Comments

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Cover: Loading Mexican pine seedlings for transportation to the outplanting site (photograph courtesy of John Mexal, New Mexico State University Las Cruces, NM).

Methyl Bromide in Forest Tree Nurseries: Imperative or Opiate?

For decades, the forest tree nursery industry has enjoyed the benefits of seedbed soil treatment with the biocidal soil fumigant methyl bromide. Use of methyl bromide has reduced the threat and actuality of negative impacts of soilborne plant pathogens, insects, and weeds, making successful crop production a relatively sure and worry-free process.

It might serve us well to remember, however, that not all has been well. Fumigation "failures" have occasionally resulted in boomerang or kick-back disease scenarios caused by fumigation-resistant pathogens operating with increased efficiency in post-fumigation, competition-free soil. Fumigation "successes" have sometimes created mycorrhizal deficiencies with concomitant and costly crop failures. In recent years, awareness of and concern regarding health risks associated with exposure to methyl bromide have been on the rise, and related worker protection and safety standards have added both complexity and costs to methyl bromide application. The handling/disposal of plastic tarping materials required for methyl bromide use is increasingly problematic, especially in areas where landfill operation policies refuse acceptance of such materials. And to this is now added concern over the ozone depletion potential of methyl bromide and its relationship to the earth's apparently fragile and diminishing stratospheric ozone layer. These and related political, administrative, and economic issues are forcing forest nursery managers, among a host of others, to examine and evaluate alternative strategies for the successful conduct of their business.

With these realities in mind, it is most appropriate to critically examine what 1 am at times inclined to *believe is* our psychological addiction to an *expensive, dangerous,* and habit-forming drug. I have practiced forest pathology in the southern United States for nearly 20 years. During that time, I have personally observed and worked with a variety of "forest nursery diseases" occurring under operational conditions. These diseases have included root rots ***caused*** by *Fusarium* spp., *Pythium* spp., *Phytophthora* spp., and *Macrophomina phaseolina* In every case, disease occurrence and associated losses occurred in methyl bromide-fumigated seedbeds and in areas of same which were predictably disease prone due to either poor soil drainage and/or "management error". I have worked with diseases *caused* by the "soilborne" pathogens *Cylindrocladium scoparium* and *Rhizoctonia* or *Rhizoctonia*-like spp., all of which were clearly related to disease-promoting cultural practices (habits?) and none of which was successfully controlled by soil "sterilization." I have also observed poor crop performance-indeed crop failure-due to methyl bromide-incurred mycorrhizal deficiencies. Why do we fumigate?

In 1986, I suggested to the Southern Forest Nursery Association meeting in Pensacola, Florida, that pest management in forest tree nurseries often consists of detection, identification, and reaction ex post facto (that is, "crisis management") and that our reactions are often based more on fear of the unknown than on documented biological or economic realities. Is this integrated pest management (IPM)? I further suggested that some "preventive" controls (for example, soil fumigation) are applied cost ineffectively in anticipation-– or fear?— of pest problems that in actuality may never materialize. I still believe this to be true.

In recent years, an industrial forest nurseryman in Florida has successfully grown 4 successive pine crops in unfumigated seedbeds. The Florida Division of Forestry has successfully produced 2 successive pine crops in unfumigated soils at a savings to the taxpayer of about $40,000 in fumigation costs. Over the past 4 years, we have successfully produced the equivalent of 7 pine seedling crops in forest nurseries in Florida and South Carolina in soils unfumigated for up to 6 years as part of a USDA Forest Service Technology Development Project. And, in a current Florida forest nursery study, germination of loblolly pine in unfumigated seedbeds is equivalent to that in fumigated seedbeds despite the fact that about 2 million seedlings failed in the same nursery block in 1996, possibly due to damping-off. Apparently, these are not stand-alone scenarios.

To be sure, the "to fumigate or not to fumigate" question is still on the table, and the answer(s) to same will likely vary from situation to situation. Decision criteria have included tradition, appearances or aesthetics, anticipated pest losses /prevention (and the related concept of "insurance" for which reliable actuarial figures are sparse, if not lacking altogether), and legitimate attempts at benefit/cost analyses. I, for one, am not convinced that methyl bromide (or other) soil fumigation is as necessary or essential as we used to-or still?-think. In some cases, it may be. In others, perhaps not. Discussions and analyses will continue, but I submit that at least within the forestry arena we may need to (and perhaps should) carefully reconsider the criteria and/or models we employ to define and determine our *need(s).*

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(This Commentary is adapted from a presentation given by the author to the 1995 Annual International Research Conference on Methyl Bromide Alternatives and Fmissions Reductions on November 6-8, 1995, held in San Diego, California.)

Note: Our concept of this editorial space is that it should be a place to publish opinions and ideas relating to the nursery, reforestation, and restoration professions. We invite you to submit ideas for commentaries. The views expressed here are solely those of the author(s) and do not necessarily reflect those of the Tree Planters Notes editorial staff, the Forest Service, or the U.S. Department of Agriculture. — RN and the editorial board

Measurement of Soil Water Content in a Peat-Vermiculite Medium Using Time Domain Reflectometry (TDR): A Laboratory and Field Evaluation

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In Quebec, Canada, the estimation of soil water requirements in container tree seedling production is generally based on a qualitative approach. However, recently the development of large seedling cultivation and the use of air-slit containers have made nursery irrigation more complex. In order to improve irrigation management ice evaluated the use of time domain reflectometry (TDR) equipment to measure the volumetric content of substrates. Trials carried out show that this type of equipment can be used to measure substrate water content in real tune. Comparison with measures of soil water content determined gravimetrically corn firms that measurements obtained by TDR are very precise. Tree Planters' Notes 47(3): 88-93; 1996.

More than 115 million shippable container tree seedlings are produced annually in the various private and public nurseries of Quebec, Canada. During recent years, particular emphasis has been put on developing cultural management of different species based on their specific nutritional needs (Langlois and Gagnon 1993).

Although irrigation techniques have been constantly improved for production in tunnel-style greenhouses, few studies have been undertaken to determine the seasonal soil water requirements of seedlings during the growth period. Nevertheless, irrigation plays an important role in seedling physiology (Heiskanen 1993; Langerud and Sandvik 1991; Rao and others 1988). Soil biology (Nielsen and others 1995) and substrate properties are also affected by media water content (Haase and Rose 1994; Heiskanen 1993; Langerud and Sandvik 1988; Nielsen and others 1995). For this very reason, the precise measurement of soil water content in the root zone should be an essential prerequisite to the establishment of effective nursery irrigation management (Schmugge and others 1980).

The lack of development in this area of tree seedling production can be attributed, firstly, to the difficulty in routinely quantifying the water content of peat substrates. Gypsum blocks, tensiometers (Pelletier and Tan 1993), xylem potential (Jacobsen and Schjonning 1993; Nielsen and others 1995), and the gravimetric technique (Herkelrath and others 1991; Nielsen and others 1995) are direct or indirect measurement methods that are often time-consuming, difficult to apply in nurseries, and sometimes destructive.

Secondly, during the last 20 years, production of small seedlings in closed containers (that is, without slits) has generally posed few irrigation problems for nursery managers. However, for the past 3 years, cultivation of large seedlings (Gingras 1993b) and the use of air-slit containers (Gingras 1993a) have significantly altered moisture conditions in the peat-vermiculite medium used. Because the latter is characterized by low water-holding capacity under conditions of high water-potential, moisture levels inside the cavities often oscillate between drying conditions that are harmful to the seedling and saturation conditions that can result in inadequate aeration (Heiskanen 1993). This recent problem thus makes it necessary to develop an empirical approach for evaluating soil water content in container production.

During recent years, researchers have focused on time domain reflectometry (TDR), the principles of which were developed by Fellner-Feldegg (1969). TDR has several advantages: it is simple to use (Tope and others 1980); it is little affected by soil conditions such as density (Tope and Davis 1985), temperature (Pèpin and others 1995; Topp and Davis 1985), and salinity (Hook and others 1992; Topp and Davis 1985; Topp and others 1980); and it can be used in peat substrates (Anisko and others 1994; Pèpin and others 1992). In 1993, a new generation of equipment based on the principles of time domain reflectometry and operating with a single-diode probe (which had been improved for the study of complex media) was put on the market. Given this context, the present study aimed at 2 specific objectives: first, to measure, in the laboratory, the precision of this equipment and the reproducibility of results obtained under different conditions; and second, to evaluate the applicability of this equipment under operational conditions in a tunnel seedling production facility.

Materials and Methods

Two specific trials-a laboratory trial and a tunnelhouse trial-were carried out to meet the objectives of this study.

Laboratory trial. In order to determine the precision of the equipment used, we measured the water contents of different substrates by time domain reflectometry (TDR) and gravimetry under different moisture conditions and at different times. The trial was carried out on 3 types of peat:

peat 1– Sogovex light sphagnum peat moss (company 1)
peat 2– sphagnum peat moss (company 1)
peat 3– Canadian sphagnum peat moss (Fafard Ltd.)

Because the precision of the equipment studied may vary according to substrate water content, moisture levels of 25, 37.5, and 50%, respectively, were applied to each peat according to the following volumetric proportions of peat-vermiculite– water: mix 1, 3:1:1; mix 2, 3:1:1.5; and mix 3, 3:1:2. These were prepared on the eve of the experiment, then homogenized for 30 minutes the following morning in a concrete mixer immediately before the measurements were taken.

Containers used in the experiment were polyvinyl chloride (PVC) cylinders that were 7.5 cm (3 in) in diameter and 42 cm (16.5 in) high and had an average volume of 1905 cm^3 (116.3 in^3). Because the density of growing medium may be a significant factor in variability, the following method was used for filling the tubes: the substrate was poured to the top with one of the prepared mixes; the cylinder was then dropped twice from a height of 10 cm (3.9 in) from the ground; and then mix was added to the top and the compaction operation was repeated.

Measurement by reflectometry was carried out with an MP-917 (GS Gabel Corporation, ESI Environmental Sensors Division, Victoria, BC) equipped with single-diode probes made from 2 parallel stainless steel rods that were 39 cm (15.4 in) long and 3.17 mm (0.12 in) in diameter. These probes were placed vertically at the center of the cylinders. The probes and the equipment were interconnected with a 25-cm (9.8-in)-long coaxial line. The *ViewPoint*™ software (version 1.35) allowed the values of certain internal parameters of the equipment specific to the peat medium to be maximized.

For each of the peats and each prepared mix, percentages of volumetric water were measured every 15 minutes-at 0, 15, 30, 45 and 60 minutes-with the MP-917. After each measurement, the peats of 4 tubes (or 5 tubes, peat 1 and 2, mix 1) were extracted and their water content determined by gravimetry (weight difference) (ovendried at 225 /C (437 /F) for 24 hours). All water contents were expressed as percentages (cm^3 H_2O/cm^3 peat × 100 or % v/v).

Tunnel-house trial. Black spruce seedlings— *Picea mariana* (Mill) BSP— 1+0 starting their second year of growth and produced in air-slit containers (IPL 25-350A) were monitored during the 1995 season. Three irrigation schedules were determined in order to test the reliability of MP-917: dry (30%, v/v), moderate (40%, v/v) and wet (50%, v/v). During the autumn period, percentages aimed at were lowered to 20, 30, and 40%, respectively. Twenty-one containers per schedule (block) were placed inside a polythene tunnel-style greenhouse. In each of the 3 blocks, 5 single-diode probes were placed in specific locations: 1 at the center of the block (low drying) and 4 others on the periphery (high drying). Each probe was inserted horizontally through the slits of 5 cavities halfway up the container (figure 1). It can be seen from the diagram that each probe alternately passes through specific air and peat spaces. Since the estimation of water content only takes into account the portion of the probe that is situated in the substrate, 2 parameters in the *Environmental Sensors* software (version 1.35) must be changed: the total length of the rods and a factor A, defined as the displacement time (nanoseconds) of the electromagnetic signal in the air. This value is substracted from the total displacement time of the probe. A fertilization schedule applied weekly (Blue White injector Model VS-1860) ensured adequate growth of the seedlings during the summer (total application by seedling: 60.0 mg N (2.1×10^{-3} oz), 19.23 mg P (0.7×10^{-3} oz), and 8.63 mg K (0.3×10^{-3} oz). At the end of July and in mid-September, readings were taken at set times: 8:30, 11:00, 13:00, and 15:00, respectively. Irrigation was applied using a mobile ramp (Harnois, Aquaboom model on a ground rail) equipped with 22 nozzles (Model 8006; except at ramp ends, when Model 8010 was used). Temperatures (in Celsius) were recorded with a data logger (Campbell Scientific Model CR-10) fitted with temperature sensors (Model 107B). In each block, a sensor was placed in the air at seedling level and another in the substrate. Measurements were taken every 5 minutes and average hourly temperatures were subsequently calculated.

Results

Laboratory trial. Figure 2 shows the results of paired comparison of all water measurement data using the MP-917 and gravimetry. For each of the mixes, a slight point dispersion can be noted even though slight skewing is observed with the increase in water content in the substrate. The average percentages of water measured with the MP-917 were 22.4, 47.6, and 58.2%, respectively, whereas the gravimetry measurement

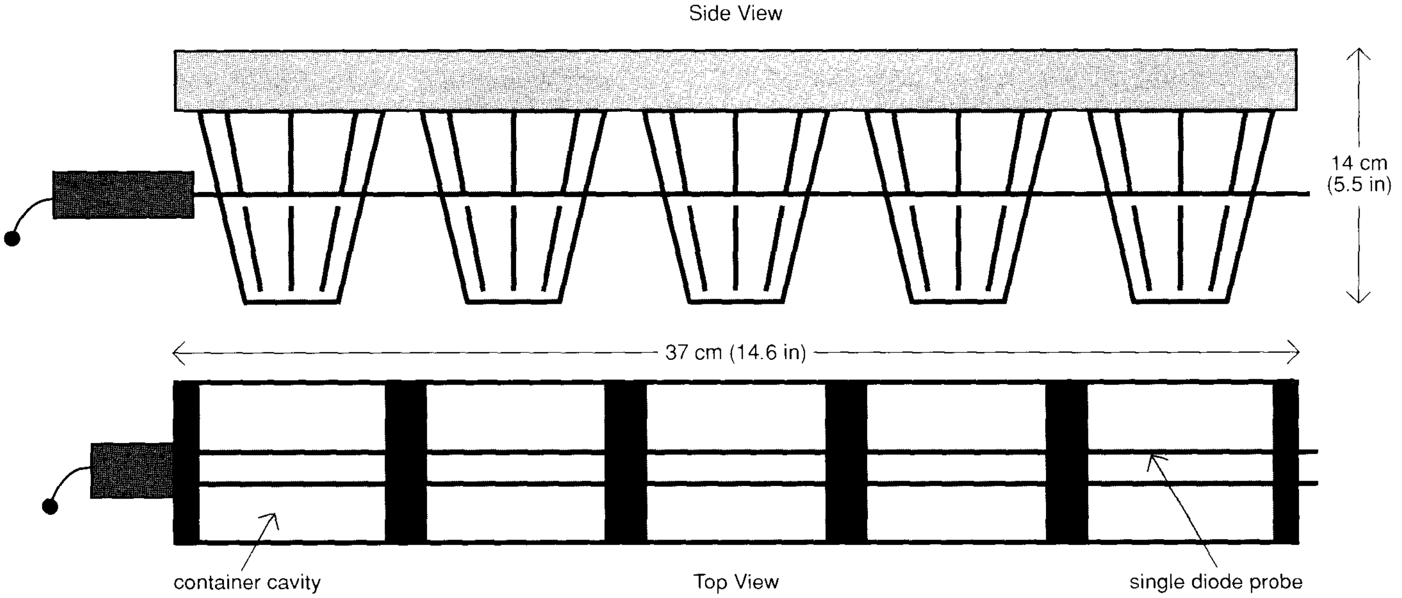

Figure 1—*Diagram of installation of single-diode probes through 5 cavities of an air-slit container.*

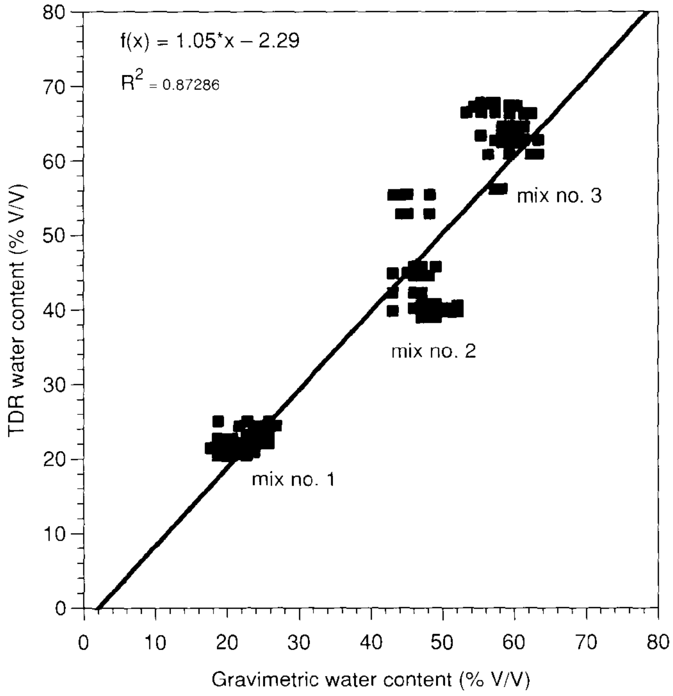

Figure 2—*Relationship between water content measured by volumetry and by gravimetry (pooled data on peat types, mixes, and times).*

values were 22.2, 42.0, and 62.3%. Graphically, a linear relationship can be outlined on a preliminary basis from the 3 clouds of points.

Detailed data analysis indicates that regardless of the measurement method used, there was little difference between the water contents of the 3 peats for the same mix and specified time. However, when measured with the MP-917, a gradual increase of water content in certain samples (peat 1 and 2; mix 2 and 3) was observed in the time. Detailed data analysis also indicates that the MP-917 does not skew water content values in one direction or another in comparison with those obtained by gravimetry.

With the exception of mix 1, water content measured by the two methods was higher than the theoretical values established for each of the mixes used (mix 1, 250; mix 2, 37.5%; mix 3, 50%).

Tunnel-house trial. Between July 24 and August 1, water content increased and decreased regularly (figure 3). These rapid daily cycles are related to particularly hot atmospheric conditions observed in the tunnel house during the summer (average weekly minimum and maximum temperature: substrate, 18.2 /C (64.8 /F) and 26.6 /C (79.9 /F); air, 16.6 /C (61.9 /F) and 30.2 /C (86.4 /F) and the frequency of irrigations (represented by the vertical dotted lines on the graph). Measurements of the dry control obtained from the probe situated in the centre of the block indicate that soil water content was maintained globally at the established target value (30%). However, for the moderate (40%) and wet (50%) controls, the percentages measured were generally exceeded from July 25-28 but were gradually reached around July 29. Results for the probes placed at the edge of each block confirm that adequate moisture levels for the moderate and wet controls were maintained. Nevertheless, water contents remained higher than 30% for the low control. For the latter, it was necessary to carry out supplementary irrigations so as to prevent excessive drying of the growing medium. This was noted in particular on July 26, when water content reached 60%. Results for the same irrigation control confirm that the level of water content varies according to the containers' position inside a block. The reproducibility of results obtained with the MP-917 equipment at short intervals confirms that the sensitivity of the system used is good. However, it should be noted that normal readings of water content could not be obtained for 12% of all probes (15) installed in the design.

During autumn, the decrease in water content was more gradual than that observed in July (figure 3). A single irrigation was carried out during this period, reflecting cooler temperature conditions at the end of the month (data not analyzed for this period). This less-demanding environment is expressed in an adequate modulation of the 3 irrigation schedules. For the probes situated at the center of the blocks, at this period of the year, the initial targeted percentages for the moderate and wet moisture controls (30 and 40%, v/v) were generally reached, except during the period preceding the September 20 irrigation. However, for the low control, water contents remained lower than the recommended target value (20%). From September 20 onwards, no measure could be taken of the low control with the probe installed in the container. At the edge of the blocks, tendencies similar to those observed at the centre of the compartments were observed: targeted moisture percentages were reached for moderate and wet controls and values below 20% in the peats of the low control were obtained. As in July, consistent differences in water content between containers positioned at the center and at the edge of the blocks were observed. Technically, abnormal or excessively low readings were recorded on certain specific probes.

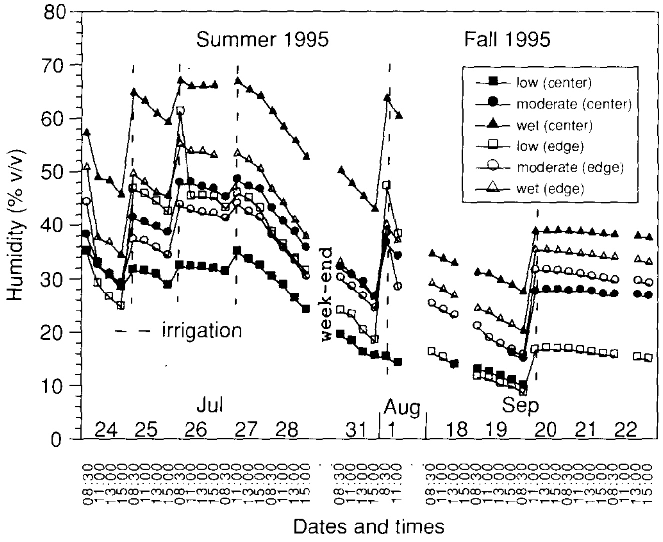

Figure 3—*Variation in water content in July and September in peats of air-slit containers according to 3 irrigation controls and 2 measurement points.*

Discussion and Conclusions

Trials carried out in the laboratory and outside in the tunnel house during the summer and autumn of 1995 indicate that the MP-917, a field instrument based on the principles of time domain reflectometry, allows rapid, precise, and reproducible measurement of volumetric water content in peat substrates. Similar percentages measured by reflectometry and gravimetry under different conditions confirm those observed in previous studies (Dasberg and Dalton 1985; Ledieu and others 1986; Topp and Davis 1985; Topp and others 1980, 1984, 1988) but refute those obtained by Jacobsen and Schjonning (1993). The adequate results observed during this trial indicate that the algorithms used by the MP-917 allow the exact estimation of water content in the peat-vermiculite medium within established moisture ranges. Similar water content results observed in 3 peats may be explained by the fact that although they originate from 3 different sources, they show identical physical properties: similar saturation rates and densities (data obtained from retention curves).

The slight increase in point dispersion in mixes 2 and 3 is possibly due to the fact that in more humid conditions, 2 internal parameters of MP-917 were not optimized. In these conditions, the estimation routine carried out by the equipment is more difficult; thus a greater variability of results was observed.

The gradual increase of water content over the period of 1 hour may be explained by 2 specific physical processes: compaction of the peat caused by the insertion of the rods and progressive replacement of air spaces by free-running water surrounding the rods (Knight 1992).

For this trial, the length of the rods of each probe was established according to the dimensions of the containers used. In the conditions tested, the length of the rods did not appear to be a factor limiting the precise measurement of water content. Comparative tests (not discussed in this article) carried out with the MP-917 and a Tektronic (Model 1502b) equipped with shorter probes (2 and 3 rods) with mixes 1 and 2 also indicate that the length of the rods does not seem to be a factor limiting the estimation of water content. The specific properties of the material used remain more significant (Heimovaara 1993).

The reliability of MP-917 observed in the laboratory was confirmed in the tunnel-house trial. The results obtained from monitorings carried out during periods when the water evaporation and evapotranspiration rates of seedlings vary, indicate that it is possible to target specific moisture levels within a limited range. Probes proved to be very sensitive to hourly variations of water content; however, special attention must be paid to the parallel alignment of the rods. The incorporation of a diode at the base of the probe ensures adequate reflection of the signal with a greater amplitude; moreover, the addition of this piece minimizes errors associated with the speed of propagation and reduces background noise (Hook and others 1992), which is often significant in this type of substrate. However, despite this technical improvement, for some of the probes, negative, overly high, and very low values were obtained. This problem, which is particular to the substrate used, is caused by an erroneous evaluation of the end of the probe by the equipment (Chambers 1996). The addition of a second diode at the end of the rods could possibly eliminate this specific recurrent problem.

The tunnel-house trial brought out 2 interesting points with regard to seedling production in air-slit containers. Firstly, significant differences in water content were observed between the centre and edges of the compartments. Therefore, appropriate water management should be developed in order to reduce these differences. Secondly, the different dynamics of evaporation and evapotranspiration observed between the periods of July and September confirm that it is possible with this type of equipment, to introduce sequential modeling of irrigation based on specific needs of seedlings and as a function of their particular phenology. Finally, in the context of the development of air-slit containers, more rigorous irrigation management opens up interesting prospects for improving the structure and pruning of roots.

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Mass Propagation of Rocky Mountain Juniper From Shoot Tip Cuttings

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Demand has exceeded supply for conservation plantings of Rocky Mountain juniper-Juniperus scopulorum Sarg. Vegetative propagation could provide an alternative source of planting stock. Ortets from 2 to 40 years of age provided cuttings from leaders and first-rank branches. Ramets, 12-cm-long (4.7-in-long) from 2-year-old ortets, rooted at rates of zip to 82%. Treatment of cuttings with 1.6 or 3.0/h indole-3-butyric acid (IBA) accelerated rooting by several months and increased overall rooting success by up to 36%. Stecklings survived at high rates (97%) and developed a normal seedling-like form. Tree Planters' Notes 47(3): 94-99; 1996.

Rocky Mountain juniper (RMJ)— *Juniperus scopulorum* Sarg..— is planted extensively across the Great Plains and Intermountain regions for windbreaks, living snow fences, and wildlife habitat, and to provide wood for fence posts and other specialty uses (Rietveld 1989; Young and Young 1992). Demand for planting stock, however, has exceeded supply recently (Wagner and others 1994), and seedling production is often hampered by erratic, delayed, and low rates of germination (Noble 1990; Rietveld 1989). Wagner and others (1992) discussed potential advantages of shorter production time and opportunity for tree improvement by propagating juniper for conservation plantings from cuttings as an alternative to seedling production.

Junipers are commonly propagated from cuttings, but species that grow upright are considered more difficult to multiply than prostrate forms (Hartmann and others 1990). Dirr and Heuser (1987) described optimal rooting treatments for RMJ cultivars using up to 4.5% indole-3-butyric acid (IBA). Wagner and others (1994) reported less than 10% rooting success of RMJ cuttings from 12-year-old selected ortets ("parent" trees) rooted after dips in liquid Dip'N Grow ®— 0.5% IBA plus 0.25% naphthaleneacetic acid (NAA)-or talc powder with 0.8% IBA.

Greenhouse culture may enhance propagation success. Ramets (vegetatively propagated "daughter" plants) taken from container-grown juniper plants often root at higher rates and develop better root systems than field-grown stock plants (Dirr and Heuser 1987). Although rooting success tends to decline as ortets mature, hedging stock plants may also prolong juvenility and high rooting rates (Hackett 1985).

Few data are available on rooting of container-grown RMJ cuttings from non-selected juvenile ortets. This study examined cutting yield from greenhouse-grown seedlings; effects of cutting size, rooting hormone, and ortet age on adventitious rooting; and growth and form of stecklings (plantable rooted cuttings).

Materials and Methods

Table 1 summarizes observations and rooting experiments conducted with different sources, ages, and containers of ortets used in this study.

Juvenile propagation material. Cuttings were provided by 2-to 5-year-old RMJ seedlings. These ortets were grown at the University of Idaho Forest Research Nursery in Moscow from wild seed (Colorado origin) operationally sown into 66-ml (4-in^3) Ray Leach® pine cells. Seedlings were grown under a regime similar to that for western white pine— *Pinus monticola* Dougl. ex D. Don (Wenny and Dumroese 1987). In both 1992 and 1993, about 200 randomly selected 1-year-old production-run seedlings, with average height of 12 cm (4.7 in) and caliper of 2.2 mm (0.09 in), were transplanted to 4-L pots (400 pots/100 ft^2 of bench area) and were fertilized twice weekly with N/P/K = 20:20:20 at 100 ppm N for 2 growing seasons. The 4-year-old ortets were then transplanted to 8L pots (178 pots/100 ft^2) and fertilized similarly.

Mature propagation material. In October 1993, 480 cuttings were collected from two 40-year-old RMJ trees in Moscow, Idaho, and 1,000 cuttings were harvested in December 1994 from non-selected 12-year-old ortets at the USDA Natural Resources Conservation Service's Plant Materials Center, Aberdeen, Idaho.

Ortet yield. Cuttings were leaders from 2-year-old ortets and first-rank branch tips from older donors. To estimate cutting yield of older ortets, maximum numbers of 12-cm-long (4.7-in-long) branch cuttings were taken from randomly selected 3- and 5-year-old ortets (40/age class). (This paper refers to age classes of ramets that correspond to their ortet age.)

General rooting procedures. For all trials, turgid branch tips were cut to within several millimeters of a pre-determined length at an angle of 45/ to the stem axis. Cuttings were immediately soaked for 30 sec in 1 g/L benomyl and dipped in commercial auxin formulations containing talc with various concentrations of IBA and NAA. Treated cuttings were inserted into 1.5-cm-deep dibble holes in a 3:1:1 (v/v/v) mixture of perlite, peat, and vermiculite. Trays of cuttings were placed on benches shaded to 60% of full sunlight. Minimum relative humidity was 86% and diurnal air temperatures ranged from 15 to 25 /C (59 to 77 /F). The rooting medium was periodically hand-watered to keep it moist, but the cuttings were not fertilized.

Cutting size trial. In mid-November, leaders were cut from 150 dormant 2-year-old RMJ stock plants chosen at random. To assess the effect of length on rooting, cuttings were randomized to alternative lengths, 50 cuttings/length, of 4, 8, and 12 cm (1.6, 3.2, and 4.7 in). All cuttings were dipped in 1.6% IBA. The experiment was repeated in mid-November with ramets from 4-year-old ortets. We recorded percentage rooting, callus formation on unrooted cuttings, basal stem necrosis, average root number, and mean maximum root length after 4 and/or 10 months. Subsequent experiments used 12-cm-long (4.7-in-long) cuttings.

Auxin treatment trials. A series of rooting experiments was conducted with 2-, 3-, 4-, and 5-year-old greenhouse-grown and 12- and 40-year-old field-grown cuttings (table 1). Cuttings were randomly assigned to one of the following treatment groups:

- control (no auxin)
- Hormex®) rooting powders containing talc and either 0.1, 0.3, 0.8, 3.0, or 4.5% IBA
- Rootone® (a powder mixture of 0.2% NAA, 0.1% IBA. and Thiram®)
- Dip'N Grow®, a liquid formulation containing 1.0% IBA and 0.5% NAAdiluted to 0.1% IBA and 0.05% NAA)

Table 1- *Observations of ortet chid steckling growth and rooting trials conducted with cuttings from juvenile containergrown acrd mature field-grown ortets of Rocky Mountain juniper—* Juniperus scopulorum *Sarg.*

Source material		Observations and rooting trials				
Ortet age (yr)	Container vol.	Ortet yield	Cutting length	Auxin trt.	Leader vs branch	Steckling growth & form
Seedlings						
1	*66 ml					
2	4 L		X	X		
3	4 L	X		X		X
4	8 L		X	X	X	
5	8 L	X		X		
Trees						
12	Aberdeen			X		
40	Moscow			X		X

* Production crop.
trt = treatment

Percentage rooting, numbers of roots produced/ steckling, and mortality of unrooted cuttings were recorded every 3 months for a year. In one trial, half of the cuttings (160) were not treated with benomyl.

Leader versus first-rank branch trial. Cuttings of leaders and first-rank branches, 146 cuttings/type, were taken from dormant 4-year-old ortets in winter. We recorded percentage rooting, percentage of stecklings and unrooted cuttings with well-developed callus, number of primary roots per steckling, and incidence of lateral rooting after 6 months.

Steckling growth and form. Stecklings from 3- and 40-year-old ortets were observed for 1 and 2 years, respectively, after rooting. In spring 1995, about 500 newly rooted 12-cm-long (4.7-in-long) stecklings (from 3-year-old ortets) were transplanted into 45/340 copperblocks — 45 cells with 340-ml (20 in^3) capacity, 18 seedlings/ft^2— containing a 1:1 (v/v) mixture of peat and vermiculite. Stecklings received nutrient applications of N/P/K = 20:7:19 at 192 ppm N once or twice weekly. After 12 months, height and caliper were measured from 40 randomly selected orthotropic (upright) stecklings. Plagiotropism (prostrate form) was assessed in 360 stecklings chosen at random. Stecklings rooted in 1994 from 40-year-old ortets were treated similarly and assessed for plagiotropism after 12 and 24 months.

Data analysis. Uncertainty in means was expressed as standard error (SE). The SAS statistical package (SAS Institute 1989) was used to examine categorical data by maximum likelihood ANOVA with procedure CATMOD. Means were compared by single-degree-of-freedom contrasts. Continuous data were subjected to ANOVA procedure GLM and count data were analvzed by the Kruskal-Wallis test using procedures RANK and GLM with Tukey's studentized test.

Results

Ortet yield. The 3- and 5-year-old ortets produced an average of 14±1 and 34±2 cuttings/ortet, respectively. Stock plants grew vigorously (figure 1) without mortality. Despite dense foliage and close packing, plants remained disease free, but root weevils Otiorhynchus spp.) increasingly infested older ortets.

Cutting size trial. The longest cuttings-12-cm-long (4.7-in-long)-of both 2- and 4- year classes rooted at the highest rate and developed the most callus, the largest number of roots per steckling, and the longest roots

Figure 1—*A hedged seedling ortet of Rocky Mountain juniper—* Juniperus scopulorum *Sarg.—after 5 years of container growth.*

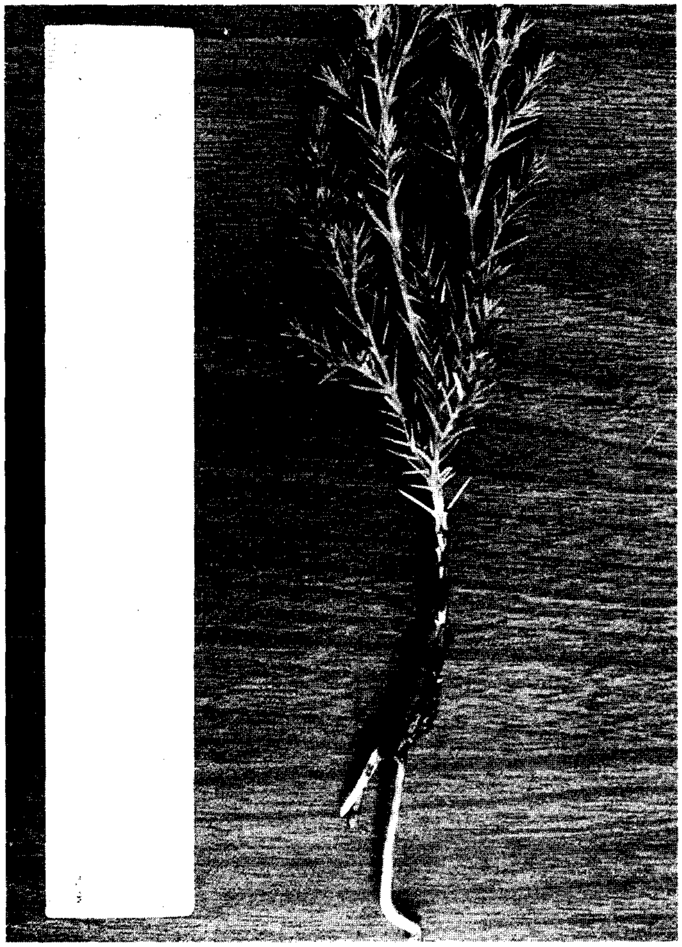

Figure 2—*A branch tip cutting of Rocky Mountain juniper—* Juniperus scopulorum *Sarg.—shortly after root emergence.*

Table 2— *Effect of cutting length on rooting of Rocky Mountain juniper—*Juniperus scopulorum *Sarg.—cuttings, callus formation in unrooted cuttings, stem necrosis, and number and maximum length of roots; data were collected 4 and 10 months after setting cuttings at a rate of 50 cuttings/size/age class*

Ortet age (yr)	Cutting length (cm)	Rooting success (%)		Callused cuttings (%)	Stem necrosis (%)	Ave. no. roots/cutting	Ave. max. root length (cm)
		(4 mon)	(10 mon)	(4 mon)	(4 mon)	(10 mon)	(10 mon)
2	4	28 a	52 a	54 a	25 a	1.3 a	12.2 a
2	8	46 b	78 b	82 b	16 ab	2.1 a	14.2 a
2	12	62 c	82 b	90 b	8 b	3.7 b	21.9 b
4	4	0 a	20 a	22 a	18 a		
4	8	4 a	34 b	46 b	20 a		
4	12	18 b	51 c	66 c	4 b		

Percentages and means within columns of each age class with the same letter are similar ($\alpha = 0.05$).

(table 2). Most unrooted cuttings that developed callus after 4 months subsequently rooted. The 4-year cuttings rooted less frequently than 2-year cuttings. About 5% of unrooted cuttings of each length and age class blackened upward from the base.

Auxin treatment trials. Roots usually emerged from cutting bases and stems within 2 months (figure 2). During the first 6 months after treatment, both 1.6% and 3.0% IBA accelerated rooting of the 2-year cuttings (figure 3). Rooting of controls was initially delayed but

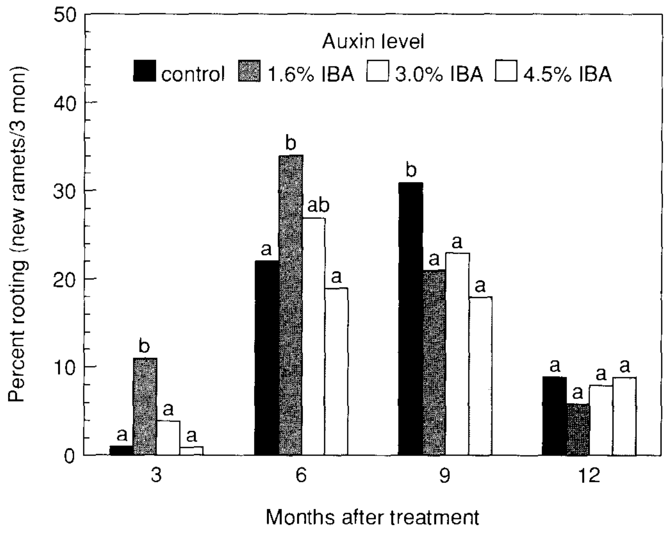

Figure 3—*Rooting of Rocky Mountain juniper*—Juniperus scopulorum *Sarg.—cuttings from 2-year-old ortets versus time.*

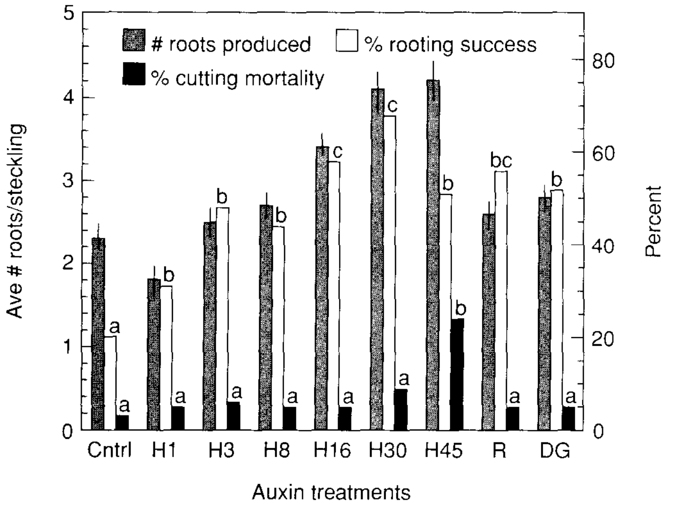

Figure 4— *Root development, rooting success, and mortality of Rocky Mountain juniper*—Juniperus scopulorum *Sarg.—cuttings (3-year-old ortets) 6 months after auxin treatment in October. (H1 to H45 = 0.1, 0.3, 0.8, 1.6, 3.0, & 4.5% IBA; R = Rootone (0.2% NAA + 0.1% IBA); DG = Dip'N Grow (diluted to 0.1% IBA + 0.05% NAA; n=225). Percentages with similar letters within a series are similar (α = 0.05).*

increased sharply between 6 and 9 months, whereas rooting of auxin treated cuttings declined or remained unchanged. Rooting subsequently slowed and ceased by 12 months.

Auxin treatment typically increased overall rooting success in all age classes of cuttings (table 3). After 12 months, highest rooting rates of 2-and 3-year cuttings set in October exceeded 70%, with36% more cuttings in the 3-year class rooted in 3.0% IBA, but only 6% more in the 2-year class. The 12-year cuttings set in January rooted up to 44% less than the 3-year class. Clones of 40-year cuttings rooted at overall respective rates of 4 and 44%.

Within 6 months of treatment in October, cuttings of the 3-year class rooted with 68% success in 3.0% IBA (figure 4). Highest numbers of roots emerged from cuttings in 3.0 and 4.5% IBA, but 4.5% IBA resulted in higher cutting mortality (24%) than other treatments. The powder formulation with 1.6 and 3.0%o IBA resulted in higher rooting success than the liquid formulation with 0.1% IBA and 0.05% NAA but was similar to the result with Rootone. About 23% (37) of the cuttings not soaked in benomyl prior to auxin treatment rotted and died;

Table 3—*Effect of auxin treatment on rooting success 12 months after setting Rocky Mountain juniper*—Juniperus scopulorum *Sarg.—cuttings from 2-, 3-, 12-, and 40-year-old ortets*

	Percent rooting							
	2 yr		3 yr			12 yr	40 yr	
							Oct (n=120)	
Treatment	Mar (n=80)	Oct (n=120)	Jan (n=150)	Jul (n=200)	Oct (n=225)	Jan (n=150)	Clone 1	Clone 2
Control	45	64 ab	22 a	18 a	42 a	6 a	0	1
0.1% IBA						51 a		
0.3% IBA						65 b		
0.8% IBA	59		33 a	42 b	64 b	8 a	8	87
1.6% IBA	65	70 b	51 b	48 b	74 bc	15 a		
3.0% IBA		62 ab	58 b	50 b	78 c	14 a		
4.5% IBA		44 a		43 b	60 b			
Rootone			41 ab		69 b	15 a		
Dip'N Grow	38				68 b			

Percentages within columns with the same letter are similar (α = 0.05); n = number of cuttings per treatment.

7.5% (12) of the cuttings treated with fungicide succumbed.

Leader versus first-rank branch trial. Cuttings from first-rank branches of 4-year-old ortets rooted at slightly higher rates than leaders, but numbers of adventitious roots developed per cutting and maximum root length were similar (table 4). More callusing occurred in both rooted and unrooted cuttings of leaders, whereas twice as many branch cuttings as leaders produced secondary roots. Mortality rates were similar for both types of cutting.

Steckling growth and form. After 1 year of indoor container growth, average height and caliper of stecklings from 3-year-old ortets was 36.1 ± 0.9 cm and 5.4 ± 0.2 mm, respectively. Leaders failed to develop normal form in 12% (43) of the stecklings: 3% (11) were plagiotropic, 2% (7) did not grow after rooting, 6% (22) produced competing leaders, and 1 % (5) died. All bent leaders, however, had begun to develop upright growth.

Two years after rooting, leaders of 92% (81) of the stecklings derived from 40-year-old ortets remained plagiotropic (figure 5). Stecklings continued to produce mature scales versus juvenile needle foliage typical of young ortets.

Table 4—*Rooting success, incidence of callus and lateral root formation, and average number of primary roots per steckling from leaders versus first-rank branches of Rocky Mountain juniper*— Juniperus scopulorum *Sarg.—(n = 146 cuttings/type)*

Cutting	Rooting success (%)	Callused stecklings (%)	Primary roots (no.)	Lateral roots (%)	Callused cuttings (%)
Leader	17 a	76 a	2.0 a	20 a	51 a
Branch	24 a	38 b	2.1 a	47 b	36 b

Percentages and means in columns with the same letter are similar ($\alpha = 0.05$).

Figure 5—*Stecklings of Rocky Mountain juniper*—Juniperus scopulorum *Sarg.—after 1 year's container growth.* ***Left:*** *plagiotropic ramet from 40-year-old donor.* ***Right:*** *normal orthotropic ramet from 3-year-old ortet.*

Discussion

Ortet yield. Although rootability of RMJ cuttings declines with increased ortet maturity, older ortets can produce more shoots for propagation than younger donors. Results from cutting harvests suggest that Sand 5-year-old ortets could yield from 5,500 to 6,000 cuttings on 100 ft^2 (9.3 m^2) of bench area. Top-pruning to control growth of 2-year-old production seedlings to a final height of 30 to 40 cm and caliper > 5.7 mm (unpublished results) could yield about 2,250 leader cuttings/100 ft^2 from ortets grown in 45/340 copperblocks. Advantages of top-pruning 2-year-old seedlings include high rootability of the juvenile cutting material and possible greater genetic diversity, as well as avoidance of rootability decline, high maintenance costs, and pest buildup in indoor stock plants. Container-grown stock plants, however, can produce multiple crops of cuttings from elite selections at preferred times of year.

Cutting length trial. The longest RMJ cuttings developed more roots than shorter cuttings, similar to increased root counts reported by Henry and others (1992) in 25-cm-long (9.8-in-long) versus 12-cm-long (4.7-in-long) cuttings of eastern redcedar (ERC)— *Juniperus virginiana* L. Higher rooting success in longer RMJ cuttings, however, is different from similar rooting rates for 2 lengths of cuttings observed in the ERC study. Shorter RMJ cuttings may possibly root less frequently because of lower carbohydrate reserves or diminished photosynthetic capacity (Davis 1988).

Auxin treatment trials. Higher IBA levels improved RMJ rooting success, whereas in ERC, 2 and 0.5%o IBA produced similar results (Henry and others 1992). Increased cutting mortality with 4.5% IBA, however, suggests a phytotoxic effect due to high concentration of growth regulator (Hartmann and others 1990). Because cuttings rooted most rapidly after treatment With 1.6 and 3.0% IBA, these concentrations would be optimal for commercial propagation.

Although our experiments did not directly compare rooting success at different times of year, high rooting rates of 2- and 3-year cuttings set in October are consistent with optimal rooting of RMJ and ERC cultivars from October to December (Dirr and Heuser 1987). Low light intensity may have limited rooting of RMJ cuttings set in January because strong light has been found to enhance juniper propagation (Hartmann and others 1990).

Our low success rates of rooting cuttings from non-selected 12-year-old ortets is similar to rooting rates reported by Wagner and others (1994) for selected RMJ ortets of the same age. Large clonal differences in gymnosperm rootability have been reported (Haissig and Riemenschneider 1988), similar to the 86%o range of rooting success between the 2 clones from 40-year-old RMJ ortets.

Leader versus first-rank branch trial. Although differences in rooting success were slight, more RMJ branches than leaders may have rooted due to maturational differences associated with aging (Hackett 1988). Leaders are generally more mature than branches lower on the stem (Geneve 1995), and cuttings taken from lateral shoots of some spruce, pine, and hardwoods consistently root at higher rates than terminal shoots (Hartmann and others 1990).

Steckling growth and form. After 1 year of indoor container growth, RMJ stecklings were similar in size but not as bushy as top-pruned 2-year-old RMJ seedlings. Results suggest that total steckling losses from stunting and mortality after transplanting are small (3%). Because RMJ is not strongly apically dominant and new upright growth developed on previously bent leaders, multiple-stemmed and plagiotropic stecklings derived from juvenile ortets will likely develop normal RMJ habit. The high incidence of plagiotropism and mature foliage developed by stecklings from 40-year-old donors, however, suggest that recovery of upright form may occur slowly if at all. Plagiotropism in stecklings from mature ortets of many conifer species may persist for years (Hackett 1985).

Conclusions

Mass propagation of Rocky Mountain juniper cuttings is feasible with 12-cm-long (4.7-in-long) leaders or terminal branch shoots tips. Treating cuttings from juvenile ortets with 1.6 or 3.0%o IBA can accelerate rooting and increase overall rooting success. Fungicidal dip with 1 g/L benomyl can improve cutting survival. Stecklings survive at high rates and develop a normal seedling-like form.

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Effects of Crown Position and Plant Age on Rooting of Jack Pine Long Shoot Cuttings

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Rooting success of long shoot cuttings of jack pine— Pinus banksiana Lamb.*— was found to be influenced by crown location effects among 5-to 30-year-old trees. Despite some variation in response, mid to lower crown cuttings generally rooted more readily than upper crown cuttings. The highest rooting frequencies observed for 4-, 5-, 6-, 7-, and 10-year-old trees ranged from 45 to 75%, whereas cuttings from 30-year-old trees rooted at 28%. These results are encouraging in light of the general perception that jack pine is difficult to propagate by rooted cuttings, and they suggest that operational asexual propagation may be feasible.* Tree Planters' Notes 47(3): 100-104; 1996.

Development of asexual propagation techniques for use in breeding programs or in larger operational scale situations is of interest for many forest species including jack pine— *Pinus banksiana* Lamb. (for example, Klein and others 1995). Richie (1991) has recently reviewed many of the potential uses of rooted cuttings in forestry. The goal of the present study was to examine the influence of crown and sampling location on the rooting success rate of jack pine long shoot cuttings from several age classes. Jack pine historically has been difficult to propagate by vegetative means (Chesick and Bergmann 1991), particularly from plants 5 years and older (Haissig 1982, 1983, 1989). Effects of crown sampling location on rooting of cuttings have been documented for several conifer species (Henry and others 1992; Roulund 1973; Tousignant and others 1995). In general, cuttings sampled from the lateral branches of the lower crown have rooted most readily. Previous investigations with jack pine have shown that there is a transitional period of decline in rooting capacity of central axis cuttings at 4 to 6 years of age (Browne and others 1997a). Agerelated declines in rooting frequency are expected to occur most rapidly and profoundly at the central leading axis, based on theories about the process of maturation in forest trees (Bonga 1982). Initially, there appears to be little difference in rooting capacity of central and lateral axis cuttings, based on trials with young seedlings (Browne 1996). It may be that as presumptive maturation-related losses in rooting capacity proceed, shoots in the lower crown regions retain some degree of juvenile potentiality, resulting in higher levels of regenerative capacity (Bonga 1982; Hackett 1985). This study is also part of a larger scale study on general aspects of asexual propagation of jack pine (see Browne and others 1997a, b; Klein and others 1995) aimed at developing improved methodologies.

Materials and Methods

Cuttings were sampled from different age classes of jack pine— *Pinus banksiana* Lamb.— originating from sites planted in the Sandilands Provincial Forest area of southern Manitoba, Canada. All sites had been planted with 2+0 seedlings (open-pollinated seed) from the Provincial Government Tree Seedling Nursery at Hadashville, Manitoba. Ages of plants at the time of sampling were confirmed by consultation with the Manitoba Department of Natural Resources planting records.

In an initial study, age-related changes in rooting potential had been identified and appeared to be most influential between ages 5 to 10 years (Browne and others 1997a). By 7 years, there was a marked decline in rooting potential. This change was explored in greater detail with respect to crown location. In the first trial, cuttings from only 7-year-old plants were used. A total of 10 trees were randomly selected and cuttings bulked according to crown sampling location (upper, mid, and lower). These positions were assigned based on ratios of lateral branch whorl number from the tip of the tree to total number of branch whorls. A score of <0.35 was considered upper crown, 0.35 to 0.65 mid crown, and >0.65 lower crown. The distal 20-cm lateral shoots were removed and bulked into 3 groups based on relative position within each tree. All sampling was done in late spring, just before to visible bud burst. Cuttings were kept in cold storage for 2 months before preparation for rooting experiments. Storage of harvested material has been shown not to influence subsequent rooting potential (Browne 1996). Rooting response of these cuttings was monitored at the end of an 8-week period under propagation conditions. A completely randomized block experimental design, with 18 replicates of 10 cuttings each for each crown position, was used. In addition, tissue nutrient contents by crown location were determined by a local commercial laboratory (NorWest Laboratories, Winnipeg, Manitoba). This material was equivalent to that used for cuttings in the rooting trial. All shoot samples were harvested and frozen at -20 /C (-4 /F) before analysis. Foliar and stem tissue were analyzed for N, P, K, and micronutrients.

In the second trial, 6 uniformly aged stands of trees were sampled. Plants ranged from 4 to 30 years of age (4, 5, 6, 7, 10, and 30). Terminal shoots from lateral branches were sampled from 1 of 3 designated crown locations as previously outlined (upper, mid, and lower) and placed in rooting trials. A completely randomized block design with 12 replicates of 6 cuttings for each crown position and age class were used. Due to limited lateral branch development in the 4- and 5-year age groups, fewer cuttings were collected. Cuttings were kept in cold storage for 2 months before preparation for rooting experiments.

Treatment of cuttings. Terminal shoot segments were removed from the tree about 2 cm above the end of the previous season's growth, trimmed to 8 to 12 cm in length and the basal foliage from 1 to 2 cm (0.4 to 0.8 in) was removed. Cuttings were then dipped in a rooting hormone (5.4 μM naphthalene acetic acid dissolved in 95% ethanol) for 10 seconds, inverted for 30 seconds, and inserted into rooting medium. This medium consisted of 1:1 (v/v) Forestry Mix (Grace Horticultural Products, Edmonton, Alberta) and vermiculite (medium grade), filled into PBI-45 (110 ml cell volume) multipots (Plastiques Gagnon, Quebec, Quebec).

The rooting trials were all completed in a 15 (6 m (52.5 (19.7 ft) plastic-covered propagation greenhouse located at the Agriculture and Agri-Food Canada Research Centre at Morden, Manitoba. The containers were placed on raised beds filled with sand and misted from single lines of overhead anviltype nozzles spaced at 1-m (3.3-ft) intervals. Misting was delivered in 10second bursts every 8 minutes (18-hour cycle), maintaining a relative humidity of 50 to 90%. Air was drawn through the poly-house with a fan-louver system. Temperatures ranged from 20 to 38 /C (60 to 100 /F) during the day and 10 to 20 /C (50 to 68 /F) at night. Irradiances ranged from 1,030 to 1,980 μE/m^2/sec on sunny days and 270 to 770 μE/m^2/sec on cloudy days, under natural photoperiod.

Rooting assessments were made after 2 months under propagation conditions. The presence of roots >2 mm and total number of roots were counted and the length of longest roots were measured. Means and standard errors were calculated. Analysis of variance (ANOVA) was done using a SAS statistical program (SAS 1991) and least-squares-means comparisons to determine significant effects of age and crown location. Least-squares-means comparisons allows statistical comparisons among the various treatments to determine if differences are significant or not.

Results

In the first trial (table 1), rooting frequency was significantly affected by crown position (P=0.0064). Cuttings from the lower crown position rooted with the highest frequency, with progressively lower values from mid to upper crown positions. Crown position did not affect the numbers of roots produced on the rooted cuttings (P=0.4610). Similarly, root lengths observed did not vary among the various crown locations sampled (P=0.5479).

Nutrient analyses showed that nitrogen content was lower for mid and lower crown shoot tissue (table 2). In addition, boron content was lowest among lower crown cuttings, while copper and manganese were higher. No trends were found in the other elements with respect to descending crown position; contents appeared similar (data not presented).

In the second trial, both age (P<0.0001) and crown position (P= 0.0002) were found to significantly affect rooting frequency. As cutting age increased there was a general decline in rooting potential (table 3). Similarly; there was also a tendency for lower and mid-crown sampling locations to root at a higher frequency than upper locations, but this was not consistent throughout the trial.

Cuttings from the lower crown of 4-year-old trees rooted at a 74%, frequency, and rooting frequencies from the other 2 crown locations were not significantly different (table 3). All rooting frequencies of cuttings from 5-year-old plants were significantly lower than those of

Table 1—*Effect of crown position on rooting of long shoot cuttings from 7-year-old jack pine* —Pinus banksiana *Lamb.*

Crown location	Rooting frequency (%)	*P* values	Mean total no. of roots	*P* values	Mean root length (cm)	*P* values
Upper	17.8	0.0017	5.4 ± 0.6	0.2837	16.4 ± 1.2	0.3958
Mid	24.4	0.0591	5.3 ± 0.6	0.2911	15.5 ± 1.2	0.8410
Lower	33.3	—	4.2 ± 0.4	—	15.9 ± 0.9	—

Note: Least square means comparisons were made with the lower crown location; P values indicate significant level of difference from lower location.

Table 2—*Mineral nutrient levels from foliar samples of 7-year-old jack pine*—Pinus banksiana *Lamb.*

Crown location	N (%)	B (ppm)	Cu (ppm)	M (ppm)
Upper	1.6	23.3	1.4	112.0
Mid	1.2	19.3	1.8	143.0
Lower	1.2	17.4	2.6	203.0

Table 3—*Effect of crown position on rooting of long shoot cuttings from 4-, 5-, 6-, 7-, 10-, and 30-year-old jack pine* —Pinus banksiana *Lamb.*

Age (years)	Crown location	Rooting frequency (%)	*P* values	Mean total number of roots	*P* values	Mean root length (cm)	*P* values
4	Upper	62.5	0.1868	1.6 ± 0.2	0.0885	9.0 ± 1.4	0.1543
4	Mid	70.1	0.6711	2.5 ± 0.4	0.6562	11.3 ± 1.5	0.5107
4	Lower	73.8	—	2.7 ± 0.3	—	12.0 ± 1.2	—
5	Upper	23.6	0.0001	2.0 ± 0.3	0.4663	12.0 ± 2.0	0.8519
5	Mid	44.2	0.0006	2.8 ± 0.4	0.8795	12.3 ± 1.2	0.9921
5	Lower	45.0	0.0009	2.7 ± 0.3	0.9126	11.5 ± 1.4	0.8551
6	Upper	52.8	0.0144	3.9 ± 0.4	0.1198	13.2 ± 1.1	0.7352
6	Mid	72.2	0.8574	4.1 ± 0.3	0.0409	14.3 ± 0.8	0.2839
6	Lower	44.4	0.0007	3.5 ± 0.4	0.2264	12.5 ± 1.2	0.9953
7	Upper	45.8	0.0012	5.0 ± 0.6	0.0001	12.2 ± 1.1	0.6244
7	Mid	54.2	0.0222	5.5 ± 0.4	0.0001	14.9 ± 1.0	0.2184
7	Lower	48.6	0.0035	4.2 ± 0.5	0.0774	12.3 ± 1.5	0.6355
10	Upper	22.2	0.0001	3.6 ± 0.7	0.0626	17.5 ± 2.4	0.0040
10	Mid	43.1	0.0004	1.7 ± 0.2	0.1636	11.1 ± 1.4	0.7506
10	Lower	44.4	0.0007	1.5 ± 0.1	0.0636	10.1 ± 1.1	0.5029
30	Upper	16.7	0.0001	2.4 ± 0.4	0.6647	14.0 ± 1.7	0.4732
30	Mid	27.8	0.0001	2.6 ± 0.4	0.8241	12.7 ± 1.7	0.8063
30	Lower	18.1	0.0001	1.5 ± 0.2	0.0927	9.2 ± 2.2	0.2313

Note: Least square means comparisons were made with lower crown position of 4-year group; *P* values indicate significant level of difference from 4-year old plants.

4-year-old plants (table 3). Rooting frequencies for the other age classes (6, 7, 10, and 30 years) were also significantly lower than those of the 4-year-old plants, except for the 72% rooting frequency for the mid crown cuttings of 6-year-old trees, which were not significantly different than the lower crown cuttings of 4-year-old plants (table 3). Based on results from this experiment, rooting frequency as high as 44 to 54% can be obtained from 7- and 10-year-old trees, and 28% for 30year-old trees grown in the forest with no additional cultural treatments.

Differences in root length were generally not significant within any age class (table 3). However, root number varied somewhat with crown position (P=0.0409) and with age (P<0.0001). Numbers of roots in any age class or crown location were not significantly different than those from lower crown cuttings of 4-year-old plants, with the exception of significantly higher values obtained from mid crown cuttings of 6-year-old plants and upper/mid crown cuttings of 7-year old plants (table 3). In the 4-year age class, the number of roots and root length tended to be greater for mid lower crown cuttings. In 10- and 30-year groups, the number of roots tended to be lower for mid and for lower crown locations, and the roots tended to have shorter lengths. Trends were less apparent in other age classes.

Discussion

Within each age class, the highest rooting frequency tended to originate from the lower and/or mid crown, but differences appeared marginal in some cases. Notably, there was a crown-location effect observed in the first trial on 7-year-old trees, but none seemed to exist within the 7-year-old age group in the second trial. In this latter trial, cuttings from 7-year-old trees rooted at relatively high frequencies compared to the first and no clear positional effect was observed. These 2 groups of plants originated from different locations, and results may have been affected by genotypic and environmental influences. Selby and others (1988) found that upper crown cuttings from average (rated on vigor) Sitka spruce— *Picea sitchensis* (Bong.) Carriere— rooted at a significantly lower frequency than lower crown cuttings, but there were no significant influences of crown location on rooting of cuttings from elite trees.

There is a general lack of physiological evidence to explain crown location effects on rooting of cuttings from forest trees. One possibility is that there are regional differences in nutrient status, which secondarily affects rooting capacity. Results from analyses of 7-year-old jack pine indicated that lower N content may be associated with higher root capacity. Fertility studies have shown that N levels affect root initiation and lower levels are sometimes beneficial (Blazich 1988). Both manganese and boron are known to influence endogenous auxin levels, via activation of IAA oxidase (Blazich 1988; Jarvis and others 1984). The implications for this study are unclear, but perhaps there was a combined effect on the balance of auxin levels. There appears to be a lack of information for possible copper effects on adventitious root initiation (Blazich 1988). In general, interpretation of nutrient effects on adventitious rooting is constrained by a lack of information on their role at the cellular level during the early critical stages of root initiation (Blazich 1988).

During the course of this study, it became apparent that there were differences in shoot characteristics with respect to crown position. Preliminary measurements indicated that shoots from the lower and mid crown tended to have lower stem caliper, lower new--growth increments, and needles with higher length to width ratios (Browne, data not presented). The significance of these characteristics as a means of determining rooting potential (morphological markers) remains to be determined. Clearly; there appeared to be less vigor among lower crown shoots, particularly for the 10- and 30-year-old trees. This may, in part, account for differences in root number and length in comparison to upper crown cuttings.

This study successfully demonstrated that improvements in rooting of jack pine cuttings from 4- to 30-year-old plants can be realized through selection of mid to lower crown cuttings. The highest rooting frequencies obtained from these age classes exceeded those reported in other studies from jack pine of similar age (Haissig 1983, 1989; Zsuffa 1974). In light of these current findings, the feasibility of developing an operational rooted cutting program for jack pine appears more tenable. Populations of rooted cuttings from the various age classes were established in pots under greenhouse conditions and have now been out-planted for continued assessment in field trials.

Conclusions

The rooting of jack pine cuttings is affected by a variety of factors. Plant age and sampling location in relation to crown position appear to play an important role in the rooting process. Younger plants root more readily than older ones. Lower crown to mid crown cuttings typically root at a higher frequency than upper crown cuttings. However, this may be a tenuous conclusion, due to observed variations in rooting responses among age classes. It is apparent that rooting response of jack pine cuttings can likely be enhanced by judicious shoot selection, and that results reported here demonstrate a marked improvement over those of previous studies.

The relative success of this study may not solely be due specifically to crown location effects, but also to other aspects of rooting methodology (for example, rooting environment, date of sampling). Further investigations may delineate possible effects of other factors on the rooting of jack pine cuttings.

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"Jellyrolling" May Reduce Media Use and Transportation Costs of Polybag-Grown Seedlings

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Growing medium and transportation are major costs for polybag nursery systems. Both could be reduced if the medium could be removed for reuse, and the seedlings stored as bareroot seedlings before planting. The objective of this study was to evaluate the effect of the "jellyroll" system on root growth potential (RGP), water status, and survival of Pinus pseudostrobus *Lindl. and* P. ayacahuite *var.* veitchii *Shaw, conifers native to central Mexico. Seedling root systems, grown in polybags, were removed from the media, soaked in hydrophilic polymer, and planted in a greenhouse study and field trial. Seedling survival decreased linearly with storage. Storage temperature had little effect on survival or RGP, and RGP was not correlated with survival or seedling water status. Needle pressure potential was highly correlated with survival. Jellyrolling also reduced the survival of seedlings outplanted in Mexico. Implications for polybag nurseries are discussed.* Tree Planters' Notes 47(3):105-109; 1996.

Pinus pseudostrobus Lindl. and *P. ayacahuitc* var. *veitchii* Shaw are important timber species growing in the highlands of central Mexico between 1,600 and 3,200 m (~5,250 to 10,500 ft). Trees often reach heights of 30 to 40 m (~98 to 131 ft), with diameters exceeding 1 m (~3.3 ft) (Perry 1991). Although both are important timber species, little research has been conducted on the nursery production and outplanting performance of these and other pine species in Mexico (Patino V. and Marin C. 1993). This paper is one of a series of studies conducted to gain more information on nursery production to aid in reforestation efforts.

Nurseries in Mexico and many other countries grow seedlings for reforestation in polybag nurseries. Seedlings are grown in plastic bags filled usually with forest soil. This container system is heavy and often expensive. One nursery in Mexico City uses 35,000 m^3 (45,500 yd^3) of forest soil every year at a cost of over \$13 /m^3 (\$10/yd^3). Not only is the resource expensive, but also limited. Each harvest of forest soil for this nursery alone destroys about 1 ha (2.47 ac) of forest land. There are 137 federal nurseries and more than 1,800 forest nurseries in Mexico using this type of production system (Sanchez V. 1995). Developing alternatives would conserve a valuable resource and possibly reduce the production costs for nurseries.

One possible alternative is to reuse the container medium. This would entail removing the medium at time of harvest, treating the root systems to minimize desiccation and transporting the seedlings as bareroot seedlings. One technique of protection is the "jellyroll" system consisting of dipping the roots in a hydrophilic slurry and then wrapping the roots in burlap or toweling (Lopushinsky 1986). This technique has been used primarily for bareroot seedlings (Dahlgreen 1976), but it does show promise for container seedlings (Fidelibus and Bainbridge 1994).

In addition to the reduction of forest soil used, this technique would facilitate transport of seedlings to the planting site. Virtually all of the weight and much of the volume is associated with the medium. Eliminating the medium would greatly reduce transportation costs, and reduce storage requirements. In some cases, it may also increase the productivity of planters who must wait for seedlings to be transported to remote sites.

The objectives of this study are to examine the effect of jellyrolling on the survival and root growth potential of polybag-grown *Pinus pseudostrobus,* and evaluate the potential of using the jellyroll system in an operational trial in Mexico with *P. ayacahuite* var. *veitchii* seedlings.

Root growth potential (RGP) has been used as an indicator of seedling survival potential for many species (Ritchie and Dunlap 1980). However, much of the work has focused on the RGP of seedlings during dormancy. Little work has examined RGP during the growing season, or with species with little or no dormancy (Donald 1988). Typically, RGP is low in late summer, increases to a mid-winter peak, and drops again in spring as growth begins (Johnsen and others 1988). This may be a problem with warm temperate and tropical pines, as they lack a true temperature-induced dormancy (Johnsen and others 1988), which may affect the RGP. Furthermore, some regions, such as Mexico, have planting seasons coinciding with the late summer to early fall rainy season, when RGP of conifers is generally low.

Materials and Methods

Greenhouse trial. On February 21, 1995, *Pinus pseudostrobus* seeds were planted in double-thickness black polybags— 10 cm (~4 in) wide (15 cm (~ 6 in) deep–-containing 2 parts composted bark, 1 part scoria (lava rock), and 1 part sand. These bags have a surface area of about 32 cm^2 (5.0 in^2), and an effective growing density of about 300/m^2 (28/ft^2). Seedlings were grown under greenhouse conditions of 15 to 27 /C (59 to 81 /F), and "fertigated" daily with a 1:100 injector applying 100 mg N/L of irrigation water. In September, 120 seedlings were graded by height and diameter into 15 groups of 8 similarly sized seedlings, with 1 from each group dedicated to each treatment. The study was a 2 × 4 factorial with 2 storage temperatures (6 and 22 /C; that is, 42 and 72 /F) and 4 storage times (0, 1, 4, and 7 days) with 15 seedlings/ temperature × storage combination.

At 7 days before planting (September 5, 1995), the first treatment (7-day storage) was lifted. Shoot length and root collar diameter were measured on 30 seedlings. The roots were then rinsed carefully of growing medium, dipped in a TerraSorb® slurry (3.7 g/L water), and wrapped in a moist cotton cloth (figure 1). The cloth was rolled to accommodate the entire treatment group of 15 trees, and then dipped in the slurry once again. The cloth rolls were placed in plastic bags and 1 bag was stored at 6 /C and the other at 22 /C (room temperature). This was repeated for each of the subsequent storage periods (4 and 1 day). The 0-day treatment (control) was lifted, measured, dipped, and planted immediately.

All treatments were planted the same day in 3-L (2.7gal) pots filled with sand in a randomized block along a greenhouse bench. The greenhouse temperature during the 28 days was 23/C (73.4 /F) (figure 2). Predawn xylem pressure potential (R) of needle fascicles was measured at 1, 3, 7, 14, and 21 days after planting for each treatment to assess seedling water stress following transplanting. Plants were watered as needed for 28 days. At the end of the study, live plants were measured for shoot growth (length and root collar diameter) and the number of white root tips greater than 0.5 cm (0.2 in). The length of new white roots greater than 0.5 cm was measured on a subset of live seedlings.

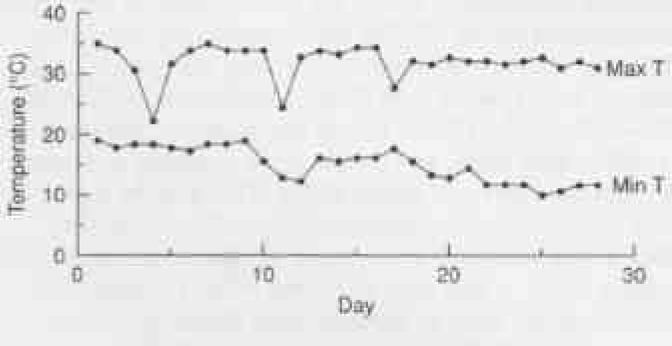

Figure 2—*Minimum and maximum temperatures in the greenhouse during the "outplanting" phase of the RGP test.*

Operational field trial. On July 25, 1995, seedlings of *Pinus ayacahuite* were outplanted on a reforestation site near Mexico City, Mexico. The seedlings were removed from the polybags and carefully shaken to remove the growing medium (forest soil). The roots were dipped in Terra-Sorb® slurry (2.7 g/L water), wrapped in cotton toweling and transported to the planting site by horseback (figure 3). Seedlings were planted the same day by 5 community tree planters.

Figure 1—*Wrapping roots of* Pinus pseudostrobus *seedlings in a moist cotton cloth.*

Figure 3—*Seedlings awaiting transport to a planting site in central Mexico.*

Each planter planted 5 jellyroll seedlings adjacent to 5 polybag seedlings for 5 replications. Initial seedling size and planting quality was determined. The seedlings were reevaluated on May 3, 1996.

Results

Greenhouse trial. *Pinus pseudostrobus* responded poorly to the combination of jellyrolling and short-term storage in late summer (table 1). Survival ranged from 97% for nonstored seedlings to 0% for seedlings stored 7 days at 22 /C (figure 4). The decline in survival was linear with no significant difference in slope for the 2 storage temperatures. The roots of seedlings given the 4-day/6 /C treatment appeared to be drier than those of seedlings given the other treatments at the end of the storage period. This may have contributed to the poorer survival of these seedlings compared to those given the 4-day/22 /C treatment.

Root growth potential as measured by number of new roots was highly correlated with total length of new roots (figure 5). Thus, this quick assessment of RGP was a reasonable assessment of overall root growth over the test period. RGP was highest for the control treatment, and tended to be higher for the 6 /C storage temperature for all storage durations (table 1).

However, only the control was different from the 22 /C storage temperature. Length of storage had no significant effect on RGP of surviving trees. If a seedling survived, the root growth was comparable among treatments. The only difference was survival varied among treatments. Neither storage length nor temperature had a significant effect on seedling growth over the 28 days. However, height growth ranking was control > 6 /C > 22 /C (table 1). Although there appeared to be a poor relationship between RGP and seedling response to the treatments, water stress as measured by xylem R (MPa) was more closely related to treatments. Storage temperature had no significant effect on seedling water stress over the test period. However, time in storage and time after planting affected seedling water status (figure 6). Seedling R tended to decline from day 1 to day 14, and increase from day 14 to day 21 as the seedlings recovered from transplant shock. The control treatment had the highest R throughout the study. Seedlings stored for 7 days had the lowest R. Beginning 1

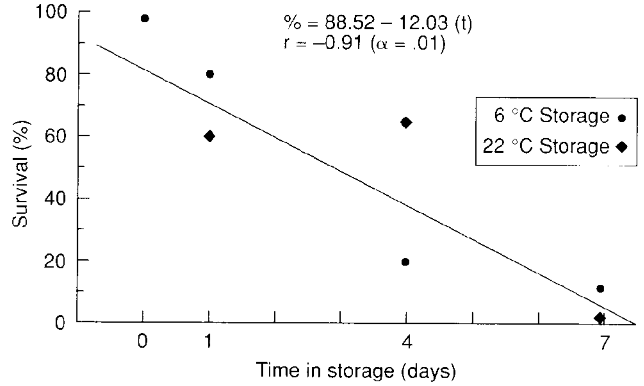

Figure 4— *Effect of time in storage at 6 and 22 °C (42 and 72 °F) on survival of* Pinus pseudostrobus.

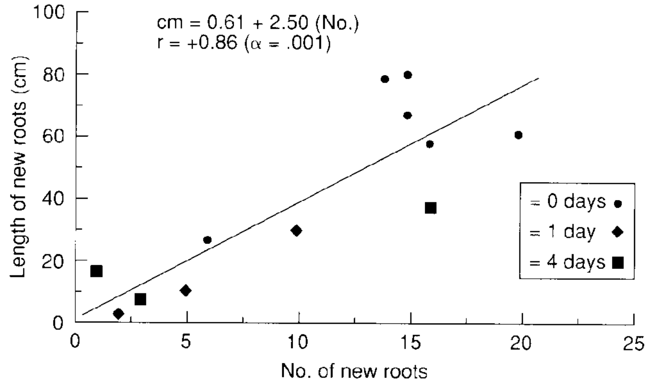

Figure 5— *Relationship between the number of new roots regenerating on* Pinus pseudostrobus *and the total length of those roots after 28 days.*

Table 1—*Survival, RGP, and growth of* Pinus pseudostrobus *seedlings after storage at 6 and 22 °C for different time periods*

Days	Temp (°C)	Survival (%)	RGP (no.)	Initial height (cm)	Height growth (cm)	Initial diameter (mm)	Diameter growth (mm)
0	—	97	9.7 (1.0)	16.7 (0.7)	7.4 (2.0)	3.8 (0.1)	0.48 (0.7)
1	6	80	7.3 (1.6)	18.5 (1.2)	5.8 (2.8)	3.8 (0.2)	0.63 (0.11)
1	22	60	3.6 (1.8)	17.7 (1.0)	3.9 (3.7)	3.6 (0.2)	0.55 (0.13)
4	6	20	6.0 (2.6)	17.8 (1.1)	5.0 (2.9)	3.8 (0.2)	0.66 (0.13)
4	22	67	2.9 (1.6)	18.5 (1.1)	3.0 (2.1)	3.6 (0.2)	0.54 (0.12)
7	6	7	7.0 (—)	17.9 (1.1)	5.0 (—)	4.0 (0.2)	0.52 (—)
7	22	0	0	18.0 (1.0)	0	3.7 (0.2)	0

Values in parentheses are standard errors of the mean.

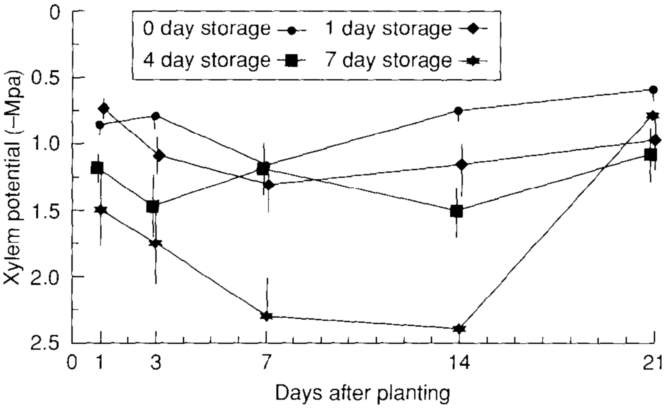

Figure 6—*Relationship between time after planting on seedling pressure potential (MPa) after different lengths of storage.*

day after planting, seedlings had a R of 21.5 MPa that declined to 22.4 MPa on day 14. The lone surviving seedling from this treatment had a pressure potential of 20.8 MPa on day 21.

Seedling R appeared to be a good predictor of the survival potential of the seedling. Equations relating seedling R for each day to seedling survival on day 28 ($\%_{28}$) were

$\%_{28} = 159 + 96\ (\text{MPa1})$ $r = 0.82\ (p = 0.05)$

$\%_{28} = 138 + 68\ (\text{MPa3})$ $r = 0.99\ (p = 0.01)$

$\%_{28} = 159 + 75\ (\text{MPa7})$ $r = 0.82\ (p = 0.05)$

$\%_{28} = 250 + 100\ (\text{MPa14})$ $r = 1.00\ (p = 0.01)$.

These equations were used to construct isolines of survival versus seedling R (figure 7). Populations that had 100% survival had high R values throughout the study. One day after planting, these seedlings had R values greater than -0.75 MPa. By day-14, the predawn R of populations with 100% survival was -1.5 MPa. Populations that had 75% survival had R values averaging 0.25 MPa less than those of the population that had complete survival throughout the study. Populations with 50% survival averaged 0.55 MPa less than the population with 100% survival. Seedling populations which ultimately had 100% mortality had R less than -1.5 MPa on day 1, declined to -2.5 MPa on day 14, and recovered to less than -1.7 MPa by day 21.

Operational field trial. Performance of the jellyroll system was not as high as the performance of the polybag system with *P. ayacahuite* (table 2). Survival of the jellyroll seedlings was 68% compared to 96% for the seedlings transported as polybag seedlings. Growth was not significantly affected, although the jellyroll seedlings had less than 50% of the height growth of the polybag seedlings.

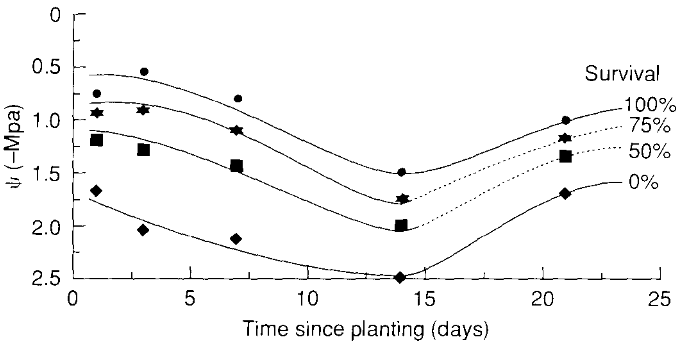

Figure 7—*Isolines of survival as a function of seedling pressure potential and time after planting for* Pinus pseudostrobus.

Table 2—*Survival and growth of* Pinus ayacahuite *var.* veitchii *seedlings using conventional polybags and the jellyroll system*

Stocktype	Survival (%)	Initial (cm + SE)	Height (cm + SE)	Initial (mm + SE)	Diameter (mm + SE)
Polybag	96	51.4±1.3	7.8±1.4	11.10±0.56	2.02±0.23
Jellyroll	68*	45.3±2.3	1.9±2.6	9.26*±0.76	1.84±0.42

* Significantly different at the 5% level according to a paired t test using the arc sin transformation of survival.

Discussion

Long-term storage of 30 to 90 days of dormant seedlings often has little effect on survival (Jiang and others 1994; McKay 1993). However, short-term storage of actively growing seedlings has not be examined, especially for a species from a subtropical latitude. Short term storage of *Pinus pseudostrobus* had the drastic effect on survival. Survival decreased linearly with increasing storage up to 7 days. Mortality was likely caused by the storage rather than by the medium removal and treating with hydrophilic polymer. Although problems with hydrophilic polymers have been reported (South and Lowenstein 1994), the high survival of the control treatment points to storage as the cause of poor survival. However, RGP was not correlated with survival. This finding is not unusual. Others have reported no or poor relationships between survival and RGP (Binder and others 1988; Feret and Kreh 1985). RGP was lower than reported for other species, which is probably a function of the sampling during the summer "monsoon" season, when RGP is inherently low for many species (Ritchie and Tanaka 1990). Donald (1988) found a similar response for *Pinus radiate,* a warm-temperate conifer. The fluctuation in RGP was not great, but RGP was low in the fall and summer and higher in the winter and early spring. Conifers from Mexico might behave similarly.

Seedling R was the best predictor of seedling survival potential. McCreary and Duryea (1987) also found Rto be a good predictor of survival of Douglas-fir— *Pseudotsuga menziesii* Mirb. (Franco). Seedling R measured 8 days after outplanting provided the best estimate of survival. In this work, a model was developed to estimate survival from R values measured during the first 14 days after outplanting. Tabbush (1986) found that rough handling could reduce predawn xylem pressure potential for at least 27 days after planting. In his study; rough handling reduced survival, RGP, mycorrhizal formation, and budbreak.

An inability to maintain seedling water balance may be caused by a loss of membrane integrity in the fine roots of recently planted conifers. McKay (1993) found long-term storage of conifers resulted in deterioration of fine roots as measured by electrolyte leakage. This loss of integrity would result in not only leakage of nutrients but also in an ability to absorb water to maintain water balance. This would lead to decreasing R and subsequent death if integrity was not restored. Early lifting during the dormant season resulted in the greatest damage. It might be expected that lifting in the latesummer, when seedlings are actively growing, would accelerate the progression of damage. This could explain the rapid decline in R and survival in this study.

It may be possible to develop a "jellyrolling" system for polybag nurseries in warm climates. The outcomes of the operational trial were marginally successful. In this particular trial, considerable delays in planting were caused by the lack of planting material. The horse could carry about 200 polybag seedlings/trip, which required about 1 hour. However, the planting crew could plant these seedlings in about 30 min. Thus, productivity was about half of what it could be. With the jellyroll system, the horse could carry over 1,000 seedlings. Jellyrolling the seedlings could result in significant improvements in productivity in remote sites if techniques can be developed to improve the performance of jellyroll seedlings.

Conditioning practices, such as undercutting of bareroot seedlings, improve the tolerance of fine roots to storage (McKay 1993). Conditioning practices for polybag nurseries, such as mild water stress or nutrient stress, may alter the sensitivity of Mexican conifers to removal of the medium and storage. The system would have to provide acceptable survival after 4 to 5 days storage before it could be recommended for operational use.

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Windbreak Benefit to Potato Yield in Tropical North Australia

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A study was conducted on the Atherton Tablelands of tropical north Australia to quantify the benefit of a 18-month-old windbreak to the production of potato (Solanum tuberosum *L.). In the leeward side, wind velocity and potato yield were measured at various distances from the windbreak. Wind direction on the study site was also monitored. Non-linear modeling was used to describe the relationship between potato yield and distance from the windbreak. The definite integral was applied to the developed model to calculate the net increase percentage of potato yield. Wind velocity was greatly reduced by the windbreak, and potato yield was increased by 6%. It appears that fitting non-linear models is a useful method to determine an accurate net increase of crops from windbreaks.* Tree Planters' Notes 47(3):110-115; 1996.

As wind can cause losses to crop yields (Bates 1917; Caborn 1957; Frank and others 1974; Grace 1988), windbreaks have been considered as an important component in agriculture management systems (Marshall 1967; Sturrock 1988). Kort (1988) noted that windbreaks increase crop yield and the degree of this positive effect varies with climatic condition, soil type, crop variety, and the management practices. Because of the variety of these variables, studies on windbreak benefits to specific crops grown under different conditions are necessary (Sturrock 1988).

Potato growing is a major agricultural activity on the Atherton Tablelands of north-eastern Australia, where frequently strong winds can reduce the yield of this high--value crop (Sun and Dickinson 1994). Accurate information on the windbreak benefits to this crop is urgently needed to provide guide-lines for windbreak design, establishment, and management. Many studies have shown that crop yield was increased by windbreaks (Puri and others 1992; Stoeckeler 1962; Sturrock 1981). Kort (1988) reported an approximate 3.5% net increase in spring wheat yield. Sturrock (1981) reported an average increase of 35% in wheat yield. Puri and others (1992) found an up-to-10% increase in cotton yield. In these studies, crop yields were generally measured at various positions away from the windbreak. As these data are non-linear, the accuracy of the net gain of windbreaks on crops calculated from them are questionable. In order to quantify net gain from windbreaks in relation to crop yield, there is a need to develop a more accurate method.

Sun and Dickinson (1994) studied the effects of mature windbreaks on potato yield. However, it appears that young windbreaks have different patterns in affecting wind velocity and crop growth from mature windbreaks, suggesting that the age of windbreaks is important. This paper reports a study carried out from June to October 1993 to quantify the benefit of a young windbreak to the production of potato *(Solanum* tuberosum L.) on tropical farm land of northeastern Australia.

Methods

The study site was on a paddock, 5 km (3.1 m) from Atherton, in northeastern Australia— lat. 17/10' S, long. 145/28' E, alt. 710 m (2,329 ft). The site is flat, with a red euchrozem soil. The paddock has been used to grow crops of maize, peanuts, and potatoes in rotation for at least 60 years. The prevailing winds in this area are southeasterly. The average daily maximum temperature is about 32 /C (90 /F) for the hottest months (December and January) and the mean daily minimum temperature for the coolest month (July) is about 10 /C (50 /F).

The site is sheltered by three 18-month-old windbreaks that were planted in the direction as shown in figure 1. The windbreaks were 4.5 m (14.8 ft) tall. As the study was carried out in the dry season, the windbreak grew little during the period of the study. Seven native species with different heights when mature were used to form the windbreaks:

- 1 tall species— *Eucalyptus microcorys* F. Muell. (up to 40 m tall)
- 2 medium species— *E. tessellaris* F. Muell. and *E. torelliana F.* Muell. (up to 30 m tall)
- 4 short species— *Callistemon salignus* (Smith) DC., *C. viminallis* Smith, *Melaleuca armillaris* Smith, and M. linariifoli Smith (up to 6 m tall)

The southern boundary windbreak (figure 1) was used for the study. It was made up of 4 rows: 1 row of short trees on the windward side, 1 row of medium trees in the middle, and 2 rows of tall trees on the

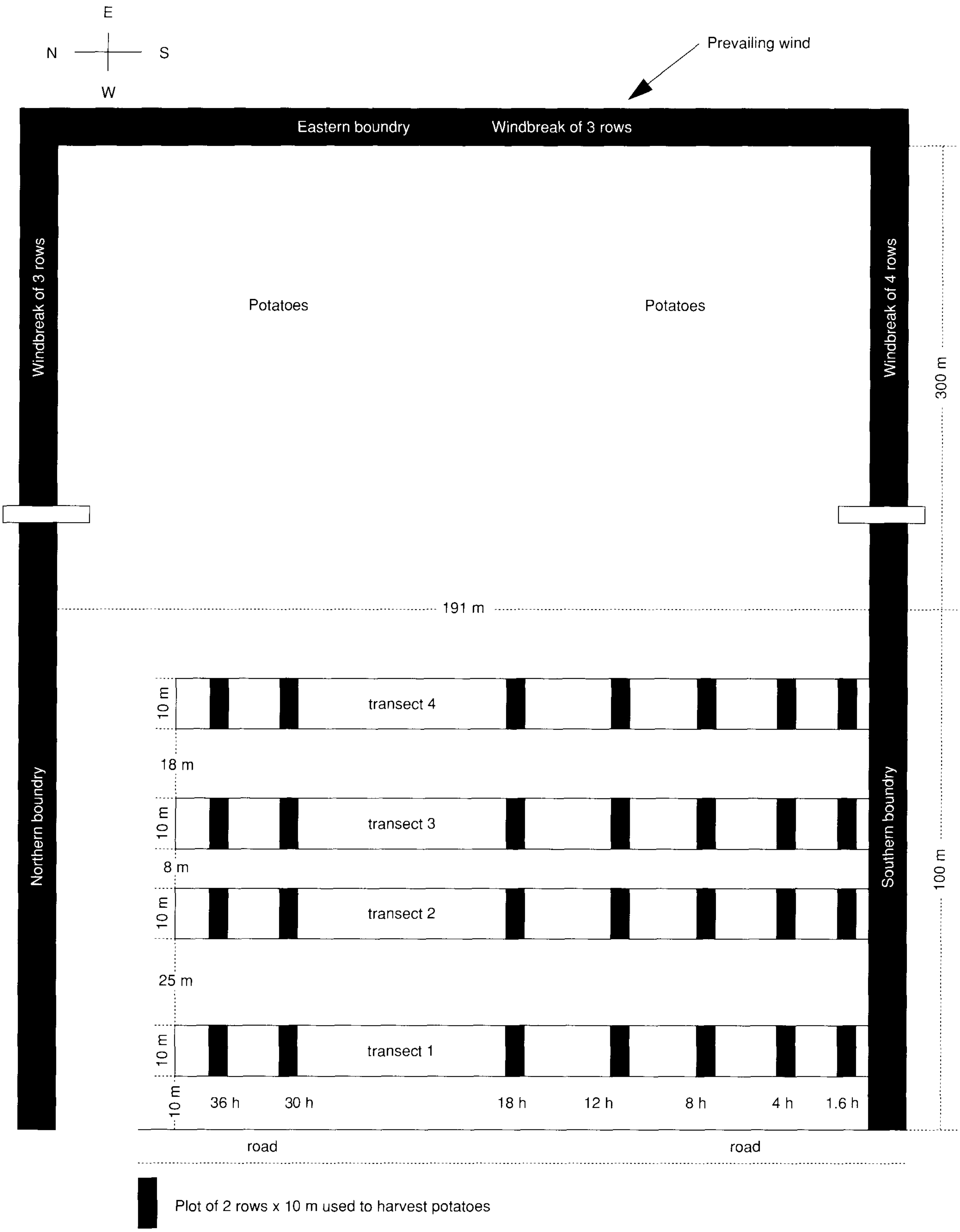

Figure 1— *The layout of windbreaks and the transects for potato sampling adopted on the study site.*

leeward side. The short-tree row and the middle row were 2 m (6.6 ft) apart, and the middle row and the tall-tree rows were 4 m (13.1 ft) apart. The intra-row spacing of trees was 2 m on the short-tree row and 4 m on both the middle and tall-tree rows. The 2 medium species were planted in a sequence of 20 trees/species whereas the 4 short species were planted in a sequence of 5 trees/species.

Windbreak porosity and wind measurements. Windbreak porosity was measured using the SCISCAN software developed by the Commonwealth Scientific and Industrial Research Organization (CSIRO) of Australia. The software was based on the principles of image digitization (Yanuka and Elrick 1985). A photograph of the windbreak was taken and was then scanned into a PC computer using a HS3000 scanner. As the windbreaks were orientated 45/ to the prevailing wind, the photograph was taken at an angle of 45/ towards the prevailing wind direction. The porosity was then calculated using the SCISCAN. The porosity of the windbreak was 51 %. There were some small gaps in the top section of the windbreaks.

During the period of potato plant growth, wind velocity was measured at 7 positions along a transect perpendicular to the south boundary windbreak. In order to avoid potential small animal damage to the wind velocity sensors, wind velocity was measured at a height of 2 m (6.6 ft) above the ground, although a height of 0.5 m (20 in) above the ground would be more appropriate as mature potato plants were only slightly shorter than 0.5 m. A GBL-8+8-128 data logger was used to collect these measurements at 30-minute intervals throughout the experiment. The 7 positions were at 4.5, 13.5, 27.0, 54.0, 81.0, 108.0, and 144.0 m (14.8, 44.3, 88.6, 177.2, 265.7, 354.3, and 472.4 ft) from the south boundary windbreak, which were 1, 3, 6, 12, 18, 24, and 32 times the windbreak's height (*h*), respectively. Wind direction was measured at 18 *h* every 30 minutes. It would be desirable to monitor wind velocity on the windward side while measuring wind velocity at those 7 positions mentioned above. This was, however, not practical as only 7 channels in the logger were available to measure wind velocity and the cable lengths between the 7 wind-velocity sensors were limited. Because 32 *h* was far enough from the windbreak, this position was most likely to be fully exposed to the wind. For all the southeasterly winds, the wind velocity measured at this position was used as a control in the present study.

Potato yield measurements. Potato seeds of the certified variety called 'Atlantic' were planted on a 100 × 191 m (328.1 × 626.6 ft) section on the leeward side of the southern boundary windbreak (figure 1) on June 25, 1992. "Q5", a commercially available fertilizer (5% N, 6.8% P, 4% K), was applied at planting at a rate of 2.2 t/ha (0.9 t/ac). Urea (46% N) was applied 2 weeks after planting through irrigation at a rate of 0.25t/ha (0.1 t/ac). Four transects (replicates) with 10 m in width by 162 m (32.8 × 531.5 ft) in length, were set up perpendicular to the windbreak. To avoid the effect from the eastern boundary windbreak, the 4 transects were randomly set within the potato section >300 m (328.1 ft) from the eastern boundary windbreak (figure 1). Along each transect, 7 plots of 2 rows, 1 m (3.28 ft) in width and 10 m (32.8 ft) in length were placed at 1.6, 4, 8, 12, 18, 30, and 36 *h* from the southern boundary windbreak. Potatoes were harvested from each plot and yield measured (t/ha) on 8 October 1993. The harvested potatoes were graded into 2 groups according to their sizes:

grade A— diameter >8 cm (3.2 in)
grade B— diameter<8 cm (3.2 in)

Grade B has a lower commercial value than grade A. Potatoes grown at <1.6 *h* were not harvested because the landholder had grown section different varieties of potatoes between the windbreak and 1.6 *h*.

Data analyses. The difference in potato yield between the 7 distances from the windbreak was tested using analysis of variance. The differences between any 2 distances were further tested using LSD (least significant difference). Non-linear modeling using GENSTAT (Genstat 5 Committee 1988) was used to describe the relationship between potato yield and distance from the windbreak. The curve of best fit, based on the value of correlation coefficient, was selected from fitted linear, power and exponential functions.

Results

Wind parameters. Throughout the period of the experiment, 75% of the wind measured came from the southeast whereas 3.5% (the smallest proportion) came from the north and northeast (table 1). Overall, for the south easterly winds, the velocity increased with the increase in distance from the windbreak (table 2). The relative wind velocity shown in figure 2 indicates that wind velocity at 1, 3, and 6 *h* was 77, 68, and 24% less than that in the open area. Wind velocity became constant after 18 *h*.

Table 1—*Percentage of wind direction throughout the period of the experiment (wind direction was divided into 5 categories according to their potential effect on the potato section studied)*

N–NE 0–80°	NE–SE 81–110°	SE–S 111–180°	SW–W–SW 181–270°	SW–W–NW 271–359°
3.5%	6.6%	74.5%	7.3%	8.1%

Table 2—*Mean wind velocity with standard errors at various distances from shelterbelts (in multiples of height of shelterbelt* h)

Mean wind velocity (km/hr)						
1 × *h*	3 × *h*	6 × *h*	12 × *h*	18 × *h*	24 × *h*	32 × *h*
2.68±0.07	3.73±0.11	8.79±0.13	10.74±0.13	11.55±0.19	11.57±0.14	11.58±0.13

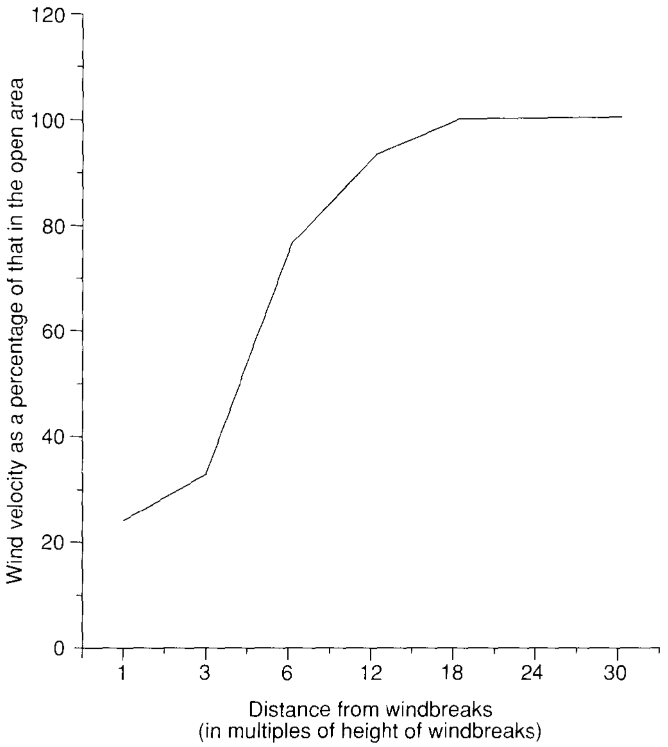

Figure 2— *Wind velocity expressed as a percentage of that in the open areas versus distance along the perpendicular line from the windbreak in the leeward side.*

Potato yield. With the increase in distance from the windbreak, the yield of grade B potatoes changed little (table 3). Potato production for total and grade A changed significantly with the distance from windbreak (table 3). They increased in the areas between 1.6 and 8 *h* and decreased in the areas between 8 and 18 *h* (table 3). Both grade A and total potato yield became relatively constant after 18 *h*. The mean yield at each of 18, 30, and 36 *h* was considered as the average of the open areas (unsheltered areas) which was 15.976 t/ha for total and 17.349 t/ha for grade A. Based on the further LSD test results (table 3), the 7 distances can be divided into 2 groups. The distances of 1.6, 4, and 8 *h* form the first group, while the others form the second group. Potato yield for both the grade A and total in the first group was significantly greater than that in the second group.

Table 3—*Potato yield with standard errors measured at various distances from shelterbelts with ANOVA results (df=21), LSD is calculated at* P=0.05

Distance from shelterbelts (*h*)	Potato yield (ton/ha) Grade A	Grade B	Total
1.6	18.793 (±0.370)	1.185 (±0.037)	19.978 (±0.354)
4	19.188 (±0.289)	1.365 (±0.015)	20.553 (±0.285)
8	19.370 (±0.293)	1.255 (±0.045)	20.625 (±0.296)
12	16.518 (±0.427)	1.308 (±0.075)	17.825 (±0.454)
18	15.838 (±0.405)	1.350 (±0.117)	17.188 (±0.514)
30	16.140 (±0.412)	1.345 (±0.128)	17.485 (±0.482)
36	15.950 (±0.380)	1.423 (±0.048)	17.373 (±0.424)
ANOVA			
F-value	21.74**	1.12	16.44**
LSD	1.014		1.134

A critical exponential model was developed to describe the relationship between the potato yield and the distance from the windbreak (represented by d in the model).

$$\text{Yield}_{\text{grade A}} = 15.831 + (-0.1 + 2.79 \times d) \times 0.7658^{d}$$
$(R^2=0.785)$

$$\text{Yield}_{\text{total}} = 17.191 + (-0.68 + 3.04 \times d) \times 0.7575^{d}$$
$(R^2=0.789)$

Figure 3 shows the fitted curves of both the total and grade A potato yield using the models given above. The total and grade A yield in the section of 1.6 to 18 *h* was above the average and was an increase (figure 3). Based on the models, the net increase % in potato yield resulting from the windbreak was calculated as below.

$$\text{Increase}_{\text{grade A}} = \int_{1.6}^{18} (f(d)_{\text{grade A}} - 15.976)\, dd$$

$$\text{Increase}_{\text{total}} = \int_{1.6}^{18} (f(d)_{\text{total}} - 17.349)\, dd$$

$$f(d)_{\text{grade A}} = \text{Yield}_{\text{grade A}};\quad f(d)_{\text{total}} = \text{Yield}_{\text{total}}$$

$$\text{Net increase}_{\text{grade A}} = \text{increase}/(18\text{-}1.6) = 0.9602\ (\text{t /ha})$$

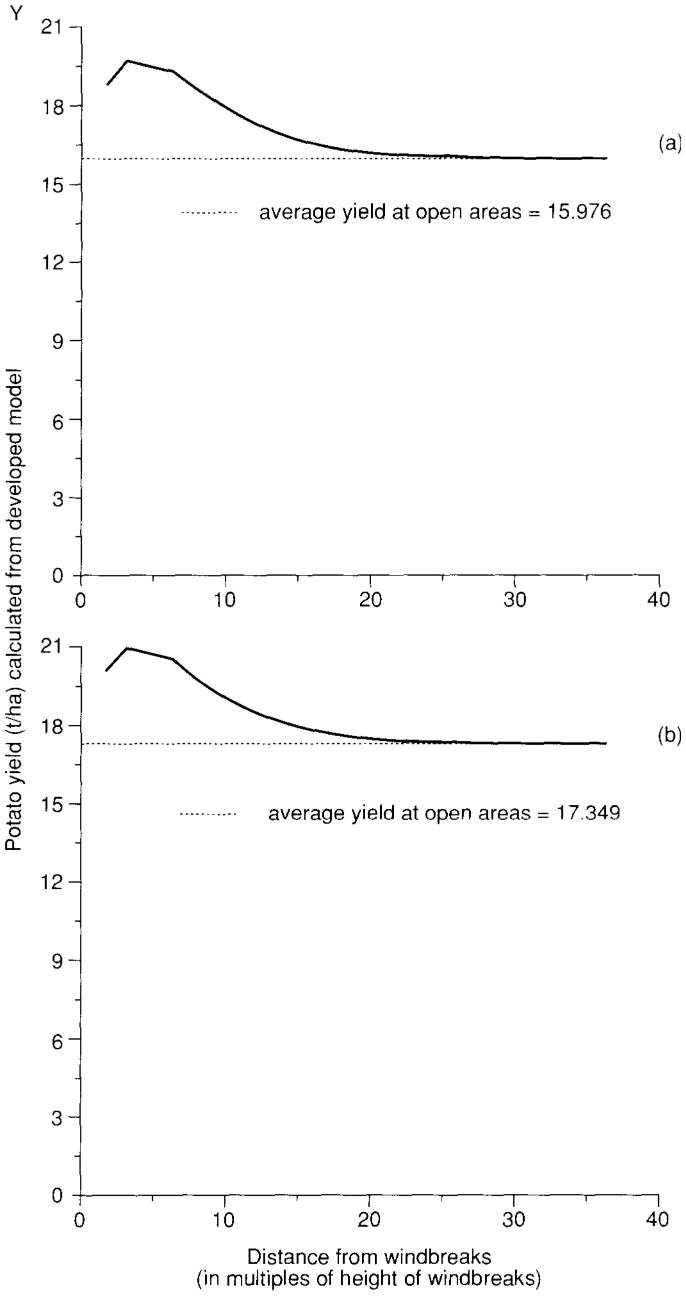

Figure 3— *The fitted potato yield versus distance from the windbreak calculated using the developed critical exponential model; a = the grade A yield and b = the total yield.*

$$\text{Net Increase}_{\text{total}} = \text{Increase}/(18\text{-}1.6) = 0.8527 \text{ (t /ha)}$$

Net increase % of the average grade A yield in open

$$\text{area} = \frac{\text{Net increase}_{\text{grade A}}}{15.976} \times 100\% = 6.0\%$$

Net increase % of the average total yield in open

$$\text{area} = \frac{\text{Net increase}_{\text{total}}}{17.349} \times 100\% = 4.9\%$$

The net increase% of the average grade A yield is greater than that of the average total yield.

Discussion

It appears that the 18-month-old windbreak studied can effectively reduce wind velocity to 12 *h* in the lee of the windbreak. This effect is likely to be improved when the windbreak becomes older and more branches and leaves are developed. Some mature windbreaks were found to reduce wind velocity to 30 *h* in the leesides (Marshall 1967). The windbreak studied is also likely to be more effective if it was oriented on a NE/SW direction as the optimal windbreak orientation is 90% to prevailing winds (Sturrock 1988).

Because only a small proportion of winds came from the NW-NE, the northern boundary windbreak would have little effect on the sampled potato yield. This was evidenced by the fact that the potato yield was similar at 18, 30, and 36 *h* from the southern boundary windbreak, which were 24.4, 12.4, and 6.7 *h* from the northern boundary windbreak, respectively.

The windbreak studied had a positive effect on potato yield. It appears that the benefits of windbreaks may be greater to potato size than to overall quantity. Overall, the positive effect was much smaller than that found by Sun and Dickinson (1994), Sturrock (1981), and Puri and others (1992). Although this may be because crops vary in their response to windbreaks (Kort 1988), the main reason may be because the windbreak in the present study was young.

Lyles and others (1984) reported a reduction of winter wheat production to a distance of 2 *h* from windbreaks due to shading effects and competition between trees and crops. The fact that the potato yield at 1.6 *h* was greater than that in the open areas suggests that the windbreak studied did not cause a loss at least from 1.6 *h*. However, as the wind velocity increase dramatically between 1 *h* and 12 *h* but the yield at 1.6 *h* was less than that measured at 4 and 8 *h*, there may be a competition and shading effect from the windbreak on the potato plants at 1.6 *h*. This competition effect was likely to be smaller than the positive effect from windbreak and therefore did not cause a loss.

It appears that when soil conditions and management practices throughout a growing season are relatively uniform, fitting non-linear models and applying the definite integral of the models is a useful method in determining a net increase of crops from windbreaks. However, the usefulness of this method depends greatly on whether an accurate assessment of the average crop yield on the open areas is achieved. In the present study, the yield became relatively constant after 18 *h*. The evaluated average yield in the open areas was, therefore, reasonably accurate.

It appears that young windbreaks do have different patterns in affecting wind velocity and crop growth from mature windbreaks. Studies are needed to determine the age at which a windbreak starts to have a full effectiveness. This information is important when planting windbreaks is considered as a necessary component in a farm management system.

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