

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

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## 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<sup>-1</sup>. 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

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## 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 20<sup>th</sup> 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 (Purnell 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 ( $4 \mu\text{g g}^{-1}$  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
<i>Pinus contorta</i>	Field	0.27	Binggeli et al. 2000
<i>Pinus contorta</i>	Bareroot nursery	0.37	Landis 1976
<i>Pinus elliottii</i>	Greenhouse	0.24	McGee 1963
<i>Pinus elliottii</i>	Greenhouse	0.21	Mead and Pritchett 1971
<i>Pinus elliottii</i>	Greenhouse	0.20	Brendemuehl 1968
<i>Pinus radiata</i>	Field	0.35	Raupach and Hall 1971
<i>Pinus radiata</i>	Bareroot nursery	0.35	Knight 1978
<i>Pinus resinosa</i>	Field	0.29	Heiberg et al. 1959
<i>Pinus resinosa</i>	Field	0.31	Madgwick 1964
<i>Pinus resinosa</i>	Greenhouse	0.41	Rosendahl 1943
<i>Pinus strobus</i>	Field	0.33	Heiberg and White 1951
<i>Pinus strobus</i>	Greenhouse	0.41	Schomaker 1969
<i>Pinus strobus</i>	Field	0.44	Walker 1956
<i>Pinus strobus</i>	Bareroot nursery	0.16	Gilmore and Kahler 1965
<i>Pinus sylvestris</i>	Under roof	0.27	Ylimartimo 1990
<i>Pinus sylvestris</i>	Greenhouse	0.34	Holopainen and Nygren 1989
<i>Pinus taeda</i>	Field	0.29	Carlson et al. 2014
<i>Pinus taeda</i>	Bareroot nursery	0.18	Gilmore and Kahler 1965
<i>Pinus taeda</i>	Greenhouse	0.26	Sucoff 1961
<i>Pinus taeda</i>	Field	0.34	Albaugh et al. 2010
<i>Pinus virginiana</i>	Greenhouse	0.28	Sucoff 1962

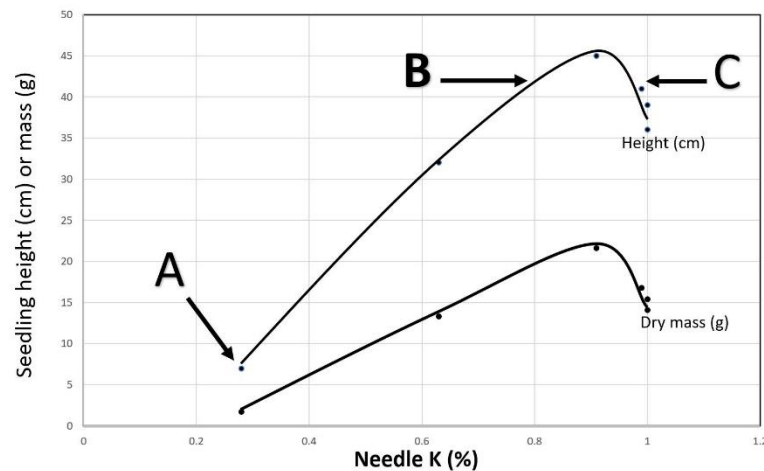


Figure 1. Response curves for pine seedlings to potassium (K). Data are for greenhouse-grown pine seedlings in sand (after Sucoff 1962). Point (A) illustrates the beginning of the hidden hunger zone and point (B) is the end. Visual deficiency symptoms occur at “A” while “B” is the critical level, defined 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  $\mu\text{g g}^{-1}$  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  $\mu\text{g g}^{-1}$  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 (Frayse and Crémère 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.

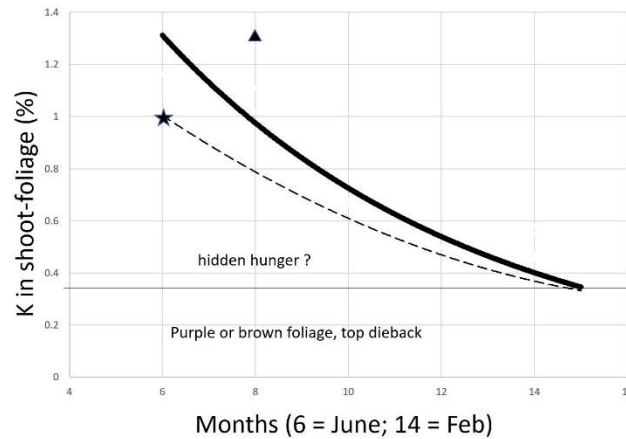


Figure 2. Foliar tests can be used to determine when to apply foliar applications of potassium (K). When foliar tests for loblolly pine needles are above the dashed line, K fertilization is not expected to affect seedling performance. Visual deficiency symptoms may occur when foliar tests are less than 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 <sup>-1</sup>	% K	Reference
<i>Pinus taeda</i>	Shoot	June	0	1.16	Switzer and Nelson 1956
<i>Pinus taeda</i>	Needle	July	??	1.11	Starkey and Enebak 2012
<i>Pinus taeda</i>	Shoot	Aug	??	1.11	Danielson 1966
<i>Pinus taeda</i>	Shoot	Aug	56	1.02	South et al. 1988
<i>Pinus echinata</i>	Needle	Aug	0	0.98	Brissette and Carlson 1987
<i>Pinus taeda</i>	Needle	Sept	??	0.95	Miller et al. 1985
<i>Pinus taeda</i>	Shoot	Oct	0	0.68	Switzer and Nelson 1956
<i>Pinus taeda</i>	Shoot	Oct	??	0.66	Starkey and Enebak 2012
<i>Pinus elliottii</i>	Shoot	Nov	167	0.92	Munson and Stone 1984
<i>Pinus elliottii</i>	Shoot	Dec	0	0.56	Steinbeck 1962
<i>Pinus elliottii</i>	Shoot	Dec	0	0.55	Steinbeck 1962
<i>Pinus echinata</i>	Needle	Dec	0	0.54	Brissette and Carlson 1987
<i>Pinus taeda</i>	Shoot	Dec	0	0.54	Rowan 1987
<i>Pinus taeda</i>	Needle	Jan	0	0.60	Wall 1994
<i>Pinus taeda</i>	Needle	Jan	0	0.52	May 1957a
<i>Pinus taeda</i>	Needle	Jan	0	0.54	May 1957a
<i>Pinus taeda</i>	Needle	Jan	??	0.57	May et al. 1962
<i>Pinus taeda</i>	Needle	Jan	??	0.35	Miller et al. 1985
<i>Pinus taeda</i>	Shoot	Jan	??	0.31	Starkey and Enebak 2012
<i>Pinus taeda</i>	Needle	Feb	69	0.58	Switzer and Nelson 1963
<i>Pinus taeda</i>	Stem	Feb	69	0.55	Switzer and Nelson 1963
<i>Pinus taeda</i>	Shoot	Feb	108	0.74	South et al. 2017
<i>Pinus taeda</i>	Seedling	Feb	??	0.49	Bryan 1954
<i>Pinus taeda</i>	Needle	Feb	??	0.47	Danielson 1966
<i>Pinus taeda</i>	Stem	Feb	??	0.46	Danielson 1966
<i>Pinus taeda</i>	Seedling	Feb	??	0.45	Sung et al. 1997
<i>Pinus echinata</i>	Needle	March	13	0.27	Gilmore and Kahler 1965
<i>Pinus taeda</i>	Needle	March	13	0.25	Gilmore and Kahler 1965
<i>Pinus elliottii</i>	Shoot	March	167	0.82	Munson and Stone 1984
<i>Pinus palustris</i>	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<sup>-</sup>) 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 ( $\text{HNO}_3$ ) along with various rates of potassium nitrate ( $\text{KNO}_3$ ) (Brown et al. 1981; Holopainen and Nygren 1989). Likewise, it would be informative to compare a response curve for  $\text{KNO}_3$  (Figure 4) with an equivalent response curve for  $\text{HNO}_3$ . Future researchers should not assume that only one element (in  $\text{KCl}$  or  $\text{K}_2\text{SO}_4$ ) qualifies as the dependent variable.

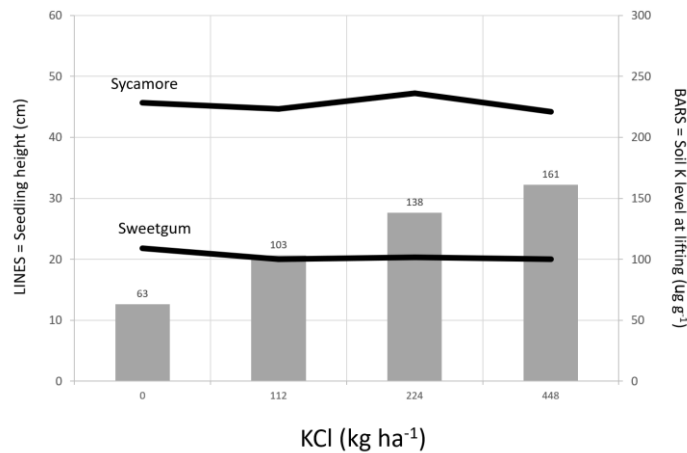


Figure 3. Response curves for hardwoods seedlings growing in bareroot seedbeds (silt loam). With no nitrogen fertilization, applying  $\text{KCl}$  at this nursery did not improve height growth of either sycamore or sweetgum but the level of  $\text{K}$  in the soil was increased. Applying  $224 \text{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

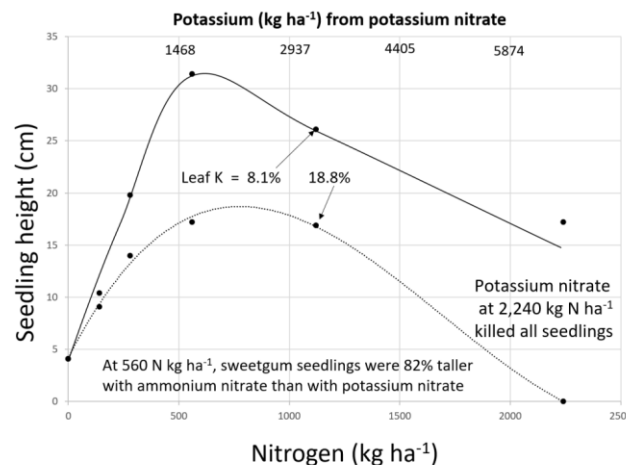


Figure 4. Response curves for 5-month-old sweetgum (*Liquidambar styraciflua* L.) seedlings. Seedlings were growing in a soil-sand-bark mix and were treated with ammonium nitrate (solid line) and  $\text{KNO}_3$  (dotted line). Applying too much  $\text{KNO}_3$  can increase foliar  $\text{K}$  concentration and reduce height growth (Brown et al. 1981). All nitrogen ( $\text{N}$ ) treatments were applied in eight equal applications spaced about two weeks apart. Therefore, the highest  $\text{KNO}_3$  treatment received eight applications of  $2,154 \text{ kg ha}^{-1}$  each (i.e., a total of  $2,240 \text{ kg ha}^{-1}$  of  $\text{N}$ ). When the growing medium contains  $72 \mu\text{g g}^{-1}$   $\text{K}$ , sweetgum seedlings can grow well with only ammonium nitrate fertilization. Rates of  $\text{K}$  at the top of the graph apply only to  $\text{KNO}_3$  treatments and rates this high are not used to grow sweetgum in bareroot nurseries. Applying too much  $\text{KNO}_3$  ( $\text{N}/\text{K}_r$  ratio = 0.35) can kill seedlings. Due to the high cost per kg (as either  $\text{N}$  or  $\text{K}$ ),  $\text{KNO}_3$  is used primarily by researchers. As a comparison, 5-month-old sweetgum seedlings were  $21.8 \text{ cm}$  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; Purnell 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  $35 \mu\text{g g}^{-1}$ , a growth response from KCl fertilization might occur. For example, a sterile soil with  $30 \mu\text{g g}^{-1}$  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  $300 \mu\text{g g}^{-1}$ , adding KCl ( $100 \mu\text{g g}^{-1}$  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  $217 \text{ kg ha}^{-1}$  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 ( $224 \text{ kg ha}^{-1}$  KCl before sowing plus  $224 \text{ kg ha}^{-1}$  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  $27 \mu\text{g g}^{-1}$  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  $\text{K}_2\text{SO}_4$  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  $\text{K}_2\text{SO}_4$  before sowing resulted in only  $13 \mu\text{g g}^{-1}$  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  $78 \mu\text{g g}^{-1}$ . 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%  $\text{K}_2\text{O}$ ) before sowing, especially when seedbeds are low in magnesium (Mg).

Although fertilized sandy nurseries may contain about  $50 \mu\text{g g}^{-1}$  of available K at time of sowing, infertile fields may contain less than  $30 \mu\text{g g}^{-1}$  before fertilization (Figure 5). When seedbeds contain  $12 \mu\text{g g}^{-1}$  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  $13 \mu\text{g g}^{-1}$  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  $200 \text{ kg ha}^{-1}$  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  $\text{KNO}_3$  (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<sup>-1</sup> 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<sup>-1</sup> of KCl was applied before sowing (Steinbeck 1962). Most managers now apply zero to 300 kg ha<sup>-1</sup> of KCl before sowing while others apply 224 to 336 kg ha<sup>-1</sup> 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 <sup>-1</sup>	Soil K µg g <sup>-1</sup>	K Fertilizer after sowing	K applied kg ha <sup>-1</sup>	Total K kg ha <sup>-1</sup>	N/K <sub>f</sub> ratio
Buckeye/FL	1977	95	5-10-15	98	26	KCl**	17	115	1.7
Andrews/FL	1977	94	K <sub>2</sub> SO <sub>4</sub>	153	13	K <sub>2</sub> SO <sub>4</sub> *	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 <sub>2</sub> SO <sub>4</sub> *	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 <sub>2</sub> SO <sub>4</sub> *	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
<b>Median values</b>	--	84	--	65	61	--	56	113	1.8

\* = one top-dressing; \*\* = two top-dressings; \*\*\* = three top-dressings  
Fertilizer code = (N-P<sub>2</sub>O<sub>5</sub>-K<sub>2</sub>O)

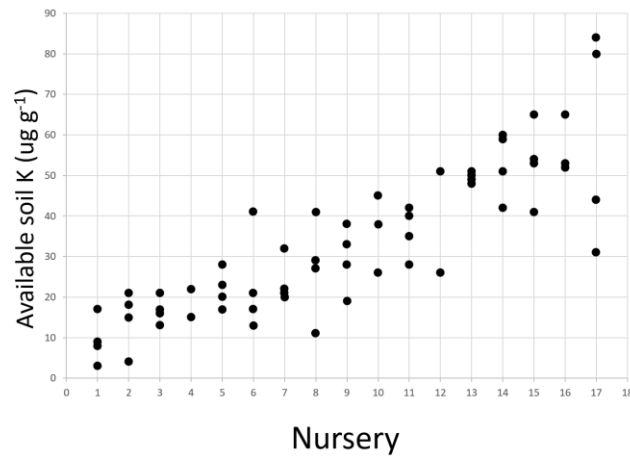


Figure 5. Pre-fertilization soil test results for available K (Mehlich 3) from 17 nurseries. Each dot represents the lowest reported value for a particular year (two, three or four years per nursery). Nurseries are ranked from the lowest soil K (#1) to highest (#17). Course textured soils have numbers below 11 while higher numbers represent finer textured soils. After fertilization (at time of sowing), the average K value for sandy nurseries is about  $54 \mu\text{g g}^{-1}$  K and the average for finer-textured nurseries is  $105 \mu\text{g g}^{-1}$  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  $61 \text{ kg ha}^{-1}$  (Table 3). Applications to bareroot seedbeds ( $12 \text{ kg ha}^{-1}$  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 ( $300 \text{ kg ha}^{-1}$ ) 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 ( $310 \text{ kg ha}^{-1}$ ) 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  $310 \text{ kg ha}^{-1}$  of KCl was applied eight months after sowing (Hodgson 1977). Several researchers have demonstrated that pine seedlings 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  $66 \text{ kg ha}^{-1}$  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  $\text{KNO}_3$  is a “waste of both time and money” (Davey 2002). Growers in the western United States prefer to use  $\text{K}_2\text{SO}_4$  (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  $\text{K}_2\text{SO}_4$  and one applied K-mag (Table 3). In other countries, about half of nursery managers prefer to apply  $\text{K}_2\text{SO}_4$  (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	$\text{K}_2\text{SO}_4$	0-0-50	41	granular	882	2.15
K magnesium sulfate	$\text{K}_2\text{SO}_4\cdot 2\text{MgSO}_4$	0-0-22	18	granular	441	2.45
Potassium hydroxide	KOH	0-0-83	69	granular	2346	3.40
Potassium thiosulfate	$\text{K}_2\text{S}_2\text{O}_3$	0-0-25	21	liquid	735	3.50
Potassium nitrate	$\text{KNO}_3$	13-0-44	37	granular	1764	4.46
Potassium nitrate	$\text{KNO}_3$	3-0-12	10	liquid	485	4.59
Mixture	$\text{KCl} + \text{K}_2\text{SO}_4\cdot 2\text{MgSO}_4$	10-10-10	8	granular	468	4.75
Potassium phosphate	$\text{KH}_2\text{PO}_4$	0-52-34	28	granular	1372	4.90
Potassium carbonate	$\text{K}_2\text{CO}_3$	0-0-30	25	liquid	2425	9.70
Potassium sodium nitrate	$\text{KNa}(\text{NO}_3)_2$	15-0-14	12	granular	1530	11.65
Potassium acetate	$\text{CH}_3\text{CO}_2\text{K}$	0-0-29	24	liquid	7172	29.80
Potassium silicate	$\text{K}_2\text{O}_3\text{Si}$	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<sub>2</sub>O<sub>5</sub>-K<sub>2</sub>O)

Some nursery managers apply K-mag as a top dressing at a rate of 224 kg ha<sup>-1</sup> (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<sup>-1</sup>. 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  $\text{KNO}_3$  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  $\text{K}_2\text{SO}_4$  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<sub>2</sub>SO<sub>4</sub> 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<sub>2</sub>SO<sub>4</sub> (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<sup>-1</sup> 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<sub>3</sub>) 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<sup>-1</sup> of KCl reduced survival of stored pine seedlings by 10 to 13% (Dierauf 1982). In another trial, N (179 kg ha<sup>-1</sup>) plus KCl (372 kg ha<sup>-1</sup>) 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<sup>-1</sup>) 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  $200 \mu g g^{-1}$  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).

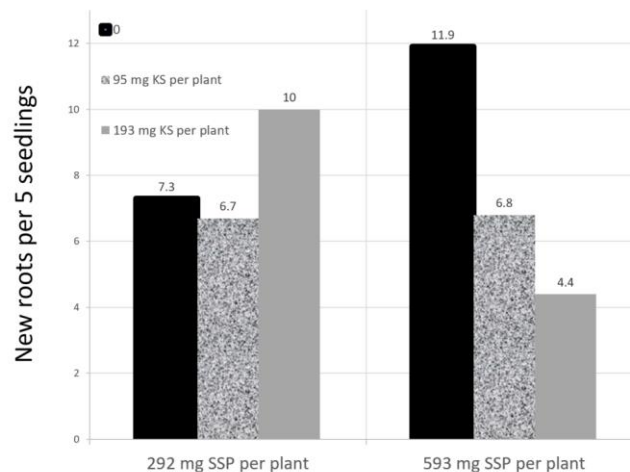


Figure 6. The effect of  $K_2SO_4$  (KS) and single superphosphate (SSP) on root growth potential (RGP). A factorial fertilizer study tested the effects of three fertilizers on RGP of bareroot pine seedlings (Donald 1988). Fertilizers included KS, and SSP (which contains P, Ca and S) and lime ammonium nitrate (LAN) (which contains N, Ca, and Mg). Fertilizer rates are listed as mg per seedling with 100 mg equivalent to  $133 \text{ kg ha}^{-1}$ . 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  $3 \times 3 \times 3$  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 ( $\alpha=0.05$ ). 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  $42 \mu\text{g g}^{-1}$  K) was treated with  $100 \text{ kg ha}^{-1}$  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  $134 \text{ kg ha}^{-1}$  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 *Anthraxnose* 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  $2^\circ\text{C}$  (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  $\$3,000 \text{ ha}^{-1}$  ( $336 \text{ kg ha}^{-1}$  of product). In a study with greenhouse-grown slash pine, KCl or  $K_2SO_4$  (approximately  $20 \text{ Mg ha}^{-1}$ ) 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<sup>-1</sup> 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<sup>-1</sup> 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<sup>-1</sup> in July plus 270 kg ha<sup>-1</sup> 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<sub>2</sub>SO<sub>4</sub> did not affect bud formation when shoots contained 1% K (Timmis 1974). Likewise, adding KH<sub>2</sub>PO<sub>4</sub> 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<sub>3</sub> (160-320 kg ha<sup>-1</sup>) 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<sup>-1</sup>) 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 ( $\text{mg seedling}^{-1}$  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  $N = 200 \text{ kg ha}^{-1}$ ).

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

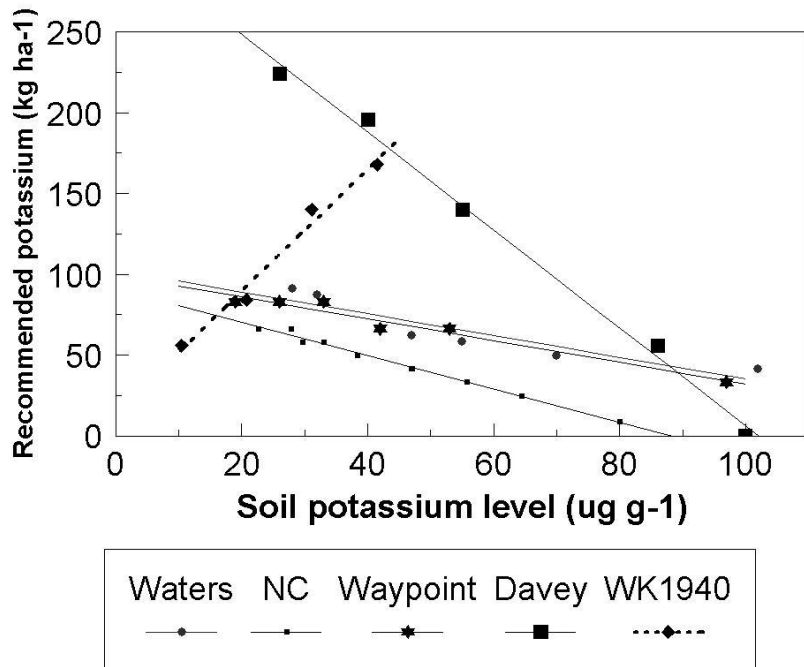


Figure 7. Soil tests (x-axis) are used as a tool for making potassium (K) recommendations (y-axis). Rates for loblolly pine seedbeds will depend on if recommendations are based on soil cation exchange capacity [dotted line - Wilde and Kopitke (1940)] or on results from soil K extraction tests (solid lines). When soil tests indicated less than 40 µg g<sup>-1</sup> K, three soil laboratories (Waters, North Carolina and Waypoint) suggest applying less than 100 kg ha<sup>-1</sup> 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<sub>f</sub> ratio of 2.7 (224 kg N and 83 kg K ha<sup>-1</sup>) and there is no economic reason to justify applying a N/K<sub>f</sub> 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<sup>-1</sup> of K to 1-0 bareroot seedbeds. Although low N/K<sub>f</sub> 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<sub>f</sub> with K<sub>2</sub>SO<sub>4</sub> will sometimes reduce the growth of container-grown pines (Srivastava et al. 1979; Del Campo et al. 2011a). Fertilizers with a N/K<sub>f</sub> ratio of 0.6 will cost more (vs N/K<sub>f</sub> ratio = 2.0) to achieve equal-sized seedlings (Oliet et al. 2004). As a result, some researchers do not even test N/K<sub>f</sub> ratios that are lower than 1.0 (Struve 1995; van den Driessche 1997). Although data indicate no benefit to low N/K<sub>f</sub> 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<sub>f</sub> 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  $\mu\text{g g}^{-1}$  to more than 160  $\mu\text{g g}^{-1}$  (Table 6). Deficiencies have been reported when sandy soils contain less than 20  $\mu\text{g g}^{-1}$  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 $\mu\text{g g}^{-1}$	Upper value $\mu\text{g g}^{-1}$	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  $\mu\text{g g}^{-1}$  K would receive perhaps 56  $\text{kg ha}^{-1}$  of K while a loam soil (CEC = 8) with 42  $\mu\text{g g}^{-1}$  K would receive about 168  $\text{kg ha}^{-1}$  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 ( $< 25 \mu\text{g g}^{-1}$ ) 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  $112 \text{ kg ha}^{-1}$  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), nursery 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  $\text{K}_2\text{SO}_4$  before sowing pines or hardwoods.
- 3) KCl is commonly used in bareroot nurseries because it is readily available and costs less than  $\text{K}_2\text{SO}_4$ .
- 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  $100 \text{ kg ha}^{-1}$  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  $10 \mu\text{g g}^{-1}$  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 20<sup>th</sup> century.

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