ROOT FORM OF PLANTED TREES

SESSION A: REGIONS WITH FAST-GROWING SPECIES

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Abstract.--Gales in New Zealand can sometimes reach a level at which forests are severely windthrown. As well there are more frequent gales of lesser intensity which cause some toppling and windthrow of trees in most parts of New Zealand. Instability in stands is related to the method of preparing planting stock in the nursery, to methods of cultivating planting sites, to planting methods, and to silviculture, including thinning and rotation length, all of which the forest manager is able to manipulate.

Trees grown from seed in situ normally develop a strong taproot and well-distributed laterals, which tend to increase stability, while unthinned stands with a more or less smooth canopy are more stable than thinned stands or those with an uneven canopy. The objective of planting should thus be to use methods which allow the root system to develop a form as close as possible to that of naturally regenerated trees.

Conventional ways of raising seedlings in nurseries (whether bare-rooted or container-grown) make it difficult to distribute roots satisfactorily during normal planting operations, whether by machine or with hand tools. A method of conditioning trees is described which includes undercutting and four-sided root pruning, and which promises to alleviate this problem.

On all sites any form of soil compaction inhibits taproot growth. Overall cultivation with discs or rotary hoes tends to induce or aggravate toppling, and it is suggested that a better method is to prepare compacted sites with winged rippers (to give maximum soil shatter).

In regard to tending, the evidence suggests that initial wide spacing and early thinning may induce greater stability, as well as allowing shorter rotations, thus reducing the period that stands are at risk. Pruning in such stands is necessary for many species, if high quality sawlogs and veneer logs are to be produced.

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INTRODUCTION

New Zealand is a country periodically subjected to severe gales. Thomson (1976) estimates, however, that over the last 50 years only 1 to 1/5% of the volume growth of exotic tree species has been windthrown. He points out that the incidence of windthrow varies considerably in different parts of the country and relates this to maximum windspeeds. The maximum recorded was during the "Wahine" gale of August 1968, when a gust of 270 km/hour was registered in Wellington. Gusts of over 165 km/hour have been recorded in North Auckland, East Cape, Canterbury, Otago, and central North Island; over 150 km/hour in Whangarei, Wanganui, Masterton, Nelson, Timaru, Dunedin, and Milford Sound. Severe windthrow has occurred in some conditions where maximum gusts have reached only 96 km/hour, but most records do not go back sufficiently far to indicate the "gale-of-a-century". The evidence from native forests is that severe gales can occur at long intervals - perhaps 400 to 500 years. Irrespective of Thomson's (1976) estimate, periodic local disruption of timber supplies has caused serious consequences in the short term and, in windy districts (especially Canterbury), the long-term loss of increment is large.

Wendelken (1966) records that exotic forests in Canterbury were badly damaged in a series of gales in March 1964. During the third and most severe gale maximum gusts varied from 86 to 106 km/hour. A much more serious gale occurred in Canterbury in August 1975, over 25% of the local exotic forests being severely damaged by windthrow and windbreak. The maximum gust was 170 km/hour. Thomson (1936) and Ure (1970) both discuss a strong gale which devastated farm trees (exotic) and thousands of hectares of native forest on the western flanks of the Tararua Range in 1936. Irvine (1970) describes serious windthrow in Golden Downs Forest in April 1968, after a fairly long period of scattered and sporadic losses from wind damage. Chandler (1968), in discussing windthrow in the Tapanui district in Otago, estimated that long-term losses from windthrow would be about 10% of total increment.

Species vary in their ability to withstand wind. Thomson (1936) found that Cupressus macrocarpa shelterbelts were badly windthrown, while most Pinus radiata (radiata pine) belts were either windthrown or broken off the stump. Broadleaved trees were much more windfirm: from most to least he listed Populus nigra (Lombardy poplar), Tilia x europaea (common lime), Eucalyptus spp. (eucalypts), Quercus spp. (oaks), Ulmus spp. (elm), and Platanus (plane), but the last two suffered considerable crown damage. Wilson (1976) found that Pinus nigra ssp. laricio (Corsican pine) was no more windfirm than radiata pine of similar height, but that P. ponderosa (ponderosa pine) suffered less throw and more breakage. Pinus lambertiana (15 m high) and P. strobus (13 m high) in the midst of the windthrown area had most of their needles blown off, but remained stable. Pinus muricata was less affected than radiata pine. Pseudotsuga menziesii (Douglas fir) in pure stands was notable for windfirmness except for stands that had recently been thinned, or where it was growing in mixture with Corsican and ponderosa pines. Eucalypts were only sporadically damaged while Sequoia giganteum was almost universally windfirm.

Susceptibility to windthrow has been attributed to numerous factors related to the site (and methods of preparation), to planting methods (and root distribution), to silvicultural measures (especially thinning), to weather, and to terrain. For example Wendelken (1966), Chandler (1968), and Irvine (1970) all list wet soils as an important factor. The last two authors also include shallow soils, wind turbulence on lee slopes, and wind funnelling in valleys as contributory causes of windthrow, and Chandler found that the four major windthrows over the previous 35 years were in conjunction with snow storms. Obviously, however, the major factor in most severe cases of windthrow is simply the excessive windspeed. But the effect of wind on trees and stands is, according to Papesch (undated), a matter of great complexity, related to many characteristics of the tree and the terrain, to soil factors, stand factors, and wind characteristics. In regard to stands, Papesch found that edge trees remain stable at wind speeds higher than those needed to throw trees in the interior of stands. Any measures which increase wind turbulence over stands increase the risk of windthrow.

Instability early in the life of stands has come to be termed "toppling" in New Zealand. It occurs on a small scale quite frequently but is rarely of major importance (fig. 1). The "Wahine" storm of 1968 (in which a tropical cyclone moving south met a cold front moving north) led to widespread topping throughout New Zealand. Chavasse (1969a; b) reports the results of a survey carried out shortly after this storm. The survey was mainly concerned with radiata pine, but several other pines (P. elliotii, P. contorta, P. pinaster, P. muricata), Thuja plicata (western red cedar), Chamaecyparis lawsoniana (Lawson cypress), Douglas fir, Cupressus macrocarpa, Larix decidua (larch),
and even some eucalypts also suffered toppling. An analysis of the survey replies (which included both facts and opinions) led to the following conclusions:

1. **Radiata pine is susceptible to toppling from 2 to 6 years (earlier and later on wet sites) but stabilises when canopy closes if there is more or less full stocking.**

2. In bad gales, up to 100% of the trees on some sites can be affected.

3. Age of planting stock (within the range examined) seems unimportant.

4. Method of planting does not appear to be an important variable.

5. Toppling is likely to occur on wet soils, or on shallow indurated soils, where there is wind turbulence (e.g., on lee slopes) or heavy snow.

6. Susceptibility to toppling can be increased by unsatisfactory tree stocks (e.g., ill-balanced with poor root systems); by unsatisfactory planting (quality - not method); by high soil-fertility leading to lush growth of tops; by soil texture (heavy silts and clays); by excessive weed competition and lack of timely releasing.

Examination of root systems of windthrown or toppled trees has not been very detailed. Menziez (1974) reported that topped trees usually had poor or nil taproot development, and poor distribution of lateral roots. Wendellken (1955), in a study in Eyrewell Forest, Canterbury, found that root systems of naturally regenerated trees had lateral roots evenly distributed "like the spokes of a wheel" and, where regeneration was in closely stocked groups, these roots crossed those of other trees and there was some root grafting. In planted trees the root distribution was irregular. Where trees were widely spaced (either planted or regenerated) they had individual root plates with no root grafting. Similar discrete root systems were found by Irvine (1970) in Nelson. Chandler (1968) also observed the marked differences between planted and naturally regenerated trees, in that planted trees had "clumpy" ill-distributed roots compared with a more regular pattern for trees grown from seed in situ. Potter and Lamb (1974) found that distribution of lateral roots was equally good for naturally regenerated and direct-seeded trees on ripped sites in Canterbury. However, both Wilson (1976) and Brummer (1976) report that naturally regenerated stands were badly damaged in the 1975 gale. Wilson attributes this to lack of ripping on shallow soils (pan at about 45 cm) but Brummer notes that trees planted in shallow rips were more affected than naturally regenerated stands of the same age on non-ripped sites. However, windthrow in older, naturally regenerated stands was worse than in hand-planted areas of comparable age; this may have been because of a much more irregular canopy in the naturally regenerated stands - an explanation that would be in line with Papesch's findings. Wilson (1976) notes that shelterbelts (often only one or two rows) of radiata pine were much less damaged than stands. Single-row shelterbelts, where 50% of trees had been pruned, were more or less unaffected. Most free-grown trees up to 45 years old, with massive root plates and heavy branching, survived.

In the remainder of this paper I shall examine the various aspects of stand stability that can be manipulated by the forest manager - methods of establishment, methods of site preparation, tending, and seedling quality. The information is related mostly to radiata pine.

**TENDING**

Papesch has shown that an irregular canopy surface can increase risk of windthrow as it induces increased wind turbulence. The objective of tending should thus be to maintain a more or less even canopy, the first step obviously being to achieve full stocking initially.

Thinning can make stands more susceptible to windthrow (Chandler 1968). Irvine (1970) found that stands which had been belatedly thinned were more prone to windthrow than unthinned stands of the same age. James and Dier (1968) found that in Scotland stands thinned regularly and on schedule suffered just as much as those in which thinning had been delayed. If anything, unthinned stands suffered less. This is endorsed by Andersen (1954); although information from the literature is to some extent conflicting, the Scottish evidence (after the severe 1953 gales) was that the heavier the thinning the worse the wind damage, and that unthinned stands suffered least. Wilson (1976) reports similar results for Canterbury: unthinned stands 6.5 m high were unaffected while recently thinned stands of the same height were windthrown (both on unripped sites). On the other hand, stands 12 m high and thinned 3 years previously to 660 stems/ha were unaffected (possibly because by that time radiata pine had again closed canopy).
Probably the important point is the timing of thinning in relation to the height of trees at risk, and several authors recommend early heavy thinning. Wendelken (1966) gives no details, but Chandler (1968) suggests that stands should be thinned at a mean height 9 m less than the height at which stands become susceptible to windthrow (which depends on the location). At Tapanui the critical height is 18 m, so stands should be thinned heavily at a mean height of 9 m. This means that, in order to obtain some stability, the early thinning would take no account of merchantability of the thinnings. Irvine (1970) recommends thinning to final crop density at 9 years in Nelson. This general view is reinforced by Papesch’s (undated) findings; because trees with larger diameters are more stable than those of the same height with smaller diameters, thinning early to obtain maximum diameter-growth may be one means of reducing risks of windthrow. It would also tend to shorten the rotation, so that fewer occasions of risk would occur for any particular stand.

Wilson (1976) noted that where trees had been planted on ripped lines, were up to 9 years old, and had been pruned to 4.5 m, they tended to straighten up sufficiently after the 1975 gale for a final crop to be selected. Brummer (1976) confirms this for Eyrewell Forest, where pruning was shown to be the most effective variable in reducing wind damage. He attributed this to the site – on a flat plain well away from any hills, so that windspeeds over the canopy would have been more or less constant with little turbulence. At Balmoral Forest (also in Canterbury) where hills are nearby, pruned trees were rather more affected than unpruned (as one might expect, since the centre of gravity of pruned trees would be higher).

It should be noted that, if early thinning of radiata pine crops is to be undertaken, then pruning is essential in order to produce good grades of timber. The alternative of carrying out no thinning would be unacceptable on economic grounds, apart from the longer period of risk associated with the longer rotations thereby made necessary.

The classical silvicultural systems (strip, wedge planting, etc.) have not been generally adopted in New Zealand. Advocated by Wendelken (1966) the strip system has been adopted in Canterbury, but it is too early yet to say whether it will be effective in the long term. The gale of 1975 was so severe that no human measures are likely to be able to cope with winds of like force.

DIRECT SOWING

There is widespread evidence in New Zealand that naturally regenerated or direct-seeded trees develop a strong taproot and several main laterals generally distributed to all points of the compass, provided the soils allow this (either naturally or through suitable types of human manipulation). One possible method of reducing wind damage would thus be to grow trees from seed in situ. Up to about 1970 substantial areas of cut-over radiata pine forest were air seeded, and improved aircraft equipment was developed for this purpose (Levack 1973). Nevertheless, this is an expensive and fairly inefficient means of re-establishing crops and could lead to increased wind damage because of the irregularity of the resultant stands. It was also becoming less effective with time owing to the increasing predation of seeds by birds and rodents, and costly blanking was essential if gappy stands were to be avoided. The cost of this, and two or three pre-commercial thinnings to obtain a more or less regular stand, was very high. Moreover, seed orchard seed was being used increasingly and it was 4½ times as costly as unsolicited. The method was abandoned, but research is now being conducted into hand seeding with mini-tents (Lähde 1974; Jackson 1975), with encouraging results. This method is probably suitable only where the correct mycorrhizae are already present on the site, not for afforestation of grass or scrublands.

SITE PREPARATION

The two main forms of site cultivation in New Zealand are discing (usually with super-giant discs, 78 cm in diameter) and ripping. Discing is used principally for control of vegetation, especially bracken. Observations in Kaingaroa State Forest showed that complete discing in pumice soils with an underlying indurated layer encouraged lateral root growth substantially, but that taproot growth was negligible in the first 5 years after planting. Trees on these sites are very readily toppled and their long-term stability is doubtful. Rotary hoeing on such sites gives even worse results. Hetherington and Balneaves (1973) found that discing resulted in poorer survival and growth on a tussock-grassland site than ripping, but was better than burning in this respect. Chavaise (1969c) reported that mechanical tilling leads to enhanced growth of tops in early years but that this may not be advantageous since trees are difficult to firm in fully cultivated ground, and on some
sites there can be a great deal of subsequent toppling. In some areas, because of butt sweep after toppling and the need to discard the malformed lower end of the butt logs the first commercial thinning showed a volume loss of 27%.

Over the last 5 years ripping has been increasingly used to prepare sites for planting. Chavasse and Brunnen (1977) report results of a nation-wide survey of ripping. Its main purpose is to improve soils which are naturally compacted (heavy clays, some compacted gravels, soils with hard pans) or which have become compacted by forestry (particularly logging) operations, in order to obtain better growth (including root growth). However, most rippering operations are performed with conventional rock rippers which give only a small amount of soil shatter. Ripping depth varies from 45 to 120 cm, but is mostly at a nominal 60 cm depth. The addition of wings to conventional ripper (Page 1977) greatly increased soil shatter and improved efficiency as measured by drawbar-pull divided by the cross-sectional area of shattered soil. The addition of two forward times to give shallow rips ahead of the main tine led to reduced power requirements for an equal amount of shatter. A conventional rock ripper cutting to a depth of 80 cm shattered a narrow trench of soil (1800 cm² cross-sectional area) with a drawbar pull of 5800 kg. A winged tine shattered a large volume of soil (5300 cm² cross-sectional area) to 72 cm depth, with a drawbar pull of 5300 kg.

Ripping in the compacted gravel soils of Canterbury was first advocated by Wendelken (1966) and was tried shortly afterwards (Wilson 1969). Both shallow (45 cm) and deep (120 cm) ripping was attempted, the latter requiring a tractor of 300 hp. Full evaluation of the effects of these site preparation methods is not yet complete in Canterbury in other soil types. Potter and Lamb (1974) reported that all naturally regenerated and direct-sown trees developed taproots on ripped sites in Canterbury, and Brummer (1976) confirmed this after the 1975 gale, reporting that naturally regenerated trees had taproots to 60 cm. However, he found that trees planted at the intersection of shallow and deep rips were slightly less stable than those planted in-shallow rips. As the oldest stand was only 9 years old this could change with time. Guild (1971) found that in Canterbury ripping led to greatly improved survival of planted radiata pine, greater initial height growth, and height uniformity. Ripping did not influence the amount of toppling in planted stands 2 to 8 years old, even when they had what appeared to be adequate tap and lateral root development. He thought that this was due to the lack of compaction in ripped lines for several years after the operation because of the texture of the soil and the low rainfall.

On clay soils in Otago, Hetherington and Balneaves (1973) found that height growth of radiata pine was markedly increased on ripped sites compared with non-ripped; in the first 3 years growth was 139 cm compared with 108 cm. On ripped sites the mean taproot depth was 320 mm, but only 104 mm on unripped sites; oven-dry weight of roots was 133 g and 42 g respectively; number of lateral roots was 19 and 9 respectively. A strong wind 2 years after planting, with gusts up to 150 km/hour, showed 45% toppling on ripped sites and 68% on non-ripped.

Evidence from trials not yet reported upon seems to indicate that, for both radiata pine and some eucalypts, vigorous top growth is associated with the development of a large taproot.

PLANTING METHODS

Irvine (1970) advocated wider initial spacing (2.4 × 3.6 m) so that planted trees would become more windfirm at an early age. But from the evidence of Chavasse (1969a) it would seem that this would not be effective because planted trees usually have distorted roots. Balneaves (1970) presents photographs of grossly distorted root systems resulting from: single-notch spade planting; T-notch spade planting; "one lick" mattock planting; and "Lowther" machine planting. Both Brummer (1976) and Potter and Lamb (1974) report that machine-planting trees are less stable than hand-planting in Eyrewell Forest. Machine-planting trees had roots aligned along the direction of travel (i.e., along ripped lines); two-thirds had no taproots (ages 2 to 4 years since planting); and distribution of laterals was poor. Subsequent evaluation of machine planting in Canterbury, however, indicates that the operation was carried out at too great a speed, which invariably leads to "dragging" roots along the line of travel. One-third of hand-planting trees had no taproots, but distribution of laterals was better than that of machine-planting trees. However, roots of hand-planting trees were usually "bunched up and crisscrossed" (fig. 2).

Chavasse (1969a) reported that it is difficult to get labourers to apply "quality" prescriptions. There was no difference in toppling between relatively slow planting on wages (300-500 trees/day) and more rapid
planting with incentive payments (1200+ trees/day); and Menzies (1974) found that toppling was less with single-notch spade planting than with careful pit planting, on clay soils.

Menzies (1973) developed a points system for evaluating root systems which has proved useful in subsequent studies (presented as Appendix 1).

NURSERY PRODUCTION

Container-grown seedlings

Very little work has been done on container-grown seedlings in New Zealand as the method is less efficient and more costly for radiata pine than production of bare-rooted nursery stock. An early trial with small polystyrene "bullets", using several eucalypt species, resulted in a considerable degree of failure; excavation of trees that survived showed very poor root development. A stand established in Kaingaroa State Forest with radiata pine in fairly large polythene tubes suffered considerable toppling. It was found (Chavasse and Balnave 1971) that 15% of the trees toppled 2 years after planting, but that nearly half of these had completely stabilised 4 years later. A further 10% of trees toppled between the second and sixth years. Toppling was well distributed throughout all d.b.h. classes, 50% being dominants or co-dominants. Most of the trees that had toppled badly became grossly malformed because of smothering by weeds (bracken and tree lupin). Three-quarters of the toppled trees had "over-corrected", giving rise to sinuous stems, and on 50% of the toppled trees this sinuosity continued to 6 m or more, which would result in considerable sawn timber degrade. On 8% of the crop butt lengths of 0.6 to 2.0 m would have to be discarded owing to butt sweep. As a comparison, only 10% of bare-rooted stock, interplanted with the tubed stock, showed signs of toppling, mostly of a minor nature.

Current work with tubed stock of radiata pine and eucalypts shows that planting date must be strictly related to the size of the container. Any delay can lead to root distortion within the container. If trees cannot be planted at that point, it is necessary to line them out in the nursery. Furthermore, the size of the seedling is also strictly related to the size of the tube and with eucalypts the growing space for tops is also of importance if the maximum advantage of tubed stock (no planting check) is to be achieved. It is considered that it may be possible to avoid root distortion in tubed stock, provided techniques are strictly tailored to the biological needs of the seedling. However, where damage by animals or competition from weeds can be expected, rather large containers will be required, and this presents logistical problems.

Bare-rooted seedlings

Because it seemed that, during normal planting operations, there was little chance of roots being placed in the ground correctly, it was decided that one area of study should be nursery production to see if it were possible to produce a root system which could be planted without gross distortion. The conventional method of "conditioning" bare-rooted seedlings in New Zealand is described by van Dorsser and Boek (1972). The method consists of cutting taproots with a sharp blade operated by a reciprocating machine, "wrenching"1/ several times, and giving one or two lateral root prunings along the sides of the drills. More recent work has shown that quality of seedlings depends to a major extent on the spacing of seedlings within the drills (Chavasse 1973; Menzies, van Dorsser and Moherly 1974; Chavasse and Bowles 1975; 1976; Balnave 1976; Balnave and McCard 1976). For 1/0 radiata pine in warmer nurseries the optimum spacing is 2.5 cm; in colder localities, 7 cm. For 1/2 radiata pine seedlings in warmer climates the optimum spacing is 4.5 cm; colder 9 cm. The normal spacing between drills is 15 cm.

One effect of wrenching is that the taproot may not re-develop (fig. 3). 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.

Another effect of the conditioning treatment is to induce root growth along the drill. Although these straggling roots are trimmed to some extent during bundling and packing, they still invariably tend to get twisted up in the soil beneath seedlings in nursery beds with the objective of aerating the soil, which in turn leads to increased growth of feeding roots and mycorrhizae.

1/ Wrenching consists in passing a blade through the soil beneath seedlings in nursery beds with the objective of aerating the soil, which in turn leads to increased growth of feeding roots and mycorrhizae.
planting hole, and this in turn may lead to instability or "root strangulation". The root systems of planted trees therefore have no resemblance to root systems of trees grown from seed in situ, which tend (on suitable soils) to have a marked strong taproot and several strong laterals well-distributed in all quadrants.

The objective therefore is to develop a root system closely resembling that of a naturally regenerated tree. After a series of trials the method adopted was as follows:

A deep undercut to sever the taproot (and no subsequent wrenching);

Lateral root pruning on all sides (i.e., along and across the drill twice at an interval of 3-4 weeks);

A final undercut shortly before lifting, shallower than the first undercut (fig. 4).

Preliminary results are presented by Brunsden (1976). His findings were:

(a) Lateral pruning (alone) on two sides does not condition seedlings satisfactorily; severing the taproot seems to be the most effective operation.

(b) Conditioning regimes which include undercutting and wrenching but not lateral pruning showed lower survivals than those in which lateral root pruning was included.

(c) In terms of survival and initial growth, the best conditioning treatments included undercutting and four-sided lateral pruning ("box pruning") at 4-weekly intervals. Favourable results were much more marked on hard frosty sites than on warm sheltered sites, indicating that box pruning induced greater "hardiness" or quality. Best root systems, including both taproot and laterals (scored by Menzies' points method) were produced by box-pruned trees.

Although it cannot be stated that this method has been proven, results are encouraging.

Further trials, not yet evaluated, show that on a variety of sites box pruning is as effective in hardening seedlings as conventional methods; that box-pruned trees put on greater growth (both height and diameter) over the first two growing seasons than normally wrenched seedlings; and that development of taproots and laterals is substantially superior on box-pruned trees (fig. 5). Moreover, the amount of distortion of root systems of box-pruned trees during normal planting operations is reduced. The problem now is to mechanise the cross-drill wrenching. However, it has still to be shown that this method reduces toppling and increases windfirmness.

CONCLUSION

There are evidently many means by which risk of instability in stands can be reduced, including nursery treatment of seedlings, site preparation methods, tending regimes, and possibly planting methods. Nevertheless, storms reach an intensity in some parts of New Zealand during which no forest, having reached a critical height, could remain standing. The major means for reducing windthrow hazard in normal storms appear to be:

(1) Producing a seedling in the nursery with root systems which are least likely to be badly distorted at planting and which will, as far as possible, develop in a way similar to those of a tree grown from seed in situ. Alternatively, to develop efficient direct-sowing methods which can be relied upon to produce full stocking, and not overstocking or the normal clump- and-gap distribution of natural regeneration.

(2) Thinning heavily and early in order to promote root growth and diameter growth. This, for sawlog and veneer crops, would necessarily have to be coupled with pruning of at least the butt log.

(3) Adopting shorter rotations so that the period at risk (after the stand reaches a critical height) is minimised.

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Figure 1.--Young radiata pine, approx. 3 m tall, showing toppling on clay soil.
Figure 2.—Root systems of radiata pine seedlings two years after planting by spade.

Figure 4.—Box-pruned seedling of radiata pine showing short laterals and callus formed at the tip of the taproot.

Figure 3.—Root system of wrenched radiata pine seedlings taken at right angles to the drill, showing long laterals and distorted taproot.

Figure 5.—Taproot development of box-pruned seedlings two years after planting.
APPENDIX 1

Points system for evaluating root systems (after Menzies 1973)

<table>
<thead>
<tr>
<th>Ideal Root System</th>
<th>Score 0</th>
</tr>
</thead>
<tbody>
<tr>
<td>Worst Root System</td>
<td>Score 32</td>
</tr>
</tbody>
</table>

1. **Taproot (maximum = 10)**
   - Well-developed, straight
     - 0
   - Stunted but definite
     - 1
   - Does not come below horizontal
     - 10
   - Laterals now vertical as sinker roots
     - + 1 per sinker
     - (subtract from 10 for no taproot)

2. **Deformation**
   - Score 2 4 6 8 10

3. **Lateral roots (maximum = 10)**
   - 4-5 well-distributed
     - 0
   - 3 well-distributed
     - 1
   - Laterals opposite
     - 4
   - Laterals at right angles or on one side
     - 8
   - No laterals
     - 10

4. **Tangled roots (maximum = 6)**
   - 0-6 scale subjectively assessed.

5. **Fracture zones (maximum = 6)**
   - Taproot
     - 2-4
   - Laterals
     - 1 per major lateral.

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APPENDIX 2

Remedial measures for toppled trees

Toppling is a minor problem except in occasional periods when a violent storm occurs, when it can affect regions or (exceptionally) the whole of New Zealand. Normally forest managers can safely ignore the small proportion of toppled trees in a stand as they will most likely be removed in thinning. Where a greater proportion of trees is toppled, some loss of yield is likely, but most toppled trees will stabilise over a period of 12 months after toppling provided no gales occur.

Menzies (1974; 1975) evaluated methods of "propping up" toppled trees. In practice it may not be necessary to stabilise more than about 30% of trees even where severe toppling has occurred. Menzies found that some trees less than 1.5 m tall could be adequately stabilised by placing a substantial turf against the base of the bole, but on a site where toppling was particularly bad (with a plastic clay soil) over 70% of trees propped up in this way re-toppled. Trees larger than 1.5 m tall can best be stabilised by tying them to stakes driven into the ground alongside the stem. The stakes and twine should be treated with preservative to a level sufficient to last at least 1 year. Stakes should be of the same cross-sectional area as the d.b.h. of the tree, and twine should be tied to branches not around the stem because it may strangle the tree. An important point which emerged from these studies is that roots respond very quickly to toppling. If toppled trees are not straightened very shortly after toppling, then there is a tendency to break off the roots remaining, and the tree will often die. Menzies also found that vigorous growth is needed to promote root growth and thus stability, so straightened trees should not be pruned for at least a year.
CONTAINER-INDUCED ROOT MALFORMATION AND ITS ELIMINATION PRIOR TO PLANTING

Edward C. Stone and Edward A. Norberg

Abstract.—When root spiraling in container-grown seedlings is not removed prior to transplanting, many of the transplants produce malformed root systems. If sufficiently marked, malformation can result in structural failure near the root crown or in a one-sided root system incapable of providing satisfactory stability later in the life of the tree.

INTRODUCTION

The study reported here is an evaluation of container-induced root malformation and two methods by which it has been successfully reduced. The study was an outgrowth of a review by the senior author in 1968 of the planting program in northern Tunisia and the relationship between time of planting and seedling survival, made at the request of the Institut de Reboisement de Tunis.

It has long been the practice in Tunisia to plant with container-grown seedlings, and containers of a variety of shapes, sizes and materials have been used. The Tunisian Forest Service currently employs a perforated plastic bag that expands to form a 5 x 5 x 20 cm container. Filled with a mixture of oak-humus and sand, these containers are seeded in April, and germination is complete by the middle of May. Beginning in October, and throughout the planting season, which is generally over before the end of April, the seedlings are shipped to the planting sites as needed.

Root malformation could always be found in the plantations visited, and did not appear to be associated with initial seedling survival. In some plantations it was closely associated with stunting, and much of this could be traced to the former practice of planting seedlings without first removing the plastic container—a practice that had been reported to increase seedling survival (Monjaute 1956, Duruel 1966). But in other plantations, where stunting was not apparent, root malformation sometimes produced a structural weakness just below the ground line; trees exhibiting this weakness could often be broken off by simply rocking the tree back and forth. At other times, root malformation produced a shallow one-sided root system which in some areas resulted in extensive windthrow.

Based on these observations, the advisability of employing container-grown seedlings in Tunisia was questioned and the alternative of substituting bare-root seedlings was discussed. In these discussions it was pointed out that bare-root Pinus ponderosa seedlings can be successfully planted in California, on planting sites that are every bit as arid as those in northern Tunisia, provided planting is scheduled to take advantage of seasonal periodicity in the root growth capacity (Stone 1955, Stone and Schubert 1959a, 1959b, Stone and Bensier 1962, Krugman and Stone 1966, Stone and Jenkinson 1971).

The Institute staff, however, did not believe that such an approach was feasible because of the shortage of technical and supervisory personnel in the Tunisian Forest Service. If bare-root seedlings were employed, they argued, more often than not the seedlings would be dead, or at least beyond hope of survival when planted, because there was no way to insure proper lifting, shipping, and subsequent storage on the planting site. With container-
grown seedlings, on the other hand, death en-route or even during prolonged storage on the planting site, is at most a minor problem.

Faced with this consensus, two alternative planting systems were proposed in which container-grown seedlings could still be employed. Since root malformation is the result of the downward spiraling of the roots in the container, malformation can be prevented if the spiraled roots are: (a) unspiraled prior to planting or (b) destroyed. Most of the roots can be unspiraled by pulling the root-ball apart. Then all except the tight spirals formed in the bottom of the container fall out, and when the roots are pruned to a length of 15 cm or less these are removed. Most of the spiraled roots can be destroyed by making one or more 0.5 cm deep vertical cuts along the length of the root-ball and slicing off the bottom 1.5 cm.

Because suitable facilities were available at Berkeley and the Institute staff otherwise committed, we were asked to evaluate for the Institute these two alternative solutions for eliminating root malformation. Specifically, we were asked to characterize the root systems of container-grown seedlings of Pinus pineaster and Pinus halepensis that developed following transplanting when: (a) the root-ball was left intact, (b) 1.5 cm was sliced off the bottom and three 0.5 cm deep equidistant vertical cuts were made down the length of the root-ball, and (c) the root-ball was pulled apart, the spiraled roots were shaken loose and, while hanging free, were cut off 15 cm below the cotyledon scar. Because of the worldwide interest in Pinus radiata we also included it in the study.

All three species responded in the same general way. Therefore, to simplify presentation, data relating to only one of these species is reviewed here; and for this purpose, Pinus pineaster was chosen.

MATERIALS AND METHODS

Two different nursery climates were employed. One was based on temperatures recorded at Zerniza by the Institute, from January, 1967 to December, 1968; and was designed to approximate the effect the temperature sequence at Zerniza has on seedling development. The other which we will refer to as a Berkeley-1 climate, has proved earlier, in a variety of root-growth capacity studies, to be a satisfactory climate for producing vigorous seedlings with a low top/root ratio. Seedlings produced in these two different climates—Zerniza and Berkeley-1—did not differ appreciably in size or in the amount of root spiraling. And again to simplify presentation, only the response of seedlings grown in the Berkeley-1 climate is reviewed here.

The Berkeley-1 climate was developed in an air-conditioned glasshouse in which the light intensity and photoperiod that prevailed at Berkeley was employed (38° N latitude). The temperature was maintained at 24° during the day and 18° at night from June to December 15; it was maintained at 7° during the day and 5° at night from December 15 to January 22; and it was maintained at 5° during the day as well as at night from January 22 to April 6. Relative humidity was not controlled; it did not, however, drop below 60 percent at any time.

Seeds collected in 1968 by the Institute at Dar Chichou in northern Tunisia, were used. After stratification for 3 months at 5° in fungicide-drenched sand, seeds were germinated in vermiculite at night. Germination began in early June, 1969, and only those that germinated during the first 10 days were used. Once germinated, and after the radicle was approximately 3 cm long, the seeds were planted in 5 x 5 x 20 cm perforated plastic bag containers, filled with a forest sandy loam.

Except during the first 3 months, when a 1/10 strength Hoagland solution (Hoagland and Arnon 1950) was employed, seedlings were watered with tap water. During the first three weeks following germination they were also drenched weekly with a fungicide to minimize "damping-off".

The following spring, the seedlings were ready for treatment and transplanting. On April 1, 10 months after germination 500 seedlings of each species were selected for uniformity in size and bud development. Of these selected seedlings, 350 were moved by covered truck to field plots located in an unused portion of the State Forest Nursery at Ben Lomond. The nursery is located approximately 100 miles south of Berkeley and at an elevation of 2,100 feet. The climate does not differ greatly from that at Tamis in northern Tunisia, in terms of temperature and photoperiod. The soil is a sandy loam developed on granite and has a water-holding capacity of around 15 percent at a pressure of -0.1 bar.

The remaining 150 seedlings of each species were moved a short distance to a field plot on the University of California Gill Tract. The Gill Tract is located in west Berkeley near the bay, and the climate is different from any in Tunisia—cool in the summer with almost daily
fog and mild in the winter with temperatures rarely dropping below freezing at night. The soil is a heavy clay developed on deep alluvium and has a water holding capacity of around 55 percent at a pressure of -0.1 bar.

Seedlings were randomly divided into three treatment groups and the root-ball in each group subject to a different treatment (fig. 1). Treatment in the first group consisted of removing the container without injuring the roots that occupied the interface between the container and the root-ball. Treatment in the second group consisted of slicing 1.5 cm off the bottom of the root-ball and making three 0.5 cm deep equidistant vertical cuts down its length. Treatment in the third group consisted of pulling the root-ball apart, shaking out the spiraled roots and, while they were hanging free, cutting them off at 15 cm below the cotyledon scars.

At Ben Lomond, the seedlings were transplanted after treatment into three separate beds. Each bed consisted of 9 blocks of 40 plants each, 10 for each of the 3 treatments and 10 border plants.

At Berkeley, the seedlings were transplanted after treatment into one bed. It consisted of 9 blocks of 40 plants each, 10 for each of the 3 treatments and 10 border plants.

At the end of the first growing season following transplanting 3 blocks of transplants at Ben Lomond were excavated to a depth of 6 cm. Excavation was with a high pressure stream of water; with the soil was washed from around the roots and into a ditch dug along the side of each bed. Prior to excavation the tops of each transplant were cut off to make it easier to get to the roots. None of the transplants in the field plot at Berkeley were excavated. They are to be held until 1980, at which time a 10 year evaluation of the treatments will be made.

Following excavation, the angle through which each of the secondary roots rotated as it grew out and down from the primary root, was measured and recorded by 90° classes (i.e., > 90° but ≤ 180°, > 180° but ≤ 270°, etc.). Next, the length of each of these secondary roots, plus the length of the attached tertiary roots > 10 cm, were measured. From these measurements the mean rotational angle and the percent of the total root length attached to the primary root with a rotational angle > 360° were calculated.

Shoot growth was measured in terms of dry weight, height, and total branch length. The main stem was measured from the severed end to its tip and each branch from its junction with the main stem to its tip. Top weight was determined following drying for 48 hours at 65°.

Models of a "typical" root system of transplants from each of the treatment groups were constructed. These were developed from seedlings planted in raised beds at Berkeley for this purpose. The raised beds simplified root excavation and minimized breakage. In preparing these models the tops of the transplants were cut off just above the soil surface. To keep the severed stem bases in place and erect, as the soil was washed from around the roots, each base was connected to an overhead wire support. The sides of the bed were then removed and the soil washed away with a fine stream of water in 15 cm deep increments (fig. 2). After each increment was removed, the roots that had been exposed were permitted to dry for 2 hours; they were then sprayed with one of four colors of fast-drying lacquer which identified their vertical position; and finally their horizontal distribution was plotted on a large scale map of the transplant bed.

Construction of the model involved four steps. First, the roots were soaked in warm water to restore their flexibility. They were then positioned vertically, according to their color, and horizontally, according to their mapped position, in a three-dimensional rack so that each root occupied the same spatial position it had occupied in the soil. The rack consisted of a wire-mesh base in which vertical support rods were inserted as needed. Roots were attached to the rods by masking tape after which they were sprayed with successive layers of a fast-drying white lacquer. The root system, now made rigid by accumulated layers of lacquer, was then freed from the rack and mounted on a plywood base into which small diameter doweling, cut to predetermined lengths, had been inserted near the edges to support the roots without altering their vertical or horizontal positions. These models are shown in Figures 3, 4, and 5. Each model was also photographed twice--the second time after it was rotated through six degrees—from which stereo-pairs showing the three-dimensional relationships of the roots have been prepared. These have been included for viewing in Figure 10.

At the end of the second growing season following transplanting, another three blocks of transplants were excavated at Ben Lomond. Again, following excavation, the angle through which each of the secondary roots rotated as it grew out and down from the primary root was
again measured and recorded by $90^\circ$ classes. The length of the secondary roots and tertiary roots, however, were not measured as they were at the end of the first and second growing seasons. Instead, each root system was rated according to: first, whether or not there was a strongly developed primary root or an equivalent replacement; second, when a strongly developed primary root or an equivalent replacement was present, whether or not it was encircled by strongly developed secondary roots; and third, when a strongly developed primary root or an equivalent replacement was absent, whether or not the dominant secondary roots produced a one-sided or a radially symmetrical root system. Shoot growth was measured in the same way it was measured at end of the first and second growing seasons following transplanting.

RESULTS

After One Growing Season

At the end of the first growing season following transplanting each root-ball treatment had produced a different type of root system.

In the first treatment group, where the root-ball was left intact, most of the secondary roots exhibited a pronounced spiral with many rotating through $360^\circ$ or more. This treatment resulted in a loose basket of intertwined roots of the same dimensions as the container, from which the roots produced subsequent to transplanting radiated out and down (fig. 3).

In the second treatment group, where 1.5 cm was sliced off the bottom and three 0.5 cm deep, equidistant, vertical cuts were made down the length of the root-ball, many of the secondary roots included sections that displayed some degree of spiral. Rarely, however, did they incorporate a rotation of more than $180^\circ$. This treatment resulted in a cap of roots of the same dimensions as the container, from which the roots produced subsequent to transplanting radiated out and down (fig. 4).

In the third treatment group, where the root-ball was pulled apart, the spiraled roots were shaken apart and, while hanging free, were cut off 15 cm below the cotyledon scars. Only a few of the secondary roots included sections that displayed little if any spiral. When they did, rarely did they incorporate a rotation of more than $90^\circ$. This treatment resulted in a crowding together of the roots to a depth of 15 cm, from which point roots produced subsequent to transplanting radiated out and down (fig. 5).

In the first, second, and third treatment groups: (a) the mean rotational angle varied between $110^\circ$ and $190^\circ$, $30^\circ$ and $70^\circ$, and $10^\circ$ and $25^\circ$; (b) the percent of seedlings with a rotational angle of $\geq 360^\circ$ was 80%, 0%, and 0%; and (c) the percent of the total root length with a rotational angle of $\geq 360^\circ$ or more was 30%, 0%, and 0%.

Root elongation was closely correlated with the total length of the root that had been left intact prior to transplanting. In the first treatment group root elongation was greater than in the second and third treatment groups. In the second and third treatment groups there was no difference.

Height growth was unaffected in any of the treatment groups. Dry weight and total branch length, however, were significantly reduced in the third treatment group.

After Two Growing Seasons

At the end of the second growing season following transplanting, there was no difference in the general form of the root systems, although the roots were considerably larger. A "typical" root system of a seedling from the first treatment group is shown in Figure 6.

The mean rotational angle, the percent of seedlings with a rotational angle of $\geq 360^\circ$, and the percent of total root length with a rotational angle of $\geq 360^\circ$ did not change significantly during the second year.

Top growth was highly variable, due in part to crowding. Unlike at the end of the first growing season, no correlation could be established between top growth and root-ball treatment.

After Three Growing Seasons

At the end of the third growing season following transplanting, the effect of leaving the root-ball intact was still very apparent, and the mean rotational angle had not changed significantly among the transplants. The degree to which the primary root or its equivalent had developed subsequent to transplanting, however, varied considerably. In those instances where it had failed to develop, the dominant secondary roots often formed a one-sided root system while at other times they formed a radially symmetrical one (Figs. 7, 8 and 9).

The mean rotational angle in these root systems was $165^\circ$. In 80 percent, the primary
root or its equivalent had continued its development subsequent to transplanting and a number of secondary roots were tightly entwined around it. Among those transplants in which the primary root or its equivalent failed to develop subsequent to transplanting, the dominant secondary roots formed a one-sided root system in approximately 60 percent, and a radially symmetrical root system in approximately 40 percent.

SUMMARY AND CONCLUSIONS

The roots of 1 year old Pinus pinaster, Pinus halepensis, and Pinus radiata grown in 5 x 5 x 20 cm plastic containers had a marked spiral which resulted in a malformed root system when not removed prior to planting. At the end of the third growing season following transplanting, up to 40 percent of the transplants lacked a well-developed primary root or its equivalent, and of these 60 percent or more had developed a pronounced one-sided root system.

Whether or not root malformation of this type will in time retard top development was not determined, inasmuch as the study was not designed to answer this question. Such malformation, however, can be expected to introduce a structural weakness in those trees whose secondary roots are tightly entwined around a well developed primary root or its equivalent, and to produce a one-sided root system in many of the others.

Container-induced root malformation can be prevented by removing the spiraled roots prior to transplanting. This can be accomplished in either of two ways. The spirals can be cut by making three equidistant 0.5 cm deep vertical slices running the length of the root-ball and then cutting off 1.5 cm from the bottom. Or the root-ball can be pulled apart, the spiraled roots shaken apart and, while hanging free, pruned at 15 cm below the cotyledon scars.

LITERATURE CITATIONS


Figure 1.—Container-grown seedlings prior to receiving one of three root-ball treatments.

Figure 2.—Excavating transplants from raised beds to be used in producing root system models.

Figure 3.—Typical root system of a transplant at the end of the first growing season whose root-ball was not modified prior to planting.

Figure 4.—Typical root system of a transplant at the end of the first growing season whose root-ball was cut to a depth of 0.5 cm by three equidistant vertical cuts and 1.5 cm cut off the bottom prior to planting.

Figure 5.—Typical root system of a transplant at the end of the first growing season whose root-ball was pulled apart, the spiraled roots shaken loose and, while hanging free, pruned at 15 cm below the cotyledon scars.
Figure 6.—Typical root system of a transplant at the end of the second growing season whose root-ball was not modified prior to planting.

Figure 7.—The first of three classes of root systems of transplants at the end of the third growing season whose root-balls were not modified prior to planting. The primary root or its equivalent continued to develop subsequent to transplanting and is now entwined by strongly developed secondary roots.

Figure 8.—The second of three classes of root systems of transplants at the end of the third growing season whose root-balls were not modified prior to planting. The primary root or its equivalent failed to develop subsequent to transplanting and the dominant secondary roots have a symmetrical distribution.

Figure 9.—The third of three classes of root systems of transplants at the end of the third growing season whose root-balls were not modified prior to planting. The primary root or its equivalent failed to develop subsequent to transplanting and the dominant secondary roots have a one-sided distribution.
Figure 10.—Stereo-pairs of the root systems shown in Figures 3, 4, and 5. Upper pair: root-ball was not modified prior to planting. Middle pair: root-ball was cut to a depth of 0.5 cm by three equidistant vertical cuts and 1.5 cm cut off the bottom prior to planting. Bottom pair: root-ball was pulled apart, the spiraled roots shaken loose and, while hanging free, pruned at 15 cm below the cotyledon scars.
CARBOHYDRATE RELATIONSHIPS IN ROOT SYSTEMS OF PLANTED LOBLOLLY PINE SEEDLINGS

Ronald L. Hay and Frank W. Woods

Abstract.—Deformation of loblolly pine roots acquired during outplanting affected carbohydrate physiology and tissue anatomy. Severe kinks in the taproots were effective impediments to carbohydrate translocation. $^{14}C$-labeled carbohydrates, principally $^{14}$SUC and $^{14}$GLU, were found to accumulate in significant (p<.01) concentrations above the impediment. $^{14}$GLU was evidence that the blockage was being maintained for some time. Lateral root tips had large amounts of $^{14}$GLU. Tissue structure had also been influenced by the translocation impediment. Most of the sieve cells had collapsed above the blockage and the enlarged parenchyma cells were filled with starch. There were several bands of functional sieve cells in normal roots and starch appeared less abundant. The accumulation of carbohydrate relatively close to the root collar was projected to have an important impact on development of a profuse lateral root system, probably at the expense of a functioning taproot system.

INTRODUCTION

The need to regenerate our forests has not always been recognized. For many years, harvesting the forest was more important to more people than forest regeneration. Sometimes this exploitation was an instrument of greed and sometimes it was an excuse for civilization and progress, but it was commonplace; it reflected the mood of the times. However, some people were urging regeneration of our forest resources, e.g., George Perkins Marsh wrote in "Man and Nature" that denuding forest lands was equated with the action of fools. Many others have referenced early writings, including the Bible, to document that there was once abundant forest vegetation in the Mediterranean area.

President Theodore Roosevelt and his good friend Gifford Pinchot brought attention to the need to regenerate forests in the United States. President Roosevelt used the "Big Stick" to muster support and Gifford Pinchot knew how to plant trees. Even the United States Congress, which is not always noted for timely or logical or profound actions, became engrossed with the reforestation movement when in 1924, the Clarke-McNary Act was passed (USFS, 1974).

With increased tree planting throughout North America during the 1920's and 1930's, some researchers began to study root systems of planted trees and to compare them with those of naturally-seeded trees. Thousands of acres of newly acquired national forest lands in Michigan were being reforested annually (Rudolf 1937). Many questions arose as how best to plant these trees, although most plantings were by the "slit method" or the "deep-hole method" with preference to the former due to least cost. Rudolf (1937) cautioned that the effects of improper planting techniques could be significant for thirty or more years. He speculated that windthrow would be a problem.

In a thorough study of new plantations, Rudolf (1939) reported that seedling root shape acquired during outplanting had slightly
affected survival, but height growth of red pine (Pinus resinosa, Ait.) and jack pine (P. banksiana, Lamb.) on the Huron National Forest was substantially affected. Trees with roots in a single plane had greater mortality than others and those that lived were shorter than the others. The net result of much of this early work on planting technique, root shape, survival, and stem growth was to prescribe that sturdy, vigorous planting stock (2-2 transplants) be planted using the "wedge method" to assure good lateral root spread and all the benefits attributed to it.

Planting was quickly recognized as a major financial investment, and not just as a problem in biological/site compatibility. Foresters were urged to maintain minimum investments by planting the cheapest stock as quickly as possible. The severe drought preceding the 1936 study on the Huron National Forest was blamed for the low survival and growth rates. Root shapes acquired during planting probably didn't have any impact anyhow, for some later studies in Minnesota showed good survival regardless of the planting technique utilized (Schantz-Hansen 1945). Soon, many reforestation workers began talking about the "final word being middle-ground"; they recognized the need to be conscious of the economic investment as well as the biological/site compatibility problems.

Again in 1959, the profession was urged to use caution and care in planting techniques (Gruschow 1959). Significant numbers of saplings with root systems deformed during outplanting had been found in some three-year-old pine plantations in Virginia. Stem growth differences were not found, but the implications were still made that root deformation was bad. We just are not sure when or how the bad effects will appear.

Anxiety concerning the effects of root placement at outplanting on subsequent stem growth has remained with us. New techniques of culturing seedlings have created new planting techniques. Before we answered all the questions relative to bare-root planting, we changed the rules and now our profession is plunging ahead without knowing the full ramifications of our actions. Containerized seedling culture, be it roottrainers, styro-blocks, or paper pots, has necessitated new techniques and introduced new problems. Root physiology, however, remains an area of justified importance and increased interest.

CARBOHYDRATE DISTRIBUTIONS
IN DEFORMED ROOT SYSTEMS

Seedling survival and growth are visible expressions of many life functions, all working in an interrelated fashion to determine structure and vigor of the individual. Carbohydrate metabolism is one such function! Carbohydrate synthesis in the leaves supplies the roots with energy, assimilates, and carbon chains for amino acid synthesis. Due to the obvious metabolic importance of carbohydrates in roots, we chose to investigate their relationships within roots of outplanted seedlings. Ample literature indicates the importance of carbohydrate metabolism in roots (Gilmore 1962; Thimann and Delisle 1942; van Overbeek et al., 1946).

Other metabolic functions are important in roots as well as carbohydrates. Auxins and other growth hormones have important roles in initiating root primordia and subsequent root growth (Warmke and Warmke 1950; Torrey 1950). Due to our laboratory limitations, these phenomena were not initially investigated.

There are numerous roles and functions of carbohydrates in roots and there are many ways to study carbohydrate influence on root relationships. For example, if root deformation exerted influence upon the movement of carbohydrates into and within the root system, some means to study their immediate movement and distribution in roots would have to be designed. Long-term carbohydrate relationships might also be important, and would require studies to quantify soluble carbohydrates within roots after extended growth periods. Starch would also reflect extended-time metabolism significance.

Soluble Carbohydrate Flow

\[ ^{14}C \text{-labeled Carbohydrate} \]

Radioactive elements make excellent "tracers" of plant pathways (Bassham 1965). Radioactive molecules can be used to isolate carbohydrates produced during a short period as they move into the supporting root system, therefore, \[^{14}CO_2\] was introduced into an enclosed atmosphere surrounding the leaves of loblolly pine (Pinus taeda L.) seedlings that had been growing on variously deformed root systems.

Seedlings had been planted in deep trays with roots deformed to simulate those root shapes occurring under field conditions (fig. 1). After growing in the greenhouse for seven months, some seedlings were exposed to \[^{14}CO_2\] and others were used for soluble carbohydrate analyses. Taproots were sectioned with
Figure 1.—Seedling root shapes analyzed for carbohydrate distributions: #5 represents the "double-J" treatment, #7 represents the "straight" treatment, and #3 represents the "knotted" deformation treatment. Note the lateral root development of the "knotted" root.

reference to the principal curvature, in respect to distance toward the root collar and root tip, plus the upper/lower halves. Appropriate carbohydrate separation, isolation, and identification techniques were used for analysis (Hay and Woods 1968; Hay and Woods 1975). Sucrose (SUC), glucose (GLU), fructose (FRU), and raffinose (RAF) were the only soluble carbohydrates found, and in that order of decreasing abundance. Other compounds may have become 14C-labeled, but they may have been lost during the carbohydrate separation techniques. They may also have been eluted from the paper with the solvent front.

Translocation Impediment.—"Double-J" and "straight" root treatments made interesting and meaningful comparisons (fig. 2 and 3). The relationships of carbohydrate distribution in the roots after a one-day flux (fig. 2) and those from wall into the first growing season (fig. 3) are quite similar considering all the potential sources for difference. Both the 14C-labeled carbohydrate distribution and the soluble carbohydrate distribution in "double-J" taproot showed the effect of the principal curvature. The bottom of the "J", so common in handplanting operations, was effectively serving as an impediment to carbohydrate movement toward the taproot tip. Total 14C-labeled carbohydrates were significantly more abundant (0.01 probability level) between the root collar and the principal curvature in both the upper and lower phloem halves than below the principal curvature in the "double-J" roots. The phloem positions immediately adjacent to the principal curvature were significantly different (0.01 probability level), with more carbohydrate toward the root collar (fig. 2).

14C in "double-J" root systems showed the same relationships as total 14C-labeled carbohydrate distribution, i.e., more radioactivity was found between the root collar and the principal curvature than below the curvature, however, most of the significance was in the upper phloem half. 14SUC was ten times more abundant in all root systems than either 14CGLU or 14CFRU. Polysaccharides, including sucrose, are the most common carbohydrates in translocation fluids and they are rendered into their monomer components by enzymes within the root systems (Zimmerman 1957). These monomers are utilized for energy and carbon chains in root metabolism.
Figure 2.—Distribution of $^{14}$C-labeled carbohydrate in loblolly pine seedling root systems that were deformed at planting. Sampling was completed 24 hours after $^{14}$CO$_2$ was introduced into the atmosphere surrounding the leaves. Both the "double-J" and "knotting" taproot had blockage of carbohydrate flow.
Figure 3.—Soluble carbohydrate distribution in loblolly pine seedling roots after growing for seven months on deformed roots in the greenhouse. Without timing the carbohydrate flux into the roots, there was an accumulation between the root collar and the principal curvature.
GLU distribution in the "double-J" roots was significantly different than in the "straight" roots. The concentration of GLU between the root collar and the principal curvature of the "double-J" was significantly more abundant (0.01 probability level) than the GLU concentrations between the principal curvature and the taproot tip. GLU concentrations in the two sampling positions adjacent to the principal curvature were significantly different at the 0.05 probability level. Again, more GLU was found above the principal curvature.

FRU was significantly more abundant (0.01 probability level) in the lower phloem tissue halves between the root collar and the principal curvature than between the root collar and the tip. The upper phloem tissue halves showed the same trends (0.05 probability level). FRU was not as plentiful as GLU but the distribution showed the effect of the principal curvature as an impediment to carbohydrate translocation.

Soluble Carbohydrates

Without using C-labeled molecules to establish a time reference for translocation discharge into the roots, soluble carbohydrate distributions in the same root deformation treatments were analyzed. It is logical to assume that a concentration gradient reflecting the production and influx from several photosynthetic periods occurred within the root systems. Analytical techniques were similar to the C-labeled work.

Double-J.—Soluble carbohydrate concentrations (fig. 3) in the "double-J" roots showed the same trends as those reported with radioactive tracers. The accumulation zone between the root collar and the principal curvature, the accompanying blockage of the principal curvature, and the decreasing carbohydrate amounts toward the taproot tip were all present. Here also much of the measured carbohydrate between the root collar and the principal curvature was glucose.

Soluble carbohydrate concentrations in the root xylem showed the same basic distribution as that in the phloem, although the magnitude was somewhat less. The translocation impediment of the principal curvature was apparent in the xylem, for C-labeled carbohydrates in the xylem of "double-J" roots showed the same trend as the concentration of C-labeled carbohydrates in the phloem, except that the sampling positions nearest the taproot tip were not radioactive above background.

Straight Roots.—Neither the concentrations of soluble carbohydrates nor the concentrations of C-labeled carbohydrates in the phloem showed any significant differences between sampling positions along the taproots of "straight" root treatment. The amount of C-labeled carbohydrates appeared to increase slightly from the root collar toward the tip, but there was no statistical significance.

The distribution of carbohydrates in the xylem of straight roots was quite uniform; carbohydrate levels were essentially the same along the root.

Knotted Roots.—In the beginning of these experiments a treatment was sought that would emulate the worst possible cramming of seedling roots into a planting slit. To assure treatment repeatability, the "knotted" treatment was devised; taproots were tied in a simple overhand knot and planted in the trays. Seedlings used in the soluble carbohydrate analyses strongly confirmed the taproot impediment in the principal curvature, primarily because the tissue below the principal curvature was so inadequately defined that analyses were not possible. Between the root collar and the principal curvature where analyses were possible, the distribution of glucose was similar in magnitude and gradient steepness to that in "double-J" roots. There was every indication that the knot was an efficient translocation impediment. In the C-labeled carbohydrate analyses, the translocation impediment was well defined with a greater accumulation between the "knot" and the root collar than below the "knot" (fig. 2).

Starch Analysis

Some of the "straight" and "double-J" taproot segments were embedded in collodion for sectioning with a sliding microtome. Sections were made in reference to the principal curvature, the root collar, and the taproot tip, similar to partitioning for carbohydrate analyses. Starch grain determinations were made at 100X magnification with polarizing light.

Traumatic tissue was common in the principal curvature of the "double-J" roots, with cells losing normal, or at least anticipated, orientation. Compression wood was frequent and occasionally a transverse section revealed partial tangential cell orientation. Enlarged parenchyma cells with associated starch grains were quite numerous in "double-J" roots above the principal curvature.
"Straight" roots had some starch grains within the enlarged parenchyma cells which were scattered throughout the taproot sections. There did not appear to be any grouping or concentration of parenchyma or starch grains along the taproot. The "straight" root treatment plus a wild seedling that was also sectioned had several, relatively even bands of functional sieve cells within the phloem. Enlarged parenchyma cells were scattered throughout. "Straight" root and wildling root tissues appeared to lack the abundant starch storage potential of the deformed roots.

The "double-J" roots tended to accumulate several bands of non-functional, collapsed sieve cells in the phloem between the principal curvature and the root collar. Throughout the collapsed sieve cells were numerous enlarged parenchyma cells which contained many starch grains. The starch storage potential of the phloem was high compared to similar tissue in "straight" roots. Tissues below the principal curvature were less clearly defined.

Trends evident from the microsections were:

1. phloem cells had adjusted to the physiological effects caused by the principal curvature by maintaining more storage capacity at the expense of functional sieve cells,

2. normal bands of sieve cells in "straight" roots had fewer starch grains and fewer places to put them, and

3. within the principal curvature of "knotted" and "double-J" roots, functional sieve cell bands were limited, evidence of physical restriction to carbohydrate flow.

To recapitulate, there can be little doubt that deformation of seedling roots imposed during outplanting modified the physiological and anatomical relationships within the phloem and to a lesser extent within the xylem. Specifically, the more severe kinks in the seedling taproot functioned as impediments to carbohydrate translocation, thereby causing a significant carbohydrate accumulation zone above the deformation. A 24-hour flux of 14C-labeled carbohydrate coming into this accumulation zone provided evidence of the translocation impediment because there were significant amounts of 14C-labeled carbohydrates.

The accumulation was maintained for a while, as witness the high concentrations of 14C-glucose in the leaves mostly supplied 14C-sucrose for translocation and 14C-glucose was derived by enzyme action in the roots. The few lateral root tips that were analyzed were 10 times more radioactive than taproot tips on the same root system. 14C-glucose was being supplied from the accumulation zone to the lateral tips much faster and/or in larger amounts than it was being supplied to the taproot tips.

Starch grains were more abundantly present in the enlarged parenchyma cells between the principal curvature and the root collar in deformed roots than anywhere in "straight" roots. The excess carbohydrates in the accumulation zone were not only supplying lateral tips, but starch grains were also being formed. In the deformed roots there were more enlarged parenchyma cells in which to store starch.

Micrographs in the principal curvature confirmed the translocation impediment. Functional sieve cells in the principal curvature of "double-J" roots were restricted to one band, while "straight" roots had several bands of functional sieve cells. Many of the xylem cells in deformed roots appeared abnormal, at least they stained unlike normal tracheids or even compression wood cells.

THE SIGNIFICANCE OF CARBOHYDRATE ACCUMULATION

Carbohydrates have important functions in root physiology. They are synthesized in leaves and translocated through phloem sieve elements down stems into root systems. Carbohydrates that reach roots are used in metabolic functions, e.g., they may be assimilated into tissue, they may supply the organic chains used in amino acid synthesis, they may be stored as starch, or they may supply energy for growth functions (Kramer and Kozlowski 1960).

An ample supply of carbohydrate has been found to be conducive for root formation. Thimann and Delisie (1942) found a rooting response with conifer cuttings treated in a two percent sucrose solution for 48 hours. They stated that sucrose probably manifested its effect by maintaining metabolism while rooting occurred. Tomato cuttings that were high in carbohydrate and low in nitrogen rooted well in humid air (Kraus and Kraybill 1918). Conversely, tomato cuttings that were low in carbohydrates did not root well.
Several investigators have shown that substances produced in leaves are necessary for root formation and subsequent root growth (Went 1938; van Overbeek et al., 1946; Gilmore 1962; Gilmore 1965). Went (1938) hypothesized that a specific hormone-like substance or group of substances was necessary for root formation in tomato. Without labeling the substances as carbohydrates, van Overbeek (1946) felt that the main function of leaves in the process of root initiation was to supply the rooting zone with nutritional substances. Using various phloem girdling treatments in 1-0 loblolly pine, Gilmore (1965) did not observe new lateral root formation or elongation of existing laterals when the leaves were isolated from the roots. Stimulus from the leaves was necessary in order to trigger root growth, and the stimulus could not be stored in the roots for extended periods. There would appear to be little question that root formation and elongation phenomena are quite complex, but carbohydrates are involved in these processes.

Accumulated carbohydrates can be stored as starch. The specific effects of excess starch accumulation are not clear from our work, but it is conceivable that more energy would be available for root growth during mid-winter. Some of this energy, however, might also be utilized in stem growth during the spring. Allen (1964) reported that roots supplied 15 percent of the food reserves used in spring height growth of longleaf pine (Pinus palustris Mill.). Needle reserves contributed the majority of food used in height growth of red pine stems with root reserves exerting only a slight influence (Kozlowski and Winget 1964). However, an abundance of starch could have a positive effect on root growth during that early spring period when leaves are doing well to satisfy their respiratory demands. It is not unreasonable to assume a vigorous seedling root system would develop from abundant starch reserves.

Lateral Root Development

Much of the early concern relative to the bad effects of careless planting techniques had to do with the extent of lateral root development in planes other than that defined by the dibble (Rudolf 1939). If substances necessary for root formation and elongation were concentrated within a portion of the taproot, lateral root development should flourish. Not only should existing laterals grow well, but new laterals should be initiated and they too should grow well. Development of a profuse lateral root system would appear to have numerous advantages for early seedling survival. Many small absorbing roots are located close to the soil surface and due to their location and abundance they are important water and mineral absorbing surfaces (Kramer and Kozlowski 1960). The first few inches of soil are almost always the most important to plant growth, e.g. water, aeration, minerals, organic matter and mycorrhizal fungi are more favorable. Through root elongation and branching, new soil volumes are occupied and minerals are supplied to photosynthesis plus other metabolic functions in the leaves. Optimum efficiency in leaves results in maximum flow of energy to the roots, thereby creating more root growth potential. Subsequently, there is more absorption of water and minerals and the cycle continues. Transformation of C-labeled sugars into white pine roots has been shown to be facilitated by a well-developed root system (Shirya et al., 1962). For survival and early growth of loblolly pine seedlings, an extensive lateral root system might have advantages over a strong taproot system with sparse lateral root development.

Assuming that growth stresses caused by the environment are minimal, the cyclic reinforcement of roots and leaves continues for much of the growing season. The effects might include increased seedling survival and larger seedlings. The potential effects on future growth and stem form are not clear from our work with seedlings.

The Cause For Concern

As Rudolf discovered in his pine plantation analysis following the severe drought of 1936, environmental stresses can cause severe mortality, especially on marginal sites. Seedlings that tend to concentrate most of their feeder roots in the upper soil layers will be stressed by severe drought. In regions with frequent summer rains, seedling mortality the first few years would be insignificant; so it was with many studies in the Southeast, including our own. Neither Gruschow (1959) nor Cabrera (1975) found survival to be significantly affected by seedling root deformation. However, in areas noted for infrequent summer rains, drought could claim many seedlings the first year.

Except for problems magnified by environmental stress, survival and early life of a plantation probably wouldn't show many detrimental effects from deformed root systems. Brace (1964) confirmed that early survival was not affected by root deformation. Jansson (1971) working with Scots pine in which the roots had been induced to grow in a spiral pattern, did not find significant differences in survival between treated and control plants; root stranngulation was not a cause of early
mortality. In Tennessee, Cabrera (1975) found no differences in survival of loblolly pine seedlings through the fourth year even though some of the treatments embodied severely deformed root systems. Trends in survival were consistent, however, and the more severely deformed roots had the lowest survival, i.e. the most extreme treatment (ball-root) had the lowest survival. Under conditions of extreme environmental stress, which did not occur during the time of this study, differences in survival could be expected. There may also be cause for concern as the trees mature.

Sapling Growth Effects

Numerous excavations of seedling/sapling-sized loblolly pine in the Lower Piedmont and Coastal Plain of North Carolina showed a positive correlation between height and severely deformed root systems, i.e., the tallest trees were usually growing on a severely deformed root system (Hay and Woods 1974). These plantations were part of commercial forest operations and they were not established through controlled research procedures. There is a real possibility, therefore, that the large trees with deformed roots were larger than average at outplanting. It is more difficult to plant large seedlings correctly; most frequently the roots are crammed into the hole instead of enlarging the hole to accommodate the roots. Large seedlings at outplanting often maintain their initial size advantage (Brace 1964). The observed correlation between sapling size and root shape may not have been a reflection of growth response to the deformity so much as a result of seedling size at outplanting.

However, Jansson (1971) found that Scots pine forced into spiral root configurations by pot-culture, obtained greater height when outplanted than did Scots pine controls. In a study of planting methods and growth rates of slash pine (Pinus elliottii Engelm.) in Florida, Shultz (1973) concluded that deformed root systems did not significantly alter top growth.

Several researchers have reported that height growth was suppressed by severely deformed root systems. Deformed rooted Scots pine did not grow as tall as trees with normal roots, regardless of planting method (Erteid 1968). Likewise, Lacaze (1968) found spruce with deformed roots, primarily "L-shaped" and "J-shaped" roots, not as tall as normal trees; the "J-shaped" roots supported the smallest seedlings and the differences were significant at the 0.01 probability level after the fourth year. Rudolf (1939) reported a 20 percent reduction in height growth for pine seedlings growing on deformed root systems in the Lake States.

Two loblolly pine plantings in Tennessee yielded results that support both sides of the height growth question. One planting, which was made within the natural range of loblolly pine, showed no height growth differences after four years (Cabrera 1975). On the other site, which was abandoned agricultural land in East Tennessee, "ball-rooted" saplings were significantly shorter than all other treatments. The "straight" root trees were tallest. Since the seedlings in this study were subjected to uniform size criteria and specific root configurations were imposed upon them, the effects of root deformation might be distinct from those of initial size and inherent growth rate. However, the compounding effects of competitive stress brought about by outplanting on a marginal site in East Tennessee tend to make the conclusions less decisive. Deformation of supporting root systems may be a greater problem on marginal sites than on really good ones.

It is impossible to project the Tennessee growth statistics far enough into the future to ascertain if the current trends will be maintained, or perhaps, at some point in time, height growth of the deformed treatments will nearly equate with the controls. Some researchers have speculated that height growth of maturing trees may nearly be equal, regardless of the shape of the root system at outplanting. Brace (1964) maintained that mortality resulting from deformation may be expected to occur within a few years after planting or not at all. Both Erteid (1968) and Schultz (1973) reported that by 12 years of age, trees with deformed roots exhibited nearly complete recovery of form and growth rate. However, Rudolf (1939) speculated that adverse growth effects may persist up to 30 years following outplanting, and they would only become manifest when the trees were subjected to environmental stress.

Windthrow.—The effects of root deformation become more apparent when trees are windthrown. Grano (1953) found that shortleaf pine (Pinus echinata Mill.) with poorly developed root systems were subject to windthrow. The root problems did not result from planting deformation, rather poor soil conditions had caused the shallow root systems. Not many studies can directly trace windthrow susceptibility to deformed roots at outplanting. Once a tree has become established, it becomes difficult to accurately judge the source of deformed root growth. Rudolf (1939) felt that the restriction of lateral roots to the
plane defined by the planting bar created windthrow potential. He defined a well-anchored root system as having laterals growing in all directions.

A loblolly pine excavated after growing seven years on a severely deformed root system, showed real windthrow potential (fig. 4). This "ball-rooted" seedling had developed into a truncated club that relied almost exclusively upon its laterals for support. This root pattern resembles the ball-and-socket joint of animal skeletons, which is known for its movement efficiency.

![Roots from a seven year old loblolly pine that was planted as a "ball-rooted" seedling. Most of the laterals are in one plane, presumably that defined by the dibble at outplanting.](image)

**Figure 4.**--Roots from a seven year old loblolly pine that was planted as a "ball-rooted" seedling. Most of the laterals are in one plane, presumably that defined by the dibble at outplanting.

**SOME OBSERVATIONS ON ROOT DEVELOPMENT**

Seven years after outplanting some loblolly pine seedlings with roots variously deformed, were excavated for study. Selected ones are illustrated in figure 5.

**Figure 5-1.**--This tree was planted as a "ball-rooted" treatment; the "knotted" treatment of Figure 1 provides the closest approximation. The translocation impediment has clearly been maintained beyond the seeding stage. The swelling just above the root collar is obviously the result of root strangulation. Although this example was extreme and not frequently repeated in the excavated sample, it did offer overwhelming proof of root deformation effects through blockage of carbohydrate translocation.

Lateral roots developed in many directions, instead of a single plane. One of the laterals had assumed the role of taproot. We can only speculate on how long such a root system could have maintained the tree, but a good guess would be not for very long.

**Figure 5-2.**--This tree was also "ball-rooted". The lateral root development here is noteworthy, especially the large lateral root originating near the root collar and above the severe deformation. This root may well have profited by the carbohydrate accumulation above the severe deformation in the taproot. Its development has been disproportionately larger than other roots.

Although it is not clear from the photo, the apparent taproot is really a lateral that has assumed the taproot function. It is likely that the original taproot ceased to function soon after outplanting.

**Figure 5-3.**--This tree was planted with a severely deformed root system. There is no clear counterpart in Figure 1; however, the growth response has not been too dissimilar from that of other severely deformed roots, regardless of the original configuration.

The original taproot is gone and a system of lateral roots has been providing all necessities. Note the three large laterals, one of which appears to be functioning as a taproot, that have originated from the carbohydrate accumulation zone between the root collar and the severe deformation. Unlike the tree depicted in Figure 5-1, this tree probably would have maintained its position in the stand, i.e., it appears to have a well-anchored root system.

**Figure 5-4.**--When outplanted, this seedling was a "straight" root treatment. Its development in the ensuing seven years has been typical of the correctly planted tree. Taproot development has been strong. There are no visible problems of root strangulation or evidence of carbohydrate translocation blockage.

**Summary.**--Figure 5 was selected to illustrate some advanced stages of growth and development of trees with deformed root systems. Seedling studies showed the presence of carbohydrate accumulation in the taproot and the shunting of much of it into lateral roots. These larger root systems confirm that the effects of root deformation have persisted, at least through the seventh year. Almost every root system we excavated that had been deformed at outplanting showed significant lateral root development, but the original taproots were not apparent. Some of the laterals existed in a single plane, as per Rudolf's concern, but those
systems that had been totally disarrayed at outplanting, frequently had lateral roots extending in all directions. With but few exceptions, windthrow potential was not well-developed on these-seven-year old pines.

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Figure 5.--Seven-year-old loblolly pines planted on deformed root systems: (1) "ball-root" treatment showing a severe blockage of carbohydrate movement into the taproot, (2) "ball-root" treatment with quite large lateral roots originating from the carbohydrate accumulation zone, (3) severely deformed root system with large laterals for good anchorage, and (4) "straight" root treatment that represents normal taproot development.
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ROOT DEVELOPMENT OF PLANTED LOBLOLLY PINE SEEDLINGS

John Mexal and Sally Burton

Abstract.—The root systems of loblolly pine were examined two, three, and four years after plantation establishment. The seedlings were planted as 1-0 bareroot stock. Although many trees were planted improperly, deformation of the taproot was not correlated with seedling growth. As much as 60% of the variation in height at harvest and 72% of the variation in DBH could be accounted for using such variables as seeding size at time of planting, number and distribution of laterals, and depth of planting in a stepwise multiple regression equation. The impact of these findings are discussed relative to successful plantation establishment.

INTRODUCTION

Concern over the root development of bareroot seedlings following outplanting has been the subject of many studies (Rudolf 1939, Little 1973). Of particular interest is the effect of root deformation on seedling performance. Unfortunately, published reports offer conflicting conclusions. Laclea (1968) reported that the J-rooting of 2-0 spruce seedlings resulted in significantly reduced growth the first two years in the field. Reimer (1971) found the effects of root deformation still evident after 15 years with 1-0 Douglas-fir. Both survival and height growth was reduced by either J-rooting or entangling the lateral roots. However, 2-0 seedling performance was not related to planting quality, and, in fact, seedlings with entangled laterals exhibited the greatest growth after 15 years. Others (Rudolf 1939, Gillgren 1972) have concluded that root deformation does not adversely impact height growth of seedlings. In fact, the deformation is gradually concealed as the root system develops with age (Gillgren 1972).

The literature on deformation of southern pine root systems is equally conflicting. Little and Somes (1964) and Griswold (1959) found that most excavated bareroot seedlings exhibited eithertaproot deformation or lateral root entanglement when excavated. However, both studies were unable to correlate above-ground seedling performance with the patterns of root development. In a more recent study, Little (1973) found that improperly planted loblolly pine seedlings were more susceptible to windthrow than were properly planted seedlings, but that survival and growth were not affected by planting quality.

Hay and Woods (1968, 1974a, b, 1975) have developed the most extensive case history on the role of root deformation in seedling growth. Although root deformation was positively correlated with seedling size, they hypothesized that larger seedlings are more easily misplanted (Hay and Woods 1974). This hypothesis is supported by others (Sutton 1969, Little and Somes 1964), and it is also well supported that larger trees maintain their height advantage despite misplanting (Wakeley 1969, Grigsby 1971). However, the long-term effects of root deformation have not yet been ascertained, and it is unclear how large seedlings and root deformation interact in plantation management schemes.

There is some evidence to indicate that root deformation may in fact stimulate lateral root development. Sucrose translocation in the phloem is impeded by taproot deformation (Hay and Woods 1968, 1975). The authors intimate that this accumulation of sucrose above the deformation will result in better lateral root development and improved nutrient and water
absorption. They claim lateral roots are more important in water absorption during dry periods than taproots (Hay and Woods 1974).

The objectives of this study were to: (1) examine the root systems of planted lobolly pine (P. taeda L.) seedlings in Arkansas, and (2) develop a predictive model to relate seedling height to initial seedling size and planting quality.

MATERIALS AND METHODS

Root morphology of bareroot seedlings and its relationship to tree growth of two, three, and four-year-old trees was investigated on four plantations in Arkansas.

For each plantation, five transect lines were randomly established. To sample all tree planters each transect was twenty trees long, cutting diagonally across planting rows; the height of all twenty trees in each transect was recorded, and from each transect, five of the twenty trees were excavated for study of root morphology. The five trees were selected according to height distribution. The sampling procedure was designed to provide an unbiased selection of root structures. The trees selected corresponded to the 0, 25, 50, 75, 100 percentage points of height distribution. Therefore, the smallest and tallest trees in the transect were taken, as well as the trees whose heights were nearest the 1/4, 1/2, and 3/4 marks.

When the five trees from each twenty-tree transect were selected, they were tagged at ground level, excavated, and air-dried. The soil at each planting hole was examined to ascertain if soil compaction could be the cause for reduced growth or root malformation. The trees were collected and returned to the laboratory where several variables were measured on each root and shoot. The variables included:

1. **Shoot height (mm)**
   a. initial height when outplanted
   b. annual increments to present height

2. **Ground level diameter (mm)**, measured on cross-section of stem
   a. initial GLD when outplanted
   b. annual increments to present GLD

3. **Dry weight of foliage (g)**

4. **Dry weight of stem and branches (g)**

5. **Taproot structure**, was classified into one of the following categories:
   a. absent (perhaps severely J or L shaped at planting, but taproot never regenerated. A lateral root may have assumed the role of taproot.)
   b. strangled (laterals are twisted around the taproot, binding it)
   c. J-shaped (taproot shaped like a J but has recovered and exhibits positive geotropcic response)
   d. L-shaped (recovered and descends)
   e. normal (resembling natural root growth with taproot directed almost straight downward)
   f. other (any unique variation in taproot structure)

6. **Root collar depth (RCD)**, is the distance from ground level to the top of the root collar. This indicates depth of planting in the field.

7. **Total number of laterals**, extending perpendicular from the taproot.

8. **Root distribution scores**, counting absolute numbers of laterals provides an incomplete picture of root structure. A procedure similar to that developed by Nischiiber (1978) was employed to evaluate the distribution of laterals. The method assigned a higher score for a root with well distributed laterals than for a root with laterals that were pressed into one plane or knotted in one mass. The scoring process divided the root system into 12 quadrants - 4 horizontal, and 3 vertical, beginning with the north-facing tag at ground level, rotating clockwise and downward. The first lateral root located in a quadrant was given a value of 1.000; the second in the same quadrant scored .500; the third was .250; etc... Each quadrant accumulated a score determined by the number of laterals contained in that quadrant. A quadrant with no laterals scored 0.0. A quadrant with 3 laterals scored 1.750. The scores were summed and then multiplied by the number of quadrants with lateral roots. This technique attaches a large value to a tree whose roots are uniformly distributed and a small value for a one-planed or knotted system.

9. **Lateral root deformation**, is the ratio of the odd quadrants (1,3,5, etc.) to the even quadrants. This method was used to estimate the planar distribution of laterals due to dibble bar planting.
RESULTS

Excavation of planted loblolly pine seedlings in Arkansas revealed a very high incidence of root deformation (fig. 1). However, examination of the soil profile indicated no hardpans or other microsite problems which might have resulted in root deformation. All deformation was apparently caused by improper planting. Over 60% of all the root systems examined had what were considered deformed taproots (Table 1). However, growth reduction could not be ascribed to taproot deformation.

Simple linear regression revealed the correlation between shoot height and both root and shoot parameters. The analysis revealed seedling height (FHT) was highly correlated with both shoot dry weight and D^2H at time of harvest, and also highly correlated with initial seedling size, the number of lateral roots, and the distribution of these roots as reflected in the correlation between height and the root scores (Table 2). Taproot deformations were not correlated with seedling height (average \( r^2 = .01 \)). Deformation of laterals (Lat. Def.), which is typically associated with bar planting, was also uncorrelated with seedling height (average \( r^2 = .03 \)). Planting depth (RCD) was negatively, albeit poorly correlated with seedling height except on Site 2 which had been bleded. Correlation on this droughty site was highly positive (\( r^2 = .27 \)). Apparently planting ease on Site 2 (bedded) was such that proper planting was possible even with deep planting.

Seedling volume (D^2H) was generally better correlated to seedling and planting parameters than height (Table 3). Again, planting depth, taproot and lateral root deformation were not highly correlated with D^2H. However, 10% of the variation (\( r^2 = .10 \)) in volume in the 3 year old plantation (Site 3) was explained by taproot deformation.

In developing predictive models to relate seedling height to variables occurring at plantation establishment, the stepwise multiple regression model was limited to four variables. The variables were chosen because they tended to reflect factors related to both seedling quality and planting quality. These included: (1) initial seedling D^2H, (2) number of laterals, (3) depth of planting, and (4) root distribution scores. Tables 4 and 5 list the coefficients of determination between height and D^2H and these four variables. Depending upon plantation age, the four variable model successfully accounted for up to 60% of the variation in height and 72% of the variation in volume.

DISCUSSION

This study was not designed to assess the effects of deformation on seedling survival. The study was instituted during the second growing season of the youngest plantations, so any mortality due to poor planting should have occurred previously.

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. In general, the number of laterals was a more potent variable than the root score (modified from Rischbieter 1978). The absolute number of lateral roots appeared to remain unchanged with increasing age. The seedlings averaged 9.6 lateral roots on the four plantations. Since the number of lateral roots changed little as the seedling grew, these data indicate the advantages of a fibrous root system at time of planting. A fibrous lateral root system could better utilize the available nutrients following transplanting.

Taproot deformation was correlated with planting depth. Obviously, with limited size of dibble bars, the deeper the planting, the greater the likelihood of misplanting. Planting depth was negatively correlated with seedling performance albeit insignificantly. These data support other studies which show deep planting can be detrimental (Slocum and Maki 1956, Switzer 1960).

Initial seedling size (D^2H) was also a potent variable. The larger seedlings at time of planting tended to maintain that advantage. Grigsby (1971) and Wakeley (1969) reported similar findings in long-term studies with loblolly pine.

However, in this study the correlation between seedling and planting quality appeared to decrease with increasing age. As plantation age increased, the amount of variability explained by the four parameters decreased from 60% at age 2, to 50% at age 3, to less than 40% at age 4. This relationship contradicts previous studies which claim seedling and planting quality result in long-term effects (Grigsby 1971, Mullin 1974, Wakeley 1969). The reason for this discrepancy is not entirely clear. It is possible that such site
specific factors as competition or microsite variation could account for the loss of correlation.

These data would indicate that large seedlings with fibrous root systems which are properly placed in the planting hole offer the best possibility for successful plantation establishment with loblolly pine.

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Table 1.—Average seedling height and root parameters of seedlings from the four plantations examined.

<table>
<thead>
<tr>
<th>Site</th>
<th>Age</th>
<th>Height (m ± 1 SE)</th>
<th>Deformed Taproots (%)</th>
<th>Laterals (N) ± S.E.</th>
<th>Root Score θ ± S.E.</th>
<th>Soil</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>2</td>
<td>69.5 ± 5.3</td>
<td>50</td>
<td>7.0 ± 0.7</td>
<td>26.1 ± 4.5</td>
<td>Fine sandy loam</td>
</tr>
<tr>
<td>2</td>
<td>2</td>
<td>69.3 ± 3.7</td>
<td>83</td>
<td>11.0 ± 0.6</td>
<td>44.8 ± 4.9</td>
<td>Sandy loam</td>
</tr>
<tr>
<td>3</td>
<td>3</td>
<td>164.6 ± 9.9</td>
<td>58</td>
<td>9.0 ± 0.8</td>
<td>37.9 ± 5.3</td>
<td>Fine sandy loam</td>
</tr>
<tr>
<td>4</td>
<td>4</td>
<td>229.0 ± 14.9</td>
<td>68</td>
<td>11.6 ± 0.8</td>
<td>60.4 ± 5.7</td>
<td>Silt loam</td>
</tr>
</tbody>
</table>

Table 2.—Coefficients of determination (r²) between final height (FHT) of two-to four-year-old bareroot seedlings and other morphological parameters. A negative relationship is indicated by (-).

<table>
<thead>
<tr>
<th>Variable</th>
<th>Site 1</th>
<th>Site 2</th>
<th>Site 3</th>
<th>Site 4</th>
</tr>
</thead>
<tbody>
<tr>
<td>1 FD²H</td>
<td>.74</td>
<td>.68</td>
<td>.66</td>
<td>.80</td>
</tr>
<tr>
<td>2 Dry Wt.</td>
<td>.65</td>
<td>.62</td>
<td>.65</td>
<td>.83</td>
</tr>
<tr>
<td>3 Initial Ht.</td>
<td>.35</td>
<td>.04</td>
<td>.19</td>
<td>.09</td>
</tr>
<tr>
<td>4 Initial Dia.</td>
<td>0</td>
<td>.34</td>
<td>.24</td>
<td>.28</td>
</tr>
<tr>
<td>5 Initial D²H</td>
<td>.38</td>
<td>.38</td>
<td>.27</td>
<td>.26</td>
</tr>
<tr>
<td>6 Taproot Def.</td>
<td>0 (-)</td>
<td>.02</td>
<td>.02 (-)</td>
<td>.03 (-)</td>
</tr>
<tr>
<td>7 Root Col. Depth</td>
<td>0 (-)</td>
<td>.27</td>
<td>.02 (-)</td>
<td>.19</td>
</tr>
<tr>
<td>8 Laterals (n)</td>
<td>.42</td>
<td>.26</td>
<td>.37</td>
<td>.19</td>
</tr>
<tr>
<td>9 Lat. Def.</td>
<td>.04</td>
<td>.01 (-)</td>
<td>.05</td>
<td>.01 (-)</td>
</tr>
<tr>
<td>10 Root Score</td>
<td>.38</td>
<td>.19</td>
<td>.22</td>
<td>.13</td>
</tr>
</tbody>
</table>
Table 3.—Coefficients of determination ($r^2$) between final $D^2H$ of two- to four-year-old bareroot seedlings and other morphological parameters. A negative relationship is indicated by (-).

<table>
<thead>
<tr>
<th>Variable</th>
<th>Site 1</th>
<th>Site 2</th>
<th>Site 3</th>
<th>Site 4</th>
</tr>
</thead>
<tbody>
<tr>
<td>1 FHT</td>
<td>.74</td>
<td>.67</td>
<td>.65</td>
<td>.81</td>
</tr>
<tr>
<td>2 Dry Wt.</td>
<td>.92</td>
<td>.96</td>
<td>.95</td>
<td>.99</td>
</tr>
<tr>
<td>3 Initial Ht.</td>
<td>.37</td>
<td>.01</td>
<td>.17</td>
<td>.17</td>
</tr>
<tr>
<td>4 Initial Dia.</td>
<td>.42</td>
<td>.41</td>
<td>.12</td>
<td>.18</td>
</tr>
<tr>
<td>5 Initial $D^2H$</td>
<td>.52</td>
<td>.52</td>
<td>.13</td>
<td>.27</td>
</tr>
<tr>
<td>6 Taproot Def.</td>
<td>.01</td>
<td>.04</td>
<td>.10</td>
<td>0</td>
</tr>
<tr>
<td>7 Root Col. Depth</td>
<td>.05 (-)</td>
<td>.14</td>
<td>.11 (-)</td>
<td>.07 (-)</td>
</tr>
<tr>
<td>8 Laterals (n)</td>
<td>.52</td>
<td>.28</td>
<td>.41</td>
<td>.12</td>
</tr>
<tr>
<td>9 Lat. Def.</td>
<td>0</td>
<td>.02 (-)</td>
<td>0</td>
<td>.03 (-)</td>
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<tr>
<td>10 Root Score</td>
<td>.58</td>
<td>.18</td>
<td>.46</td>
<td>.13</td>
</tr>
</tbody>
</table>

Table 4.—Changes in coefficients of determination ($r^2$) between height of bareroot seedlings and variables used in developing the multiple regression equation.

<table>
<thead>
<tr>
<th>Variable</th>
<th>Site 1</th>
<th>Site 2</th>
<th>Site 3</th>
<th>Site 4</th>
</tr>
</thead>
<tbody>
<tr>
<td>5 Initial $D^2H$</td>
<td>.39 **</td>
<td>.38 **</td>
<td>.27 **</td>
<td>.26 **</td>
</tr>
<tr>
<td>8 Laterals</td>
<td>.13 **</td>
<td>.11 **</td>
<td>.22 **</td>
<td>.11 **</td>
</tr>
<tr>
<td>7 Root Col. Depth</td>
<td>.08 **</td>
<td>.11 **</td>
<td>.001 **</td>
<td>.01 *</td>
</tr>
<tr>
<td>10 Root Score</td>
<td>-----</td>
<td>.01 **</td>
<td>.01 **</td>
<td>.002 *</td>
</tr>
</tbody>
</table>

Table 5.—Changes in coefficients of determination ($r^2$) between $D^2H$ of bareroot seedlings and variables used in developing the multiple regression equation.

<table>
<thead>
<tr>
<th>Variable</th>
<th>Site 1</th>
<th>Site 2</th>
<th>Site 3</th>
<th>Site 4</th>
</tr>
</thead>
<tbody>
<tr>
<td>5 Initial $D^2H$</td>
<td>.51 **</td>
<td>.52 **</td>
<td>.18 **</td>
<td>.27 **</td>
</tr>
<tr>
<td>8 Laterals</td>
<td>.15 **</td>
<td>.10 **</td>
<td>.28 **</td>
<td>.06 *</td>
</tr>
<tr>
<td>7 Root Col. Depth</td>
<td>.01 **</td>
<td>.02 **</td>
<td>.03 **</td>
<td>.001 *</td>
</tr>
<tr>
<td>10 Root Score</td>
<td>.04 **</td>
<td>.03 **</td>
<td>.06 **</td>
<td>.0002 †</td>
</tr>
</tbody>
</table>

** Significant at 1% level.
* Significant at 5% level.
† Significant at 10% level.
THE EFFECT OF SEEDLING CONTAINER RESTRICTIONS ON THE DEVELOPMENT OF PINUS CARIBEAURA ROOTS

T. I. W. Bell

Abstract.—Pine seedlings in Fiji are grown in plastic containers. Root coiling in the containers often continues after outplanting and is related to stem breakage at ground level. Cutting a section from the base of the pots while in the nursery has given encouraging results. Further trials are underway.

INTRODUCTION

Pine planting in Fiji is mainly confined to the dry western side of the two main islands Viti Levu and Vanua Levu. The Fiji Islands lie between 16° and 19°S latitude and have a distinct dry season. For example, Lautoka city on the west coast of Viti Levu, has a mean annual rainfall of 1860 mm, of which 51% falls in the first quarter of the year. The mean annual number of days with rain is 112, with 41% in the first quarter of the year. The four driest months average 60 mm of rain a month and have an average number of five days with rain per month (Gabites 1977).

Tree species trials established during the late 1950's and early 1960's showed that Pinus caribaea var. hondurensis gave better results on the dry western hills than all other species tried. At about the same time, many other tropical countries were showing an interest in this species. By the end of 1970 the total P. caribaea area planted in the world was 32,000 ha, of which 26,448 ha were var. hondurensis. The country with the largest area of P. caribaea var. hondurensis plantations at that time was Fiji with 4,654 ha (Lamb 1973). By the end of 1977 the total area planted in Fiji had risen to 33,000 ha, with an annual planting programme of nearly 6,000 ha. The Fiji Pine Commission is responsible for about 83% of pine plantations in Fiji, with a target of 75,000 ha growing on a 15-year rotation.

USE OF CONTAINERS

In climates with long dry-periods, planting of trees is mainly accomplished with stock raised in containers. One advantage of this is that a large part of the nursery-grown root system remains encased in the soil in which it was raised at the time stock is planted. With proper soaking in the nursery before transporting to the field enough water can be stored to keep the seedling alive during a long period of drought (Stone and Goor 1967).

In common with most other countries growing P. caribaea (Lamb 1973), it has been found in Fiji that poorer results are achieved when plantations are established with bare-root stock than with container-grown stock. Most of the pine stock in Fiji is currently raised in perforated black polythene bags filled with soil to give a pot size of 14 cm high by 3.5 cm diameter. In the nursery, seedlings are grown in these pots for five or six months, by which time they are about 30 cm high. When ready for outplanting, the seedlings are transported to the field in the pots. The polythene is removed without disturbing the soil or roots. The seedlings are planted in a shallow hole prepared with a spade, with the roots still encased in the nursery soil.

ROOT DEFORMITIES

There is a strong tendency for P. caribaea to produce tap-roots and to develop a contorted root system inside the polythene pots. A root mass develops at the base and some of the roots coil round the sides of the pot. This root coiling or balling can continue in the field and is related to breaking of the stem at ground level some years after outplanting.

Foresters throughout the world are becoming increasingly concerned about the development of deformed root systems in container-grown stock. Ball (1976) has noted that the
degree of coiling in the nursery is related to the size of plant grown if root pruning is not practiced. He quotes examples of basal stem snap in several species of pine in tropical countries and recommends root pruning in the nursery. In the case of polythene pots, he recommends two vertical cuts on either side of the container before planting, and that the bottom 2 cm of the root ball should be cut off.

Hiltt (1974) carried out studies with Ponderosa pine and found that seedlings grown in containers with vertical grooves had less coiling than those grown in smooth-walled containers. When containers with ridges and/or grooves were used, the roots were directed straight to the bottom. In Sweden, deformation of roots in nursery containers is experienced, but these have not been related to strangulation or a reduction in survival or growth after outplanting. Hultén (1976) states that the main problem is one of lack of stability that planting with containerised stock sometimes shows. This is thought to be a consequence of too slow a development of supporting secondary roots.

WINDBLOW DAMAGE IN FIJI

The Fiji Islands lie in a hurricane prone area and crop stability is therefore of prime importance. Although severe hurricane damage is only experienced about once every seven years, storm-force winds from distant hurricanes are experienced during the wetter months in most years. Extensive damage to pine plantations was caused by hurricane 'Bebe' in October, 1972 and more localised damage was caused by hurricane 'Bob' in January, 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. Figure 1 shows the roots of one of the windblown three-year-old trees.

Trees in older plantations were also windblown, although not in such high proportions. In the younger plantations nearly all the damage was from uprooting, while in plantations of four years or older, many of the stems snapped off at the base. This snapping is clearly related to deformities developed during the nursery container stage. Figure 2 shows the base and roots of a windblown four-year-old tree with a strongly developed coiling root. This root completely encircled the base of the tree just below ground level, thereby restricting stem development; the tree snapped off at this weakened point. Figure 3 shows a cross section of the stem and roots viewed from the same angle. The strangling root can be seen in cross section on both sides of the break.

Figure 4 shows a windblown six-year-old tree that was 14 m high when toppled. Although an encircling strangling root was not evident, a cross section of the stem showed how the root mass had developed around the nursery root ball creating a potential weak spot where the stem snapped off.

FIJI TRIALS

Bare Root Planting

Trials have been carried out to compare the performance of bare root stock raised in seedbeds, ex-potted bare root stock that had been raised in polythene pots but had the soil removed before leaving the nursery, and potted stock. After outplanting, the potted stock has generally given significantly better survival and growth than bare root or ex-potted stock. Some success has been achieved by dipping the roots of bare root and ex-potted stock in a clay slurry or an Agricote paste (derived from Alginate acid) while in the nursery, but the results have been inconsistent. More research is required in this field, particularly on how to produce a well balanced plant with a fibrous root system suitable for the climatic conditions of Fiji.

Planting Method

A trial was established in 1974 to study the effect of planting method on root development after outplanting. The seedlings were raised in polythene pots 14 cm x 3.5 cm which were removed immediately before planting. The soil in the planting area is a deep, easily worked latosol. Two planting methods were used:

(a) A pit 30 cm in diameter and 23 cm deep was dug in which the seedling was planted and the soil was replaced firmly around the roots.
(b) The seedling was planted in a hole, from which a plug 3.8 cm diameter and 15 cm deep was removed by a tool made from metal piping.
Figure 1.—Deformed roots of three-year-old pine. (Background squares in all photos are 10 cm x 10 cm.)

Figure 2.—Base of four-year-old pine showing strong coiling root.

Figure 3.—Cross section of pine base shown in figure 2. Note coiling root to left and right of photo and snapped off stem at restriction.

Figure 4.—Windblown six-year-old pine snapped off at weak point resulting from nursery root balling.
Roots from each treatment were dug up in March, 1978. Some corking that had developed in the pots was still apparent, but in all cases good tap and lateral roots had developed. The planting method did not have any noticeable effect on subsequent root development.

**Plastic Bullets**

Trials were carried out raising *P. caribaeae* seedlings in 6 cm x 2 cm diameter plastic bullets, and comparing their field performance with seedlings raised in polythene pots 14 cm x 3.5 cm. Seeds were germinated in vermiculite before pricking out and the bullets were embedded in a sand-soil mixture while in the nursery.

One year after outplanting, height and survival of the stock raised in polythene pots were significantly superior to that of stock raised in plastic bullets. Two years after outplanting, trees representing the best and worst growth of bullet-raised stock were dug up to check bullet breakage. In some cases, the bullets were still intact, enclosing the tap root. As long as the bullet remained attached, root development was poor. The poorer root development corresponded with smaller crown development and poorer growth in all cases. Where the tops were better developed, the bullets were either cracked or partially missing. The method was not adopted because of the higher cost of bullets and the poorer root development and tree growth.

**Paper Pots**

Paper pots were tried out on a small scale using pots of 15 cm height and with diameters from 4 to 7.5 cm. The pots remained in the nursery for seven months before transporting to the field for planting. At that stage they had started to disintegrate and the seedlings were bound together by interwoven roots between the pots. Many of the seedlings lost their soil cover during transportation or when the pots were being separated.

Results of the trial were inconclusive; further trials are planned, particularly to produce a large enough plant for satisfactory outplanting in a shorter nursery period.

**Different Pot Sizes**

A trial was established in 1976 to determine whether seedlings grown in larger diameter polythene pots have advantages when planted in the field. Polythene pots with filled dimensions of 15 x 6 cm and of 14 x 3.5 cm were used for raising the seedlings in the nursery. Two years after outplanting, stock raised in the larger pots had significantly greater height and diameter growth than stock raised in the smaller pots. A study of roots two years after outplanting showed variation between different trees, but no clearly defined advantages of one treatment over the other. The main disadvantage of using larger pots is the extra expense of transporting potting soil.

**1976 Root Pruning Trial**

In order to study the effects of root pruning seedlings while still in the pots, different treatments were carried out in January, 1976. The seedlings were raised in polythene pots 14 cm height x 3.5 cm diameter. Treatments consisted of, (a) severing the bottom 2.5 cm from the pots, (b) making four vertical cuts to the sides of the pot to a depth of 0.3 cm, (c) a combination of 'a' and 'b', and, (d) no pruning. Each treatment consisted of 20 trees replicated five times.

The pruning was carried out just before planting when the seedlings were five months old and had a mean height of 20.8 cm. The planters were contract labourers with little planting experience.

Assessments for height, diameter and survival 15 months after planting showed no significant difference between treatments. Five trees from each treatment were dug up two years after planting. The trees from the 'b' and 'd' treatment all showed signs of root balling or corking. This was also noticeable on some of the roots of treatment 'a' and 'c', but in other cases balling or corking were not evident. An example of this can be seen in figure 5 which shows trees two years after planting. The tree on the left had no nursery pruning while the tree on the right had 2.5 cm cut from the base of the pot.

The trial has given some indication of the advantages of root pruning stock in polythene pots. However, the sample was small and it was decided to carry out further root pruning trials.

**1978 Root Pruning Trial**

This trial was established to study the effect on survival, growth rate and root development of severing different depths of the coiled mass of roots at the base of the pots. The seedlings were raised in black polythene pots 14 x 3.5 cm and were planted on 21st February, 1978, when five months old. Treatments consisted of severing the bottom 0, 3 and 6 cm from the pots at periods of 0, 21 and 42 days before planting. Seventy-seven trees were planted in each treatment and replicated four times.
After treatment the pots were placed in wire baskets lined with polythene sheets. It was noted that three weeks after severing, a small number of new root tips had appeared at the base of the pots extending up to 2 cm. Roots of trees that had been severed for six weeks extended in a mass up to 10 cm from the base of the pots. The polythene bags were removed before planting but extending roots were not cut.

One immediate advantage of severing the base of the pots is the saving of potting soil for future use and the reduction in weight of material to be transported to the field. By removing 3 cm from the pots, there is a 23% reduction in overall weight, and removing 6 cm gives a 45% weight reduction. Another advantage is that pruned roots are shorter and are, therefore, less likely to be folded into the hole at planting time.

**CONCLUSION**

Large scale harvesting of pine is due to start in three years time in Fiji. By 1992 the income from pulp and chipwood is estimated to exceed U.S. $34,000,000 annually and become second only to sugar as an export earner.

The greatest threat to plantations is hurricane damage, and trees with malformed roots are particularly vulnerable. Research will continue to investigate the problem of malformed roots in nurseries and plantations. Of particular interest will be the interchange of ideas with other countries studying this problem.

**ACKNOWLEDGMENTS**

The writer is now responsible for all pine research in Fiji under the Forestry Department and the Fiji Pine Commission. Thanks are due to both authorities for making records available, to their research foresters for showing such a keen interest in the problem and to the Commonwealth Foundation for making it possible to attend this symposium.

**REFERENCES**

Ball, J. B.

Cobites, J. F.

ROOT FORM OF PINUS PINEA SEEDLINGS
GROWN IN PAPERPOT CONTAINERS

B. Ben Salem

Editor's Note
Due to unforeseen circumstances, Mr. Ben Salem had to withdraw from personal participation in the Symposium. As a substitute for his proposed paper, he submitted an excerpt from: "Research Activities of the Reforestation Techniques Section--Main Results", which he prepared during his tenure at the National Forestry Research Institute of Tunisia in 1975.

INTRODUCTION

Among the various containers which claim to have no harmful effect on root form and tree growth is the paperpot. This type of container offers at least two advantages: i) the container material is bio-degradable, and therefore seedlings can be planted with the container with no danger of root coiling, ii) the container wall is soft and, consequentially, root egress is not impeded. In addition, the paperpot is presently the only container which offers an excellent opportunity for mechanization. This explains why the use of paperpots is currently gaining momentum in reforestation programs in many countries. Paperpots were suggested for Tunisia as a viable alternative to the polyethylene bag. The latter is still being used, but results in unacceptable mortality due to root deformation.

Before embarking on large scale reforestation with the paperpot, an evaluation of this new type of container was judged necessary. The task was assigned to the National Forest Research Institute, and the study reported here is a preliminary evaluation of the paperpot's effect on root form and seedling growth.

MATERIALS AND METHODS

Three hundred Pinus pinea germinants were planted in 3 types of containers: these were paperpots 5 cm in diameter and 20 cm in length; hexagonal pots made of pressed soil 5 cm in diameter and 20 cm in length; plastic bags 6 cm in diameter and 20 cm in length and made from 6 mil clear polyethylene. Seedlings were started in March, and were watered throughout the course of the rearing period. On 1 January, 10 months after seeding, 20 seedlings from each container were selected for uniformity in diameter, shoot height, number of branches and bud condition, and transplanted at a spacing of 30 x 30 cm in a 3.1 x 1.8 x 1 metre deep transplant bed filled with a soil having an equilibrated texture. Seedlings were planted according to a completely randomized design, consisting of 15 plots of 4 plants each and with 5 plots for each container type. Before transplanting, only the seedlings grown in plastic bags were treated. The root ball was cut full length to a depth of 1 cm on 3 sides, and a 1 cm thick section was cut off the bottom.

During the next 16 months, transplants were grown under Tunisian climatic conditions of air temperatures ranging from 20 to 32°C during the growing season, and 6 to 18°C during the dormant phase. Transplants were watered regularly and soil moisture tension rarely exceeded 1 or 2 atmospheres.

At the end of 16 months, the shoots were excised at the root collar, and soil in the transplant ball was washed away from the roots using a fine spray of water. Root system distribution and seedling growth were evaluated using the same method as Ben Salem (1971).

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2/ Forestry Officer, Food and Agriculture Organization of the United Nations, Rome, Italy.
Data were analysed with an analysis of variance and the means were compared using Duncan's multiple range test.

RESULTS

The characteristic root form of representative seedlings are illustrated for the paperpot, the soil pot and the polyethylene bag in figures 1, 2 and 3, respectively. Figure 4 shows the root system of a paperpot seedling after the soil in the transplant bed was washed away. Figure 5 shows the general morphology of the root system after the paperpot was removed and the main laterals had been excised.

The relationship of seedling growth to container type is presented in Table 1 for several parameters. Measurement of total lateral root length per seedling differed in the 3 treatments. Root length of seedlings grown in the polyethylene bags was greatest, while that of seedlings grown in paperpots was least. Roots in the pressed soil pot grew better than those in the paperpot, but these were shorter than roots in plastic bags. The mean number of primary laterals ≥1.0 mm in diameter displayed the same trend as the total lateral root length with the treated polyethylene bag ranking first, the pressed soil pot second, and the paperpot third.

Total root dry weight was similar for the paperpot and pressed soil pot, but both means were significantly lower than that of the treated plastic bag seedlings.

The height of seedlings was similar in 3 treatments, but average dry weight of shoots of seedlings grown in polyethylene bags and pressed soil pots was higher than dry weights of seedlings grown in paperpots.

Strangulation angle was measured for the primary laterals ≥1.0 mm in diameter. Strangulation angles were arranged in 6 distinct angle classes, and the percentage of laterals falling in each of these 6 angle classes was calculated along with an average strangulation angle per root (Table 2). For paperpots, 75% of the total primary lateral roots showed a strangulation angle greater than 45°, compared to 5% and 46% for the pressed soil pot and sliced plastic bag treatments, respectively. Neither of the latter 2 treatments had any roots in angle classes 120, 180 or 270°, whereas 10, 5, and 5%, respectively, of the paperpot seedling roots fell in these classes. Almost all primary laterals in the pressed soil pot were in the 0 to 45° angle class.

DISCUSSION

The root form of Pinus pinea seedlings grown in paperpots was unexpected. It had been anticipated that the paperpot wall would be permeable to lateral root emergence, precluding root deformation. This was not the case; distinct root deformation was caused by this type of container. Sixteen months after transplanting, the paperpot was still nearly intact in the soil bed. Primary lateral roots grew downwards and no lateral root emergence was evident. In most instances, one single lateral root originating immediately near the root collar grew into a second main root to the extent that the original main root was not easily recognizable. This form of growth seems to have induced a marked decrease in

<table>
<thead>
<tr>
<th>Treatment</th>
<th>No. Primary Lateral Roots&lt;sup&gt;1/&lt;/sup&gt;</th>
<th>All Lateral Roots</th>
<th>Shoot</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Length (cm)</td>
<td>Dryweight (g)</td>
<td>Height (cm)</td>
</tr>
<tr>
<td>Paperpot</td>
<td>6.0&lt;sup&gt;a&lt;/sup&gt;</td>
<td>1065.8&lt;sup&gt;a&lt;/sup&gt;</td>
<td>19.85&lt;sup&gt;a&lt;/sup&gt;</td>
</tr>
<tr>
<td>Pressed soil pot</td>
<td>9.2&lt;sup&gt;a&lt;/sup&gt;</td>
<td>1510.0&lt;sup&gt;b&lt;/sup&gt;</td>
<td>19.34&lt;sup&gt;a&lt;/sup&gt;</td>
</tr>
<tr>
<td>Polyethylene bag</td>
<td>13.45&lt;sup&gt;b&lt;/sup&gt;</td>
<td>2020.6&lt;sup&gt;c&lt;/sup&gt;</td>
<td>29.07&lt;sup&gt;b&lt;/sup&gt;</td>
</tr>
</tbody>
</table>

<sup>1/</sup> Number of primary laterals ≥1.0 mm in diameter.

<sup>2/</sup> Figures having different superscripts are significantly different at the 95% level of probability.
Table 2.—Strangulation of the primary laterals: percent of primary laterals >1.0 mm in diameter falling in each of the angle classes, and mean strangulation angle per root.

<table>
<thead>
<tr>
<th>Treatment</th>
<th>Angle Classes - Degrees</th>
<th>Total</th>
<th>Mean Angle Per Root</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>0-45°</td>
<td>45-74</td>
<td>75-105</td>
</tr>
<tr>
<td></td>
<td>0</td>
<td>60</td>
<td>90</td>
</tr>
<tr>
<td>Paperpot</td>
<td>25</td>
<td>25</td>
<td>25</td>
</tr>
<tr>
<td>Pressed soil pot</td>
<td>95</td>
<td>5</td>
<td>-</td>
</tr>
<tr>
<td>Polyethylene bag</td>
<td>55</td>
<td>25</td>
<td>20</td>
</tr>
</tbody>
</table>

<sup>1</sup> Roots having a strangulation angle class (0°-45°) are considered normal.
<sup>2</sup> Mid-point of the angle class.
<sup>3</sup> Figures having different superscripts are significantly different at the 95% level of probability.

number and length of roots. This form of root growth suggests that tree growth will be seriously affected. Also it may be expected that the asymmetric root distribution will lead to fragile tree stability.

At this stage, root strangulation generated by the paperpot would appear to be of minor concern, as both the number of laterals and the mean strangulation angle are very low. However, the long term effect of this strangulation needs to be evaluated.

Unlike the paperpot seedlings, both the pressed soil pot and polyethylene bag seedlings displayed similar root distribution patterns and growth performances. Treated seedlings grown in the plastic bags were, however, slightly superior to seedlings grown in the pressed soil pot. This is essentially due to the slicing treatment which enhanced root elongation. The effects of the slicing treatment are in agreement with the findings of Ben Salem (1971) on Pinus pinaster.

CONCLUSION

This study shows that the paperpot wall is not permeable to lateral root emergence, and that the container material is not readily bio-degradable. Paperpots modify root systems, resulting in an asymmetric root form, a decrease in lateral root number, and a marked reduction in root elongation.

LITERATURE CITED

Ben Salem, B.

Figure 1.—Root distribution of a hydraulically excavated Pinus pinea seedling, grown for 10 months in a paperpot and for 16 months in the transplant bed.
Figure 2.—Root distribution of a hydraulically excavated Pinus pinea seedling, grown for 10 months in a pressed soil pot and for 16 months in the transplant bed.

Figure 3.—Root distribution of a hydraulically excavated Pinus pinea seedling, grown for 10 months in a polyethylene bag and for 16 months in the transplant bed, after slicing off the bottom 1 cm of the container, in addition to making 3 longitudinal cuts of 1 cm depth.

Figure 4.—Washed paperpot root system, 16 months after transplanting.

Figure 5.—General morphology of root system after the paperpot was removed and the main laterals had been excised.