Questions about toppling of pine seedlings

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Abstract

The term used to describe blow down of old trees is windthrow. In contrast, toppling is used when planted pines lean more than 15° during the first decade after transplanting. Pines tend to topple more than other conifers and fast-growing species topple more than slow growing genotypes. Large areas of pine plantations have toppled before age 8 years. This paper describes some toppling events that have occurred in 18 countries and includes 16 questions about toppling.

Keywords

Windthrow; Container; Bareroot; Root deformation; Taproot

Contents

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1 Introduction

High winds can blow trees over, especially on soils that are wet and loose. This is a global problem and in some areas the rotation age is reduced in hope of avoiding an economic loss. Synonymous terms used to describe these events in mature forests include blown over, blowdown, windthrow and windfall and some of these terms have been used for over a century (Weidman 1920). This paper, however, does not cover windthrow of plantations older than 9 years but, instead, pertains to the toppling of younger stands.

Although the term topple can mean the tree is resting on the ground, in reforestation jargon, a "toppled" tree has a lean of 15° or more from vertical (Mason 1985). Toppling affects fast-growing pines and is often not a concern when early height growth is less than 15 cm year^{-1} (Alm 1974; Sloan et al. 1987; Ferguson et al. 2005). This paper reviews literature from the 20th century and proposes several questions about toppling.

2 History

Although storms affected the lean of planted trees during the 19th century, the term "toppling" in regards to young plantations seems not to appear in the literature until after 1960. Although citations in the following section represent toppling events from 18 countries, several references did not specify toppling height and stand age. Selected references that included age and height data are plotted in Figure 1. Additional references are not listed since numerous reports were not translated into English.

2.1 Australia

[Bareroot; *Pinus radiata*; Pryor 1937] "In the first year or two after planting out, the roots are of little mechanical value, and if the soil is at all boggy most trees will blow over." **[Bareroot; *Pinus radiata*; Clarke 1956; AU56]** "In a study made at Mount Stromlo Forest in 1955 it was found that the stability of slit-planted *Pinus radiata* 5 years of age and younger against wind pressure is largely dependent upon the nature and extent of its root system. The planted pines were generally found to have a shallow, poorly developed root system compared with natural regeneration, and were less wind-firm."

"The root system of the planted pines consisted of either a short tap-root or no tap-root at all, with only comparatively few shallow lateral roots. These lateral roots were generally not evenly spaced in all directions, but tended to develop in two main opposite directions along the plane of the slit. Laterals going in other directions were not as large as those referred to above." In one compartment, 35 to 50% of the bareroot stock toppled compared to less than 1% of natural pine seedlings.

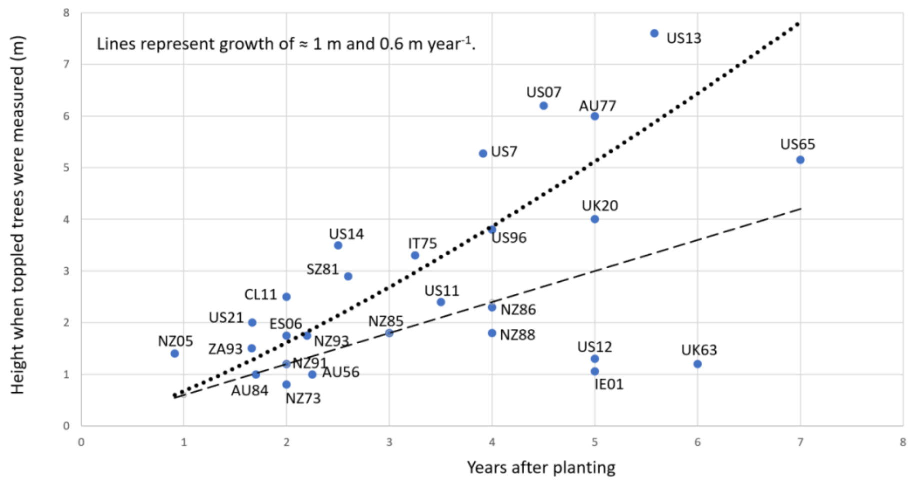

Figure 1. Toppling of pines is related to stand age and height growth. Gale force winds can topple pines before a plantation is eight years old. The risk of toppling is greatest when the rate of height growth is >0.5 m per year. The codes listed in this graph indicate country and year of publication (AU77 = Australia; Bacon and Hawkins 1977). Additional information on the 27 points on this graph are included in the following text. Species represented in this graph include *Pinus caribaea* (1), *P. contorta* (2), *P. echinata* (1), *P. elliottii* (2), *P. palustris* (2), *P. patula* (1), *P. radiata* (14), *and P.taeda* (4).

[Bareroot, container; *Pinus caribea*; Bacon and Hawkins 1977; AU77] Root wrenching trials were conducted at two bareroot nurseries in Queensland. Seedlings allowed to grow freely were 47 to 65 cm tall when lifted in the summer while seedlings root-wrenched twice a month were 29 to 42 cm tall. Some toppling of outplanted seedlings occurred when seedlings were root-wrenched at a soil depth of 7.5 cm but no toppling was observed if root-wrenching was conducted at a 15 cm depth. There was no mention of toppling if pines were grown in tubes.

[Bareroot; *Pinus elliottii*; Francis et al. 1984; AU84] In May 1974, bareroot seedlings were planted on a shallow soil on the coastal lowlands of Queensland. A cyclone occurred in January 1976 and some trees in experimental plots had a lean of 14°. Ripping the soil prior to planting had no effect on windfirmess but fertilization with ammonium nitrate five months after planting reduced the degree of lean. Additional root growth (October 1974 to January 1976) might have increased windfirmess.

[Bareroot; *Pinus spp.*; Cremer 1984] The "tilting of saplings probably affected about 1000 ha/yr." "Tilting occurred mainly in planted stock. *P. radiata* was prone to tilting till it was 2-3 m tall, while *P. elliollii* var. *elliollii* and *P. caribaea* var. *hondurensis* in Queensland commonly tilted till they were about 10 m tall. The ability to grow upright and straight diminished with size. Saplings tilted when about 1 m tall recovered completely, but those over 2 m tall retained curved butts and sinuous stems."

[Bareroot; *Pinus elliottii*; Stewart and Flinn 1984] "In an irrigated situation, where there is a wide spectrum of vigorous weeds, the most damaging effect is overtopping of small trees, causing toppling and competition for light. The aim of weed control was to provide trees with a competitive advantage, rather than to eliminate the weeds, for a low cover of weeds assists in stabilising softs during the tree establishment phase."

[Container; *Pinus radiata*; Lyons 2002] "Given that the toppling on NE Tasmanian farms was due to poor root development, most plantations of Hiko-propagated trees were replanted by the landholders with open rooted plants. Some plantations of Hiko-propagated plants not showing toppling were also replanted, because toppling is likely to occur later and especially immediately after first thinning." A common factor among toppled plants in 2000 was that all were propagated in Hiko containers and fertilised with phosphorous and nitrogen after planting. Toppled trees had a large bulbous knob below the ground at the base of the trunk and the roots were balled or wrapped about the bulb. The nursery advised that the containers were used according to specification. In discussions about the suitability of the containers for growing radiata pine, the manufacturers and distributors had not raised concerns.

2.2 Brazil

[Containers, direct seeding; *Pinus radiata*; Mattie 1993] "The southern coast of Brazil has extensive pine plantations, where the constant occurrence of winds has caused many toppling-off problems. Direct sowing in the field can mitigate such risks by providing greater stability to plants due to a better distribution of roots." [Text translated from Portuguese]

2.3 Canada

[Bareroot; *Pinus contorta*; Dykstra 1974] "Basal sweep and toppling may be caused by the lack of development and growth of a dominant taproot after the primary taproot has been severed, such as in root pruning, undercutting, and lifting." Taproot growth was 50 cm for control seedlings while growth was 50 to 80% less for undercut seedlings.

[Container; *Pinus banksiana*; Carlson and Nairn 1977] Three years after outplanting, "Three types of root deformities were noted: spiraling, container compression, and kinked roots. Spiraling and container compression were most severe with seedlings grown in the BC/CFS Styro 2 and the 408 paperpot. The use of a rib-type container should eliminate spiraling. Seedling growth was directly related to the volume of the original containers, but could not be correlated with deformities."

[Container; *Pinus contorta*; Burdett 1978] "In a minority of cases, the tap root of seedlings grown in the painted Styroblocks had aborted upon coming into contact with the copper-coated container wall. However, this usually had little effect on root form, since in most cases a first-order lateral root took over the growth habit and function of the tap root."

[Review; Van Eerden 1981] "The degree of root deformation of newly planted trees is governed by nursery practice, container design, planting method and quality, and site conditions. Evidence suggests that root systems of planted trees become increasingly "normal", and that toppling of planted trees will not be a major problem in Canadian forests." "In my view, there are three approaches to dealing with root deformation: 1) cease planting of container-grown stock for species that are particularly susceptible to root deformation; 2) assess the risks associated with root deformation of container stock in economic terms, and then decide whether to accept the risk or not; 3) minimize root deformation through improvements in container design and cultural practice."

[Container; *Pinus contorta*; Burdett et al. 1986] "Toppling has occurred in lodgepole pine (*Pinus contorta* Dougl.) plantations throughout British Columbia. Generally the number of trees has been small; although in the southern interior of the province the majority of trees in some plantations have toppled. In areas where toppling in planted trees has occurred, naturally established lodgepole pine is relatively stable. Since planted trees are usually of the native provenance, this suggests toppling in plantations is primarily the result of nursery and planting effects on root morphology. More normal root morphogenesis, and hence greater stability can be achieved by planting young seedlings that retain the capacity to initiate primary lateral roots. Pruning the lateral roots of older stock provides another approach. A chemical method for pruning lateral roots of container-grown lodgepole pine seedlings has been developed and adopted commercially in British Columbia and elsewhere."

[Review; Arnott and White 1991] "Trewin – Have you done any studies on root form comparing bare-root stock with container stock? Arnott – Yes, we studied root development and we see no reason to indicate a difference in stability. Better studies were done in Scandinavia related to problems with paper pots; as a result they have got away from those. A root-pruning chemical is also available for use in styro container."

[Container, natural seeded; *Pinus contorta*; Halter et al. 1993] "We detected significant differences in growth and root morphology of artificially and naturally-regenerated lodgepole pine 11 years after planting on the north coast of British Columbia. Research from southern and central United States with bareroot loblolly pine (*Pinus taeda* L.) and shortleaf pine (*P. echinata* Mill) (Harrington et al. 1989), from Sweden with containerized Scots pine (*P. sylvestris* L.) (Lindstrom 1990), and from southeastern British Columbia, Canada, with containerized lodgepole pine and Douglas fir (Halter and Chanway 1993) has indicated that planted seedlings and saplings, aged 3-12 years undergo changes in root system morphology that may lead to instability or toppling." "In addition, root stocks of planted saplings possessed remnants of vertical container shaping and a number of deformed roots that were either constricted, coiled and/or kinked. Naturally regenerated saplings illustrated elaborate sinker root development, and an assortment of self-grafted roots which were not observed on planted saplings. Possible effects of containerization on root morphology are discussed in relation to difficulties which may arise from artificial regeneration of cut-over sites."

[Container, natural seeded; *Pinus banksiana*; Balisky et al. 1995] "The root form photographs show that jack pine seedlings with juvenile rooting systems in fragile plugs (which are not yet "root-bound") produced "natural" root form when outplanted. Longer nursery rearing in walled cavities results in the growing points of primary support roots being directed to the lower part of the root plug. Stability problems with pines tend to increase with increasing time that the seedlings have grown in container cavities (A. Lindström, Swedish University of Agricultural Sciences, pers. comm. with Salonius)."

[Container; *Pinus contorta*; Krasowski 2003] “The troubles with stability of pines develop mainly on moist, fine-textured soils, and sites with such soils should not be planted to pines in the first place. The importance of proper choice of species and stock types best suited for the requirements of particular sites cannot be underestimated.” “Interestingly, it was determined that taproots in lodgepole pine were often rudimentary even in naturally regenerated trees. The presence or absence of a taproot had no significant relationship to the strength of anchorage, which is dependent on the numbers, sizes, and distribution of the lateral and sinker roots.”

[Container, natural seeded; *Pinus contorta*; Robert and Lindgren 2006] “The other root characteristics that distinguish planted trees from natural trees (poor taproot, spiral root, poor lateral spread, lateral compression, braiding, and root pairs) cannot be attributed definitively to poor planting and may be the result of container constraints.”

[Review; Grossnickle and El-Kassaby 2015] “There can be a stocktype effect on long-term root development patterns (i.e. lack of a natural root form and root distribution for both stocktypes) that can potentially affect long term stand stability, though inherent species characteristics, nursery root culturing practices and site environment also shape root system form. The risk of windthrow has not been consistently demonstrated for either stocktype. This topic would benefit from further research.”

2.4 Chile

[Bareroot; *Pinus radiata*; Escobar et al. 2002] “Currently, there is still controversy about the rooting form and grade of the cuttings. Some people think that more roots at the base of the cutting indicates higher seedling quality and greater stability after planting. During this winter, about 15,000 ha of 1- to 3-years-old plantings were severely affected by the wind. On the other hand, others consider that the origin and vigor of the roots is more important for quality of the root system. They consider that the wind problem depends more on the interaction of the soil characteristics, such as moisture, texture, depth, and structure, than the structure of the root system."

[Bareroot; *Pinus radiata*; Toral et al. 2011] Wind in July 2000 toppled seedlings two years after planting. “Trees with a strong, dominant and well-developed tap root (Menzies value equal to zero) showed a toppling probability of 0.34 (1 of each 3 trees being damaged). At the other extreme, trees with a horizontal tap root or with no tap root (Menzies value equal to 10) showed a toppling probability of 0.72 (i.e., three of each four trees were damaged). A toppling probability of 0.50 (or damage observed in one of each two trees) was found for trees with a tap root distinctly hooked but functional (Menzies value equal to 4). ”The study suggests that “all measures favoring a strong, dominant and well-developed tap root, in the nursery and in the field, are likely to considerably reduce toppling damage in young *P. radiata* plantations in Chile.”

2.5 China

[Bareroot; *Pinus elliottii*; Toral et al. 2011; CL11] “The 2008 ice storm brought extensive damage to subtropical forests in China. Ice damage was characterized with a variety of patterns, i.e., bending, leaning, branch breakage, stem breakage, decapitation, and uprooting." "Three-year-old *P. elliottii* was the most extensively damaged by the ice storm, with an overall damage rate of 55.32%." Planted stands of slash pine and loblolly pine received much more damage than *Pinus massoniana.*

2.6 Eswatini

[Container, bareroot; *Pinus patula*; Germishuizen and Marais 1981; SZ81] "There is some evidence that under the slash conditions at Usutu, young *Pinus patula* trees (2 to 3 years old) could be subject to toppling in strong wind. On examination of the root systems of young trees which had toppled we found that excellent lateral root growth had taken place, but no tap-root or sinker roots had formed. It is felt that the nursery system (polythene tube) could be a contributary factor, but that the ideal rooting conditions (moist soil even in winter, with limited evaporation; slow release of nutrients at the soil surface etc., Donald, 1979) favoured lateral root growth to the detriment of sinkers or tap-roots." "To substantiate the theory that the nursery system also played a role, *Pinus patula* seedlings were examined in a field trial where the polythene system was being compared to the open-rooted system. A substantially higher percentage of open-rooted seedlings showed tap-root formation than did polythene tube seedlings."

2.7 Fiji

[Container; *Pinus caribaea*; Bell 1978] "The greatest damage from hurricanes is caused to two or three-year-old plantations. Large numbers of this age group are blown over and have to be propped up with stakes to prevent development of crooked stems. After damage from hurricane 'Bob', the number of two and three-year-old trees propped up in the Lautoka-Lololo area was 634,101 at a cost of U.S. $30,000 (Fiji Pine Commission report). Of 10 of the blown trees that were dug up, 9 had severe root deformities associated with nursery container restrictions, bad planting, or a combination of both."

2.8 France

[Bareroot; *Pinus nigra*; Deleporte 1981] Roots were deformed into L, J, and ball shapes at time of planting. Excavations after 3 years showed that root deformations were still apparent and roots under the deformations had reduced growth and "the configuration of root system of deformed trees does not allow for a good anchoring and stability." After 5 years the height of trees with deformed roots did not differ from those with I-roots.

[Container; *Pinus pinaster*, *P. taeda*; Ba et al. 2010] "Stems are often leaning and sinuous, thus inducing [compression wood] CW formation, and wood quality is considered poor (Timell 1986; Fourcaud 1999). Trials have therefore been carried out for several decades in the south-west of France in search of another timber and pulp species with superior growth and wood properties to maritime pine. Loblolly pine (*Pinus taeda* L.), a fast-growing native North American species, has been tested in several trials (Abraham et al. 2003) and was also reported as better resisting uprooting during the severe wind storm which hit France in 2009 (G. Chantre, pers. comm.)."

[Container; *Pinus pinaster*; Dorval et al. 2016] A storm in January 2009 toppled trees 11 years after planting in south-western France. Trees were approximately 8 m tall and toppling of three stands ranged from 30 to 38%. "A large main taproot, either short and thick or long and thin, and guyed by a large volume of deep roots, was the major component that prevented stem leaning. Greater shallow root flexural stiffness mainly at the end of the zone of rapid taper on the windward side also prevented leaning. Toppling in less than 90-cm-deep soil was avoided in trees with a stocky taproot or with a very big leeward shallow root. Toppled trees also had a lower relative root biomass – stump excluded – than straight trees."

2.9 Iceland

[*Pinus contorta*; Loftsson 2013] "As yet, lodgepole pine has not suffered serious injury from insects or fungal diseases, but it has been damaged by snow due to the heavy-branching habit of the provenance most commonly planted. Furthermore, instability has been observed in pole stands, where trees have been toppled during wind storms. Tree toppling can be traced to root deformation caused by improper cultural practices in the nursery or at planting."

2.10 Ireland

[Container, bareroot; *Pinus contorta*; Pfeifer 1982] "Containerised seedlings have been used on an experimental basis in both Britain and Ireland to try to reduce the incidence of basal sweep. It was argued that they would reduce the early rapid growth and low root/shoot ratio to which transplants were prone and thus produce a better balanced plant. Results to date appear encouraging and Lines (1980) reports that the tubed seedlings described by Low (1975) have markedly reduced the incidence of basal sweep, though without eliminating the problem completely. This can perhaps be attributed to the fact that root spiralling occurs in hard walled containers and illustrates the type of root system that a tubed seedling can develop."

[Container, bareroot; *Pinus contorta*; Seaby and Schaible 2001; IE01] "Kopparfors seedlings (KS) were the least successful stock, often producing a spiral root system. After a few years this appeared like a huge snail shell. Spiral root configuration for KS, combined with wind exposure on top of the plough ribbons led to exceptionally bad early onset-bowing. It may be noted the Kopparfors company later made grooves in their seedling trays to channel roots vertically."

"A policy change to stop planting SCPC [south coastal providence of *Pinus contorta*], due to bowing, meant that even the most efficient cone planting spade was used only experimentally. Despite the growth and survival advantages it gave, even to Sitka spruce, the method had been linked with SCPC and both were relegated together."

2.11 Italy

[Container; *Pinus radiata*; Eccher 1975; IT75] A trial at the "Ovile Farm" (Rome) was installed to investigate the effects of seedling age and root pruning on early tree growth and stability of *Pinus radiata*. After sowing, seedlings were grown in 1-liter plastic bags for 12, 14, 16, 18, 20 and 22 months. Height in the nursery ranged from 20 cm (12 months) to 60 cm (22 months). At transplanting, half of the bags were slit (from top to bottom) and tangled roots at the bottom were removed. Seedlings were measured for height and lean 3.25 years from planting (Figure 2). Growing container seedlings in the nursery for more than 14 months increased toppling and reduced height growth. Cutting roots (lengthwise) and removing malformed roots at the bottom of the plastic bag increased tree stability and growth of the 20-22 month-old seedlings.

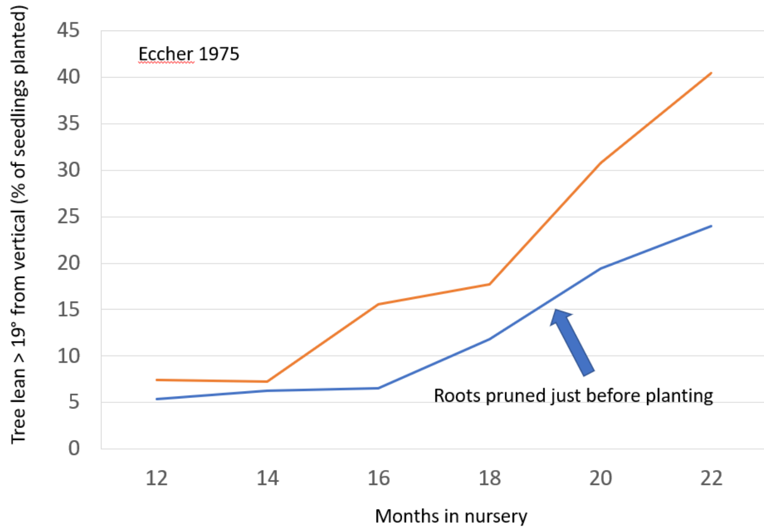

Figure 2. Toppling after planting was related to pot-binding in the nursery (Eccher 1975). When *Pinus radiata* seedlings were grown for 22 months in the nursery in 1-liter plastic bags, without root pruning (orange line), four out of ten seedlings toppled 3.25 years after transplanting. Pruning roots of pot-bound seedlings prior to outplanting (blue line) increased stability.

2.12 Mauritius

[*Pinus taeda*; King 1945] In 1945, cyclones hit the island in January and again in February with winds exceeding 195 km h^{-1}. “Young plantations 1939-43 suffered about 30-60 per cent loss from plants broken or blown over. Staking of plants is only a partial remedy since few regain a perfectly straight habit.”

2.13 New Zealand

[Bareroot; *Pinus spp.;* Matthews 1905] “A great many failures occur through too deep planting of trees more especially in windy localities, where they are frequently put in deep with the idea that it may save time and trouble afterwards in straightening them up or "staking." It is better to err on the side of planting too shallow, for then the plant can assist itself by sending its roots out for support or down in search of moisture; whereas when a tree is planted too deep it cannot produce roots above the collar to maintain itself in an erect position.”

[Bareroot; *Pinus spp.;* Wendelken 1955] “Initially, these laterals grow radially outwards; in the case of naturally regenerated stands they are disposed regularly like the spokes of a wheel. With planted stock, especially following spade planting, the radial habit may be neither so pronounced nor regular but develops over one or more growing seasons. This difference between planted and self-sown trees does not, however, appear to have any bearing upon subsequent wind-firmness. Along the length of the laterals peg-roots then extend downward, but meet the same fate as the primary roots. They become club-shaped and distorted and growth soon ceases. The overall pattern, therefore, is for development of a very shallow, wide-spread rooting system with numerous small peg-roots."

[Bareroot; *Pinus spp.*; Chavasse 1969] "On the worst affected sites, the proportion of trees affected was between 30% and 100%." In addition to *P. radiata*, toppling occurred is stands planted with "…Corsican pine in Dusky Forest planted in 1924; lodgepole pine in Beaumont Forest, 1928 planting; many species, including western red cedar and Lawson cypress, planted from 1928 to 1930 in Mahinapua Forest in Westland; and lodgepole pine planted in 1938 in Naseby Forest." Other species affected were *Pinus elliottii, P. patula, P. pinaster*, and "southern pines."

[Bareroot; *Pinus radiata*; Wilkinson 1969] "Toppling of young *P. radiata* occurred at Herbert Forest in 1968 because of heavy rainfall and strong winds during April of that year. Weather conditions were extreme and resulted in some 362 acres of three- to five-year-old radiata pine being damaged, with the roots of scattered trees being loosened and trees being displaced from the vertical. It has been estimated that almost 40% of the trees within the area were affected. Little damage occurred in stands over six years old, apparently because a better balance between roots and top gave more stability. From early investigations, it seems that growth of vertical roots is inhibited in the early years of establishment and that lateral roots do not give the necessary stability.

[Bareroot, container; *Pinus radiata*; Chavasse and Balneaves 1971] Seedlings grown in polyethylene tubes were planted in 1964 and toppled in the autumn of 1966. At this site, 15% of the trees toppled 2 years after planting and an additional 10% toppled by 1970. About half of the trees that toppled initially had recovered by the sixth year. Trees 7.9 m tall in 1970 (13 cm diameter) had 32% toppling. Bareroot seedlings had 9.5% toppling while 19.9% of tubed stock toppled.

[Bareroot; *Pinus radiata*; Rook 1971] "Wrenched seedlings are easily lifted because their roots are confined to the top 6 in. of soil. A seedling undercut once only and then left to grow will, within a few weeks, send down new roots arising mainly from callus tissue, and will be as difficult to lift as an undisturbed seedling."

[Bareroot; *Pinus radiata*; Menzies 1973; NZ73] "A planting methods trial, using 1.5-0 *Pinus radiata* from Kaingaroa Nursery, was established in 1970 to evaluate various methods for spade, mattock, and auger planting on different soil types." Stock with short (8-10 cm) or long (15-20 cm) taproots were planted on three sites using five planters and eight planting methods. On one site, mortality was less when seedlings were planted in pits. During the second growing season, due to site variability, there was no significant difference in toppling among planting methods.

[Bareroot, direct seeded, natural seeded; *Pinus radiata*; Potter and Lamb 1974] Toppling of 3- to 4-year-old trees occurred after spring gales in 1971. Direct seeded and natural seeded had taproots while half of the excavated 1.5-0 stock (12/24) had no taproots. When machine planted seedlings "are planted too deeply, there is a tendency for a hockey stick root to develop…"

[Container, bareroot; *Pinus radiata*; Chavasse 1978] "One effect of wrenching is that the taproot may not re-develop. It is cut cleanly by undercutting with a sharp blade and forms a callus. This sends out brittle fleshy roots which are either broken off or swept aside by wrenching, so that by the time this process has been undertaken several times, and the tree has been planted out, no further taproot development takes place, and it may be several years before sinker roots take over the role of a taproot; during this period trees can be expected to be unstable to some degree, although on some sites deep planting can alleviate this."

[Bareroot; *Pinus radiata*; Somerville 1979] "…nursery stock (particularly 2-0 stock) formed few tap roots." From a sample of 39 machine-planted seedlings, only eight (20.5%) had taproots 11.5 years after transplanting.

[Bareroot; *Pinus radiata*; Brunsden 1981] At the Mangatu forest, 8% of normal wrenched Puha stock toppled while 22% of seedlings crammed in the planting hole toppled. Box pruning seedlings in the nursery toppled at the same rate as the normally wrenched seedlings.

[Bareroot; *Pinus radiata*; Mason 1985; NZ85] "Trees which have socketed are more likely to topple than trees which have not, as toppling usually occurs after a period of tree sway. Trees with straight-grained taproots and plenty of sinkers are less likely to topple at ages 2 and 3 than trees with twisted or no vertical roots, at least on pumice sites. A kink in the grain of a taproot may be a point of stress which fatigues as the tree sways. Cultivation can increase the likelihood of toppling. This may be because trees on such treatments grow rapidly and larger trees can be more topple-prone. Also, some cultivated soils lack mechanical strength and a combination of loose soil and poor planting methods will promote instability. However, ripping on sites with compact soils can improve vertical root development, reducing the likelihood of toppling. The rare form of toppling in which trees snap below ground-level results from constriction of the stem where lateral roots are wrapped around the bole."

[Bareroot; *Pinus radiata*; Guild 1986] Snow can cause toppling. **"**Brush weeds such as gorse (*Ulex europaeus*) and broom (*Cytisuss coparius*) competing with young trees will increase snow damage. These fastigate brush weeds lean onto trees when snow builds up on them, which results in stem lean, toppling or uprooting. This phenomenon has also been reported by Hughes (1976). Furthermore, trees growing in competition with brush weeds are more spindly than normal and are thus easily damaged by snow."

[Review; Hunter and Skinner 1986; NZ86] "Concern is expressed about the effects of cultivation on toppling, windthrow, and root configuration. Cultivation admittedly often increases rootable depth by only 60 cm. Limited and constrained root development and rapid top growth could predispose trees to toppling at an early age, and windthrow at a later age. Equally, stock with poorly trimmed roots and therefore poor root regeneration potential may produce inherently unstable young trees. However, in later trials there has been only a low level of toppling in the first four to six years. Furthermore, at Utakura toppling was of the same low intensitv in the large trees of the cultivated plots as in the small trees of the uncultivated plots.

[Bareroot; *Pinus radiata*; Mason and Trewin 1987] "Toppling mainly affects trees less than 6 years old and usually occurs after a period of wind-induced tree sway. Since stability in young trees seems to be primarily related to the development of straight-grained, vertical roots, any actions which promote the growth of such roots should help to reduce the frequency of toppling."

[Bareroot; *Pinus radiata*; Mason et al. 1988; NZ88] "By age 4, 45% of the trees in the experiment had toppled (that is, they had a lean greater than 15° from vertical). Differences between cultivation treatments were not significant although the mean toppling rate was lower in the control treatment. The difference between the stocks was highly significant ($p<0.01$) - 57% of the Bulls stock were toppled, and 33%

of the FRI stock." The 1.5-0 Stock from the Bulls Nursery was larger and more difficult to plant then the 1-0 stock from the FRI Nursery at Rotorua.

[Bareroot; *Pinus radiata*; Mason 1989] "Instability of young plantation trees, or toppling, is a source of large financial losses to the New Zealand forest industry. The problem is widespread, although the effects on trees vary with tree size and toppling severity. The overall effect is a reduction in the rate of return from forest crops." **"**An analysis of 21 permanent sample plots located in a variety of sites throughout New Zealand indicated that 20% of radiata pine trees planted in plantations acquire a lean greater than 15 degrees from vertical during their first five years…"

[Bareroot; *Pinus radiata*; Menzies et al. 1991; NZ91] When compared to seedlings, "Cuttings from 3-year-old parents were significantly less prone to tree toppling at both sites." At one location toppling at age two (1 to 5%) had corrected by age 3 and at the other site **"**Seedlings had significantly more toppling than cuttings (27% versus 4%). There was no significant effect of initial spacing." "Either a taproot or sinker roots growing down straight will give stability. If cuttings are planted with their lateral roots pointing downwards, they should be as stable or better than seedlings. The amount of foliage (or "sail area") is also important; the greater it is, the more chance that toppling will occur."

[Review; Trewin and Mason 1991] "It has been estimated that 20% of all seedlings planted topple to at least 15 degrees from vertical during their first 5 years in the field. Given the costs associated with this, it is surprising that planting methods, crop-tree selection and toppling were rated so low a priority. Also, large areas of more mature trees are damaged by high winds which are common in New Zealand."

[Bareroot; *Pinus radiata*; Mead et al. 1993; NZ93] "At age two years the experiment has also shown that seedlings are more prone to toppling and have more malformation than the trees derived from tissue culture. While the larger trees within a tree type are more liable to topple, the fastest growing genotype from tissue culture had almost no toppling, indicating that there is also a clonal effect not related to growth rate." When trees were taller than 1.8 m, lean was greater than 15° and toppling exceeded 50%.

[Bareroot, container, unrooted cutting; *Pinus radiata*; Aimers-Halliday et al. 1999] "The setting of unrooted cuttings in the field ('direct setting'), may be another option for sites prone to toppling, particularly if field-collected cuttings with a physiological age of 2 years or more are used. Early results from small field trials indicate that direct-setting of unrooted cuttings promotes natural root development and reduces early top growth, thereby decreasing the like likelihood of toppling."

[Container, Bareroot; *Pinus radiata*; Menzies et al. 2001] When propagated as cuttings, there was no significant difference in height growth by age 4 years (4.6 m vs 4.3 m) or toppling (37% vs 26%) between container-grown stock and bareroot stock, respectively. "In recent field trials, root distribution around the base of cuttings was expected to be important, particularly if there were only a few roots from one side of the callus. However, neither height or diameter growth for the first 2-3 years after planting was significantly affected by having roots in 1, 2, or 3 quadrants. Heavy root trimming (to <2 cm), to encourage more root growth from the callus, only affected height growth on one site for a year, but was still having an effect in the second year on the other trial site. The improved growth and the perceived lessening of the risk of tree toppling from roots in 4 quadrants has led to a recommendation that bare-root cuttings should have roots in at least 3 quadrants, although this is not universally accepted."

[Bareroot; *Pinus radiata;* Davies-Colley and Turner 2001] "Toppling is recognized as an increasing problem in *Pinus radiata* plantations, particularly on fertile farm sites. Toppling can be costly to forest and woodlot owners due to the loss of value of the final crop, arising from poor stem form, and reduced selection ratios. Crown lightening, the reduction of a tree's "sail area" by shortening branches, is one method being applied to reduce the likelihood of topple."

[Bareroot, container, direct seeded; *Pinus radiata*; Fawkner 2002] A trial at Taranaki included direct seeding, standard bareroot stock and container-grown stock. "The tendency of the treatments to topple was demonstrated by a serendipitous period of 80 km hr^{-1} winds along with heavy rain in July 1998, which allowed the degree of toppling to be measured." Toppling was greatest for container stock (41%), intermediate for standard bareroot stock (22%), and least for the direct-seeded treatment (0.6%).

Bareroot, container, direct seeded; *Pinus radiata*; Watson and Tombleson 2002] "It would appear that the strong emphasis placed by previous investigations on evenly balanced lateral root distribution and strong well-developed tap roots as the major contributors to juvenile-tree wind stability may require re-evaluation. In this study, it was found that neither the size or development of the tap root systems nor the degree of symmetrical distribution of lateral roots of the direct-sown seedlings was significantly better than the more wind-prone bare-root plant types."

[Bareroot; *Pinus radiata;* Maclaren 2002] "The establishment phase of plantation forestry is undoubtedly a triumph. We have grown accustomed to 98% survival and are increasingly relaxed about initial stockings of 600 s/ha or lower. The FRI nursery team were the main players, with their emphasis on well-conditioned bare-root stock, as was Robin Trewin for his fierce advocacy of good seedling care and proper planting techniques. But the high levels of toppling, particularly on farm sites, tell us that we may have gone too far with nursery conditioning. We don't need 98% survival, but we do need a tree (like the self-sown sort) that stays upright in a storm. Nobody gets a prize until this one is sorted out."

[Bareroot; *Pinus radiata*; Coxe et al. 2004] "Three trials were established in one- and two-year-old radiata pine stands, following toppling after a severe storm, with the aim of evaluating various treatments to correct the toppling. The treatments included straightening the trees and turfing, tying up with string, staking, and topping at different heights, some with or without crown lightening through wind-proof pruning. None of the remedial treatments was particularly effective, and it may be better to focus on measures to prevent toppling."

[Bareroot; *Pinus radiata*; Coxe and Menzies 2005; NZ05] Juvenile stoolbed-cuttings were planted in July 1995 and in June 1996 there was a severe storm that caused 0.9% of the cuttings to topple. Wind speed was 54 km hr^{-1} with gusts up to 94 km hr^{-1}.

[Bareroot, container; *Pinus radiata*; Sutton and Trewin 2005] "In the gales of February 2004 almost all of the trees that had toppled had thrust-up root systems, whereas there was almost no toppling in trees that had developed good vertical roots. Inspections of the root systems of toppled and malformed stems in young and mature stands invariable revealed major root distortion."

[Bareroot?; *Pinus radiata*; Rooney 2006] The snowstorm of June 2006 caused millions of dollars to crops, livestock and property. "The worst affected trees were young pines, less than nine years old, particularly those planted in the hope of suppressing heavy gorse or broom. In many places the weight of the snow, which was very wet and heavy in contrast to the more powdery snow of our last two snowfalls, flattened the weeds. These in turn flattened the young trees growing amongst them. Many young plantations will have to be written off.

[Review; Moore et al. 2008] "The risk that a young stand of trees will topple is a combination of many different factors. Clearly, strong winds (or snow) are required, but a number of other factors can act to predispose trees to toppling. In 1968, a survey of New Zealand Forest Service Conservators (Chavasse 1969) concluded that toppling was most likely to occur on sites that have wet soils and where there are strong turbulent winds. However, forest managers believed that susceptibility to toppling could be increased by the choice of planting stock, poor planting, high soil fertility or by excessive weed competition. These are still viewed by present forest managers as the key factors contributing to the occurrence of toppling and are consistent with those noted by other authors (e.g. Lines 1980; Burdett et al. 1986)."

2.14 South Africa

[Box-container; *Pinus patula*; Nänni 1960] "Only 57 per cent of the planted trees appeared to be normal while 33 per cent were damaged or completely destroyed by wind." "(1) Special care must be exercised in the nursery and transplants must be planted deeply in the field. Deep planting will afford the roots greater protection from continual movement by wind. (2) When pitting sites for tree planting, the soil should not be loosened as had hitherto been the practice. The natural vegetation should be removed but the soil left undisturbed. At planting, a hole just large enough to accommodate the roots should be made. (3) When the seedlings are pricked out, they may be established in conical tarred paper cups instead of nursery trays."

[Bareroot, *Pinus radiata*; Zwolinski et al. 1993; ZA93] Seedlings were planted September 1989 and in May 1991 the average height of seedlings was 1.5 m. A wind (39 m/s) occurred 24-25 May, 1991 and toppled seedlings had a lean of 22°. In plots with no herbicides, half of the seedlings planted in holes leaned while only 28% leaned in disked soil. By August, 1991, "the trees showed a strong trend towards recovering their vertical positions. This means that under the experimental conditions the trees stabilised within only two months…."

"The impact of vegetation is somewhat more complex. The positive effect of vegetation height and biomass on tree stability can be explained as a sheltering effect of the vegetation surrounding the trees. In opposition the high aerial cover was associated with grass (Zwolinski, 1992) which, most probably, was the greatest competitor to the trees for water, nutrients and rooting space. This could explain the positive effect of vegetation cover on wind damage." When soil was disked before planting, toppling was 28% with weeds and 45% with total weed control.

[Container, *Pinus patula*; Terblanche 2000] Seedlings were raised in a composted pine bark medium in Unigro 128 containers (61 cc volume, 32 mm opening, 587 cells m^{-2}). Seed were sown to produce seedlings that were 7, 9 and 12 months old. The average heights were 67 mm, 212 mm and 404 mm, respectively.

"Containerised trees lacked taproot development in most cases. The reason for this is that initial taproot development in seedlings is so dominant that taproot air pruning takes place very early in the containers. When planted in the field, containerised seedlings have to reorganise their root configuration, with lateral roots taking over the function of the pruned taproot. This results in lateral roots growing in all directions resulting in bad spatial root distribution."

"Although cuttings had high growth vigour and the roots were evenly distributed and balanced, less than three roots (in most cases only one) grew from the base of the stem. A callus was formed at the point of initial root growth. When pulled, these roots broke off easily at that point. The callus is a point of potential weakness."

[Container, *Pinus spp.*; Theart 2002] "The trees that survived the initial planting period began to show stability problems in the second and third year. "Windthrow" occurs when roots are unable to support the tree against the wind, either because they are unevenly distributed around the tree or because they are so twisted amongst themselves that they break off from the continual swaying of the trees. Such "windthrow" still occurs in the oldest stands of eight and nine year old trees (Darrow 1997)."

"Later, Van Laar (1995) concluded that wind damage was statistically significantly correlated with the type, degree and severity of root distortion in planted trees. It was impossible, however, to quantify the common causes for damage across all estates. It can, however, be said that poor planting practices by unqualified, poorly supervised field workers, linked with the use of over-mature "root-bound" seedlings, were the major causes of the distortions and resultant "windthrow" (Darrow 1997)."

2.15 Spain

[Container; *Pinus radiata*; Ortega et al. 2006; ES06] Seedlings grown in four types of plastic containers were outplanted on three sites. "Seedlings grown in containers that permitted lateral air p[r]uning presented less growth and lower biomass production. However, root deformations were more frequent and severe in plants produced in closed-wall containers. Field performance was likewise mainly affected by container type and plant growth rate, as faster grown plants showed more problems of stability than plants with a balanced root and stem development." "…faster grown plants showed more problems of stability than plants with a balanced root and stem development." Seedlings grown in 270 cm^3 cells had topping rates of 63 to 83%, two years after planting.

2.16 Sweden

[Container, naturally seeded; *Pinus sylvestris*; Lindström and Rune 1999] Root system deformation was studied in plantations in central Sweden. Naturally regenerated roots were uniformly distributed but severely spiralled root systems were observed when seedlings were grown in Paperpots. "Naturally regenerated trees were more stable than those which had been planted." "The conclusions from this study are that root distribution, tree stability and stem straightness of planted Paperpot-grown trees will improve after a certain time and approach the state of naturally regenerated trees."

2.17 United Kingdom

[Bareroot; *Pinus contorta, P. nigra, P. sylvestris*; Edwards et al. 1963; UK63] At two sites, there was no toppling with deciduous larch while 5 to 15% of *P. contorta* seedlings toppled. "(6) Pine trees planted in the furrow of single furrow ploughing of several types are susceptible to loosening, but not those planted on complete ploughing. (7) Lack of care in planting is unimportant if the trees can develop new balanced root systems, as happens on softer soils; on hard heaths the soil must be cultivated adequately to obviate this planting problem."

[Container; *Pinus contorta*; Moss 1971] "Frequently, after about three to five years of growth, trees of South Coastal and other fast-growing provenances have been blown over at an angle of some twenty to seventy degrees from the vertical, away from the source of the prevailing wind, especially in exposed sites. It is unusual for most British Columbia Interior provenances to show this lean. The dense crowns of the South Coastal and certain other provenances and the light crowns of most Interior provenances probably contribute to the difference. The greater wind resistance of the former places a greater strain upon the stabilizing root system in a wind of given force."

[Container; *Pinus contorta*; Low and Oakley 1975] "Eight week old conifer seedlings raised intensively in small plastic tubes are capable of high survival and vigorous growth when step planted on ploughed peatland. The effective planting season is from April to August, and very high planting rates are possible with a special tool." "Root development is generally satisfactory (Plate 10), and in the case of Lodgepole pine provenances from coastal Washington and Oregon, tubed seedling stock is likely to give improved early stability and a consequent reduction in the development of basal bowing."

[Bareroot, Container; *Pinus contorta*; Cannell and Willett 1976] "Inherent differences of 10-30% in root:shoot dry weight ratios found in young trees in this study and by others, very probably contribute to differences in wind stability after planting, if not by differences in root anchorage, then by differences in shoot development and 'sail area'."

[Bareroot, Container; *Pinus contorta*; Lines 1980] "Trees grown from seed sown direct in the forest have roots with a better structure than either tubed seedlings or transplants, the last being least stable. Experiments to limit basal bow have not yet shown a practical method, apart from using a slower-growing origin or tubed seedlings."

[Bareroot; *Pinus contorta, P. sylvestris*; Quine et al. 1995] "Where there is a risk of early instability (toppling) avoid applying fertilisers as this may increase the shoot/root ratio."

[Bareroot; *Pinus contorta*; Lines 1996] "Once a young tree has become loosened it tends to rock backwards and forwards in the 'socket' until either the lateral roots become sufficiently stiff to stabilise it, or it progresses to a point where the stem is nearly lying on the ground and then grows up wards again. Most commonly a basal bow develops, which results in the main mass of the tree exerting a vertical force at some distance laterally from the centre of the root system. Thus such trees are very prone to later wind and snow damage, even though the tree is now apparently firm Each year on windy sites the tree may develop a leader that leans away from the prevailing wind, even if there is little basal sweep. Some origins are very prone to this -

particularly the South Coastal ones, while other on the same site grow with little tendency to lean. Even slightly leaning trees may develop compression wood in the same way that this is developed to an excessive degree in the wood associated with the basal bow."

[Review; Savill et al. 1997] "There is general agreement that natural regeneration or direct seeding offer the best prospects for good root development. There is little hard evidence that planted trees, whether of bare-rooted, container-grown, or cutting stock, suffer seriously impaired root development as the huge areas of successfully planted forests demonstrate. Moreover, while the pattern of root growth can be considerably influenced by nursery and planting practices, the subsequent development of a root system is often more affected by soil physical conditions (such as rooting depth, impervious layers, and anaerobic conditions), by cultivation and ploughing on the planting site itself, and the proximity of the planting position to old stumps (Quine et al. 1995)."

[Container; *Pinus spp.*; Reynolds et al. 2020; UK20] Two trials (including 9 pine species) were established in Westonbirt in 2012/13. Five years later average heights were 4, 3.9, and 3.7 m for container-grown *Pinus taeda*, *P. pinaster* and *P. radiata*, respectively. A winter snow in December 2017 caused toppling of these container-grown pines. "The cause could be a number of factors but mainly appear attributable to an imbalance between rapid shoot growth and slow root development (Burdett, 1979)." Most pines less than 3 m tall did not topple. [Note: some seedlings may have been pot bound when planted. Growing seedlings in copper-treated styroblocks did not prevent pot binding and subsequent toppling of *P. pinaster* (Figure 3). After two growing seasons, some *Pinus taeda* showed signs of socketing.]

Figure 3. A 10th of December 2017 snow (12 cm) toppled several pine species in a 5-year-old plantation at Westonbirt (Reynolds et al 2020). Photo of toppled *Pinus pinaster* taken by Chris Reynolds on December 20, 2017.

2.18 United States

[Bareroot; *Pinus* spp.; Cockrell 1936] "After a recent high wind, the following observations were made in 3- to 5-year old mixed plantings of the important southern pines at Clemson College, in the upper Piedmont of South Carolina. The longleaf and shortleaf pine appeared to be unaffected by the wind. With the exception of one tree that was slightly loosened in the ground, the loblolly pine was not noticeably affected. A large number of the slash pines, however, were severely bowed by the wind and in places many trees were considerably loosened in the ground and were inclined appreciably from the vertical.

[Bareroot; *Pinus spp*.; McKeller 1942] A glaze storm in January 1940 was followed 16 days later by a 25 cm snow. A survey of damaged plantations (≈5.3 m tall) included one 11-year-old longleaf stand, two 7-year-old loblolly stands and four slash pine stands (6 to 7 years from planting). Four of these plantations had uprooted trees; 6% longleaf, 1% loblolly and 8% slash. The averages for badly bent stems were 38% longleaf, 51% slash and 4% loblolly. “Approximately 40 percent of the slash and longleaf pine and 56 percent of the loblolly pine which were badly bent in February recovered completely by October. In addition, from 20 to 30 percent of the badly bent trees of all species may be expected to make partial recovery. Slightly bent trees of all three species showed better than 90 percent recovery."

[Bareroot; *Pinus elliottii*; Wakeley 1954] “Slash pines planted with U-roots sometimes develop globes of root just under the soil surface, which form "ball and socket joints" when the soil is wet, and let the trees go over in high wind. Experimental evidence and wide observation both show, however, that the danger of windthrow from planting U-roots has been exaggerated.”

[Bareroot, direct seeded; *Pinus spp*.; Little and Somes 1964; US64] “All direct-seeded seedlings had relatively normal root systems. Taproots usually had penetrated nearly vertically into the soil. Laterals had developed on all sides and had grown away from the taproots almost at right angles.” “The roots of planted seedlings differed from those of seeded seedlings in several ways. One of the most notable differences was the occurrence in the planted trees of twisted, intertwined roots in the upper 3 inches or so of the root systems. This condition was not found in the direct-seeded trees. Such intertwined roots characterized 94 percent of the excavated planted seedlings. They were most conspicuous on seedlings planted in poor slits as 1-0 stock, but some occurred also on similar seedlings planted in center holes or good slits.”

[Potted, bareroot; *Pinus spp*.; Schmitt and Namkoong 1965; US65] An arboretum was established near Gulfport, Mississippi using 45 pine species. “The seedlings were lifted and potted in the fall, held in a lathhouse until the following April, and then hole-planted…” *P. echinata*, *P. glabra*, *P. palustris* and *P. taeda* were planted bareroot. Seven to nine years after planting, wind injured *Pinus clausa, Pinus echinata, Pinus elliottii*, and *Pinus taeda*. This report includes a photograph of a toppled *Pinus clausa*.

[Bareroot; *Pinus elliottii*; Klawitter 1969] “In January 1962, slash pine seedlings were machine-planted at 8x8-foot spacing. After two growing seasons, survival averaged about 90 per cent on sampled plots-but nearly 10 per cent of the survivors had a pronounced lean. Closer examination revealed that the base of each leaning tree was encircled by a cavity. Also, for several inches above the root collar, the stem was swollen and scraped. Excavation of a number of trees showed that the leaners all had L-shaped root systems. This shape is characteristic of seedlings whose roots are dragged in the planting slit rather than being inserted properly. Further experimentation and observations led to the conclusion that the combination of improper planting, wet sandy soil, and strong winds caused the trees to lean. Winds sweeping across the open ground whipped the tree tops. When the roots were planted parallel to the surface in wet sandy soil, the whipping of the stem caused them to rotate back and forth. The tree stem, whipping in an elliptical fashion, scraped the ground around the root collar and packed it into a circular depression leading to the roots. How serious is the problem? Our experience showed that about 75% of the leaning trees died. Those that survived became firmly anchored by the sixth year after planting. Leaners can be recognized, nevertheless, even after they are 10 feet or more in height - the bottom two or three feet of the stem remains curved after the top begins to grow upward. Much of the solution to the leaning-tree problem in wet soils depends on proper planting. The wind will have less chance to loosen seedling roots if they are not allowed to drag in the planting slits."

[Bareroot; *Pinus monticola*; Leaphart et al. 1972] In 1959, 2-2 stock was planted in northern Idaho on slopes that averaged 55% at an elevation of approximately 1,100 m. During the winter, prevailing winds are from the southwest and any accumulated snow may remain until late May. Snow movement in deep snowpack zones contributed to the frequency and severity of a variety of stem deformities. Butt sweep probably starts when the tree is less than 6 years from planting and when the lean is at 45° or more.

[Container; *Pinus ponderosa;* Hiatt and Tinus 1974] "The upper laterals of ponderosa pine are usually the roots with the high strangle angles. It is especially important that these roots be directed to the bottom of the container and air pruned. The proper container for a large seedling for the Plains must be shaped to direct roots straight to the bottom. Ridges and grooves on the container sides seem to accomplish this. The opening in the bottom of the container is also important. When the root reaches the bottom, the tip should die, otherwise it may be deflected upward and coil in a vertical plane. If a properly shaped container is used for the proper length of time, a good root system can be developed on ponderosa pine. We still don't know, however, how much deformity a root system can have before growth is restricted or the structural support of the tree is weakened."

[Bareroot; *Pinus taeda;* Mexal and Burton 1978] No toppling occurred even though "A large percentage of the loblolly pine seedlings planted in Arkansas are improperly planted and the results are still obvious up to four years after establishment. Although seedling growth could not be correlated to taproot deformation, it was significantly correlated to the lateral roots. Both the number of laterals (a product of nursery practices), and the distribution of the laterals (a product of planting quality), were positively correlated with seedling performance." For height growth of seedlings two years after transplanting (n=25), the Pearson correlation coefficient (r) for number of lateral roots was +0.65 and +0.51 for site 1 and 2, respectively.

[Bareroot, container; *Pinus ponderosa*; Owston and Seidel 1978] Seedlings grown in milk cartons (1.9 liter) were removed from the container and either planted with the bottom roots intact or cut. "Clipping spiralled roots definitely improved subsequent root form. The usually normal, undisturbed appearance of clipped taproots indicates that lateral roots which took over the same function were initiated at or just above the cuts. This pattern of root initiation has also been observed on ponderosa pine seedlings undercut in nursery beds (James W. Edgren, personal communication, 1976). Good outward extension of main laterals and masking of the container outline were not expected, because the lateral roots along the sides of the container were not cut. Lateral root initiation, stimulated by removal of the lower spiralled roots, must have occurred.”

[Bareroot; *Pinus taeda;* Hunter and Maki 1980] In 1954, seedlings were hand-planted in slits with straight roots or the roots were deliberately curled back at the time of planting. At age 7 years four trees from each treatment were excavated and “lateral root distribution had developed more uniformly in straight-rooted trees.” When measured 24 years after planting, the basal area of straight planted trees was, numerically, 12% greater on a per surviving tree basis and 18% greater on an area basis.“ In spite of the results of this study, the authors believe that young curl-rooted southern pines do go through a period of high susceptibility to blowdown before their lateral root systems become well developed. This vulnerability to heavy winds is due to a "ball-and-socket" relationship formed between the balled roots and the soil (Wakeley 1951). Excavations of leaning and prostrate seedlings from throughout the South have consistently revealed evidence of this ball-and-socket effect. The most vulnerable period seems to be between the ages of 3 and 5 on average and better sites. As lateral root development and distribution improve, the trees become increasingly less susceptible to windthrow. Roots of the 7-year-old trees excavated in this study appeared to have outgrown the ball and socket stage.”

[Container; *Pinus ponderosa*; McDonald et al. 1981] By painting container walls with copper carbonate, **“**There is potential for development of container seedlings that will have root tips, pointing outward and ready to grow, all over the surface of the root plug. Upon planting, the rapid extension of these roots into surrounding soil could very quickly produce a root system as good as, or better than the root system of a tree seeded in place. Roots would grow into the upper soil layers for good lateral force resistance and absorbtion of nutrients as well as downward. Such trees would be healthier, become fully established faster, and be less prone to windthrow in later life. Much more research needs to be done, but initial results are very encouraging.”

[Bareroot; *Pinus taeda*, *P. echinate*; Harrington et al. 1989] “Our study was not designed to evaluate wind firmness; however, we did notice infrequent toppling of some planted but none of the seeded trees. Excavation of these trees revealed: (1) the taproot had been bent or J-rooted at planting (two or more major turns present), and (2) major lateral roots were largely absent from one side of the tree. Apparently the turns in the taproot served as pivots or rocking points under stress, and the unbalanced distribution of major lateral roots allowed the pivot or rocking motion to develop. The lack of stability associated with such gross root morphologies probably does not become evident until tree crown mass surpasses some critical size and one or more environmental stress factor increases (e.g., high wind or heavy snow)."

[Stock not reported; *Pinus taeda;* Dunham and Bourgeois 1996; US96] Five months after hurricane Hugo (September 1989) toppled seedlings were measured on plantations in South Carolina. Approximately 64% of trees younger than 6 years toppled and the average lean was 37° to 40°. About 3% of two-year-old trees were laying on the ground.“ After three years, the tips of most of the surviving leaners had essentially returned to vertical.”

[Container; *Pinus palustris;* South et al. 2001] “More than 95% of container-grown longleaf pine (*Pinus palustris* P. Mill.) seedlings had roots growing downward vertically (geotropically) when examined 7 to 8 mo after transplanting into sand. Geotropic roots were rarely the original taproot (<0.5%) but were usually adventitious lateral roots that had formed about the callus tissue. Air-pruning in the nursery results in callus formation at the end of the taproot and typically, 1 or more adventitious roots emerge just above the callus tip. Although many first-order lateral roots were deflected downward by container walls, few exhibited positive geotropic growth after transplanting. Most grew in directions other than straight down. In this study, about 4% of the seedlings lacked geotropic roots. Longleaf pines with a long taproot or sinker roots are less susceptible to toppling at a young age than are trees without vertical roots."

[Bareroot, container; *Pinus palustris;* Pickens and Howell 2003] Container and bareroot longleaf seedlings were planted in 1994 and 1996 and 27 of each stock type were measured in 2000. "One site was a wet sandy soil with the high water table about 4 feet (1.2 m) below the surface. The other was a dry deep sand. The trees were destructively sampled by digging them out of the ground using a backhoe." "Based on this study, it seems the risk of windthrow in longleaf pine is just as likely for trees from bareroot seedlings as for those from container seedlings. Longleaf is susceptible to windthrow at an early age. The site characteristics, the type of storm, storm intensity, and storm frequency factor into the susceptibility." Due limited height growth (<110 cm) and no hurricane winds, toppling did not occur.

[Bareroot, *Pinus taeda;* Gresham 2004] Two years after planting, hurricane Hugo (September 1989) toppled seedlings and half were righted and attached to stakes. Tree heights were measured 8.5 growing seasons after Hugo. Results of a 2022 ANOVA indicate staked trees at the Greeleyville site were 1.2 m taller than unstaked trees (P>F = 0.019; n = 8) but at the Snow mill site the 0.6 m gain was not statistically significant (P>F = 0.32; n = 8). The authors concluded that "Saplings left in a leaning (ca 45 degrees) position following a hurricane do not lose measurable growth compared to those staked upright immediately after a hurricane."

[Review; South 2005] "Toppling of fast-growing pines is a problem in some windy countries such as South Africa and New Zealand (Mason 1985, Zwolinski and others 1993). For *Pinus radiata,* researchers believe that bent roots will give poor anchorage to the seedling and it will result in toppling at a later date (Maclaren 1993). However, even in areas with hurricanes, toppling of bare-root loblolly pine is rare in the United States. Infrequent toppling has occurred when planting bare-root stock on good sites between the ages of 3 and 5 (Klawitter 1969, Hunter and Maki 1980, Harrington and others 1989), especially when the foliage is loaded with ice or snow (Dierauf 1982)."

[Container; *Pinus elliottii*, *P. taeda*; Roth et al. 2007; US07] Seedlings grown in RLC4 containers (Figure 4) were transplanted at four locations in January 2000. "In the summer of 2004 two hurricanes, Frances and Jeanne, passed in close proximity to the Waldo, FL location. While damage was not extensive, there were a substantial proportion of trees toppled or leaning at varying degrees throughout the study area. Damage from these storms was minimal at the Perry, FL location and barely evident at either of the two loblolly pine locations. There was significant G x E for wind damage in slash pine between locations (p<0.0001). Trees on the slash pine locations may have toppled due to indirect effects of weak root systems in combination with relatively large canopies. Diseased trees may have broken due to fusiform rust galls located on tree stems." Wind damage to slash pine at the Waldo location in the summer of 2004 ranged from 10% to 40%.

Figure 4. The Ray Leach "Pine cell" RLC4 (66 ml) has a top diameter of 25 mm and a height of 160 mm. When seedlings have a root-collar diameter (RCD) of 2.5 mm at planting, the root-bound index (South and Mitchell 2006) for this container type is 0.1 (i.e. 25 mm/2.5 mm). In most toppling studies with container stock, seedling age, RCD and root-bound index values at planting are typically not reported. The RLC4 containers have been used to grow pine seedlings in the USA (Wenny and Woolen 1989, LeBude et al. 2006, Roth et al. 2007, Zhai et al. 2015). Photo by Stuewe and Sons.

[Bareroot; *P. taeda*; Aubrey et al. 2007; US7] Hardwood and pine seedlings were planted in February 2000 and an ice storm occurred January 2004. Deciduous hardwoods suffered no apparent injury but 71% of the pines bent and 15% broke. "Bent stems straightened significantly throughout the growing season (P<0.0001). Within 11 weeks, 15.3 ± 3.7% of previously bent trees had returned to vertical, and within 28 weeks, 83.3 ± 6.3% had returned to vertical. Neither fertilization nor irrigation affected bent stem recovery rates (P>0.05) after the ice storm."

[Bareroot, container; *Pinus spp*.; Stanturfet al. 2007] "In pine plantations, bending and breaking of stems raises the question of whether to replant or let the stand continue to develop. Based on work done after Hurricane Hugo, pine trees of any age with >45° of lean, and trees age 8 and older with >25° of lean, should probably be harvested and replanted immediately after storm damage (Dunham and Bourgeois, 1996). These trees will grow significantly slower, and be undesirable for solid wood products because of a higher proportion of compression wood."

[Bareroot, container; *Pinus palustris;* South 2011; US11] Two stock types were machine planted on a fertile soil in November 2006 in Alabama. Average height son scalped areas (3.5 years after planting) were 2.4 m for container stock and 3.1 m for bareroot stock. No pines toppled on plots not scalped while a total of four toppled on scalped plots (one bareroot plus three containers).

[Container; *Pinus palustris;* Leduc et al. 2012; US12] Hurricane Gustav (September 1, 2008) with winds of 59 km h^{-1} (Alexandria LA) toppled several trees five years after planting. To illustrate time required for recovery, photographs of were taken periodically until January 2011. One tree had a 51° lean in August 2009 and a 8° lean was recorded on January 2010.

[Container; *Pinus taeda*; Steiger 2013; US13] Hurricane Irene toppled trees at the Hofmann Forest in North Carolina on August 27, 2011. Seven months before the hurricane, 5-year-old trees averaged 6.8 m in height. The wind caused "significant damage" with 55% of the trees leaning more than 9° and 26% leaning more than 20°. Planting density affected toppling with 60% leaning at a spacing of 538 ha^{-1} and 49% leaning at 1076 ha^{-1}.

[Bareroot, container; *Pinus taeda*; Kelley and King 2014; US14] Hurricane Irene toppled bareroot and container stock at the Hofmann Forest in North Carolina with wind gusts of 151 km h^{-1}. Stock planted in January 2009 were toppled on August 27, 2011 and many were still leaning in January 2012. Trees with a 30° to 45° lean averaged 3.5 m tall while those with no lean were 3.1 m tall. One container-grown genotype had the greatest "proportion of trees leaning over 30° from vertical."

[Container; *Pinus elliottii, P. taeda;* Zhai et al. 2015]Seedlings were raised in RLC4 containers (Figure 4). Tropical storm Matthew impacted DeRidder, Louisiana in October 2004. Two years after planting, wind injury was >20% for four loblolly pine sources and about 8% for one slash pine genotype. "However, in the current study, sinuosity was recorded after a major storm and had not been previously identified for the measured trees."

[Container; *Pinus palustris, P. taeda;* Starkey and Enebak 2016] "Toppling of young stands is defined as an instability in young stands that occurs when the trees are not completely wind-thrown, but lean at various angles and continue to grow. Of the documented cases of wind-thrown trees dating back to the late 1980's, nearly every case has been associated with container seedlings. When toppled seedlings have been examined, many do not have a normal tap root extending into the soil profile. There is a lack of documentation of windthrown trees correlating the seedlings to the type of container in which they were grown. This study has shown that polystyrene containers have a relatively uniform distribution of roots throughout the horizontal profile of the plug, whereas, hard plastic containers have the greatest proportion of root numbers and weight toward the bottom of the plug. Does an even distribution of roots throughout the plug provide better stability than when the majority of roots are located toward the bottom of the container? Further research is needed to determine which root morphology form provides the best stability in times of high winds."

[Container; *Pinus palustris;* Pickens and Crate 2019] "Toppling in pines has been reported in the Southeast since the 1980's for both loblolly and longleaf pine. Reports of toppling are usually correlated with passage of hurricanes or strong winds. Recent field observations indicate many of the trees blown over are longleaf pine, typically container longleaf seedlings planted in former agricultural fields. Close examination of the affected trees reveal a deformed root system, poor lateral distribution, and no tap or sinker roots."

[Container, bareroot; *Pinus palustris*; Sung et al. 2020] "In this and other studies, only a few saplings had stem displacement which might be the result of once-leaned or toppled saplings that later grew upward by stem overcorrection (Sung et al. 2012). Unlike the improved stem stability for lodgepole pine seedlings grown in Cu containers (Krasowski 2003), the positive effects of lateral root pruning treatment (by Cu or air) on the physical stability of longleaf pine are yet to be realized in this study."

[Container; *Pinus taeda*; Caisley 2021; US21] In October 2018, "Hurricane Michael laid 90% of treatment trees horizontally on the ground" (Figure 5). "Trees were propped up with stakes and twine, the effort by the rescue crew saved both sites with only a 13% mortality rate between the two sites."

Figure 5. Hurricane Michael toppled container-grown *Pinus taeda* at the Hofmann Forest in North Carolina (photo taken October 3, 2018). Seedlings were planted in 2017 and trees toppled 20 months later. Early growth was rapid and height in December 2021 was approximately 5.1 m (Caisley 2021). Photo provided by Rachel Cook.

3 Questions

3.1 Taproot

A taproot is the main descending root that develops from the primary root (Sutton and Tinus 1983). Most natural pines have a long taproot but some planted bareroot and container seedlings have short taproots (e.g.<18 cm) after several growing seasons from seed (Figure 6). At some nurseries, the taproot is cut to a length of 8 to 10 cm (Menzies et al. 1985). A disadvantage with root-wrenching in the nursery is that a true taproot often does not develop (Chavasse 1980). Normally, pines have a well-developed taproot but cutting/wrenching the taproot in the nursery can cause a loss of geotropism (Menzies et al. 1985). [1] When high winds topple planted pines, does the lack of a long taproot explain why two-year-old seedlings toppled? The answer to this question is often yes. Direct seeded pines have true taproots and resist toppling when wind topple saplings with no taproots or short taproots (Clarke 1956; Potter and Lamb 1974; Fawkner 2002; Watson and Tombles 2002; Pickens and Crate 2019).

Figure 6. Root system of a toppled container-grown *Pinus palustris*. The taproot air-pruned and did not elongate after planting. The two adventitious sinker roots that formed at the taproot base did not prevent toppling.

3.2 Sinker root

[2] When a first-order lateral root takes over the function of a taproot (Burdett 1978; South et al. 2001), will the sinker root resist toppling to the same degree as a normal taproot? When sinker root and taproot diameters 30 cm below the surface are the same, we might assume toppling rates would be the same. In contrast, juvenile instability is greater when the diameter of a primary sinker root is one-fourth that of a true taproot. Future research might determine if root origin (sinker root vs. taproot) affects juvenile instability.

Some seedlings have no geotropic roots (Figure 7). When a lateral root or adventitious root grows geotropically or at a 46° angle to the soil line, it may be classified as a sinker root (Sutton and Tinus 1983; Watson and Tombleson 2004). [3] Does a seedling with four sinker roots (each at 47° but none at 90°) resist toppling to the same degree as a normal geotropic taproot? Although unrooted cuttings do not form a taproot, sinker roots emerge and one or more may grow geotropically. It is incorrect to call these taproots since, by definition, taproots are not adventitious roots. Therefore, some rooted cuttings have multiple sinker roots but they cannot have one, two or three taproots. In one study, approximately 47% of rooted *Pinus taeda* cuttings had no vertical sinker roots (Goldfarb et al. 1998). Seedlings with a strong dominant vertical root resists toppling more than seedlings with many sinker roots that are not well developed (Gautam et al. 1999; Fawkner 2002).

Due to improved stem form and better genetics, millions of pine cuttings have been planted in New Zealand (Menzies et al. 2001). Even though cuttings do not have taproots, cuttings with less sail area are more resistant to toppling than bareroot seedlings.

Figure 7. Container-grown *Pinus palustris* seedling were transplanting into sand-filled boxes and then were excavated after four months. For both seedlings, the true taproot air-pruned at the bottom of the container. After transplanting, adventitious roots formed lateral roots with no geotropism (left) and sinker roots formed on the seedling on right. Sinker roots may or may not exhibit geotropic growth (photos by Tom Starkey).

3.3 Sail area

[4] When high winds topple planted pines, does leaf area (i.e. "sail area") determine which trees topple? When 2 m tall trees have the same root form, those with less "sail area" have a lower risk of toppling. Pfeifer (1982) said "morphological differences in shoot development and "sail area" are much greater and are therefore likely to have a more significant effect on stability" than root/shoot ratios. For planted

pines, the risk of toppling can be reduced by pruning branches before high wind events (Aimers-Halliday et al. 1999; Davies-Colley and Turner 2001). When toppling is positively related to seedling height, sail area will be related to toppling.

3.4 Socketing

[5] Does socketing increase the probability of toppling? Wakeley (1954) said that pines planted with a u-root could develop a “ball and socket” which is caused by excessive rocking due to wind. The “ball” is a large bulbous knob below the ground at the base of the trunk and roots may be wrapped about the ball (Lyons 2002). The “socket” is the hole that surrounds the ball (Figure 8). Typically, “ball and socket” trees do not have a true taproot and they rely almost entirely on lateral roots for support (Hay and Woods 1978). In England, container-grown *Pinus taeda* showed signs of socketing two years after transplanting (Reynolds et al. 2020). Pines with this type of root structure have a higher probability of toppling.

Jobling and Stevens (1980) said the “motion of the tree may also inhibit root development. Unfortunately, careful planting cannot wholly prevent socketing in some situations. Pines are especially prone to socket in almost any position. There is little or no evidence to suggest that the condition of the spoil at planting influences socketing. Planting in wet spoil, favoured because preparation of the holes is made easier, is not considered a contributory factor.”

Figure 8. An example of socketing of a container-grown *Pinus palustris* seedling. This phenomenon is also called “wind loosening.”

3.5 Sinuosity

[6] Does toppling result in stem sinuosity? After a seedling topples, it often resumes an upright growth with sinuous growth (Coxe et al. 2004). Some genotypes with no sinuosity will exhibit sinuosity after a high-wind event (Zhai et al. 2015). With no toppling, root bending at planting may have little to do with the development of sinuosity (Murphy et al. 2018). Since toppled trees may regain a vertical positing withing as little as three months (Zwolinski 1993), some managers concerned with sinuosity might assume sinuosity is due to some other reason (e.g. poor planting).

There is a correlation between stem sinuosity and branch sinuosity (McKeand and Jett 1993; Harrington et al. 1999; Espinoza et al. 2012). If toppling triggers a hormonal response in the stem, this might also cause branches to grow in a sinuous pattern. Is it possible to find a pine with sinuous branches and no sinuous stem?

3.6 Weeds

[7] Do weeds increase or decrease the probability of toppling? Some weeds will overtop and smother pine seedlings (Chavasse 1978; Harrington et al. 2003; Lauer and Quicke 2022). When taller pines topple, the mass of weeds can keep seedlings in a prone position (Chavasse and Balneaves 1971). However, on sites where wind speed is low, 1.5 m tall pines typically do not topple (Brunsden 1981; Lauer and Quicke 2022). Likewise, in a species trial, pine species taller than 3.5 m (year 5) toppled while shorter species did not (Reynolds 2020). The keys to a stable "three-legged-stool" are: no wind, dry soil and slow height growth.

In South Africa, weed control with herbicides increased topping by 5% and 17% on ripped and disked areas, respectively (Zwolinski et al. 1993). In New Zealand, weed control on one site increased toppling by 28% (Mead et al. 1993). This is one reason why some farmers will just trample down weeds to reduce the chance of weeds smothering seedlings without increasing height growth of the pines. The trampled weeds will slow growth of planted stock and produce "completely stable trees compared to those in an adjacent spray-released block" (Coxe 2006). Likewise, in one irrigation study, the "aim of weed control was to provide trees with a competitive advantage, rather than to eliminate the weeds, for a low cover of weeds assists in 89 tabilizing softs during the tree establishment phase" (Stewart and Flinn 1984). Therefore, there exists a "yin-yang" aspect of controlling weeds during the first two years of establishment. Too much weed growth can smother seedlings while too much early height growth can increase toppling during high winds.

Excessive weed competition can increase toppling (Chavasse 1969) especially when gorse (*Ulex europaeus*) and broom (*Cytisuss coparius*) collapse due to the weight of snow (Guild 1986; Rooney 2006). In England, heavy snow toppled several fast-growing pines while five species that were shorter than 3 m did not topple (Reynolds et al. 2020). In addition to higher wind speed, toppling due to snow might explain why toppling frequency is often greater at altitudes above 300 m.a.s.l. (Leaphart et al. 1972; Mason 1992; Guild 1986).

On some sites, competition from broom increases the height/diameter ratio of pine (Richardson et al. 1997) and reduces root mass. Chavasse (1978) said that toppling can be increased by "excessive weed competition and lack of timely releasing." Perhaps when trees compete with gorse, bracken and tree lupin, these weeds reduce diameter and root growth but not height growth. Then when tall weeds are removed or killed, subsequent high winds topple the spindly pines due to a lack of support and buffering from adjacent plants (Personal communication Mike Menzies 2022).

3.7 Fertilizer

[8] In regions with high wind events, will fertilizing with N or P affect toppling? Delaying fertilization with P reduced height growth and reduced the rate of toppling of *Pinus contorta* (Lines 1980). In New Zealand, some say fertilization in previous years increases sail area and this can increase toppling (Coxe and Menzies 2005). "The worst case of toppling in Southland was where a farmer had planted radiata pine with half a barrow-load of sheep manure to each tree" (Chavasse 1969). In Chile, however, toppling was less in fertile soils with good taproot development when compared with sandy, low fertility soils (Toral et al. 2011). At some locations, fertilization of pines

increased the root-mass ratio (Johnson 1990, King et al. 1999) which could explain why N fertilization reduced the rate of toppling (Francis et al. 1984).

3.8 Copper

[9] Treating container walls with copper or embedding copper into polystyrene-foam will modify root growth (McDonald et al. 1981; Wenny et al. 1988; Zahreddine et al. 2004; Montagnoli et al. 2022) but does this improve stability during high winds? Except for one trial in Louisiana (Leduc et al. 2012), high winds seem to avoid most "copper-treated" trials. Height growth data can be analyzed (South et al. 2005) and roots can be excavated (Sung et al. 2020; Dumroese et al. 2022), but data on tree lean is absent due to low wind-speed or because leaning pines self-correct before researchers arrive to measure trees.

In the past, millions of seedlings were produced in copper treated cells and trays (Donald 1986; Zwolinski and Bayley 2001; Jones et al. 2002; Ersson et al. 2014; Regan et al. 2015; Larsson 2016; Aguilera-Rodríguez et al. 2020) with the expectation that altering root growth would improve static stability (Krasowski et al. 1997). However, the trend now is to not use copper-treated containers (Nelson and Ayres 1992). Currently, only a few nurseries grow pines in copper-treated containers. Using copper-treated containers increases production costs without increasing static stability or seedling sales. When purchasing Cu-treated polystyrene-foam containers, the initial cost may be 20% more than untreated containers (Landis et al. 2010). Replacement costs are greater since the longevity of polystyrene-trays is less than hard-plastic containers. In addition, some customers do not like to see small amounts of media remaining at the bottom of cells after Cu-treated seedlings are extracted from the container tray.

Thus far, most low-wind experiments with Cu-trials do not show any reduction in toppling of pines. However, in 2008, a hurricane (59 km hr^{-1}) passed over one copper-treated trial but only two pines leaned more than 15° (Leduc et al. 2012). Currently most container-grown pine seedlings in the USA are produced in hard-walled plastic containers (Starkey et al. 2015) or in containers with walls designed for air-pruning of laterals (Figure 9). Toppling has occurred when seedlings are grown in RLC4 containers.

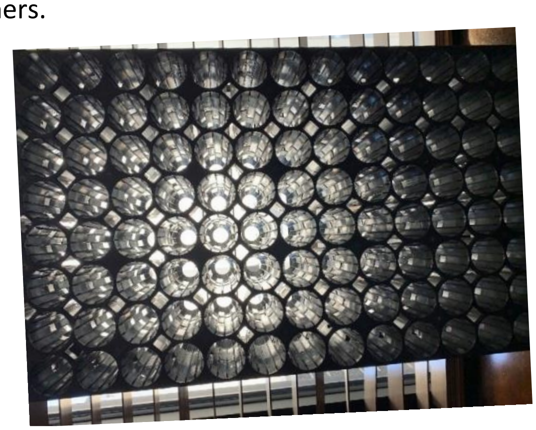

Figure 9. Millions of pine seedlings are grown each year in plastic trays without use of copper coatings. In this example, vertical ribs direct lateral roots down and, after they reach a square hole, the root tip exits the cell and is air-pruned. This third-generation version is exclusive to the International Forest Company (photo by Mike Coyle).

3.9 Planting hole

[10] Will digging a square or conical hole affect toppling? When planting trees by hand, workers either make a slit or a hole prior to planting. At one time, dug holes were 20 cm square and 25 cm deep (Matthews 1905) but most pines now are planted in a slit made using a planting bar or spade (Trewin 2016). At one site, making a “cone” shaped hole (Balneaves and Cullen 1981) and pushing a 1-0 seedling firmly into the tapering hole reduced early bowing of *Pinus contorta* stems (Seaby and Schaible 2001). Even though this technique tends to produce a “bird’s-nest” root shape at the bottom of the hole (Trewin 2003), early height growth increased by 20% when compared to slit planting on the top of the “plough ribbons”. Since making a hole increases the time required to plant a seedling (Dun 1956; Sloan 1988; Harrington and Howell 1998; Trewin 2003; Sutton and Trewin 2005), most supervisor sallow planters to use quicker methods that are less expensive (Trewin 2016). A common method used in Ireland involved cutting a slit in the shape of an “L” or “T” (Nieuwenhuis and Egan 2002) while others make a single “I” shaped slit to produce a V-shaped opening (Stoate1945; Menzies 1973; Balneaves and Cullen 1981; Blake and South 1991; Maclaren 1993).

Sometimes, making a square hole increases the rate of toppling (Brunsden 1981; Menzies 1973). Similar results occurred in the Eastern Cape of South Africa, where planting seedlings in 20 or 40 cm deep holes increased toppling (Zwolinski et al. 1993). Compact soil (37 cm depth) restricted root growth and ripping plus disking resulted in 38% toppling. Making a hole (45 cm diameter and 20 cm deep) increased toppling rate to 51%.

3.10 Depth of planting

[11] Will digging a deep hole and planting the root-collar 15 cm below the surface reduce the risk of toppling? Although Matthews (1905) was against deep planting, Nänni (1960) said “Deep planting will afford the roots greater protection from continual movement by wind.” When seedlings are 30 cm tall with a 10 cm taproot, some suggest making a 30 cm deep hole, placing roots in the bottom of the hole, distributing soil around the roots, and then pulling the seedling up about 10 cm so the root-collar is 6 to 10 cm below the soil surface (Trewin and Cullen 1985). In some trials, planting the root-collar below the surface will increase survival (Stoate 1945; Mullen 1964; South 2005) and, therefore, planting the root-collar 8 to 10 cm deep is now a common practice (Moore et al. 2008). An exception is for container-grown *Pinus palustris* that may survive better after shallow planting (Hainds 2004), especially on sites where the root-collar is buried due to sediment (Hooker et al. 2020).

In one trial, planting 2+1 stock deep (i.e. 0.5 stem length) reduced early height growth by 20% but this had minimal effect on average tilting 13 years after planting (Huuri 1978). It is possible deep planting reduced toppling two years after planting but tree lean was gone after one growing season. Unfortunately, most toppling trial studies do not provide the size of the planting hole and root-collar depth.

3.11 Cutting roots

[12] Will cutting the bottom roots of a pot-bound seedling reduce the risk of toppling? In one trial with polybags (Eccher 1975), clipping pine roots reduced toppling

(Figure 2). In contrast, cutting roots of container-grown *Pinus contorta* vertically had no effect on percentage of acceptable seedlings for (Seaby and Schaible 2001). In other trials with no toppling, cutting roots reduced spiraling of roots (Persson 1978), improved the appearance of subsequent root growth (Bell 1978; Owston and Seidel 1978), and stimulated growth of geotropic sinker roots (Khurana 2001).

Several root pruning trials have been conducted on container-grown pine seedlings. In British Columbia, *Pinus contorta* seedlings grown in Styroblock containers were root pruned just before transplanting (Khurana 2001). Due to air-pruning at the nursery, taproot elongation after planting averaged 49% for seedlings not pruned with a knife. However, taproot elongation averaged 63% when the bottom 2 cm was cut with a knife prior to outplanting. Similar results occurred with *Pinus palustris* seedlings at the Goldsboro Nursery in North Carolina (Personal Communication Tom Starkey 2022). About 22% of seedlings with root tips clipped before planting had no taproots while 29% of unclipped seedlings had no taproots (P>F = 0.047).In contrast, when the air-pruned callus tip was removed in another trial from seedlings in Georgia, the percentage of seedlings with taproots (86.5%) was not affected by clipping the end of the taproot (P>F = 0.74).

[13] Will trimming lateral roots reduce the risk of toppling? Roots are sometimes cut just prior to packing in the nursery. For sandy soils, trimming roots to a 10 cm length (Stoate 1945; Dun 1956) or cutting roots before transplanting reduced survival by 2% to 16% (Mexal and South 1990). Pine survival can be a problem in dry soils in the USA while toppling can be a problem in wet soils in New Zealand. To reduce the frequency of U-roots and subsequent toppling, it is standard practice in New Zealand to cut lateral roots to a 10 cm (or shorter) length before packing in boxes (Maclaren 1993). In contrast, survival of bareroot pines can be positively related to seedling root mass (Mexal and South 1990; South and Mitchell 1999). Therefore, after lifting roots are typically not trimmed at nurseries in the USA and cutting and stripping roots in the field is discouraged.

3.12 Seedling age

[14] Will outplanting younger container stock reduce root deformation and lower the risk of toppling? Sutton (1980) said "restricting size of root system by using younger or smaller planting stock would generally reduce the chance of deformation prior to and during planting." For example, when measured five years after planting, 3-month-old tubed stock had less lean (14 to 17%) than 14-month-old seedlings (20 to 43%) grown in Kopparfors trays (Seaby and Schaible 2001). Likewise, Barnett and Brissett (1986) said the "development of adverse root forms increases rapidly with the length of time seedlings are grown in containers. With 12- to 15-week growing cycles and removal of the seedlings from the container, there should be no problem if you are using properly designed containers." Terblanche (2000) said that small seedlings experienced less detrimental (caging) effect than large seedlings, "because small seedlings were kept in the nursery tray for a shorter period than the large seedlings." Others also warn against growing seedlings too long in the container (Bergman 1976; Zwolinski and Bayley 2001; Salonius et al. 2002; South and Mitchell 2006).

For some species, juvenile instability is related to pot-binding in the nursery. For example, seedlings kept in bags in the nursery for 22 months had more toppling than seedlings planted after 12 months (Figure 2). Likewise, air-pruning can inhibit root elongation of a true taproot. In the past, several researchers planted container stock younger than 10-weeks old (MacKinnon 1970; Low 1971; Dickerson 1974; Goodwin 1976).

In four studies, container seedlings were sampled on a monthly basis (personal communication Tom Starkey). Samples were planted in sand-filled boxes, and root growth was examined after 4 or 5 months. Seedling ages at transplanting ranged from 1to 10 months and taproot growth was near normal when seedlings were transplanted before they were three-months old (Figure 10). Since most container-grown seedlings are transplanted when older than five month, most true taproots are air-pruned prior to outplanting. As a result, stability is reduced when true taproots do not elongate after outplanting. When adventitious roots grow near the callused taproot, they can be easily broken (Terblanche 2000).

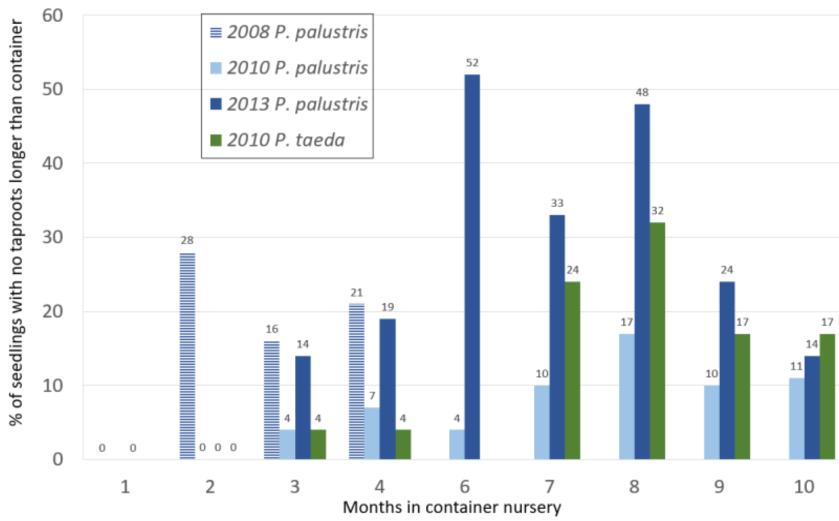

Figure 10. Pine taproots will air-prune and form a callus after the root meristem emerges from the bottom of the container. This typically occurs before seedlings are two months old (from seeding). The 2008 study involved 93-ml containers and 122-ml containers were used after 2009. After transplanting into sand, seedlings were grown outside for four or five months. Except for the youngest seedlings, more than 15% of *Pinus palustris* seedlings did not have true taproots in 2008 and similar results occurred in 2010 for *Pinus taeda*. Data provided by Tom Starkey.

3.13 Recovery

[15] How long does it take for toppled pines to regain a vertical position? The answer depends on tree height. Recovery is rapid when trees are two years old but when more than four years old the “defect in the form of the stem may never be completely eliminated” (Pryor 1937). In South Africa, pines, less than 2 years from planting, toppled and two months later they showed a strong trend of recovering their vertical positions (Zwolinski et al. 1993). In New Zealand, newly planted pines toppled but self-corrected after an additional six months of growth (Coxe 2006). Pines up to 2 m tall grew upright within 12 months of toppling (Cremer 1998). At another location, 15% of two-year-old trees toppled and about half of these had recovered after six years (Chavasse and Balneaves 1971). About 42% of the 7-year-old *Pinus elliottii* trees that were badly bent in February regained a vertical position after eight months (McKeller 1942). Trees that topple all the way to the ground do not recover.

3.14 Species

[16] Do fast-growing genotypes increase the risk of toppling in young pine plantations? The answer is yes. Policy changes were adopted to stop planting a fast-growing provenance of *Pinus contorta* due to the risk of toppling (Lions 1980; Seaby and Schaible 2001). In two species trials, the faster-growing pines toppled (Schmitt and Namkoong 1965; Reynolds et al. 2020). However, exceptions do exist. In some locations a fast-growing family can have less wind injury than a slow growing family (Zhai et al. 2015).

4 Conclusion

#1 Pines established by direct seeding have a true taproot and are more resistant to toppling than planted seedlings.

#2 Bareroot pines undercut once before lifting, are more resistant to toppling than faster-growing container-stock with air-pruned taproots.

#3 When two planted bareroot pines have the same height, the one with less leaf area has a lower risk of toppling.

#4 Pines that grow in height more than 1 m year^{-1} are more likely to topple than those that grow 1 m in five years.

#5 When a true taproot is air-pruned, a callus is formed and this increases the risk of toppling for pine seedlings.

#6 When the true taproot in a pine seedbed is wrenched multiple times, a large callus is formed and this increases the risk of toppling.

#7 An adventitious sinker root is not a taproot (Sutton and Tinus 1983).

#8 Heavy snow can topple young planted pines.

#9 For pines less than 9 years old, most toppling events involve saturated soil, high winds and rapid height growth.

#10 Assumptions about toppling outnumber toppling trials with hypothesis testing.

#11 During a high wind, the risk of toppling for three-year-old container-grown *Pinus taeda* seedlings (Figure 4) is greater than 1 in a million.

Several myths regarding toppling can be found throughout the literature. Some myths evolved from flawed assumptions and were subsequently published without any verification.

Myth #1: In a research paper, there is no need to list the age (in months) or root-collar diameter of transplanted container-grown seedlings since pot-binding does not affect either survival or toppling.

Myth #2: For seedlings, the absence of a true taproot does not increase the risk of toppling.

Myth #3: There is no “hard evidence” (α=0.05) that air-pruned container-grown stock suffer impaired taproot development.

Myth #4: Multiple root-wrenchings in a bareroot nursery reduce the risk of toppling.

Myth #5: On no account should a pine seedling be planted deeper than it stood in the nursery.

Myth #6: Sinuosity of pine seedlings does not begin after toppling.

Myth #7: Good planting will prevent toppling of container-grown pines.

Myth #8: Not one study has been established to investigate the effect of deep planting on the rate of toppling.

Myth #9: Adventitious sinker-roots are taproots.

Myth #10: A large callus on a taproot is a sign of a good quality seedling.

Myth #11: Pine seedlings do not produce adventitious roots.
Myth #12: Butt sweep at age 4 years does not affect stand value at harvest.
Myth #13: After 9 years of growth, the toppling risk is the same for both planted seedlings and naturally regenerated seedlings.
Myth #14: The risk of pines toppling can be consistently determined.

"There seem to be two schools of thought about toppling - one, that it doesn't matter very much, and two that it does matter quite a bit" (Sweet 1981). Those who live in low wind regions may say toppling does not matter very much while those from windy areas might say landowners can suffer an economic loss from toppling (Bell 1978; Mason 1989; Dunham and Bourgeois 1996).

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