the central states. J Agric Res 70(12): 405-426.

Autry LL (1972) The residual effects of nursery fertilization and seedbed density levels on the growth of 12, 14, and 16 years old loblolly pine stands. MS thesis, Mississippi State University, State College. 59 p.

Barnett JP, Brissette JC (1986) Producing southern pine seedlings in containers. Gen. Tech. Rep. SO-59. USDA Forest Service, Southern Forest Experiment Station, New Orleans, LA: 71 p. https://doi:10.2737/so-gtr-59

Bassaco MVM, Motta ACV, Pauletti V, Prior SA, Nisgoski S, Ferreira CF (2018) Nitrogen, phosphorus, and potassium requirements for *Eucalyptus urograndis* plantations in southern Brazil. New Forest

49(5): 681-697. https://doi:10.1007/s11056-018-9658-0

Baule H, Fricker C (1970) The fertilizer treatment of forest trees. BLV Verlag, Munich.

Beattie DJ, Flint HL (1973) Effect of K level on frost hardiness of stems of *Forsythia* X *intermedia* Zab. 'Lynwood'. J Am Soc Hort Sci 98(6): 539-541.

Bengtson GW, Voigt GK (1962) A greenhouse study of relations between nutrient movement and conversion in a sandy soil and the nutrition of slash pine seedlings. Soil Sci Soc Am J26(6): 609-612. https://doi:10.2136/sssaj1962.03615995002600060027x

Benzian B, Brown RM, Freeman SCR (1974) Effect of late-season top-dressings of N (and K) applied to conifer transplants in the nursery on their survival and growth on British forest sites. Forestry 47(2): 153-184. https://doi:10.1093/forestry/47.2.153

Benzian B (1966) Effects of nitrogen and potassium concentrations in conifer seedlings on frost damage. Rothamsted Experimental Station Report Forestry. 1965: 58-59. https://doi:10.23637/ERADOC-1-60

Berry CR (1980) Sewage sludge affects soil properties and growth of slash pine seedlings in a Florida nursery. In: Lantz CW (ed) Proceedings, southern nursery conference. USDA Forest Service, State and Private Forestry, Atlanta, GA: 46-51.

Bickelhaupt DH, Ulzen-Appiah F, White EH (1987) Effect of horse manure on white pine seedling production in a forest tree nursery. Mis. Pub. 14 (ESF 87-003). Syracuse, NY: State University of New York, College of Environmental Science and Forestry. 20 p.

Binggeli P, Blackstock P, McGill C (2000) Potassium deficiency in conifers on former agricultural land. Quarterly J Forest 94(3): 229-233.

Birchler TM (1997) Fall Fertilization Effects on Douglas-fir Seedling Quality. MS thesis, Oregon State University, Corvallis. 124 p.

Birchler TM, Rose R, Haase DL (2001) Fall fertilization with N and K: effects on Douglas-fir seedling quality and performance. West J Appl For16(2): 71-79. https://doi:10.1093/wjaf/16.2.71

Biswas PK, Bonamy PA, Paul KB (1972) Germination promotion of loblolly pine and baldcypress seeds by stratification and chemical treatments. Physiologia Plantarum 27(1): 71-76. https://doi:10.1111/j.1399-3054.1972.tb01139.x

Bjorkbom JC (1973) Response of paper birch seedlings to nitrogen, phosphorus, and potassium. Research Note NE-157. USDA Forest Service, Northeastern Forest Experiment Station, Upper Darby, PA: 4 p.

Boyer JN, South DB (1985) Nutrient content of nursery-grown loblolly pine seedlings. Circular 282. Auburn University, AL: Auburn University, Alabama Agricultural Experiment Station. 27 p.

Brendemuehl RH (1968) Research progress in the use of fertilizers to increase pine growth on the Florida sandhills. In: Forest Fertilization-Theory and Practice. Muscle Shoals, AL: Tennessee Valley Authority. pp. 191-196.

Brendemuehl RH, Mizell L (1978) Nursery practices for Choctawhatchee sand pine. Tree Planters' Notes 29(1): 8-11.

Briggs RD (2008) Soils and nutrition: a forest nursery perspective. In: Dumroese RK, Riley LE (eds) Proceedings, forest and conservation nursery associations-2007. RMRS-P-57. USDA Forest Service, Rocky Mountain Research Station, Fort Collins, CO: 55-64. https://doi:10.5962/bhl.title.99309

Brissette JC, Carlson WC (1987) Effects of nursery density and fertilization on the morphology, nutrient status, and root growth potential of shortleaf pine. In: Phillips DR (ed) Proceedings, fourth biennial southern silvicultural research conference. GTR-SE-42. USDA Forest Service, Southern Forest Experiment Station, Asheville, NC: 198-205.

Browder JF, Niemiera AX, Harris JR, Wright RD (2005a) Growth of container-grown pin oak and Japanese maple as influenced by sulfur and sulfated micronutrients. HortScience 40(5): 1521-1523. https://doi:10.21273/hortsci.40.5.1521

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

Brown RW, Schultz RC, Kormanik PP (1981) Response of vesicular-arbuscular endomycorrhizal sweetgum seedlings to three nitrogen fertilizers. Forest Sci 27(2): 413-420. https://doi:10.1093/forestscience/27.2.413

Bryan MB (1954) Some effects of winter application of inorganic fertilizers to pine seedlings in the nursery. MS thesis, North Carolina State University, Raleigh. 70 p.

Callan NW, Westcott MP (1996) Drip irrigation for application of potassium to tart cherry. Journal of Plant Nutrition 19(1): 163-172. https://doi:10.1080/01904169609365114

Carlson CA, Fox TR, Allen HL, Albaugh TJ, Rubilar RA, Stape JL (2014) Growth responses of loblolly pine in the Southeast United States to midrotation applications of nitrogen, phosphorus, potassium, and micronutrients. Forest Sci 60(1): 157-169. https://doi:10.5849/forsci.12-158

Chapin JB, Smith FW (1960) Germination of wheat at various levels of soil moisture as affected by applications of ammonium nitrate and muriate of potash. Soil Sci 89(6): 322-327. https://doi:10.1097/00010694-196006000-00004

Chen GC (1995) Fungal decay resistance of loblolly pine or sweetgum reacted with aqueous potassium iodate. Wood Fiber Sci27(2): 155-159.

Christersson L (1975) Frost-hardiness development in *Pinus silvestris* L. seedlings at different levels of potassium and calcium fertilization. Can J For Res 5(4): 738-740. https://doi:10.1139/x75-101

Christersson L (1976) The effect of inorganic nutrients on water economy and hardness of conifers. II. The effect of varying potassium and calcium contents on water status and drought hardiness of pot-grown *Pinus silvestris* L. and *Picea abies* (L.). Karst. seedlings. Studia Forestalia Suecica 136: 1-23.

Chung IK, You TK (1970) Effect of potash application on needle cast of the Korean Red Pine, *Pinus densiflora* S. et Z. Journal of Korean Forestry Society 8: 17-27.

Cutter BE, Murphey WK (2007) Effects of potassium on growth and wood anatomy of a Populus hybrid. Wood Fiber Sci 9(4): 282-288. https://wfs.swst.org/index.php/wfs/article/download/1725/1725

Danielson RM (1966) The effects of soil fumigation on seedling growth, mycorrhizae and the associated microflora of loblolly pine (*Pinus taeda* L.) roots. MS thesis, North Carolina State University, Raleigh. 148 p.

Datnoff L, Elmer W, Prabhu A, Fageria N (2006) Balanced chloride, potassium and silicon nutrition for plant disease management. In: Benbi DK, Brar MS, Bansal SK (eds) Balanced fertilization for sustaining crop productivity. International Potash Institute, Horgen, Switzerland. pp. 481-509. https://www.ipipotash.org/uploads/udocs/BALANCED_FERTILIZATION_FOR_SUSTAINING_CROP_PRODUCTIVITY.pdf

Davey CB (1972) Nursery soil management. In: Proceedings, southeastern area forest tree nurserymen's conference." USDA Forest Service, State and Private Forestry, Atlanta, GA: 182-187.

Davey CB (1991) Soils aspects of nursery management. In: van Buijtenen JP, Simms T (eds) Proceedings, nursery management workshop. Publication 148. Texas Forest Service, College Station, TX: 1-23.

Davey CB (2002) Using soil test results to determine fertilizer applications. In: Dumroese RK, Riley LE, Landis TD (eds) Proceedings, forest and conservation nursery associations-1999, 2000, and 2001. RMRS-P-24. USDA Forest Service, Rocky Mountain Research Station, Ogden, UT: 22-26. https://doi:10.5962/bhl.title.99309

Davis AS, Ross-Davis AL, Dumroese RK (2011) Nursery culture impacts cold hardiness in longleaf pine (*Pinus palustris*) seedlings. Restor Ecol 19(6): 717-719. https://doi:10.1111/j.1526-100x.2011.00814.x

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. PhD thesis, North Carolina State University, Raleigh. 80 p.

Del Campo AD, Hermoso J, Ceacero CJ, Navarro-Cerrillo RM (2011a) Nursery location and potassium enrichment in Aleppo pine stock 1. Effect of nursery culture, growth, allometry and seedling quality. Forestry. 84(3): 221-234. https://doi:10.1093/forestry/cpr008

Del Campo AD, Hermoso J, Flors J, Lidón A, Navarro-Cerrillo RM (2011b) Nursery location and potassium enrichment in Aleppo pine stock 2. Performance under real and hydrogel-mediated drought conditions. Forestry 84(3): 235-245. https://doi:10.1093/forestry/cpr009

Dierauf TA (1982) A test to induce earlier dormancy. Occasional Report 59. Virginia Division of Forestry, Charlottesville, VA: 7 p.

Dobrahner JJ, Iyer J, Hey JV (2007) Slow-release fertilization reduces nitrate leaching in bareroot production of *Pinus strobus* seedlings. Soil Sci 172(3): 242-255. https://doi:10.1097/ss.0b013e31803063e2

Domisch T, Finér L, Lehto T, Smolander A (2002) Effect of soil temperature on nutrient allocation and mycorrhizas in Scots pine seedlings. Plant Soil 239(2): 173-185. https://doi:10.1023/A:1015037127126

Donald DGM (1986) South African nursery practice – the state of the art. South African Forestry Journal. 139(1): 36-47. https://doi:10.1080/00382167.1986.9630055

Donald DGM (1988) The application of inorganic fertilisers to conditioned *Pinus radiata* prior to lifting as a means of improving root growth capacity. South Afr For J 146(1): 23-25. https://doi:10.1080/00382167.1988.9630354

Donald DGM (1991) Nursery fertilization of conifer planting stock. In: van den Driessche R (ed) Mineral nutrition of conifer seedlings. CRC Press, Boca Raton, FL: 135-167.

Dordas C (2008) Role of nutrients in controlling plant diseases in sustainable agriculture. A review. Agronomy for Sustainable Development. 28(1): 33-46. https://doi:10.1051/agro:2007051

Dumroese RK (2003) Hardening fertilization and nutrient loading of conifer seedlings. In: Riley LE, Dumroese RK, Landis TD (eds) Proceedings, forest and conservation nursery associations-2002. RMRS-P-28. USDA Forest Service, Rocky Mountain Research Station, Ogdon, UT: 31-36. https://doi:10.5962/bhl.title.99309

Dumroese KR, Barnett JP (2004) Container seedling handling and storage in the southeastern states. In: Riley LE, Dumroese RK, Landis TD (eds) Proceedings, forest and conservation nursery associations-2003. RMRS-P-33. USDA Forest Service, Rocky Mountain Research Station, Fort Collins, CO: 22-25. https://doi:10.5962/bhl.title.99309

Dumroese RK, Wenny DL (1997) Fertilizer regimes for container grown conifers of the Intermountain West. In: Haase DL, Rose R (eds) Proceedings, forest seedling nutrition from the nursery to the field. Corvallis, OR: Oregon State University, Nursery Technology Cooperative. pp. 17-26.

Edwards IK (1986) How to maximize efficiency of fertilizers in a forest tree nursery. In: Landis TD, Fischer JW (eds) Proceedings, intermountain nurseryman's association-1985. GTR-125. USDA Forest Service, Rocky Mountain Forest and Range Experiment Station, Fort Collins, CO: 99-103. https://doi:10.5962/bhl.title.99552

Edwards IK (1989) The effects of mineral nutrition on hardening-off of conifer seedlings. In: Landis TD (ed) Proceedings, intermountain nurseryman's association-1989. GTR-RM-184. USDA Forest Service, Rocky Mountain Forest and Range Experiment Station, Fort Collins, CO: 98-102.

Khan SA, Mulvaney RL, Ellsworth TR (2014) The potassium paradox: Implications for soil fertility, crop production and human health. Renewable Agriculture and Food Systems 29(1): 3-27. https://doi:10.1017/S1742170513000318

Erdmann GG, Metzger FT, Oberg RR (1979) Macronutrient deficiency symptoms in seedlings of four northern hardwoods. GTR NC-53. USDA Forest Service, North Central Forest Experiment Station, St. Paul, MN: 36 p.

Fernández M, Marcos C, Tapias R, Ruiz F, López G (2007) Nursery fertilisation affects the frost-tolerance and plant quality of *Eucalyptus globulus* Labill. cuttings. Ann Forest Sci 64(8): 865-873. https://doi:10.1051/forest:2007071

Flaten CM (1939) A study on chlorosis of *Pinus resinosa* in a forest nursery. MS thesis, University of Michigan, Ann Arbor. 35 p.

Fløistad IS, Eldhuset TD (2017) Effect of photoperiod and fertilization on shoot and fine root growth in *Picea abies* seedlings. Silva Fenn 51(1). https://doi:10.14214/sf.1704

Fløistad IS, Kohmann K (2004) Influence of nutrient supply on spring frost hardiness and time of bud break in Norway spruce (*Picea abies* (L.). Karst.) seedlings. New Forest 27(1): 1-11. https://doi:10.1023/A:1025085403026

Foulger AN, Freese F, Shire EA (2007) Effect of nutrient concentration on stem anatomy of eastern cottonwood seedlings. Wood Fiber Sci 2(4): 340-346.

Fraedrich BR, Witcher W (1982) Influence of fertilizations on pitch canker development on three southern pine species. Plant Disease 66(10): 938-940. https://doi:10.1094/PD-66-938

Fraysse JP, Crémière L (1998) Nursery factors influencing containerized *Pinus pinaster* seedlings' initial growth. Silva Fenn 32(3): 261-270. https://doi:10.14214/sf.686

Garcia K, Zimmermann SD (2014) The role of mycorrhizal associations in plant potassium nutrition. Front Plant Sci 5: 337. https://doi:10.3389/fpls.2014.00337

Geilfus CM (2018) Review on the significance of chlorine for crop yield and quality. Plant Science. 270: 114-122. https://doi:10.1016/j.plantsci.2018.02.014

Gilmore AR, Kahler LH (1965) Fertilizers and organic additives in pine nursery seedbeds: effects on field survival, field growth, and chemical content of foliage. Tree Planters' Notes 73: 21-27.

Gleason JF (1989) Fertilization of 2-0 Ponderosa pine seedlings in the nursery and field: morphology, physiology, and field performance. MS thesis, Oregon State University, Corvallis, OR: 109 p.

Gleason JF, Duryea M, Rose R, Atkinson M (1990) Nursery and field fertilization of 2+0 ponderosa pine seedlings: the effect on morphology, physiology, and field performance. Can J For Res 20(11): 1766-1772. https://doi:10.1139/x90-235

Glerum C (1985) Frost hardiness of coniferous seedlings. In: Duryea ML (ed) Proceedings, evaluating seedling quality: principles, procedures, and predictive abilities of major tests. Corvallis, OR: Oregon State University, Forest Research Laboratory. pp. 107-123.

Gómez-Ruiz PA, Lindig-Cisneros R, de la Barrera E, Martorell C (2016) Potassium enhances frost tolerance in young individuals of three tropical dry forest species from Mexico. Functional Plant Biology 43(5): 461-467. https://doi:10.1071/FP15329

Goslin WE (1959. Effects of deficiencies of essential elements on the development and mineral composition of seedlings of Scots pine (*Pinus sylvestris* L). MS thesis, Ohio University, Athens, GA: 114 p.

Greene TA, Britt JR (1998) Effect of density and spacing on seedling uniformity in a loblolly pine nursery. In: Waldrop TA (ed) Proceedings, ninth biennial southern silvicultural research conference. GTR-SRS-20. USDA Forest Service, Southern Forest Experiment Station, Asheville, NC: 9-11. https://doi:10.2737/srs-gtr-20

Grossnickle SC (2012) Why seedlings survive: influence of plant attributes. New Forest 43(5-6): 711-738.

Grossnickle SC, MacDonald JE (2018) Why seedlings grow: influence of plant attributes. New Forest 49(1): 1-34.

Hagan AK, Olive JW, Stephenson J, Rivas-Davilla M (2003) Impact of application rate and treatment interval on the control of Entomosporium leaf spot, dayliliy rust, and powdery mildew on container-grown nursery crops with MilStop. Timely Information - Plant Pathology. Series PP 557. Auburn University, AL: 3 p. https://pdfs.semanticscholar.org/59ed/c179ef6fa1c62fe900af9456bcb16374f6f0.pdf

Hannah PR (1973) Phosphorus stimulates growth of yellow birch seedlings. Tree Planters' Notes 24(1): 1-2.

Hans RR (2013) Initial growth responses to controlled release fertilizer application at establishment of commercial forestry species in South Africa. MS thesis, University of Stellenbosch, Stellenbosch. 158 p. https://pdfs.semanticscholar.org/f898/91ac09c6cbdea8728a7dc5e4f46aa8a7f84e.pdf

Hansen TS, Kenety WH, Wiggin GH, Stakman EC (1923) A study of the damping-off disease of coniferous seedlings. Technical Bulletin 15. Minnesota Agricultural Experiment Station. 35 p.

Hare RC (1981) Nitric acid promotes pine seed germination. Res. Note SO-281. USDA Forest Service, Southern Forest Experiment Station, New Orleans, LA: 2 p. https://doi:10.2737/so-rn-281

Harvey HP, van den Driessche R (1999) Nitrogen and potassium effects on xylem cavitation and water-use efficiency in poplars. Tree Physiol 19(14): 943-950. https://doi:10.1093/treephys/19.14.943

Hatchell GE (1985) Seedling quality and field performance of longleaf pine seedlings affected by ectomycorrhizae and nursery cultural practices. In: Shoulders E (ed) Proceedings, third biennial southern silvicultural research conference. GTR SO-54. USDA Forest Service, Southern Forest Experiment Station, New Orleans, LA: 395-402. https://doi:10.2737/so-gtr-54

Heckman JR (2007) Chlorine. In: Barker AV, Pilbeam DJ. (Eds) Handbook of plant nutrition. Taylor & Francis, Boca Raton, FL: 279-291.

Heiberg SO, Leyton L, Loewenstein H (1959) Influence of potassium fertilizer level on red pine planted at various spacings on a potassium-deficient site. Forest Sci 5(2): 142-153. https://doi:10.1093/forestscience/5.2.142

Heiberg SO, White DP (1951) Potassium deficiency of reforested pine and spruce stands in northern New York. Soil Sci Soc Am J15: 1625-1629. https://doi:10.2136/sssaj1951.036159950015000c0084x

Heit CE, Nelson C (1941) Approximate germination tests of dormant seeds by excising embryos. Proceedings of the Association of Official Seed Analysts 33: 87-89.

Hernández G, Haase DL, 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.

Hernández R, Lombardo C (1987) Deficiencias de macronutrientes en *Pinus caribaea* var. *hondurensis* Morelet. Barr and Golf. Facultad de Ciencias Forestales, ULA, Mérida, Mexico, pp. 109.

Hicks GH (1900) The germination of seeds as affected by certain chemical fertilizers Bulletin 24. USDA, Washington, DC: 15 p.

Hinesley LE, Maki TE (1980) Fall fertilization helps longleaf pine nursery stock. South J Appl For 4(3): 132-135. https://doi:10.1093/sjaf/4.3.132

Hobbs CH (1944) Studies on mineral deficiency in pine. Plant Physiol 19(4): 590-602. https://doi:10.1104/pp.19.4.590

Hodgson TJ (1977) Preliminary investigations on the manipulation of pine seedling growth and development. MS thesis, University of Stellenbosch, Stellenbosch. 193 p.

Holopainen T, Nygren P (1989) Effects of potassium deficiency and simulated acid rain, alone and in combination, on the ultrastructure of Scots pine needles. Can J For Res 19(11): 1402-1411. https://doi:10.1139/x89-215

Houman F, Godbold DL, Shasheng W, Hüttermann A (1990) Gas exchange in *Populus maximowiczii* in relation to potassium and phosphorus nutrition. J Plant Physiol 135(6): 675-679. https://doi:10.1016/S0176-1617(11)80878-3

Huang JW, Kuhlman EG (1991) Mechanisms inhibiting damping-off pathogens of slash pine seedlings with a formulated soil amendment. Phytopathology 81(2): 171-177. https://doi:10.1094/phyto-81-171

Hubbel KL, Ross-Davis AL, Pinto JR, Burney OT, Davis AS (2018) Toward sustainable cultivation of *Pinus occidentalis* Swartz in Haiti: effects of alternative growing media and containers on seedling growth and foliar chemistry. Forests 9(422): 1-14. https://doi:10.3390/f9070422

Huber DM, Graham RD (1999) The role of nutrition in crop resistance and tolerance to disease. In: Rengel Z (ed) Mineral nutrition of crops fundamental mechanisms and implications. Food Product Press. New York, NY: 205-226.

Irwin KM, Duryea ML, Stone EL (1998) Fall-applied nitrogen improves performance of 1-0 slash pine nursery seedlings after outplanting. South J Appl For 22(2): 111-116. https://doi:10.1093/sjaf/22.2.111

Islam MA, Apostol KG, Jacobs DF, Dumroese RK (2008) Effects of fall fertilization on morphology and cold hardiness of red pine (*Pinus resinosa* Ait.) seedlings. In: Dumroese RK, Riley LE (eds) Proceedings, forest and conservation nursery associations-2007. RMRS-P-57. USDA Forest Service, Rocky Mountain Research Station, Fort Collins, CO: 72-78. https://doi:10.5962/bhl.title.99309

Jackson DP, Dumroese RK, Barnett JP (2012) Nursery response of container *Pinus palustris* seedlings to nitrogen supply and subsequent effects on outplanting performance. Forest Ecol Manag 265: 1-12. https://doi:10.1016/j.foreco.2011.10.018

Jacobs DF, Rose R, Haase DL, Alzugaray PO (2004) Fertilization at planting impairs root system development and drought avoidance of Douglas-fir (*Pseudotsuga menziesii*) seedlings. Ann Forest Sci 61(7): 643-651. https://doi:10.1051/forest:2004065

Jalkanen RE, Redfern DB, Sheppard LJ (1998) Nutrient deficits increase frost hardiness in Sitka spruce (*Picea sitchensis*). needles. Forest Ecol Manag 107(1-3): 191-201. https://doi:10.1016/S0378-1127(97)00338-1

Janssen BH, De Willigen P (2006) Ideal and saturated soil fertility as bench marks in nutrient management: 1. Outline of the framework. Agriculture, Ecosystems & Environment 116(1-2): 132-146. https://doi:10.1016/j.agee.2006.03.014

Johnson LPV (1946) Effect of chemical treatments on the germination of forest tree seeds. Forest Chron 22(1): 17-24. https://doi:10.5558/tfc22017-1

Jokela A, Sarjala T, Huttunen S (1998) The structure and hardening status of Scots pine needles at different potassium availability levels. Trees 12(8): 490-498. https://doi:10.1007/s004680050179

Jokela A, Sarjala T, Kaunisto S, Huttunen S (1997) Effects of foliar potassium concentration on morphology, ultrastructure and polyamine concentration of Scots pine needles. Tree Physiol 17(11): 677-685. https://doi:10.1093/treephys/17.11.677

Jopson TM, Paul JL (1985) Influence of fall fertilization and moisture stress on growth and field performance of container-grown Douglas-fir seedlings. In: Landis TD (ed) Proceedings, intermountain nurseryman's association. GTR INT-185. USDA Forest Service, Intermountain Forest and Range Experiment Station, Ogden, UT: 14-19. https://doi:10.5962/bhl.title.99552

Jozefek HJ (1989) The effect of varying levels of potassium on the frost resistance of birch seedlings. Silva Fenn 23(1): 21-31. https://doi:10.14214/sf.a15528

Juntunen ML, Rikala R (2001) Fertilization practice in Finnish forest nurseries from the standpoint of environmental impact. New Forest 21(2): 141-158. https://doi:10.1023/A:1011837800185

Kam M, Versteegen CM, Burg J, Werf DC (1991) Effects of fertilization with ammonium sulphate and potassium sulphate on the development of *Sphaeropsis sapinea* in Corsican pine. Netherlands Journal of Plant Pathology 97(5): 265-274. https://doi:10.1007/bf01974222

Knight PJ (1978) Fertiliser practice in New Zealand forest nurseries. NZ J Forest Sci 8(1): 27-53.

Knight PJ (1981) The maintenance of productivity in forest nurseries. In: Chavasse CGR (ed), forest nursery and establishment practice in New Zealand. FRI Symposium 22, Rotorua, NZ: 48-69.

Koo RCJ (1985) Effects of nitrogen and potassium fertilization on winter injury of citrus trees. Proceedings Florida State Horticulture Society 98: 53-56. https://journals.flvc.org/fshs/article/view/94991/91012

Kopitke JC (1941) The effect of potash salts upon the hardening of coniferous seedlings. J Forest 39(6): 555-558. https://doi:10.1093/jof/39.6.555

Kormanik PP, Sung SJS, Kormanik TL (1994) Irrigating and fertilizing to grow better nursery seedlings. In: Landis TD (ed) Proceedings, northeastern and intermountain forest and conservation nursery associations. GTR-RM-243. USDA Forest Service, Rocky Mountain Forest and Range Experiment Station, Fort Collins, C): 115-121. https://doi:10.5962/bhl.title.99309

Krause HH, Wilde SA (1960) Uptake of potassium by red pine seedlings and losses through leaching from fertilizers of various solubility. Soil Sci Soc Am J24(6): 513-515. https://doi:10.2136/sssaj1960.03615995002400060028x

Landis TD (1976) Nitrogen fertilizer injures pine seedlings in rocky mountain nursery. Tree Planters' Notes 27(4): 29-35.

Landis TD (2005) Macronutrients - potassium. Forest Nursery Notes 25(1): 5-11.

Landis TD, Davey CB (2009) Determining fertilizer rates and scheduling applications in bareroot nurseries. Forest Nursery Notes 29(2): 14-21.

Larsen JB (1978) Investigations on the significance of potassium and nitrogen supply for drought hardiness in Douglas-fir (*Pseudotsuga menziesii*) in winter. Flora 167(2): 197-207. https://doi:10.1016/S0367-2530(17)31110-6

Larsen HS, South DB, Boyer JN (1988) Foliar nitrogen content at lifting correlates with early growth of loblolly pine seedlings from 20 nurseries. South J Appl For 12(3): 181-185. https://doi:10.1093/sjaf/12.3.181

Larsen HS, South DB, Williams HM, Boyer JN (1989) Survival and early growth of loblolly pine seedlings from six nurseries. In: Miller JH (ed) Proceedings, fifth biennial southern silvicultural research conference. GTR-SO-74. USDA Forest Service, Southern Forest Experiment Station, New Orleans, LA: 151-154.

Lauer FI (1963) Influence of high and low levels of N and K on adventitious bud formation in the potato. American Potato Journal 40(9): 302-307. https://doi:10.1007/bf02862780

Leach GN, Gresham HH (1983) Early field performance of loblolly pine seedlings with *Pisolithus tinctorius* ectomycorrhizae on two lower coastal plain sites. South J Appl For 7(3): 149-153. https://doi:10.1093/sjaf/7.3.149

Leaf AL (1968) K, Mg and S deficiencies in forest trees. In: "Forest Fertilization-the Theory and Practice". Tennessee Valley Authority, Muscle Shoals, AL: 88-122.

Lunt HA (1938) The use of fertilizers in the coniferous nursery. Bulletin 416. New Haven, CT: Connecticut Agricultural Experiment Station. pp. 721-766.

Lyle S (1960) A comparison of chemical analyses for various nurseries. In: Craig DA (ed) Proceedings, southern region nurserymen's training meeting. USDA Forest Service, Southern Region, Atlanta, GA: 8-16.

Lyle ES (1969) Mineral deficiency symptoms in loblolly pine seedlings. Agronomy Journal 61(3): 395-398. https://doi:10.2134/agronj1969.00021962006100030019x

Lyle ES, Pearce ND (1968) Sulfur deficiency in nursery seedlings may be caused by concentrated fertilizers. Tree Planters' Notes 19(1): 9-10.

Madgwick HAI (1964) Variations in the chemical composition of red pine (*Pinus resinosa* Ait) leaves: a comparison of well-grown and poorly grown trees. Forestry 37(1): 87-94. https://doi:10.1093/forestry/37.1.87

Maki TE (1950) Effect of varying amounts of potash and nitrogen on the development and vigor of longleaf pine seedlings. In: Proceedings, annual convention of the association of southern agricultural workers. p. 141.

Manikam D, Srivastava PBL (1980) The growth response of *Pinus caribaea* mor. var. *hondurensis* bar and golf seedlings to fertilizer application on the Serdang soil series. Forest Ecol Manag 3: 127-139. https://doi:10.1016/0378-1127(80)90010-9

Martian BF (1989) Soil management practices at the Big Sioux Nursery. In: Landis TD (ed) Proceedings, Intermountain forest nursery association. GTR RM-184. USDA Forest Service, Rocky Mountain Forest and Range Experiment Station, Fort Collins, CO: 82-85. https://doi:10.5962/bhl.title.99623

Martin JP, Bingham FT (1954) Effect of various exchangeable cation ratios in soils on growth and chemical composition of avocado seedlings. Soil Sci 78(5): 349-360. https://doi:10.1097/00010694-195411000-00005

Marx DH (1990) Soil pH and nitrogen influence *Pisolithus* ectomycorrhizal development and growth of loblolly pine seedlings. Forest Sci 36(2): 224-245. https://doi:10.1093/forestscience/36.2.224

Marx DH, Artman JD (1978) Growth and ectomycorrhizal development of loblolly pine seedlings in nursery soil infested with *Pisolitus tinctorius* and *Thelephora terrestris* in Virginia. Research Note 256. USDA Forest Service, Southeastern Forest Experiment Station, Asheville, NC, 4 p.

Marx DH, Cordell CE, France RC (1986) Effects of triadimefon on growth and ectomycorrhizal development of loblolly and slash pines in nurseries. Phytopathology 76(8): 824-831. https://doi:10.1094/Phyto-76-824

Marx DH, Cordell CE, Kenney DS, Mexal JG, Artman JD, Riffle JW, Molina RJ (1984) Commercial vegetative inoculums of *Pisolithus tinctorius* and inoculation techniques for development of ectomycorhizae on bare-root tree seedlings. Forest Sci 30 (Suppl 1): 1-101. https://doi:10.1093/forestscience/30.s1.a0001

Marx DH, Cordell CE, Maul SB, Ruehle JL (1989) Ectomycorrhizal development on pine by *Pisolithus tinctorius* in bare-root and container seedling nurseries. New Forest 3(1): 57-66. https://doi:10.1007/BF00128901

Marx DH, Hatch AB, Mendicino JF (1977) High soil fertility decreases sucrose content and susceptibility of loblolly pine roots to ectomycorrhizal infection by *Pisolithus tinctorius*. Can J Botany 55(12): 1569-1574. https://doi:10.1139/b77-185

May JT (1957a) Effects of soil management practices in a forest tree nursery on soil properties and on loblolly pine seedlings. PhD thesis, Michigan State University, East Lansing. 215 p.

May JT (1957b) Soil management. In: Cossitt FM (ed) Proceedings, nursery training session. USDA Forest Service, Southern Region, Athens, GA: 13-19.

May JT (1985) Nutrients and fertilization. In: Lantz CW (ed) southern pine nursery handbook. USDA Forest

Service, Southern Region, Atlanta, GA: 1201-1241.

May JT, Johnson HH, Gilmore AR (1962) Chemical composition of southern pine seedlings. Research Paper 10. Georgia Forest Research Council, Macon, GA. 11 p.

McComb AL (1949) Some fertilizer experiments with deciduous forest tree seedlings on several Iowa soils. Research Bulletin 369. Ames, IA: Iowa State College, Iowa Agriculture and Home Economics Experiment Station. pp. 405-448.

McComb AL, Griffith JE (1946) Growth stimulation and phosphorus absorption of mycorrhizal and non-mycorrhizal northern white pine and Douglas fir seedlings in relation to fertilizer treatment. Plant Physiol 21(1): 11-17. https://doi:10.1104/pp.21.1.11

McGee CE (1963) A nutritional study of slash pine seedlings grown in sand culture. Forest Sci 9(4): 461-469. https://doi:10.1093/forestscience/9.4.461

McKee WH. Jr (1978) Slash pine seedling response to potassium and calcium on imperfectly drained coastal plain soil. Plant Soil 50(1-3): 615-624. https://doi:10.1007/BF02107213

McNabb KL (1985) The relationship of carbohydrate reserves to the quality of bare-root *Pinus elliottii* var. *elliottii* (Engelm.) seedlings produced in a northern Florida nursery. PhD thesis, University of Florida, Gainesville. 146 p.

Mead DJ, Pritchett WL (1971) A comparison of tree responses to fertilizers in field and pot experiments. Soil Sci Soc Am J35(2): 346-349. https://doi:10.2136/sssaj1971.03615995003500020046x

Menzies MI, Holden DG, Green LM, Rook DA (1981) Seasonal changes in frost tolerance of *Pinus radiata* seedlings raised in different nurseries. New Zealand J ForestScience 11(2): 100-111.

Michniewicz M, Stopińska J (1980) The effect of potassium nutrition on growth and on plant hormones content in Scots pine (*Pinus silvestris* L.) seedlings. Acta Societatis Botanicorum Poloniae 49(3): 235-244. https://doi:10.5586/asbp.1980.021

Miller AE, Rose RW, Ray KF (1985) Root wrenching and top pruning effects on loblolly pine nursery seedling development. In: Shoulders E (ed) Proceedings, third biennial southern silvicultural research conference. GTR SO-54. USDA Forest Service, Southern Forest Experiment Station, New Orleans, LA: 11-17. https://doi:10.2737/so-gtr-54

Mitchell HL, Finn, RF, Rosendahl RO (1937) The relation between mycorrhizae and the growth and nutrient absorption of coniferous seedlings in nursery beds. Black Rock Forest Papers 1(10): 58-73.

Moore JA, Mika PG, Schwandt JW, Shaw TM (1994) Nutrition and forest health. In: Baumgartner DM, Lotan JE, Tonn JR (eds) Proceedings, conference on interior cedar-hemlock-white pine forest: ecology and management. Washington State University, Department of Natural Resource Science, Pullman, WA: 173-176.

Munson KR, Stone EL (1984) Seedling and soil nutrient status during the lifting period in a north Florida nursery. In: Lantz CW (ed) Proceedings, southern nursery conference. USDA Forest Service, State and Private Forestry, Atlanta, GA: 152-157.

Murison WF (1960) Macronutrient deficiency and its effects on coniferous growth. PhD thesis, University of British Columbia, Vancouver. 258 p. https://doi:10.14288/1.0106016

Murphey WK, McAdoo JC (1969) Effects of nutrient deficiencies on tensile properties of the xylem of *Robinia pseudoacacia* L. seedlings. Forest Sci 15(3): 251-253. https://doi:10.1093/forestscience/15.3.251

NCSFNC (North Carolina State Forest Nutrition Cooperative) (1991) Descriptive statistics and relationships among soil and foliar characteristics in midrotation loblolly pine plantations. Research Note #7, North Carolina State Forest Nutrition Cooperative, Raleigh, NC. 29 p. https://doi:10.2172/5006030

Neely D (1981) Application of nitrogen fertilizer to control anthracnose of black walnut. Plant Disease 65(7): 580-581. https://doi:10.1094/PD-65-580

Nelson LE, Switzer GL (1985) Trends in the maintenance of soil fertility in Mississippi nurseries. In: South DB (ed) Proceedings, international symposium on nursery management practices for the southern pines. Auburn, AL: Auburn University, Alabama Agricultural Experiment Station. pp. 222-236.

Nowak J, Friend AL (2006) Loblolly pine and slash pine responses to acute aluminum and acid exposures. Tree Physiol 26(9): 1207-1215. https://doi:10.1093/treephys/26.9.1207

Oliet J, Planelles R, Segura ML, Artero F, Jacobs DF (2004) Mineral nutrition and growth of containerized *Pinus halepensis* seedlings under controlled-release fertilizer. Scientia Horticulturae 103(1): 113-129. https://doi:10.1016/j.scienta.2004.04.019

Perez BAP, Valeri SEV, da Cruz MCP, de Vasconcelos RTO (2016) Potassium doses for African mahogany plants growth under two hydric conditions. African J Agric Res. 11(22): 1973-1979. https://doi:10.5897/AJAR2016.11026

Perrenoud S (1990) Potassium and Plant Health. Vol. 3. International Potash Institute, Bern, Switzerland, pp. 365. https://www.ipipotash.org/uploads/udocs/ipi_research_topics_no_3_potassium_and_plant_health_2nd_completely_revised_edition.pdf

Pessin LJ (1937) The effect of nutrient deficiency on the growth of longleaf pine seedlings. Occasional Paper 65. USDA Forest Service, Southern Forest Experiment Station, New Orleans, LA. 7 p.

Phares RE (1964) Mineral nutrition of forest tree seedlings. PhD thesis, Iowa State University, Ames. 168 p. https://lib.dr.iastate.edu/rtd/2713

Phares RE (1971) Fertilization tests with potted red oak seedlings. Research Note NC-114. USDA Forest Service, North Central Forest Experiment Station, St. Paul, MN. 4 p.

Pitel JA, Wang BSP (1985) Physical and chemical treatments to improve laboratory germination of western white pine seeds. Can J Forest Research 15(6): 1187-1190. https://doi:10.1139/x85-194

Plassard C, Guerin-Laguette A, Véry AA, Casarin V, Thibaud JB (2002) Local measurements of nitrate and potassium fluxes along roots of maritime pine. Effects of ectomycorrhizal symbiosis. Plant, Cell & Environment 25(1): 75-84. https://doi:10.1046/j.0016-8025.2001.00810.x

Pritchett WL, Fisher RF (1987) Properties and management of forest soils. John Wiley and Sons, NY.

Puértolas J, Gil L, Pardos JA (2003) Effects of nutritional status and seedling size on field performance of *Pinus halepensis* planted on former arable land in the Mediterranean basin. Forestry 76(2): 159-168. https://doi:10.1093/forestry/76.2.159

Pwrnell HM (1958) Nutritional studies of *Pinus radiata* Don. Australian Forestry 22(2): 82-87. https://doi:10.1080/00049158.1958.10675852

Radwan MA, DeBell DS (1994) Fertilization and nutrition of red alder. In: Hibbs DE, DeBell DS, Tarrant RF (eds) The biology and management of red alder. Oregon State University Press. Corvallis, OR: 216-228. https://doi:10.2737/pnw-rn-370

Ramírez-Cuevas Y, Rodríguez-Trejo DA (2010) Frost resistance in *Pinus hartwegii* subjected to different potassium treatments. Revista Chapingo. Serie Ciencias Forestales y del Ambiente 16(1): 79-85. https://doi:10.5154/r.rchscfa.2009.09.032

Raupach M, Hall MJ (1972) Foliar levels of potassium in relation to potassium deficiency symptoms in radiata pine. Australian Forestry 36(3): 204-213. https://doi:10.1080/00049158.1972.10675586

Richards BN, From FR (1965) Effect of ammonium nitrate and lime on germination and early growth of *Pinus caribaea*. Australian Forestry 29(4): 263-274. https://doi:10.1080/00049158.1965.10675967

Rikala R, Repo T (1997) The effect of late summer fertilization on the frost hardening of second-year Scots pine seedlings. New Forest 14(1): 33-44. https://doi:10.1023/A:1006505919556

Rosendahl RO (1943) The effect of mycorrhizal and nonmycorrhizal fungi on the availability of difficultly soluble potassium and phosphorus. Soil Sci Soc Am J7(C): 477-479. https://doi:10.2136/sssaj1943.036159950007000c0080x

Rosendahl R, Korstian CF (1945) Effect of fertilizers on loblolly pine in a North Carolina nursery. Plant Physiol 20(1): 19-23. https://doi:10.1104/pp.20.1.19

Rowan SJ (1971) Soil fertilization, fumigation, and temperature affect severity of black root rot of slash pine. Phytopathology 61: 184-187. https://doi:10.1094/Phyto-61-184

Rowan SJ (1982) The control of phytotoxic fermentation of wetted packaging material during storage. Tree Planters' Notes 33(3): 20-21.

Rowan SJ (1987) Effects of potassium fertilization in the nursery on survival and growth of pine seedlings in the plantation. Research Paper 68. Georgia Forestry Commission, Macon, GA. 8 p. https://archive.org/details/effectsofpotassi68rowa

Rowan SJ, Steinbeck K (1977) Seedling age and fertilization affect susceptibility of loblolly pine to fusiform rust. Phytopathology 67: 242-246. https://doi:10.1094/phyto-67-242

Rupe JC, Widick JD, Sabbe WE, Robbins RT, Becton CB (2000) Effect of chloride and soybean cultivar on yield and the development of sudden death syndrome, soybean cyst nematode, and southern blight. Plant Disease 84(6): 669-674. https://doi:10.1094/PDIS.2000.84.6.669

Russell GE (1978) Some effects of applied sodium and potassium chloride on yellow rust in winter wheat. Annals of Applied Biology 90(2): 163-168. https://doi:10.1111/j.1744-7348.1978.tb02623.x

Sakai A (1962) Studies on the frost-hardiness of woody plants; 1. The causal relation between sugar content and frost-hardiness. Contributions from the Institute of Low Temperature Science, B11: 1-40. https://eprints.lib.hokudai.ac.jp/dspace/bitstream/2115/20257/1/B11_p1-40.pdf

Sarjala T, Taulavuori K, Savonen EM, Edfast AB (1997) Does availability of potassium affect cold hardening of Scots pine through polyamine metabolism? Physiologia Plantarum 99(1): 56-62. https://doi:10.1111/j.1399-3054.1997.tb03430.x

Scarratt JB (1986) An evaluation of some commercial soluble fertilizers for culture of jack pine container stock. Information report OX-377, Great Lakes Forestry Centre, Canadian Forest Service, Sault St. Marie, Ontario, Canada, pp. 27. https://www.cfs.nrcan.gc.ca/publications/download-pdf/9053

Schaedle M (1959) A study on the growth of Douglas fir (*Pseudotsuga menziesii*) seedlings. MS thesis, University of British Columbia, Vancouver. 171 p.

Schomaker CE (1969) Growth and foliar nutrition of white pine seedlings as influenced by simultaneous changes in moisture and nutrient supply. Soil Sci Soc Am J33(4): 614-618. https://doi:10.2136/sssaj1969.03615995003300040035x

Schultz RC, Kormanik PP, Bryan WC, Brister GH (1979) Vesicular–arbuscular mycorrhiza influence growth but not mineral concentrations in seedlings of eight sweetgum families. Can J For Research 9(2): 218-223. https://doi:10.1139/x79-038

Shaw TM, Moore J, Marshall JD (1998) Root chemistry of Douglas-fir seedlings grown under different nitrogen and potassium regimes. Can J For Research 28(10): 1566-1573. https://doi:10.1139/cjfr-28-10-1566

Shear CB, Myers AT, Crane HL (1953) Nutrient element balance: response of tung trees grown in sand culture to potassium, magnesium, calcium, and their interactions. Technical Bulletin 1085. Washington, DC: U.S. Department of Agriculture. 52 p.

Shi W, Grossnickle SC, Li G, Su S, Liu Y (2018) Fertilization and irrigation regimes influence on seedling attributes and field performance of *Pinus tabuliformis* Carr. Forestry 92(1): 97-107. https://doi:10.1093/forestry/cpy035

Shirley HL, Meuli LJ (1939) The influence of soil nutrients on drought resistance of two-year-old red pine. American Journal of Botany 26(6): 355-360. https://doi:10.1002/j.1537-2197.1939.tb09287.x

Shoulders E, Tiarks AE (1987) Slash pine shows mixed response to potassium fertilizer. In: Phillips DR (ed) Proceedings, fourth biennial southern silvicultural research conference. GTR-SE-42. USDA Forest Service, Southern Forest Experiment Station, Asheville, NC: 425-428.

Silva MD, Klar AE, Passos JR (2004) Efeitos do manejo hídrico e da aplicação de potássio nas características morfofisiológicas de mudas de *Eucalyptus grandis* W.(Hill ex. Maiden). Irriga 9(1): 31-40. http://actaarborea.fca.unesp.br/index.php/irriga/article/download/3148/1939

Simpson JA (1985) Use of inorganic fertilizers and cover crops in exotic pine nurseries of southern Queensland, Australia. In: South DB (ed) Proceedings, international symposium on nursery management practices for the southern pines. Auburn University, AL: Auburn University, Alabama Agricultural Experiment Station: 203-221.

Smethurst P, Knowles A, Churchill K, Wilkinson A, Lyons A (2007) Soil and foliar chemistry associated with potassium deficiency in *Pinus radiata*. Can J For Res 37(6): 1093-1105. https://doi:10.1139/X06-307

Smethurst PJ, Comeford NB, Neary, D.G (1993) Weed effects on early K and P nutrition and growth of slash pine on a Spodosol. Forest Ecol Manag 60(1-2): 15-26. https://doi:10.1016/0378-1127(93)90020-N

South DB (1975) The determination of nursery practices for the production of quality sweetgum (*Liquidambar styraciflua* L.) and sycamore (*Platanus occidentalis* L.) planting stock. MS thesis, North Carolina State University, Raleigh. 90 p.

South DB (2007) Freeze injury to roots of southern pine seedlings in the USA. Southern Hemisphere Forestry Journal 69(3): 151-156. https://doi:10.2989/SHFJ.2007.69.3.3.353

South DB (2019) Questions and considerations for the next generation of seedling fertilization researchers. Tree Planters' Notes 62(2): 69-89.

South DB, Donald DGM (2002) Effect of nursery conditioning treatments and fall fertilization on survival and early growth of *Pinus taeda* seedlings in Alabama, USA. Can J For Res 32(7): 1171-1179. https://doi:10.1139/x02-039

South DB, Donald DGM, Rakestraw JL (1993) Effect of nursery culture and bud status on freeze injury to *Pinus taeda* and *P elliottii* seedlings. South Afr For J166(1): 37-45. https://doi:10.1080/00382167.1993.9629397

South, DB, Lyons A, Pohl R (2015) Transplant size affects early growth of a *Pinus taeda* clone. Mathematical and Computational Forestry & Natural Resource Sciences 7(2): 39-48.

South DB, Mitchell RJ, Dixon RK, Vedder M (1988) New-ground syndrome: an ectomycorrhizal deficiency in pine nurseries. South J Appl For 12(4): 234-239. https://doi:10.1093/sjaf/12.4.234

South DB, Nadel RL, Enebak SA, Bickerstaff G (2017) Effect of sulfur and lime on soil pH and nutrients in a sandy *Pinus taeda* nursery. Reforesta 4: 12-20. https://doi:10.21750/REFOR.4.02.41

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.

South DB, Zwolinksi JB (1996) Chemicals used in southern forest nurseries. South J Appl For 20(3): 127-135. https://doi:10.1093/sjaf/20.3.127

Srivastava PBL, Naruddin A, Zainorin BA (1979) The response of *Pinus caribaea* mor. var. *hondurensis* seedlings to nitrogen, phosphorous and potassium fertilizers. Plant Soil 51(2): 215-232. https://doi:10.1007/BF02232885

Starkey T, Enebak S (2012) Foliar nutrient survey of loblolly and longleaf pine seedlings. Research report 12-02. Auburn University, AL: Auburn University Southern Forest Nursery Management Cooperative. pp. 11.

Steinbeck K (1962) Effects of nutrients on slash pine seedlings grown in different media. M.S. thesis, University of Georgia, Athens, GA: 67 p.

Stoeckeler JH, Arneman HF (1960) Fertilizers in forestry. Advances in Agronomy 12: 127-195. https://doi:10.1016/S0065-2113(08)60082-6

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

Stoeckeler JH, Slabaugh PE (1965) Conifer nursery practice in the prairie-plains. USDA Forest Service, Agriculture Handbook 279. Washington, DC: 98 p.

Stone JM (1986) Topdress fertilization. In: Schroeder RA (ed) Proceedings, southern forest nursery association. Tallahassee, FL: Florida Division of Forestry. pp. 86-91.

Struve DK (1995) Nitrogen, phosphorus and potassium recovery of container-grown red oak and blackgum seedlings under different fertilizer application methods. J Environ Hort 13(4): 169-175.

Sucoff EI (1961) Potassium, magnesium, and calcium deficiency symptoms of loblolly and Virginia Pine seedlings. Station Paper NE-164. USDA Forest Service, Northeastern Forest Experiment Station, Upper Darby, PA: 18 p. https://www.nrs.fs.fed.us/pubs/sp/sp_ne164.pdf

Sucoff EI (1962) Potassium, magnesium, and calcium requirements of Virginia pine. Station Paper NE-169. USDA Forest Service, Northeastern Forest Experiment Station, Upper Darby, PA: 16 p. https://www.nrs.fs.fed.us/pubs/sp/sp_ne169.pdf

Sung SS, Black CC, Kormanik TL, Counce PA (1997) Fall nitrogen fertilization and the biology of *Pinus taeda* seedling development. Can J For Res 27(9): 1406-1412. https://doi:10.1139/x97-112

Switzer GL (1962) Some effects of nursery soil fertility on loblolly pine (*Pinus taeda* L.) planting stock. PhD thesis, Syracuse University, Syracuse. 151 p.

Switzer GL, Nelson LE (1956) The effect of fertilization on seedling weight and utilization of N, P, and K by loblolly pine (*Pinus taeda* L.) grown in the nursery. Soil Sci Soc Am J20(3): 404-408. https://doi:10.2136/sssaj1956.03615995002000030029x

Switzer GL, Nelson LE (1963) Effects of nursery fertility and density on seedling characteristics, yield, and field performance of loblolly pine (*Pinus taeda* L.). Soil Sci Soc Am J27(4): 461-464. https://doi:10.2136/sssaj1963.03615995002700040028x

Taulavuori K, Taulavuori E, Sheppard LJ (2014) Truths or myths, fact or fiction, setting the record straight concerning nitrogen effects on levels of frost hardiness. Environ Exp Bot 106: 132-137. https://doi:10.1016/j.envexpbot.2013.12.022

Tint H (1945) Studies in the fusarium damping-off of conifers II. relation of age of host, pH, and some nutritional factors to the pathogenicity of fusarium. Phytopathology 35(6): 440-457.

Timmis R (1974) Effect of nutrient status on growth, bud set, and hardiness in Douglas-fir seedlings. In: Tinus RW, Stein WI, Balmer WE (eds) Proceedings, North American containerized forest tree seedlings symposium. Great Plains Agricultural Council Publication 68. USDA Forest Service, Rocky Mountain Forest and Range Experiment Station, Fort Collins, CO: 187-193. https://doi:10.5962/bhl.title.99921

Triebwasser M, Altsuler SL (1995) Fertilization practices and application procedures at Weyerhaeuser. In: Landis TD, Gregg B) Proceedings, forest and conservation nursery associations. PNW-GTR-365. USDA Forest Service, Pacific Northwest Research Station, Portland, OR: 84-88.

Trejo DAR, Duryea ML, White TL, English JR, McGuire J (2003) Artificially regenerating longleaf pine in canopy gaps: initial survival and growth during a year of drought. Forest Ecol Manag 180(1-3): 25-36. https://doi:10.1016/S0378-1127(02)00557-1

Trolldenier G (1985) Effect of potassium chloride vs. potassium sulphate fertilization at different soil moisture on take-all of wheat. J Phytopathology 112(1): 56-62. https://doi:10.1111/j.1439-0434.1985.tb00790.x

Ursic SJ (1956) Late winter prelifting fertilization of loblolly seedbeds. Tree Planters' Notes 26: 11-13.

Vaartaja O (1956) Screening fungicides for controlling damping-off of tree seedlings. Phytopathology 46(7): 387-390.

van den Driessche R (1984) Soil fertility in forest nurseries. In: Duryea ML, Landis TD (eds) Forest nursery manual. Martinus Nijhoff/Junk Publishers, The Hague, Netherlands, pp. 63-74. https://doi:10.1007/978-94-009-6110-4_7

van den Driessche R (1991) Effects of nutrients on stock performance in the forest. In: van den Driessche R (ed) Mineral nutrition in conifer seedlings. CRC Press, Boca Raton, FL: 229-260.

van den Driessche R (1992) Changes in drought resistance and root growth capacity of container seedlings in response to nursery drought, nitrogen, and potassium treatments. Can J For Res 22(5): 740-749. https://doi:10.1139/x92-100

van den Driessche R (1997) Are differences in formulations of fertilizers for use at planting important? In Haase DL, Rose R (eds) Proceedings, forest seedling nutrition from the nursery to the field. Corvallis, OR: Oregon State University, Nursery Technology Cooperative: 101-111.

van den Driessche R, Ponsford D (1995) Nitrogen induced potassium deficiency in white spruce (*Picea glauca*) and Engelmann spruce (*Picea engelmannii*) seedlings. Can J For Res 25(9): 1445-1454. https://doi:10.1139/x95-157

van Rees KCJ, Comerford NB (1990) The role of woody roots of slash pine seedlings in water and potassium absorption. Can J For Res 20(8): 1183-1191. https://doi:10.1139/x90-157

Vanderschaaf C, McNabb K (2004) Winter nitrogen fertilization of loblolly pine seedlings. Plant Soil 265(1): 295-299. https://doi:10.1007/s11104-005-0510-x

Wahlenberg WG (1930) Experiments in the use of fertilizers in growing forest planting material at the Savenac Nursery. USDA Circular 125. Washington, DC: 38 p.

Wakeley PC (1954) Planting the southern pines. USDA Agriculture Monograph 18. Washington, DC: 233 p.

Walker LC (1956) Foliage symptoms as indicators of potassium-deficient soils. Forest Sci 2(2): 113-120.

Walker RF, Susfalk RB, Johnson DW (2016) Root system development of juvenile ponderosa pine as influenced by soil type and nutritional augmentation. Forest Res 5(4): 1-18. https://doi:10.4172/2168-9776.1000187

Wall MM (1994) Influence of fertilization on nutrient status of bare-root *Pinus taeda* L. seedlings. MS thesis, Texas A&M University, College Station. 98 p. http://hdl.handle.net/1969.1/ETD-TAMU-1994-THESIS-W1875

Ward D, Johnson TN (1985) Determination of optimum seedling bed density for bare-root Honduras Caribbean pine. In: South DB (ed) Proceedings, international symposium on nursery management practices for the southern pines. Alabama Agricultural Experiment Station, Auburn University, AL: 118-125.

Westveld RH (1946) Response of slash pine (*Pinus caribaea* Morelet). to various nutrients in Norfolk soils in Florida. MS thesis, Michigan State College of Agriculture and Applied Science, East Lansing. 251 p. https://d.lib.msu.edu/etd/4912

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

Wilde SA (1938) Soil fertility standards for growing northern conifers in forest nurseries. J Agric Res 57(12): 945-952.

Wilde SA (1946) Forest soils and forest growth. Chronica Botanica, MA.

Wilde SA, Kopitke JC (1940) Base exchange properties of nursery soils and the application of potash fertilizers. J Forest38(4): 330-332. https://doi:10.1093/jof/38.4.330

Wilde SA, Wittenkamp R (1939) The phosphate and potash starvation of forest seedlings as a result of the shallow application of organic matter. J Forest37(4): 333-335. https://doi:10.1093/jof/37.4.333

Will GM (1961) Magnesium deficiency in pine seedlings growing in pumice soil nurseries. New Zealand J Agric Res 4(1-2): 151-160. https://doi:10.1080/00288233.1961.10419929

Will GM (1978) Nutrient deficiencies in *Pinus radiata* in New Zealand. NZ J Forest Sci 8(1): 4-14. https://pdfs.semanticscholar.org/7930/48a5055b9bc2da6d6b48a86256d575b8f8b9.pdf

Will GM, Youngberg CT (1978) Sulfur status of some central Oregon pumice soils. Soil Sci Soc Am J 42(1): 132-134. https://doi:10.2136/sssaj1978.03615995004200010029x

Williams RD, Funk DT, Phares RE, Lemmien W, Russell TE (1974) Apparent freeze damage to black walnut seedlings related to seed source and fertilizer treatment. Tree Planters' Notes 25(3): 6-8.

Ylimartimo A (1990) The effect of nitrogen and potassium availability on Scleroderris canker of Scots pine seedlings. Water Air Soil Poll 54(2): 307-313. https://doi:10.1007/BF02385249

Young C (1981) Open-root nursery techniques and planting methods. South Afr For J 117(1): 68-70. https://doi:10.1080/00382167.1981.9630032

Youngberg CT (1952) Maintenance of nursery soil fertility. In: Nursery practice committee. New Westminster, BC: 16-31. https://npn.rngr.net/publications/proceedings/1952/maintenance-of-nursery-soil-fertility/?searchterm=youngberg

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