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ROOT GROWTH POTENTIAL: PRINCIPLES, PROCEDURES AND PREDICTIVE ABILITY

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ABSTRACT--Root growth potential (RGP) is the ability of a tree seedling to initiate and elongate roots when placed into an environment favorable for root growth. The magnitude of RGP is often correlated with survival, and even growth, of the seedling following outplanting. RGP develops in seedlings during their tenure in the nursery or greenhouse. The most critical factors over which the grower can exercise control are date of lifting and duration of cold storage. Following planting, the expression of RGP, or actual root growth, is affected by soil temperature, soil moisture, and other factors.

RGP is measured by (1) placing seedlings into an environment, such as a warm greenhouse, which is favorable for root growth, (2) holding them for a standard period of time, then (3) removing them and assessing the amount of root growth which occurred. This procedure can be shortened by increasing temperature and by using subjective indices to quantify root growth.

Of the various tests devised to assess stock quality, RGP is perhaps the most reliable predictor of field performance. This is particularly true with species which exhibit a long period of winter dormancy and have a pronounced chilling requirement to release dormancy -- this includes probably all northwest conifers and many northeastern hardwood species.

8.1 INTRODUCTION

One of the most widely used, and perhaps most important (Day 1982), tests of seedling quality is the root growth potential (RGP) test developed by Stone and his colleagues at Berkeley in the 1950s (Stone 1955, Stone and Schubert 1959a, 1959b, Stone and Jenkinson 1970). The test can be conducted using

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simple, inexpensive materials and generally gives results which are repeatable and easily interpreted.

In this report we will define RGP simply as the ability of a seedling to initiate and/or elongate roots when held in an environment which is conducive to root growth. Surprisingly, seedlings do not always grow new roots in such an environment. A seedling which does is said to have high RGP and can be expected to be of high vigor and performance (survival and growth) potential.

High RGP is an important seedling quality attribute presumably because it enables the seedling to become established rapidly after planting. The rationale for this is that when a seedling is planted it has a finite root system. Although it is capable of exploiting moisture and nutrients in its immediate vicinity, these reserves are soon depleted. So for establishment to occur new soil reserves must be tapped, hence new roots must be grown. Seedlings which are unable to grow roots rapidly are doomed to water stress and, ultimately, death.

In this paper I will (1) briefly review some of the factors which affect the development and expression of RGP (this subject was extensively reviewed by Ritchie and Dunlap (1980)), (2) outline the standard procedure for conducting an RGP test and suggest some alternatives to this procedure and (3) examine the relationship between measured values of RGP and actual field performance.

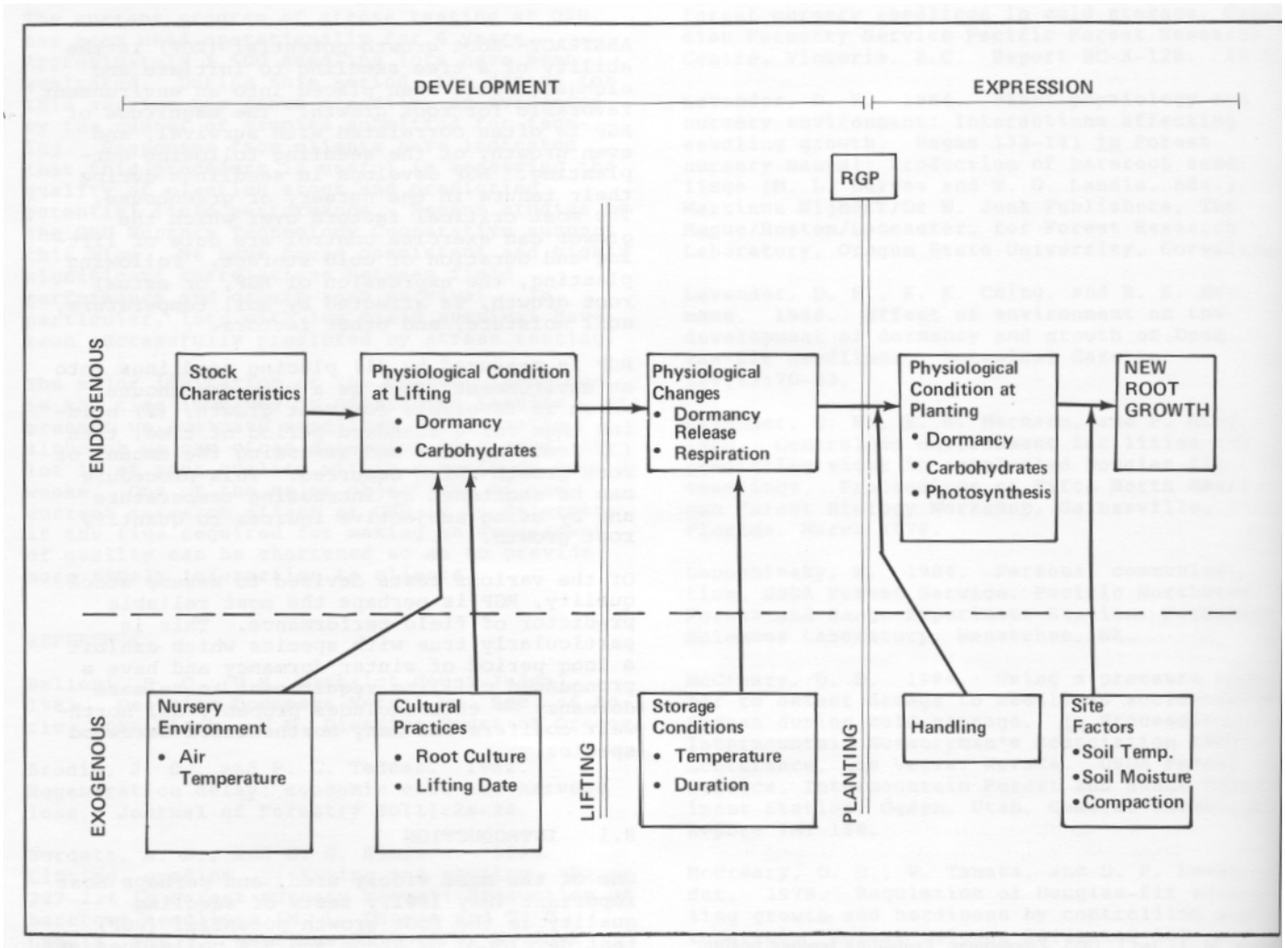

Figure 1 -- Diagram illustrating the processes of RGP development and expression and the factors which influence them. Reproduced with permission from the New Zealand Journal of Forestry Science Volume 10, page 241 (1980).

8.2 FACTORS INFLUENCING DEVELOPMENT AND EXPRESSION OF RGP

A seedling develops RGP while it is growing in the nursery or greenhouse but RGP is not expressed until the seedling is planted. The internal (endogenous) and external (exogenous) factors which influence these processes are outlined in Figure 1.

8.2.1 Development of RGP

Planting stock characteristics such as species, seed lot, family and stock type play a key role in the intensity of RGP that the stock develops. Lodgepole pine (Pinus contorta Dougl.), for example, can developer greater RGP than can Englemann spruce (Picea engelmanii Parry) grown under the same nursery conditions (Ritchie et al., in prep). Ponderosa pine seedlings from seed zone 721 (near Klamath Falls) have consistently poor RGP from year to year and tend to show high mortality as well. Coastal Douglas-fir (Pseudotsuga menziesii (Mirb) Franco) seedlings from seed zone 070-15 (near Coos Bay) have generally high RGP, while those from 030-05 (near Gray's Harbor) have poor RGP. Sutton (1983) reported large differences in RGP among several lots of jack pine (Pinus banksiana Lamb.) and black spruce (Picea mariana (Mill.) .S.P.) seedlings. Even heritable between family differences have been reported in Pinus radiata D. Don. (Nambiar et al. 1982). Far more examples could be cited.

Other key factors influencing RGP are the physiological condition (esp. status of winter dormancy) of the seedling at the time it is lifted (Webb 1977, Farmer 1975) and possibly the size of the carbohydrate pool available for root growth. The former is a factor over which the grower can exercise considerable control. Growers can also control the length of time during which stock is held in cold storage. This interacts with lifting date to impact RGP at planting time. In general, seedlings lifted in mid-winter tend to have higher RGP than fall- or spring-lifted seedlings (see Ritchie and Dunlap 1980, Table 2) and also have higher RGP following storage. Storage temperature is also important since temperatures above 0°C permit the proliferation of storage mold which tends to weaken seedling vigor and RGP.

The condition of the seedling shoot and foliage is also important for RGP. Since leaves of many tree species export an essential rooting co-factor (Haissig 1983), removal of, or damage to, the foliage can impede root growth. So a seedling which has suffered defoliation by insects, frost or other agents in the nursery would be expected to have low RGP (Colombo and Glerum 1984).

8.2.2 Expression of RGP

Recalling that RGP represents only a potential to grow roots, it follows that this potential may or may not be fully expressed when the seedling is outplanted. If it is planted into an environment optimal for root growth it will, by definition, fully express its RGP. If not, it will not. Since planting site conditions in winter and early spring are rarely optimum for root growth, it is probably rare for RGP to be fully expressed after outplanting.

Perhaps the most important limiting factor to RGP expression is soil temperature. The optimum for seedling root growth for many species is near 20 degrees (e.g. Stupendick and Shepherd 1979, Stone and Schubert 1959a, 1959b). Figure 2 shows the impact of soil temperature on RGP of Douglas-fir seedlings across a range of dormancy intensities. [a/] Clearly, unless the soil during the planting season is near 20°, RGP will not be fully expressed.

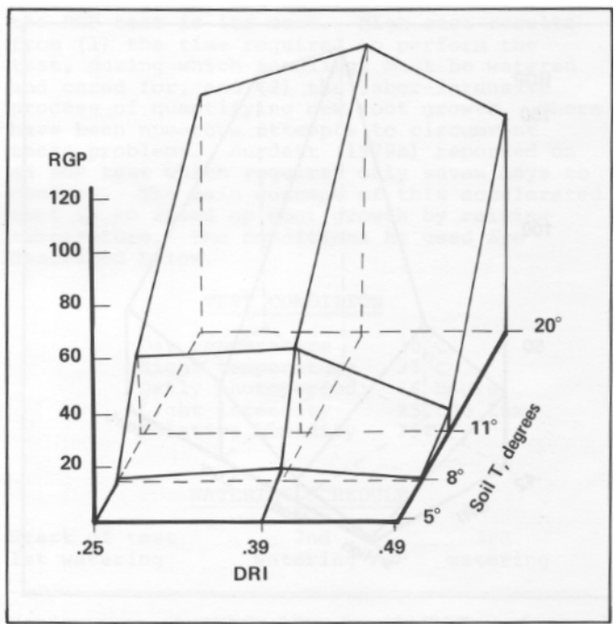

Figure 2 -- Effect of soil temperature on root growth potential (RGP) of Douglas-fir seedlings. Tests were conducted at three levels of bud dormancy intensity (DRI; see text, footnote a). Each value represents a mean number of new roots of 60 seedlings.

Soil moisture is another key factor. Tree seedlings are very sensitive to soil moisture stress. This is exhibited as a reduction in root growth when stress is imposed after

a/ Dormancy intensity is expressed with a dormancy release index (DRI). When DRI 0, winter dormancy is at its peak; when DRI = 1 dormancy is fully released and buds will break within 10 days of exposure to warm temperatures (see Ritchie 1984).

planting. In one experiment (Figure 3) Douglas-fir seedlings were potted in forest soil and held under four different watering regimes for 30 days. Controls were maintained at near field capacity. Soil in the low, moderate and high stress regimes was permitted to dry down to -1, -2 and -6 bars by the end of the period. These data show that soil moisture stresses approaching -2 bars depressed RGP to about 1/3 of the control value. Similar data are available for other species (Larson and Whitmore 1970, Stone and Jenkinson 1970, Abod et al. 1979, Nambiar et al. 1982, Stupendick and Shepherd 1979).

Other factors which probably depress RGP expression are soil compaction, poor planting and other agents, which are reviewed in Ritchie and Dunlap (1980).

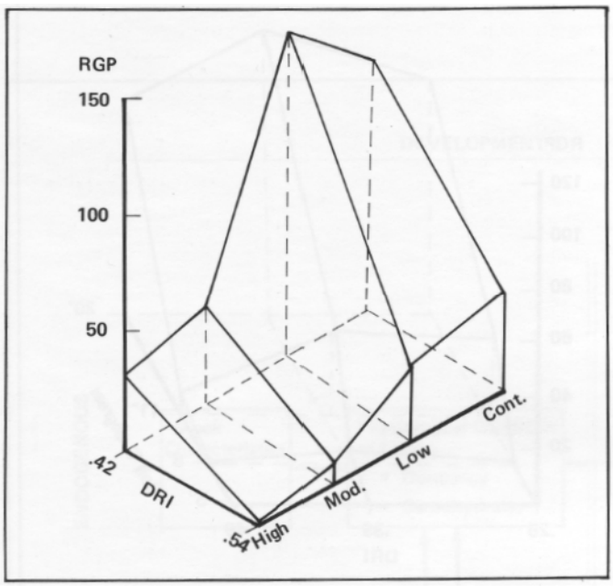

Figure 3 -- Effects of soil moisture stress on root growth potential (RGP) of Douglas-fir seedlings. Tests were conducted at two levels of bud dormancy intensity (DRI; see text, footnote a). Each value represents a mean number of new roots of 20 seedlings.

8.3 PROCEDURES FOR MEASURING RGP

The basic procedure for estimating RGP is as described by Stone and his co-workers and has not changed markedly over the past 25 years. It involves placing seedlings in a greenhouse or growth chamber which is programmed at conditions near optimum for root growth for the species in question. Following some standard time period (normally 4 weeks) seedlings are washed out of the medium and the new root growth which occurred during this period is quantified in some manner. Below, I will outline this procedure in detail. Then I will suggest some alternative procedures which have been devised to shorten the test period or otherwise reduce the cost of the test.

8.3.1 Basic root growth test

The first step in testing RGP is to decide upon an appropriate sample size. This will depend on the nature of the seedling population in question and the reasons for making the measurements. Material propagated from wild seed will be highly variable and require fairly large samples. This is in contrast to half- or full-sib orchard material. If you are concerned only with a quick-and-dirty evaluation of a batch of stock, 15 to 20 seedlings randomly selected (from different packing bags) may be sufficient. On the other hand, if your aim is to detect small differences in RGP among seed lots, certain nursery treatments, etc., then larger samples are required. Experience is the best guide. We have sampled up to 60 seedlings per treatment in some experiments. Also, since seedling size can affect RGP, it may be desirable either to (1) select seedlings of relatively uniform size for the test (which will bias the results) or (2) collect data on seedling height, caliper and weight, along with RGP, and analyze the results using the morphological properties as covariates.

Before potting, root systems are normally washed briefly to make them more visible and any white tips that might be present are pinched out. Then the seedlings are potted in large (15-L or 5-gal) plastic pots -- normally 5 to 10 per pot depending upon size -and each pot is considered as one replicate.

As a potting mix, we have had excellent results with a 1:1 peat:vermiculite forestry mix, although many mixes have been used successfully. It is important that the mix be well drained, however, and sand or perlite can be incorporated for this purpose if necessary. Pots are watered initially to saturation and then maintained near field capacity by watering every two or three days. Fertilizer is not needed since the test will probably not go beyond 30 days. Seedlings have adequate nutrient reserves to carry them through this period. Some workers recommend liming the medium to maintain pH near 5.5, but we do not do this.

The key point to remember is that the test environment must remain constant from test to test. If this is not done, then differences in RGP between tests cannot be ascribed only to seedling condition. For maintaining constant environmental conditions, growth chambers are far superior to greenhouses. Realistically, however, few operational growers can afford growth chambers for seedling testing, while inexpensive greenhouses are within the means of many. Most RGP testing is therefore done in greenhouses, despite control problems.

A simple and easy-to-maintain environmental regime which promotes root growth in most

northwest conifers is a constant 20° day/ night temperature and a 16-hour photoperiod, normally supplemented with fluorescent lights. It would be desirable to control relative humidity as well but this is rarely done due to its difficulty and expense. Since most RGP testing is done in winter and early spring, the greenhouse must be heated. If testing is done in late spring or summer -say, for high elevation stock -- a shade cloth is essential for temperature control. Considerable errors can arise from extreme temperature fluctuations.

8.3.2 Quantifying root growth

Following the 4-week test period, seedlings are removed for root counting. This is easily done with a low pressure hose, using gentle force and care not to break the brittle new roots. If it is not possible to measure the roots immediately, they may be stored in a cold, dark room or refrigerator for several days before counting. This may be done either before or after unpotting.

New roots can easily be distinguished from old roots by color and general appearance. Old roots will have a rough surface and be dark brown. New ones will have pearly white tips and grade to a light tan and then brown as they become suberized. The point of transition from old to new root can usually be detected as a fairly abrupt change in diameter and/or color.

Quantifying root growth can involve counting and/or measuring the length of new roots present. The intensity of measurement should depend upon test objectives. In some cases it may be sufficient to determine only whether or not any root growth has occurred. In other cases, you may need to count and measure each new root. We will discuss this more later. An efficient method of root counting, in our experience, is first to break the root system down into its major laterals, then count each lateral system individually. This can be done while holding the roots against a dark background and tallying with a lab counter.

Interpretation of the results of the RGP test depends on how the information will be used. First you should be generally familiar with the species you are working with and what sorts of RGP values are normal for that species. As a starting point in helping you make some beginning judgments, I have assembled a table of RGP values from the literature (Table 1). Note that various authors have used different test durations and have quantified RGP in different ways.

The test procedures described are not without problems and sources of error. First, it is easy to break and lose roots during the extraction process, especially if a heavy potting medium is used. This, obviously, will introduce measurement errors. Secondly, if environmental conditions change from test to test this will also introduce error.

Sources of these problems can involve changes in photoperiod, potting medium, soil moisture, soil and air temperature and other variables (see Thompson and Timmis 1978). Errors can also arise in the quantification procedure, especially if indirect methods, such as volume displacement, are used. It is also important to standardize measurement procedures to some extent. There can be considerable variation, for example, among root counters. So the same person or persons should be employed to count roots across treatments rather than having one person assess results of only one treatment.

8.3.3 Alternative testing methods

Aside from the various technical problems mentioned above, the major disadvantage of the RGP test is its cost. High cost results from (1) the time required to perform the test, during which seedlings must be watered and cared for, and (2) the labor-intensive process of quantifying new root growth. There have been numerous attempts to circumvent these problems. Burdett (1979a) reported on an RGP test which requires only seven days to conduct. The main concept of this accelerated test is to speed up root growth by raising temperature. The conditions he used are described below.

TEST CONDITION

Day temperature	30°C
Night temperature	25°C
Daily photoperiod	16 hours
Light intensity	25,000 lux
Relative humidity	75%

WATERING SCHEDULE

Start of test lst watering	2nd watering	3rd watering
Monday a.m.	Wednesday noon	Friday a.m.
Wednesday noon	Friday p.m.	Monday a.m.
Friday a.m.	Monday a.m.	Wednesday noon

We tried the accelerated method with lodgepole pine and interior spruce (Picea engelmannii glauca complex) and were impressed with how well it worked. Burdett (pers. comm.) has also experimented with interior Douglas-fir (Pseudotsuga menziesii glauca (Mayr) Sudw) and coastal Douglas-fir. With both species he reports that results of the seven-day test are well correlated with results of 30-day tests. The only drawback of this test is that it requires a controlled environment chamber.

We have also had good results with a hydroponic test system (Winjum 1963). A 40-L (10 gallon) aquarium was painted black and covered with a black plywood lid. No. 12 laboratory stoppers were drilled through the center and slit radially to hold seedling stems. The

Table 1: Reported values of root growth potential (RGP) for a variety of North American forest tree species.

SPECIES	MEASURED VARIABLE	TEST PERIOD (days)	RGP LOW	RGP HIGH	AUTHOR
Pinus banksiana	Number/Length (cm)	28	18/90	60/440	van den Driessche (1978)
P. resinosa	% root volume increase	30	10	60	Sutton (1983)
P. taeda	Number/Length (cm)	28	20/70	50/190	Rhea (1977)
P. taeda	Length (cm)	28	5	110	Brissett & Roberts (1984)
P. ponderosa	Length (cm)	28	50	210	Jenkinson (1976)
P. ponderosa	Number	30	5	60	Stone & Schubert (1959)
P. ponderosa	Number > 2.5 cm	30	5	95	Krugman & Stone (1966)
P. ponderosa	Length (cm)/Number	28	20/3	180/35	Stone (1970)
P. jeffreyi	Length (cm)	28	90	160	Jenkinson (1976)
P. contorta	% root volume increase	28	0-20	50-100	Burdett (1979b)
P. contorta	Index	7	0-1	2-5	Burdett (1979a)
P. contorta	Index	7	0-1	4-5	Burdett et al. (1983)
P. contorta	Number of white tips	7	20	350	Ritchie et al. (in prep.)
P. radiata	Number > 0.5 cm	30	74	940	Krugman et al. (1965)
P. radiata	Number/Length (cm) [a]	32	38/109	205/377	Nambiar et al. (1982)
P. radiata	Number/Length (cm)	21-28	20/100	200/500	Stupendick & Shepherd (1979)
Picea glauca	Index	7	0-0.5	2-5	Burdett et al. (1983)
P. glauca	Index	7	1-2	3-4	McMinn (1980)
P. glauca	% root volume increase	28	5	30	van den Driessche (1978)
P. mariana	Number/Length (cm)	30	8/18	60/180	Sutton (1983)
P. glauca engelmannii	Number of white tips	7	10	150	Ritchie et al (in prep.)
Pseudotsuga menziesii menziesii	Number	30	50	300	Winjum (1963)
P. menziesii menziesii	Number	30	1	115	Todd (1964)
P. menziesii menziesii	Number > 1.3 cm.	30	50	300	Todd (1964)
P. menziesii menziesii	Length (cm)	30	100	400	Ritchie (1982)
P. menziesii menziesii	Length (cm)	30	100	400	Ritchie & Dunlap (1980)
Abies concolor	Length (cm)	28	0	210	Stone & Norberg (1979)
A. concolor	Length (cm)	28	30	260	Stone & Norberg (1979)
A. magnifica	Length (cm)	28	30	140	Stone & Norberg (1979)
A. procera	Number	30	20	250	Winjum (1963)
Juglans nigra	Weight (mg)	28	40	240	Rietveld & Williams (1978)
Quercus alba	Weight (mg)	56	3	200	Farmer (1975)
Q. alba	Weight (mg)	42	5	25	Farmer (1979)
Q. rubra	Number/Length (cm)	42	1/10	4/50	Larson & Whitmore (1970)
Q. coccinea	Number	42	10	290	Lee et al. (1974)
Q. palustris	Number	42	10	490	Lee et al. (1974)
Q. acutissima	Weight (mg)	42	10	400	Farmer (1979)
Liriodendron tulipifera	Number/Length (cm)	28	2/5	8/20	Rhea (1977)
Liquidambar styraciflua	Number/Length (cm)	28	3/3	30/68	Rhea (1977)
Platanus occidentalis	Number/Length (cm)	29	25/50	50/225	Rhea (1977)
Acer saccharum	Number white tips	30	0-13	40-115	von Althen & Webb (1978)
A. saccharum	Number	30	15	80	Webb (1977)
A. saccharinum	Number	30	20	150	Webb (1977)
Fraxinus americana	Number	30	20	150	Webb (1977)

[a] Tested at 14°C

tank lid contained holes to accommodate the stoppers, thus suspending the seedlings with tops exposed and roots submerged in the tank. The water was aerated with an aquarium pump and bubble stone. No mineral nutrients were added. In a series of trials we measured RGP of Douglas-fir seedlings in the aerated water baths and compared results to RGP measured in the standard manner on subsamples of the same seedlings. Results of these trials showed good agreement between the two methods in terms of number and total length of roots produced per seedling (Figure 4).

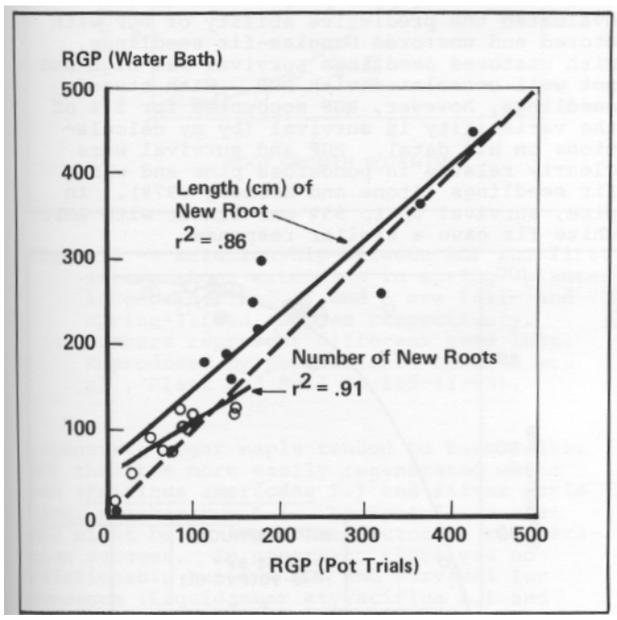

Figure 4 -- Comparative root growth potential (RGP) values of Douglas-fir seedlings as determined in eleven parallel pot and water bath trials. Each value represents a mean of 30 seedlings. Regressions were conducted on the means.

The hydroponic approach has a number of advantages over the pot approach:

(1) The time-consuming process of potting and unpotting seedlings is avoided as is the need for large quantities of expensive potting medium,

(2) much greater spatial and temporal uniformity is achieved in the rooting environment,

(3) assessment of new root growth is more accurate because (a) new roots are clean, not stained by the potting medium, and therefore easily distinguished from old roots, and (b) roots are not broken or lost in the unpotting process,

(4) the technique facilitates alternative root counting methods, such as photography and liquid displacement (discussed later), which are rapid and non-destructive,

(5) new root growth can be monitored visually during the test, which may offer an opportunity for shortening the test period,

(6) trials require about 50% less bench space,

(7) water baths require no maintenance, while pots need frequent watering.

Mist or aeroponic systems may also offer an advantage over potting for clean, rapid root growth measurement (Day 1982). We have attempted to use mist boxes to assess RGP in Douglas-fir seedings with mixed results. In some tests mortality and water stress were unexpectedly high for no apparent reason. New fogging nozzles and other aeroponic devices are now available, however, which might make this approach very attractive.

8.3.4 Alternative methods for quantifying root growth

Once the test has been completed, the next task is to determine how much root growth occurred. Much work has been done to simplify this tedious procedure. Initially, workers tended to count and measure total length of all new roots produced on each seedling. This apparently led to the realization that the two values tend to be fairly well correlated. This gave rise to a subsequent approach of counting only. This alone halves the time involved. There have been other short cuts -- counting only the tips longer than some critical length, measuring only the three or five longest new roots, tallying only the percent of seedlings tested which showed any new root growth at all, and etc. Each of these procedures might be appropriate under some circumstances but not others.

Burdett (1979a) has developed an index which involves stratifying RGP results into six classes based upon numbers of new roots greater or less than some critical value:

Class	Description
0	No new root growth
1	Some new roots but none over 2 cm long
2	1-3 new roots over 1 cm long
3	4-10 new roots over 1 cm long
4	11-30 new roots over 1 cm long
5	More than 30 new roots over 1 cm long

This has proven to be a good predictor of field survival for some species (discussed later). Another valid approach is to develop a set of reference photographs of seedlings with known RGP. The technician then matches

a root system in hand with the photo which it most closely resembles.

Some workers clip off new roots and weigh them as an estimate of RGP (e.g. Rietveld and Williams 1978). Our experience has been that this method is as laborious as measuring. Still others use volumetric determinations (van den Driessche 1978, Burdett 1979b). One approach involves placing a large beaker of water on a weighing balance. If a root system (or any object) is submerged in the water, the balance will record the weight of water displaced. This weight in grams is essentially equal to the volume of the root system in cm^3 (since one cm^3 of water weighs 1 g at STP). Volume determinations are made on a root system before and after a root growth test. These are then subtracted to give an estimate of the volume gained during the test. This then is a measure of RGP. While elegant and simple, the method does suffer from two serious problems. First, if any part of the root system touches the sides or bottom of the beaker it will introduce an error in the volume determination. Second, if the same root system is measured several times in succession, different values are obtained each time. This may be due to absorption of water by the roots or incomplete drying of the roots between measurements or some other cause. For these reasons, we have been unable to obtain consistent, accurate RGP values using this technique.

Another volumetric method, which is less elegant but perhaps more repeatable, is diagrammed in the Appendix. The same problem with water absorption operates here also, however, and our success with this method has also been limited. This is not to discourage others from trying either method, however.

Morrison and Armson (1968) reported on a device they developed and called a "rhizometer" for measuring root area and volume. It employs a photoelectric cell and provides rapid, non-destructive estimates of root area or volume. While it appears to have some promise in RGP assessment, the method does not seem to have caught on. We have had no experience with it. We have, however, evaluated the prospects for using photography. Root systems are photographed against grids and grid intersections counted and calibrated against total root length. The method is quite accurate but is more laborious than hand measuring.

8.4 PREDICTIVE ABILITY OF RGP TESTS

A major objective of seedling quality assessment is to predict field survival and performance. Thus it is surprising that more data on the relationship between RGP and postplanting performance are not available. A cursory search of the English literature turned up about twenty such studies -- most with conifers. In many cases, good agreement was reported between RGP and survival, both in field and greenhouse trials. In an early study, Stone (1955) found that RGP was a fairly good predictor of survival in jeffrey pine (Pinus jeffreyi Grev. and Bal.), ponderosa pine ponderosa Laws.), white fir (Abies concolor Gord. & Glend. Lindl.), red fir (A. magnifica A. Murr.) and Douglas-fir. Seedlings of these species which failed to initiate roots within 60 days did not survive an additional 120 days in the greenhouse. Rhea (1977) found a close correlation between RGP and field survival in loblolly pine (Pinus taeda L.), as did Burdett et al. (1983) with white spruce (Picea glauca (Moench.) Voss.) (Figure 5) and odgepole pine, and McMinn (1980) with lodgepole pine. Todd (1964) evaluated the predictive ability of RGP with stored and unstored Douglas-fir seedlings. With unstored seedlings survival was high and not well correlated with RGP. With stored seedlings, however, RGP accounted for 53% of the variability in survival (by my calculations on his data). RGP and survival were clearly related in ponderosa pine and white fir seedlings (Stone and Norberg 1979). In pine, survival up to 95% was linear with RGP. White fir gave a similar response.

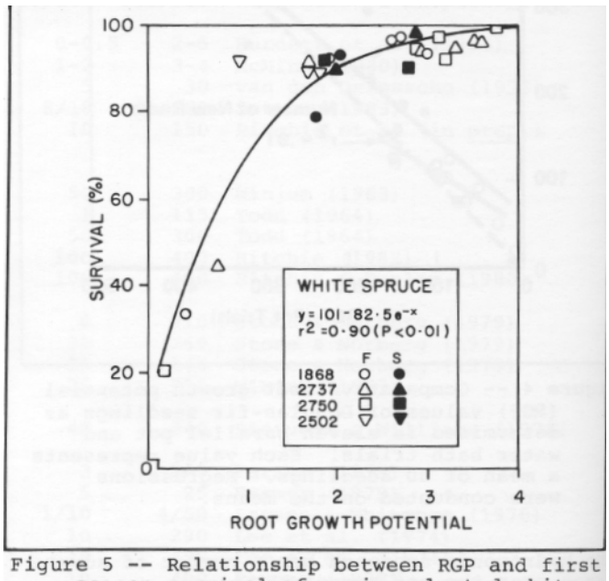

Figure 5 -- Relationship between RGP and first season survival of spring-planted white spruce. F and S are fall- and spring-lifted samples, respectively. Numbers represent different seed lots. Reproduced by permission: Burdett et. al., Plant and Soil 71:105 (1983).

In some cases, RGP has also been a good predictor of growth after planting. Notable among these are the data of von Althen and Webb (1978) with sugar maple (Acer saccarum Marsh.) and Burdett et al. (1983) with lodgepole pine and white spruce. In the latter study, RGP accounted for 82% and 96% of the variability in first year shoot extension of pine (Figure 6) and spruce, respectively.

Results with hardwoods have been more mixed. Webb (1977) found that the difficult-to

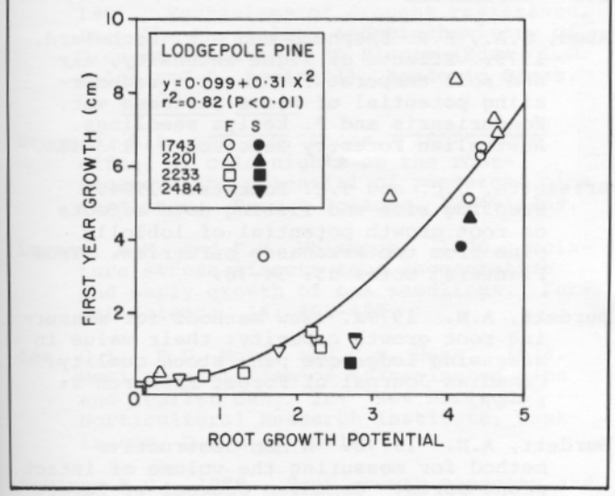

Figure 6 -- Relationship between RGP and first season shoot extension in spring- planted lodgepole pine. F and S are fall- and spring-lifted samples respectively. Numbers represent different seed lots. Reproduced by permission: Burdett et. al., Plant and Soil 71:105 (1983).

regenerate sugar maple tended to have weaker *RGP* than the more easily regenerated white ash (Fraxinus americana L.) and silver maple (Acer saccharinum L.). He speculated that *RGP* might be an important factor in regeneration success. In contrast, there was no relationship between RGP and survival for sweetgum (Liquidambar styraciflua L.) and yellow poplar (Liriodendron tulipifera L.) and an inverse relation in sycamore (Platanus occidentalis.) (Rhea 1977).

There are a few examples of studies with conifers in which RGP did not predict performance. In an extensive field trial with jack pine and black spruce, Sutton (1983) was not able to demonstrate this relationship, probably due to diverse weather and site conditions. He also found, in a nursery outplant trial with jack pine, that large RGP differences were not reflected in survival differences. With spruce, however, RGP differences of an order of magnitude were correlated with significant performance differences. Interestingly, Sutton examined root growth of seedlings planted in the field and found no relationship with measured values of RGP before planting. Brissette and Roberts (1984) found only low correlations of RGP with survival and height growth in loblolly pine. They note, however, that survival was excellent (89%) and that first year field conditions were not very stressful. This may have obscured the sought-after relationships.

So, although there is not total agreement on the ability of RGP to predict field performance, the weight of available evidence to date does indicate a strong relationship -at least with conifers in the Northwest.

8.5 CONCLUDING OBSERVATIONS

It was stated earlier in this paper that one reason RGP is believed to be a good predictor of seedling performance after planting is that it is a measure of the seedling's ability to re-establish soil-root contact. This would assure water and nutrient uptake and establishment on the site. I have difficulty reconciling this argument with the known fact that RGP is greatly impeded by cold soil (e.g. Figure 2). We have monitored soil temperatures during the planting season on low elevation western Washington sites. Rarely, if ever, does soil temperature reach 10 before early May (Table 2). Thus a seedling planted before then would be unable to produce new roots when planted even if RGP were very high. Further, by the time soil temperature has reached a range favorable for root growth (around late June) dormancy release is completed, shoot elongation is underway and RGP is very low. Why then should RGP predict performance?

Table 2: Soil temperature at 15 cm depth on a low elevation site near Pe Ell, Washington.

Date	Temperature (°C)
January 10, 1980	1.7
February 6	4.4
February 28	4.4
March 30	6.7
April 18	8.3
May 8	11.7
June 7	12.7
July 5	14.0
August 1	18.0

I would like to set forth a working hypothesis to explain this apparent paradox. I propose that RGP is a good predictor of performance because it is correlated with other seedling quality attributes which directly impact performance -- specifically cold hardiness and stress resistance. That is, periods of high RGP coincide with periods of high cold hardiness and stress resistance, so that a measure of one is, in effect, a measure of the others. These relationships are shown in generalized form in Figure 7 and are based on actual data for coastal Douglas-fir seedlings. The RGP curve is similar to that given by Winjum (1963) and Stone et al. (1962). The cold hardiness data were developed by Timmis (R. Timmis, Weyerhaeuser Company, pers. comm.) for 2+0 seedlings growing in coastal nurseries. The stress resistance curve is derived from measurements of osmotic potentials at zero turgor ,made also on young Douglas-fir seedlings (Ritchie and Shula 1984). This value is considered by many

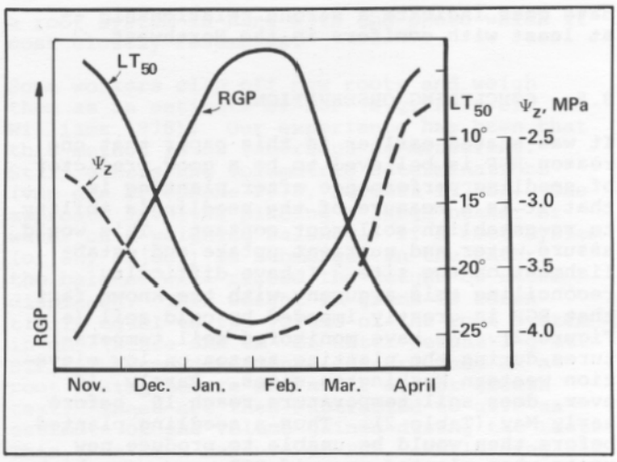

Figure 7 -- Seasonal changes of root growth potential (RGP), cold hardiness (LT_{50})b/ and water potential at zero turgor (Ψz) in Douglas-fir seedlings.

workers to be a critical value for water stress (e.g. Hsaio et al. 1976; Jones et al. 1981) because it establishes the highest level of stress that can be endured before turgor is lost in the cells and permanent wilting occurs (e.g. if the value of turgor -25 bars, then a pressure bomb reading greater than 25 bars would indicate zero turgor).

I am suggesting, therefore, that when we measure RGP we are obtaining an estimate of relative cold and stress resistance in the seedling and it is these properties -- not the ability to grow roots per se -- that influence how the seedlings will perform on the site. A test of this hypothesis would be to measure RGP, cold hardiness and stress resistance over the course of a winter and following different durations of cold storage. If the relationship held up in the storage trials it would seem to be valid.

8.6 RECOMMENDATIONS

RGP is a robust, relatively inexpensive and very flexible method for assessing seedling physiological quality. Its use at nurseries and in regeneration operations for routine testing or trouble-shooting of planting stock would seem a worthwhile expense.

8.7 ACKNOWLEDGSIENTS

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b/ LT_{50} designates the subfreezing temperature at which 50 percent of a sample population will be killed.

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8.8 Appendix -- Procedure and apparatus for determining volume of seedling root systems by water displacement. Source: Dr. M.I. Menzies, Forest Research Institute, Rotorua, New Zealand.

1) Prepare 5 liters of water
2) Set the 50-ml syringe at zero (Figure 1A).
3) Isolate the 3000-m1 flask using stopcock "A"
4) Isolate the 50-m1 syringe using stopcock "$_B$".
5) Fill the entire system with water, then using the 20-m1 syringe carefully zero the buret at 25 ml and the flask at the meniscus.
6) Isolate the 20-m1 syringe with stopcock "$_B$"
7) Isolate the 25-m1 buret with stopcock "A"
8) Using the 50-m1 syringe pull 50 ml of water from the flask.
9) Suspend the root system in the flask with the root collar at the meniscus using a ringstand and ringstand clamp.
10) With the 50-m1 syringe carefully bring the water level back to the meniscus.
11) Isolate the flask with stopcock "A". 12) Expel the entire volume of water from the 50-m1 syringe.
13) Read the water volume on the buret. This value subtracted from 25-m1 is the volume of the root system.
14) Record the root system volume, remove the seedling and refill the system with water. Use make-up water as needed.

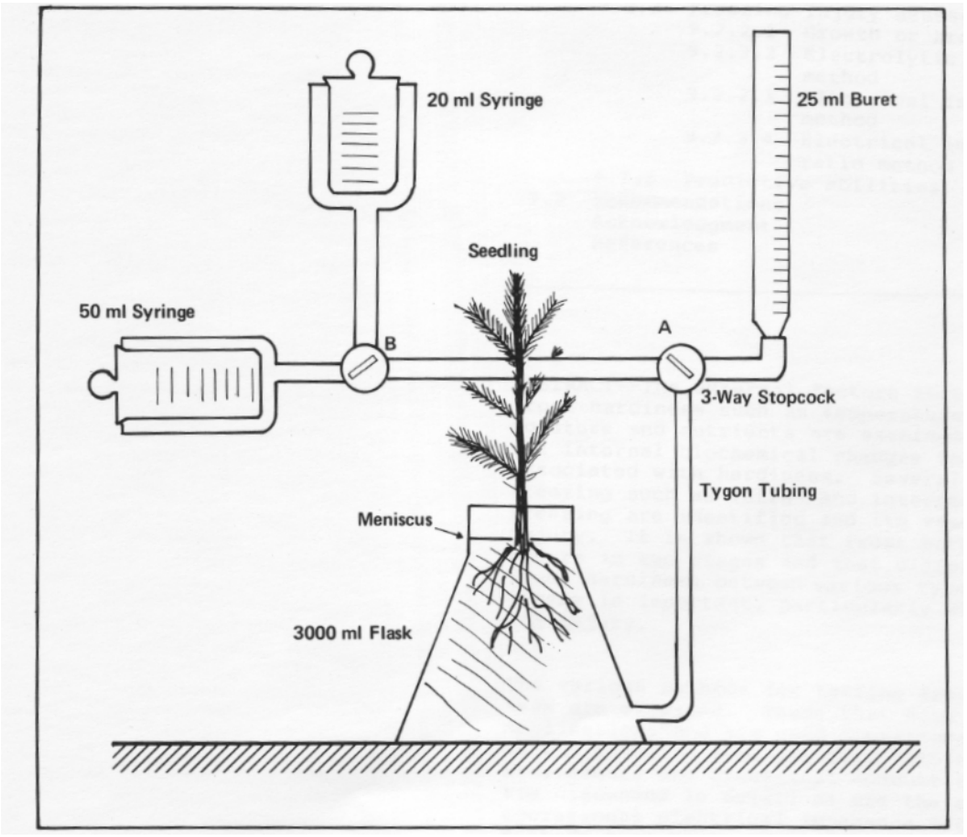

Figure 1A: Diagram of apparatus for determining root system volume by water displacement.