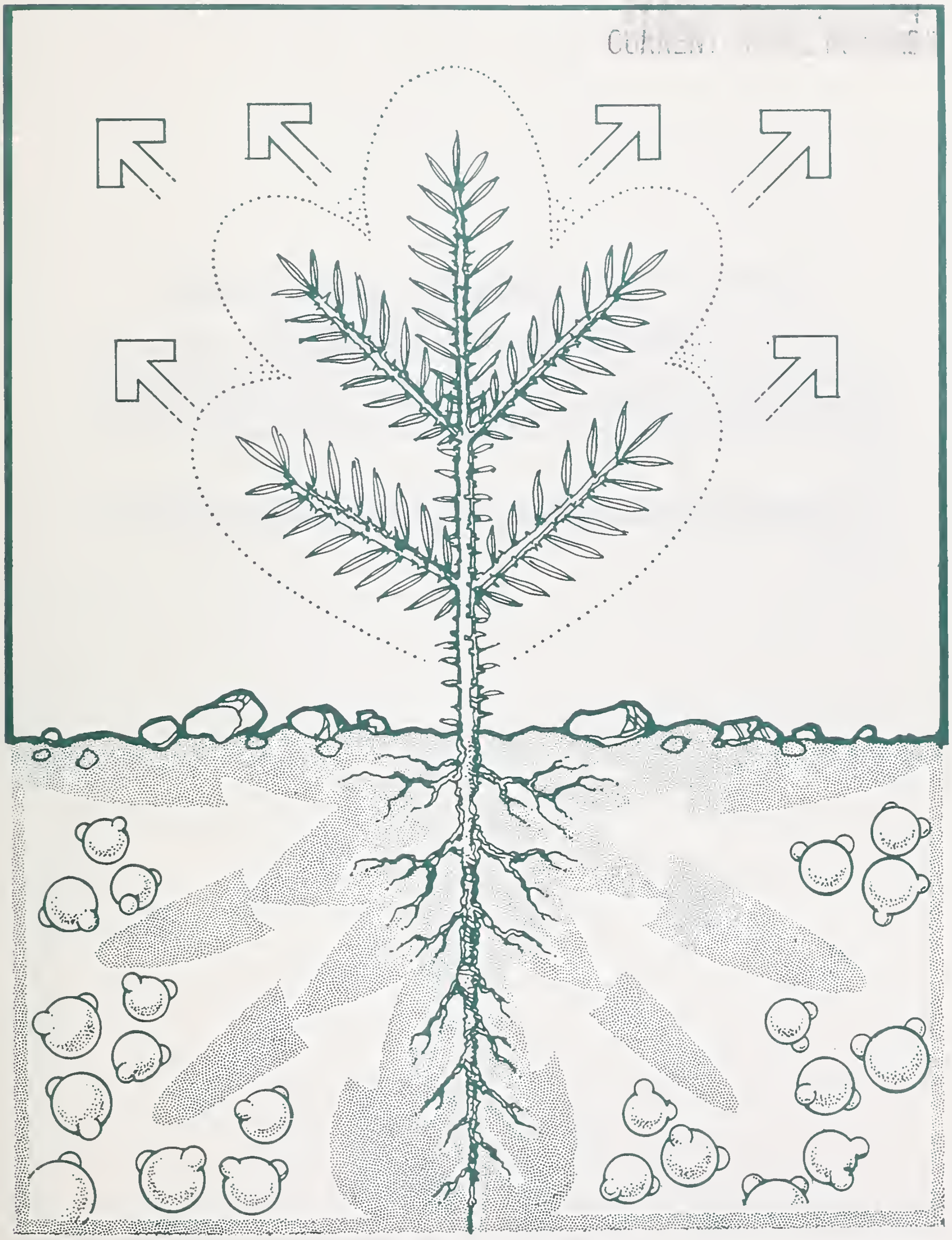
Monitoring Irrigation in Western Forest Tree Nurseries

Stephen E. McDonald and Steven W. Running



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Abstract

This report reviews instruments available for soil and seedling water measurement, and makes recommendations for improvement of irrigation monitoring techniques. Guidelines for use of the pressure bomb to measure seedling water stress and interpretation of the results are included.

Keywords: Tree nursery, greenhouse, irrigation, pressure bomb, water stress.

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[1]*Western Nursery and Greenhouse Specialist, State and Private Forestry, USDA Forest Service, Rocky Mountain Region, Lakewood, Colo., and Research Forester, Rocky Mountain Forest and Range Experiment Station, central headquarters maintained at Fort Collins, in cooperation with Colorado State University.*

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Seedling Water Relations

Effects of Water Stress

Numerous studies have documented adverse effects of water stress on physiological and biochemical plant functions. Cell elongation and cell division, important factors in forest tree seedling growth, are the first plant functions to be retarded by low level water stresses (Hsiao et al. 1976).

Plant water transport can be viewed as a simple input-output system, with soil water as the input and plant transpiration to the atmosphere as the output.

Under optimal conditions, transpired water loss is replenished by root water uptake during the course of a day, although some lag between transpiration and root uptake is normal due to a lag in transmission of water stress through the plant.

Diurnal effects.—When atmospheric evaporative demand exceeds the ability of the root system to provide water, the result is short-term water stress. Atmospheric evaporative demand is generated primarily by increasing air temperature and decreasing humidity, although radiation intensity and windspeed contribute less directly.

At constant relative humidity, the evaporative demand increases exponentially with air temperature, not linearly, because the atmosphere can hold more water vapor as air temperature rises (fig. 1). Consequently, as air temperature rises, evaporative demand can become very high and cause significant short-term water stress even with well-watered soil. The nursery manager can moderate evaporative demand by shading and midday overhead sprinkling. These measures may or may not be worthwhile depending on the nursery's location and the tree species being grown.

Soil water content effects.—Low soil water content also will induce plant water stress. This variable can be controlled by the nursery manager. The ability of a plant root system to extract water from soil depends on the difference between water potential of the plant root system and water potential of the soil. Total water potential is a physical-chemical parameter with a number of components. These components quantify soil particle-water attractions, salt solution influences, plant xylem tension, and cell turgor effects. Kramer (1969) provides a complete definition of water potential. In general, optimum plant or soil water conditions are at a water potential near 0 bar (1 bar = 14.7 pounds per square inch). As water stress increases, water potential decreases, becoming more negative. Mild midday tree seedling water stress might be -7 to -10 bars.

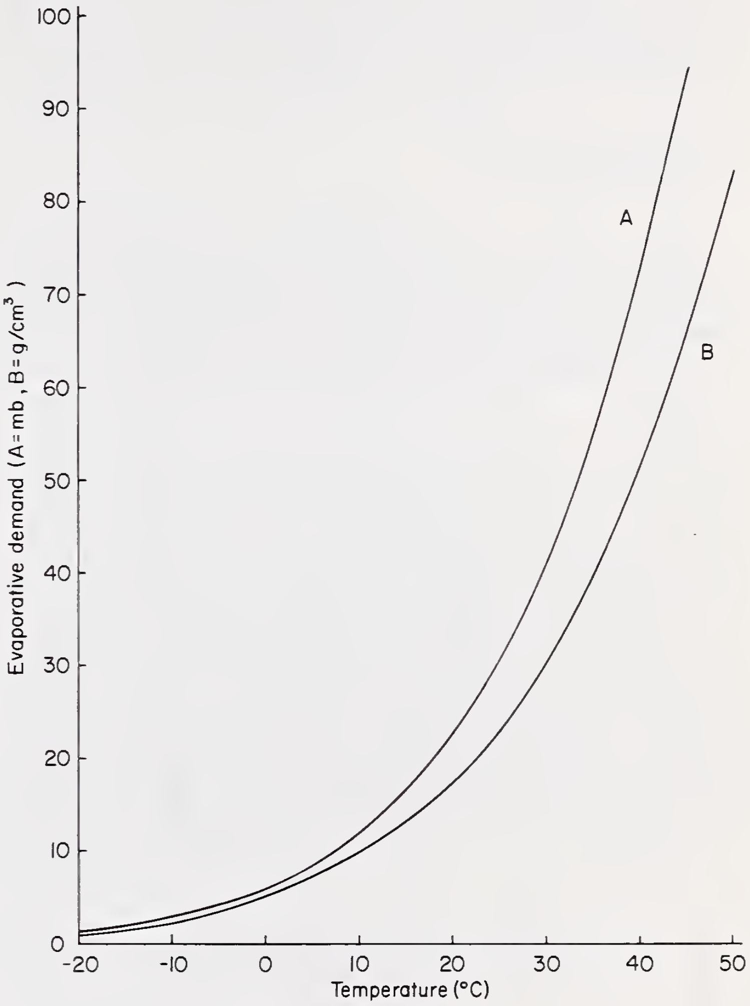

Figure 1.—Effect of air temperature on the ability of the atmosphere to hold water vapor, expressed in two frequently encountered units: A — saturation vapor pressure in millibars, and B — saturation vapor density in grams per cubic centimeter of air (x10^{6}).

Soil water potential decreases as soil water content drops. As figure 2 demonstrates, the relationship is both nonlinear and changes with soil texture

(Hausenbuiller 1972). Such soil moisture retention curves are very useful at tree nurseries and can be acquired from soil testing labs for $25 to $30. Notice, for the sandy-loam soil in figure 2, 77% of the water can be removed before soil moisture tension exceeds -0.8 bar. Any additional water depletion increases tension rapidly. Consequently, to maximize water use efficiency while minimizing plant water stress, plants should be irrigated at soil water potentials of no lower than -0.5 to -0.8 bar. This is within the range of soil tensiometer measurement capabilities.

Shoot/Root Ratio

The shoot/root ratio significantly affects development of plant water stress. Increasing root area of a seedling with a constant top leaf area allows it to better withstand high evaporative demand and low soil water potential, because total root water uptake is increased.

Seedlings cultured (through water stressing or top pruning) or selected (graded) for lower shoot/root ratios should tolerate water stress following outplanting better than those that are not. Lopushinsky and Beebe (1976) have reported on the operational significance of these ideas.

Plant Water Potential

Internal plant water potential is dynamic. It changes both diurnally and seasonally, and integrates effects of soil water potential and atmospheric evaporative demand with plant response. The parameter produced is the single most useful measure of water stress in the plant. Figure 3 illustrates expected diurnal patterns of plant water potential in nursery seedlings under different conditions. Pre-sunrise water potential readings are indirect measures of soil water potential and are the

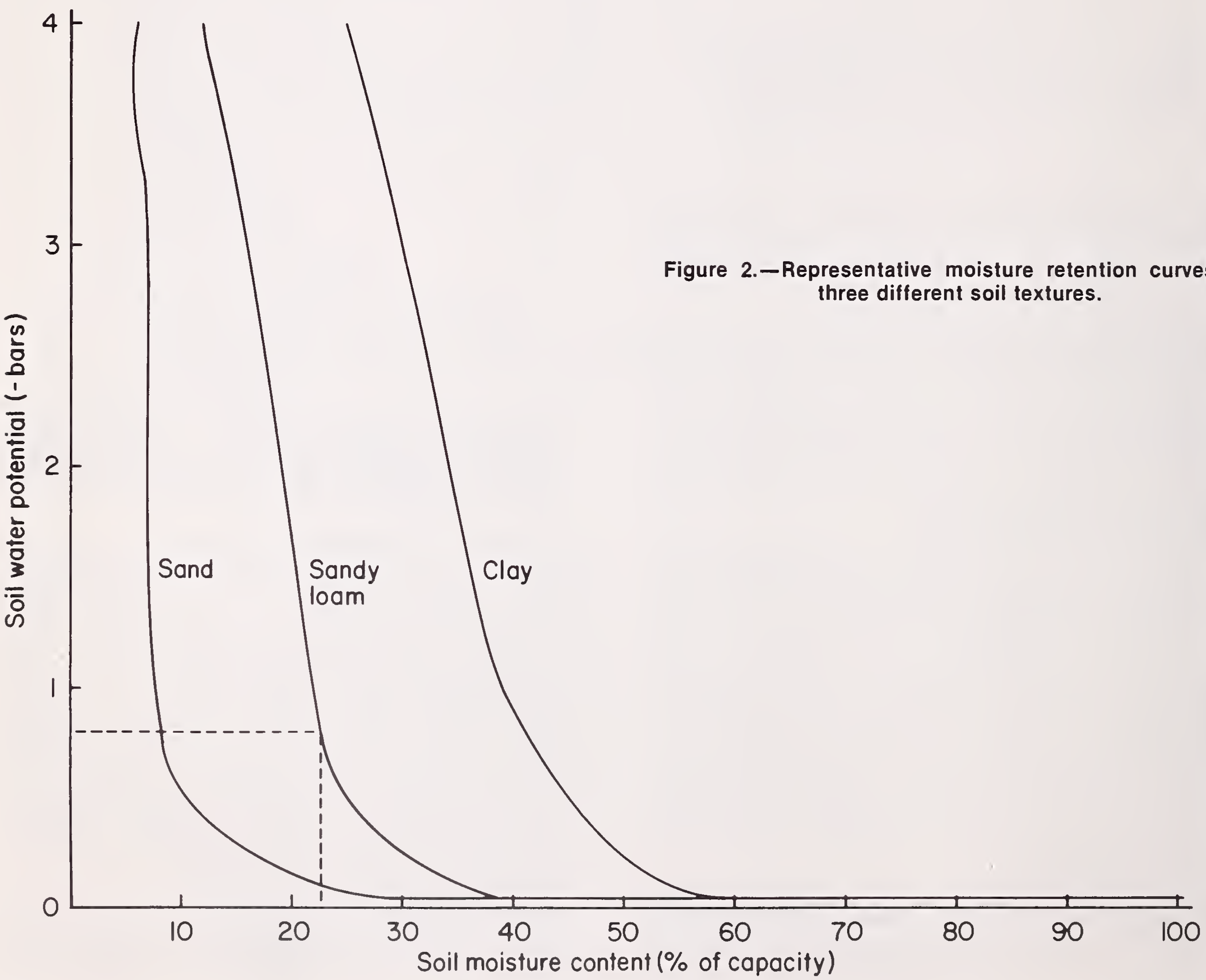

Figure 2.—Representative moisture retention curves for three different soil textures.

most stable measures of plant water potential that can be acquired. When taking pre-sunrise measurements, it should be completely dark. Generally, if it is light enough to walk without a flashlight, it is too late.

Plant water potential usually drops to a plateau between about 0900 and 1100 in summer and remains roughly at that level until late afternoon. This midday plateau is the second most stable time to measure plant water potential. However, interpretation of midday measurements is more difficult, because they reflect soil water potential, atmospheric evaporative demand, and physiological plant response through stomatal closure. Even under well-watered soil conditions plant water potential may remain in the range of -7 to -9 bars on a cool humid day but on a hot dry day may drop to -9 to -12 bars (fig. 3). As soil water is depleted, the midday plateau may drop to -15 bars or lower. Without irrigation, the reading will continue to drop until the plant dies at values of -40 to -50 bars. Figure 4 illustrates that, as soil water potential decreases, first midday then pre-sunrise plant water potential decreases (Slayter 1967). Generally, when midday plant water potential reaches -12 to -15 bars, water stress is probably beginning to impair growth. The time required to reach this water stress level depends on soil water available to each seedling and evaporative demand.

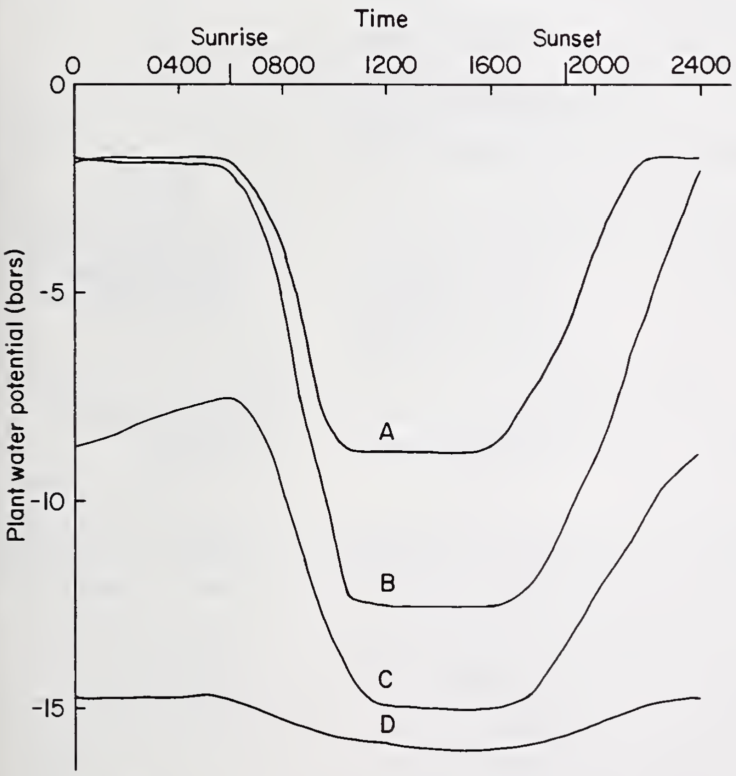

Figure 3.—Diurnal patterns of plant water potential for a nursery seedling under varying conditions of soil and atmospheric water stress. A — low soil water tension and low evaporative demand; B — low soil water tension and high evaporative demand; C — high soil water tension and high evaporative demand; D — extreme plant water stress.

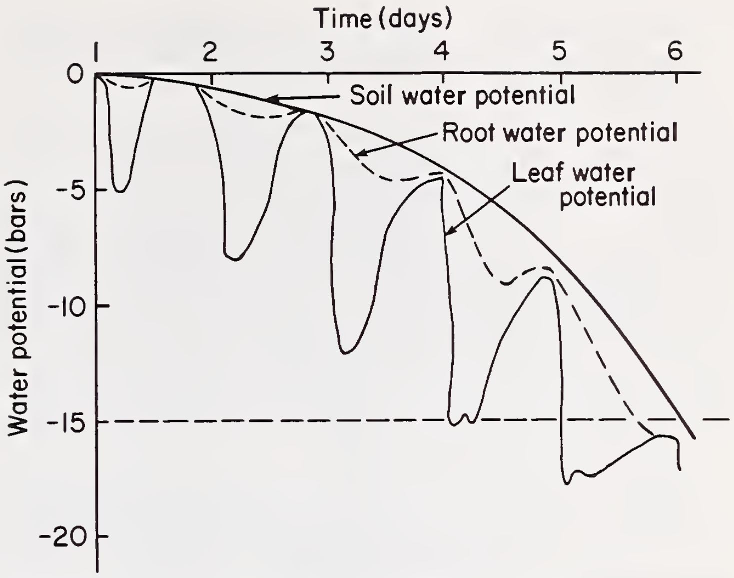

Figure 4.—The influence of decreasing soil water potential on development of plant water stress.

Variability in plant water potential at midday is significantly greater than at pre-sunrise. When using plant water potential measurements for water stress monitoring in outdoor nurseries, the effect of changing evaporative demand on seedling midday water potential must be accounted for. Seedlings in a greenhouse with less climatic variability should produce more consistent readings. Absolute variation in water potentials depends on tree species, seedling age, phenological stage, and other factors. Consequently, while some indication of expected values is given here, it is best for each nursery to do some tests under its conditions.

Methods of Irrigation Monitoring

Visual and Tactile Irrigation Monitoring

This method consists of looking at and feeling plants and soil to determine irrigation need. Hardwood seedlings are sometimes used as indicators (wilting), but more often, the water content of the soil is assessed either at the surface, in the root zone, or both, by eye and touch. There are, however, problems with the visual and tactile approach. They are subjective, since the observations are not based on the indications of a quantifiable mechanical or chemical procedure. The method requires experience and judgement on the part of the irrigator. One rule of thumb is:

"When the water in the soil glistens, the soil is wetter than field capacity. When it is impossible to mold a ball of soil, it has a soil moisture tension of less than one (-1) bar. When the soil has a light color, it is drier than the hygroscopic point. At the wilting point the soil is crumbly, feels slightly moist, and has a dark color (though somewhat lighter than at one atmospheric tension)." (Kohnke 1968)

A more detailed version of this is provided in table 1. The idea of irrigating when a ball of soil can no longer be formed is imprecise and will certainly vary from soil to soil. Observations should be gaged against gravimetric samples or tensiometer readings. For container nurserymen, the first problem is getting to the proper part of the medium. Few containers can be opened. Keeping the growing medium at, or near, field capacity (about −0.3 bar) is recommended (Goodwin 1975, Tinus 1970).

The other major problem with the visual-tactile method is personnel. The individual checking irrigation must be experienced, observant, and methodical.

The visual-tactile method has some advantages: (1) no mechanical equipment that can fail is relied on, and (2) the irrigator is forced to closely observe the soil and plants and determine the need for irrigation.

Of 99 nurseries checked nationwide, nearly all determine irrigating schedules by visual observations of soil dryness (Abbott and Fitch 1977). Very few nurseries use instruments to measure soil moisture. The visual-tactile method should be accompanied by a mechanical method for calibration, continuity, and quantification.

Weight Loss

Weighing seedling containers is a useful irrigation monitoring practice in containerized seedling nurseries. It is used in about 25% of western container nurseries (McDonald 1978). When the weight of a filled container declines to some predetermined percentage of the saturated weight, the crop is irrigated. This percentage is often around 75-80% of the saturated weight. A moisture tension curve similar to figure 2 can be developed for the medium used.

The weighing procedure can be automated by placing a representative container on a weighing device that electrically turns on the water when the weight of the container falls below a certain point (White and Shaw 1966). This method becomes less accurate as seedlings grow and their weight confounds the process. Weighing is useful for keeping growing medium damp, but is poorly related to plant water stress.

Electrical Resistance Blocks

Electrical resistance blocks (fig. 5) are made of some porous material like gypsum, plaster of paris, or fiberglass (Bouyoucous 1954). The water content

Table 1.—Visual-tactile guidelines to soil water content

Available soil moisture remaining	Feel or appearance of soil			
	Coarse texture	Moderately coarse texture	Medium texture	Fine and very fine texture
0% to 25%	Dry, loose, single grained, flows through fingers.	Dry, loose, flows through fingers.	Powdery dry, sometimes slightly crusted but easily broken down into powdery condition.	Hard, baked, cracked, sometimes has loose crumbs on surface.
25% to 50%	Appears to be dry, will not form a ball with pressure.[1]	Appears to be dry, will not form a ball.[1]	Somewhat crumbly but holds together from pressure.	Somewhat pliable, ball under pressure.[1]
50% to 75%	Appears to be dry, will not form a ball with pressure.	Tends to ball under pressure but seldom holds together.	Forms a ball somewhat plastic, will sometimes stick slightly with pressure.	Forms a ball, ribbons out between thumb and forefinger.
75% to field capacity (100%)	Tends to stick together slightly, sometimes forms a very weak ball under pressure.	Forms weak ball, breaks easily, will not stick.	Forms a ball, is very pliable, sticks readily if relatively high in clay.	Easily ribbons out between fingers, has slick feeling.
At field capacity (100%)	Upon squeezing, no free water appears on soil but wet outline of ball is left on hand.	Upon squeezing, no free water appears on soil but wet outline of ball is left on hand.	Upon squeezing, no free water appears on soil but wet outline of ball is left on hand.	Upon squeezing, no free water appears on soil but wet outline of ball is left on hand.

[1] *Ball is formed by squeezing a handful of soil very firmly.*

of these blocks changes with soil moisture content. The electrical resistance between two electrodes, buried in these blocks, varies with water content of the block. Readings on a resistance bridge connected to these electrodes are converted to an index of soil moisture content. Consequently, electrical resistance blocks provide only an indirect measure of soil moisture content which is not directly related to internal plant moisture stress. Resistance is also decreased by salt in the soil and increasing temperature, so, calibration is a problem. Seedling roots must be near the blocks for readings to be meaningful.

Resistance blocks are sensitive over a range from -0.5 to -15 bars of matric potential, so, they are effective in dry soil. The electrical resistance is calibrated against actual soil moisture content by taking readings on a soil at various moistures, finding the soil moisture content by the gravimetric method, and plotting the curve. This method is of little use in forest tree seedling containers, because the blocks are influenced by fertilizer solutions and usually are too large to fit in the container.

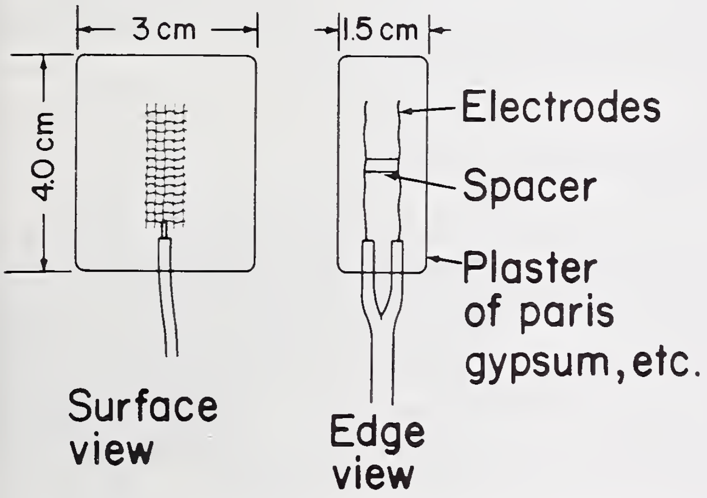

Figure 5.—Diagram of an electrical resistance block.

Tensiometers

Direct field measurements of the matric, or capillary, potential of a soil can be made with tensiometers (fig. 6). They are used in about 10% of western bareroot nurseries (McDonald 1978). A porous cup filled with water is buried in the soil and connected to a manometer or vacuum gage. The gage registers the pressure drop on water in the porous cup, which is in equilibrium with the matric potential of water in the soil. Tensiometers work well in wet soils, but when matric potential drops to -0.8 bar, air begins to enter the porous cup, and the tensiometer becomes useless. In the sandy loam shown in figure 2, the range in soil moisture tension from 0 to -0.8 bar covers about 77% of the water available in the soil. Consequently, the instrument really covers the prime irrigating range for nurseries. Although the tensiometer measures matric potential in the soil directly, it still provides only indirect inferences about internal plant moisture stress.

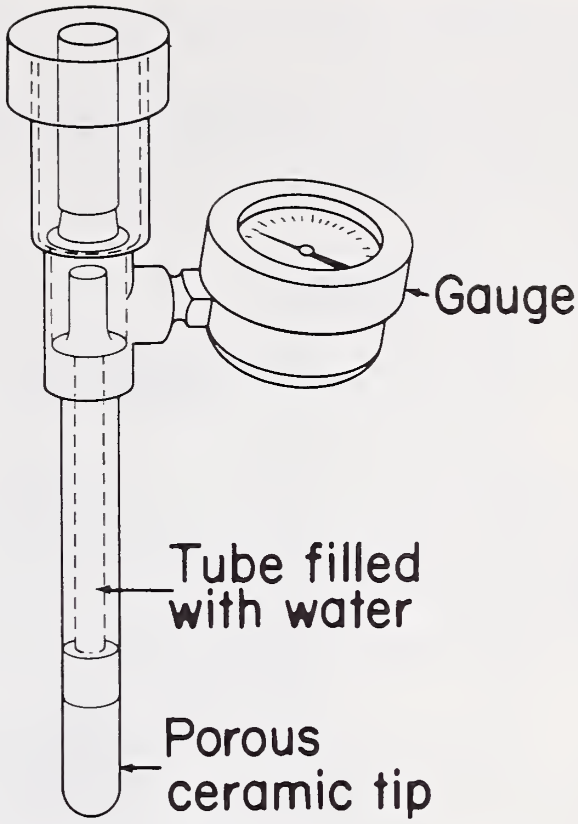

Figure 6.—Diagram of a soil tensiometer.

Pressure Bomb

The pressure bomb is the quickest, most foolproof method of measuring plant water potential in seedlings (Scholander et al. 1965). They are currently used in about 10-15% of western tree nurseries (McDonald 1978). 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. 7). A useful analogy is to think of the water column in a seedling as a rubber band. As water 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, the 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. By reading the pressure gage the instant water appears at the cut surface, and converting (14.7 pounds per square inch is equal to about 1 bar), the plant water potential is obtained.

Certain precautions are important in using this instrument. First, the sample should be measured within 1 minute, preferably instantly after cutting. Second, the pressure should be increased slowly, at about 3 pounds per square inch per second. Third, it is best if the size of the cut sample is consistent. Fourth, the cut end should not protrude more than 1 cm from the gasket. Read Ritchie and Hinckley (1975) before using the pressure bomb for seedling water stress measurements.

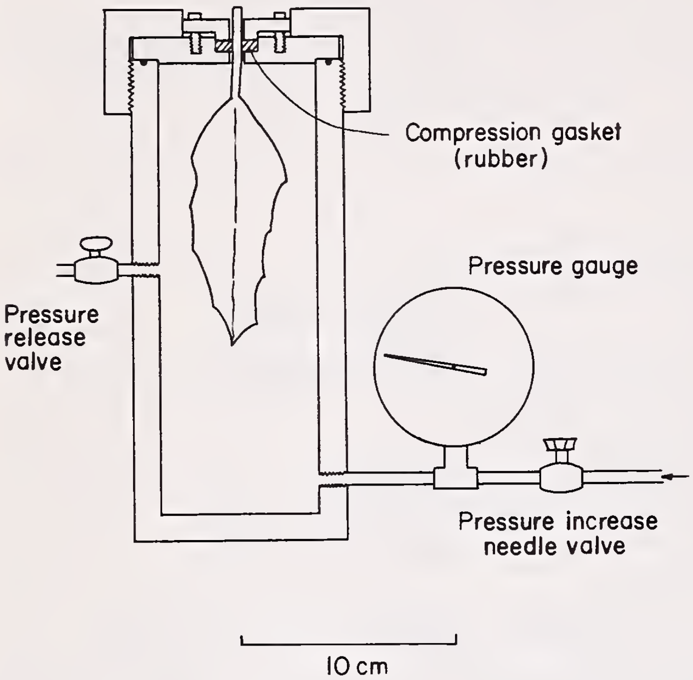

Figure 7.—Diagram of a pressure bomb.

Other Methods

Gravimetric samples are weighed, then dried in an oven, at about 105° C, until the weight becomes constant. The weight difference is considered water. The gravimetric method (weighing, then drying and reweighing the soil) normally takes too long for everyday use. However, it is very useful for calibration of other methods.

A few nurseries irrigate according to a "time schedule" or "water budget." The term "water budget" really refers to calculation of consumption. This is the water lost to evaporation and transpiration, which can vary with a great number of factors. The local use rates for most agricultural crops have been worked out, so, good consumptive use indexes exist for them. For tree nurseries, there appears to be little opportunity for practical application of this method. More precision is needed. However, a time schedule based on observation and experience can be useful. If coordinated with frequent soil moisture inspections, it can work, but it really is a poor substitute for proper observation and instrumentation.

The thermocouple psychrometer can be used to measure soil and plant water potential. It is very accurate when properly used, but is extremely sensitive to a number of variables. Consequently, routine field use is not recommended.

Neutron probes are used to determine soil water content by measuring the degree of deflection of neutrons from a radioactive source by water in the soil. They are accurate, but are expensive, cumbersome, and require highly trained and licensed personnel to operate. They are generally not practical for tree nursery use.

Recommended Methods

Bare-Root Nurseries

Visual and tactile subjective observations and interpretations of soil moisture conditions are the most commonly used monitoring method. While there is no substitute for personal observation and judgement based on experience in nursery operations, every nursery should use some kind of quantifiable method indicating available water in the soil or plant internal stress. Tensiometers are the best instruments for measuring soil moisture at tree nurseries. They cover the critical 0 to -0.8 bar tension range, or most of the water that is readily available to the seedlings. The pressure chamber should be used at every nursery, because it is the only method giving direct readings of internal plant moisture stress.

Container Nurseries

In container nurseries, the weighing method is a good choice to supplement visual and tactile observations while the trees are small when used in conjunction with a soil moisture curve. After the trees become larger, a switch to the pressure bomb is suggested. The pressure bomb correlation method described next can be used in greenhouse situations as well as in conventional nurseries.

Relating Pressure Chamber Readings to Seedling Water Needs

The pressure bomb is the best field tool for plant moisture stress monitoring. To use it effectively, however, the readings acquired must be interpreted to provide indication of need for irrigation. Diurnal pressure bomb reading curves were discussed earlier for a species at a given nursery (fig. 3). Such curves will show a progressively more negative plant water potential as available soil moisture declines. We suggest charting the midday pressure bomb readings for a group of tree seedlings as they dry out, providing a curve relating available soil water to midday plant water potential (fig. 8). Note that at high soil moisture availabilities, plant water potential is highly influenced by humidity of the air at the leaf surface. Midday water potential curves can be broken into segments representing different levels of plant water stress. For this illustration, the curve segments are designated "adequate," "stressed," and "dangerous." The "adequate" segment reflects water stress developed solely by evaporative demand. Watering seedlings is unnecessary—adequate soil water is available.

The "stressed" segment is where plant water stress increases as soil moisture is depleted. The influence of soil water tension gradually overwhelms the effect of air humidity.

The "dangerous" segment is where, despite total stomatal closure, the seedling is still coming under increasing water stress. If the trees are not irrigated, irreversible damage can occur.

A primary problem in interpreting midday water potentials occurs along lines A-B and B-C. Note that from A to B the soil moisture is the same, but plant water potential can be different as a result of differing evaporative demands. Conversely, along line B-C the plant water potential is the same despite differing soil water tensions, again because of differing evaporative demand. Each nurseryman will have to determine where the midday water potential curve is for a given humidity or humidity band by accumulating data points at known humidities and then plotting the needed curves. This problem is simplified in greenhouses where humidities are more uniform.

Where internal plant stress is intentionally induced to stimulate root growth or to induce apical dormancy, the midday water potential curve can provide quantitative guides to the degree of plant water stress that is safe.

Development of midday water potential curves requires patient collection of data points over a period of time, and at different humidities, to generate accurate and reliable curves. Local research scientists with pressure bomb experience may be able to contribute helpful advice and data. The effort is

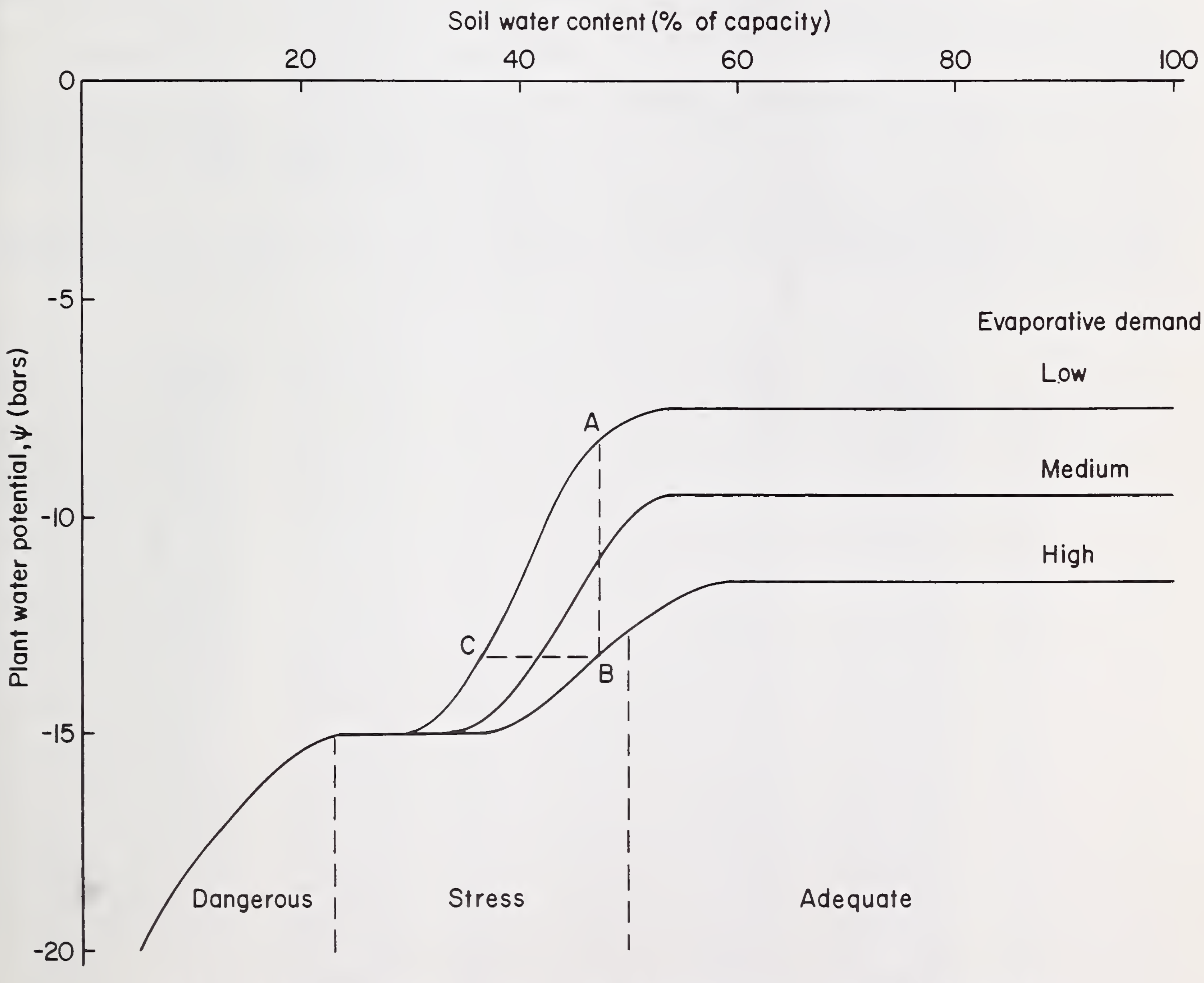

Figure 8.—The change in midday plant water potential produced by changing soil water content and different levels of evaporative demand.

worthwhile, for once a nursery has experience in pressure bomb work, the managers will have a direct, reliable, rapid, and inexpensive measure of seedling moisture stress to base their operational decisions on. The manager can also monitor the water stress condition of lifted and stored seedlings prior to outplanting. After outplanting, internal moisture stress of seedlings can be followed closely using the pressure bomb.

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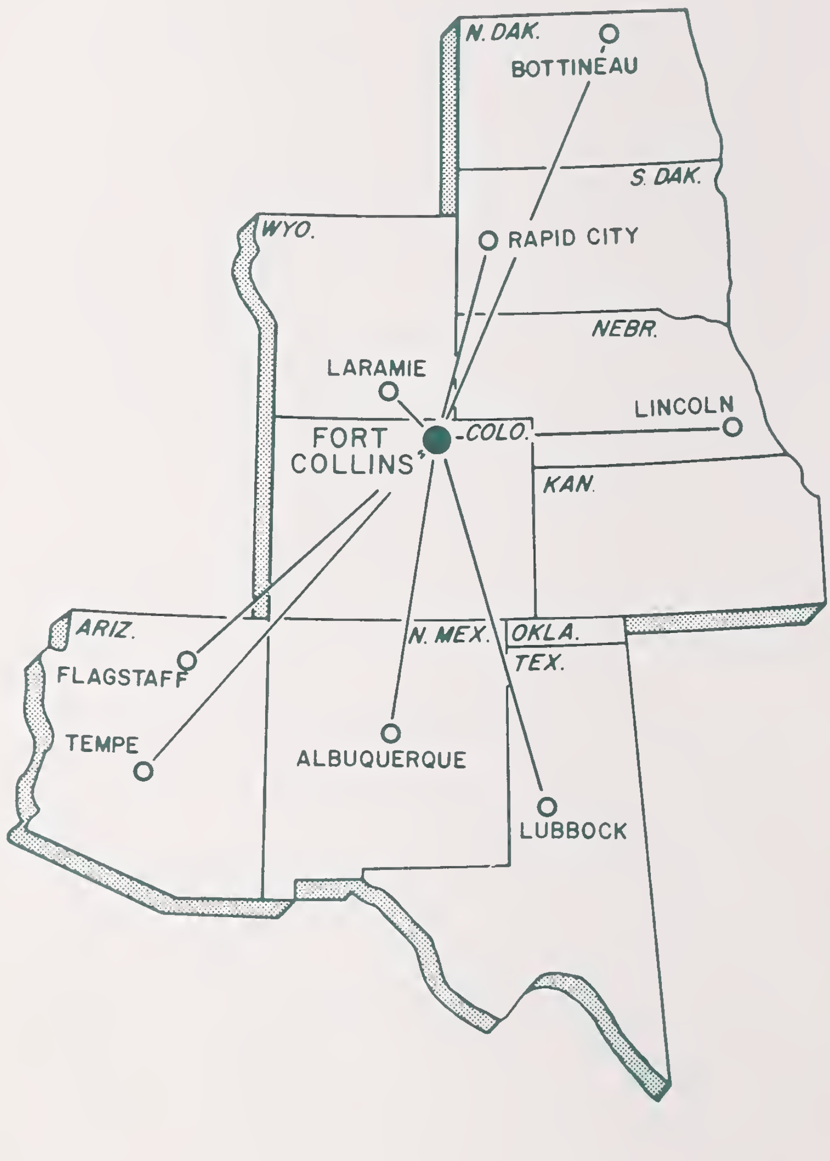
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