Target Seedling Symposium

Chapter 3
Target Seedling Concepts: Height and Diameter

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ABSTRACT

The target seedling concept involves morphological and physiological seedling attributes which affect outplanting performance. Both morphological and physiological attributes are directly influenced by nursery cultural practices. Among the cultural practices which influence target seedling attributes are transplanting, growing density, and both root and shoot pruning.

Morphological features, specifically height and stem diameter, currently provide the best estimate of seedling performance after outplanting. Diameter is the best predictor of survival, while height seems to predict height growth. Parameters such as root mass or number of laterals are also useful in assessing potential performance, but their utility diminishes as stem diameter increases above 5 mm.

Seedling morphology does not always predict performance because the morphology does not indicate vitality or vigor of the seedling, in the future, nursery cultural practices will target specific morphological attributes as well as acceptable ranges of other important variables. One such approach is discussed.

3.1 Introduction

Tree planting has been the primary means of achieving artificial regeneration over the past six decades. As concerns about global deforestation increase, planting programs also will increase to mitigate potential climate changes. This emphasis on tree planting has focused renewed attention on identifying those seedling attributes in the nursery, that can predict establishment success. A simple, easy-to-measure index of these seedling attributes is needed. Nursery managers also need a seedling index to help them make cultural decisions during the growing season—particularly during the critical seedling harvesting season.

These seedling attributes necessary for reforestation success have been collectively termed "seedling quality." Perhaps the best definition of seedling quality has been "fitness for purpose" (IUFRO 1980). For reforestation purposes, seedling quality may be defined as those attributes necessary for a seedling to survive and grow after outplanting (Duryea 1985). Many seedling attributes have been studied with respect to field survival. However, much less is known about those necessary for early growth, and the question of acceptable growth following outplanting has been ignored.

Measurements of seedling quality can be categorized in several ways. Ritchie (1984) separated measures of seedling quality into two categories: material attributes and performance attributes. Material attributes, either morphological or physiological, are directly measurable, and include mineral nutrient status and seedling dimensions such as height and stem diameter. Performance attributes are physiological tests measuring a specific seedling function, such as root growth potential or cold-hardiness.

Morphological characteristics, such as seedling size, have been used traditionally to rate seedling quality in the nursery and match seedlings to the environmental conditions on the outplanting site. These morphological indices fail to account for differences in seedling physiology. As an extreme example, rating a seedling on morphological dimensions alone does not indicate whether the seedling is dead or alive.

Beginning with the investigations of Wakeley (1949) in the 1930s, forestry researchers began to search for physiologically based indices of seedling quality. Many aspects of seedling physiology have been evaluated to better understand seedling quality, including cold-hardiness and root growth potential. New techniques continue to be developed, such as the recent work on chlorophyll fluorescence (Vidaver et al. 1988). However, none of these individual physiological factors has proven to be the critical key factor to measuring seedling quality and predicting outplanting success. Physiological estimates of quality have the same limitations as traditional morphological ratings in that they provide only a narrow glimpse of the complex nature of seedling quality.

Part of the problem is that seedling quality cannot be viewed as a static parameter. It is a dynamic process that is a culmination of all the practices that have preceded and will succeed the point of measurement. Seedling quality can vary as it is estimated at specific points in time during crop growth, harvesting and storage, and shipping to the outplanting site (Duryea 1985). Consequently, the appropriate rating technique can also change over time. Also, seedling quality indices that are useful at particular stages in the nursery process are less reliable for predicting how well a seedling will perform on the outplanting site. For example, measures of seedling cold-hardiness are useful in determining proper lifting time (Faulconer 1988), but are useless for prescribing when to irrigate in the nursery, when plant moisture stress measurements are more relevant.

Root growth potential (RGP) has been widely used during seedling harvesting and shipping season to predict outplanting success. However, such predictions have limited utility because RGP and other physiologically based seedling quality indexes change considerably from lifting through storage (Landis and Skakel 1988). Seedling quality is particularly vulnerable after seedlings leave the carefully controlled and monitored nursery environment and can deteriorate rapidly during shipping and field storage. Even stock with a high quality rating may perform poorly due to unfavorable outplanting conditions (Rietveld 1989).

It may be possible to identify one specific rating index that will suffice in all situations, but this is doubtful. Some seedling quality ratings, however, have application for both the nursery manager and tree planter because they can be used during nursery culture, seedling harvesting, and also help match stock to outplanting site conditions. This paper discusses traditional morphological parameters, shoot height and stem diameter, within the context of defining the "target seedling." It discusses how these culling criteria are related to nursery and field performance, relates them to other morphological and physiological seedling quality measurements, and explains how they are affected by nursery cultural practices.

3.2 Defining the Target Seedling: Height and Caliper

3.2.1 Definitions and measurement procedures

Morphology in the classical sense is the study of external structures. For purposes of this discussion, morphology will be defined as the physical manifestation of a seedling's physiological response to the growing environ-

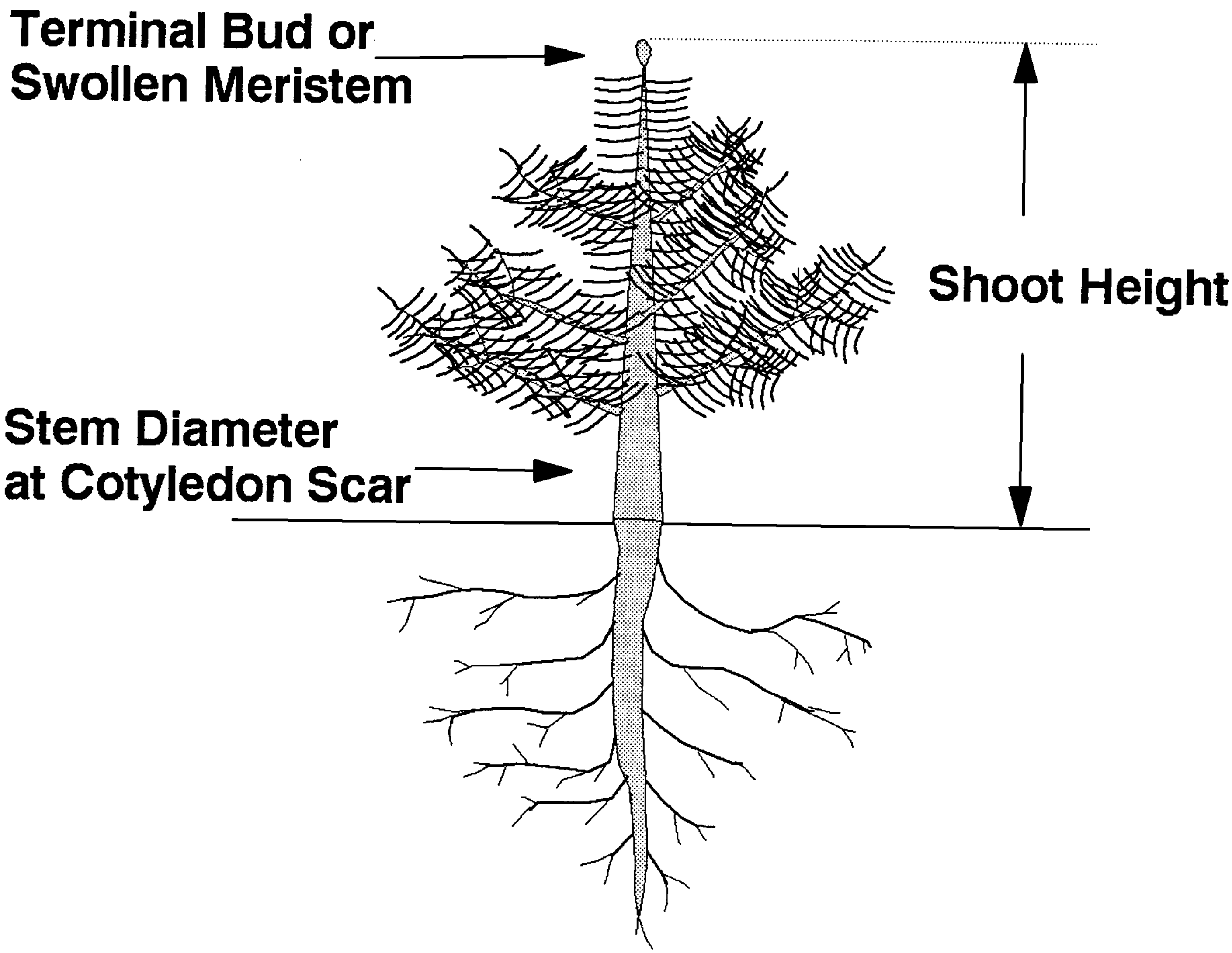


Figure 3.1—*Measurement points for shoot height and stem diameter can be determined from the cotyledon scar or original ground line.*

ment. This is an important distinction because morphological attributes of the harvested seedling are the result of a cumulative series of physiological processes reacting to resources and stresses during the nursery production phase.

Shoot height is the vertical distance from the ground line to the tip of the terminal leader (Figure 3.1). The ground line is obvious in the nursery bed but must be established on harvested stock by close observation. One physical indication of the original ground line is the point where the color of the inner bark changes from white to green when the outer bark is scraped aside. This technique is slow and destructive. Nurseries measure height either 1 cm above the uppermost lateral root (Hodgson and Donald 1980), or approximately halfway between the uppermost lateral root and the cotyledon scar.

The top of the seedling shoot can be difficult to ascertain, particularly when the seedling is actively growing. Erroneous readings occur when measurements include the highest point on a growing seedling, usually the tip of the foliage (Thompson 1985). If there is no obvious terminal bud, the measurement should be taken from the slightly swollen part of the shoot tip indicating the position of the terminal meristem (Figure 3.1).

Stem diameter, often called root collar diameter or caliper, is the diameter of the main stem of the seedling at ground line. Because the stem diameter can change significantly in this area, measurements should be made at a standardized location. Some nurseries specify that stem diameter be measured at the cotyledon scar or 1 cm above the first lateral root (Figure 3.1).

3.2.2 Target seedling specifications

A historical review of height and stem diameter grading standards may improve understanding of current applications. In one of the first U.S. nursery manuals (Tillotson 1917), seedling grading standards were only briefly dis-

Table 3.1–*Target seedling specifications from Intermountain Area forest nurseries in the early 1920s (Korstian and Baker 1925).*

Species and Stock Type	Shoot Height (cm)	Stem Diameter (mm)	Seedling Biomass Shoot (g)	Roots (g)
Ponderosa Pine 2+1	10.4	3.8	4.20	1.86
Ponderosa Pine 3+0	14.2	4.3	4.00	1.17
Douglas-fir 2+2	11.9	4.1	3.64	2.12
Douglas-fir 3+1	16.8	3.6	3.82	2.54

cussed and no actual stock specifications were given. At that time, transplants were the only stock types considered suitable for outplanting in those early nurseries, and target seedlings were considerably shorter and smaller in diameter (Table 3.1) than today's standards (Table 3.2). This size difference can be attributed to improved nursery cultural practices; in the past, seedlings were grown at extremely close spacing (400 to 2000/m^2), and fertilization was not "accorded much attention" (Tillotson 1917).

Seedling grading standards were adopted by the late 1930s. Nursery manuals devoted sections to grading standards, and the importance of stem diameter as a target seedling specification was firmly established. Engstrom and Stoeckeler (1941) concluded stem diameter was "the best and most practical basis of grading deciduous nursery stock," and discussed proper measurement techniques.

Stoeckeler and Slabaugh (1965) continued to stress the importance of establishing seedling grades. They concluded stem diameter was the most important grading characteristic, followed by shoot height and root development. The classic nursery manual of Wakeley (1954) described three different seedling grades for southern pines based primarily on shoot height and stem diameter. However, he recognized the limitations of using morphological standards by themselves, and presented one of the first detailed discussions of physiological seedling characteristics.

Most modern nurseries have substituted sophisticated seedling culling systems for grading with seedling height and diameter serving as the standards. Seedling heights are typically listed as ranges between some minimum and maximum, whereas stem diameter is usually a minimum standard. Occasionally, root length or the number of primary lateral roots is specified. Other components of seedling morphology such as needle length, terminal bud

Table 3.2—*Median shoot height and stem diameter targets for conifer species and stock types from the Pacific Northwest (Iverson 1984).*

Species	Stock Type	Shoot Height (cm)	Stem Diameter (mm)
Douglas-fir	1+0	11.5	3.0
	2+0	30.5	5.0
	1+1	38.0	8.0
	Plug+1	46.0	9.0
Truefir	2+0	15.0	4.5
	2+1	23.0	6.0
Spruce	2+0	18.0	4.0
	2+1	23.0	5.5
Ponderosa pine	2+0	13.0	4.0
Lodgepole pine	2+05	13.0	4.0

size, root:shoot (R:S) ratio and presence of mycorrhizas may be listed in target seedling specifications (Mexal and South 1990), but are rarely used as culling standards. Regardless, nursery managers and tree planters recognize that shoot height and stem caliper specifications vary by species, seed zone, stock type, and operational requirements, particularly the environmental conditions on the outplanting site.

The ideal shoot height for a particular planting site will depend on moisture conditions, the extent of vegetation competition and the presence of predatory animals such as deer or elk. Generally, tree planters prefer shorter, stockier seedlings for arid sites, and taller seedlings where vegetative competition or animal damage is severe. Stem diameter is not as site specific, although larger caliper seedlings have proven superior on difficult sites, where high soil temperatures or unstable soils are a problem (Iverson 1984). Normally, managers prefer seedlings with as much stem diameter as operationally possible regardless of site.

It would be impossible to provide a complete listing of seedling specifications for all species, seed sources and stock types although some typical examples are provided here. Iverson (1984) listed morphological targets for some species and stock types from the Pacific Northwest (Table 3.2). Similar targets are provided by Mason and others (1989) for Scots pine and spruce, and for the southern pines by (Mexal and South 1990). Menzies (1988) provides a comprehensive listing of both morphological and physiological specifications for radiata pine.

In actual practice, target height and stem diameter specifications for custom-grown seedlings are individually negotiated between the nursery manager and the seedling buyer when the seedling order is placed. These specifications may be adjusted, however, because of actual seedling performance later in the growing season. Those who buy speculation seedlings usually have to accept whatever stock is available for their particular species and seed zone, unless several nurseries have trees for that particular area. Therefore, target seedling specifications for a nursery can vary among customers and across years.

3.3 Factors Influencing Height

3.3.1 Transplanting

One of the first decisions that influences seedling height in the nursery is stocktype. That is, should the crop be grown as seedlings or transplants? In the western United States, seedling stocktypes range from 1 .5+0 to 3+2 with dramatic effects on seedling height (Figure 3.2). In the Pacific Northwest, Douglas-fir seedlings are often transplanted after the first growing season and grown as either 1+1 or 1+2 transplants, or transplanted after the second year for 2+1 transplants (Iverson 1 984). The age of the seedling at time of transplanting is important, because 1+1 and 1+2 transplants are typically taller than seedlings of similar age. On the other hand, 2+1 transplants are shorter than 3+0 seedlings. These growth differences may be due to greater transplant shock of older 2+0 seedlings as well as shade-induced height growth response of the 3+0 seedlings.

A relatively new stocktype that larger seedlings in less time is the plug + one (P+1). This is a small, containerized seedling, transplanted to the nursery bed for one addition-

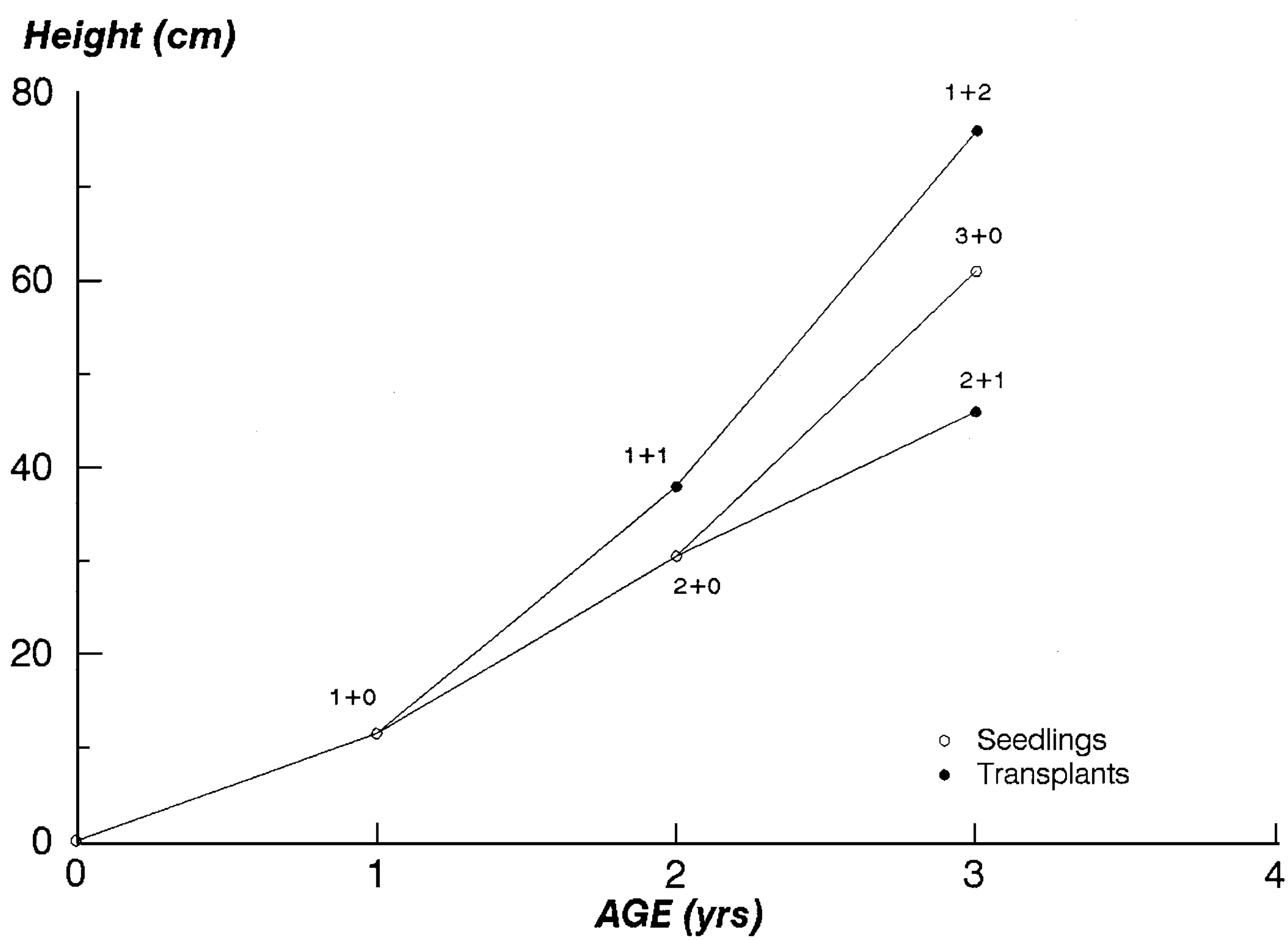


Figure 3.2—*Relationship between age and seedling height (or nursery bed grown and transplanted seedlings (after Iverson 1984).*

al growing season. These seedlings are comparable in size to a 2+1 but attain the size in less than 2 years (Hahn 1984).

3.3.2 Growing density

Seedlings compete for resources necessary for growth, especially light, moisture, and nutrients. The amount of growing area afforded an individual seedling affects the growth habit and growth potential. The relationship between shoot height and growing density is complex and variable. However, the growth response can be divided into four phases based on published literature (Figure 3.3). While these four phases have been illustrated as being continuous, that is most likely not the case. It is likely that different responses are attainable over the same growing densities, depending on other variables that may become limiting. Phase A demonstrates decreasing height with increased density (van den Driessche 1982, 1 984). The increased height at lower densities can be attributed to larger summer shoot or lammas growth, or simply greater resource availability. Phase B demonstrates no consistent relationship to density (Neilly 1983, van den Driessche 1984). Phase C illustrates the classic competition-induced shade-response (Brissette and Carlson 1987, Timmis and Tanaka 1 976). Phase D occurs at high densities where other resources such as water and nutrients can severely limit growth (Hulten 1989). At high densities, seedling crops appear stunted and contain a high proportion of culls.

As competition increases (Phases C and D), photosynthate allocation will be driven by the response to mutual shading. That is, more carbon will be allocated to shoot extension at the expense of root growth. The R:S ratio will decrease with increasing seedling density, and outplanting performance may suffer (Mexal and Dougherty 1982). At higher growing densities, height growth should be restricted through water stress and undercutting. These practices tend to shift the allocation of photosynthates into diameter and root growth.

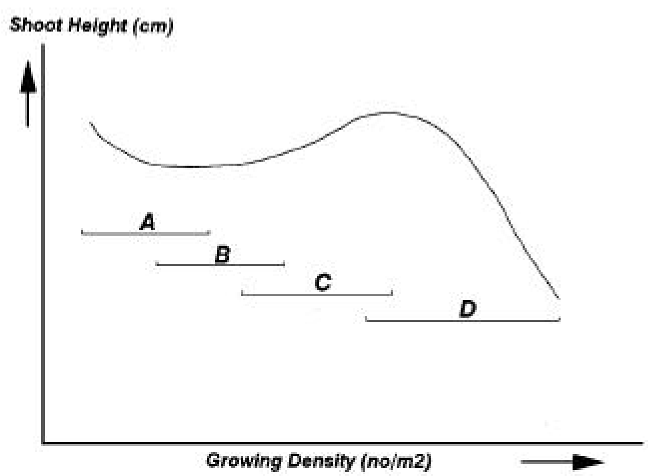


Figure 3.3—*Idealized height growth response to growing density.*

Seedling growing density can be controlled in bareroot nurseries by careful calculation of seed sowing formulae and by using precision seeders. Overly dense seedbeds can be manually thinned early in the growing season, but this is difficult to economically justify. Some nurseries use specially designed equipment to mechanically thin their seed beds. For seedbeds that are marginally dense, height growth can be restricted with moisture stress and undercutting.

3.3.3 Fertility

In bareroot nurseries, nitrogen fertilization markedly increases seedling biomass and caliper but has only slight effects of shoot height (Armson and Sadrieka 1979, Switzer and Nelson 1963, van den Driessche 1982). Furthermore, height response to fertilizer may not be apparent until the second growing season (van den Driessche 1988). This does not infer fertilizer should not be applied; only that height growth is not greatly influenced by fertility. Other parameters are, however, dependent on level of fertility. Of course, all fertilizer amendments should be based on a regular program of soil and seedling foliar analysis, and applications should be timed to seedling phenology (Landis and Fischer 1985).

3.3.4 Irrigation

Shoot extension is more sensitive to mild water stress than are diameter or root growth (Stransky and Wilson 1964). Furthermore, there is a strong interaction between level of irrigation and fertility (Armson and Sadrieka 1979, Schomaker 1 969). Maximum growth occurs at high soil water regimes and moderate to high fertility levels. At low soil water regimes, fertilizers can actually depress growth because of salt toxicity. Likewise, excessive fertilizer rates depress height (Colombo and Smith 1987).

3.3.5 Pruning

Pruning is commonly used in many nurseries to regulate height. Most western nurseries top-prune the shoots (Duryea 1984). Seedling growth response to top-pruning is a function of the stage of seedling development and the amount of shoot removed. Top-pruning typically removes only the succulent 3-7 cm of new growth. Regrowth is delayed until fascicular buds form (usually three to five weeks). Top-pruned trees grow longer into the season (Duryea and Omi 1987). Nevertheless, top-pruning reduces shoot length, diameter, and biomass. Top-pruning improves height uniformity (Mexal and Fisher 1984) and yield (South unpubl.). However, uniformity based on biomass or diameter may not be improved, and yield is not always improved (Mexal and Fisher 1984). Recent work with southern pines indicates that top-pruning can improve survival on difficult sites (South unpubl.).

Root culturing, by undercutting, sidecutting, or the more severe wrenching is also a common nursery practice. Undercutting and wrenching effectively limit height growth (Benson and Shepherd 1977, Koon and O'Dell 1977). The crop must be actively growing for undercutting to be effective (Venator and Mexal 1981), and undercutting must be relatively shallow (<15 cm). However, Tanaka et al. (1976) did not reduce the height of either Douglas-fir or loblolly pine by undercutting. Nevertheless, R:S ratio was improved in both species. Undercutting also improves crop uniformity (Koon and O'Dell 1977, Mexal and Fisher 1 984). Undercutting increases root fibrosity, which often increases seedling survival following outplanting (Tanaka et al. 1 976). However, the increased root growth caused by undercutting also can increase the harvest and handling cost to the nursery.

3.4 Factors Influencing Stem Diameter

3.4.1 Transplanting

As seedlings grow, stem diameter increases concomitantly with height; however, the relationship is not absolute. It is influenced by other nursery cultural factors such as growing density, fertility and pruning. Consequently, some nurseries prescribe both height and stem diameter culling guidelines (Mason et al. 1989). These guidelines vary based on age, species, and stocktypes. However, for the species examined, the relationship is linear regardless of age or timing of transplanting. With limitations, stem diameter is a reasonable predictor of seedling height at time of lifting.

3.4.2 Growing density

Increasing growing density decreases seedling caliper, and the response is often curvilinear (Edgren 1977, Mexal 1982, van den Driessche 1982). Consequently, yield based primarily on seedling diameter may be curvilinear (Figure 3.4) and dependent on the culling standard. In these studies, less strict grading standards (3 and 2.5 mm,

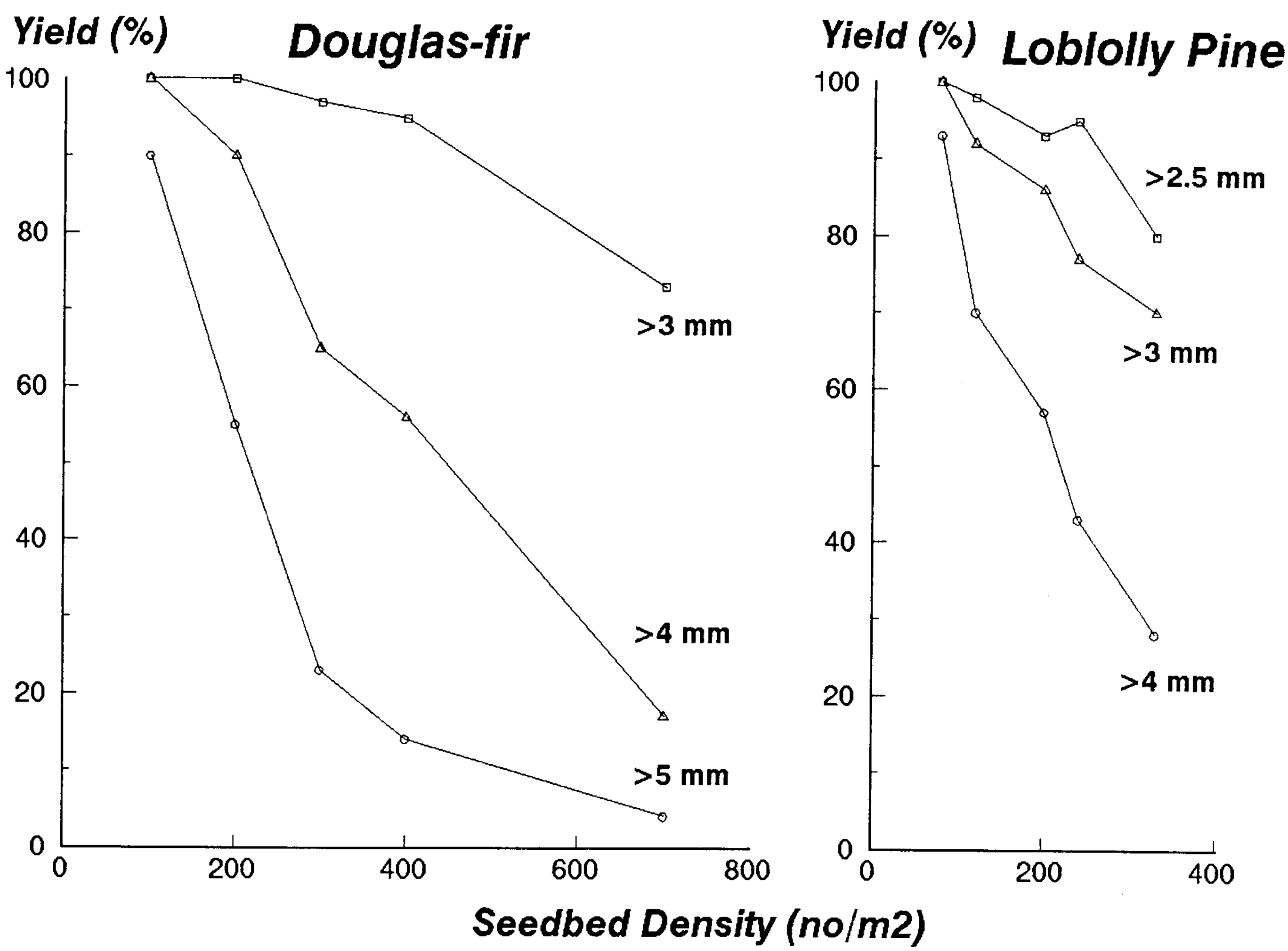


Figure 3.4—*Effect of seedbed density and culling standard on yield of Douglas-fir (Edgren 1976) and loblolly pine (Mexal 1982).*

for Douglas-fir and loblolly pine, respectively), impact yield only at the higher densities. With moderate standards (4 and 3 mm), yields fall below 80 percent at growing densities above 200/m2. With the strictest standards (>5 mm), yields exceed 80 percent only at growing densities less than 100/m^2.

While percent yield is sensitive to, and decreases with, increasing growing density, the yield per unit area usually increases as stocking increases (van den Driessche 1982). The value of the land and the associated costs of production are often greater than the costs of culling. Consequently, economics may favor growing at densities that maximize the yield per unit area, regardless of percentage culls. However, this assumes seed efficiency is of little economic importance and the performance potential is identical for comparably sized seedlings grown at different densities. In one study, this appears to be true (Burns and Brendemuehl 1971), despite changes in root morphology and R:S ratio with changes in growing density (Mexal 1982). However, other studies (e.g., Blake et al. 1989) infer density-induced changes in root morphology will translate into performance differences at time of outplanting.

3.4.3 Fertility

Nitrogen nutrition is a major determinant of seedling stem diameter and subsequent yield based on caliper. Switzer and Nelson (1963) found seedling dry weight and yield were a function of amount of nitrogen applied. Over 3 years and 4 growing densities, nitrogen (measured as amount applied per plant) accounted for 81 percent of the variation in dry weight and yield (Fisher and Mexal 1984). In spite of this relationship, many nurseries probably apply too little nitrogen over the growing season (Boyer and South 1985). The diameter of several western species increased with increasing nitrogen, up to 235 kg/ha (van den Driessche 1982). Furthermore, fertilization-induced changes in seedling size results in improved height growth, RGP, and survival following outplanting.

3.4.4 Pruning

Top-pruning and undercutting decrease seedling diameter. However, the effects on diameter are not as dramatic as on height growth. Top-pruning decreases shoot and root biomass; undercutting tends to maintain or increase root biomass while decreasing shoot biomass (Mexal and Fisher 1984). Root pruning can improve seedling quality by increasing root fibrosity, while top-pruning can only maintain quality by restricting height growth.

3.5 Relationships With Other Target Seedling Measurements

3.5.1 Morphology

Height. The relationship between height or diameter and other morphological measurements is often confounded by the cultural practices employed to attain the target height or diameter. While height is frequently highly correlated with seedling diameter, it is often weakly correlated with other parameters such as total seedling weight, root:shoot ratio, or root morphology. Factors such as growing density and fertility have a small or complex effect on seedling height, yet have such a strong impact on other parameters that any relationship between height and other parameters is tenuous at best.

One factor that logically should be correlated with height is terminal bud size. Intuitively, larger seedlings should have larger terminal buds. However, cultural practices late in the growing season can impact bud size with no appreciable effect on seedling height. Consequently, shoot height often is not an indicator of bud size (van den Driessche 1984). Seedlings that are water stressed or undercut to promote early bud set will be shorter and have larger buds than nonstressed seedlings. Conversely, top-pruned seedlings will be shorter than non-pruned seed lings, yet have a smaller bud because budset is often delayed in top-pruned seedlings. Fall fertilization will have little effect on seedling height, yet increases bud size (Hinesley and Maki 1980). Furthermore, fertility increases the number of needle primordia in the terminal bud, regardless of height development (Colombo and Smith 1987).

Seedling stem diameter is correlated with most morphological characteristics because it seems to integrate the entire seedling's morphological response to the environment. Certainly, diameter is correlated with height. It is also highly correlated with total seedling dry weight (Figure 3.5). While the absolute relationship between diameter and dry weight varies among species (van den Driessche 1982), stem diameter accounts for more than 97 percent of the variation in seedling dry weight. Diameter is equally well correlated with shoot and root weight as well as total seedling weight.

Diameter is also related to root characteristics including root weight and root morphology, when seedlings are carefully lifted. At harvest, large diameter seedlings have more primary laterals (Rowan 1986), which has been related to improved survival (Hatchell 1986). While it is possible that large diameter seedlings inherently have a more fibrous root system, it is more likely that smaller seedlings have thinner primary lateral roots that are more easily stripped during the lifting operation. The improved field performance ascribed to larger diameter may, partially, be the result of decreased root stripping.

Even though stem diameter is strongly correlated to both root and shoot weight, the relationship between diameter and R:S ratio is less clear. For southern pines, R:S ratio increases with increasing diameter (Harms and Langdon

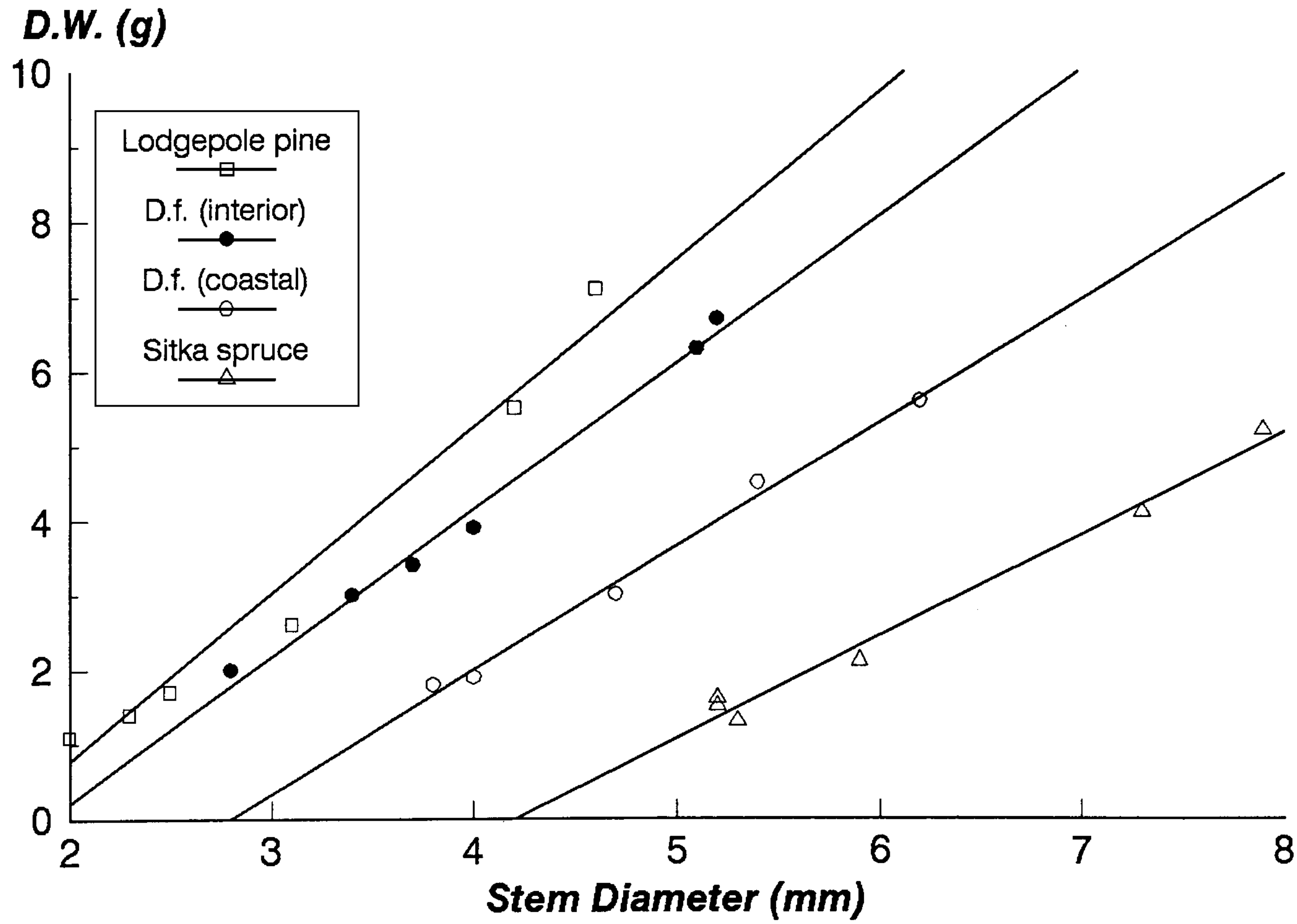


Figure 3.5—Relationship between seedling dry weight and diameter for Douglas -fir (O, ?), Sitka spruce (?) and lodgepole pine (?) (after van den Driessche 1982).

1977). However, others (Mullin 1981, van den Driessche 1982) found R:S was either unrelated or negatively correlated with caliper for several species. Negative correlations held regardless of whether the increase in diameter was accomplished through increased growing area or fertility (van den Driessche 1980, 1982, 1988). This discrepancy between southern and western species is not explained.

The relationship between diameter and bud size is complex. The timing of budset largely determines final bud size. Concomitantly, early bud set corresponds to increased diameter and root growth. Seedlings that set buds early tend to have larger diameters than comparably sized seedlings that set bud later. Seedlings that invest carbon in stem elongation may not have the excess carbon to invest in diameter accretion. This relationship is transitory because seedlings with greater leaf mass can acquire more carbon. Greater leaf area through stem elongation ultimately leads to greater caliper growth. However, as nursery-grown seedlings approach harvestable size, it is desirable to have more biomass in diameter and roots than needles. Grigsby (1971) demonstrated long-term growth advantages attributable to bud morphology. Seedlings with well-formed and presumably early-formed buds performed the best in terms of ten-year volume growth. Apparently, early bud set imparted a survival and growth advantage following outplanting. However, it is possible another factor, such as simple size differences, could have accounted for the response.

3.5.2 Physiology

Root growth potential (RGP) is a measure of a seedling's ability to quickly regenerate new roots under controlled conditions. As such, it has been correlated with performance potential (Larsen et al. 1986, Ritchie and Dunlap

1980, Ritchie 1984). However, it is not well correlated with other seedling parameters, especially stem diameter (Feret et al. 1985). Factors such as undercutting tend to increase RGP while decreasing shoot size (Bacon and Bachelard 1978). However, growing density appears to have little effect on RGP compared with the strong influence it has on seedling size (van den Driessche 1984). In these studies there was more variability in RGP associated with species, year, and nursery than was associated with spacing-induced changes in seedling size (van den Driessche 1984).

While growing density per se has little or no effect on RGP, seedling stem diameter or biomass does influence RGP. Williams et al. (1988) found loblolly pine seedling weight predicted RGP (r^2 = .66). However, RGP is more a function of root architecture than absolute size (Nambiar 1980). Larger seedlings can have more root apices from which new roots originate. It may be, within a population, larger seedlings have higher RGP. However, among populations, such as a growing density experiment, the variability precludes statistical differences.

The relationship between nursery cultural practices and RGP appears complex, but no less so than between RGP and field performance. This may explain the conflicting results reported. Seedlings with low RGP can perform well because of other attributes not readily apparent such as site conditions (Burdett 1987). Many studies do not report variables tangential to the research objective, which may help explain negative results. Survival of seedlings with similar RGP values can vary by more than 40 percentage points on the same site (Binder et al. 1987, Burdett 1987), yet seedling morphology and cultural practices are often unreported in these publications. Many questions will remain unanswered until more complete morphological and physiological characterization of the stock type is reported.

3.5.3 Stress tolerance

Stress tolerance is the ability to survive exposure to low temperature (cold-hardiness), high temperature, drought and toxicants. A seedling's ability to tolerate these stresses is usually at a maximum during mid-winter upon satisfaction of the chilling requirement. This period also marks the transition between endodormancy and ecodormancy (Lang 1987), or at the end of rest (Fujigami and Nee 1987). Furthermore, RGP often reaches a maximum at this point (Ritchie 1985). While these factors are correlated, the cause of the relationship is not fully understood. Furthermore, stress tolerance and seedling morphology are probably related in an indirect manner.

Size per se should not alter the relative stress tolerance of a seedling crop, although seedlings with larger diameters and more fibrous roots may be more tolerant of physical stress, such as poor handling. However, cultural practices which influence seedling diameter are likely to also influence stress tolerance. Timmis and Tanaka (1976) found cold-hardiness of container Douglas-fir seedlings was related to growing density. Seedlings grown at lower densities were more cold-hardy and were also sturdier, heavier seedlings with lower leaf water contents. Seedlings grown at lower densities were exposed to greater environmental stresses—higher temperatures, higher incident radiation, and greater evaporative demand—as evidenced by leaf water content and potential (Timmis and Tanaka 1976). It would appear that this higher stress exposure accounted for the increased cold-hardiness, rather than the increased seedling size per se.

3.6 Utility in Performance Prediction

3.6.1 Survival

Harvested seedlings are routinely culled to remove damaged or diseased seedlings and seedlings that fail to meet specified size criteria. Typically, size standards are based on planting trials that have demonstrated smaller seedlings (especially smaller diameter) have lower survival than larger seedlings (e.g., Wakeley 1949). For example, Mullin (1959) found survival of cull seedlings was 18-23 percentage points less than survival of plantable white fir seedlings. While the percentage of the crop culled ranged from 10-30 percent over the 3 years, the relative survival advantage of plantable seedlings over cull seedlings remained similar (ca 20 percentage points). Obviously, culling does not separate trees that will live from those that will die. Rather, culling provides relative performance prediction. Smaller seedlings have lower survival potential, regardless of the environmental conditions and subsequent survival of plantable seedlings.

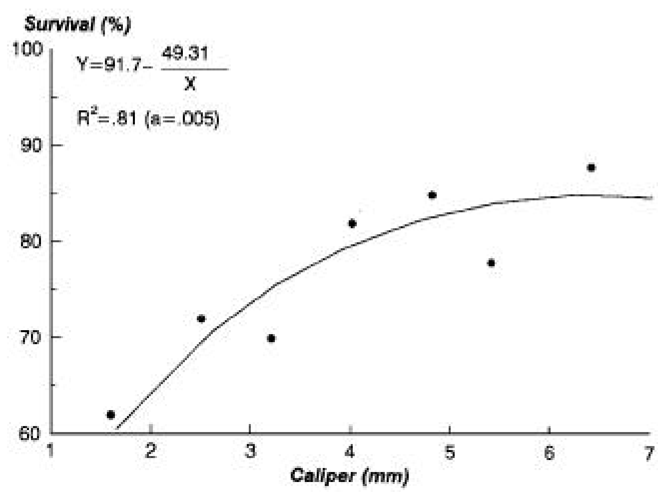


Figure 3.6—*Relationship between seedling diameter at time of lifting and outplanting survival (South and Mexal 1984).*

A major culling criterion in nursery production is shoot height. Yet, initial seedling height is not be a good predictor of seedling survival. Above a minimum size, the best seedling height is a function of outplanting site conditions. Mullin and Svaton (1972) found white spruce survival increased with increasing height up to about 20 cm and did not change between 20 and 30 cm. Tuttle et al. (1988) found survival of loblolly pine seedlings planted on adverse sites decreased if seedling height after planting exceeded 20 cm. However, on non-adverse sites, survival increased slightly with increasing height up to 35 cm. Lopushinsky and Beebe (1976) found heights ranging from 7-21 cm had no effect on survival of Douglas-fir or ponderosa pine.

The relationship between height and survival is confounded by other morphological parameters, especially R:S ratio. Thompson (1985) elegantly displayed the impact of R:S ratio on survival of seedlings in different height classes. Within the height range of 9-47 cm, seedlings with higher R:S had higher survival. The R:S ratio decreased with increasing seedling height, and above 30 cm, there was little difference in R:S ratio between seedlings with high survival and low survival. Other factors, such as site conditions, influenced seedling survival.

Stem diameter is a much better predictor of outplanting survival than shoot height. South and Mexal (1984) summarized studies dealing with loblolly pine seedling grade and survival. Seedling stem diameter predicted survival, and this relationship was curvilinearly over the range of stem diameters (Figure 3.6). They concluded, to consistently average survival above 80 percent, southern pine seedlings should have stem diameters greater than 4 mm.

Blake et al. (1989) reported a similar relationship between outplanting survival and stem diameter for Douglas-fir (Figure 3.7). He found the relationship between survival and diameter was also affected by seedling root mass, especially for smaller diameter seedlings. Seedlings with

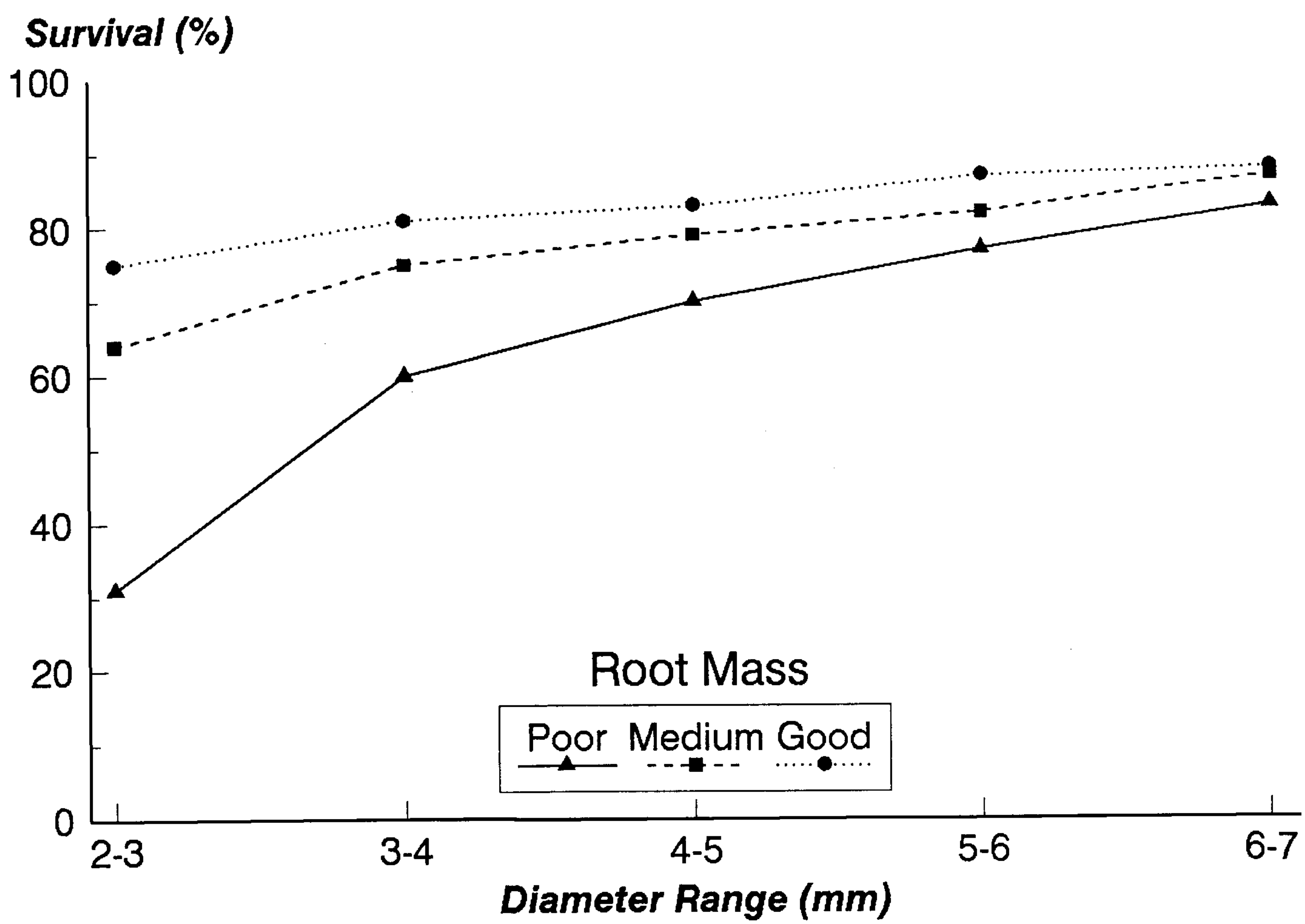


Figure 3.7—*Effect of seedling diameter on survival of Douglas-fir with good (?), medium (¦), or poor (?) root mass (after Blake et al. 1989).*

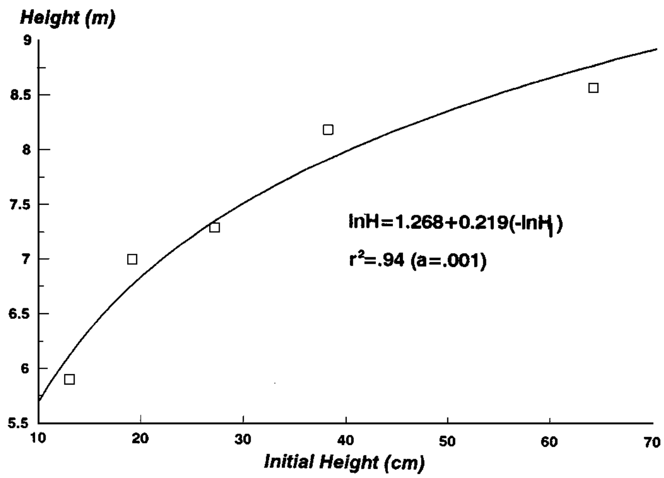
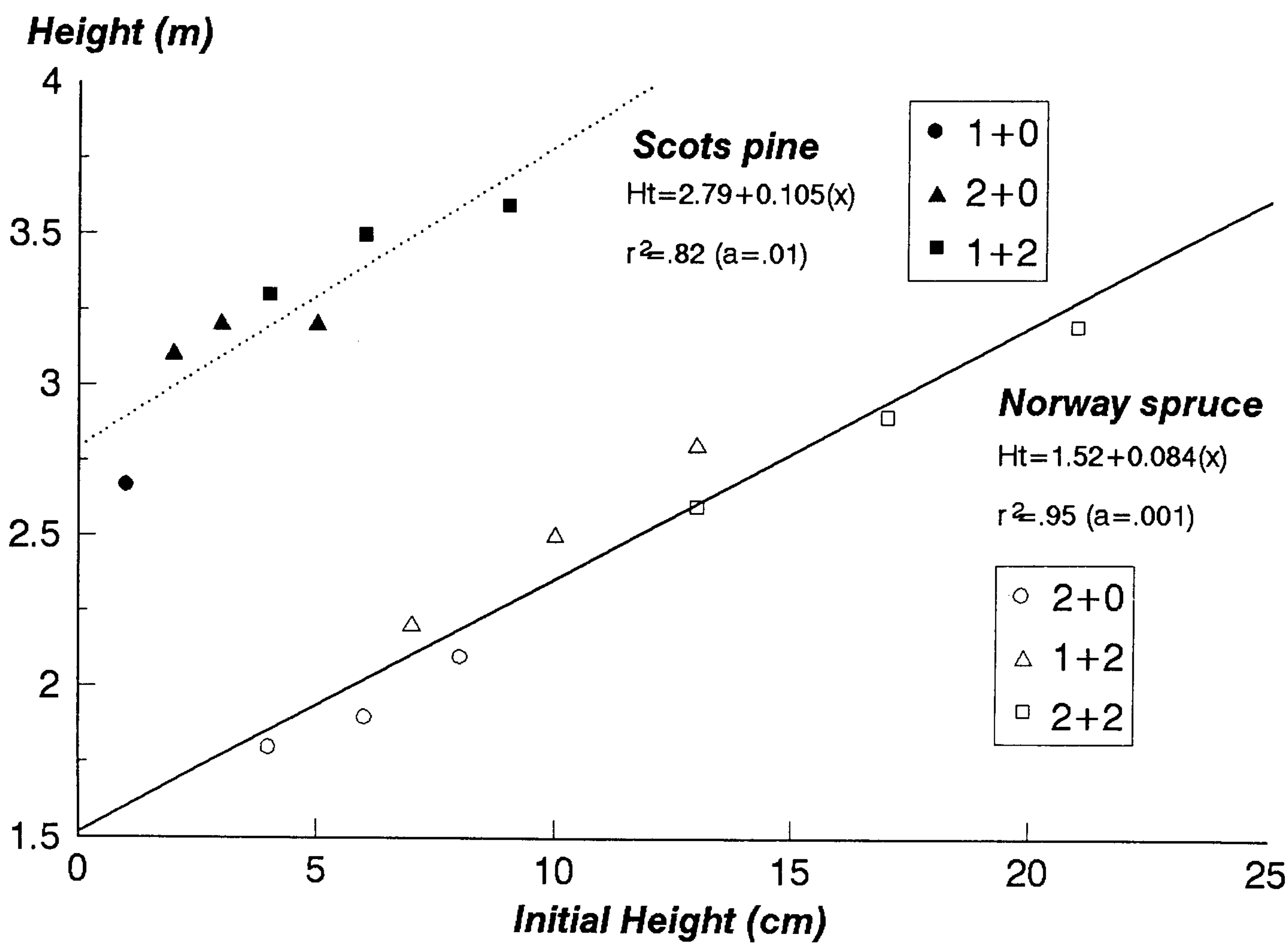


Figure 3.8—*Effect of initial seedling height on 11-year height growth of Douglas-fir (after Smith 1975).*

good root mass consistently survived better than those with poor root mass. Even seedlings normally considered culls (< 3 mm stem diameter) had high survival (> 70 percent) if they possessed a good root mass. However, only large seedlings (> 5 mm) had comparable survival potential with a poor root mass. In addition, cull seedlings with poor root mass had low survival. It would appear from these data, to ensure survival of 75 percent or greater, the nursery should provide large seedlings (> 5-6 mm), regardless of root mass, or incorporate root grades into the sorting operation.

From a practical standpoint, culturing the seedling crop to produce consistently large seedlings is the easiest choice, but it may not be the most economical. If grading based on root mass occurs, the nursery must be concerned with root stripping and exposure as a result of increased handling. This impact on performance must be considered

Figure 3.9—(*Below*) *Effect of initial seedling height on 15-year height of Scots pine and Norway spruce (after Mellberg and Naslund 1987).*



when weighing the benefits of growing to grade or culling to grade.

3.6.2 Growth

Growth following outplanting is more complex than initial survival and is related to the planting environment, the genetic potential of the seedling, and the physiological and morphological status at time of outplanting. Consequently, performance prediction based solely on seedling morphology may be clouded by other factors that may not be related with either morphology or nursery cultural practices, such as site conditions. Despite these confounding factors, there are many reports correlating subsequent height growth in the plantation with initial seedling height at time of planting. Smith (1975) found growth of 3+0 Douglas-fir seedlings was correlated with initial height of the seedlings (Figure 3.8). In the first growing season, height growth was not correlated with initial height. However, shoot growth in years 2 through 7 was highly correlated with initial height. For years 7-11, the growth rate among height classes was statistically different only for the shortest seedlings. Nevertheless, by year 11, a 0.5 m difference in seedling height at time of outplanting had grown to 2.7 m between the shortest and tallest seedlings.

The effect of initial seedling size on growth after outplanting appears to hold, regardless of how seedlings are cultured to attain the specified height. Mellberg and Naslund (1987) examined 15-year growth of Scots pine and Norway spruce seedlings of different stocktypes. They found height growth of different stock types was linearly related to initial seedling height (Figure 3.9). Thus, a 1+0 seedling would have the same performance potential as a 2+2 seedling if they were the same height at time of outplanting. For these species, large seedlings tend to outperform smaller seedlings, regardless of stocktype.

A similar relationship seems to hold for the effect of seedling diameter on long-term volume growth. South et

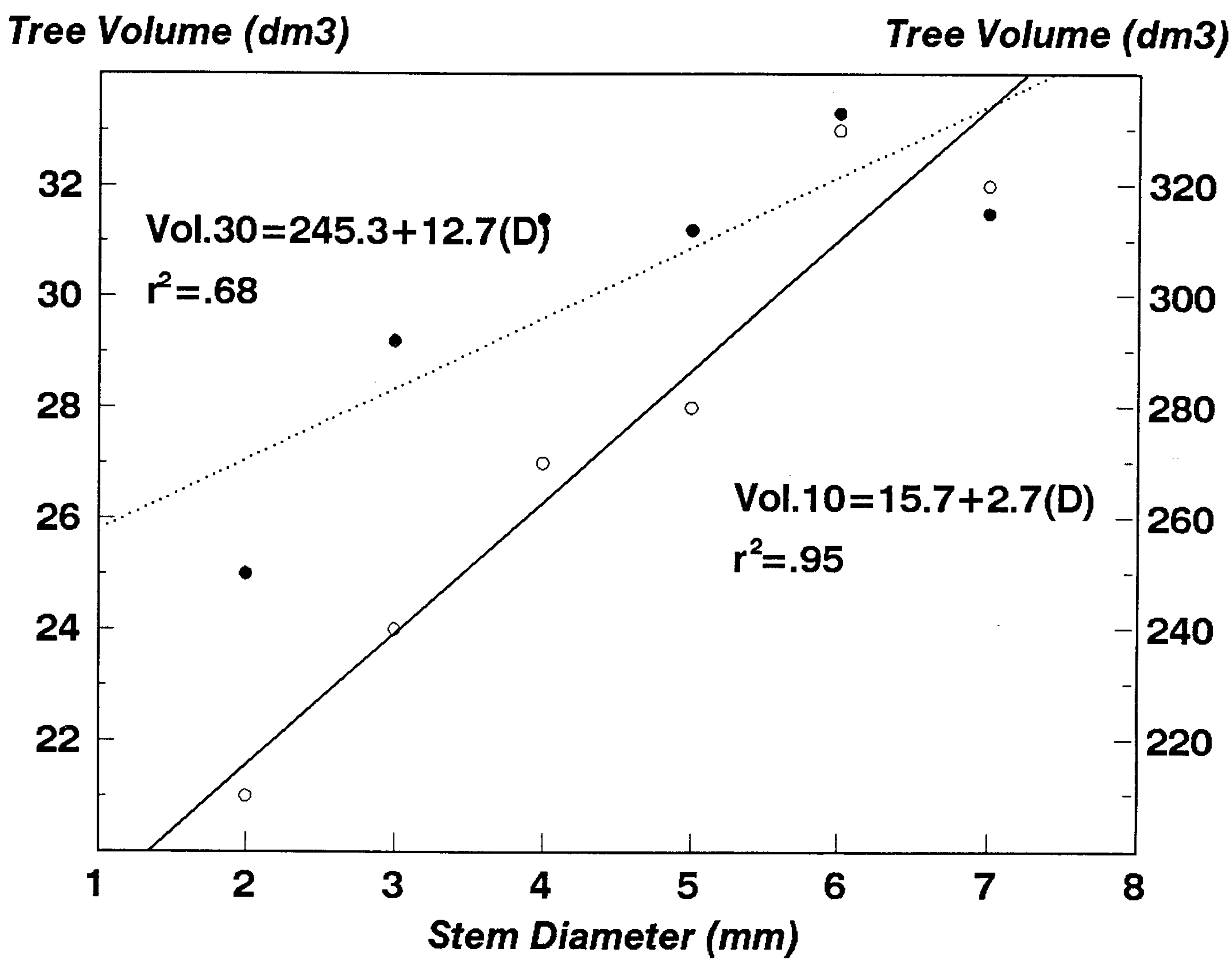


Figure 3.10—*Effect of initial seedling caliper on 10-year (O) and 30-year (?) volume of loblolly pine (South et al. 1988).*

al. (1988) examined 30-year growth of loblolly pine and found average tree volume was highly correlated with initial seedling diameter at time of planting (Figure 3.10). At 10 years of field growth, there was a 20 percent volume increase between 3 mm seedlings and 5 mm seedlings. At 30 years, the difference was 6.5 percent or 10.9 cubic decimeters/mm. The authors concluded the larger seedlings did not grow faster than smaller seedlings, but small differences in diameter at time of planting were maintained and expanded overtime. This suggests small diameter seedlings are not likely to catch large diameter seedlings.

3.6.3 Outplanting site interactions

Few studies have examined the interaction between seedling size and outplanting site quality. South and Mexal (1984) felt taller seedlings may have a competitive advantage on sites with severe weed competition or slash where shading may occur. On the other hand, shorter seedlings with less transpirational surface area may have the advantage on droughty sites. Blake et al. (1989) examined the interaction among seedling diameter, root mass and site quality for Douglas-fir outplanting sites. The sites were classified into average and severe sites. Severe sites were south facing slopes greater than 15 percent, and all other sites were classified as average. They found seedling survival was high (> 70 percent) on average sites when diameter exceeded 5 mm or root mass exceeded 0.6 g (Figure 3.11 A). Only seedlings with diameters less than 5 mm failed to survive well on average sites. Survival seemed to plateau when root mass exceeded 1 .0 g, regardless of diameter.

On severe sites, the relationship was similar, although survival in general was lower (Figure 3.11 B). Survival exceeded 70 percent only for large diameter seedlings and only if root mass exceeded 2.0 g. Furthermore, it appeared that further improvements in survival were attainable with seedlings larger than those tested.

For both sites, the relationship between survival and root mass was linear within a given stem diameter size. In general, as diameter increased, root mass increased and the advantage in survival of incremental gains in root mass decreased. Nevertheless, it appears, if the culling standards were 6 mm in diameter with a minimum root mass of 2.0 g, 7 survival percentages of 80 percent and 70 percent could be expected on average and severe sites, respectively.

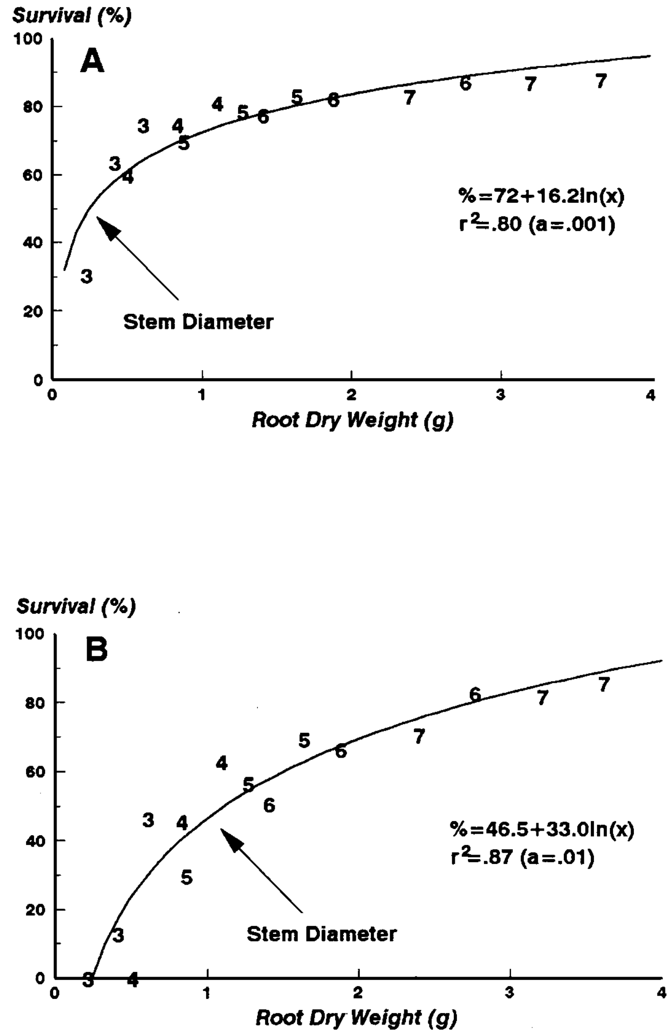


Figure 3.11—*Effect of root dry weight and seedling diameter on survival of Douglas-fir on average (A) and severe (B) planting sites (after Blake et al. 1989). Severe sites were classified as south facing with> 15% slopes.*

3.7 Future Directions

3.7.1 Current applications

The increased reliance on artificial reforestation over the past six decades has spawned an equally intense effort to identify reliable predictors of regeneration success. The term seedling quality was coined to described the attributes a seedling should possess in order to thrive folowing outplanting. Initially, easily measured parameters such as height and root collar diameter provided reasonble estimates of quality. However, exceptions were noted and the quest for physiologically based parameters began (Wakeley 1949).

Since 1949, many publications have focused on aspects of seedling quality. Among the many topics that are or were popular are cold-hardiness, dormancy, carbohydrate content, root growth potential, hormonal content, stress tolerance, electrical impedance, chlorophyll fluorescence and nutrient content. All of these define an important, albeit narrow, component of the myriad of factors that determine seedling performance. Consequently, none of these individual parameters reliably predicts field survival and growth across the many reforestation systems and cliates. They fall victim to the same criticisms that befell morphological parameters. That is, these parameters preict seedling performance under restricted circumstances and are, at times, even more restrictive.

Most discussions of seedling quality deal with measurble, quantifiable attributes of a seedling—the contents of the seedling. What attribute does the seedling possess that imparts success? How many new roots does it generate? How cold-hardy? How fast does it release from bud dorancy? How big is it? However, quality is not a simple, measurable parameter. It is not the content of the seedling that determines whether it will live or how rapid it will grow. It is the process of seedling production that deterines the quality of the seedling. What was the growing density? What was the fertilization schedule? When were the seedlings lifted? How long were the seedlings stored? These factors determine the degree of quality. We propose the process of seedling production defines the morphological quality as well as the physiological quality of the seedling at time of lifting. This process also defines the seedling's ability to withstand the rigors of harvesting and handling. Mistreatment following lifting can be ascerained by comparing physiological test results with expected results based on the process of production. However, seedlings produced through a quality process will better withstand mistreatment. As the process of seedling production becomes more important in defining quality, so will seedling morphology become more imporant in assessing seedling lots.

3.7.2 Future: engineering seedling grade

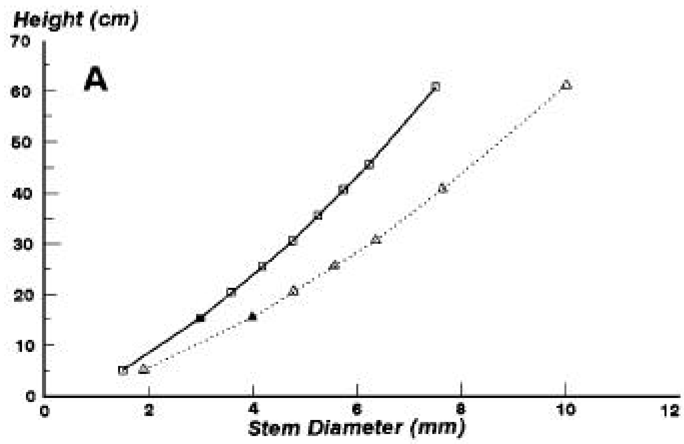
Today, most nurseries can grow seedlings to certain size specifications. All nurseries can cull to any size specificaion. However, few nurseries know how to grow to speciied quality standards. To do that, they must understand the process of quality seedling production and how envionmental conditions interact with the physiological makeup of the seedling to yield the resultant seedling morphology. The seedling morphology provides an insight into past cultural practices including sowing date, growing density, fertilization, irrigation, and root or shoot pruning. However, we often fail to look at the entire morhology. To most, seedling height and caliper are the only attributes examined.

It is difficult to characterize a seedling population in relatively simple terms. A sturdiness quotient (H/D) has been proposed and adopted in some production systems, most notably in New Zealand (Menzies 1988). Various quality indices have been proposed but not widely adopted (Dickson et al. 1960). This may be the result of the lack of data relating performance to the index. It is also the result of the changing relationships among morphological parameters as growing conditions change.

A technique that may prove useful in the future is to view the seedling as a cantilever beam. As a seedling (beam) extends in length, it must expand in diameter to maintain the same relative strength properties. This relationship is described by the equation

$$d_2^3 = \frac{w_2 l_2^2 d_1^3}{w_1 l_1^2}$$

where d is diameter (mm), l is shoot length (mm) and w is the specific shoot weight (g/mm). Over a narrow range (15-30 cm), w may be considered constant. However, over larger ranges (1 5-60 cm), w may vary 1 5 percent for pines (Rikala 1989) and 20 percent for Douglas-fir (Deans et al. 1989). Regardless, d changes as the cube root of w. For most purposes w can be considered constant.



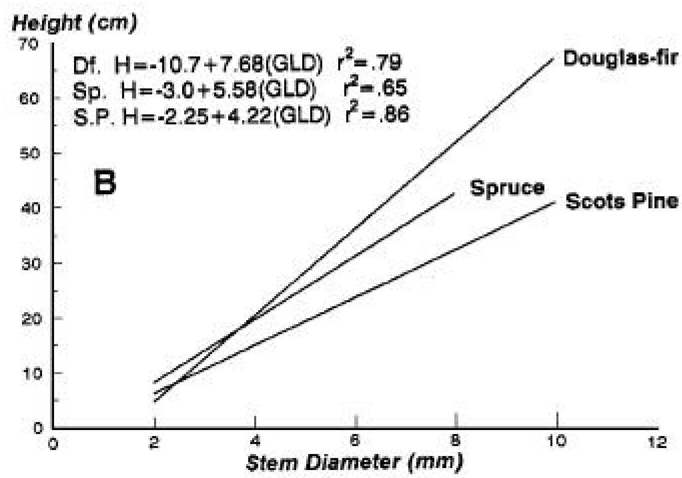


Figure 3.12—*A. Relationship between diameter and height using the cantilever beam equation and the standard height of 15 cm and diameter of 3 mm (¦) or 4 mm (?) B. Relationship between height and diameter for nursery grown seedlings (after Iverson 1984, after Mason et al. 1989).*

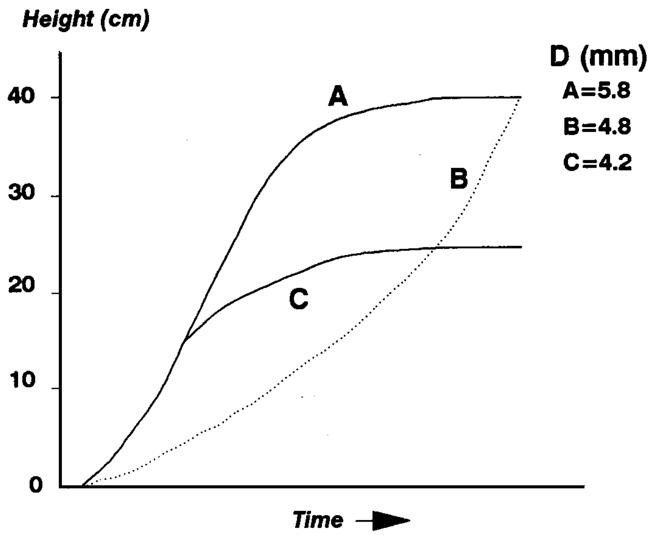


Figure 3.1 *3—Idealized height growth and final diameter of seedlings grown under three regimes.*

Consider a minimum size for plantable seedlings is 15 cm in length and 3 or 4 mm in diameter. Given these standards, the relationship between height and diameter can be calculated without correction for w (Figure 3.12A). For the tallest seedlings, d_2 is underestimated by about 7 percent without the correction for w. Theoretically, seedlings with height and diameter measurements falling along the curve would have similar strength properties and, therefore, similar performance attributes. Coincidently, the height-diameter relationships for Douglas-fir and spruce fall to the right of the curve developed using 15 cm and 3 mm as the standard (Figure 3.1 2B). Scots pine falls to the right of the curve using 15 cm and 4 mm as the standard. It appears empirical data collected over time support this hypothesis. Given minimum standards of 15 cm in height and 3 mm stem diameter, a 20 cm tall seedling would not be acceptable with a diameter of only 3 mm. This model suggests the diameter should be at least 3.6 mm. If the standards were 15 cm and 4 mm, a 20 cm seedling should have a diameter of 4.8 mm.

This relationship can be used to compare seedlings grown under different regimes. In the example in Figure 3.13, seedlings A and C have different morphologies but similar strength properties. Both seedlings fit the curve using 15 cm and 3 mm standards. Seedling B falls to the left of this curve. It is spindlier than the others and should not have the same strength properties. This seedling meets the minimum culling standards, yet the quality of this seedling is not the same as the others. Theoretically, seedlings A and C would survive better than seedling B, and seedling A would grow faster than B and C. The growth differences between B and C would depend on the severity of transplant shock for seedling B. Seedling C would suffer less transplant shock and exhibit greater absolute growth. At the end of the transplant phase, the taller seedling would expand any growth advantage.

The target seedling is not one seedling possessing specific morphological features. The target is a continuum of variables fitting the general concept of sturdiness and size. The process of achieving the target specifications is much more important than the actual attainment of those specifications. In fact, the crop may fail to reach the target height requirements, yet exceed the target diameter requirements. This seedling would have exceeded the target. The target cannot be economically attained by culling the crop to meet the standard; the crop must be grown to achieve the standard.

3.8 Conclusions

Growing the target seedling is a process that can not be easily quantified by snapshots-in-time of either the morphological or physiological features of the seedling. These provide some, but not all of the picture. It is likely no single factor will ever be found that will provide a perfect prediction of outplanting success. Stem diameter and shoot height have proven their utility over many years. These two parameters are universally accepted measures of seedling performance potential.

Both stem diameter and shoot height are affected by cultural practices in the nursery, especially growing density, transplanting, top-pruning, and root culturing. Stem diameter is a good predictor of other morphological characteristics, including height, and both shoot and root dry weight. Apparently, stem caliper reflects the entire seedling's response to the environment. However, stem diameter and shoot height may not be correlated with physiological measures of performance prediction. Reasons for this are discussed.

Stem diameter is a good predictor of outplanting survival, especially when an estimate of root mass is included. It is also correlated with long-term tree volume growth. Shoot height is not highly correlated with seedling survival, but is a good predictor of growth following outplanting. While these characteristics indicate a seedling's performance potential, they do not reflect seedling vitality or vigor. Combining morphological measurements with an appropriate measure of physiological quality may result in improved indices of outplanting performance.

Future target standards will integrate the process of producing seedlings with the content (measurements at the end of the production). Future target standards may resemble the cantilever beam equation which integrates several variables into one equation. Undoubtedly, future standards will include information on cultural practices that produced the visible morphological features, as well as the unseen physiological parameters, both of which play a critical role in reforestation success.

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