Chapter 12

Irrigation in Forest-Tree Nurseries: Monitoring and Effects on seedling Growth

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Abstract

The main objective of nursery irrigation is to avoid unwanted seedling moisture stress and its negative consequences for seedlings. Soil water potential, best measured by the tensiometer, decreases as soil water content drops; this relationship changes with soil texture. The secret of effective nursery irrigation is to keep soil pores filled with the proper balance of water and air to minimize moisture stress. Plant water potential, best measured by the pressure chamber, is the single most useful indicator of seedling moisture stress; predawn readings are the most stable, midday readings the second most stable. Soil-moisture retention curves, soil- and plant-moisture monitoring procedures, and careful observation together form the best approach for properly monitoring and controlling irrigation, assuming the irrigation system is a good one. However, because crop responses vary due to environmental modification, nursery climate, tree species, and seed source, managers need phenological information to fully anticipate seedling response to cultural operations. Seedlings must be protected from the damaging effects of frost and heat; overhead irrigation sprinkling is the most common, effective method for accomplishing both. Top dormancy of seedlings in late summer should be encouraged so that trees can become hardy long before the first frost; proper irrigation scheduling assures the desired seedling growth early in the season and induces dormancy (by imposing a *moderate* moisture-stress level) later on, thereby enhancing frost hardiness. in sum, knowing when and when *not* to irrigate should help nursery managers implement the most effective irrigation monitoring and application programs possible.

12.1 Introduction

The distribution of vegetation over the earth's surface is controlled more by the availability of water than by any other single factor [25]. The ecological importance of water thus reflects the physiological importance of water in plant processes.

Growth-and all related physiological and metabolic functions [l9, 20, 23, 26, 50]—is the first process to be retarded when sufficient water is lacking. The effect of the resulting seedling moisture stress on growth of nursery stock can be profound; elongation of roots and shoots and growth in volume and dry weight are usually severely limited. Yet, although continued severe stress will either damage or kill stock, moderate stress can benefit seedlings, for example, by inducing dormancy ([58]; see also chapter 15, this volume). In addition, water applied at the proper time and in the proper way can prevent heat damage or help make seedlings frost hardy in fall. Therefore, applying or withholding water to benefit plants requires a thorough knowledge not only of species and site but also of seedling physiology (see chapter 14, this volume).

Water in forest-tree nurseries is best regulated through carefully designed irrigation systems and practices (see chapter 11, this volume). This chapter should help nursery managers plan and implement the most effective irrigation monitoring and application programs possible.

In Duryea. Mary L., and Thomas D. Landis (eds.). 1984. Forest Nursery Manual: Production of Bareroot Seedlings. Martinus Nijhoff/Dr W. Junk Publishers. The Hague/Boston/Lancaster, for Forest Research Laboratory, Oregon State University. Corvallis. 386 p.

12.2 Basic Water Relations

The main objective of irrigation—the artificial application of water to plants-is to avoid unwanted moisture stress in plants. In simple terms, moisture stress occurs whenever the rate of transpiration (loss of water from plants as vapor) exceeds the rate of absorption, leaving plant cells and tissues less than fully turgid [25]. Such stress can vary in degree from a small decrease in water potential (see 12.2.1), detectable only by instruments, to transient midday wilting, to death by desiccation.

Plant water transport can be viewed as a simple input-output system: soil water is the input and plant transpiration to the atmosphere the output [39]. Under optimal conditions, water transpired to the atmosphere is replenished by water absorbed by plant roots, although some lag between transpiration and root uptake is normal [24]. Midday water deficits occur in most plant species because absorption tends to lag behind transpiration (Fig. 1). This lag results because water flowing through plants meets resistance and because rates of water absorption and transpiration are controlled by different sets of factors. Transpiration rate is controlled by (1) leaf area and structure, (2) stomatal opening, and (3) those factors affecting the steepness of the vapor-pressure gradient from plant to air. Absorption rate, on the other hand, is controlled by (1) rate of water loss, (2) extent and efficiency of the root system, and (3) water potential and hydraulic conductivity of the soil. It is not surprising that processes controlled by different sets of factors are not perfectly synchronized, even though they are partly interdependent and linked together by the continuous water columns extending from roots to leaves.

Atmospheric evaporative demand is generated primarily by increasing air temperature and decreasing humidity, although radiation intensity and windspeed contribute indirectly. At constant relative humidity, evaporative demand increases exponentially, not linearly, with air temperature because the atmosphere can hold more water vapor as air temperature rises (Fig. 2) [25]. Consequently, under conditions of increasing temperature and low humidity, plants can suffer significant short-term moisture stress even in well-watered soil. The nursery manager can moderate evaporative demand by shading (see 12.5.2.2) and midday overhead sprinkling (see 12.5.2.1), depending on nursery location and tree species being grown [39]. Low soil water content can also induce seedling moisture stress, but this can easily be controlled by the nursery manager (see 12.3).

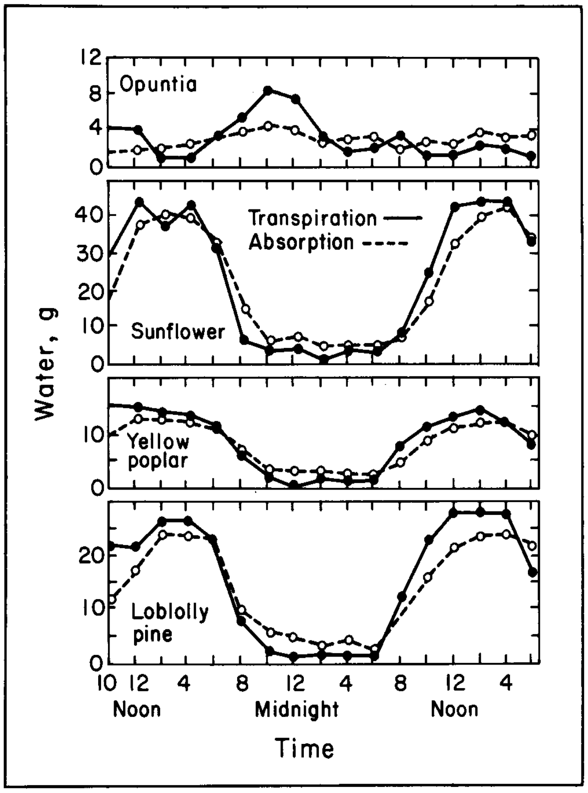

Figure 1. During the day, absorption lags behind transpiration in each of these four plant species (adapted from [24]).

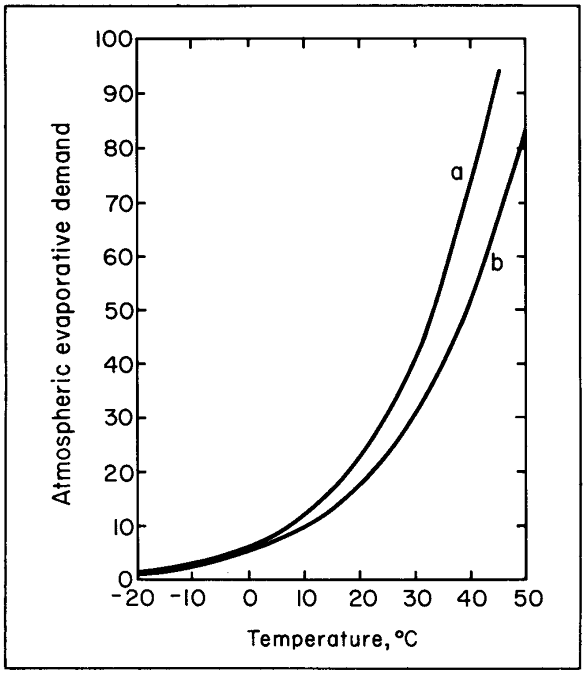

Figure 2. Effect of air temperature on the ability of the atmosphere to hold water vapor, expressed as (a) saturation vapor pressure, in millibars, and (b) saturation vapor density, in grams/ cubic centimeter of air (x 10^6) (adapted from [25]).

12.2.1 Water potential

Water relations in plants and soil were once discussed in terms such as "suction" and "diffusion pressure deficits" but are now considered in thermodynamic terms—that is, as **potentials** ([25]; see also chapter 23, this volume).

Total water potential (Y) is a physical-chemical parameter whose components quantify soil particle-water attractions, salt-solution influences, plant-xylem tensions, and cell-turgor effects. For our purposes here, it is probably sufficient to say that Y is a measure of the capacity of water to do work, expressed in dynes/square centimeter (dynes/cm^2) or ergs/cubic centimeter (ergs/cm^3), but more commonly in atmospheres (atm), bars, or megaPascals (MPa).[1]

The water potential in any system is decreased by:

- Matric forces (surface and microcapillary forces in soils, cell walls, protoplasm, and other substances that adsorb or bind water)
- Addition of solutes
- Negative pressures (tensions), such as those in the xylem of transpiring plants

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[1] MPa = 10 bars ~ 10 atm ~ 150 psi ~ 10^6 dynes/cm^2 (or ergs/cm^3).

12.2.2 Soil water potential

The chemical potential of soil water (soil water potential, Y_{soil}) is of considerable importance in soil-water relations. The principal forces contributing to Y_{soil} are those associated with the soil matrix, with the osmotic characteristics of the soil solution, and with the total pressure on the soil water [25]. Adsorption and capillarity-the two mechanisms by which water is retained in shrinking and nonshrinking soils—are associated with the structure and characteristics of the soil matrix and are termed matric forces; together, these constitute the **matric potential,** Y_m. The osmotic forces associated with the soil solution constitute the **osmotic potential,** Y_p; the pressure forces generate the **pressure potential,** Y_p. Thus, soil water potential comprises three main component potentials:

$$Y_{soil} = Y_m + Y_p + Y_p$$

Soil water potential is also affected by external force fields such as gravity, which constitutes a **gravitational potential,** Y_g The equation can then be written:

$$Y_{soil} = Y_m + Y_p + Y_p + Y_g$$

Gravitational and matric potentials are the most important components of nursery Y_{soil} and are the ones nursery managers are normally concerned with.

Apart from these thermodynamic terms, several other terms have been used in soil and plant science to describe soil-water characteristics significant to plant growth. The two most important of these are **field capacity** and **permanent wilting percentage** (see also chapter 6, this volume). The field capacity of a soil-its water content after gravitational drainage has slowed such that water content is relatively stable [25]—has been widely used to refer to the upper limit of soil water stored for plant growth. Field capacity is not a true equilibrium value, but a condition of such slow water movement that moisture content does not change appreciably between measurements; it is usually reached 1 to 3 days after soil has been thoroughly wetted by rain or irrigation. Permanent wilting percentage—the soil water content at which plants remain permanently wilted unless water is added to the soil [25]—has been widely used to refer to the lower limit of soil water available to plants.

Soil water potential decreases nonlinearly as soil water content drops (Fig. 3) [39]. Furthermore, the relationship changes with soil texture [18]. For example, in coarse-textured nursery soils (e.g., sands and sandy loams), the soil pores are large, and the amount of water retained by adsorptive and capillary forces is small compared to that retained in fine soils (clays).

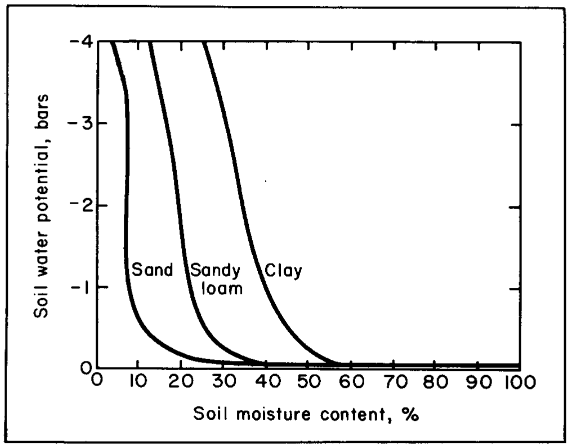

Figure 3. Typical soil-moisture retention curves for three different soil types (adapted from [39]).

Adsorptive forces at the surface of soil particles cause the water in the pores to adhere to the particle walls and form menisci (curved surfaces) at all water-air boundaries. Because pore size directly affects the curvature of such menisci, it therefore affects the matric potential. Thus, a coarse-textured soil with a few large pores partially filled with water would have low angles of curvature of the menisci and low matric potential. Conversely, a fine-textured soil at the same moisture content containing numerous, smaller pores would have high angles of curvature of the menisci and high matric potential (Fig. 4) [12].

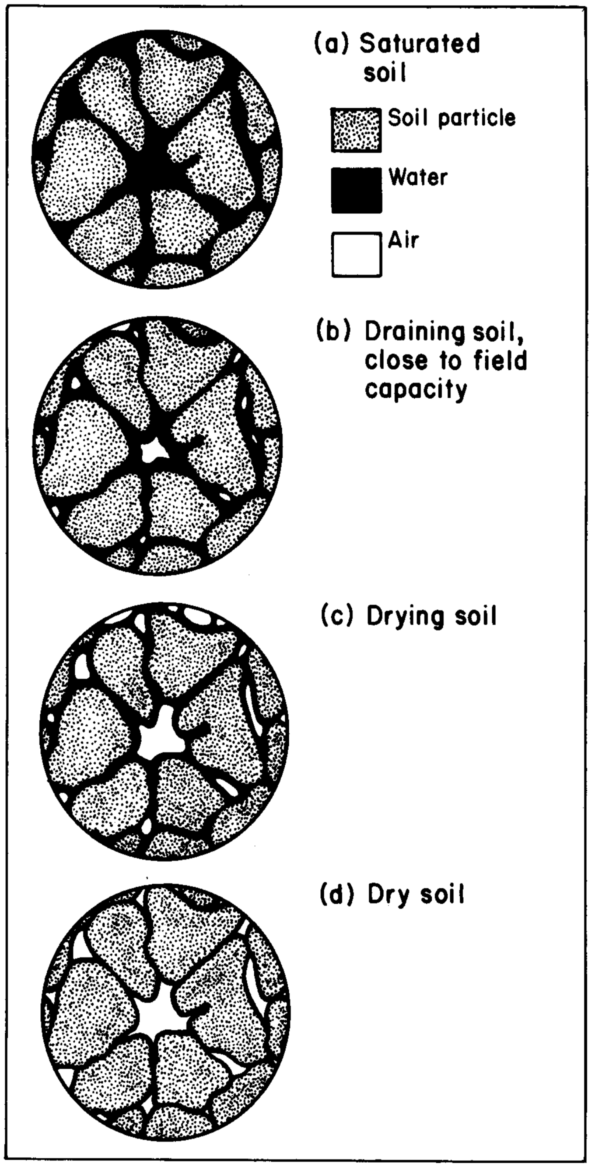

Figure 4. The changing status of water and air in soil pores (adapted from [12]). (a) All pores filled with water; soil at very high matric potential; photosynthesis and transpiration negligible; growth impossible due to lack of oxygen. (b) Large pores now partly filled with air; matric potential still high; excellent growth possible due to good supply of air and water. (c) All large pores and some medium pores filled with air; matric potential decreasing; satisfactory growth possible unless high atmospheric evaporative demand causes daytime moisture stress. (d) All large and medium pores filled with air; matric potential very low; root extension negligible and top growth severely limited due to long periods of moisture stress.

As the water held in either fine- or coarse-textured soils is depleted by drainage, drying, or absorption by seedling roots, the water held in the large pores at high matric potential is withdrawn first, followed by that at successively lower matric potentials. Thus, as water contained in soil pores is used up, matric potential decreases, and the space initially filled with water becomes filled with air [12].

The secret of effective nursery irrigation is to keep soil pores filled with *both* water (at high matric potential—i.e., -0.1 to -0. 5 bar) *and* air to minimize seedling moisture stress [12].

12.2.3 Plant water potential

Traditionally, irrigation has been controlled by measuring and adjusting soil moisture content and inferring the resultant effects on seedling moisture stress. More recently, internal plant water potential (Y **plant**) has also been measured directly. As a dynamic indicator and an integrator of effects of soil water potential and atmospheric evaporative demand with plant response [39], Y **plant** is the single most useful measure of moisture stress in plants and will be used throughout this chapter. Plant moisture stress (PMS) is the absolute value of Y **plant**.

Predawn Y**plant** readings, which indirectly measure Y**soil**, are the most stable measures of Y**plant** available. For greatest accuracy, predawn readings should be taken while it is still completely dark [39]. In summer, Y **plant** usually drops to a plateau by midmorning and remains roughly at that level until late afternoon (Fig. 5). These midday readings are the second most stable measures of Y **plant** [39]. However, interpreting midday measurements is more difficult because they reflect Y**soil**, atmospheric evaporative demand, and physiological plant response through stomatal closure. Even when soils are well watered, Y **plant** may remain in the range of -7 to -9 bars on a cool, humid day and may drop to -9 to -12 bars on a hot, dry day. As soil water is depleted, the midday plateau may drop to -15 bars or lower (Fig. 5); without irrigation, the reading will continue to fall to as low as -50 bars—until the plant dies [39]. As Y**soil** decreases, first midday and then predawn Y**plant** decreases (Fig. 6) [50]. Generally, when midday Y**plant** drops to -12 to -15 bars, moisture stress probably begins to impair growth [39]. The time required to reach this level depends on soil water available to each seedling, evaporative demand, and seedling characteristics.

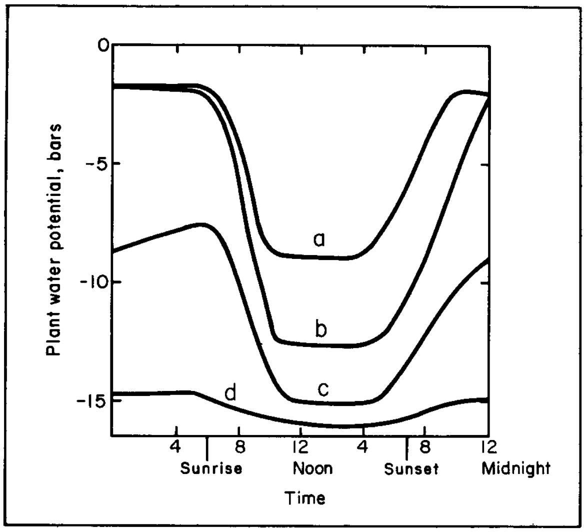

Figure 5. Patterns of plant water potential for a nursery seedling at (a) high soil-water potential and low atmospheric evaporative demand, (b) high soil-water potential and high evaporative demand, (c) low soil-water potential and high evaporative demand, and (d) extremely low plant water potential (severe seedling moisture stress) (adapted from [39]).

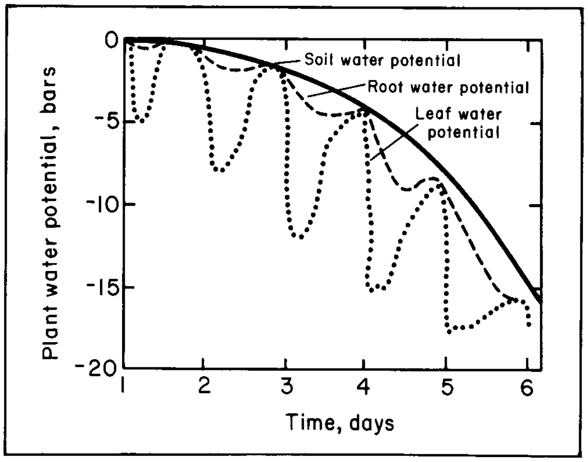

Figure 6. As soil water potential decreases, plant water potential also decreases (seedling moisture stress rises) (adapted from [50]).

Variability in Y **plant** is significantly greater at midday than before dawn. Therefore, when Y**plant** measurements are used for monitoring moisture stress at outdoor nurseries, the effect of changing evaporative demand on midday Y**plant** must be accounted for. Seedlings in a greenhouse experience less climatic variability and should produce more consistent readings. Besides atmospheric influences, Y **plant** can vary with tree species, age, phenological stage, and other factors. Consequently, although some indication of expected values is given here, each nursery should conduct tests under its own conditions [39].

12.3 Monitoring Irrigation

To monitor irrigation completely and professionally at a nursery, managers must rely on:

- **Soil-moisture retention curves** for individual nursery soils
- An effective procedure for rapidly assessing **soil moisture status**
- An accurate means of monitoring **seedling moisture stress**
- An understanding of **seedling response to irrigation**

12.3.1 Soil-moisture retention curves

Soil-moisture retention curves (Figs. 3 and 7), which illustrate the relationship between the percentage of soil moisture by weight and matric potential, provide nursery managers a means for monitoring the matric potential of a soil. These curves must be developed for each soil type at the nursery and can be obtained from most soil laboratories. Soil samples should be collected from the plow layer of the nursery field; ideally, these samples should be undisturbed cores although, in practice, samples from cultivated soils have been satisfactory [3].

Figure 7 illustrates how a soil-moisture retention curve should be used in nursery irrigation scheduling. Irrigation should usually be initiated at a matric potential of approximately -1 bar, although the exact point at which seedling growth is affected is not known. Armson and Sadreika [3] and Glerum and Pierpoint [17] indicate that the top growth of coniferous nursery stock is curtailed well before the wilting point (Fig. 7, d) is reached. Day and MacGillivray [13] and Day et al. [15] have shown that the roots of coniferous nursery stock would not develop in sandy loam soils at matric potentials of less than -0.6 to -1.5 bars. McDonald and Running [39] recommended that irrigation be initiated at approximately -0.5 to -0.8 bar for western U.S. nurseries. Because the matric potential that restricts either top or root growth is not known, irrigation should be applied to maintain the plow layer between field capacity (Fig. 7, a) and the point on the soil-moisture retention curve at which the matric potential begins to drop towards the wilting point (Fig. 7, c) [12].

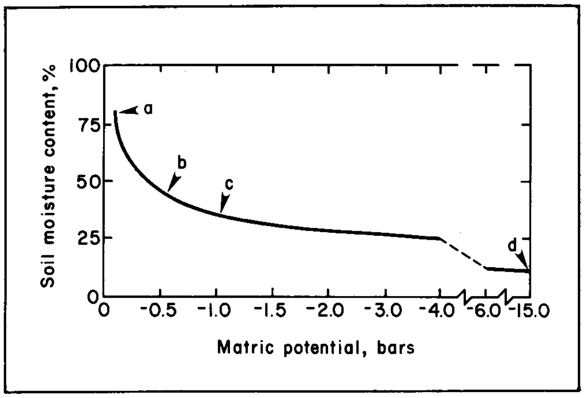

Figure 7. Soil-moisture retention curves for heavily peated nursery soil at Dryden, Ontario (adapted from [14]). (a) At 80% soil moisture content and -0.1 bar matric potential, the soil is at field capacity; lust drained, it is moist and well aerated, ideal for crop growth. (b) At 45% soil moisture content and -0.5 bar matric potential, the soil is at the upper limit for irrigation but still ideal for crop growth. (c) At 37% soil moisture content and -0.1 bar matric potential, matric potential begins to drop steeply; further soil moisture losses cause large decreases In matric potential. (d) At 12% soil moisture content and -15.0 bars matric potential, the soil is at the wilting point; crops may survive in this very dry soil, but growth is impossible and physiological quality will decline.

12.3.2 Monitoring soil moisture status

Moisture in nursery soils is monitored by estimating either soil moisture content or matric potential [12]. Because several excellent reviews are available [11, 22, 35, 55, 56], only the merits of the more practical methods for Northwest nurseries—gravimetric, neutron probe, visual and tactile, tensiometer, and electrical resistance—are described here.

It is essential to remember that soil moisture content usually varies both horizontally and vertically in the plow layer [3, 43]. Soil moisture varies horizontally in nursery soils due to changes in soil type or irregular irrigation patterns. Soil moisture varies vertically after irrigation or rainfall because water applied to the soil surface moves downward into the plow layer with a definite wetting front over 48 hours [12], leaving the zone behind the wetting front at field capacity. Vertical arrangement of water in a nursery soil is important because inadequate irrigation will not permit the wetting front to advance to the bottom of the plow layer; this is a common cause of poor root development in nurseries [2, 37].

12.3.2.1 Gravimetric method

This most basic of all methods is generally used for calibrating other methods [12]. Soil samples are randomly collected from the plow layer with a soil auger or sampling tube; samples are then placed in preweighed metal containers, weighed, and dried to constant weight in an oven at 105°C for 12 hours.

Samples are reweighed after drying, and the percentage of total soil moisture content by weight [%TSMC(wt)] is computed as follows:

$$\%\text{TSMC(wt)} = \frac{\text{wet wt - dry wt}}{\text{dry wt}} \text{ x } 100$$

If the bulk density (BD) is known, %TSMC by volume [%TSMC(vol)] may also be computed:

$$\%\text{TSMC(vol)} = \%\text{TSMC(wt) x } \frac{\text{BD}}{\text{density of water}}$$

Usually, from 10 to 25 samples are needed to estimate mean %TMSC for a nursery field.

The gravimetric method works well in most nursery soils because of their homogeneity; however, it normally takes too long for everyday use.

12.3.2.2 Neutron probe

The neutron probe can indirectly measure %TSMC(wt) if bulk density is known. High-energy neutrons are emitted into the soil from a radioactive source contained in the probe. The neutrons are slowed down and thermalized by elastic collisions with other nuclei [12]. Because the slowing down or moderating of the neutrons is caused almost entirely by hydrogen nuclei in soil water, the number of thermal neutrons detected per unit time is directly proportional to the %TSMC(wt). Though accurate, neutron probes are expensive and cumbersome and require highly trained, licensed personnel for their operation.

12.3.2.3 Visual and tactile approach

Most often, soil water content is assessed at the surface and (or) root zone by eye and by touch to evaluate irrigation need [39]. Of 99 U.S. nurseries, nearly all determined irrigation schedules by visually observing soil dryness [1].

There are, however, problems with the visual and tactile approach. First, it is entirely subjective; observations are not based on quantifiable procedures. Second, water status may not be assessed at the proper sampling depth; for example, seeing and feeling the surface soil are useless when the irrigation need is at the bottom of the plow layer. Third, guidelines compiled for use by irrigators are, at best, imprecise; even the most experienced and methodical personnel could reach different conclusions due to differences in interpretation or judgment.

In its favor, this method requires no mechanical equipment that can fail and forces the irrigator to closely examine the plants and soil [39].

For best results, the visual and tactile approach should be accompanied by some mechanical method-for example, gravimetric sampling (see 12.3.2.1) or tensiometer readings (see 12.3.2.4)-for calibration, continuity, and quantification [39].

12.3.2.4 Tensiometer

Tensiometers, used in about 10% of western bareroot nurseries [38], can measure matric potential directly in the field [39]. But they can only provide indirect inferences about internal seedling moisture stress.

A tensiometer is basically a porous cup filled with water which is buried in the soil and connected to a vacuum gauge. This gauge registers the pressure drop on the water in the cup, which is in equilibrium with the matric potential of the soil water. Because tensiometers operate well in the 0 to -0.8 bar range, they are ideal for monitoring irrigation in forest-tree nurseries [12]; however, when matric potential drops below -0.8 bar, air begins to enter the porous cup, and the tensiometer becomes inoperative [25].

A minimum of 10 to 12 tensiometer readings is needed to determine mean matric potential. Therefore, one portable tensiometer may be more practical than a large number of static ones. If mean matric potential is used to monitor irrigation, soil-moisture retention curves are required to determine the equivalent %TSMC(wt) when computing the irrigation need [12].

12.3.2.5 Electrical resistance

Sensors containing a pair of electrodes, usually in "blocks" or "sandwiches" made of gypsum, plaster of paris, or fiberglass cloth, are planted in the soil at specified depths to indirectly measure matric potential. As the water content of these blocks changes with soil moisture content, so does the electrical resistance between the two electrodes. Readings on a resistance meter connected to these electrodes are converted to an index of soil moisture content. Resistance blocks are sensitive over a -0.5 to -15 bar range of matric potential and are therefore effective in dry soils.

The electrical resistance is calibrated against actual soil moisture content by taking readings at various soil moistures, finding the soil moisture content by the gravimetric method (see 12.3.2.1), and plotting a curve relating the true soil moisture content to the electrical resistance reading. However, calibration can be a problem because resistance is decreased by salt in the soil and by increasing temperature [39]. Furthermore, seedling roots must be near blocks for readings to be meaningful. The major problem is that electrical resistance does not usually calibrate well with matric potential, %TSMC, or available soil moisture content [12].

Only if equipment can be satisfactorily calibrated can electrical resistance methods be useful for monitoring soil moisture. However, the problems are great, and better methods are available [12].

12.3.3. Measuring seedling moisture stress

The principal methods of monitoring the internal water status, or water potential, of plants include thermocouple or thermistor psychrometer, gravimetric vapor exchange, dye, freezing point, and pressure chamber ([12, 45]; see also chapter 23, this volume). Of these, only the pressure chamber method developed by Scholander et al. in 1965 [47; also 10, 16] is sufficiently practical for nursery use and probably is the simplest, most rapid, and most accurate method suitable for the field [6, 38].

A small twig or needle is cut from the seedling and placed in a steel chamber with the cut end protruding from the lid (Fig. 8). Think of the water column in a seedling as a rubber band [39]. As moisture stress increases in the seedling, this rubber band is stretched. When the twig or needle is cut from the seedling, the tension on that rubber band water column is released, so that water shrinks back from the cut surface. By slowly applying pressure to the cut twig in the chamber, water will be forced back to the cut surface by a pressure equal to the tension originally on that water column. Y **plant** is determined by reading the pressure gauge the instant water appears at the cut surface and recording the pressure in negative bars [39]. Step-by-step instructions for using the pressure chamber are given in Day and Walsh [16].

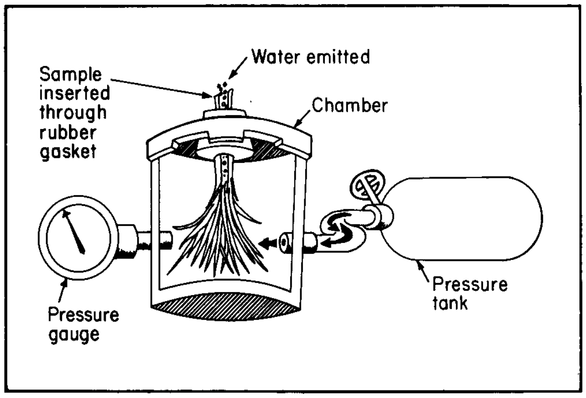

Figure 8. Pressure chamber for monitoring plant water potential (adapted from [10]).

Even though the measurement of Y **plant** cannot be used to monitor soil moisture or to compute the irrigation need, it tells nursery managers whether the seedlings are adequately irrigated or under stress. As such, pressure-chamber measurement is the final test of any system of monitoring soil moisture supply and applying irrigation [12].

Seedling moisture stress depends on: (1) the supply of soil moisture and the ability of seedlings to absorb it, (2) the atmospheric evaporative demand, which is related to the temperature, relative humidity, or vapor-pressure saturation deficit, and (3) the ability of stock to control moisture loss by closing stomata [12]. For example, charting the midday pressure-chamber readings for a group of tree seedlings as they dry out produces a curve relating available soil water to midday Y **plant** (Fig. 9) [39]. Note that at high soil-moisture availabilities, Y **plant** is highly influenced by evaporative demand of the air at the leaf surface. The "adequate" segment (Fig. 9) reflects moisture stress developed solely by evaporative demand. The "stressed" segment reflects increased stress (lower Y **plant**) as soil moisture is depleted and as the influence of available soil water gradually dominates the effect of evaporative demand. The "dangerous" segment indicates increasing stress despite total stomatal closure; if trees are not irrigated, damage will be irreversible.

However, a primary problem in interpreting midday Y **plant** occurs along lines a-b and b-c in Figure 9 [39]. Note that from a to b soil water content is the same, but Y **plant** differs as a result of differing evaporative demand. Conversely, from b to c Y **plant** is the same, but soil water content differs, again because of differing evaporative demand. Each nursery manager will have to determine the midday Y **plant** curve for levels of evaporative demand at the nursery. This problem is simplified in greenhouses, where evaporative demand is more uniform [39]. Where internal seedling moisture stress is intentionally induced to stimulate root growth or apical dormancy (see chapter 15, this volume), the midday Y **plant** curve can provide quantitative guides to the degree of stress that is safe.

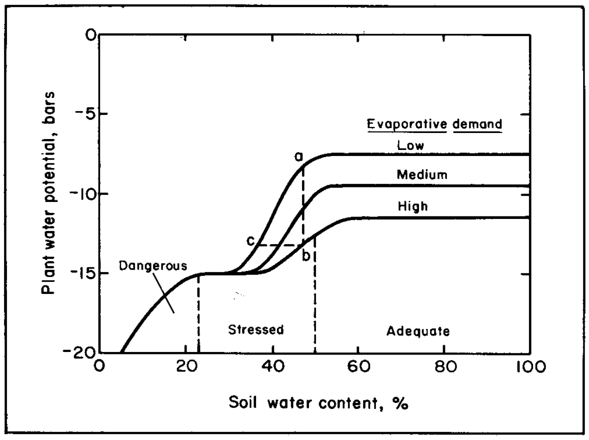

Figure 9. Changes in soil water content and atmospheric evaporative demand affect midday plant water potential (adapted from [39]).

12.3.4 Seedling response to irrigation

12.3.4.1 Seed germination and emergence

The first critical period of irrigation begins immediately after seed is sown and lasts until the seedling is established in the soil and is autotrophic (self-nourishing). A seed must imbibe (absorb) water additional to that present in its "dry" state. it is this first water, entering the seed either during stratification or in the seedbed (if seed is not stratified), that initiates biochemical and physiological processes leading to germination. Practically all seed can absorb enough water to germinate from soil at field capacity, and some seed can germinate in relatively dry soil (i.e., matric potential of -1 to -5 bars). However, germination on dry substrates inhibits root growth [4, 26, 27].

The frequency and rate of water application during germination are influenced by amount of rainfall, soil texture, type of mulch, temperature, sun, and wind. However, a moist germination period is preferred over a wet one because excessive moisture during that period can kill germinating seed [36]. The respiration that fuels metabolic processes during germination requires oxygen, and too much water can limit oxygen supply, especially after the seed coat begins to crack [27]; the embryo may not survive if conditions are too wet. Furthermore, overly wet conditions encourage certain diseases (damping-off) that may damage seedlings. May [36] indicated that the amount of water needed to keep the soil moist may vary from 1/4 to 1/2 inch (6.4 to 12.7 mm) daily on sandy soils to 1/2 inch or more at 2- to 3-day intervals on heavy soils. Because some mulches, such as hydromulch, absorb-;moisture during watering and lose water rapidly by evaporation, special care is needed to provide enough moisture for both mulch and soil.

Irrigation during germination should be frequent and in small amounts. Amounts should be increased over time to wet the entire rooting depth as seedlings develop [36]; if managers continue to apply only small amounts of water once seedlings have emerged, shallow rooting will result. However, frequency of irrigation should be gradually decreased so that seedbeds are kept moist but not wet.

In many nurseries, irrigation may be needed not only to enhance germination but also to prevent hardening of the soil surface into a crust the emerging seedling cannot penetrate. This condition occurs in some interior western tree nurseries that have alkaline soils or water [36]. At some locations frequent sprinkling may also be needed once seedlings have emerged to keep the surface soil cooled by evaporation (see 12.5.2).

12.3.4.2 Seedling growth

Once the new seedling is established, it enters a true growth stage characterized by three primary phases [44, 49]. In the first (logarithmic) phase, the growth rate is initially slow (Fig. 10), apparently because the germinating seed has fewer cells capable of growth, but the rate continuously increases as more cells are formed. in the second (linear) phase, size continues to increase at a constant (usually maximum) rate for some time. We do not understand exactly why the growth rate should be constant in this phase, but one reason might be that stems and roots grow by meristems, which produce cells that grow mainly in length [46]. The final (senescence) phase is characterized by a decreasing growth rate (note drop in rate curve in Fig. lob) as the plant reaches maturity. Although the curves in Figure 10 are generalized representations of many plant species, measured growth curves of trees often only approximate these generalized curves.

Trees commonly cease height growth temporarily in late summer, when temperatures are still warm and days are long [26]. Growth sometimes resumes again before true winter dormancy, a deeper dormancy that results in part from increasing night lengths and in part from low fall temperatures ([46]; see also chapter 14, this volume). Stem diameter continues to grow at a decreasing rate (due to expansion of cells produced by the vascular cambium) until well after height growth stops, and photosynthesis continues until leaves become senescent and yellow (in deciduous trees) or until temperatures become too cold (in evergreens). Root growth can persist as long as water and nutrients are available and soil temperatures remain high enough.

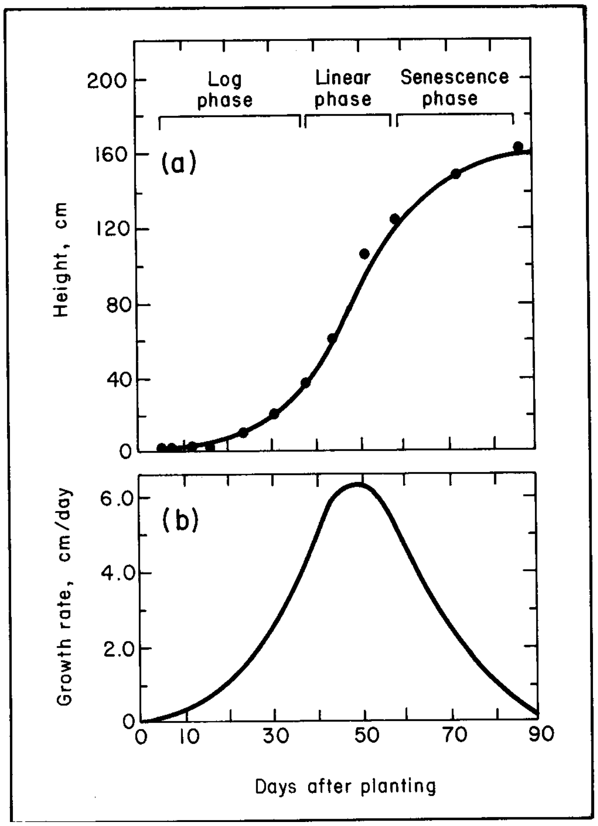

Figure 10. Idealized curves indicating seedling (a) height and (b) growth rate. The rate curve of (b) was obtained by taking the first derivative of (a).

12.3.4.3 Sensitive periods

All crops have moisture-sensitive periods—times during which a water deficit depresses growth much more than would typically be expected. These critical periods are not well defined for forest-tree seedlings. Plants are probably especially sensitive to moisture stress during budbreak and the early part of the linear growth phase (see Fig. 10) in spring and during budset and hardening in fall. Specific seedling reactions would depend, however, on interactions with the environment at a given nursery and, within a species, on the responses and tendencies of given varieties.

12.3.5 Irrigation-monitoring recommendations

Although there is no substitute for personal observation and judgment based on nursery experience, every nursery should use some kind of quantifiable method to indicate available soil water or internal seedling moisture stress [39]. Tensiometers are best for measuring soil moisture at forest-tree nurseries because they cover the critical 0 to -0.8 bar range, and pressure chambers are best for directly measuring Y **plant.** Nursery managers using soil-moisture retention curves and soil and plant-moisture monitoring procedures that can be correlated with both observed and measured crop responses have all the necessary tools for properly monitoring and controlling irrigation-assuming their irrigation system is a good one. However, because crop responses to any environmental modification—be it irrigation, fertilization, spacing, or shading—differ depending on nursery climate, tree species, and seed source, managers need phenological information to fully anticipate seedling response to cultural operations.

The OSU Nursery Survey (see chapter 1, this volume) provided a profile of irrigation monitoring at 21 Northwest nurseries. Though many nurseries use more than one moisture-monitoring method, all use the visual and tactile approach. Two-thirds use a pressure chamber; half use tensiometers, most of which are fixed installations; and only one out of five uses electrical resistance blocks. Only about 30% have soil-moisture retention curves for their soils, and several having them said they did not use them. Most nurseries alter irrigation practices and monitoring as the crop grows older and the season passes. About 75% feel the need for better equipment and guides for irrigation monitoring and control.

Obviously, considerable work is needed at most nurseries to refine irrigation monitoring and control, not only to improve water use and plant growth but also to maximize the benefits of other cultural practices.

12.4 Frost Protection with Irrigation

12.4.1 Damaging effects of low temperatures and frost

Plants vary greatly in their ability to tolerate cold. When properly conditioned, trees are among the most cold-hardy plants. Many temperate-zone trees will tolerate -40°C [21], and boreal forest species, like paper birch (*Betula papyrifera* Marsh.) and jack pine (*Pinus banksiana* Lamb.), will tolerate winter temperatures as low as -196°C [32]. On the other hand, newly emerged seedlings and lush new foliage are not conditioned to withstand cold weather and may be severely damaged by subfreezing temperatures.

Even for the same plant, the frost killing temperature may vary widely, depending on the manner of temperature change, the season, and the physiological state of the plant [32]. The killing temperatures of even the most frost-sensitive plants are slightly below the freezing point of free water, due to freezing-point depression of cell solutions by the solutes in the cell sap [46]. When intracellular freezing of water occurs, it is always fatal to the cell [33]. Plants may be killed at higher temperatures if freezing is rapid rather than gradual, and greater injury to plants may occur after long-continued freezing than after short freezing periods at the same temperature. However, plants that survive one freezing without damage may be injured after two or more freezings at that same temperature.

It is generally during spring that nursery managers are concerned about frost protection; some plants that survive the cold in winter may be killed by a very slight freezing during spring [28]. In some locations, early fall frosting of recently grown foliage also is a problem, though this problem may be avoided by discouraging late-summer top growth (see 12.6). Whether spring or fall, the frost-protection steps a manager can take are the same.

In woody plants, the freezing process can begin on leaf surfaces, in xylem elements, or both [7]. Initial formation of ice crystals on leaf surfaces near the freezing point of water is abetted by so-called "ice-nucleating bacteria," which serve as focal points for the crystallization process [34]. Ice that forms on leaf surfaces around bacteria or other nucleation centers (e.g., dust) can migrate and spread into leaves via stomates and into cells, killing them. The number of ice-nucleating bacteria on leaves has been experimentally reduced with bactericides such as streptomycin and cupric hydroxide; with competing bacteria that are not ice-nucleating types; and with chemicals such as chloroform, which inactivate nucleating bacteria [34]. Although such practices may ultimately have some application in forest-tree nurseries, especially those rearing broadleaved trees, there is little current indication that ice-nucleating bacteria significantly affect the freezing point of conifer leaves.

12.4.2 Other (nonfrost) winter damage

Several types of damage attributable to cold weather, but not directly to frost [7], can affect plants:

- **Frost heaving:** Repeated freezing (expansion) and thawing (contraction) of surface layers of soil can work small or recently transplanted seedlings up and out of the ground. This is common between the first and second growing seasons but can be avoided through mulches of straw or needles.
- **Frost smothering:** When saturated soil freezes so that little or no oxygen can reach tree roots, seedlings may die unless the soil thaws. Damage usually occurs if the situation persists over 48 hours.
- **Frost cracking:** The bark and outer layers of a tree trunk can crack because of forces in the bole caused by differentials of expansion when (1) the exterior thaws or (2) the interior xylem freezes.
- **Winter desiccation:** When roots are frozen and cannot absorb water, but the stem, branches, or needles are not frozen, dry winter air can desiccate foliage.
- **Winter burn:** The sun can raise foliage temperatures above freezing on the south side of plants in winter, even when air temperature is below freezing. At sunset, the thawed foliage refreezes very rapidly. The rapidity of the freezing causes winter burn.
- **Winter scald:** Winter scald is like winter burn but affects the bark, not the foliage, of a woody plant. Often, trees' lower trunks are painted white to lessen this type of damage.

12.4.3 Frost types and conditions

Frosts can be divided into two types: (1) radiation frosts and (2) wind and advection frosts [9]. The two types may occur simultaneously; moreover, in some instances, a radiation frost may intensify a wind frost.

Radiation frosts occur on cloudless nights with little or no wind, when excessive amounts of heat energy in the soil and plants are lost to the sky as long-wave radiation, and leaves, air near the ground, and the soil surface may fall below freezing. Advection frosts occur when cold air flows from a higher location to a lower one, displacing lighter, less dense warm air; such flows will "pool" and concentrate if they encounter an obstruction, causing a "frost pocket." Wind in excess of 4 mph from cold regions causes a wind frost [9], which can occur at any time of the day or night and is not necessarily related to topography.

12.4.4 Protecting seedlings from frost damage

All agricultural frost-protection measures are meant to prevent crop freezing to the point that intracellular water crystallizes to ice and cell membranes rupture. Generally, crops are protected by preventing the air around them from becoming too cold or by placing insulating barriers between them and the cold air. However, only some agricultural methods are appropriate for forest-tree nurseries.

The major frost-protection methods used in agriculture are overhead sprinkling, heating, and wind machines. Less common but also sometimes employed are brushing, sanding, and windbreaks. Managers should be aware, however, that most frost-protection schemes can raise the temperature by only a few degrees, and some are effective only against radiation frost.

12.4.4.1 Overhead sprinkling

Overhead sprinkling-the most commonly used frost-protection method in tree nurseries-is effective against radiation or advection frosts or any combination of the two unless high winds cause poor sprinkler coverage [7]. Water droplets suspended in the air help check the flow of outgoing long-wave radiation. Sprinkling prevents frost by increasing the thermal conductivity and heat capacity of the ground and by releasing latent heat when water freezes [9]. The temperature of the plant will not fall below the freezing point as long as the change of state from water to ice is taking place.

In most tree nurseries, the new succulent growth is most vulnerable to frost damage; older wax-covered needles are usually more frost hardy. Overhead sprinkling is commonly begun in nurseries as the temperature drops to near 32°F and is continued until the temperature again rises above 32°F. Plant temperature declines immediately if sprinkling stops [9]. However, prolonged sprinkling should be avoided because the ice formed on plants can cause damage due to its weight and because overland flows resulting from extended sprinkling can become excessive; where sprinkling is commonly employed for frost protection, drainage ditches should be constructed to carry excess water away. Irrigation water may require a wetting agent to create a more uniform protective water film on hydrophobic surfaces like conifer needles [9].

The success of sprinkling largely depends on the amount and frequency of water application. ideally, sprinkler rotation speed should be such that all water has just turned to ice at the next pass of the sprinkler. Thus, rotation speed should generally increase with the severity of frost. However, overhead sprinkling may have limited effectiveness or even increase frost damage if administered improperly. Many observers have noted that, under *light* radiation-frost conditions, minimal damage occurs to trees in unsprinkled areas whereas serious damage occurs to trees sprinkled with an insufficient amount of water. Businger [8] suggests two possible explanations for increased damage due to inadequate sprinkling: (1) when the air is dry, temperature of the sprinkled leaves will approach the wet-bulb temperature, which may be significantly lower than the dry-bulb temperature; (2) the small amount of ice that forms on a leaf will prevent the undercooling of the cell solution and also may dilute the solution, thereby raising the freezing temperature. Another potentially dangerous situation is when air humidity is low (20% or less), a strong inversion exists, and temperature is barely subfreezing. If sprinklers are not operated until the air temperature rises *well above* the freezing point, the wet-bulb temperature of the leaves can fall back below freezing when sprinklers are shut off [7]. The principal lesson, then, is that frost damage can occur if sprinkler irrigation is improperly applied; to avoid such damage, continue to irrigate until all frost danger has passed.

Seventeen (80%) of 21 Northwest nursery managers use sprinkler irrigation to avoid frost damage (OSU Nursery Survey). Application varies with tree species, season (spring vs. fall), and nursery location. One nursery protects against frost only in spring and three only in fall, but most protect against frost in both seasons. Over 75% of the nurseries begin to irrigate when the air temperature is at or slightly above freezing (32 to 33°F); the rest wait until the temperature drops to as low as 25 to 28°F. Two nursery managers commented that their seedlings had experienced frost injury after irrigation for frost protection but admitted that they may have turned off the water too soon.

Nearly all nursery managers stipulated that irrigation must continue until all ice has disappeared if frost damage is to be avoided. Several said that the treatment was effective into the low 20s (°F) and that spring frosts were of more concern than fall frosts. No frost-protection method other than sprinkling was mentioned; however, the OSU Nursery Survey did not specifically solicit such a response.

12.4.4.2 Other potential frost-protection methods

Heating.—Heaters were utilized in the first successful attempts to prevent frost injury in California in the late 1800s [9] and have since been acknowledged as the best agricultural frost-protection measure. The idea is to warm the cold air in the lower layers of an inversion.

Heating is most effective on a night with a strong temperature inversion. An ordinary inversion ceiling is typically between 10 and 15 m above the ground; therefore, the depth of air to be heated is rather shallow [9]. In the absence of a temperature inversion, however, the principal value of direct heating is to radiate heat to trees and ground surfaces and to produce a pall of humid smoke, which forms a moderating screen that diminishes net radiation loss from the ground [9]. In the United States, the use of heaters generating large amounts of smoke has recently been declared illegal because of environmental degradation.

In general, a large number of small heaters are more effective than a few larger heaters [9] because the latter may set up a current that actually punctures the inversion layer and destroys the valuable warm ceiling. To protect trees against radiation frost, heaters should be evenly distributed so trees can absorb infrared radiation equally. However, to protect trees against advection frost, heaters should be placed in heavier concentrations along the upwind border. In hilly country, heaters should be concentrated mainly in the valleys so that the heat produced will move upward along the slope [9].

Oil heaters have been widely used in the United States; in Germany, coal, briquettes, and wood are the principal fuels. Oil is by far the most efficient because solid fuels cannot often be ignited quickly enough to avert frost damage [9]. In most areas, liquefied petroleum (LP) gas heaters are now legal to use. Because of its high cost, however, heating for frost protection is used only for a few high-priced crops, such as citrus fruits.

Wind machines.—Wind machines break up a nighttime temperature inversion by mechanically mixing air, their effectiveness increasing with the strength of the inversion [9]. Though several machines are needed to do any good, their combined effect is instantaneous.

Wind machines have been used increasingly, largely because their operating cost is only about 20% of that of heaters; however, they cannot protect trees in a freeze with cold daytime conditions, on cold soils, or with relatively warm air overhead on a clear, cold night. in steep valleys, the elevation of the temperature inversion may be too high for wind machines to be useful. Even when inversions are strong, the gain in ground-surface temperature with wind machines is rather small, usually less than 3 to 5°C. Therefore, it is common practice to install both wind machines and heaters in the field [9].

Brushing.—Brushing is a frost-protection scheme extensively used for vegetable crops in California [9]. Shields of brown kraft paper are attached to stakes on the north side of east-west rows, leaning over the plants. No plants are located on the shaded side, which is used for irrigation ditches. During the day, the shields deflect radiation to the plant and soil and also act as a windbreak; at night, the shields reduce radiation loss to the sky.

Brushing is more effective in protecting against radiation frost than wind frost. It is also more effective for small plants that have not outgrown the height of the kraft paper. This procedure may have a future in the culture and protection of tree-seedling crops grown from high-value genetically improved seed.

Sanding.—A sandy surface warms up easily and cools only slowly by radiation. Sand also minimizes evaporation, because of its low water content. Sanding can raise the temperature of loam and clay by several degrees and that of organic soils by even more, thus diminishing frost hazard [9]. In nurseries with sandy soils, this measure would be useless; but in nurseries with heavier soils and recurrent problems with spring frosts, it may have merit.

Windbreaks.—By excluding or diminishing the inflow of cold air and by shielding the field somewhat from the night sky, windbreaks can protect against frost [7]. However, windbreaks that are too dense can produce radiation frost in the lee or allow frost pockets to develop. Obviously, the merits of a shelterbelt like a windbreak for frost protection must be analyzed for specific instances. Where a nursery is subject to regular advection frosts, a windbreak to deflect the flow of cold air could be useful.

12.5 Controlling Heat in Seedbeds with Irrigation

12.5.1 Effects of heat

The number of seedlings that die outright because of heat stress is unknown. Even more uncertain is how many seedlings die from longer term heat stress and resultant indirect damage. Direct heat injury is due to cellular membrane injury, cell-component decomposition, or both; the effects are immediate and obvious. Indirect heat injury—due to metabolic disturbances—is more subtle and varies from minor reversible damage to death. If heat stress is moderate or short lived, the effect may be negligible; but if stress is severe or long term, the effect may be major.

The physiological complexity of plants precludes precise determination of cardinal temperatures because different processes and species have different temperature requirements [42]. Such temperatures also depend on the plant's state of development. General cardinal temperatures for cool- and warm-season plants are [9]:

	Temperature, C°	
Cardinal points	Cool-season plants	Warm-season plants
Lowest temperature for survival (killing point)	1 to very low	-1 to 10
Lowest temperature for growth	-1 to 5	15 to 18
Optimum temperature for growth	25 to 31	31 to 37
Highest temperature for growth	31 to 37	41 to 50
Highest temperature for survival (killing point)	40 to 45	50 to 52

12.5.1.1 Young seedlings

Very young trees are susceptible to heat damage because they are physically ill-equipped to deal with heat. The most apparent injury is direct, irreversible damage to tender seedling tissues, which can lead to death. Such damage, which often occurs just above the soil surface on the south and west sides of the stem, may be seen as depressed areas of necrotic tissue called "heat lesions."

Seedbed surfaces can become very hot in spring and summer. Evidently, the proximity of the seedling's tender cortical stem tissues to the hot soil surface is the key factor—because that is where the damage occurs (Fig. 11). Stem temperature reaches the killing point (about 40°C) there first because of energy concentrated at the hot soil surface, infrared radiation reflected from the soil surface to the stem, and lack of conduction and convection of heat away from the stem by moving air. The amount of direct insolation absorbed by the seedling seems less important than the amount absorbed by the soil, and air temperature is only indirectly related. Transpirational cooling, quite low in young trees, probably is inconsequential. Stems of young, heat-injured seedlings shrivel and become pale. At first, there is a definite boundary between the healthy and shriveled parts; then the healthy parts slowly decay. Drought-stricken seedlings, on the other hand, wilt along the entire length of the stem, which sometimes curves before shriveling or rotting at any one point; digging may show that soil is dry well below seedling roots [54].

The nursery manager's job is to keep the temperature of susceptible plant tissues below the lethal level. In the case of very young tree seedlings, the soil surface must be kept cool to prevent seedling damage. Where the nursery has high insolation rates, heavy soils, dark soils or mulches, or poor air circulation, sensitive species will have to be protected from heat damage most of the first growing season. Most true firs (*Abies* spp.), spruces (*Picea* spp.), coastal Douglas-fir [*Pseudotsuga menziesii* (Mirb.) Franco var. *menziesii*], white pines (*Pinus* spp.), hemlocks (*Tsuga* spp.), Northwest cedars (*Thuja* and *Chamaecyparis* spp.), and redwood [*Sequoia sempervirens* (D. Don) Endl.] are susceptible to heat damage as young seedlings. However, the degree of protection is contingent on the nursery environment and must be determined for each species at each nursery.

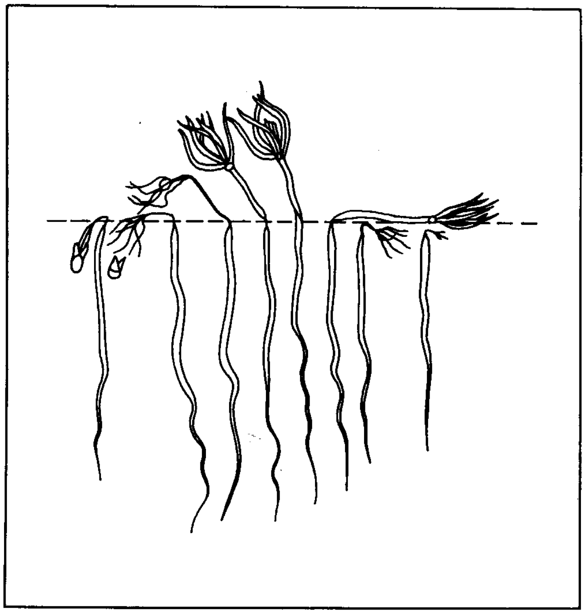

Figure 11. Pine seedling killed due to overheating at the soil surface (adapted from [41]).

12.5.1.2 Older seedlings

older seedlings have developed a lignified outer stem that insulates sensitive tissues from hot soil—which is why older tree seedlings are more heat resistant than younger ones. But heat lesions may still develop on older seedlings, either on only one side (usually the south) or all around the stem. Fresh lesions are typically pale but sharply defined, at or just above the soil surface; older lesions on larger seedlings may be surrounded by slight swellings [54].

Indirect heat injury such as growth loss is more of a concern with older seedlings than direct heat injury. Although growth loss due to heat damage is hard to diagnose, it may be sizable, especially in low-elevation nurseries growing heat-sensitive species like true firs and spruce. Heat sensitivity can be expressed in growth curves from seedlings reared in growth chambers at various temperatures [53] (Fig. 12). Note that seedling growth is optimal within a certain temperature range, depending on species; growth of coastal redwood, which is particularly sensitive to heat, drops off dramatically outside a narrow optimum range (Fig. 12c).

12.5.2 Keeping seedlings cool

Sprinkling seedlings is the most common way to keep them cool, although other methods, like shading or mulching, also are employed.

Generally, soil temperature can be modified in two ways. First, the incoming or outgoing energy can be altered by: (1) placing an insulating layer, such as paper, mulch, screen, or glass, on or near the ground surface; (2) changing the absorptivity of the ground; or (3) varying the air temperature with a wind machine or shelterbelt. Second, the thermal properties of the ground can be modified by: (1) increasing or decreasing the absorptivity of the ground; (2) changing the thermal conductivity by rolling the seedbed before sowing or by cultivation and irrigation; (3) altering the heat capacity by adding or draining water; or (4) varying the rate of evaporation by removing weeds, regulating soil moisture, and placing mulch, screen, or sand on the soil surface [9].

12.5.2.1 Irrigation

Reducing soil-surface temperature with irrigation is the principal cooling method available to the forest-nursery manager. Managers need to know the soil-surface temperatures that cause irreversible damage to their crop at a given stage of development-and must prevent the soil from becoming that hot.

Irrigation is normally applied regularly after seed is sown and until it germinates to keep the soil surface moist. This not only prevents the development of a surface crust which the emerging seedlings may have difficulty penetrating but also assures adequate available moisture for seedling development. Additionally, irrigation cools seedbed surfaces as water evaporates. Evaporation is a powerful cooling process. Some 540 calories are required to convert 1 g of water at the boiling point (100°C) to vapor. When I g of water evaporates at 20°C, it absorbs 586 calories; at 30°C, it absorbs 580 calories. Irrigation during the heat of the day can reduce soil-surface temperatures by as much as 20°F (11°C) [36]. Once germination is complete, the intervals between irrigations gradually lengthen as seedlings develop deeper roots and are physiologically better equipped to endure normal moisture stresses. However, during this same period, the seedling is most susceptible to heat damage, and with some species in some locations, frequent, brief irrigations are needed to cool the soil surface.

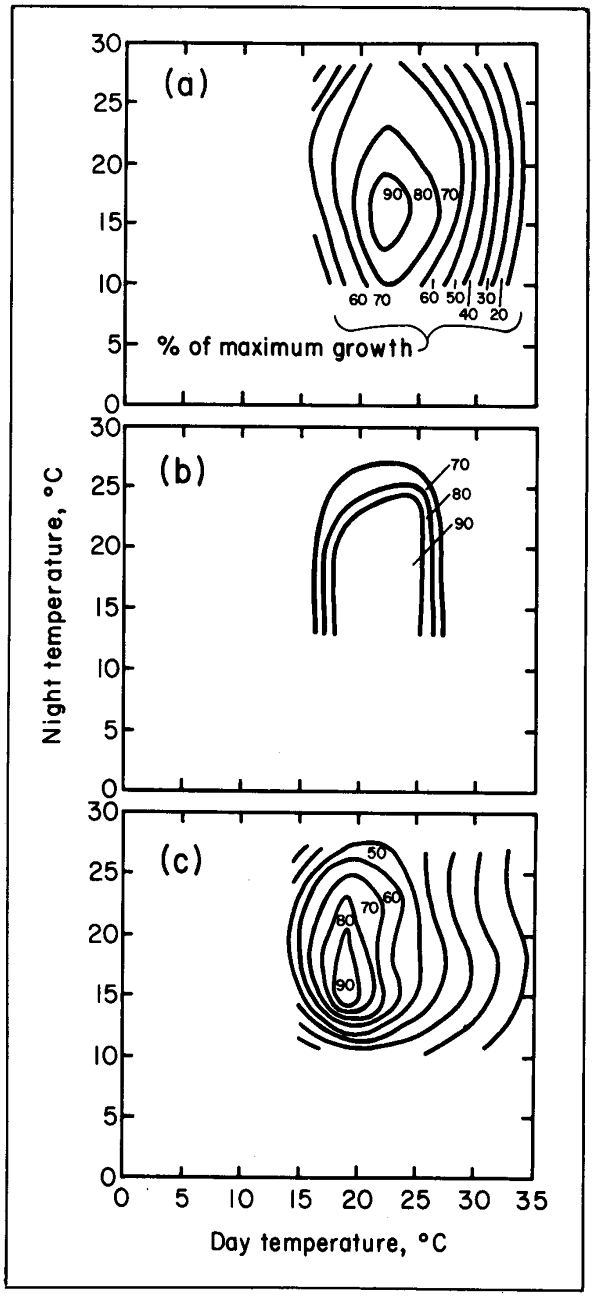

Figure 12. Curves indicating the effect of heat sensitivity on growth of (a) white spruce, (b) Douglas-fir, and (c) redwood (adapted from [53]). Values within curves represent the percentage of maximum possible growth.

An easy, reliable, and accurate method for determining soil-surface temperature is essential. Temperature is usually measured by a thermometer placed immediately below the soil surface. Dial thermometers can be read without disturbing the probe. Thermocouples or other sensing devices also can be used. An infrared thermometer would be an ideal device because no surface contact is needed, but it must be calibrated frequently. In any case, thermometers should be evenly distributed over the area monitored to account for variation in soil texture, slope, tilth, and soil color and to compensate for any instrument that may be defective.

In addition to cooling the soil surface, sprinkler irrigation during the hottest period of the day can drop the air temperature 10 to 15°F (5 to 8°C) or more around trees [36], cooling seedling foliage and reducing overall plant heat stress. The benefits of such cooling to seedling growth—in terms of increased photosynthesis, less photo-oxidation, or respirative energy loss—are hard to determine-, but effects on growth could be estimated from the growth curves in Figure 12. Whether sprinkling in the heat of the afternoon is justified to enhance growth and development is debatable but probably deserves further study.

Guidelines for cooling seedlings with irrigation must be developed which consider seedling species, soil type, and climate. For example, the cooling regime for the U.S.D.A. Forest Service). Herbert Stone Nursery in Medford, Oregon, begins with irrigation just after germination, in early June, when the soil-surface temperature is about 35°C, and continues through late August to the end of the summer growing season, when soil-surface temperature may reach 46°C [40]. Critical soil-surface temperatures are raised gradually through the growing season as seedlings develop greater heat tolerance; at the Stone Nursery, critical temperatures are increased by 1 to 2°C every 2 weeks. The cooling irrigation period is 30 minutes long when wind speed is 6 mph or less, 45 to 60 minutes long when wind speed exceeds 6 mph. Normally, this regime also provides all the water needed for normal seedling growth.

At the Coeur d'Alene (Idaho) Nursery, soil-surface temperature is never allowed to exceed 90°F during germination of Engelmann spruce (*Picea engelmannii* Parry ex Engelm.) and grand fir [*Abies grandis* (Dougl. ex D. Don) Lindl.] and for the first 2 weeks afterward, 95°F for the first 2 months, and 100°F for the first summer. Midday irrigation is applied as frequently as necessary to adhere to these rules and only long enough to reduce soil temperature to a stabilized lower level.

Overhead irrigation of pine seedlings in North Dakota, begun when soil temperature reached 120°F, reduced that temperature to 100°F after 1/2 hour of watering; the temperature reduction lasted for 4 hours or more (Fig. 13) [52].

About % of Northwest nursery managers irrigate to cool air temperature (OSU Nursery Survey), primarily to reduce seedling moisture stress and air temperature around plants and to enhance growth and development. This type of irrigation is not intended to prevent direct heat damage.

Over 3/0 of Northwest nurseries surveyed use irrigation to reduce soil-surface temperatures. In most instances, irrigation to cool the soil surface was relatively brief, beginning in the 85 to 90°F range, with the critical temperature increasing gradually as seedlings became older and more heat tolerant. Differences among species were recognized; generally, spruces and true firs were regarded as more heat sensitive than Douglas-fir and pines. In sum, the variation in guidelines from one nursery to another suggests that nursery managers should experimentally determine what works best for their sites and the particular species grown there.

12.5.2.2 Shading

Shading prevents the buildup of high soil-surface temperatures by intercepting solar radiation and, in effect, insulating seedlings from the heat source. Though this technique is quite effective, the materials are expensive and their installation and removal labor intensive. Because shading simulates the early growth environment of many "shade-tolerant" species, "half-shade" (50% light transmission) has been recommended for many heat-sensitive species such as spruces, firs, and hemlocks in the Lake States [51] and the Great Plains [52].

Shading can be effected by suspending wooden snowfence on wires or boards over the sown seedbeds. However, snowfence is expensive and must be removed for cultural operations such as hand weeding; detailed information on this practice is given in Stoeckeler and]ones [51]. Woven polypropylene "shadecloth" can be used instead of snowfence; although somewhat more efficient and less cumbersome, it is still expensive. Wakeley [54] thoroughly tested seedbed shading in nurseries in the southern U.S. and found it to be costly and unnecessary for southern pines.

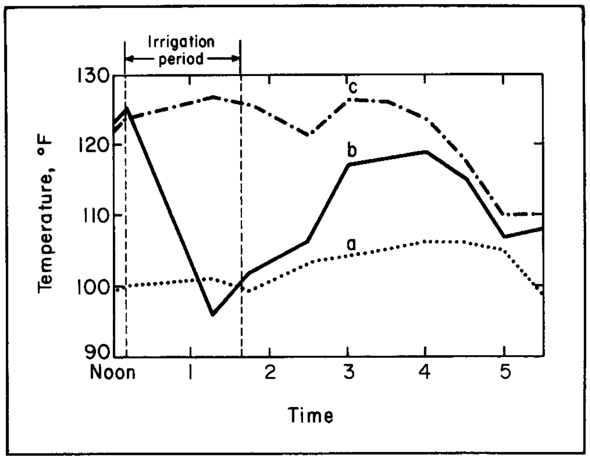

Figure 13. Effect of watering on soil-surface temperatures at Towner Nursery, North Dakota: (a) air temperature in shade: (b) soil-surface temperature In sun with 1½ hours of wetting; (c) soil-surface temperature in sun with no wetting (adapted from [52]).

"High shade" is employed at some nurseries that rear very heat-sensitive tree species. In such cases, shadecloth is suspended on cables between utility poles high enough to clear sprinkler irrigation and nursery equipment. However, most tree nurseries have abandoned costly shading in favor of irrigation cooling. As the value of tree crops rises due to increased seed values and nursery capital investments, shading—especially mechanized versions or "high shade"—may become economically viable at some nurseries, especially where irrigation water is scarce or where very sensitive or high-value species are grown.

12.5.2.3 Mulching

Different soils vary considerably in their ability to conduct and dissipate heat (Fig. 14). Sandy soils are very porous, so the sun's energy is concentrated in a thin surface layer which can

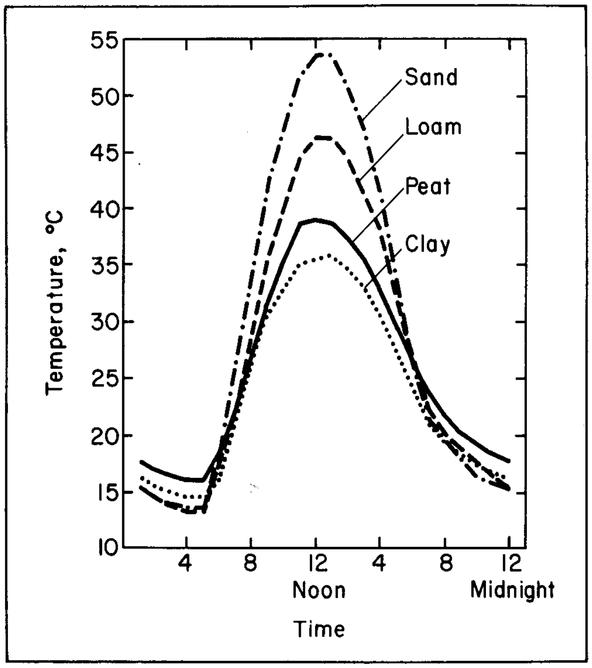

Figure 14. Daily pattern of surface temperatures of different soil types at Sapporo, Japan (adapted from [57]).

reach temperatures exceeding 50°C (122°F). Finer textured soils such as clays contain less air space and can therefore conduct heat away from the surface.

Mulches can either foster or hinder temperature buildup in soil surfaces. A thin, light-colored layer of fibrous or particulate organic matter can help hold down surface temperatures in newly sown seedbeds. A light-colored mulch has a higher heat capacity, greater surface area, and higher albedo (reflectivity) than most nursery soils and can reflect or dissipate incoming solar radiation. A dark porous mulch, on the other hand, absorbs more sunlight and can allow soil-surface temperatures to rise high enough to damage young seedlings.

12.6 Controlling Seedling Dormancy with Irrigation

12.6.1 Importance of top dormancy

Northwest nursery managers realize the importance of encouraging seedling dormancy in late summer so that the trees can become frost hardy before the advent of freezing weather and be adequately hardy for lifting and storage (see chapters 14, 15, and 21, this volume).

Frost hardiness develops in two stages. The first stage prepares seedlings for temperatures down to -1 to -2°C [7, 31]; in this stage, physiological activity actually increases [48] and moderate moisture stress is apparently tolerated without negative effect, although severe stress is disruptive [7]. Though genetically controlled, the first stage is triggered by photoperiod and temperature. The second stage of hardening is actually triggered by frost and, once invoked, proceeds rapidly. No photoperiodic or translocatable factors are involved, and the numerous physiological changes occurring at that time make protoplasm more resilient [31]. But frost hardiness cannot develop in actively growing seedlings.

For many temperate-zone conifers, the relatively long, cool nights of late summer and early fall provide the required stimulus for inducing top dormancy. However, Lavender [29] found that moisture stress inhibited top growth and induced dormancy in conifer species such as Douglas-fir, white fir [*Abies concolor* (Gord. & Glend.) Lind]. ex Hildebr.], and blue spruce (*Picea pungens* Engelm.). This is of particular interest to nursery managers: because irrigation can extend active shoot growth of Douglas-fir and ponderosa pine well into the fall [30], seedlings will be subject to frost injury unless nurseries develop irrigation schedules that include a period of late-summer moisture stress to induce seedling dormancy before the first fall frosts.

12.6.2 Scheduling irrigation to induce dormancy

Obviously, no single irrigation schedule will work at all nurseries because of differences in climate, cultural regimes, species, and genotypes (see chapter 15, this volume). One of the few actual examples of an irrigation regime designed to induce seedling dormancy was developed over a 5-year period at the D. L. Phipps Oregon State Nursery at Elkton, Oregon [58]. These researchers used a pressure chamber to monitor predawn Y_{plant} in 2+0 Douglas-fir seedlings for three different watering regimes: wet (-5 bars), medium (-8 bars), and dry (-15 bars). Intermediate tests revealed that wet-regime seedlings were not sufficiently dormant in fall but that dry-regime seedlings were too small to meet minimum size standards. After additional testing, an intermediate water regime was found to produce a balance between seedling size and dormancy. The final irrigation schedules emphasize the importance of seedling size class and timing of the various irrigation stress treatments (adapted from [58]):

Seedling class	Predawn Y_{plant} bars			
	Until July 9	After July 9	About Aug 3	About Aug20
1+0	-5	-10	-12	-15
	Until June 1	June 1-15		After June 15
2+0	-5	-8 to -10		-15[1]
	Until July 1	July 1-Aug 1		After Aug 1
2+1	-7	-10		-15

[1] In seedlings held for 2+1, keep predawn Y_{plant} between -10 and –15 bars during this period.

Blake et al. [5] also studied the effect of moisture on seedling dormancy and found that lower Y_{plant} between mid-July and late August consistently halted shoot growth and increased frost hardiness of Douglas-fir seedlings. Of particular interest is their observation that delaying the moisture stress treatment until late August interfered with hardiness development; they concluded that this stress must be relieved in the fall if frost hardiness is to develop properly. Supplemental irrigation may even be needed to complete the first stage of hardening before the weather becomes too cold [30].

Zaerr et al. [58] emphasize that any irrigation schedule is only a guide and must take seedling growth rates and nursery climate into account. They recommend the following principles to regulate seedling growth, induce dormancy, and enhance frost hardiness:

- Monitor predawn Y_{plant} to schedule irrigation
- Promote shoot growth early in the season
- Induce dormancy in late summer by gradually increasing moisture-stress levels
- Deepen dormancy by relieving stress in early fall
- Tailor irrigation schedules to accommodate the soil, climate, species, seedling class, and cultural practices of the particular nursery

Twenty of 21 (95%) Northwest nurseries reduce watering to harden seedlings in fall (OSU Nursery Survey). Of those 20, approximately half monitor Y_{plant} to schedule irrigation, and half cease irrigation after seedlings reach a certain size or on a certain date.

There was no consensus regarding regimes among nursery managers who monitor Y_{plant} to induce dormancy—which reflects both site variation among nurseries and a difference in opinion about the required stress levels. The various regimes can be summarized as follows:

- 46% of the nurseries allow predawn Y_{plant} to decrease to the -10 to -15 bar range in June or early July and maintain this stress level until the fall rains begin
- 27% use the calendar date of August 1 to allow *midday* Y_{plant} to fall to -20 bars
- 27% allow predawn PMS to fall to -8 to -10 bars by July 15 and then usually begin to irrigate again after budset in August or September

Nursery managers using calendar date as a criterion for irrigation scheduling felt that irrigation should be reduced after root pruning in late June or early July and stopped altogether in September.

Although all nursery personnel clearly were aware of the importance of inducing seedling dormancy with moisture stress, there were obvious differences in the timing and magnitude of stress levels. More research in this area is needed.

12.7 Conclusions and Recommendations

- The main objective of irrigation is to avoid unwanted seedling moisture stress-which can vary from a small decrease in water potential to death by desiccation. Knowing when and when *not* to water should help nursery managers implement the most effective irrigation monitoring and application programs possible.
- Soil water potential—a combination of matric, osmotic, pressure, and gravitational potentials—as well as field capacity and permanent wilting percentage are soil-water characteristics significant to plant growth. As water held in soil pores is depleted, matric potential decreases, and soil pores initially filled with water become filled with air. The secret of effective nursery irrigation is to keep soil pores filled with the proper balance of both water and air to minimize seedling moisture stress.
- Plant water potential is the single most useful measure of moisture stress in plants. Predawn readings, which indirectly measure soil water potential, are the most stable; midday readings are the second most stable, but are more difficult to interpret because they reflect not only soil water potential but also atmospheric evaporative demand and physiological response through stomatal closure.
- Every nursery should use a quantifiable method to monitor available soil water or internal seedling moisture stress. Tensiometers are best for measuring soil water in forest-tree nurseries because they cover the critical 0 to -0.8 bar range, and pressure chambers are best for directly measuring plant water potential. Soil-moisture retention curves (which relate matric potential to percentage of soil moisture by weight), soil- and plant-moisture monitoring procedures, and careful observation together form the best approach for properly monitoring and controlling irrigation-assuming the irrigation system is a good one. However, because crop responses vary due to environmental modification, nursery climate, tree species, and seed source, managers need phenological information to fully anticipate seedling response to cultural operations.
- Seedlings must be protected from the damaging effects of frost resulting from intracellular water crystallizing to ice and rupturing cell membranes. Overhead irrigation sprinkling is the most common frost-protection method and is the most effective, unless high winds cause poor sprinkler coverage. The success of sprinkling largely depends on the amount and frequency of water application; to avoid the damage that can occur from improper application, continue to irrigate until the temperature rises above 0°C. Heaters, wind machines, brushing, sanding, and windbreaks are used for agricultural frost protection at varying costs with varying degrees of success.
- Heat injury to seedlings can be direct (due to cell-membrane injury or decomposition) or indirect (due to metabolic disturbances). The soil surface around young seedlings must be kept cool to prevent heat damage, especially where the nursery has high insolation rates; heavy, dark soils or mulches; or poor air circulation. Older seedlings, whose lignified outer stem helps insulate tissues from hot soil, may suffer indirect injury such as growth loss and therefore also warrant attention. Sprinkling seedlings with irrigation water is the most common, effective method for keeping soil-surface temperatures down, although shading and mulching also have been used; in addition, sprinkling helps lower air temperature, reducing overall heat stress. However, guidelines for cooling seedlings with irrigation must take into account species, soil type, and climate.
- Nursery managers should encourage top dormancy of seedlings in late summer so that trees can become frost hardy long before the first fall frost. Frost hardiness, which progresses in two stages, cannot develop in actively growing seedlings. Scheduling irrigation to produce a *moderate* level of moisture stress allows managers to aid dormancy induction. Monitoring predawn plant water potential to schedule irrigation, promoting shoot growth early in the season, inducing dormancy in late summer by gradually increasing moisture-stress levels, deepening dormancy in early fall by relieving moisture stress (through irrigation, if necessary), and tailoring irrigation schedules to soil and stock types, climate, and cultural practices should assure the desired seedling growth and enhance frost hardiness.

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