

The Role of Plant Water Relations in Achieving and Maintaining the Target Seedling

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Abstract: Water management is one of the most important factors in achieving the target seedling. Water is required for cell growth, nutrient transport, cooling through transpiration, and in small amounts for the photosynthetic reaction. Furthermore, judicious use of limiting water availability during the hardening phase can induce budset and increase seedling cold hardiness. Nursery managers typically measure seedling moisture status with the pressure chamber and medium water status using the block weight method. Newer soil moisture sensors, such as time domain reflectometry (TDR) units, offer increased control over irrigation scheduling. Few growers utilize climatological data to estimate evapotranspiration and schedule irrigation based on demand. An example of how these data can be used is explored, as well as the consequences of inadequate monitoring during the hardening phase. Proper water management will help achieve the target seedling as well as maintain the target seedling during the hardening phase.

Keywords: irrigation scheduling, evapotranspiration, soil moisture, plant water potential

Introduction

Of all the resources that must be supplied to nursery crops, water is required in the greatest amount. Seedlings “consume” 400 to 700 g (14 to 25 oz) of water through transpiration in order to “capture” a single gram of biomass through photosynthesis. At the same time, that same plant may absorb less than 20 mg of nitrogen, the next most important constituent. To say water is important almost trivializes the critical role in both meeting and maintaining the target seedling. Water transports nutrients from the soil (or soilless growing medium), through the roots, to the leaves; provides positive pressure for cell enlargement; cools leaf surfaces through transpiration; and is a reactant in the photosynthetic process.

Colombo and others (2001) categorized the morphological, physiological, and chemical attributes of seedlings needed for successful reforestation. Every attribute, including the genetic components of seedling quality, are regulated or affected by water availability. Water, or lack thereof, can result in genes being expressed or repressed. Thus, water is important to defining the target seedling at the most fundamental and basic level.

Water management is also an important responsibility of the nursery manager. Overwatering increases pumping costs of unnecessary water, fertilizer costs as nutrients are leached through the soil/medium profile, pest management costs to combat moss, *Botrytis*, and insect outbreaks (for example, fungus gnats). Furthermore, overwatering increases the risk of environmental problems from runoff either to groundwater or surface waters. Supplying insufficient water during the growth phase can result in failure of seedlings to reach target size specifications, and that could decrease production and create employment risks. Consequently, most nursery managers tend to overwater and confront the cost issues brought about by overwatering (Carles and others 2005). The objective of this paper is to review the role of water in achieving and maintaining the target seedling and to discuss technologies currently in use or available to the nursery manager.

Survey Results

A brief survey conducted at this Target Seedling Symposium was completed by 16% of the participants; 58% use English units, while 42% prefer metric units. This likely represents the split between US and Canadian participants completing the survey. Most nursery managers were container growers (64%), while 21% grew both container and bareroot seedlings, and only 14% operated bareroot nurseries exclusively. Most (75%) of the container nurseries had travelling boom irrigations systems for at least part of the nursery, while 25% had only fixed irrigation systems.

Over 90% of respondents used the block weight method to schedule container irrigation during the growth phase (Figure 1a). This is higher than earlier surveys reported (McDonald 1978; Landis and others 1989), and likely indicative of improved grower expertise. Grower experience was the second most important resource for scheduling irrigation. During the hardening phase, medium moisture monitoring was the most important tool, followed by block weight (Figure 1b). For both growth and hardening, seedling moisture status was the least important characteristic to monitor. Bareroot seedling monitoring techniques were less clear cut because of the small sample size. Nevertheless, bareroot seedling moisture status appeared to be the most important criteria for both growth and hardening, followed by soil moisture monitoring. While it appears that container and bareroot growers use different criteria to schedule irrigation, those growers that grew both seedling types tended to prefer seedling water status over other criteria; again, this is an improvement over past practices (Johnson 1986).

Definitions

The status of water in a system is defined by its water potential. Water potential (ψ) is the chemical free energy of water, or, basically, the ability of water to do work. The units of water potential are the units of force per unit area, or Pascal. Thus, pure free water would have a water potential of 0 Pascals. For reference, the traditional term of field capacity can be represented in the following units: -30 kPa, -0.03 MPa, or -0.3 bars; while permanent wilting point can be expressed as -1500 kPa, -1.5 MPa, or -15 bars (note that bars are often used to denote plant moisture stress [PMS], in which case they are expressed in positive units; -1.0 MPa = 10 bars). Lowering or reducing the water potential makes the water potential more negative while increasing water potential makes the number more positive, or closer to zero. In the case of reforestation seedling production, almost anything (for example, adding fertilizer) done to water will lower the water potential (see Supplement I).

Water moves in response to a gradient in water potential, that is, from high water potential to lower water potential in order to equalize the system. Water moves from the soil solution at relatively high water potentials into the roots, through the plants, and ultimately through the stomata into the atmosphere as water vapor. Water in the soil is not quite at 0 MPa (or 100% RH) because of dissolved salts (osmotic or solute potential, ψ_s) and adsorption to the surface of soil particles (matric potential, ψ_m) (Table 1). As soil dries, the salts concentrate, thereby decreasing ψ_s . Furthermore, ψ_m also increases as the remaining water is more tightly bound to the soil particles. Finally, as the soil dries, the larger pores drain and the path water travels through the soil becomes more tortuous, increasing the resistance to movement to the root.

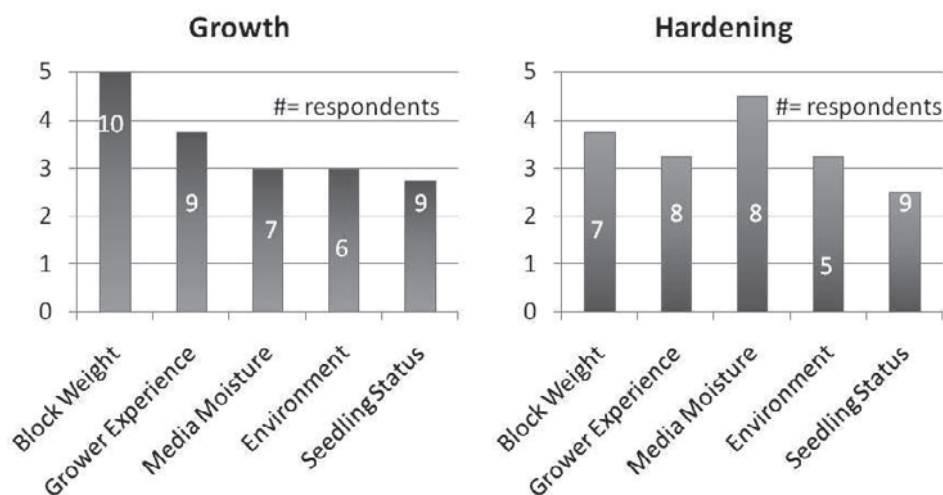


Figure 1. Container seedling survey results. Respondents were asked to rank the importance of varying factors (with 1 being least important and 5 being most important) for scheduling irrigation during a) growth or b) hardening.

Supplement I
Rules of Thumb—Water

- Water flows from high concentration to low concentration.
- Water flows from high humidity to low humidity.
- Water flows from areas of low salt concentration to higher concentration.
- The steeper the gradient, the faster the water movement.
- “A pint’s a pound, the world around” [whatever that means].
- 1 g = 1 mL = 1 cm³ (cc).
- 1 mL of water applied to 1 m² = 1 kg = 1 L [useful in estimating block weights or water flow].
- ETo ≈ 0.75 ETp.
- ETg ≈ 0.60-0.80 ETo_(outside) [depending on composition and age of covering material].
- Latent heat of vaporization (cooling) and fusion (frost protection) work only when there is freely available water (liquid).
- Under full canopy coverage, all plants consume readily available water at about the same rate (i.e. ETc = ETo).
- Plants differ only in their response to reduced water availability.
- Most water (>99%) is used in the transpiration process cooling the leaves and carrying nutrients to the leaves. Less than 0.3% is actually hydrolyzed in the photosynthetic reaction.
- Evapotranspiration is highly correlated with net radiation and vapor pressure deficit, but less so with temperature.

By the time soil dries to the permanent wilting point, the relative humidity of the soil is still 99% (Kohnke 1968). At 93% RH, ψ is below -9.8 MPa, and at an atmosphere RH of 50%, the ψ is below -980 MPa. Not only does the gradient drive water movement to and through the plant, but also the steepness of the gradient speeds the movement. Thus, the demand for water is greater at 20% RH (-3160 MPa) than when the atmosphere is relatively humid (50%). Consequently, nursery managers need to be cognizant of both available soil moisture and drivers of evapotranspiration, for example, humidity.

Evapotranspiration (ET) is the combination of soil evaporation (E) and plant transpiration (T). ET varies as a function of soil moisture, stage of plant development, and climate.

Potential evapotranspiration (PET) is the ET of a crop under non-stressed conditions. However, since the crop is not specified, the term PET is being supplanted by reference evapotranspiration (ETo or ETr). ETo is the evapotranspiration of a reference crop (usually a perennial grass) under non-stressed conditions. ETo is estimated from climatic variables using the Penman-Monteith equation (Allen and others 1998). The predominant variables regulating ETo are vapor pressure deficit (VPD), net radiation, and temperature. The variables are highly correlated, especially VPD and radiation, with ETo. The relationship for greenhouse crops is similar, albeit with simpler calculations (Seginer 2002). Thus, ETo varies with latitude, elevation, and proximity to coastal influences. For example, the annual ETo for coastal San Diego, CA, is 118 cm/yr (46 in/yr) while that of Calexico in the interior of southern CA is 182 cm/yr (72 in/yr) (CIMIS 2010). In contrast, the annual ETo for coastal Brookings, OR, near the California border is 91 cm/yr (36 in/yr), whereas the ETo of Lakeview, OR, is 134 cm/yr (53 in/yr) (US DOI 2010). The ETo of southern Oregon is about 75% of southern California, and the ETo of the interior stations is about 50% greater than the coastal stations. Consequently, the water required to produce the same seedling would be greater where the ETo is greater.

In order to schedule irrigation using the Penman-Monteith equation, typically a conversion factor (crop coefficient = kc) is needed to convert ETo to the ET of the crop in question (ETc). Unfortunately, kc varies by species and growth stage. Consequently, many growers are reluctant to adopt this seemingly complicated tool. Nevertheless, ETo can be used not only for field grown crops, but also for greenhouse grown crops. The variables of temperature, vapor pressure deficit, and incoming radiation (filtered through the greenhouse covering) individually account for nearly 80% of the variation in evapotranspiration of greenhouse-grown (ETg) garden cucumbers (*Cucumis sativa*) (Shibuya and others 2010). Thus, an instrument or service that estimates ETo is a potentially useful tool in irrigation scheduling.

Maximum or management allowable depletion (MAD) is the portion of plant available water in the soil profile allowed for plant use prior to the next irrigation (Welsh and Zajicek 1993). It is based on plant and management considerations,

Table 1. Comparison between relative humidity (%) and equivalent water potential (MPa), and the maximum soil pore size filled by water at that water potential, where ~FC is near field capacity and PWP is permanent wilting point (after Kohnke 1968).

Relative humidity (%)	Water potential (MPa)	Maximum water-filled pore	
		(mm)	(μ)
100.00	0	2	2,000
99.999	-0.001	0.2	200
99.99	-0.01 (~FC)	0.03	30
99.93	-0.10	0.003	3
99.00	-1.50 (PWP)	0.0002	0.2
98.00	-3.09	—	—
93.00	-9.8	0.00003	0.03
50.00	-980.0	na	na
10.00	-3,160.0	na	na

and typically reported as a percentage of available water (for example, 50% MAD). It is an especially important management tool in flood-irrigated agriculture. Where irrigation water is applied through sprinkler or drip systems, irrigation can be applied to meet the daily ET needs, thereby minimizing soil depletion and maintaining the crop under non-stressed conditions. However, if water is not applied daily to meet ET demands, MAD is crucial to avoiding the threshold seedling water potential, where photosynthesis and subsequent growth is reduced. For example, Dumroese (2009) found ponderosa pine (*Pinus ponderosa*) seedlings could tolerate a MAD = 40% with only a small reduction in growth. Furthermore, there was no difference in growth between 10% and 25% MAD in this study.

Water use efficiency (WUE) or biomass to water ratio (BWR) is the amount of water required to produce a unit of biomass, typically expressed as grams of water/gram of biomass (for example, 400 g/g). Generally, WUE can be increased through deficit irrigation. Plants under mild stress tend to be more efficient at fixing carbon. Until data and technologies are developed to demonstrate the benefits of deficit irrigation, however, a nursery manager should grow seedlings under non-stressed conditions to reach the target seedling. Growth (cell enlargement, biomass) is impacted much more severely and at a much higher ψ_{leaf} than photosynthesis. ψ_{leaf} must approach -1.5 MPa before photosynthesis is reduced 50%. Growth, however, can be reduced 50% by ψ_{leaf} as high as -0.25 MPa (Morison and others 2008). Finally, the economics of water conservation are dwarfed by the economic benefits of achieving target specifications for a high percentage of the crop.

Measuring Water Status

Jones (2004) discussed the advantages and disadvantages of the numerous instruments used to assess plant or soil moisture relations. Many are currently inappropriate for use beyond research, either because of expense or complexity of use. There are several, however, that have application to the nursery industry (Table 2). Currently, the pressure chamber is the only instrument in operational use that directly measures plant water potential, either ψ_{xylem} or ψ_{leaf} . Typically, seedling ψ_{xylem} is measured pre-dawn after the seedlings have fully recovered but before stomata open in the morning. Alternatively, seedlings can be wrapped in aluminum foil during the day and allowed to equilibrate for 1 to 2 hours with soil moisture before measuring (McCutchan and Shackel 1992). Pressure chamber measurements are precise, but time consuming and do not lend themselves to automation. A nursery can spend over 10 hours/week measuring seedling ψ_{xylem} (Khadduri 2010). As a consequence, some nurseries have abandoned this technique as a management tool.

Pressure chambers are used to monitor seedling water status, and irrigation is applied when a critical threshold ψ_{xylem} is reached (Figure 2). In these examples of bareroot 1+1 and 2+0 Douglas-fir (*Pseudotsuga menziesii*) seedlings, ψ_{xylem} is seemingly decoupled from ET_o. That is, when ET_o is high, ψ_{xylem} is also high, when the opposite would be expected. The reason for this is seedlings were irrigated when ψ_{xylem} reached about -0.7 MPa (actual irrigation records unavailable). As soil moisture was depleted, ψ_{xylem} could easily change

Table 2. Characteristics of irrigation scheduling tools (after Jones 2004). Note this list does not include numerous plant monitoring techniques (for example, porometer, psychrometer, sap flow) that provide valuable research information, but limited operational application.

Instrument	Advantages	Disadvantages
Pressure chamber	Direct measure of seedling ψ_{xylem}	Time consuming; training; expense; point-in-time measurement (predawn); unsuitable for automation
Block weights	Measures growing medium available moisture; inexpensive	Point-in-time measurement
Medium moisture sensor (tensiometer)	Inexpensive; ease of use; electronic recording	Soil contact is critical; soil heterogeneity requires numerous sensors (expensive)
Medium moisture sensor (TDR)	Continuous readouts; precise electronic recording	Expense; new terminology (m^3/m^3); soil heterogeneity requires numerous sensors
Pan evaporation	Continuous readouts; electronic recording available	Overestimates ET _o by ~33%
Atmometer (for example, ETGage™)	Continuous readouts; electronic recording; small size	Must be calibrated with climate data
Infrared Thermometry (for example, SmartCrop™)	Continuous readouts; precise electronic recording; wireless	Expense; line of sight communication; requires time and temperature thresholds
Climate data-historic	Estimates crop ET _o	Approximates current ET _o ; not as accurate as real time measurements; requires kc
Climate data-current	Real time measure of ET _o	Steep learning curve; requires kc

0.1 MPa/day. Thus, careful monitoring is required if ψ_{xylem} is allowed to exceed the critical threshold affecting growth, which could be as high as -0.5 MPa for Douglas-fir seedlings (Blake and Ferrell 1977; Bond and Kavanagh 1999).

The most common container monitoring technique is the block weight method. A block or tray of seedlings are watered to saturation and weighed periodically until a predetermined weight is reached (often to 50% to 60% of original weight) (Dumroese 2009). The containers are then re-watered to runoff, which leaches salts from the growing medium. Khadduri (2007) monitored Douglas-fir seedling ψ_{xylem} during repeated dry down cycles to 50% (moderate) or approaching 40% (severe) of total moisture (Figure 3). Only

after soil moisture dropped below 50% did ψ_{xylem} decrease below -0.6 MPa. Over this period, the moderate treatment had four cycles, while the severe had three cycles. Dry down to 50% required 3 to 6 days in each cycle, while the severe dry down usually required an additional day. Dumroese (2009) found container ponderosa pine in Idaho required 2 days for medium moisture to drop to 90% (MAD = 10%), 4.6 days to 75%, and 7.8 days to 60%. Furthermore, there was little impact to seedling quality under any irrigation regime, although the driest irrigation regime reduced seedling size (height, diameter, and biomass) by about 10%. There were no differences between 90% and 75% in seedling quality.

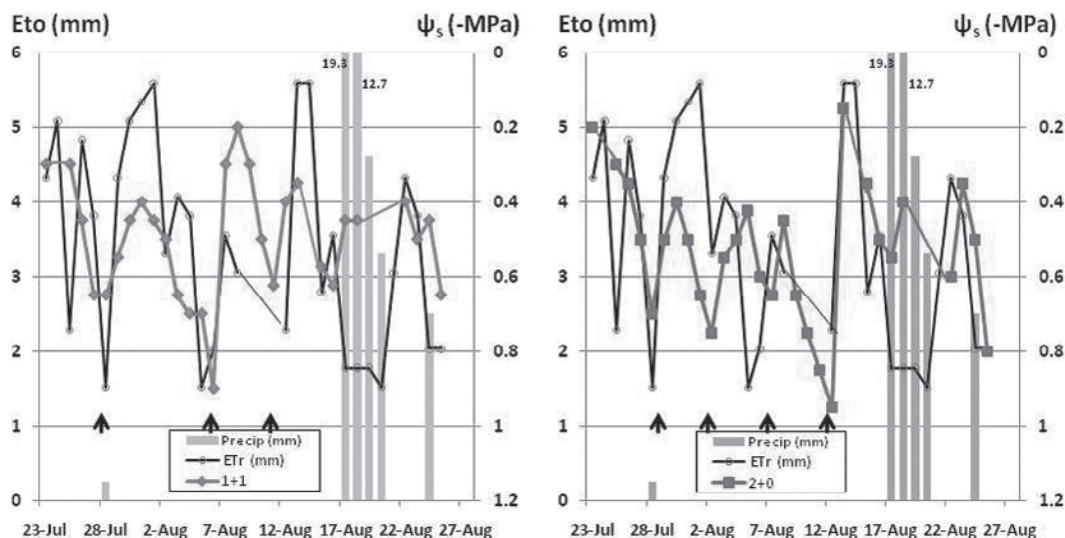


Figure 2. Comparison of pre-dawn water potential of Douglas-fir (*Pseudotsuga menziesii*) 1+1 and 2+0 seedlings to ETo for nearby Puyallup, WA in 2007, where 12.7 and 19.3 are rainfall events (mm) and ↑= scheduled irrigation (estimated) (Khadduri 2007).

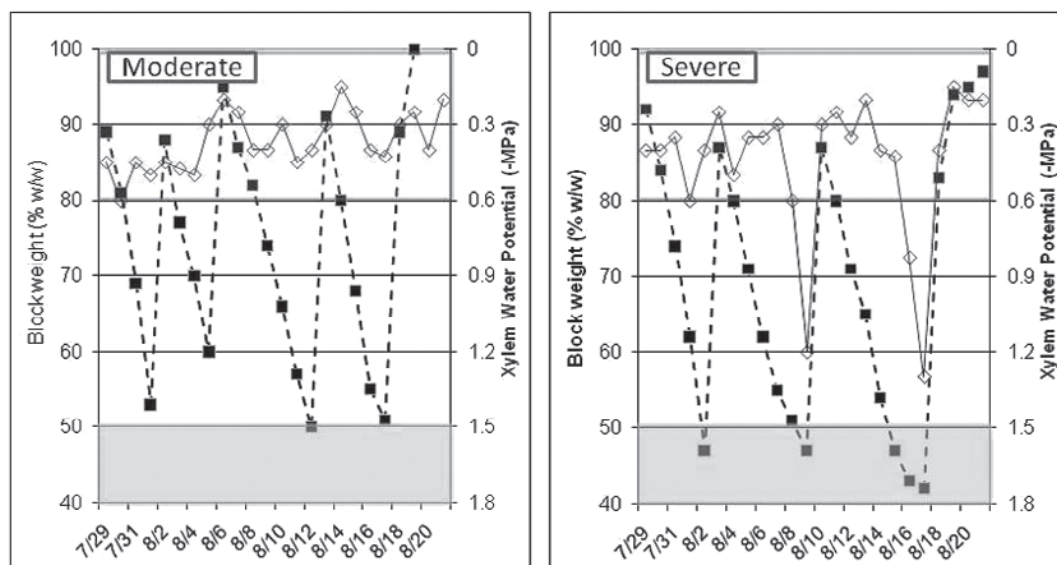


Figure 3. Container block weight (■) vs xylem water potential (◇) during sequential moderate (50%) and severe (<50%) dry down cycles of container Douglas-fir (*Pseudotsuga menziesii*) (Khadduri 2007).

In the work by Khadduri, ψ_{xylem} was only weakly correlated with moisture block measurements of container seedlings (Figure 4). In fact, there was essentially no correlation as long as block weights were above 50%. This should not be surprising. Moisture contents above 50% have a ψ_m above field capacity (-0.03 MPa), and often above -0.01 MPa (Pinto and others 2009); whereas ψ_{xylem} often is below -0.2 MPa. Thus, the transpiration gradient is still strong even at relatively low block weights. This can be disconcerting to growers since seedlings may appear relatively insensitive to block weights. It should be viewed as a management opportunity to save water and labor without sacrificing seedling quality. This is where judicious use of MAD is important. Caution is nevertheless required, especially as moisture content approaches 50%.

Alternatives to block weights are instruments that directly measure soil moisture content, such as tensiometers or time domain reflectometry (TDR) tools (Murray and others 2000; Arguedas and others 2007; Van Iersel and others 2010). These instruments are finding increasing utility in agriculture (for example, Kallestad and others 2006), in part because the data can easily be downloaded to a computer and viewed

graphically. Lamhamedi and others (2005) monitored irrigation uniformity with TDR units in an open-grown container nursery with a fixed sprinkler system (growing white spruce [*Picea glauca*]) (Figure 5). Unfortunately, application uniformity changed throughout the growing season, and crop height was only weakly correlated with soil moisture. The authors estimated the grower would need about 20 units to adequately characterize crop uniformity in the 240 m² (2580 ft²) nursery, at a cost of nearly US\$ 2000. Alternatively, the authors suggested tracking the growth of 4 seedlings would accomplish the same. It would appear additional development is warranted before widespread adoption by container nurseries is warranted.

Tools that directly measure soil moisture content are likely better suited for bareroot nurseries (Davies and Etter 2009). It is not that bareroot soil, or fixed sprinkler systems used in bareroot nurseries, are more uniform. Rather, in a container system, the sensor is measuring moisture content of a seedling completely isolated from other seedlings by the block or cell. The particular cell holding the sensor may not be representative of surrounding seedlings, as indicated by Lamhamedi and others (2005). The sensor in a bareroot

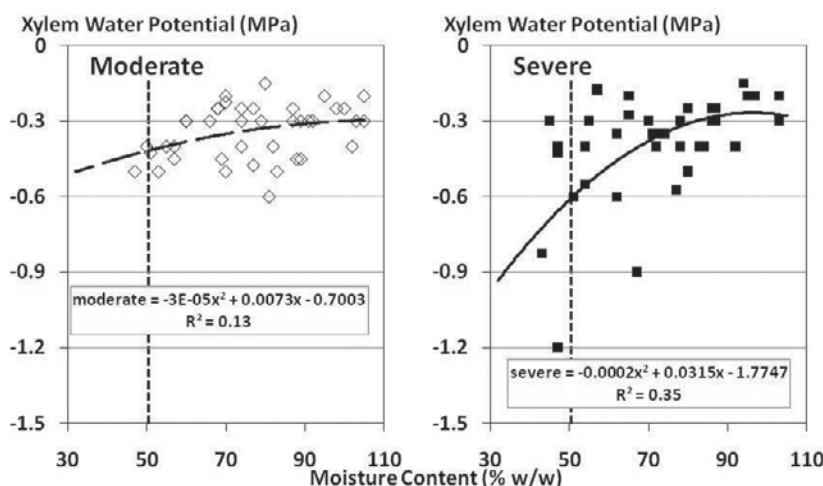


Figure 4. Container weight vs xylem water potential under moderate (50%) and severe (<50%) drydown cycles of container Douglas-fir (*Pseudotsuga menziesii*) (Khadduri 2007).

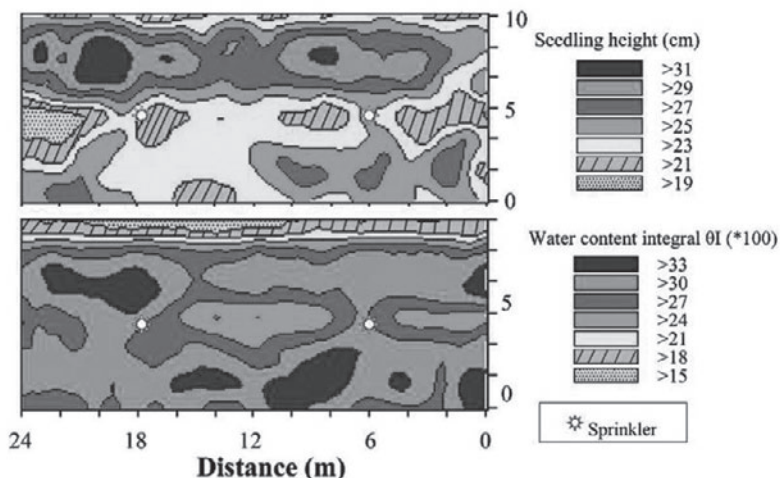


Figure 5. Utility of soil moisture sensors as a predictor of white spruce (*Picea glauca*) seedling height (Lamhamedi and others 2005).

nursery simulates the block weight technique in that the sensor measures moisture content available to more than just one seedling. The main drawback is the equipment may have to be removed for field operations, which may damage sensors.

The above-mentioned tools measure the seedling after a night of recovery or the balance of plant-available moisture remaining in the soil. While these instruments measure actual seedling water status or medium moisture, they are point in time and place measurements. They require integration or estimation over the entire crop through multiple sampling, both in place and time. Furthermore, these require labor during the growing season that the manager might be unwilling or unable to allocate to moisture monitoring, regardless of the benefit (Thompson and others 2002). Thus, often grower experience, that is, “seat-of-the-pants,” becomes the default irrigation method.

Unfortunately, none of the tools described above estimate the environmental parameters that actually drive ET, including radiation, VPD, and temperature that would provide some integration. Fortunately, these environmental variables can be easily estimated and used to schedule irrigation for the entire crop while avoiding issues of variability as discussed above. Tools such as a pan evaporimeters and atmometers integrate the impacts of radiation, VPD, and temperature on water evaporation that, in turn, can be used to approximate ETo. Pan evaporation (ETp) tends to overestimate ETo by about one-third (Snyder and others 2005), possibly explaining the lack of adoption of ETp data. Recent advances in atmometer design allow these instruments to more closely approximate ETo. Bauder (1999) found close agreement between ETgage™ and the Penman ET equation.

One tool that is rapidly gaining popularity for scheduling irrigation is the use of climate data, historic or current, available from regional or state climatologists. The reason for the increased popularity is climatologists are finally developing tools or display images that are more user friendly to managers. Growers can access real time ETo calculations for the current year, past ETo data for a specific year, or long-term average for nearby meteorological stations (Figure 6). Given the myriad of duties during the growing season and the wide fluctuations in daily ETo, it may be impractical to check climate data and adjust irrigation schedules on a daily or even weekly basis. The irrigation schedule, however, can easily be adjusted on a bimonthly or monthly basis using either current ETo or historic ETo data. Scagel (2010) used real time climatological data to provide nursery managers with PET (ETo) data on a weekly basis. The success of the program, however, was limited. A possible reason was the wealth of data that was provided at a time when the manager may have simply wanted to know if the seedlings should be irrigated. This is a common refrain among producers that has limited the adoption of irrigation scheduling tools (Thompson and others 2002). When determining irrigation schedules, time or labor is a greater concern than the equipment expense.

Growing to Target

How can ETo data (historic in this example) be used to schedule irrigation of conifer nurseries? Using mature pecan trees (*Carya illinoensis*) grown in New Mexico as our example, two points are obvious (Figure 7). First, there is reasonable similarity in ETc among 6 years and 2 orchards.

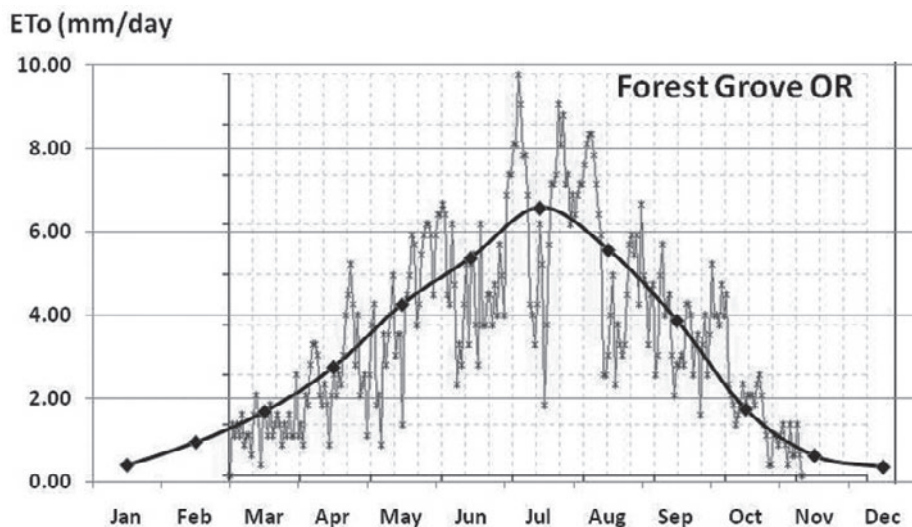


Figure 6. Comparison of real time ETo data for 2009 to long-term average for Forest Grove, OR meteorological station (<http://www.usbr.gov/pn/agrimet/agrimetmap/agrimap.html>).

Second, it is obvious ET_c bears little relationship to ET_o . Monthly ET_o ranges from about 2.5 mm/day in January and December, peaks at 9.0 mm/day in June as temperatures rise, and declines as temperature declines and RH increases during the monsoon season. In contrast, pecan ET_c is near 1 mm/day prior to budbreak in the Spring (Stage 1), increases linearly in Stage 2 as leaves and shoots expand, closely follows ET_o (Stage 3) once canopy coverage is complete, and declines as leaves senesce and drop (Stage 4).

While pecan ET_c may seem to have little relationship to ET_o , the behavior of a mature pecan orchard does have many similarities to nursery seedling production, whether in a bareroot nursery or container greenhouse.

Stage 1

During the seedling emergence phase, ET consists entirely of evaporation (E). E is higher when readily evaporable water is at or near the soil surface, but much reduced as water moves slowly from soil depths to the surface (Allen and others 1998). Mulched nursery beds or container medium covered with grit have reduced evaporation. Thus, E is typically low, that is, less than 1 mm/day in bareroot nurseries and less than 0.5 mm/day in container nurseries. Evaporation occurs only from the exposed medium surface of containers, and that may constitute less than 50% of the exposed surface area; the container or block constitutes the balance of the exposed surface. Thus, E in containers would be less than expected.

A recent study by Pinto and others (2009) examined the irrigation frequency during emergence of lodgepole pine (*Pinus contorta*). Given the container type and irrigation frequency, ET ranged from 0.24 mm/day for the low irrigation frequency to 0.90 mm/day for the high treatment during the emergence phase. In all treatments, medium ψ_m remained above field capacity (-0.033 MPa). Nevertheless,

germination was positively correlated, albeit weakly, with moisture availability. While it is important to maintain a high medium ψ_m , there can be potentially negative impacts. In the study by Pinto and others (2009), misting three times daily reduced seedbed temperature by as much as 3 °C (5 °F), potentially below the optimum temperature for both emergence and growth. Irrigating to meet the E demands will save water without impacting emergence. While irrigating in the morning can reduce temperatures below optimum, irrigating in the afternoon can reduce temperatures down into the optimum range. Better management may actually improve emergence as well as water use.

Stage 2

ET_c is a function of expanding leaf area (Asakura 1998). This is the most difficult stage to characterize or model. Nevertheless, there are common elements even in this stage. As a general rule, once crop canopy coverage reaches 65% to 70%, $ET_c = ET_o$ (Wang and others 2007). Thus, Stage 2 encompasses the time from complete emergence to 65% canopy coverage. Stage 2 ET_c can be estimated by estimating canopy coverage using digital photographs and software, such as Photoshop® (see Supplement II for examples of this technique). During this phase, irrigation should be incrementally increased as canopy coverage increases.

Stage 3

$ET_o = ET_c$ when the percentage of canopy cover exceeds 65% under non-stressed conditions. Additionally, during this phase, E can be as little as 10% of ET and can be effectively ignored (Beeson 2010). This appears to be a general rule, regardless of crop species (Allen and others 1998). Work with pecan orchards (Sammis and others 2004), honey mesquite

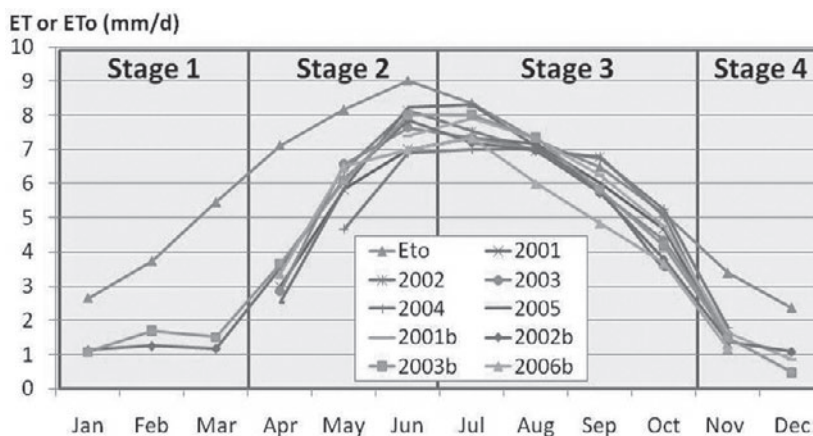
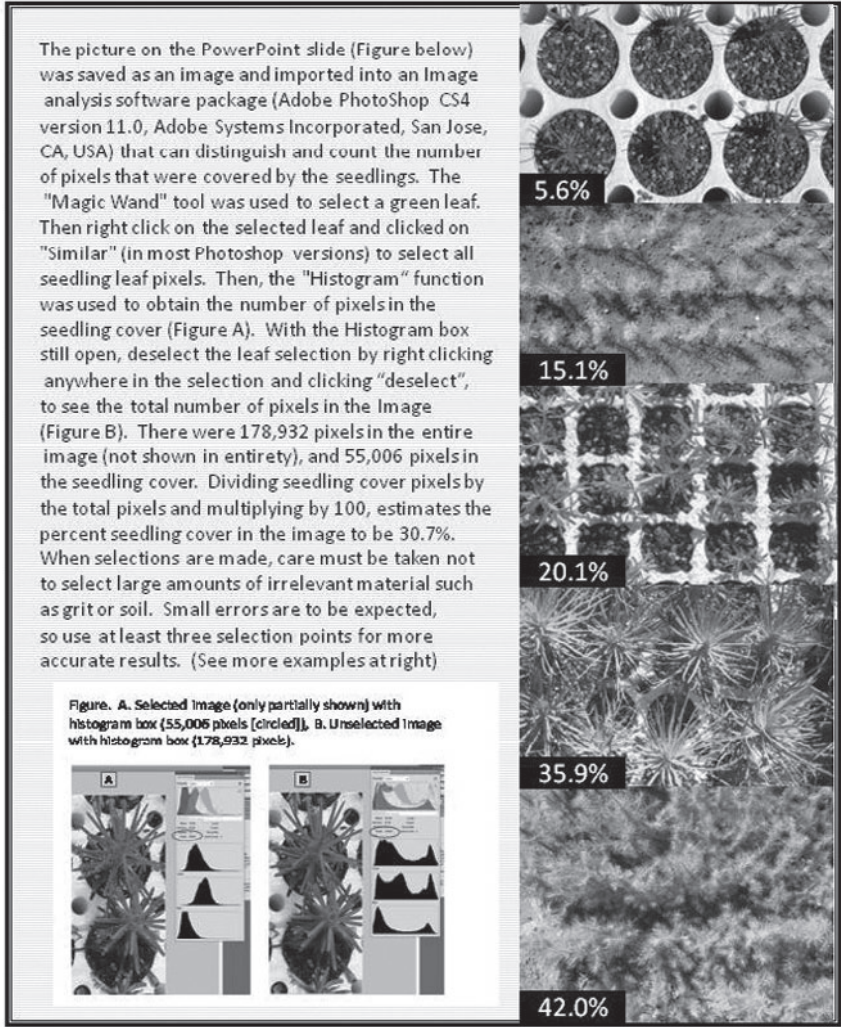


Figure 7. Daily pecan ET compared to ET_o in the Mesilla Valley, NM (Sammis and others 2004; Samani and others 2009).

Supplement II

Determining Percent Cover by the Pixel Counting Method.

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(*Prosopis glandulosa*) in landscapes (Levitt and others 1995), and creosote bush (*Larrea tridentata*) in containers (Saucedo and others 2006) has shown that all have similar water use under non-stressed conditions as the reference crop. That is, the crop coefficient (k_c) = 1.0. This should be verified for conifers; if the hypothesis holds, this may greatly ease management of irrigation during growth phases.

Stage 4

Senescence applies only to deciduous trees entering dormancy. As leaves begin to senesce, transpiration declines as the plant remobilizes nutrients to the roots in anticipation of impending shortened photoperiods and cooler temperatures. Once leaf drop is complete, only E operates. Currently, there is little information about water use of dormant conifers. However, roots do not undergo a physiological dormancy (endodormancy) typical of meristematic tissues (buds), and must be protected from desiccation.

The stages described above apply directly to bareroot or open-grown nursery crops. For greenhouse-grown crops, however, managers must determine a correction factor. Generally, the protective covering of a greenhouse reduces incoming radiation up to 60% (Seginer 2002; Möller and others 2004; Mpusia 2006), but 10% to 20% is more typical. Wind is also decreased, but the effect of air movement is minor and can be ignored. Nevertheless, ET_g is reduced below ET_o , but the exact amount will depend on covering type and age. Conversions can be accomplished using atmometers, such as ET_{gage} , or pan evaporation. Using this approach to irrigation scheduling should result in a crop grown under non-stressed conditions without excess water usage.

Using historic climate data rather than real time data introduces uncertainty about whether the crop is receiving sufficient water. Kallestad and others (2008) found long-term historic data accounted for about 90% of the variability in climate over a growing season, so the risks should be minor. As an example, a hypothetical open-grown nursery near Forest Grove, OR, meteorological station that was sown in March would have low ET_c demands (only E) until the crop completely emerged (Table 3). The ET_c demands would increase until canopy coverage reached 65% to 70% in July, after which time ET_c would equal ET_o . While irrigation scheduling to exactly meet ET_c requirements would not allow additional water for leaching salts from the medium, avoiding deficit irrigation may reduce the need for regular leaching of salts (Chartzoulakis and Drosos 1995). Periodic

Table 3. Example of irrigation requirements for a conceptual outdoor nursery at Forest Grove, OR (see Figure 6).

Date	Activity	ET _o (mm/day)	ET _c (mm/day)	ET _g /ET _o
Late March	Sow	2.70	0.8 (E only)	0.30
May 15	Emergence complete	4.25	1.25	0.30
June 15	40% canopy coverage	5.37	2.10	0.39
July 15	50% canopy coverage	6.57	3.30	0.50
August 15	75% canopy coverage	5.56	5.56	1.00
September 15	100% canopy coverage	3.86	3.86	1.00

irrigations that supply 110% of E_{Tc} could be scheduled to leach excess salts that might harm seedling growth.

Maintaining Target

Once seedlings have achieved the target size, managers may reduce irrigation frequency to maintain size, induce bud dormancy, or increase cold hardiness. Subjecting seedlings to moisture stress can have positive benefits from reducing growth and biomass accumulation, transpiration, and increasing carbohydrate accumulation (Table 4). Carbohydrates tend to accumulate because growth is more severely impacted by mild moisture stress before photosynthesis

(Morison and others 2008). Not all the changes in seedling physiology, however, are beneficial. Factors such as osmotic adjustment, root-to-shoot ratio, cold hardiness, and dormancy might not be improved by subjecting seedlings to moisture stress. Consequently, subsequent root growth potential and subsequent survival can actually decline after conditioning (Table 4).

One possible explanation for these disparate results could be the difficulty of maintaining medium ψ_m in the range where growth is reduced, but the physiological components of the target seedling are not diminished. This can be challenging. Dinger and Rose (2009) presented an elegant study on the relationship between soil moisture (ψ_m) and seedling water potential (ψ_{xylem}) following outplanting (Figure 8).

Table 4. Brief survey of the physiological effects of moisture stress conditioning on seedlings.

Parameter	Effect	Reference
Photosynthesis/Biomass accumulation	↓	Cleary 1971; Havranek and Benecke 1978; Clegg 1994; McMillan and Wagner 1995; Nzokou and Clegg 2010
Transpiration	↓	Havranek and Benecke 1978; Seiler and Johnson 1985, 1988; Villar-Salvador and others 1999
Carbohydrate accumulation	↑	Villar-Salvador and others 1999
Osmotic adjustment	↑ ↔	Seiler and Johnson 1985, 1988; Seiler and Cazell 1990; Villar-Salvador and others 1999
Root-to-shoot ratio	↔ ↓	Seiler and Johnson 1988; McMillan and Wagner 1995
Cold hardiness/Dormancy	↑ ↑↔	Timmis and Tanaka 1976; Blake and others 1979; Zaerr and others 1981; Almeida and others 1994
Root Growth Potential	↓	Vallas Cuesta and others 1999; Villar-Salvador and others 1999
Survival	↓ ↔	van den Driessche 1991; Vallas Cuesta and others 1999

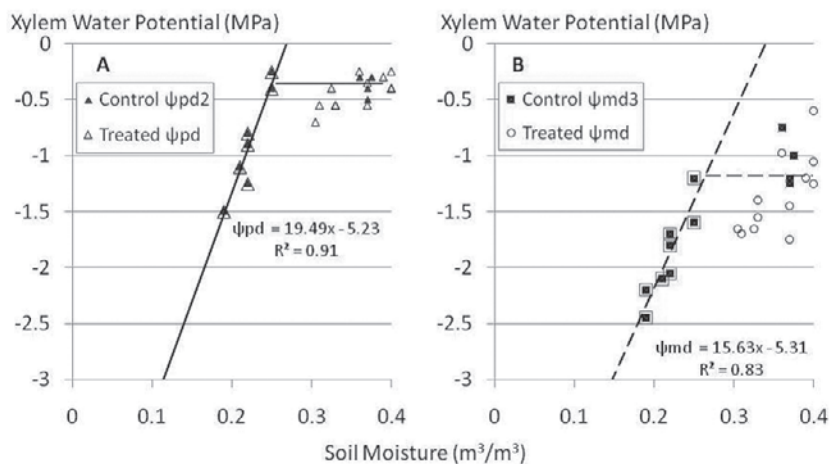


Figure 8. Low soil moisture determines seedling: (A) predawn (ψ_{pd}) and (B) midday (ψ_{md}) xylem water potential for treatments receiving complete weed control (treated) and no weed control (control) (after Dinger and Rose 2009).

Neither predawn nor midday ψ_{xylem} were highly correlated with soil moisture above $0.3 \text{ m}^3/\text{m}^3$. Once soil moisture fell below $0.25 \text{ m}^3/\text{m}^3$, however, both predawn and midday ψ_{xylem} decreased precipitously, and both were highly correlated with soil moisture. This likely could explain differences in seedling response to moisture stress in various seedling quality studies (Table 4). If moisture stress is not carefully monitored and maintained above the critical threshold, damage could result in decreased seedling performance. Work by Burr (1982, as cited in Landis and others 1989) found seedling ψ_{xylem} could decrease from -0.05 MPa to -0.10 MPa by transpiring only 2.7 mm from Ray Leach containers (163 cm^3 [10 in^3]). This would take less than one-half day in August at our hypothetical Forest Grove nursery. Work by Khadduri indicated similar rapid responses (Figure 3). Thus, a manager that successfully grows to meet target specifications can actually lose components of that target (for example, root growth potential) during the conditioning phase if moisture stress is severe.

Conclusion

There have been many changes and challenges since the first Target Seedling Symposium 20 years ago. Nursery managers are still dedicated to providing a quality seedling at reasonable cost, and irrigation management is a critical component of management strategies. Growing under non-stressed conditions allows the crop to reach target size in the shortest amount of time at the least expense. Maintaining target specifications (morphological, physiological, chemical) during the conditioning phase also requires careful water management. Fortunately, the nursery manager has an expanding suite of tools (climate data, moisture sensors) that can facilitate both growing to target specifications and maintaining the target seedling.

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