PRODUCTION OF BAREROOT CONIFER PLANTING STOCK

WITH HIGH ROOT GROWTH POTENTIAL

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ABSTRACT

The most important seedling attributes related to performance after outplanting are the abilities to resist stresses and to grow new roots. Factors that affect the development and/or maintenance of root growth potential (RGP) include genetics, seedbed density, fertilization, shoot pruning, root culture, soil moisture management, dormancy and cold hardiness status at lifting, and storage conditions and length. Cultural treatments may increase root fibrosity, increase stored carbohydrates, or speed dormancy and hardiness development, and thus indirectly increase RGP. Seedlings must be lifted within lifting window(s) to capture a high level of RGP and stress resistance that can be transferred to the field or maintained in storage. It is normal for stored carbohydrates and RGP levels to diminish in longer term storage, but the real advantage of storage is that it extends seedling dormancy and RGP levels well beyond those in seedlings remaining in the seedbeds.

INTRODUCTION

Planting stock quality is often evaluated in terms of several desirable morphological and physiological attributes, and is usually assessed at the time seedlings leave the nursery. Root growth potential (RGP) is a particularly important attribute of planting stock quality because it integrates numerous morphological and physiological factors into a single biologically meaningful estimate of performance -- the ability of seedlings to grow new roots. Basically, if there is anything physiologically wrong with a seedling, it will show up as a decrease in the ability to produce new roots in a favorable environment.

Survival and growth of transplanted bareroot seedlings are critically dependent on the seedlings' ability to resist stresses and grow new roots. New roots are necessary to: 1) re-establish the root-to-soil contact, 2) absorb water and nutrients, and 3) avoid plant moisture stress (Sands 1984). Roots also produce phytohormones that support shoot growth (Skene 1975). New, unsuberized roots are much more efficient in absorbing water and nutrients than suberized roots (Carlson 1986). Growth of new roots into the surrounding soil re-establishes the intimate root-to-soil contact necessary for efficient water and nutrient transfer, and expands the root system sorption zone.

In addition to measuring the ability of seedlings to grow new roots, RGP may also estimate seedling hardiness. Periods of high RGP apparently coincide with periods of high cold hardiness and stress resistance (Ritchie 1985, Ritchie and Shula 1984, Tinus et al. 1986). Thus, when we measure RGP we may also be obtaining an estimate of the relative stress resistance of the seedlings.

This paper discusses nursery practices that contribute to the development of RGP, and lifting and storage practices that can capture a high level of RGP and maintain it until shipping. The information and principles regarding dormancy and cold hardiness in this paper pertain to northern species and nurseries. The southern conifers do not have a well-defined and predictable dormancy progression and can be cool-stored for only short periods'.

TERMINOLOGY

The subjects discussed in this paper require a clear understanding of dormancy and cold hardiness, and their interrelationships. A brief review is provided here; for more detailed information, see Lavender (1985).

Dormancy and cold hardiness are sometimes mistakenly used synonymously, but in fact they are separate but related physiological processes (fig. 1). Dormancy is a physiological condition of the terminal bud. A dormant bud is said to be quiescent when dormancy is imposed by the environment (Lavender 1985), e.g. decreasing day length, drought stress, or low temperatures. A dormant bud is said to be in rest or deep dormancy when dormancy is maintained by agents within the bud itself (Romberger 1963). Chilling is the gradual release of rest (and transition back into quiescence) in response to exposure to temperatures of approximately 5° C (Lavender 1981). The chilling requirement is met with the accumulation of a certain number of hours of effective chilling. The time to complete chilling depends on species, seed zone, and environment.

Cold hardiness, on the other hand, is a physiological condition of the whole plant, and is defined as the lowest temperature to which a plant can be exposed without being damaged (Levitt 1980). Although the term is defined in terms of cold hardiness, cold is only one of several stresses to which seedlings are resistant during winter; others include heat, desiccation, lifting, and storage (Lavender 1985). The development of cold hardiness is termed acclimation, and the loss of cold hardiness is termed deacclimation (Levitt 1980).

In northern continental climates, determinate conifer seedlings enter dormancy (set a terminal bud) by mid-summer, and usually have reached or passed deep dormancy by late fall. Bud development must be complete and seedlings physiologically in phase with the environment before entering deep dormancy, which in turn is a prerequisite for proper development of cold hardiness (Lavender 1985). Cold hardiness develops gradually in response to drought or shortening day length, then more abruptly in response to cold temperatures (Levitt 1980). With the accumulation of chilling hours, cold hardiness intensifies and dormancy is released.

CULTURAL PRACTICES THAT AFFECT THE DEVELOPMENT OF RGP

From seed to lifted planting stock, many factors contribute to the development of RGP. These include genetics, seedbed density, fertilization, shoot pruning, root culture, and soil moisture management. The effects of these cultural treatments can be assumed to differ among species, nurseries, and years. These factors are discussed individually in the following sections.

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Genetics

RGP can differ significantly among seed sources or families within a species (Carlson 1986, Nambiar et al. 1979, DeWald and Feret 1985, Jenkinson 1980, Sutton 1983). Some of the genetic differences in level of RGP are related to soil temperature (Carlson 1986, Nambiar et al. 1979), i.e. certain seed sources or families are more capable of growing roots at lower soil temperatures. In other instances, seedlings from different seed zones may have inherent differences in the level of RGP (Ritchie 1985, Sutton 1983). Utilization of these genetic differences in RGP, as well as genetic differences in drought resistance, could contribute significantly to planting stock quality and tree growth (Newton et al. 1985).

Seedbed Density

In general, lowering seedbed density produces seedlings with larger stem diameter, and heavier shoots and roots (Duryea 1984). Carlson (1986) found a gradual increase in root volume of loblolly pine (*Pinus taeda* 1.) seedlings as seedbed density was reduced from 147 per lineal bed foot to 103 per lineal bed foot, then a more rapid increase as density was further reduced to 50 seedlings per lineal foot. Seedlings with larger root volume tend to also have higher RGP (Carlson 1986, Brissette and Roberts 1984), but this may not always be the case (Feret and Kreh 1986). The increase in RGP with larger root systems is apparently due to more sites for new root growth (Carlson 1986, Nambiar et al. 1979).

Fertilization

The possible benefits of moderately high fertilization levels to seedling quality are larger seedlings and higher nutrient and carbohydrate concentrations. The possible drawbacks, especially from high nitrogen levels, are delayed dormancy and reduced cold and drought hardiness (Duryea and McClain 1984). There is strong evidence to suggest that seedling dormancy and cold hardiness status at time of lifting are strongly related to RGP levels, as will be explained later in this paper. Thus, management of soil fertility to encourage bud development, tissue maturation, dormancy deepening, and development of hardiness in late summer can be expected to favor the development of RGP. Late summer withdrawal of nitrogen, in concert with moisture stress and decreasing day length, is an important factor in dormancy deepening (van den Driessche 1980). High potassium levels, or more specifically the ratio of potassium to nitrogen, are important for the development of cold hardiness (Timmis 1974, van den Driessche 1980).

There are few reports of specific effects of fertilization on RGP. Bickelhaupt (1987) found that additions of sulfur and sulfuric acid to seedbeds to reduce soil pH resulted in seedlings with higher RGP. Feret et al. (1984) found that increasing soil organic matter with sawdust amendments reduced RGP (measured in December) of loblolly pine seedlings. Doubling the operational levels of nitrogen enhanced RGP by approximately 35%. The negative effects of high nitrogen fertilization on dormancy deepening and cold hardiness, and the effects on RGP reported by Feret et al. (1984) appear to conflict. However, these results are not necessarily conflicting if seedlings are fertilized with nitrogen late in the growing season when dormant so that they have both a high degree of cold hardiness and high nitrogen concentration (Margolis and Waring 1986a, 1986b).

While fertilization can increase seedling nutrient and carbohydrate concentrations, and it is known that root activity requires nutrients and carbohydrates, there does not appear to be a direct relation between nutrient and carbohydrate levels and RGP (Ritchie 1982, Ritchie and Dunlap 1980). The consensus seems to be that carbohydrate levels are most likely to affect root growth after outplanting when the seedlings must rely on dwindling stored carbohydrates for maintenance respiration and new root growth until photosynthesis begins (Marshall 1985).

Shoot Pruning

Shoot pruning is used to control height of nursery stock and to facilitate lifting, packaging, and planting. The amount and timing of shoot pruning have important effects on RGP. In white spruce (Picea glauca (Moench) Voss) seedlings, 25-50% removal of shoots slightly increased the number of new roots produced, while 75% removal significantly decreased new root initiation (Carlson 1977). Feret et al. (1984) reported that shoot pruning (no degree specified) of loblolly pine seedlings significantly decreased RGP. Timing of shoot pruning is important because the seedlings must have sufficient time remaining in the growing season to develop a mature resting terminal bud.

Root Culture

Undercutting and wrenching are stress-inducing practices that are widely used to modify seedling morphology and condition seedlings before lifting. The possible effects are early cessation of shoot growth, increased root system fibrosity, improved root/shoot balance, increased drought resistance, and promotion of dormancy deepening (Duryea 1984). The actual effects may vary greatly among species, and with how and when root culture is applied. Bacon and Bachelard (1978) found that wrenching of Caribbean pine (Pinus caribaea Mot. var hondurensis) seedlings induced a ten-fold increase in RGP. Similar results were reported for radiata pine (Pinus radiata D. Don) (Rook 1969). However, other workers have reported mixed results. Duryea and Lavender (1982) found that wrenching Douglas-fir (Pseudotsuga menziesii (Mirb.) Franco) seedlings lowered the shoot:root ratio, but did not improve water relations or field survival and growth, compared to unwrenched seedlings. Similarly, van den Driessche (1983) found that wrenching of Douglas-fir (Pseudotsuga menziesii (Mirb.) Franco) seedlings produced only a small increase in survival of outplanted seedlings. When wrenching was supplemented with fertilizer treatments, the seedlings had increased nutrient concentrations, root weight, and RGP, but lowered cold hardiness. Feret and Kreh (1986) found that undercutting loblolly pine seedlings reduced shoot biomass, but did not change RGP. The net effect was an increase in the amount of new root growth per unit of shoot weight.

Basically any treatment (such as wrenching) that reduces shoot or root growth, when environmental conditions are favorable for growth, would be expected to favor accumulation of carbohydrates. The effectiveness and longevity of wrenching treatments are closely related to timing, depth, and frequency (van Dorsser and Rook 1972). Conditioning treatments should not be starvation nursery practices. Providing adequate fertilization will ensure that the seedlings also have good mineral nutrient status (Duryea and McClain 1984). However, mid-season fertilization increases the risk of unwanted late-season shoot growth, especially when temperatures and soil moisture are favorable. An alternative is to fertilize late in the growing season when the seedlings are dormant (Margolis and Waring 1986a, 1986b). The effects of wrenching on RGP appear to be mostly indirect: 1) wrenching may reduce shoot growth, increasing stored carbohydrates (Marshall 1985) and reducing the shoot:root ratio; 2) wrenching may influence the seedlings' passage into physiological dormancy (Cobb 1977); and 3) wrenching may increase root fibrosity, providing a larger framework for new root growth (Carlson and Larson 1977, Nambiar et al. 1979).

Soil Moisture Management

Soil moisture management techniques are used to induce plant moisture stress in the seedlings during mid- and late summer to push them into physiological dormancy (Zaerr et al. 1980). In climates where summer rainfall is plentiful and-restricting irrigation is not effective, undercutting and wrenching can be used to induce stress. Rook (1973) reported that seedlings that were water-stressed for 6 weeks before lifting had significantly higher RGP than unstressed controls.

LIFTING AND STORAGE PRACTICES

THAT CAPTURE AND MAINTAIN A HIGH LEVEL OF RGP

Dormancy and Cold Hardiness Status at Lifting

Key factors in producing planting stock with high RGP are dormancy and cold hardiness status at lifting. Note that in the previous section, the principal effects of the cultural factors discussed are in promoting dormancy deepening, bud development and maturation, and cold hardiness.

The best interpretation of research evidence to date suggests that RGP rises after deep dormancy has been attained, intensifies in winter coincident with the accumulation of chilling hours, peaks with the fulfillment of the chilling requirement and the development of maximum cold hardiness, and falls abruptly at approximately the time of bud break, i.e. minimum cold hardiness (Ritchie and Dunlap 1980, Ritchie 1985, Stone et al. 1963, Tinus et al. 1986). The actual pattern of RGP can vary widely, depending on climate, species, and seed zone (Jenkinson 1980). The period of maximum RGP and cold hardiness apparently also coincides with the period of maximum stress resistance (Hermann 1967, Lavender and Wareing 1972, Lavender 1985, Jenkinson and Nelson 1984, Ritchie and Shula 1984, Ritchie et al. 1985). This period when cold hardiness, stress resistance, and RGP are optimized is the "lifting window" (fig. 1), the ideal lifting period when a high level of RGP can be captured

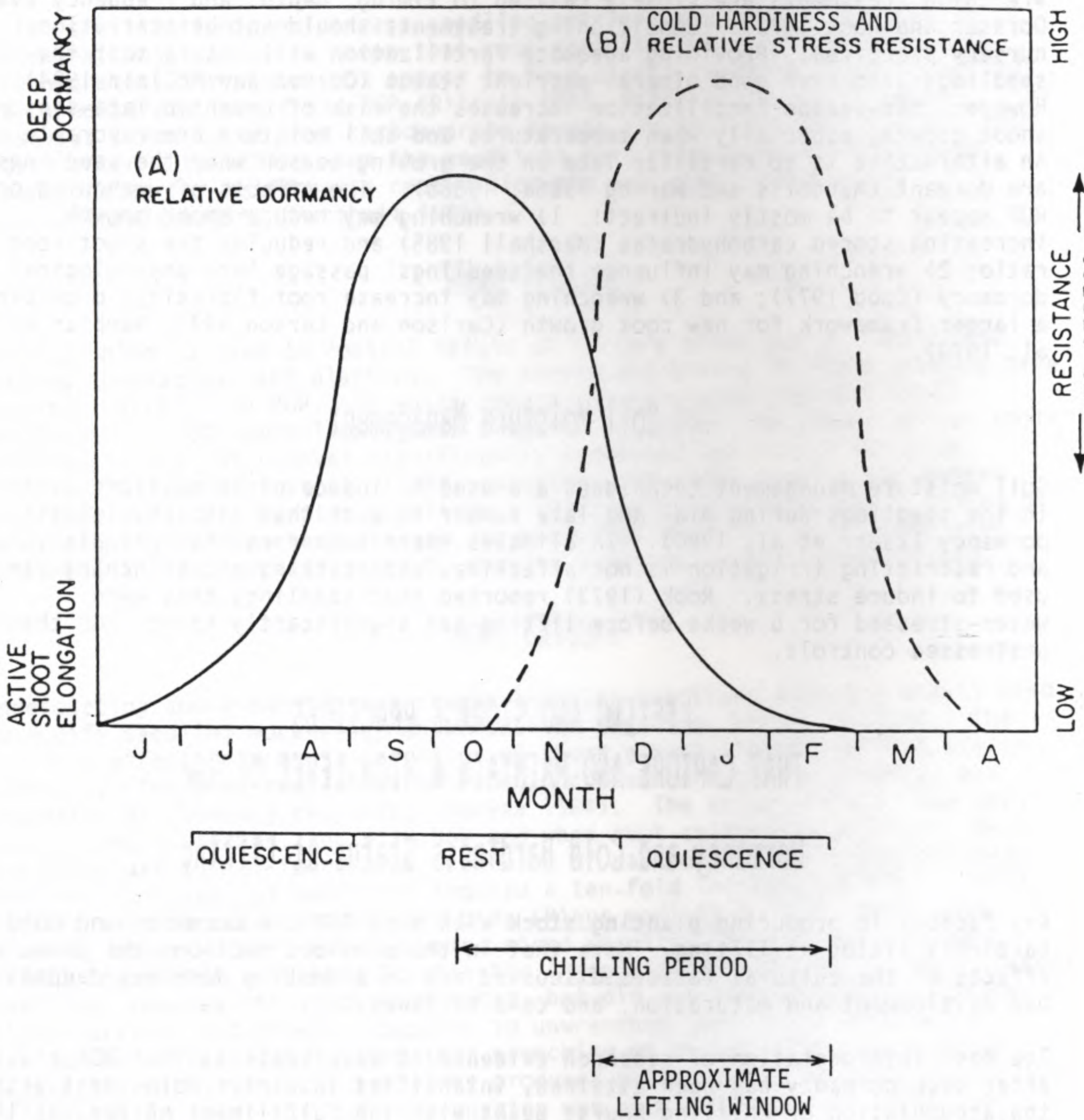

Figure 1. The generalized relationship between bud dormancy and whole plant cold hardiness, adapted with permission from Lavender 1985.

and maintained in storage. This period occurs in late winter for most species (Ritchie et al. 1985). For coastal Douglas-fir, seedlings are commonly lifted in mid-winter within the lifting window and either planted or stored with good success (Jenkinson 1980, 1984). However, in nurseries subject to winter freeze-up, the optimum lifting window is normally closed. The alternatives are late fall lifting and overwinter cold storage or late winter lifting and temporary cool storage. In either case the seedlings are not at their physiological peak when lifted. Obtaining acceptable results with either approach critically depends on timing lifting with seedling dormancy status and degree of cold hardiness.

For fall lifting, dormancy status on a particular date can vary tremendously from year to year, and lifting the seedlings when they are not sufficiently dormant or cold hardy can have disastrous results in overwinter storage. Dormancy development is usually not a problem, especially if soil moisture management and wrenching are utilized as cultural tools to induce plant moisture stress and push the seedlings into dormancy. However, dormancy release and development of cold hardiness are quite another matter, over which we have limited control. Basically, seedlings need some minimum level of cold hardiness before lifting to develop sufficient stress resistance for successful storage and maintenance of high RGP in storage (Krugman and Stone 1966). However, during fall the seedlings are adversely affected by pre-lift deacclimation, the reversal of cold hardiness caused by warm temperatures. Stone and Norberg (1979) reported that warm temperature interruption of hardening before seedlings are lifted and placed into cold storage may reduce post-storage RGP as much as 807. This is disheartening, because we have little control over the rate of acclimation of the seedlings during the fall, and the occurrence of deacclimation leads to confusion about the actual status of the seedlings. Yearly variations in the progression of dormancy and cold hardiness and the occurrence of deacclimation may partially explain among-year and among-nursery variation in the success of storage and the level of post-storage RGP. The optimum lifting time may not be attainable in some years and at some nurseries.

At the time of late winter lifting, the seedlings are typically fully chilled and in a quiescent state maintained by low temperatures. RGP may be very high in later winter, up to the time of bud burst (Stone et al. 1963, Tinus et al. 1986). However, cold hardiness, stress resistance, and RGP all decrease abruptly during this period (Tinus et al. 1986). Thus, in some years, when the transition from winter to spring is very fast, it may be operationally impossible to lift the seedlings with good physiological timing, or even with acceptable physiological timing. Ritchie et al. (1985) found that fall lifting and overwinter cold storage were better, in terms of seedling physiology, than spring lifting and cool storage. Ultimately, in order to obtain clear answers to these dilemmas, we need a better understanding of the relations among dormancy, chilling, cold hardiness, stress resistance, and RGP. Assuming that these relations are unique for species and seed zones, and are strongly influenced by environment and culture, lifting and storage strategies based on seedling physiology would have to be developed for each nursery. Such an undertaking would include: (1) identifying dormancy, cold hardiness (stress resistance), and RGP patterns for each nursery, species, and seed zone; (2) identifying the optimum and usable lifting windows; (3) relating these windows to an easily measured parameters, such as chilling sum, to predict dormancy and/or cold hardiness intensity; and (4) developing a quick test to detect the actual status of dormancy release or cold hardiness. Such an approach would provide detailed information on the patterns and relationships of these processes, a model to predict the current status, and a quick test to verify it. One chilling sum parameter that may be sui.table for predicting dormancy intensity is "accumulated chilling units" (Richardson et al. 1974) because it corrects for temperatures above and below the effective chilling range. Suitable methods to verify the degree of cold hardiness are electrical resistance and electrolyte conductivity (Glerum 1985).

Effect of Storage on RGP

When seedlings are lifted at a suitable time and placed into cold or cool storage, dormancy release does occur but at a reduced rate (Ritchie 1987). Apparently the storage temperatures are not very efficient for releasing dormancy. The net effect is that stored stock will be more dormant at planting time than stock that had been allowed to remain in the nursery beds. It is primarily because of this relationship that cold storage works as well as it does.

RGP may increase, decrease, or remain unchanged during storage, depending upon seedling bud dormancy/acclimation status at lifting, storage temperature, and duration of storage (Ritchie 1987, Stone 1970). If seedlings are lifted before the period of deep dormancy, when buds are not physiologically responsive to chilling, storage is often unsuccessful and RGP can be severely reduced during storage (Stone and Jenkinson 1971). On the other hand, seedlings lifted when fully dormant and cold hardy and placed in storage will show a gradual increase in RGP until their chilling requirement is satisfied, then RGP will decline (Ritchie and Dunlap 1980).

It is normal for seedling carbohydrate reserves to be depleted by respiratory maintenance during storage (Marshall 1985, Rietveld, et al. 1983, Ritchie 1987). The depletion rate will depend on the seedlings' physiological condition when they entered storage, storage temperature, and storage duration. Storage temperatures within the range of -2 to +5°C are most beneficial to chilling and maintenance of stored carbohydrates.

SUMMARY AND CONCLUSIONS

1. Certain cultural factors (seedbed density, undercutting, wrenching) may affect RGP by increasing root system size, and consequently the number of sites for new root growth, while others (wrenching, soil moisture management) may induce plant moisture stress and push the seedlings into physiological dormancy.

2. Dormancy and cold hardiness status of the seedlings at lifting strongly affect the level of RGP that is "captured" in lifted seedlings. Ideally, seedlings should be lifted within their "lifting window", a period when dormancy release is occurring in response to chilling, and cold hardiness, stress resistance, and RGP are at high levels. However, this ideal period occurs in mid-winter for most species, a time when frozen ground precludes lifting in most northern nurseries. The alternative late fall and late winter windows are less than ideal, and can result in unsuccessful storage and low RGP after storage if lifting is poorly timed with seedling physiology.

3. For late fall lifting, dormancy development is usually not a problem, especially if cultural practices have been utilized to induce plant moisture stress and push the seedlings into dormancy. Factors complicating the prediction of seedling readiness for lifting are yearly variation in the dormancy/cold hardiness progression and warm temperature interruptions, which cause deacclimation -- the reversal of dormancy release (chilling) and cold hardiness development. This may partially explain the among-year and among-nursery variations in the level of post-storage RGP.

4. By the time of late winter lifting, dormancy release is typically complete and the seedlings are quiescent. During that period, RGP may be at high levels up to the time of bud burst, then abruptly drop. Cold hardiness and stress resistance also drop abruptly at about the same time, so seedlings resistance to stresses (such as cold, desiccation, lifting, and cool storage) also diminishes, and is lowest at the time of bud burst. Because the transition from winter to spring can be very fast in some years, it may be operationally impossible to lift seedlings with good, or even acceptable physiological timing.

5. To enable the development of reliable operational procedures to lift seedlings when they are physiologically ready, and maintain RGP in storage, we need fundamental research on the relations among seedling dormancy, chilling, cold hardiness, stress resistance, and RGP, as well as on the interactions of these factors with culture and environment.

6. Prediction of seedling dormancy and cold hardiness status is highly desirable, but so far has not been adequately modeled and enabled. Development of such information will be a big effort, involving the determination of the dormancy, cold hardiness, and RGP progressions for each species and seed zone grown at each nursery. Then usable lifting windows can be determined and predicted by relating them to chilling sums. A chilling sum parameter that accounts for temperatures above and below the effective chilling range should be used. The predicted dormancy/cold hardiness status should then be verified with a quick test of cold hardiness such as electrical resistance or electrolyte conductivity.

7. Storage losses of RGP and carbohydrates can be greatly reduced once we better understand the relations of seedling dormancy and cold hardiness to RGP. For nurseries that can lift only in the fall and later winter, we must understand and learn to work with the limitations. Additionally, it appears that we can make significant gains in maintaining RGP and stored carbohydrates through improved storage and handling practices.

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