CHAPTER 11.—SOIL MOISTURE

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TABLE OF CONTENTS

LIST OF TABLES

LIST OF FIGURES

WATER AND PLANTS

- Water forms 60 to 90 percent of the fresh weight of actively growing tissue, particularly roots and stems.

- Water is essential in photosynthesis and hydrolytic reactions.

- Water is the solvent in which gases, other solvents and nutrients move through the plant.

- Water is essential to maintain a minimum degree of turgidity that is needed for cell enlargement and growth.

Water is an important component of living plants and is essential in the normal functioning of physiological processes and growth. Yet only a small proportion of the total amount of water absorbed by a plant is used for these functions. Some 90 percent or better is lost by transpiration (Kramer and Kozlowski 1960).

Transpiration

Transpiration by evaporation is the loss of water from plants in the form of vapor. For example, loblolly pine needles lose 5 to 6 grams of water per square centimeter of leaf surface per day during the summer. This loss continues in the winter, but at a rate of about one-tenth of the summer evaporation. The rate of evaporation of water is controlled by the relative slope of the vapor-pressure gradient from the evaporating surface when plotted against the vapor pressure of the surrounding air.

The six chief environmental factors affecting transpiration are vapor pressure, humidity, temperature, light, wind, and supply of water (figure 11-1). They are discussed in the following paragraphs.

Vapor pressure.—Because vapor pressure increases greatly with an increase in temperature, an increase in the temperature of needles of seedlings will tend to increase their rate of transpiration. Seedlings will transpire when the vapor pressure in their needles exceeds that in the surrounding air. Anything that increases the steepness or slope of this gradient increases the rate of transpiration.

Humidity.—The moisture content of the air is expressed in terms of relative humidity, which is the percentage of saturation at the existing temperature. For example, a relative humidity of 50 percent means that the air is 50 percent saturated at that temperature. Unfortunately, relative humidity is an unsatisfactory term to relate the moisture conditions of the air to evaporation or transpiration because the rate of evaporation from a water surface would be more than three times as rapid at 86 °F and 50 percent relative humidity as at 50 °F and 50 percent relative humidity. Thus, the rate of water loss by seedlings at a specific relative humidity in a micro-environment will increase or decrease with a corresponding change in temperature of the micro-environment.

Temperature.—In general, the rate of transpiration increases with an increase in temperature. Needle temperatures fluctuate considerably and may be either warmer or cooler than the surrounding air. Bright sunlight, a breeze, or a passing cloud may cause needles to become warmer or cooler than the surrounding air.

Light.—This important factor affects transpiration because of its effects on stomatal openings. Also, some of the solar energy is absorbed by needles, tending to raise their temperature.

Wind.—This factor has a two-fold effect. It tends to decrease the leaf temperature, which reduces transpiration. It also removes water vapor from the vicinity of the leaves and thus lowers humidity. A wind helps to maintain a steep vapor pressure gradient from the needles to the air and therefore tends to increase the rate of transpiration.

Supply of water.—Sustained high rates of transpiration require an abundant supply of water to the needles. The transpiration rate is generally higher for plants in moist soil than for plants in a dry soil. In other words, decreasing the soil moisture content will decrease transpiration by seedlings.

Growth

The initial food supply of young seedlings comes from the germinating seed. After germination successful growth
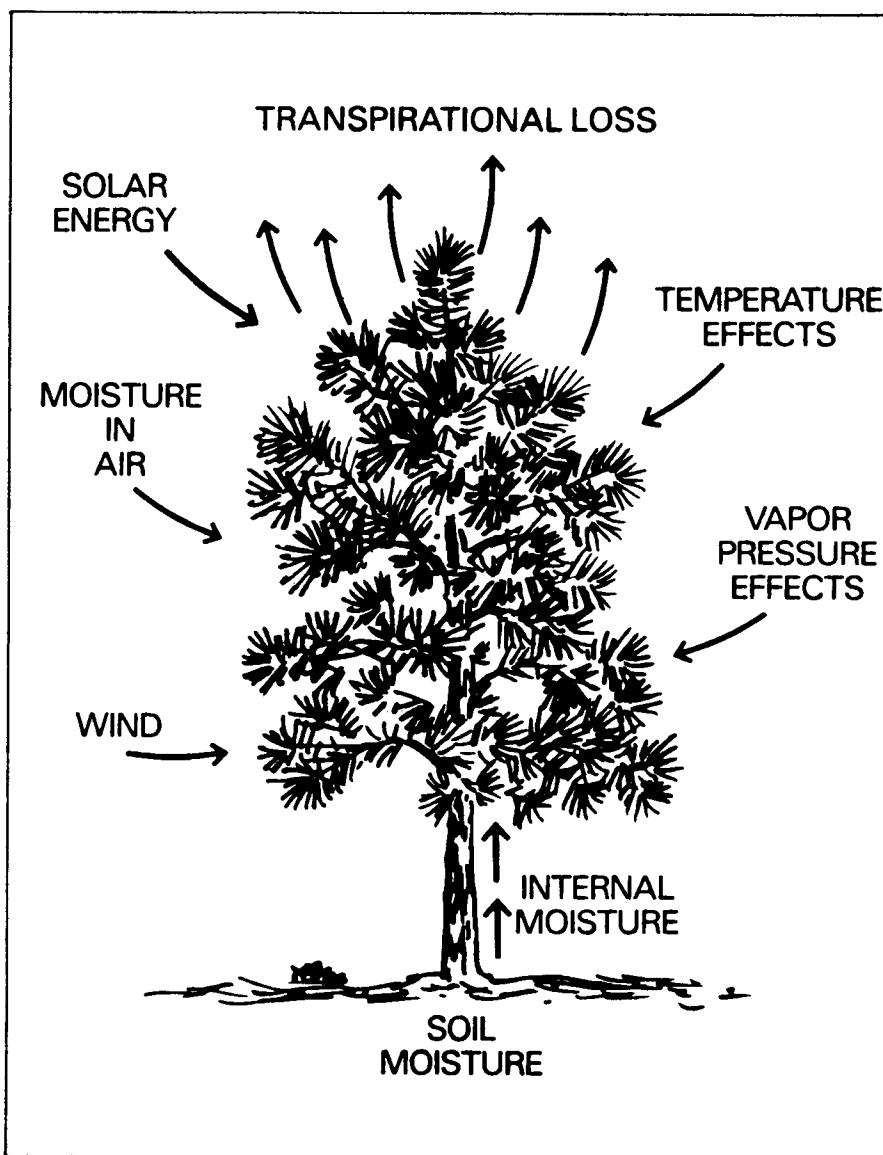
Figure 11-1. — Factors affecting transpiration (Barry Nehr).

requires adequate supplies of water, nutrients, minerals, oxygen, carbon dioxide and hormones, plus a favorable temperature. The water and food requirements are particularly important in meristematic regions where new tissue is being formed.

Sufficient water is required to maintain cell turgidity. Cell enlargement is caused chiefly by active growth of the cell wall, which occurs through water absorption. Even a slight water deficit can cause growth to stop.

A water deficit is most often the factor limiting growth. However, growth is not controlled directly by soil moisture or soil moisture stress, but by the water balance of the plant. The internal water balance of the seedling is controlled by the relative rates of absorption and transpiration. Usually, height growth rather than diameter growth is affected by a soil-moisture deficit.

Moisture Availability

When water saturates the soil some of the water moves out of the soil under the force of gravity. The point at which free drainage stops is called field capacity (F.C.) (See chapter 1 and figure 11-2). At this point the forces holding the water in the soil must be equal to or greater than the force of gravity. The F.C. for most soils is considered to be 0.3 bar and the force holding the water at F.C. is about 5 pounds per square inch.

Soil moisture tension is the ability of a soil to hold moisture against the force of gravity. These forces holding moisture in the soil result from surface tension or surface attraction. Soil moisture tension is measured in atmospheres or bars (kilopascals). One atmosphere or one

bar is equal to 76 centimeters of mercury, 1,032 centimeters of water or 14 pounds per square inch at sea level.

Plants can absorb moisture from free or gravitational water and from water held by the force of surface tension. Available plant water may be defined as that water held between field capacity of 0.3 bar and the point at which plants wilt, or about 15 bars. Figure 11-2 and table 11-1 show different methods of comparing available and nonavailable soil water.

Soil moisture stress is the total of all the different forces which the plant must overcome to take up water. The most important components of this stress are soil moisture tension and osmotic pressure. These two factors have cumulative effects.

Soil Moisture and Plant Growth

There is uncertainty about the extent to which soil moisture must be depleted before it hinders growth. As the plant extracts water from the soil at field capacity, a pressure of only about 0.1 to 0.3 bar exerted by the plant will move the water into the roots. However as soil moisture is depleted, the force needed to get the water into the plant root increases rapidly.
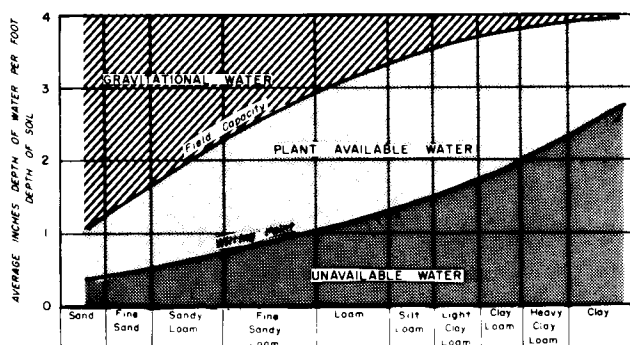
Figure 11-2.—Water characteristics of different soils.

Theoretically, any increase in soil moisture stress above 1 or 2 bars should reduce growth. Apparently some plants, especially pine seedlings, can extract water for growth or survival from the soil at field capacity down to almost the permanent wilting point (May et al 1961). However, long before the wilting point is reached, the plant will not

Table 11-1. — *Field capacity, wilting point and available water capacity of representative nursery soils in inches of water per foot of soil depth, and percent.*[1]

Soil Texture	Field Capacity		Wilting Point		Available Water Capacity	
	%[1/]	water per foot of soil depth (in)	%	water per foot of soil depth (in)	%	water per foot of soil depth (in)
Medium sand	6.8	1.2	1.7	0.3	5.1	0.9
Fine sand	8.5	1.5	2.3	0.4	6.2	1.1
Sandy loam	11.3	2.0	3.4	0.6	7.9	1.4
Fine sandy loam	14.7	2.6	4.5	0.8	10.2	1.8
Loam	18.1	3.2	6.8	1.2	11.3	2.0
Silt loam	19.8	3.5	7.9	1.4	11.9	2.1
Clay loam	21.5	3.8	10.2	1.8	11.3	2.0

Source: Water: The Yearbook of Agriculture (1955). USDA. Washington. These are general averages due to variations within any one textural group and variation in water constants.

[1]Percent soil moisture - oven dry weight basis

be able to extract water fast enough from the soil to be able to maintain a good rate of growth, and growth will slow down. This reduced growth results from at least two factors:

1. As extraction tension increases, less and less moisture and nutrients are taken into the roots, thus slowing down photosynthesis and the synthesis of proteins.
2. As the plant is put under moisture stress or an internal water deficit, the stomata close down to reduce water loss and to preserve moisture within the plant.

The closing of the stomata reduces the intake of carbon dioxide and photosynthesis and protein synthesis are further reduced (Bunting 1976). The degree to which a water deficit in the seedling influences the hydrolytic processes and the chemical composition of the plant is not clear.

The season of the year will influence the degree of moisture stress which can be tolerated by seedlings prior to resuming an acceptable rate of growth. Growth of loblolly pine seedlings occurs mostly between March and October. This period may differ slightly for each species or race, and may vary between years and locations within the region.

The rate of transpiration is almost directly proportional to the air temperature, up to a certain point. Thus, a seedling exposed to hot weather in midsummer (when maximum growth should occur) has to receive more water from the soil than in the spring or fall, when temperatures are lower.

Seedlings growing in sandy soils require careful observation and frequent watering to prevent wilting or reduced growth because 90 to 95 percent of the available water will have been depleted at tensions of 2 to 5 bars. Plant growth may be slowed gradually in a clay soil, but water can be applied before serious growth reduction occurs. Even at a tension of 2 to 5 bars the soil still retains 30 percent of its available water (table 11-2).

Table 11-2. — Percent available water at specified tensions in bars.[1]

Tension In Bars[2]	Loamy Sand	F. Sandy Loam	Sandy Loam	Loam	Clay
-----------------	percent available water		-----------------		
0-0.3	55	50	35	15	7
0.3-0.5	15	12	20	15	6
0.5-0.8	7	8	8	15	7
0.8-1	5	5	5	10	7
1-2	8	7	10	17	18
2-5	5	11	10	8	30
5-15	5	7	12	20	25

1/ From: Skinner 1976

2/ Bars and atmospheres are the same

WATER MOVEMENT IN THE SOIL

The forces holding water in the soil are primarily surface tension or surface attraction. Pore size is related to soil structure, and to the size of the soil particles, both mineral and organic. The large pores in sandy soils will not hold water very tightly and hence most of the rain or irrigation water is pulled down by gravity and carried away as deep soil drainage. If the soil particles are small, the small pores, sometimes called capillaries, will hold the water much more tightly and little is lost to deep drainage. Thus, as clay and organic matter contents increase, the soil has larger retentive capacity, and loses increasingly less of its moisture to drainage.

11-5

When the soil receives water on the surface as precipitation or irrigation, the water will move downward into the soil as a front. Above the front, the soil is moist and below the front it is relatively dry. The front will continue to move downward as long as water is added to the surface unless the front reaches an impervious layer. The infiltration and percolation rates are not fixed, but change with the moisture condition of the soil. Within the soil, the water will move from conditions of low force or suction (moist conditions) to those of high force or suction (dry conditions). The pattern of pore spaces within the soil is of great importance in any consideration of soil-water-plant relationships (Armson and Sadreika 1974). A soil with a mixture of pore sizes represents a more desirable condition than one with all-large or all-small pores. The large pores will facilitate infiltration and rapid movement within the soil, and the fine pores will ensure an adequate retention of water for plant use.

A general rule is that about 1 inch of water applied at 50 percent soil moisture will increase soil moisture to approximately field capacity. Infiltration rates plotted over time show that infiltration decreases with time and with the increase of silt plus clay. See figure 11-3.
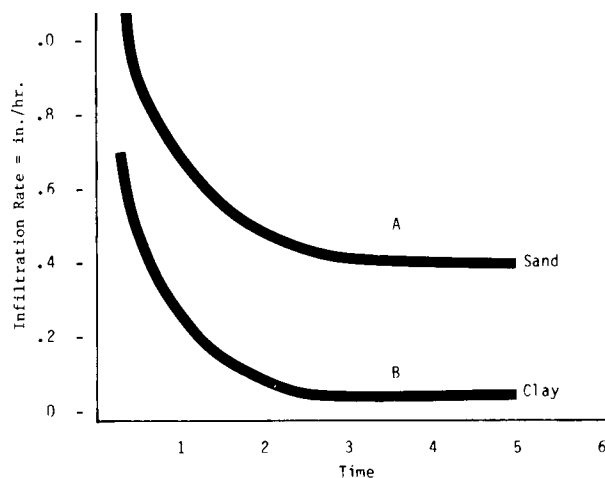
Figure 11-3. — **Change in soil infiltration rate with time. Curve A is an average for soils of inherently high infiltration capacity; Curve B, for soils in which infiltration capacity is minimal. The majority of soils lie between these extremes. (adapted from G.W. Musgrove, in Water, 1955 Yearbook of Agriculture, pp. 151-159, Washington, D.C.: Government Printing Office)**

Hydraulic conductivity is the ability of the soil to transmit water. Wetting slows down with time partly because of reduced pore size, which lowers the saturated hydraulic conductivity of the soil. Pore size may be re-

duced by puddling of the surface, movement of fines downward or by the swelling of soils high in clay.

Shallowness is another factor that causes the rate of water uptake by some soils to decrease with time. Soil depth is decreased in many nurseries because of plow layers (soles) or where impermeable lenses are created by some tillage or other cultural practice. All the pores in a shallow soil may fill quickly and then absorb no more water.

Even with none of the above effects, the rate of wetting slows with time. The slowdown occurs because friction increases as water moves farther through wet soil. At the same time, the distance to the wetting front increases.

As wetting begins, water moves downward along a continuous boundary and soil air is trapped below the wetting front. The increased air pressure tends to resist the downward flow of water. As pressure increases, the air is compressed, absorbed into the water, moved laterally through the soil or percolated through the soil to the surface.

Soil Texture—Water Relationships

One of the factors that most strongly influences wetting rates is soil texture. In general, fine-textured soils are the slowest to get wet, although some take water rather rapidly if they are well aggregated, i.e., have a high organic matter content and good soil structure. Rapid wetting in the well-aggregated soils and those of coarser structure is associated with large pores. These soils get wet quickest where a continuous system of large pores extends deeply into the soil. The large pores in sandy or well-aggregated soils remain filled most of the way down to the wetting front, which accounts for the rapid rate at which these soils get wet.

Fine-textured soils containing only small pores get wet slowly because they have a low hydraulic conductivity even when wet. The flow of water in a sandy soil is much greater downward than sideways, owing to the force of gravity. Water moves sideways as easily as downward in finer soils—suggesting that capillary forces are largely responsible for wetting of fine-textured soils regardless of the direction of flow.

The curves in figure 11-3 are not extended to the zero time point because most soils, if dry and with no impenetrable crust, have a very high infiltration rate when water is first applied. Soil wetting of any consequence may require several hours under many nursery conditions. Therefore the infiltration rate after an hour or two is much more important than the rate at the outset of wetting.

Some conceptions of soil-water-plant relationships in seedling production have changed during the past few decades. Wakeley (1954) suggested that the best nursery

soils are fine-to-coarse sandy loams underlain at 18 inches, or slightly more, by somewhat stiffer but still permeable subsoils. Experiences at many nurseries reveal that where a fine textured layer underlies a coarser textured soil, the rate of water movement downward may be reduced and, if the differences are great enough, a temporarily perched water table may result.

In contrast, where a coarser-textured layer occurs beneath a finer-textured soil, the result may be beneficial, especially if the textural boundary coincides with the lower limit of seedling or cover-crop roots. As a wetting front moves downward, it will stop at the layer of coarse pores until all the pores the same size and smaller are saturated with water at the textural boundary. The coarse layer acts as a check in water movement, ensuring a higher moisture content in the soil above than if no boundary existed. Yet, at the same time, saturation conditions cannot build up within the upper soil layer because as soon as the boundary pores are saturated, water will move downward into the coarser layer. (Armson and Sadreika 1979). The more common condition in many new nurseries is a loamy-sand surface layer, 12 to 30 inches thick, over a loamy sand to sandy clay loam subsoil.

SOIL MOISTURE MANAGEMENT

Irrigation is the artificial application of water to the soil, or the application of a measured amount of water to correct a known soil water deficiency. This definition implies that soil-moisture conditions must be monitored and, at some predetermined point, a given quantity of water is added to the soil to return it to another predetermined level of moisture. The major purposes of irrigation in forest tree nurseries are to provide moisture for seed germination and plant growth, to modify soil and atmospheric temperatures and to assure a moist soil at the time of lifting.

A prerequisite for irrigation that ensures plant growth is knowledge of the annual consumptive use of water for the selected species. *Consumptive use* is the sum of water transpired by the plant plus the evaporation from the surface of the soil. For example, the total consumptive use of water for three crops in one region is: alfalfa—27 inches; corn—19 inches; and dry beans—14 inches (Donahue et al 1971).

Thornthwaite (1948) developed a formula based on temperature, rainfall, and daylength to estimate the daily water loss from the soil by evaporation and transpiration. His formula for "Calculation of Evaporation" was surprisingly accurate over a full growing season. The formula did not take into consideration cloudiness, humidity or winds on a day-to-day basis, however. The Thornthwaite formula was used by some nursery managers in the early 1950's. Although somewhat successful, the

technique was found to need considerable modification. It did not provide a means to monitor the soil moisture conditions directly (Armson and Sadreika 1979).

Three sets of information are needed for proper irrigation control:

1. A knowledge of soil-water relationships for each soil type in the nursery.
2. A soil moisture monitoring procedure to rapidly assess the soil moisture status at any time.
3. A knowledge of the crop responses for each species growing on the particular soils in the nursery as affected by nursery management practices.

Soil-Moisture Characterization Curves

Soil-moisture characterization curves show soil moisture content over soil moisture tension. These curves should be established for each textural class in the nursery (Day 1980). See figure 11-4. These curves can be established in a suitably equipped soil laboratory, e.g., most soil science department laboratories at universities. Curves for monitoring devices should be determined at the same time. For a sandy soil such as depicted in figure 11-4, the range over which soil moisture is to be controlled, e.g., 0.6 bars (4.5 percent moisture content) to 0.1 bars (9 percent moisture content) is obviously a very small one. The amount of water is only 1.3 inches and of this about 1.0 inch is readily available for plant use.
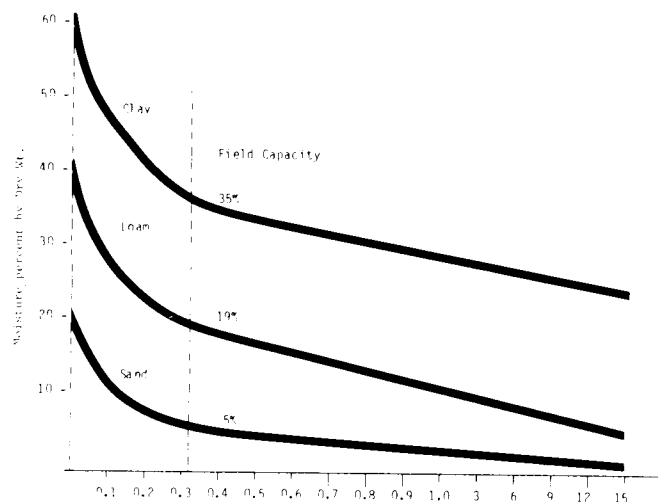

Figure 11-4. — Soil moisture and tension related to texture. (Data combined from several sources; note change in scale at 1.0 bar; values are averages.)

Soil Moisture Measurement

The three soil-moisture levels recognized in soil-plant-water relationships are:

Table 11-3. — Feel and appearance of soil at several moisture contents.

Degree of Moisture	Amount of Moisture	General Textural Classes		
		Course and Light Sandy	Medium Soil Loam	Fine and Very Fine Soil Sandy Clay Loam to Silty Clay Loam
Dry	None wilting point	Dry, loose, flows through fingers	Dry, may be crusted; easily breaks to powdery condition	Hard, cracked, may have loose crumbs on surface
Low	Less than 25% of field cap. critical	Crumbly - will not hold together		
Fair	25 to 50% of field capacity	Appears dry; will not form ball with pressure	Crumbly, hold together with pressure	Somewhat pliable, balls under pressure
Good	50 to 75% of field capacity	Appears dry; may form ball with pressure but seldom holds together	Forms ball; somewhat plastic; may stick together slightly with pressure	Forms ball; ribbon between thumb and forefinger
Excellent	75 to 100% of field capacity	Tends to stick together; may form weak ball; breaks easily; will not stick	Forms ball, pliable, sticks if high in clay	Easily ribbons between fingers; has sticky or slick feeling
Wet	Field capacity	Wet outline of ball is left on hand when sqeezing		
Too wet	Above Field capacity	Free water appears if ball is bounced in hand; or water is released with kneading	Free water may be squeezed out	Puddles; free water forms on surface

1/ Adapted from Handbook on Soils. Forest Service, USDA. June, 1961.

1. Saturation—all pores are full of water.
2. Field capacity—moisture is retained by the soil against the pull of gravity.
3. Permanent wilting point—moisture is retained by the soil when plants growing in the soil wilt and do not regain turgidity at night.

Many methods have been developed for measuring water in a soil, but only four are suitable for use in forest tree nursery management: (1) feel and appearance method, (2) gravimetric method, (3) tensiometers, and (4) electrical resistance blocks. These methods are discussed in the following sections.

The Feel and Appearance Method

This simple method is the most widely used in the southern pine nurseries. The only equipment required : a shovel or soil auger. The method does require con-

siderable skill and experience to determine when and how much water to apply to seedlings at any specific time during the growing season. See table 11-3.

Check soil moisture before and after irrigation.— The initial check will determine whether or not the soil is dry and if water should be added. After irrigation, the check will determine if the soil is wet to the bottom of the root zone. The degree of moisture, according to table 11-3, should read "fair" when the soil is ready for irrigation, and should read "excellent" at the bottom of the root zone 24 hours after irrigation.

Gravimetric Method

To use this method, obtain a moist soil sample, weigh it, then dry it in an oven at 105 °C for about 24 to 48 hours or until it loses no more water. Then determine the percentage of moisture, as follows:

$$\text{Percent moisture} = \frac{\text{moist soil weight minus oven dry soil weight}}{\text{oven-dry soil weight}} \times 100$$

A soil sample from the upper 3 inches of the soil will probably have a different soil moisture content than that of a sample from a 3- to 6-inch depth.

Another calculation can be used to determine the approximate volume of water in a soil:

Example:

$$\frac{18.1\% \ (\% \text{ of moisture in loam soil at field capacity})\times 2 \text{ million pounds of water per acre-6-inches}}{226,584 \text{ pounds (weight of water per acre inch)}} = 1.59 \text{ inches volume of water in the soil}$$

See appendix for metric conversions.

This type of calculation can be carried through to a more useful conclusion, i.e., the calculation of acre-inches of available water per acre foot of soil.

Example:

$$\frac{6.8 \ (\text{wilting } \% \text{ of some soil})\times 2 \text{ million pounds per acre-6-inch}}{226,584 \text{ pounds (weight of water per acre-inch)}} = .60 \text{ acre in-ches of water not available to plants}$$

1.59 inches = Volume of water in the soil
- .60 inches = Water not available to the plants
.99 inches = Water available to plants per 6-inch depth

Tensiometers

The tensiometer or irrometer method of measuring soil moisture is simple and accurate within the range of 0 to 0.85 bars. Tensiometers are more useful in sandy soils than in fine-textured soils. They eliminate the guesswork associated with the Feel and Appearance Method.

Tensiometer gauge readings reflect the relative wetness of the soil: high readings indicate a dry soil, low readings a wet soil. Recorded meter readings will enable nursery workers to more accurately evaluate soil-water conditions throughout the growing season.

The tensiometer is a sealed, water-filled tube with a porous ceramic tip on the lower end and a vacuum gauge on the upper end. See figure 11-5. The tube is installed
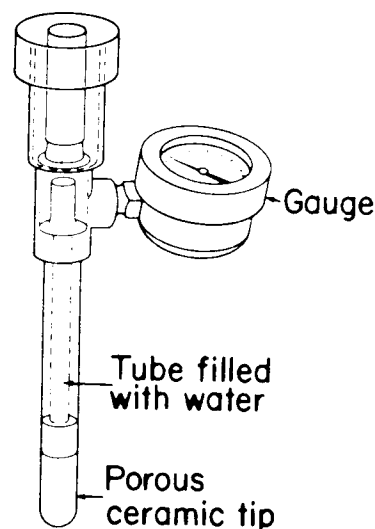
Figure 11-5. — Tensiometer.

in the soil, with the ceramic tip placed at the desired root-zone depth and with the gauge above ground. In dry soil, water is drawn out of the instrument, reducing the water volume in the tube and creating a partial vacuum, which is registered on the gauge. The drier the soil, the higher the reading. When the soil receives moisture through rainfall or irrigation the action is reversed. The vacuum inside the tube draws water back into the instrument from the soil which in turn results in lower gauge readings.

The amount of vacuum reflected by the gauge is a direct measure of soil water tension or soil suction. The standard unit of measurement is the bar which is about equal to 1 atmosphere or 14.5 pounds per square inch. Most

tensiometers are calibrated in hundredths of a bar (called centibars) and graduated from 0 to 100.

Tensiometers are usually installed in pairs, one at a shallow depth (one-fourth of root depth), the other at three-fourths of the depth of the normal root zone. Roots of most pine seedlings are within 3 to 8 inches of the soil surface, so one tensiometer per location may be adequate. The number of tensiometers required varies with the number of acres in seedlings, the size of the blocks and variation in soil conditions. Under the most favorable situations—uniform soil and large blocks—one instrument may be adequate for 10 to 15 acres.

Select representative areas of the blocks or fields for the tensiometer station. Do not place the instruments in low spots or where they will be in the way of field operations. Stations should be well marked so they can be avoided by equipment operators. The instruments also may be covered by a protective device. Methods of installation are provided by manufacturers or dealers.

Automatic tensiometers are designed for use with a controller; they also can be used to directly switch solenoid valves. This equipment is used to control an automatic irrigation system. General guidelines for interpreting gauge readings are in table 11-4.

Table 11-4. — Guidelines for interpretation of tensiometer readings.

Gauge Reading	Guideline
0-10	Indicates a saturated soil and often occurs for 1 or 2 days following a rain or irrigation. Roots may suffer for lack of oxygen if readings in this range persist.
10-20	Field capacity. Irrigation should be discontinued to prevent wasting water. Further watering could leach nutrients below the root zone.
20-30	Optimum moisture for growth.
30-60	Usual range to begin irrigation.
70+	Stress range for most soils and crops. Water level is below that required for maximum growth. Tensiometers are likely to lose vacuum in coarser textured soils.

Electrical Resistance Blocks

Electrical resistance meters determine soil moisture by measuring the electrical resistance of a block of gypsum or similar material imbedded in the soil. Stainless steel electrodes are imbedded in the blocks. Insulated wires from each imbedded block are brought to the surface where they can be plugged into a portable resistance meter for reading (figure 11-6).

The electrical resistance of the block varies with its moisture content which, in turn, depends on the moisture content of the adjacent soil. Water is transferred both ways between the soil and the porous material. As the soil moisture decreases the block loses moisture and its electrical resistance increases. Therefore, resistance changes as measured by the meter can be interpreted in terms of soil water content. An interpretation guide for the meters is given in table 11-5.
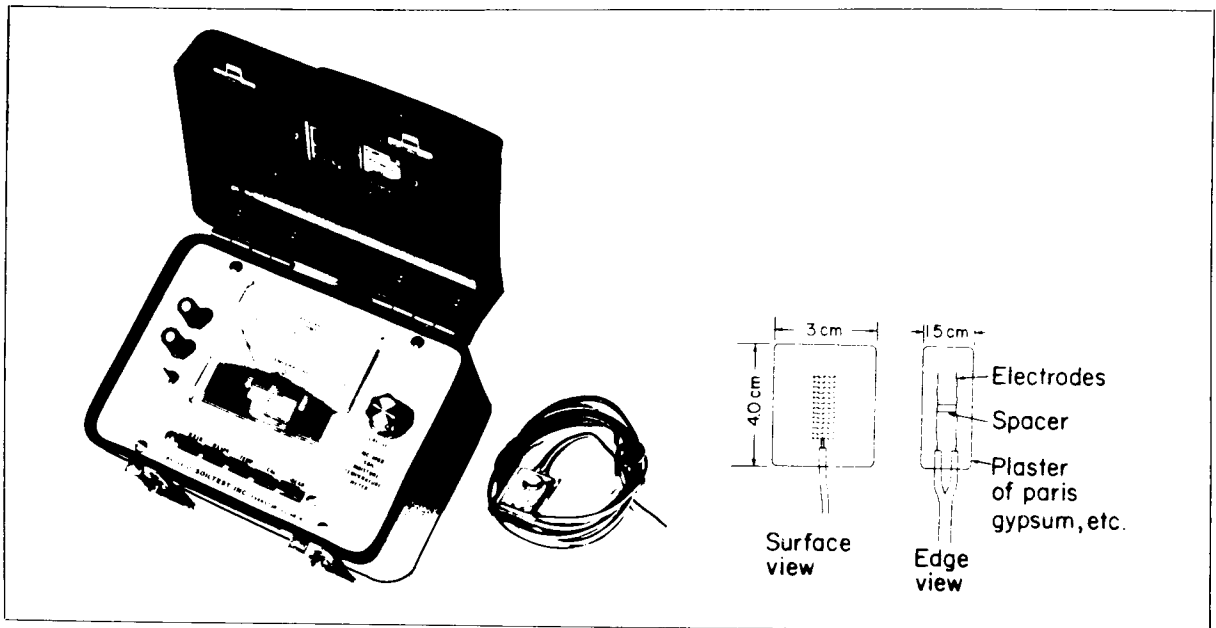
Figure 11-6.—Electrical resistance meter and blocks.

Table 11-5. — Guidelines for interpretation of electrical meter readings.

	Bars Tension	Meter Readings	Interpretation
Nearly Saturated	Less than 0.20	200 to 180	Near saturated soil. Occurs for a few hours following a rain or irrigation.
Field Capacity	0.20 to 0.32	180 to 160	Field capacity. Irrigations discontinued in this range.
Irrigation Range	0.65 to 1.2	140 to 100	Usual range for starting irrigation. Starting irrigation in this range insures maintaining readily available soil moisture at all times.
Dry	1.6	Less than 60	Stress range for most soils and crops. Some soil moisture present but dangerously low for maximum plant growth and production.

Resistance blocks are generally calibrated in terms of soil water tension so the readings will apply across soil textures. A calibration stated in terms of percent soil water or percent available soil water should be made for specific soils at each nursery.

The manner in which blocks, manufactured by different companies, respond to changes in soil water tension varies considerably. For this reason each manufacturer furnishes calibration curves for their own instruments and blocks. The location of resistance blocks follows the same principles as for tensiometers.

Line-operated instruments are designed for remote monitoring of soil-moisture availability and to control automatic irrigation systems. These devices function by activating solenoid valves in the irrigation system.

Comparison of Measurement Systems

Soils in southern nurseries can hold from as little as about 0.6 to more than 1.5 inches of available water per foot of depth. Irrigate the beds when 50 percent of the available water in the plant root zone has been used. Soil water tension gradually increases as water is withdrawn from a clay soil. However, most available water in sand can be extracted by plants, with only a small increase in soil tension.

Soil moisture release curves for three textural classes are shown in figure 11-7. These curves show that the higher the content of silt and clay in a soil, the more water is held by the soil at equivalent tensions. The variation in tension required to reach the 50-percent level of avail-

Representative moisture retention curves for three different soil textures.
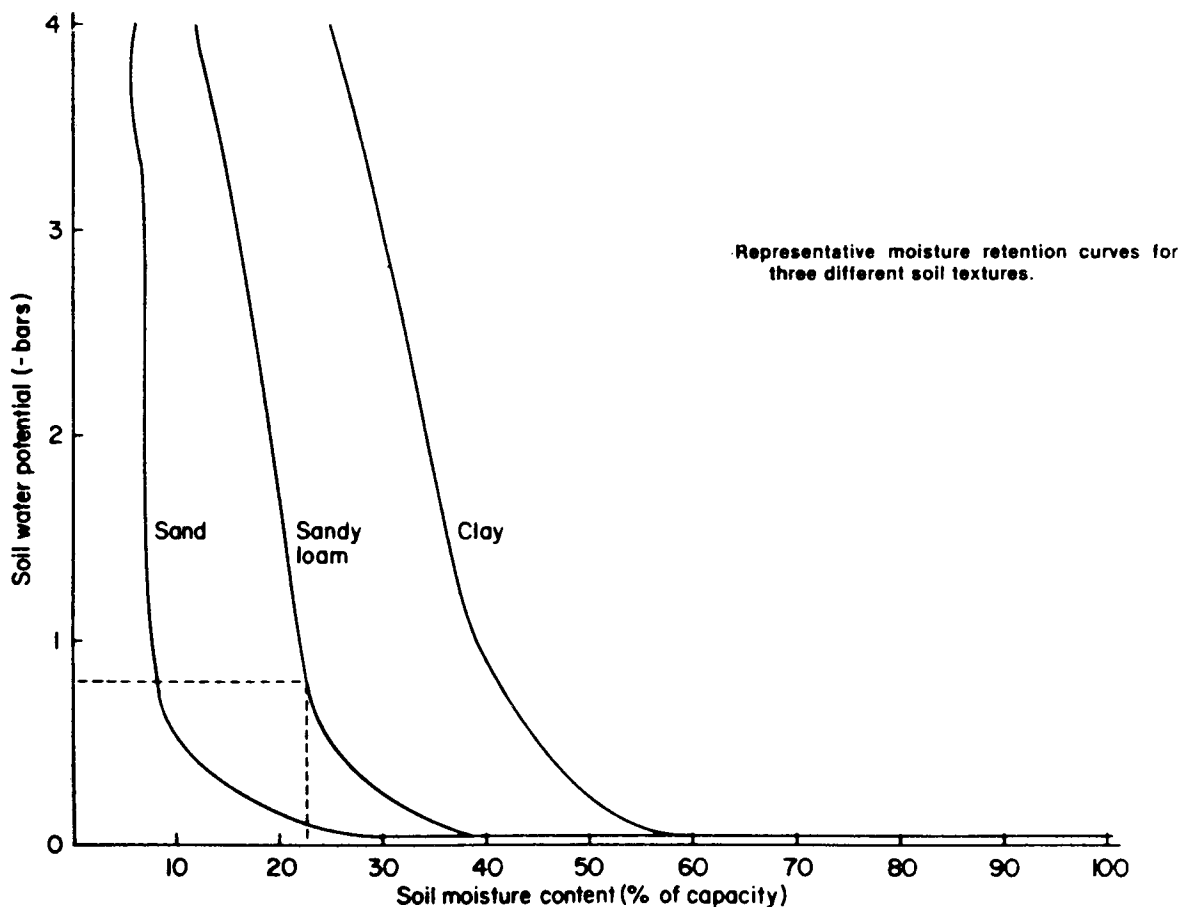
Figure 11-7. — Soil moisture release curves.

able water (usual level for irrigation) is high. Sand reaches the 50 percent level at slightly over 0.5 bar tension, while 2 bars are required for loam and 4.5 bars for clay.

Tables 11-2 and 11-6 show the relative availability of soil water for various textured soils. The effectiveness and limitations of tensiometers and resistance blocks can be

inferred from these data. For loamy sands 77 percent of the available water would be depleted when soil-water tension reaches 0.8 bar (80 centibars) as compared to 20 percent for a clay soil. Expressed another way, in a loamy sand 55 percent of the available water is held between 0 and 0.3 bar tension and 15 percent between 0.3 and 0.5

Table 11-6. — *Percent available water depleted at various tensions (Bars).*[1]

Tension In Bars	Loamy Sand	F. Sandy Loam	Sandy Loam	Loam	Clay
---------------------percent water depletion-----------------------					
* .3	55	50	35	15	7
* .5	70	62	55	30	13
* .8	77	70	63	45	20
* 1.0	82	75	68	55	27
* 2.0	90	82	78	72	45
* 5.0	95	93	88	80	75
* 15.0	100	100	100	100	100

* = less than

[1]From: Skinner 1976

bar, as compared to 35 and 20 percent respectively in a sandy loam and 15 percent in a loam.

Therefore, in a fine-textured soil, the use of resistance blocks would allow the evaluation of moisture depletion or percentage of available water over a greater range than would tensiometers. However, tensiometers are useful when scheduling irrigation in the low suction range (0 to 80 centibar), and are more accurate than resistance blocks. Tensiometers give direct readings, while electrical resistance units must be calibrated to read either moisture tension or moisture content. Resistance blocks and tensiometers are compared in table 11-7.

Table 11-7. — *Comparison of resistance blocks with tensiometers.*

Characteristic	Resistance Blocks	Tensiometer
Accuracy in fine textured soils	Good	Fair
Accuracy in coarse textured soils	–	–
Ease of reading	Must be calibrated	Direct reading
Susceptibility to: a. Mechanical damage b. Freeze damage	Moderate "	Very fragile "
Maintenance	None	Must be cleaned, stored over winter, and calibrated
Cost	Meter: $300+ Units: $8 each	(none needed) $30+

Tensiometers are subject to freezing damage and must be protected or removed in extremely cold weather. Draining the tube can protect the body, but water may still remain in the gauge, which is most susceptible to damage. Both the tensiometers and the leads from the resistance units should be protected from field equipment. Posts or stakes are effective for this purpose.

The frequency of instrument reading will depend on the rate water is used by the crop as compared to the water-holding capacity in the root zone. More frequent readings give a better picture of the soil-moisture extraction and also serve as a check for any malfunctioning instruments. A minimum of three readings should be made between irrigations, or if the irrigation cycle is fairly long, twice weekly.

To get the most value from the readings, record and plot them on a chart. This practice will provide a moisture-loss history and the basis for some short-term predictions. Plotting also shows whether irrigation is frequent and long enough for maximum seedling growth. Units should be read at about the same time each day to minimize temperature variations. An early morning reading is desirable because moisture movement in seedlings and soil has virtually ceased at that time and a condition near equilbrium exists.

Variations in soil classes are almost always so great that the soil will be the governing factor in both application rate and irrigation timing. The infiltration rate should be adjusted to the finest-textured soil (lowest infiltration rate). Adjust the timing to the coarsest-textured soil (lowest water-holding capacity).

IRRIGATION SYSTEMS

Before the 1940's, most nurseries used an overhead Skinner irrigation system. See figure 11-8. Lateral lines were mounted parallel to the ground on posts 3 to 4 feet high. Sprinkler nozzles were spaced 36 inches apart along the rotating pipes. This system provided about 1 inch of water during 8 hours of operation, or an application of water at the rate of about 0.125 inches per hour. Even at this low rate there was an appreciable runoff after 4 to 6 hours on some of the finer-textured soils.

The Rainbird systems use rotating impact sprinklers. They are much more versatile and have been used since the 1940's. See figure 11-9. The sprinkler heads for use in forest tree nurseries vary in size and capacity from about 2 to 12 gallons per minute (gpm). The area covered and rate of discharge of each sprinkler are both governed by the water pressure at the nozzle and the size of the nozzles.

The spacing of sprinklers along the lateral line is determined by the size of the wetting area and should not exceed 60 percent of the maximum wetted diameter, i.e., if the diameter of the wetting area is 100 feet, nozzle spacing should not exceed 60 feet. For practical purposes, we can assume that all lateral lines are either 40 or 60 feet apart, and the sprinklers are spaced either 40, 50 or 60 feet apart along the lateral lines, except at the end of a line.

Medium to high pressure sprinklers are used in nurseries and operate under pressures from about 40 to 80 psi. They usually have two nozzles, with one covering an outer circle and the other an inner circle. They cover a wetted diameter of 70 to 120 feet. A type commonly used is the Rainbird 40B or Buckner 18002. The Rainbird, with 3/16 by 1/8 inch nozzles, is designed to deliver 10.1 gpm to a 102-foot diameter circle at 45 psi.

As pressure is increased to 60 psi, the rate of application and coverage increases to 11.6 gpm and a 107-foot diameter circle. At a 60 by 60-foot sprinkler spacing, the beds receive about 0.27 to 0.32 inches per hour. This is about the maximum rate for use on sandy soils.
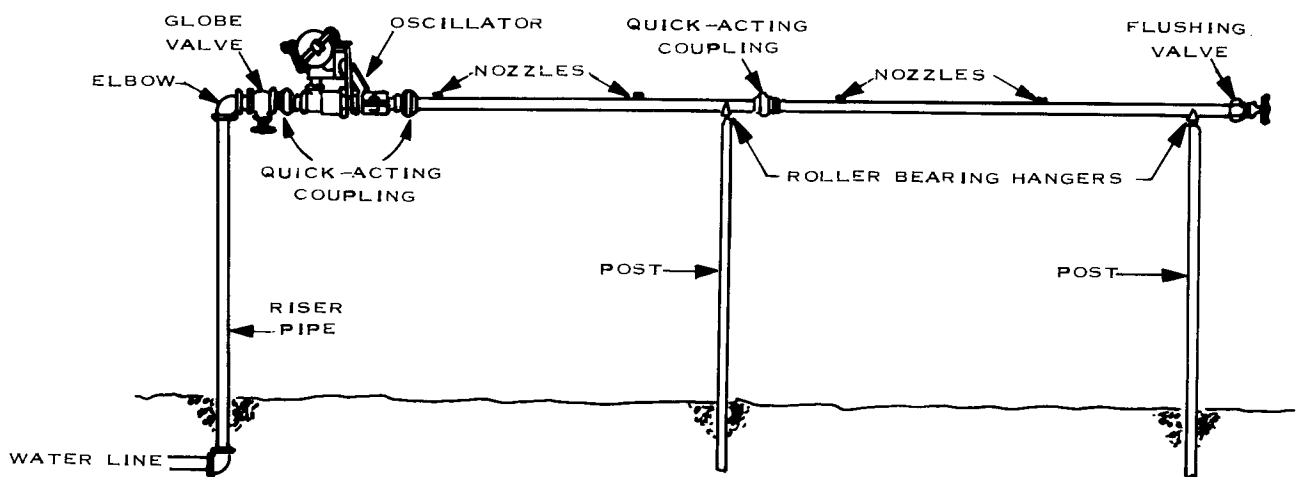

Figure 11-8. — Skinner irrigation system.

Figure 11-9. — Rainbird irrigation system.

Feel and Appearance Method of Water Control

This system of watering depends on the personal judgement of nursery managers. They must become proficient in determining the moisture content of two or three textural classes of soils by their feel and appearance and by the appearance of the seedlings. Water should be applied when the soil moisture is about 60 percent of field capacity. Sandy soils will appear dry and may form a ball with pressure, but seldom will hold together. Fine-textured soils will form a ball or will ribbon between the thumb and forefinger (table 11-3).

The timing of the watering is more important than the amount of water applied. Irrigation should continue until water reaches below the root zone or until there is a noticeable runoff. The moisture content should be between 75 to 100 percent of field capacity at 7 inches below the surface. At this point a sandy soil will stick together or form a weak ball which breaks easily. Fine-textured soils will easily form a ball or ribbon between the fingers, and may be sticky or feel slick.

Instrument Controls

An optimum irrigation system would have one or two observation stations in each block or compartment. Each station would consist of two tensiometers or gypsum blocks, one set at about 3 inches and the other at about 7 inches below the surface. Either tensiometers or gypsum blocks may be used in sands and loamy sand soils. Use gypsum blocks in sandy loam or heavier soils.

Irrigate on the basis of soil moisture readings at the 3-inch settings. Irrigate when the 3 inch layer reaches about 40 to 50 centibars on the tensiometer gauge, or about 0.6 bars of tension on the electrical resistance meter. The 7-inch block is used to ensure that sufficient moisture is applied to reach that depth, thus preventing the development of a dry layer of soil within the root zone.

Irrigation Rates

Average maximum irrigation rates for agronomic crops and southern pine seedlings on level ground are presented in table 11-8. Most irrigation systems are designed for a uniform soil texture and level ground. When soils within a nursery vary between a loamy sand, a sandy clay loam and a silty clay, the watering system must be adjusted. Different nozzle sizes are needed for different soils. Adjustments may be needed in operating pressures and the amount and rate of water applied at any given time. A change in pressure and nozzle sizes will change the discharge in gallons per minute from the sprinkler and the diameter of the circle covered by the sprinkler.

Select a nozzle size, spacing and operating pressure that will provide about 0.10 inch of water per hour on medium textured soils. See table 11-9. Sandy soils need not be

Table 11-8. — Irrigation rates for agronomic crops and southern pine seedlings.

Soil Texture	Agronomic Crops (inches/hour)	(mm/hr)	Pine Seedlings (inches/hour)	(mm/hr)
Light sandy soils	.5 - .75	12.7-19.1	.3	7.6
Medium textured soils	.25 - .5	6.4-12.7	.2	5.1
Heavy textured soils	.10 - .25	2.5-6.4	.1	2.5

Table 11-9. — Irrigation water delivered with different nozzle size, pressure and spacing (Inches/Hour).

PSI Nozzle	Spacing Feet	3/16 x 3/32 Rate gpm (lpm)	Area diam. ft.	(m)	5/32 x 3/32 Rate gpm (lpm)	Area diam. ft. (m)
45 (3.2 kg/cm²)		8.5 (32.2)	102	(31.1)	6.48 (24.5)	94 (28.7)
	60 x 40		.34			.26
	60 x 60		.22			.17
60 (4.2 kg/cm²)		9.85 (37.3)	107	(32.6)	7.47 (28.3)	98 (29.9)
	60 x 40		.39			.29
	60 x 60		.27			.20

irrigated for long periods, because the water soaks in deeply and quickly. However sandy soil needs to be irrigated often. About 0.5 inch of water at rates of 0.25 to 0.3 inches per hour at 2- to 3-day intervals should be close to optimum except during hot, droughty periods. Fine-textured soils need more water at a slower rate of application and less frequently than the sandy soils.

Supply water in amounts adequate to create favorable conditions for seedlings to grow and develop without interruption. For some nurseries, the best guide is to water when the average height growth of seedlings decreases to one-half of the maximum height growth made during a 24-hour period after the last rainfall or irrigation. Seedling growth should be continuous under this regime.

In an attempt to water according to a seedling's need, some forest nurseries (especially when growing potted seedlings) weigh potted plants at regular intervals. When weight reaches a critical level because of moisture loss, the plants are watered (Walters 1977).

Many of the problems with seedling growth and development are closely associated with either too little or too much water.

IRRIGATION FOR GERMINATION

Seeds require adequate water, oxygen and a suitable temperature to germinate. Seeds must absorb additional water beyond that present in the seed at the time of sowing, to begin the biochemical and physiological processes involved in germination. For example, the water content of eastern white pine seed, with an original content of 7 percent on a dry-weight basis, increased to 45 percent before germination started and reached 147 percent in young seedlings (Kramer and Kozlowski, 1960).

Water absorption by germinating seeds generally passes through three definable stages:

1. An initial, rapid absorption of moisture
2. A period of very little absorption
3. Another period of rapid moisture absorption

The respiration that fuels metabolic processes during germination requires oxygen and produces carbon dioxide. Most seeds will not germinate when the germination medium is too wet, when seeds are planted too deep or when other conditions limit the oxygen supply. Many species are sensitive to excessive moisture, which limits the oxygen supply, especially after the seed coat begins to crack. The embryo may not survive with an excess of moisture. The rate of oxygen absorption during seed germination varies highly among species. Normal oxygen uptake follows a pattern similar to that of moisture, i.e., a rapid rise in oxygen consumption occurs when water uptake is increased, which is concurrent with the active phase of germination.

Nearly all seeds can absorb enough water for germination at field capacity, and some seeds can germinate in fairly dry soil, i.e., when the moisture is within the range of 1 to 5 bars of soil moisture tension. Germination on extremely dry substrates inhibits radicle initiation and hypocotyl elongation, while high moisture inhibits root growth (Belcher 1975, Krugman et al 1974, Kramer and Kozlowski 1960).

The water-holding capacity of the soil varies with texture and organic matter content. Average amounts of water per foot depth of soil at field capacity for different soil textures are listed in table 11-10.

The frequency and rate of application of water during the germination period is influenced by the amount of rainfall, soil texture, type of mulch used, temperatures, sunshine and wind. A dry germination period is preferred over a period of wet weather. In a dry period the amount and rate of water applied can be controlled. Five to 10 inches of rainfall during a 2- or 3-week germination period can kill germinating seeds. The amount of water needed to keep the soil moist may vary from 1/4 to 1/2 inch of water daily on sandy soils to 1/2 inch or more at 2- to 3-day intervals on fine-textured soils.

Some mulches, such as wood pulp, absorb moisture during watering and lose water rapidly by evaporation. Special care is needed to provide enough moisture for both the mulch and the soil. Frequent irrigation in small amounts is needed during the germination period. These amounts should be increased in time to cover the entire rooting depth of the seedlings. If small amounts of water are continually applied shallow rooting will be encouraged.

MONITORING OF
SEEDLING IRRIGATION

More information is needed on water requirements of southern pine seedlings growing on soils of different tex-

tures. A certain pine seed lot will have the same moisture requirements regardless of the soil texture on which it grows. However, the amounts and frequencies of irrigation will vary as needed to supply water at the proper time.

The watering schedule for any nursery depends on the frequency and amount of precipitation. Rains of $1/2 \pm$ inches at 2- to 4-day intervals may maintain a soil moisture content within the range of 75 to 100 percent of field capacity for some soils, but not for others. *Frequency* of precipitation may be more important than the *amount* of precipitation during a specific period. Two 1-inch rains at 3- to 4-day intervals are more desirable than one intense 2-inch rain.

Studies from two nurseries show that although the total water requirements were similar, the rates of application differed. The frequency of watering was closely correlated with the frequency of precipitation:

Nursery A was a sandy loam (Faceville series, medium texture) with 25-percent silt plus clay in the upper 7-inch (17.8 cm) layer. Nursery B was a loamy sand (Eustis series, light texture) with 11-percent silt plus clay in the surface layer. Best growth of seedlings was obtained when the soil moisture content from mid-June to September was maintained within the range of about 75 to 100 percent of field capacity. The mean amount of water applied during each irrigation was 0.50 and 0.23 inch per acre for the medium- and coarse-textured soils, respectively. In each nursery, seedling growth decreased when soil moisture contents were allowed to drop as low as about 50 percent of field capacity (May et al 1961).

IRRIGATION FOR
TEMPERATURE CONTROL

Surface soil temperatures high enough to injure seedlings may occur during the first few weeks after germination, when the young seedlings are most vulnerable to heat. Watering during the heat of the day may reduce surface soil temperatures by as much as 20 °F.

This practice may prevent extensive losses if begun promptly at the first sign of injury or when air temperatures reach 90 °F, especially in April or May. When air temperatures reach 90 °F or higher during the growing season, the seedlings may suffer excessive transpirational losses, i.e. they may lose more moisture as a result of high temperatures than they can take in through the roots. Succulent shoots and needles wilt and droop and seedling growth is consequently halted.

By irrigating during the hottest period of the day, the air temperature may drop 10 to 15 °F or more, depending on the relative humidity. Watering creates a microclimate, cooling the seedlings and reversing the adverse natural conditions. By creating such a favorable, artificial growing condition, seedlings can continue to

grow and develop without interruption. Wide observations over many years have shown no instance of injury to southern pine seedlings from adequate watering in full sunlight.

At the other temperature extreme, some seedlings may also be protected against unseasonal frost damage. When water freezes it releases heat. About 140 Btu's are generated per pound of water when water changes to ice at 32 °F. By applying enough moisture throughout the time the temperature stays at or below freezing, the heat exchange involved in the water-to-ice change will keep the plant temperature in a safe zone above freezing. Apply water at about one-half the regular irrigation rate. It is important to continue to apply water until air temperatures rise above the frost danger level and any ice on the seedlings has completely melted.

Table 11-10. — Water holding capacity of the soil.

Soil Texture	Inches of Water Per Foot Depth of Soil (MM)		Soil Texture	Inches of Water Per Foot Depth of Soil (MM)	
Sand	1.1	(27.9)	Loam	3.2	(81.3)
Fine Sand	1.4	(35.6)	Silt Loam	3.4	(86.4)
Sandy Loam	1.9	(48.3)	Light Clay Loam	3.6	(91.4)
Fine Sandy Loam	2.5	(63.5)	Clay Loam	3.8	(96.5)

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