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Impact of Handling Practices on the Quality of Bare-Root Plants: A Review[1]

Bernard Goyette[2,3], Marlène Piché[4], Michael Brownbridge[3], and Darby McGrath[3]

Abstract

There is a need to develop methods that would allow plant health and survival potential to be quantified in real time, particularly in the different phases of bare-root handling. Such methods would allow the impact of different stresses experienced throughout storage and transport on establishment success and growth of the bare-root plant to be quantitatively defined. This review concentrates on the impact of pre-lifting, pre-transplanting and post-transplanting considerations and identifies tools that can be applied for monitoring plant quality. Root and shoot culturing, lifting and transplanting timing, water stress and storage/transport handling are all significant factors in the post-transplant performance of bare-root material. Different postharvest tools and indicators are also examined for their efficacy and contribution to plant quality. Chlorophyll fluorescence and root respiration are useful as indicators of water stress and dormancy; however, more practical equipment should be developed in both instances for greater adoption of these practices. Hydrophilic gel slurries can be used either during storage and immediately prior to transplant as an additional prevention of desiccation but will not restore vigor to damaged plants. Cold storage at optimum temperature should be adapted to maintain the target relative humidity; otherwise the storage period should not exceed 4 weeks for unprotected bare-root plants. Many improvements have been made in the ability to predict the effects of stresses experienced by bare-root material. However, more equipment, metrics, species and site specific research would enhance monitoring of bare-root quality.

Index words: quality, pre-lifting, postharvest, storage, pre-transplanting production.

Significance to the Horticulture Industry

There is increasing pressure for horticultural producers to become more efficient in production and to generate quality plants that can be established easily (McKay 1997). The instability in the global economy has also impacted horticultural production over the last decade. For instance, during the 2008 economic recession that impacted the United States, the industry suffered a series of nursery closures (Weilland et al. 2013). Since 2008, there has been some growth in horticultural production. The western states of California, Idaho, Montana, Oregon and Washington, for example, produced approximately 200 million seedlings in 2011; 150 million were sold as bare-root stock (Weilland et al. 2013).

Bare-root seedling production in the southern and pacific United States, British Columbia, New Zealand, France, Ireland, Britain and southern Sweden is still the preferred practice, although some growers are converting to container-grown stock (McKay 1997). However, demand for bare-root nursery stock remains important for reforestation efforts and for importing and exporting of horticultural products.

Production of bare-root horticultural plants is an excellent option for niche products or for those destined for export. Indeed, international trade regulations demand that plants that are exported must be free from soil to prevent the potential transfer of insect pests and diseases. *Phalaenopsis* sp. orchid, for example, is a high value crop that is exported around the world as a bare-root plant. The ability to access a global market has led to *Phalaneopsis* hybrids becoming one of the most important floriculture crops in the United States with a wholesale value of $144 million in 2005, an increase of 11.5% over 2004 (Weilland et al. 2013).

Bare-root plants are relatively inexpensive to purchase and shipping costs are low, owing to the absence of bulk soil around the roots. Field planting is straightforward with modest associated costs, and survival and growth of transplanted material is generally acceptable. Compared to balled-and-burlapped trees, shipping and handling costs for equivalent bare-root trees are 33 to 50% lower (Anella et al. 2008).

Bare-root production has advantages in the nursery and forestry sectors because the investment per plant is lower and the cost to the consumer is less than container-grown or balled-and-burlapped production. For the many advantages of bare-root production, there are also many challenges to be addressed and overcome, particularly having to do with reducing stress during postharvest and improving survival and performance post-transplant.

Introduction

Assessing bare-root plant quality during postharvest is challenging because combined environmental stresses can have a cumulative effect on plant performance (McKay 1997). A primary challenge for the industry is to refine production systems and metrics for monitoring plant quality towards ones which provide an end-product with high transplant survival rates. Prospective quality monitoring protocols that target plant stress in the pre-transplant phase should be expanded upon. Some parameters are more important than others when assessing the quality of seedlings, but many have been evaluated with a view of developing a practical means of predicting seedling performance after transplanting. This includes measures such as mineral nutrient content, carbohydrate status, cold hardiness, shoot-to-root ratio, root electrolyte leakage (Apostol et al. 2009), root growth potential (McKay and Morgan 2001), root moisture content (Baltazar-Bernal et al. 2011), root collar diameter (McNabb

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[2]Corresponding author, Bernard.Goyette@vinelandresearch.com.

[3]Vineland Research and Innovation Centre, 4890 Victoria Avenue North, POB 4000, Vineland Station, ON, Canada L0R 2E0.

[4]Professional consultant.

and Vanderschaaf 2005), root volume and first order lateral root development (Jacobs et al. 2005), and shoot xylem pressure potential, water status and different morphological characteristics (Cabral and O'Reilly 2005). Physiological characteristics are of interest but are often considered to be difficult to implement, strenuous to evaluate, time consuming and most of the time require destructive methods (Jacobs et al. 2005; Ritchie 1982).

The three bare-root production time periods addressed here include: pre-lifting, pre-transplanting and post-transplanting. The pre-lift phase examines the effect of lifting date, effects of shoot pruning and effects of root culturing. The pre-transplant phase includes discussion on storage, transport, acclimatization and desiccation. The tools discussed include carbohydrate fractions, root respiration, dipping and coating. The post-transplant includes discussion on planting date and tissue desiccation. The tools discussed include morphological parameters, dips and soaking.

The objective of this paper is to describe the challenges to survival and performance of bare-root material. The practical purpose of this review is to identify gaps in knowledge regarding postharvest handling of bare-root stock and examine current applications and tools for monitoring plant quality between lifting and planting. This review aims to build on existing literature, both academic and professional, and to identify the gaps and opportunities for innovation in bare-root production tools and metrics.

Pre-lift

Challenges and considerations. Pre-lift monitoring helps to determine the timing of lifting and the storability of the plants at lifting in order to ensure plants will survive in cold storage (Simpson 1986). At the pre-lift point, moisture stress is of paramount concern. Measuring xylem pressure potential allows for understanding the level of stress the plants are experiencing. The irrigation regime can then be adjusted prior to lifting, sorting and grading, all practices which will further stress the plants (Simpson 1986). Timing of lifting interacts with moisture stress, dormancy and cold hardiness of the species, which should be factored into the decision on when to lift plants. Mitotic activity of meristematic shoots has been used to predict when to lift conifer seedlings (Calmé et al. 1993). Dormancy release indexes (Ritchie 1982; Ritchie 1984) have also been used to choose lifting dates, but this measurement requires 10 to 60 d, so it is often not a practical assessment tool.

Lifting date. Cabral and O'Reilly (2005) tested different techniques to determine the quality of pendunculate oak (*Quercus robur* L.) seedlings after lifting on different dates (October, November, December, January and April), followed by cold storage at 1 to 2C (34 to 36F) and subsequently warm storage at 15C (59F) over varying time periods, before planting. Quality evaluations were based on: 1) water status measured by shoot xylem pressure potential; 2) root electrolyte leakage; and 3) root growth potential, as well as morphological quality of the shoot system. Water status and dry mass were not good predictors of plant quality as results were conflicting and unreliable (Puttonen 1997). Root electrolyte leakage was unreliable as a predictor of plant quality in this experiment considering the warm storage period at the end of the trial. Results from other studies state that root electrolyte leakage is a good indicator of quality for several broadleaf species when subjected to rough handling or desiccation (Harper and O'Reilly 2013; Puttonen 1997) but did not consistently predict field survival and growth of Douglas-fir [*Pseudotsuga menziesii* (Mirb.) Franco] and Sitka spruce [*Picea sitchensis* (Bong.) Carrière] (McKay and White 1997). Root growth potential measured over a 2 week period after lifting was higher for stock lifted early (October) or late (April) by up to 26 cm (10 in), and was reduced during dormancy periods, between November and February by 1 cm (⅜ in) (McKay and Morgan 2001). Differences might be related to shoot dormancy status and depletion of carbohydrate reserves but overall root growth potential was the most reliable indicator of plant quality. Comparable results were obtained by Lindqvist (1998) on four different deciduous species where root growth potential could efficiently predict field performance after 4 months of cold storage. It seems that the rapid development of new roots is important to good survival rates as it allows root-soil contact to be established and ensures high water status in plant tissues (Sharpe and Mason 1992).

Lifting date was an important factor for physiological status at the time of lifting and its subsequent effect on cold storage tolerance and field performance of penduncular oak and sessile oak [*Q. petraea* (Matt.) Liebl.] during two lifting seasons in Ireland (Harper and O'Reilly 2013). Pendunculate oak seedlings showed better resistance to intermediate lifting dates (November/December to March), as opposed to early (October) or late lifting dates (May). Several physiological parameters were evaluated for utility as indicators of performance potential in pre-transplant (effects of lifting and storage), including dry weight fraction, water content and xylem pressure of potential shoots, dormancy and root growth potential, seasonal effects on fine root electrolyte leakage, and seasonal and heat effect on tap root electrolyte leakage. Dry weight fraction was the most useful pre-transplant indicator of stress resistance levels and provided useful measures of good storability and field performance potential; the other physiological parameters were not as useful for evaluating performance potential. Dry weight fraction provides useful indirect information on the dormancy and stress resistance of stock (Carlson et al. 1980). Dry weight fraction is the calculation of the dry weight / turgid weight × 100 of a distal section of the leading shoot (Harper and O'Reilly 2013).

Tools for decision-making. There are several considerations for improving practices for the pre-lift phase of bare-root production to minimize plant stress. Here we will focus on timing considerations, measures and recommendations for root culturing and shoot pruning, as well tools to reduce and assess plant stress and storability.

Chlorophyll fluorescence. In a study conducted in southern Sweden by Lindqvist and Bornman (2002), lifting date and storage time had a strong effect on partial photosynthesis of common silver birch (*Betula pendula* Roth.) and pendunculate oak using chlorophyll fluorescence in newly developed leaves after transplanting. Poor response of both species was recorded for those that were lifted early (September 17th) with storage of 135 or 180 days. The highest value of maximum fluorescence in dark-adapted tissue for both species was recorded during the November 12th lifting and after 180 days in cold storage. Both species responded to later lifting dates and longer storage periods. A study by L'Hirondelle et al. (2006) supports using chlorophyll fluorescence to estimate the overwinter storability (ability to survive and grow after storage) of container grown conifer seedlings after freezing. Chlorophyll fluorescence was more useful than a qualitative assessment of injury to foliage and stems or electrolyte leakage measures because of the combined accuracy of prediction and ease of measurement.

Effects of shoot pruning. The root-to-shoot ratio at the time of planting is an important morphological attribute often considered as an indicator of the seedlings' quality and ability to survive after planting. The presence of large shoots is indicative of early leaf development, and consequently an increase in water demand, that requires appropriate functional capacity by the roots (DesRochers and Tremblay 2009; Grossnickle 2005).

Pruning to reduce the size of planting material and subsequent leaf area might enhance establishment, while also reducing the costs associated with lifting, packing, shipping and planting (DesRochers and Tremblay 2009). DesRochers and Tremblay (2009) found that stem pruning could enhance transplant performance of four dormant bare-root hybrid poplar clones: *Populus maximowiczii* × *balsamifera*, *Populus balsamifera* × *maximowiczii*, *Populus balsamifera* × *trichocarpa*, and *Populus deltoids* × *balsamifera*. Four different treatments were established: 1) non-treated bare-root; 2) stem pruned; 3) root pruned whip; and 4) cuttings (roots and shoots pruned). Treatments 1 and 2 produced 1.2 times larger trees, with respect to height and basal diameter, than treatments 3 and 4, which included root pruning. It was concluded that stem pruning can reduce plant stress without compromising growth for at least the first two years (DesRochers and Tremblay 2009).

McNabb and Vanderschaaf (2005), however, reported that there are inconsistencies between studies regarding the results on survival and growth with respect to top pruning and root pruning prior to planting of different species of hardwood. They evaluated the interaction between two different seedling sizes, 12 and 16 mm (0.5 and 0.6 in), compared to a 4 to 8 mm (0.16 to 0.31 in) root collar diameter, as well as pruning treatment on survival and growth of sweetgum (*Liquidambar styraciflua* L.) seedlings over a 3 year period. Seedlings were lifted in January and placed into cold storage for 2 weeks at >0C (32 F) in paper bags. Two initial plant sizes of root collar diameter were selected and six treatments applied: 1) no pruning; 2) root pruning to 15 cm (6 in) length; 3) top pruning by 50%; 4) root pruning to 15 cm (6 in) and top pruning by 50%; 5) top pruning to 5 cm (2 in) height; and 6) top pruning to 5 cm (2 in) and root pruning to 15 cm (6 in). Growth in terms of height was greater with top pruned trees but the average diameter growth of the control seedlings was greater than that of the pruned seedlings. Top pruning resulted in greater allocation of photosynthate to stem elongation at the expense of growth in stem diameter. In hardwoods, stem diameter may be a better indicator of treatment efficacy.

Effects of root culturing. Root wrenching (angled cutting), sidecutting (vertical cutting), undercutting (horizontal cutting) and root pruning (post lifting trimming) are all methods employed in bare-root nursery culture to produce healthy vigorous root systems. The findings on the effects of root culturing are variable and depend on species, additional management practices and bed preparation.

Benefits of root culturing include increased total root weight, superior performance of the plants, more compact root form and improved tolerance and resistance to stress (McKay 1997). However, decreased root masses can increase desiccation of shoot tissue.

Edgren (1981) found that undercut Coastal Douglas-fir [*Pseudotsuga menziesii* (Mirb.) Franco] seedlings had significantly better survival than controls, but undercut Rocky Mountain Douglas fir seedling survival was less than controls. Growth of the controls of both seedlings was better in the first year than the undercut seedlings. Engel argues that undercutting varies by variety in the ability to stimulate the root system, and other factors including time of lifting can influence survival (McKay and Morgan 2001). For instance, undercutting and wrenching significantly improved the ability of Japanese larch [*Larix kaempferi* (Lamb.) Carr.] to withstand cold storage and resulted in survival rates of >80% when storage began in mid-October and ended in early April (McKay and Morgan 2001). Freshly lifted stock survival was correlated to time of year when larch was capable of producing new roots, and mortality was correlated to time of year when new root generation was limited.

Additional cultural practices may be required for some species to optimize the effects of root culturing. Andersen (2004) found that undercutting of European oak [*Quercus petraea* (Matt.) Liebl.] decreased height and dry weight after year-1 as compared to controls, but undercutting for consecutive years increased the number of first order lateral roots.

Root growth is critical for the survival and performance of a newly-transplanted plant (Jackson et al. 2012). The ability of the plant to overcome the stress from planting is related to the size and distribution of the roots, as well as the root-soil contact and hydraulic conductivity (Jackson et al. 2012). Uptake of nutrients can be limited by poor root development and could reduce shoot growth. Bellett-Travers et al. (2004) consider the relation between water uptake and root loss in silver birch to be inconclusive. Similar physiological changes could be caused by loss of starch or other carbohydrates stored within root tissue, which are considered to be an important source of energy for shoot growth.

The research on root culturing effect as related to plant performance is inconclusive; however, moderate reductions in root mass have been found to increase bare-root plant survival (McKay 1997). Actual effects depend on a number of factors including original root:shoot proportions, the severity of root loss and the species' ability to generate new roots from the remaining root mass, following transplanting.

Pre-transplant

Arguably the most underappreciated phase of quality measures, the pre-transplant phase is a crucial stage in understanding plant stress in order to maintain or improve plant quality before transplanting. Many cultural factors can influence plant quality and field performance but it is argued that pre-transplant handling and storage practices can have the largest influence on quality (McKay 1997).

Challenges and considerations. Several factors influence bare-root transplant success. Drought conditions are responsible for many establishment failures, as well as timing of lifting and transplanting, and also any stress factors that damage bare-root stock during the interval between lifting and planting (McKay and Morgan 2001). Plant performance attributes should be measured at this juncture and are often primarily concerned with moisture stress. Fall and winter-lifted seedlings held in cold storage may exhibit moisture stress before transplanting for three main reasons: 1) if the plants were lifted under moisture stress, such plants can exhibit signs of damage or stress at planting; 2) incorrect packaging can cause more moisture loss during handling and transport and can lead to greater moisture loss in tissues; 3) conditions of storage and transport of bare-root plants may cause a major deterioration of the crop or have a detrimental effect on the plant's performance after transplanting. Temperature and duration of storage, as well as relative humidity and packing, are primary environmental parameters that need to be optimized for storage and transport. These parameters are crop specific (tropical, subtropical, etc.), as plants have different tolerances and show different sensitivities to cold storage (McKay and Morgan 2001).

Storage temperature, duration of storage and temperature variation all have an impact on the establishment success and survival rate of seedlings after transplant. There are also interactions among these parameters that should be considered when handling pre-transplant material.

Storage. Different methods are used to store bare-root seedlings or trees after lifting. Some species benefit from cold storage; for instance, McKay and Morgan (2001) reported that cold storage of plants resulted in consistently higher levels of survival of larch [*Larix kaempferi* (Lamb.) Carrière] and an unspecified hybrid, than planting of freshly lifted stock. Generally, after lifting, bare-root plants are cleaned of all soil and left to dry before storage, for periods varying between 1 h to 1 d. This drying time has an impact on the survival rate of the plants after transplanting, even more considering that some species, such as herbaceous perennials, are frequently imported and have to withstand long periods of cold storage. Roses (*Rosa* spp.) are usually field grown and lifted while dormant in fall or winter and shipped bare-root, and are then either transplanted into the field or containers. The effect of moisture loss on subsequent growth and flowering was evaluated on five cultivars of bare-root rose plants in Arizona: 'Angel Fire', 'Blue Girl', 'First Prize', 'Mister Lincoln' and 'Peace' (Schuch et al. 2007). Roses were lifted in February, allowed to dry from 0 to 7 h, and rehydrated by water spray for 1 min before storage. Moisture content was evaluated: 1) on freshly lifted plants; 2) after drying; and 3) after shipping. Moisture loss was correlated with slower vegetative growth and flowering, reduced flowering shoots and greater dieback of canes. Moisture content below 43% before shipping resulted in 80% mortality. Moisture of the whole plant was comparable to those of either the canes or the shank. Similar results were obtained with Noble fir (*Abies procera* Rehd.) bare-root transplants, as survival and growth was significantly reduced by 1.5 h of full exposure (shoots and roots) or 10 h of partial exposure (roots) to drying (Bronnum 2005). Bare-root plants should be kept moist at all times and should not be left exposed, even if tolerance to desiccation is highly variable between cultivars (Schuch et al. 2007). The challenge comes in maintaining plant moisture without creating conditions that are conducive to fungal growth.

Lindqvist (1998) found survival was poor when plants were put in cold storage in early October, but >80% of plants survived when lifted and stored between late-October to early March, and were transplanted in early April. The optimum time for cold storage was mid-November to mid-December, with greater survival rates (96%) and greater root growth than those lifted and placed in storage in January and March. Secondly, a storage temperature of 1C (34F) for plants lifted in late October to mid-February resulted in higher survival rates after transplanting than for plants stored at –2C (28F); however there were no differences in survival rates at both storage temperatures when plants were lifted and placed into storage between December and early February.

Wang (2013) studied the effect of storage and transport on the replanting success of orchids. These plants grow and flower best at temperatures between 25 and 30C (77 and 86F). For the experiment, the plants were removed from pots on September 15, cleaned of potting medium, weighed and placed in cartons to simulate international shipping conditions. The cartons were placed in dark chambers at 15, 20, 25 and 30C (59, 68, 77 and 86 F). After 4, 7, 10 and 14 d, plants were removed from each temperature regimen at random, weighed, repotted and placed in the greenhouse. Weight loss increased as the storage duration increased, and greater losses were recorded at temperatures of 25 and 30C (77 and 86F). When bare-root plants are stored at optimal temperatures, they can potentially lose up to one-fifth of their fresh weight without affecting transplanting performance. There were no visible depletion symptoms after 4, 7 and 10 d of storage. After 14 d, plants placed at 30C (86F) had yellow spots on the leaves. After a few days in the greenhouse, symptoms of chilling injuries were observed in plants that were stored at 15 and 20C (59 and 68F) for 4 and 7 d, and were more severe for plants held at 15 and 30C (59 and 86F) for 14 d. Flowering was delayed in plants stored at 15 and 30C (59 and 86F) for 7 d, and at 15, 20 and 30C (59, 68 and 86F) for 14 d.

Transport. Temperature fluctuations during transport can lead to moisture condensing between multi-layered packaging. Moisture loss during storage can also be mitigated through the use of moisture-proof containers. Lumis and Johnson (1980) reported that poly-lined Kraft bags and polyethylene bags provided effective protection for overwinter storage of white spruce [*Picea glauca* (Moench) Voss], black spruce [*Picea mariana* (Mill.) Britton, Sterns & Poggenburg] and red pine (*Pinus resinosa* Ait.). Many techniques involve cold-storage of seedlings in shredded paper. The particular storage method impacts survival rates after transplanting. Three different methods of cold storage were tested on Sitka spruce [*Picea sitchensis* (Bong.) Carrière] and Douglas fir, and efficiency was measured based on root growth potential and root moisture content after 1 and 2 years in the field (Sharpe and Mason 1992). Seedlings were lifted in December and stored for 12 weeks prior to planting. Treatments were: 1) bare-root seedlings in humidified cold room cooled by ice-bank, cold and moist air passing over the plants; 2) bare-root seedlings sealed in polyethylene bags in the same humidified cold room; and 3) bare-root seedlings sealed in polyethylene bags in a direct cold room maintained at >88% relative humidity and 1C (34F). Storage condition impacts were crop specific. Survival of both species after 1 year was significantly lower for seedlings that were held in cold storage with uncovered roots but differences disappeared in the second year. Sitka spruce had a significantly higher root growth potential than Douglas fir. Based on the results, recommendations were to: 1) maintain relative humidity up to 95% during storage; 2) have an intermediate chamber between cold storage and outside to prevent loss of moist air (which would cause storage conditions to fluctuate) when the door is opened; and 3) if impossible to maintain the target relative humidity, storage should not exceed 4 weeks for unprotected roots, or seedlings should be placed in sealed polyethylene bags to prevent moisture loss.

Prospective quality measurements post-lifting but pre-planting are less common, and quality is more challenging to quantify than retrospective quality assessments after planting. Two tests that are used include the vigor test developed at Oregon State University and root growth potential (Ritchie 1985). The vigor test still requires up to 60 d after planting for damage to become visible. The standard root growth potential test requires 28 d but as short as a 7 d test period has been used effectively. A real-time quantification of plant quality post-lifting and post cold storage is still challenging to conduct.

Acclimatization. Wang (2007) also evaluated the effect of acclimatization on orchids before packing as bare-root transplants. Plants were placed in four chambers under cool-fluorescent tubes for 12 h of light per day and temperature was lowered to 25C (77F) for 10 d, followed by 20C (68F) for another 10 d. Half of the plants were removed from pots as bare-root and packed and the remainder were undisturbed. The lights were then shut off and the holding temperature changed to 15, 20, 25 or 30C (59, 68, 77 or 86F) for different growth chambers. All plants were held at the various temperatures for another 10 d before being replanted and brought back to the greenhouse. Wang (2007) concluded that acclimatization of plants like orchids to lower temperatures seemed to prepare them for safe low temperature storage, as bare-root or potted plants. It reduced the degree of chilling injuries observed after storage at 15C (59F) for 10 d, as compared to non-acclimatized plants. Budbreak was delayed for non-acclimatized plants, as compared to acclimatized and control plants, for all storage temperatures. Flowering was delayed for non-acclimatized plants stored at 15 and 30C (59 and 86F) for 10 d.

Hou et al. (2010) tested effects of long distance shipping in total darkness on photosynthetic status and transplant survival, as well as acclimatization to light intensity after dark storage and storage temperature. Shipping of butterfly orchids (*Phalaenopsis sogo* Yukidian) was simulated as 21 d of dark shipping at 20C (68F) with 40 to 50% relative humidity. Transplant performance was evaluated by changes in net CO_2 uptake, the photosystem II efficiency and the leaf abscisic acid concentration in bare-root plants and potted plants over the simulated shipping period and post-shipping period for up to 60 d. Plants were potted on December 6 and were placed in a ventilated room for 1 d before storage in shredded newspaper and cartons. Net CO_2 uptake was recorded for 0 to 14 d of storage in simulated transport. After storage, plants were moved to growth chambers and held under different environmental conditions of 30C (86F) day/25C (77F) night, and were illuminated at 34, 72, 140, 200 or 399 $\mu mol \cdot m^{-2} \cdot s^{-1}$ (34, 72, 140, 200, or 399 ft-c) light intensities for up to 15 d of storage. Net CO_2 uptake was greatly reduced by long-term dark storage. To evaluate storage temperature over dark shipping, temperature was set at 25C (77F) day/20C (68F) night, compared to the control maintained at 30C (86F) day/25C (77F) night, for 10 days under medium light intensity of 140 to 200 $\mu mol \cdot m^{-2} \cdot s^{-1}$ (140 to 200 ft-c). Dark shipping was simulated for 21 days at temperature of 25, 20 and 15C (77, 68 and 59F).

Allowing the plants to acclimate (step changes in temperature and light intensity) after dark storage induces better photosynthesis performance. Light requirements after storage in the dark increased as time in storage increased, and post-shipping light acclimation should be provided to promote recovery. Recovery of net CO_2 uptake was greatly inhibited by exposure to a high light intensity of 399 $\mu mol \cdot m^{-2} \cdot s^{-1}$ (399 ft-c), was restricted by a low light intensity of 34 and 72 $\mu mol \cdot m^{-2} \cdot s^{-1}$ (34 and 72 ft-c) and recovered to full potential after 4 d under 140 and 200 $\mu mol \cdot m^{-2} \cdot s^{-1}$ (140 and 200 ft-c). The optimal long-term dark shipping storage temperature was 20C (68F).

When bare-root seedlings are taken out of cold storage, they are often left at ambient temperatures for a certain time before transplanting. This temporary storage at higher temperatures may contribute to poor establishment of species, considering that it may be sufficient to initiate respiration in roots, with subsequent loss of food reserves (Cabral and O'Reilly 2005). This phenomenon has been evaluated in many studies, and effects, based on survival or growth after planting, and root electrolyte leakage varied among species (Cabral and O'Reilly 2005).

Some physiological characteristics undergo change through the storage and transport periods; darkness and drought, for example, induce a drop in net CO_2 uptake by the plant and also photosynthetic status, however both functions are rapidly recovered after irrigation (Hou et al. 2010; Mena-Petite et al. 2005). Poor survival rate after storage is often attributed to seedling buds not being dormant upon entering cold storage, even though no measures of bud dormancy have been recorded to confirm this claim (Jackson et al. 2012).

Tools for decision-making. During the pre-transplant phase the objective is to determine the quality of stored plants and limit further stress to the plants. Tools that can be employed during this phase include monitoring critical thresholds of stores in roots and using dips and coatings to prevent further moisture loss during transplant activities.

Carbohydrate fraction. Carbohydrates are depleted during bare-root plant storage (Cannell et al. 1990). Moderate temperatures over prolonged periods have been found to accelerate the rate at which carbohydrates are used and can contribute to mortality or poor establishment after transplanting (McKay 1997). Although researchers have looked at decreased carbohydrate fraction as an indicator of decreased survival and growth, the closeness of the relationship has not been explicitly determined.

Root respiration. Measurement of root respiration after storage also provides information on the physiological status of the plant. This is a destructive method where respiration of root segments is evaluated by measuring CO_2 efflux after storage (Apostol et al. 2009). However, no studies have considered whether this method can be used to evaluate and predict the physiological condition of seedlings (McCreary and Zaerr 1987). Johnson-Flanagan and Owens (1986) concluded that respiration was correlated to both root and shoot development throughout the year. Results obtained by McCreary and Zaerr (1987) on Douglas fir's respiration rate did not predict growth potential but were significantly correlated to water stress or desiccation injuries: desiccation decreased root-respiration rate and these measurements might be efficiently used to predict root damage. The respiration measurement method is time consuming, not a real-time assessment of the living status and measurements of new root tips may correlate more strongly with survival and growth (McCreary and Zaerr. 1987).

Dipping and coating. Water availability is one of the most important factors that affect plant physiological responses and deficits can limit carbon fixation, growth and net primary production after transplanting (Gazal and Kubiske 2004). At budbreak, for example, low water uptake can limit cell expansion, resulting in poor photosynthetic area and photosynthetic activity (McKay and Morgan 2001). However, roots are more sensitive to water stress than shoots, especially new roots, which are the most functional roots for water transport. Water stress induced during storage or transport may delay root regeneration and induce poor seedling performance and higher mortality levels (Apostol et al. 2009).

To ensure proper relative humidity is maintained throughout storage, some postharvest treatments are available to prevent seedling desiccation: spraying stems with antidesiccants to prevent transpiration (Lumis and Johnson 1980); dipping roots into a combination of water and superabsorbent gels (Baltazar-Bernal et al. 2011); placing roots in soil slurries or sphagnum moss (Gebre and Kuhns 1991); and a range of other chemicals and bioregulatory substances that are purported to increase seedling survival and growth through nutrition enhancement or encouraging beneficial microorganisms (Beniwal et al. 2011). All are applied before seedlings are placed into storage containers, cartons or bags. Hydrogels are water-retaining polymers that can absorb water between 40 to 500 times their own weight (Sloan 2004) and make a significant portion of this water available to the plant in storage (Beniwal et al. 2011). These coatings have been used for more than 40 years and were meant primarily to improve transplanting success of conifer seedlings (Sloan 2004). There were four kinds of hydrophilic gels reviewed by Sloan (2004): hydrolyzed starch-polyacrylonitrile graft polymers, urea-formaldehyde resin foams, vinyl alcohol-acrylic acid co-polymers, and cross-liner acrylamide co-polymers.

The effectiveness of these hydrophilic gel slurries varies greatly with species, sites and methods of study. Different studies reported on by Sloan (2004) suggest that the chemical composition of a hydrogel might be phytotoxic and detrimental to seedlings during storage. These coatings can prevent desiccation and increase survival when roots are exposed to dry air for extended periods before planting, but all studies show that root dips on coniferous trees do not significantly increase survival and growth over untreated seedlings. Hydrophilic gels were also tested as a means of delivering plant growth hormones or other bioregulatory substances to the seedlings. Some studies showed detrimental effects to the plants, and more studies are necessary to define their true utility in this regard. Very little information is available on the use of hydrogels for hardwood bare-root plants.

Foliar antidesiccants have been tested to reduce moisture stress on different ornamental conifers such as juniper (*Juniperus* sp.), yew (*Taxus* sp.), Norway spruce [*Picea abies* (L.) H.Karst] and white cedar (*Thuja occidentalis* L.), combined with root wrap in polyethylene bags and/or root dip treatments (Hou et al. 2010). Plants were lifted and stored for 5 d prior to planting. Quality was evaluated after the first and second seasons. The most promising pre-transplant treatment was a foliar application combined with a polyethylene bag to enclose the entire plant; no benefits were derived from the root dip. Another study tested the spray application of 20 different antidesiccants to the top of shoots of three species of deciduous tree seedlings: red oak (*Quercus rubra* L.) (most tolerant to desiccation); Norway maple (*Acer platanoides* L.); and Washington hawthorn (*Crataegus phaenopyrum* Borkh.) (Englert et al. 1993). Plants were harvested every month from September to April and were allowed to dry for periods of 1 h up to 48 h prior to being planted in a greenhouse environment or stored for field planting in May or June. Maximum tolerance to desiccation was observed for harvest in January and February. The most efficient antidesiccant was a latex emulsion product which reduced water loss by 80%, compared to untreated plants, and promoted the highest survival rate. A clay slurry was also tested as a root dip to prevent desiccation of cocoa seedlings, together with different packaging systems, i.e. moist sacks or moist straw, with or without polyethylene bags and with or without pruning of leaves and roots (Amoah et al. 1999). The experiment was repeated over four years and quality evaluation was done at planting and again after 12 months. Plants were lifted and planted within 3 d. Treatment with a clay slurry resulted in significantly lower survival rates, as well as the treatments with moist straw, compared to the other treatments.

Post-transplant

Challenges and considerations. Arguably the most important consideration for the post-transplant phase is planting date. Late frosts and fluctuating temperatures can increase stress to bare-root material. Once plants are removed from storage it is important to establish soil-root contact as quickly and efficiently as possible to avoid tissue desiccation.

Planting dates. Freshly-lifted stock can be transplanted or transplanting can occur after a storage period. Transplanting a dormant plant results in good survival if the soil is warm enough for root growth and the stock responds well to storage, e.g. birch and oak (Lindqvist and Bornman 2002). The timing of planting is therefore an important consideration for bare-root material.

Planting in winter often results in poor survival and is a result of poor contact between soil and roots, limiting the ability to acquire resources (Grossnickle 2005). New root growth is necessary to supply water to the shoots in order to drive leaf production, allowing the plant to perform photosynthesis (Harris et al. 2002; McKay 1998). Poor establishment is likely to result in desiccation, considering that water loss from the stem and branches will occur at a higher rate than can be replaced through water uptake by the roots (McKay and Morgan 2001). Extension of the planting period could be a useful tool for plantation management. A study evaluated the effect of 10 planting dates on the establishment success of six species of deciduous trees: American ash (*Fraxinus americana* L.), black walnut (*Juglans nigra* L.), tulip poplar (*Liriodendron tulipifera* L.), black cherry (*Prunus serotina* Ehrh.), white oak (*Quercus alba* L.) and northern red oak (*Quercus rubra* L.). Seedlings for the first four planting dates were lifted 1 d prior to planting. All seedlings for subsequent dates were lifted in December, packed and stored at 0.5 to 1.7C (33 to 35F) until the day prior to planting. Planting dates varied between November and July. The experiment was repeated over two growing seasons. Trees of tulip poplar and black cherry appeared to be more sensitive to late planting dates (spring and later) possibly because these species are more sensitive to desiccation and frost heave, but there were inconsistencies across data sets and further studies incorporating different site types and management practices may be useful (Seifert et al. 2006). Poor survival rates were obtained for seedlings that were directly planted in September, but increased up to 100% if planted in mid to late-October. Survival decreased again with later planting dates, i.e. late November to February. In March, there was a second period when survival rates were >80%. Direct planting methods should be adapted to plant and site conditions. Similar results were observed with the conifers Sitka spruce and Douglas fir (McKay 1998).

Tissue desiccation. The physiological condition of seedlings after storage has a significant influence on the survival potential at transplanting. Mena-Petite et al. (2005) evaluated radiata pine [*Pinus radiata* (D.) Don] seedlings post-storage to determine: 1) the response to water stress shock (wet and dry environmental conditions) at transplanting; 2) the corresponding photosynthetic response; and 3) the relationship between gas exchange and survival. Gas exchange parameters were measured with an infrared gas analyser. Seedlings were lifted in February (in northern Spain) and were stored in the dark at 4 or 10C (39 or 50F), and 80% relative humidity for 1, 8 and 15 d. After storage, seedlings were planted and grown in a growth chamber for 26 d and monitored under the following conditions: 14 h of daylight at 400 $\mu mol \cdot m^{-2} \cdot s^{-1}$ (400 ft-c) with temperatures of 25/20C (77/68F), and 60/80% relative humidity for day/night, respectively. Some plants were subjected to drought conditions. Bare-root seedlings exhibited different photosynthesis recovery capacities after planting with nil recovery capacity for storage periods longer than 8 d at 10C (50F). Whatever the temperature or root-coverage conditions, non-irrigated seedlings that had been stored for 1 d showed 60% lower carbon assimilation than irrigated ones after planting. For seedlings stored for 8 d or more and then subjected to drought conditions, carbon assimilation was 100% inhibited 20 d after planting. When plants were irrigated after a drought period, photosynthesis recovery returned to 28% for plants stored for 1 d at either temperature, as compared to irrigated ones; but plants stored for 8 d or longer did not recover at all. Survival rate after two months for well-watered bare-root seedlings that had been stored at 4C (39F) for 1 d was 60%, while only 20% of seedlings survived that had been stored at 4C (39F) for 15 d, or 8 d at 10C (50F). Under drought conditions, survival rates of 40, 20 and 0% were observed for seedlings stored at 4C (39F) for 1, 8 and 15 d, respectively, and 30, 0 and 0% for seedlings stored at 10C (50F) for the same time periods.

Tools for decision-making. Tools for the post-transplant phase include morphological field performance measures to assess the health of stock and the use of dips and coatings. Post-transplant measures are commonly field-based measures that occur some period of time after transplanting takes place. Above ground morphology monitoring is similar to growing phase monitoring and is the most common form of plant assessment. Common parameters used as indicators of performance include height and root-collar diameter because they can be correlated with survival and growth after transplanting (Grossnickle 2005). This is a result of the lag between the plants being stressed from growing, lifting, storing, transporting and transplanting, and the plants demonstrating this stress in the field after breaking dormancy.

Morphological parameters. A study carried out in the United States compared first order lateral root and root volume to initial shoot height, stem diameter and plant fresh mass in an effort to predict the field performance of red oak, white oak, and black cherry that had been in cold storage for 5 months; evaluations occurred one and two years after transplanting. Root volume was a better predictor than first order lateral root for oak. But when the model included both first order lateral root and root volume, R^2 values suggested that multivariate models could predict field response better, and that integration of physiological indicators would be required to provide an accurate estimation of transplant quality (Jacobs et al. 2005). Most bare-root assessments occur in this phase and it is difficult to determine what the plant stress is attributable to, and it can be too late at this point to manage the plant in order to recover from the damage.

Dips and soaking. To ensure minimal transplant shock, there has been development of hydrogels that are particularly suited as a treatment application immediately before transplanting. A hydrophilic polymer was applied to roots of dormant red oak seedlings that were then subjected to pre-transplanting desiccation and post-transplanting drought (Apostol et al. 2009). Quality evaluation was done after storage through assessments of moisture content, gas exchange and electrolyte leakage, root respiration and day budbreak. Following storage, seedlings were subjected to 1, 3 and 5 h of pre-transplant drying, and long-term (45 d) drought stress after transplanting. Results showed that treated seedlings had 80% higher root moisture content than non-root dipped seedlings, following the pre-transplanting desiccation period. There were no physiological differences (growth, gas exchange) in treated as compared to non-treated seedlings after 45 d of drought, except for days to budbreak, which were reduced in hydrogel-treated seedlings.

A hydrogel (cross-linked organic synthetic polymers) was tested on Norway spruce to prevent desiccation during transplanting (McKay and Morgan 2001). Seedlings were lifted and were treated with hydrogel prior to being exposed to drying conditions for 2, 4 and 5 h; untreated control seedlings were exposed to a similar drying regime. Transplanting was done the same day. Results confirmed the need to protect roots during handling. Treated seedlings had a height and root collar diameter increments of 7 and 22% higher as compared to untreated seedlings after the first vegetation period. Anella et al. (2008) compared the survival of bare-root trees dipped in the hydrogel immediately after harvest to balled-and-burlapped trees, for winter and spring harvest and transplant. London plane 'Bloodgood' [*Platanus* × *acerifolia* (Aiton) Willd.], Autumn Blaze® (*Acer freemanii* 'Jeffsred') and baldcypress [*Taxodium distichum* (L.) Rich.], were left for 5 d in a cold room prior to transplant. There was no significant difference between the two postharvest treatments.

Beniwal et al. (2011) tested the effect of a soil amendment consisting of hydrogel and ectomycorrhizal fungi prior to planting, on already drought-stressed bare-root beech (F*agus spp.*) seedlings. For every kg (2.2 lbs) of soil, 45 mL

(1.5 oz) of fungal inoculum and 5 g (0.18 oz) of hydrogel were added. Bare-root seedlings were exposed to air at 20C (68F), 50% relative humidity, under full light, for 0, 2 and 6 h prior to planting. A hydrogel-ectomycorrhizal fungi mixture significantly improved seedling establishment as compared to non-treated soil; hydrogel increased the water retention capacity of the soil, while the ectomycorrhizal fungi appeared to increase nutrient availability. However, there was no significant difference in establishment for time exposure to air of 2 or 6 h. Percival and Barnes (2007) found combining carbohydrates, nitrogen fertilizer and a water-retaining polymer when applied as a root dip at the time of planting reduced transplant losses and improve tree vitality and growth over a growing season for silver birch and European beech (*Fagus sylvatica* L.).

A hydrogel might not be able to properly coat new roots that elongate beyond the protective gel during storage (Baltazar-Bernal et al. 2011; Sloan 2004). High losses of transplanted bare-root plants are frequently related to inadequate holding conditions during transport from the nursery to the field site, as a consequence of root exposure to air which causes drought stress (McKay 1997; Sloan 2004). Concentration of the hydrogel, treatment duration and substrate could all be factors influencing product efficiency. Further testing is required to establish the mechanical and physiological effects of hydrogel over time, as well as to confirm their utility, considering the high costs associated with their use (Apostol et al. 2009). Growers should not expect root dipping to restore seedling vigor and capacity if they have been damaged by improper handling and are an added expense (Sloan 2004).

Baltazar-Bernal et al. (2011) tested effects of drying conditions on 11 herbaceous perennials prior to their being packed, stored, and exported on their post-transplant survival. They also assessed effects of pre-soaking before transplanting. Plants were grown in the Netherlands and were lifted in December for planting in the United States in April and May. After lifting, plants were washed and allowed to dry at 9C (48F) for various times ranging from 0 to 24 h. After drying, plants were packed, stored at 2C (36F) and exported to Cornell University in the spring for transplanting. Plants were soaked for 0 or 10 min before planting. The experiment was repeated over two years. Transplant survival and performances were evaluated after three weeks. *Phlox (Phlox spp.)* was the only perennial tested that exhibited increased survival due to soaking. Drying time had no effect on any species in the first year, but survival rates were significantly lower in plants that were dried for 24 h in year two. This reduction was associated with desiccation and mold incidence.

Summary

Plant survival is greatly influenced by decisions and handling practices employed in the postharvest phase. Although many studies have been conducted on the various topics covered, some of the findings are contradictory or inconclusive, which could be the result of differences between species and sites. For instance, root and shoot culturing is beneficial to some species but has been found to negatively impact others. Moderate pruning of both above ground and below ground material is common practice for several species.

The timing of lifting and transplanting bare-root plants remains one of the most important considerations for the success of plant establishment. Lifting of dormant plants followed by storage at a suitable temperature will positively influence survival rate and growth of plants after transplanting. Several monitoring tools can be used as indicators to guide decisions on lifting dates and plant quality in the pre-transplant phase. In terms of helping to make decisions about lifting, chlorophyll fluorescence can be used on evergreen species to identify overwinter storability but is not practical for deciduous species. Dry weight fraction is a good indicator of stress resistance levels and has provided useful measures of storability, but is not a practical tool for most producers. Transplanting should be performed under ideal conditions to ensure proper root-to-soil contact is quickly established to prevent desiccation.

Water stress, prior to or after harvest, will impact root development and can induce high levels of plant mortality. The drying period between lifting and storage as well as sub-optimal conditions during transport may cause substantial damage to rootstocks. Some techniques have been explored to prevent desiccation through dipping and coating of roots and/or shoots prior to storage. Different hydrophilic gel slurries are available and their effectiveness seems to be related to species and sites. For coniferous trees, the result of various dipping studies suggests that use of these materials imparts no particular benefits by way of improved survival rate when plant stocks are properly handled and protected against detrimental exposure. Very little information is available on hydrogel applications to hardwood bare-root plants, but dipping of red oak seedlings has been shown to increase root moisture content. However, dipping will not restore the vigor and survival capacity of bare-root plants.

Postharvest indicators of plant quality in the pre-transplant phase are equally challenging. Root respiration is a good indicator of water stress and plant dormancy. However, the method used for respiration measurements is time consuming and does not provide a real-time assessment of the plant's status. Standardized qualitative measures for bare-root liner quality should be established so that subjective assessments of liners are less variable. The main mode of bare-root liner assessment still occurs in the establishment phase retrospectively, so more prospective quantitative measures of plant stress pertaining to moisture should be established. The relationship of carbohydrate fractions and storage is inconsistent and require more research.

Packaging in a moisture-proof container may help maintain proper relative humidity throughout storage. Cold storage should be adapted to maintain the target relative humidity; otherwise the storage period should not exceed four weeks for unprotected bare-roots.

Storage at low temperatures for long periods may induce dehydration of plants. However, the most problematic scenario is caused by variation in storage temperature, which can result in a resumption of roots' metabolic activity, and initiate respiration and use of food reserves, especially towards the end of winter as reserved stores become limited.

Temperature, moisture, and air-flow are interacting factors that influence survival of bare-root material during storage. Low air temperatures can inhibit or damage root growth. Desiccation of material during storage is still the primary culprit of low survival and poor performance. The optimal length of storage is also an important consideration and is species dependent.

Bare-root nursery plants exist because they are economical in large quantities and they are also an excellent option for export. This review outlined many important considerations and tools that can be utilized to help bare-root plant survival post-transplant. Some monitoring tools are arguably too expensive or intensive for producers to employ and more accessible and affordable tools and practices could be developed to address these gaps. Ultimately there is still a large reliance on post-transplant measures of performance, and more crop specific practices that occur in the pre-lift and pre-transplant phase should be researched and developed.

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