




Irrigation in pine nurseries

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Abstract

This review provides information and opinions about irrigation practices in pine nurseries. Even when nurseries receive more than 15 mm of rainfall week⁻¹, managers irrigate seedbeds to increase germination, increase seed efficiency, and increase root growth. In the southern United States, a 7-month old pine seedling in an outdoor nursery typically receives 2 to 6 kg of water supplied from either sprinklers (39 nurseries) or center-pivot irrigation (12 nurseries). Most nursery managers do not intentionally subject the crop to moisture stress, since most reforestation sites receive adequate rainfall, and many studies show that reducing root mass does not increase seedling performance. In fact, nursery profits can be reduced by more than \$13,000 ha⁻¹ when deficit irrigation reduces average seedling diameter by 1 mm. Although some researchers believe that failure to properly drought stress pine seedlings might increase outplanting mortality by up to 75%, research over the past 40 years does not support that myth. When pine seedlings average 5 mm (at the root-collar), water stress is not a reliable method of increasing tolerance to an October freeze event. In several greenhouse trials, researchers grew and tested seedlings that nursery managers would classify as culls (i.e., dry root mass < 0.5 g). Unfortunately, it is common for researchers to make irrigation recommendations without first developing a water-production function curve.

Keywords

Seedling quality; Soil moisture; Seedling survival; Hardening; Myth; Freeze protection

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ARTICLE INFO

Citation:

South BD, Nadel LR (2020)
Irrigation in pine nurseries.
Reforesta 10: 40-83.
DOI: <https://dx.doi.org/10.21750/R.EFOR.10.05.88>

Editor: **Abdenour Kheloufi, Algeria**

Received: **2020-11-02**

Accepted: **2020-12-14**

Published: **2020-12-30**



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1 Introduction

The world has more than 280 million ha of tree plantations (FAO 2020) and almost all of the *Pinus* species planted received irrigation at the nursery stage. Irrigation methods used to produce planting stock vary due to differences in environment, tradition, policy, economics, and, in some cases, myths. Although several authors discuss how much irrigation should be applied to seedlings (Day 1984; May 1984; McDonald 1984; Landis et al. 1989; NRCS 1997; Dominiewska 2002; Mexal and Khadduri 2011), sources with practical information are lacking. In this review, we document various irrigation practices used to grow pine seedlings (both current and past), and provide recommendations for researchers and managers. Information regarding water quality for irrigation is available elsewhere (May 1984; Landis et al. 1989).

2 Rainfall

The periodicity and amount of rainfall affects how much irrigation is needed to achieve the target seedling size. Regions with low or unpredictable rainfall are generally the first to invest in nursery irrigation (Figure 1). Although pines can grow with only rainfall (Mikola 1969; Minko 1976; Finn et al. 1980; Menzies et al. 1985; Klimek et al. 2008), irrigated seedbeds produce more plantable seedlings (Table 1). Faulkner (1952) listed five reasons for irrigation in nurseries, but the main purpose was to increase the conversion of seed to plantable seedlings. Without irrigation, seed requirements may be at least 20% greater than amounts required for irrigated seedbeds (Brewster and Larsen 1925; Minko 1976; Oleskog and Sahlén 2000). During dry months, the entire nursery crop could be lost due to poor germination or stunting.

Reliable rainfall explains why few nurseries in New Zealand initially had adequate irrigation to assist germination during dry periods (Menzies et al. 1985). At Rotorua, rainfall during the driest month averages more than 20 mm week⁻¹. At

Benalla Australia, seedlings received about half that amount and they grew without any irrigation (Table 1). In contrast, California nurseries might receive less than 3 mm week⁻¹ during the summer (Figure 1). Regions with low or unpredictable rainfall are generally the first to invest in nursery irrigation. After two years without irrigation, the root-collar diameter (RCD) of pine seedlings in an Idaho nursery averaged only 1.8 mm (Brewster and Larsen 1925).

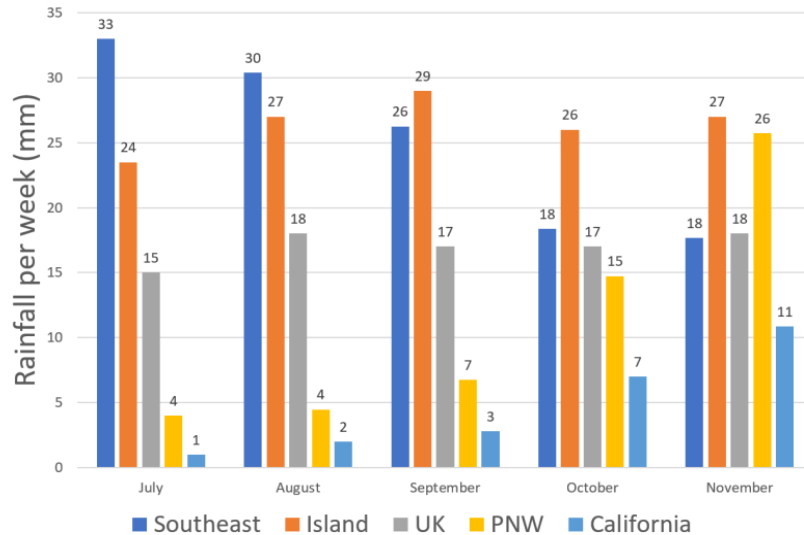


Figure 1. Average weekly rainfall will vary depending on nursery location (such as southeastern USA, United Kingdom, Pacific Northwest USA, California, and an island with a rainfall pattern similar to New Zealand but located in the northern hemisphere).

Regardless of stock type, economics is the primary way managers justify irrigation (South et al. 1989; NRCS 1997). When seed values increase, the economic returns from improving seed efficiency increases (South 1986; South 1987). For example, when irrigation increases container-grown pine seedling production by 100,000 ha⁻¹, the additional revenue might equal \$20,000 to \$60,000. It is therefore puzzling that seed efficiency is typically ignored in most irrigation studies. Many researchers report initial seed spacing and amount of fertilizer applied but fail to report the effect of irrigation on final seedling production (South et al. 1988). As a result, some irrigation recommendations end up reducing seedling diameter and nursery profits (Table 2).

Managers of *Pinus taeda* nurseries have several options: (A) strive to achieve little or no cull seedlings (e.g., target average 5-mm RCD) and sell bareroot seedlings for 5 cents each; (B) try to sell water-stressed, 4-mm RCD seedlings for 16% more (5.8 cents) and leave cull seedlings in shipping box; (C) try to sell water stressed, 4-mm RCD seedlings for 22% more (6.1 cents), and hire extra workers to keep culls from being placed in box; (D) market container-grown seedlings (4-mm RCD for 15 cents each); or (E) market water stressed, greenhouse-grown seedlings (3.5-mm RCD; 20 cents) for planting on stressful sites. Currently, company managers seem to choose options A and D to optimize profits.

Table 1. Irrigation trial at the Benalla Nursery, Victoria, Australia (Minko 1976). Seeds of *Pinus radiata* were sown 14 October 1971 at 300 m⁻², and seedbed density after six months was 129 m⁻² (no irrigation) and 155 m⁻² (irrigation). Each surviving seedling received at least 1.2 kg of rainfall while irrigated seedlings received an additional 2.4 kg of irrigation. Average root-collar diameter was 5.8 mm with irrigation and 4.0 mm without irrigation.

Month	Days of rain	Rainfall	Days of irrigation	Irrigation	Height with no irrigation	Height with irrigation	Equivalent month
	#	mm	#	mm	cm	cm	
November	3	46	0	0	3	2	May
December	2	36	4	55	5	5	June
January	2	32	4	125	9	11	July
February	2	59	3	95	14	19	August
March	1	12	3	71	21	30	September
April	1	1	1	22	27	38	October
May	?	?	0	0	29	45	November
	Total	186	15	368	-	-	

Table 2. Deficit irrigation reduces root-collar diameter (RCD) and nursery profits. In the examples listed below, stressing seedlings by withholding irrigation in the summer reduced RCD. The percentage of culls (RCD < 3.2 mm) was estimated using the following equation: $\text{cull \%} = 306 - 119 \times \text{RCD} + 11.6 \times (\text{RCD})^2$ [assume no culls when average RCD > 5 mm]. We used a theoretical 2 million harvested seedlings ha⁻¹ (culls plus sellable seedlings). Plantable seedlings are valued at 5 cents each and estimated lost revenue assumes all plantable seedlings can be sold.

RCD with operational irrigation	RCD with reduced irrigation	Operational Culls	Culls with less irrigation	Lost revenue
mm	mm	%	%	\$ ha ⁻¹
6.0	5.1	0	0	\$0
5.8	4.9	0	1.4	\$1,400
5.8	4.0	0	15.6	\$15,600
5.0	4.2	1.0	10.8	\$9,800
4.8	4.1	2.1	13.1	\$11,000
4.7	4.0	2.9	15.6	\$12,700
4.2	3.6	10.8	27.9	\$17,100
4.1	3.5	13.1	31.6	\$18,500

3 Irrigation equipment

3.1 Hose

At small nurseries (< 0.5 ha), managers might irrigate using a hose and an oscillating yard sprinkler or perhaps with a soaker hose (Biggin 1983; Dumroese et al. 2012). When irrigating seedlings at remote locations, hoses can also be attached to firetrucks or water pumps (Garcia 1979; Orchard 1981). The length of the hose is important since a long length may cause problems when the hose is dragged over seedlings (Tillotson 1917). At some nurseries hand watering with a hose was insufficient (Davis et al. 1942). Seedlings irrigated with a hose are not uniformly watered because some workers waste water while others may tire quickly and not

water seedlings sufficiently. It can be difficult, but not impossible, to document water use per seedling when using hoses.

3.2 Portable

In New Zealand and the United Kingdom nurseries, portable water systems (Figure 2) have been used (Schultz and Stoleson 1967; Menzies et al. 1985; Aldhous and Mason 1994) where monthly rainfall averages more than 13 mm week⁻¹. This system is primarily used after sowing, when weather forecasts predict no rainfall. In one hour, a 20-m irrigation boom can apply 6 mm to 0.2 ha when the flow rate is 12 m³ hr⁻¹. Due to the slow speed, this system is ineffective in protecting all seedlings from high temperatures. The system uses a hose which, when not positioned properly, can injure seedlings when it is pulled through the nursery.



Figure 2. Portable system of irrigation at a UK nursery (photo by Alex Steepe – Forestry England).

3.3 Solid-set

Before 1950, solid-set impact-head sprinkler irrigation systems were set up with sprinklers spaced 12.2 m apart in a square pattern. This layout allowed six seedling beds between pipelines that resulted in better irrigation uniformity (than wider spacings) during windy days (Robbins 2019). The direction of the wind did not matter much with a 12.2 m x 12.2 m spacing but, to reduce equipment costs, managers adopted a rectangular layout (12.2 m x 17.7 m) to fit 9 beds between pipes (Figure 3). This causes the center bed to be dryer when wind direction and pipe direction are the same. Nurseries that have this setup mitigate this effect by starting irrigation early in the morning when wind speeds are low (Wallich and Stevens 2003). Most horticultural nurseries in Louisiana irrigate before 8 am (Wilson 2017). To reduce the effect of wind on the center bed, some nurseries adopted a 12.2 m x 14.6 m spacing (Belluschi 1968).

Further issues to consider when using solid-set impact-head sprinkler irrigation system is the spring-loaded check valves are placed under each sprinkler “to prevent flow through the sprinklers at the beginning and end of each irrigation event” (Robbins 2019). These valves are useful during April and May when seed are germinating and seedlings are small. The impact of large water droplets can increase seed loss and reduces seed efficiency. Plastic check valves are, however, sensitive to freeze events (they can crack and will not operate properly), and therefore check valves should be removed before a freeze.



Figure 3. Irrigation pattern from a solid-set irrigation system (12.2 m x 17.7 m) at Opelika, Alabama.

Injecting fertilizers into the irrigation water is common in greenhouses (Wenney and Dumroese 1987; Landis et al. 1989) and at a few nurseries with center pivot systems (Starkey et al. 2015). Fertigation has also been tried with solid-set systems (Marx and Artman 1978) with unsatisfactory results. The uneven distribution pattern (Figure 3) not only creates differences in seedling growth but also can produce noticeable differences in soil pH.

3.4 Center pivots

Center pivot irrigation systems were not used in pine nurseries prior to 1980 (Conway 1986), but they are now in use at 32% of container nurseries and 11% of bareroot nurseries in the southern USA (SUSA) (Table 3). Initially, boom lengths in bareroot nurseries were over 300 m long but, once heat damage occurred, the seedbed area under a circle was reduced to reduce the potential of heat injury. Pivots with a 245 m radius might safely irrigate two-thirds of a circle during hot weather. Some believe irrigation uniformity using sprinklers (Lamhamedi et al. 2006) is less than that achieved using center pivots, but this depends on proper maintenance of equipment (NRCS 1997). Curved seedbeds are used at Aiken, SC and three bareroot nurseries use straight seedbeds (Table 3).

3.5 Linear move

Linear move systems are similar in construction to the center-pivot systems but use of a supply hose allows the entire system to move across the field (Sadeghi et al. 2017). These systems are designed primarily for use on rectangular shaped fields and can utilize more space than center pivots. The linear system makes it easy to manage different irrigation zones. During hot weather, this system can water seedlings faster than a center pivot system. A linear system is currently used at the PRT nursery in Atmore, Alabama.

Table 3. Pine nurseries with center pivot irrigation.

Stock	Year	Nursery	Location	Boom length (m)	Number of pivots
Bareroot	1985	Weyerhaeuser	Aiken, SC	245-457	4
	1989	TN	Delano, TN	335	1
	2005	Rutland Forest	Lenox, GA	107	4
	2014	K&L	Buena Vista, GA	145	3
Container	1998	IFCO	Washington, NC	85	1
	1999	Lewis Taylor	Tifton, GA	65	8
	2000	Bodenhamer	Rowland, NC	82	1
	2005	IFCO	Moultrie, GA	62	14
	2010	Westervelt	Eutaw, AL	64	1
	2014	IFCO	Deridder, LA	62	12
	2017	PRT	Atmore, AL	62	2
	2018	Virginia DOF	Courtland, VA	48	1

3.6 Subirrigation

Subirrigation occurs when water is supplied through a system of underground porous pipes or enters the soil from ditches (NRCS 1997). A system using two pipes per seedbed was installed at the Garden City Nursery in Nebraska in 1911 (Bates and Pierce 1913). At that time ditch irrigation was also referred to as subirrigation even though underground pipes were not used.

Subirrigation has been used in research greenhouses for more than 75 years (Roth and Riker 1943). Some researchers dip container trays into water (Shi et al. 2019), some add water to trays by hand (Dunlap et al. 2018), while others use pumps and timers to reduce labor costs (Landis and Wilkinson 2004; Dumroese et al. 2006; Schmal et al. 2011). Some operational nurseries use constant subirrigation (Ribeiro et al. 2014) while some use ebb-and-flow subirrigation (Schmal et al. 2011; Ferrarezi and Testezlaf 2017). Although a constant water level in trays can be used to some wetland species (Dumroese et al. 2012), this method (Trautmann and Iyer 1967) is not recommended for growing pines. Some systems use <3kg of water to produce a 3-g seedling (Shi et al. 2019; Davis et al. 2011). Although some research facilities use both sprinklers and subirrigation to grow seedlings (Landis and Wilkinson 2004; Dumroese et al. 2006; Landis et al. 2006; Table 4), they typically do not sell pine seedlings for less than seedlings grown without subirrigation.

Some greenhouse owners might invest in subirrigation if water supplies are limited (White et al. 2019). Even so, few managers of pine nurseries are willing to give up free rainfall to move seedling production under a roof where light intensity and wind levels are lower, growing space is limited, humidity levels are elevated, and where algae can grow.

The spread of disease is a concern with subirrigation systems (Schmal et al. 2011; Ferrarezi et al. 2015). Plant pathogens need to be removed or treated before irrigating with recycled water (Stewart-Wade 2011). For several other reasons, seedling quality can be lower when seedlings are grown under a greenhouse roof when compared to those grown outside (Mexal et al. 1979; Gillman and James 1980; Boyer and South 1984b; Retzlaff et al. 1990; Peterson 1994; Peterson 1997; Landhäuser et al. 2012; Goepfel 2014). This helps explain why more than 99% of pine seedlings produced in the SUSA are grown outside without any subirrigation. As soon

as the danger of a late frost is over, several nurseries in the Western USA retract or remove greenhouse roofs in order improve seedling quality (Hahn 1983; Bartok 2005). In contrast, clones grown outside in Canada (under higher vapor pressure deficits) grew slower than clones that were fertilized and irrigated more frequently in a heated greenhouse (Grossnickle 2019).

Table 4. Estimated water use from subirrigation at a Beijing Forestry University greenhouse near Jiufeng Mountain, Beijing, China (Shi et al. 2018). Seedlings of *Pinus tabulaeformis* Carr were grown in 164-cc containers with 528 cells m⁻² (Ray Leach Cone-tainers - SC10). Cells were fertilized with a slow-release fertilizer (100 mg N per cell; 528 kg ha⁻¹ of nitrogen) before sowing and about 100 g of water cell⁻¹ were applied using overhead irrigation. For the 75% treatment, each subirrigation cycle applied 17 g of water per cell when volumetric water content (v/v) dropped to 75% and the total amount applied was 0.85 kg cell⁻¹. Approximately 15% of the water applied was reused in subsequent soaking cycles. Seedlings were outplanted on April 1, 2014 and the number of dead seedlings (out of 40) were recorded on October 20, 2014. For each column, means followed with the same letter were not statistically different (Duncan's multiple range test, $\alpha = 0.05$).

Volumetric water content	Irrigation cycles	Net water use per seedling	Height	RCD	Root dry mass	Seedling dry mass	Dead seedlings
%	#	kg	cm	mm	g	g	#
55	33	0.650	8.0 b	2.57 c	0.26 b	0.77 b	12 b
65	43	0.679	8.3 b	2.66 a	0.28 a	0.83 a	3 a
75	50	0.723	9.2 a	2.72 a	0.29 a	0.84 a	2 a
85	58	0.795	9.2 a	2.73 a	0.27 b	0.82 a	7 ab

4 Water use

Several definitions of water use efficiency exist (Mexal and Khadduri 2011; Wilson 2017). Plant physiologists calculate water use efficiency (WUE) by dividing moles of water transpired by micromoles of carbon fixed ($\mu\text{mol CO}_2 \text{ mol}^{-1} \text{ H}_2\text{O}$). This value can be determined over short periods of time using specialized equipment (Smit and van den Driessche 1992). This definition of WUE is not easy to calculate, and the value does not directly relate to the cost of nursery management. Although there are some exceptions (Stowe et al. 2010; Mexal and Khadduri 2011), nursery managers from rainy regions (Figure 1) are less concerned about WUE and more concerned with increasing seed efficiency and outplanting performance. For example, the treatment with the lowest water use produced the lowest RCD and therefore the lowest field survival (Table 4).

A simple way to evaluate water use is to determine the quantity of irrigation water applied per seedling (i.e., kg seedling⁻¹; kg/S). This ratio can be used to compare irrigation water use among nurseries (Table 5). The kg/S ratio is determined by dividing the amount of irrigation (mm) by the number of seedlings per square meter (i.e., seedbed or container cell density). For example, a 3.0 ratio is determined by dividing 1,500 mm of irrigation by a container density of 500 m⁻². The kg/S is a conservative value since it does not include irrigation water applied to non-seedbed areas or irrigated areas that do not have containers. When accounting for inefficiencies, the yearly applications can be 50% to 80% greater than the kg/S ratio (Dumroese et al. 1995; Warsaw et al. 2009; Robbins 2019). Therefore, a nursery with a 2 kg/S ratio might require 3 million kg of water to grow 1 million seedlings. Although

the kg/S ratio is usually easy to determine, many managers do not know how much water they apply (White et al. 2019).

Water use is affected by species (van den Driessche 1991; Dumroese et al. 1995; Hart et al. 2020). For example, at a nursery in Georgia, 3.0 kg and 3.2 kg of water were applied to *Pinus taeda* and *Pinus palustris* seedlings respectively (personal communication: Mike Coyle). In seedbed density trials in bareroot nurseries, density has a direct effect on the kg/S ratio since irrigation rate remains fixed. In contrast with subirrigation, doubling the container density will double the amount of water applied m^{-2} (when cell volume remains constant). Likewise, the carrying capacity of nursery seedbeds is determined by soil moisture. For example, withholding irrigation at one nursery reduced the basal area (at age 6 months) by 61% (Minko 1976). It is surprising that most researchers conducting density trials in seedbeds apply the same amount of irrigation to all treatments. Is this because it is assumed that a single irrigation rate is appropriate regardless of the amount of transpiring needles, or is it just easier to assume foliage biomass does not affect soil moisture?

Instead of relying on seed efficiency and biomass data from nursery trials (e.g., May et al. 1961; Minko 1976; Hipps et al. 1997), some people make irrigation recommendations based on assumptions regarding somewhat complex water balance equations (Day 1984; Prévost 1989; Papadopol 1990). For example, open-pan evaporation (OPE) calculations predict a six-month growing season requires 1.0 to 1.7 kg of water seedling⁻¹ at rain-free nurseries (each at 500 seedlings m^{-2}) (Mexal and Khadduri 2011; Durlo et al. 2018a). However, since irrigation systems are not 100% uniform (Durlo et al. 2018b), additional irrigation is applied to avoid stunting seedlings located in dry zones. Instead of relying on flawed assumptions, most managers use more “hands-on” approaches to determining when to stop irrigating (Mexal and Khadduri 2011). In addition to preventing dry spots, checking moisture levels directly allows growers to inspect root systems and check for early signs of disease (Wenny and Dumroese 1987).

When growing a 7-g pine seedling, more irrigation is required at container nurseries than at bareroot nurseries. For example, in 2019, container nurseries in the SUSA applied more than 170 mm of irrigation per month (June to September) while a bareroot nursery averaged 120 mm. This was partly due to the higher stocking for container seedlings and because media in containers retain less rainfall than bareroot seedbeds. For horticultural nurseries, container and field nurseries apply about 1150 mm and 610 mm year⁻¹, respectively (White et al. 2019). Roots in containers typically do not have access to rain that falls below nursery tables and, therefore, more irrigation (on an area basis) is applied to container-grown seedlings. However, when container trays have twice the seedling density as bareroot seedbeds, the kg seedling⁻¹ ratio can be similar for both stock types (Table 5).

5 Cost of water

In some regions, rainfall is plentiful (Figure 1) and increasing. Annual rainfall amounts in the contiguous USA have increased by 59 mm since 1900, which helps resupply aquifers and lakes. In bareroot nurseries, about 3.3% of the overall seedling production costs are due to irrigation (Mills and South 1984), and about the same percentage occurs in container nurseries (Ingram et al. 2016). In some years, electricity costs associated with irrigation from wells may cost \$20 to \$62 per million

Table 5. Estimates of irrigation [kg seedling⁻¹ ratio (kg/S)] were determined by dividing irrigation amount (kg m⁻²) by seedling density (# m⁻²) [Note:10 mm of irrigation = 10 kg m⁻²]. Except for the hypothetical ratios, irrigation amounts were obtained from operational and research nurseries that use overhead sprinklers. The kg of irrigation water applied depends on nursery manager, rainfall, the number of months (M) irrigation was applied, size of container, type of media, and drainage slits in the container. Stock grown in containers (e.g., Con-164 cc) received less water than stock grown in 3.7-liter pots (e.g., Pot-3.7). Pine seedlings were irrigated except at ID1 (*Populus tremuloides*), FL (*Juniperus horizontalis*), QC (*Picea glauca*), UK1(*Quercus robar*) and NC1 (*Fraxinus pennsylvanica*). In some cases, estimates (e) were made when density values were not reported and county precipitation data (Rain) were used when rainfall data at the nursery was absent. Containers receiving no rain were grown in greenhouses. Examples of irrigation frequencies are provided in **Supplementary Material** (<https://journal.reforestationchallenges.org/index.php/REFOR/article/view/128/124>).

kg/S	LOC	Stock	M	Irrigation	Density	Rain	Year-nursery or Reference
			#	mm	# m ⁻²	mm	
0	ES	Bareroot	7	0	200e	894	Mikola 1969
0	AU	Bareroot	10	0	129	623	Adams 1951
0	AU	Bareroot	7	0	160	513	Flinn et al. 1980
0.25	MI	Bareroot	4	74	300e	147	Stoekeler and Aamodt 1940
0.26	UK	Bareroot	6	14	54	417	2017-Abbots Moss Nursery
0.31	WI	Bareroot	5	86	278	716	Stoekeler and Jones 1957
0.34	ON	Bareroot	5	103	300e	390	Day 1984 (hypothetical)
0.50	LA	Bareroot	5	150	300e	400	Wakeley 1954 (hypothetical)
0.50	ID	Con-107	4	264	528	0	Dumroese et al. 1992
0.78	TR	Bareroot	6	196	250e	536	Nuri and Figen 2008
0.83	WI	Bareroot	5	231	278	312	Stoekeler and Jones 1957
0.95	BC	Bareroot	5	285	300e	179	van den Driessche 1969 (hypothetical)
1.05	PL	Bareroot	5	283	269e	285	Hilszczanska 2004
1.09	PL	Con-120	6	572	526	458	Durlo et al. 2018a
1.10	WA	Con-60	6	1032	936	77	2019- Webster Forest Nursery
1.15	ID1	Con-164	4	605	528	0	Davis et al. 2011
1.18	VA	Bareroot	6	456	387	744	Dierauf and Chandler 1991
1.37	AR	Bareroot	9	410	300e	1161	1935-Ozark Nursery
1.37	GA	Bareroot	6	369	269e	518	1984-Morgan Nursery
1.46	QC	Con-350	5	283	190	0	Stowe et al. 2010
2.18	US	Bareroot	8	610	280	1010	2019- Table 8
2.27	LA	Bareroot	9	546	240	689	Huberman 1935
2.37	AU	Bareroot	6	368	155	186	Minko 1976
2.56	MO	Bareroot	7	770	300e	728	Chapman 1944
2.65	CA	Con-105	6	1407	530	29	2019-CalForest Nursery
2.70	MS	Bareroot	6	610	226	1081	1979-Ashe Nursery
3.00	AL	Con-110	7	1664	554	938	2019-Westervelt Nursery
3.03	GA	Con-115	8	1678	554	913	2018-IFCO Nursery
3.08	UK1	Bareroot	5	771	250	281	Hipps et al. 1997
3.18	TX	Bareroot	9	892	280	596	South et al. 2018
3.69	NC	Con-113	6	2145	581	944	2019-Claridge Nursery
3.85	US	Con-164	6	2035	528	0	Tinus and McDonald 1979 (hypothetical)
5.81	MX	Con-170	6	2129	366	0	Madrid-Aispuro 2020
6.42	ZA	Con-80	7	2707	423	0	2019- Pine Nursery
6.50	TR	Con-1570	8	650	100	524	Kulac et al. 2015
8.10	NC1	Bareroot	8	961	118	728	Lamar and Davey 1988
11.9	AL	Pot-2.4	4	441	37	0	Chieppa et al. 2017
42.0	FL	Pot-3.7	12	1638	39	1400	Knox 1989

seedlings (Table 6), and these costs would even be lower when pumping surface water (White et al. 2019). The cost of well water, recycled water, and municipal water can be \$0.13, \$0.26 and \$0.70 Mg⁻¹, respectively (Wright and Benson 1981; Pitton et al. 2018).

For pot-grown *Thuja* seedlings (1.5 m tall), watering with an extra 400 kg seedling⁻¹ might increase height by 3 cm (Tran et al. 2018) and tree value might increase by \$3.00 (assuming a 25 cm increase increases price by \$28). Even when water costs \$0.26 Mg⁻¹, the extra irrigation would have a benefit-cost ratio of 11.5. Likewise, when water costs \$0.0002 seedling⁻¹ and a seedling is sold for 5 cents, then water represents only 0.4% of the price. When 12 tones of water are used to produce two million seedlings, irrigating with municipal water might cost \$8,400 ha⁻¹. This explains why most forest nurseries do not irrigate with municipal water.

Table 6. Irrigation frequency, irrigation hours per cycle (5 mm per hour), total irrigation amount (Total), irrigation per seedling, rain (growing season only), water provided per seedling, and estimated electricity cost at the Georgia Forestry Commission, Morgan Nursery, Byron, Georgia (32°32'N, 83°44'W). Soil tensiometers were used in 1984 and 1985 and their use and mulch helped to reduce irrigation frequency. Irrigation water per seedling was estimated assuming 19 ha produced 34.2 million seedlings.

Year	Irrigations	Time per cycle	Total	Irrigation seedling ⁻¹	Rain	Water seedling ⁻¹	\$ ha ⁻¹
	#	hours	mm	kg	mm	kg	\$
1983	110	1.68	925	5.14	410	7.4	\$111
1984	60	1.23	369	2.05	518	4.9	\$44
1985	60	1	301	1.67	509	4.5	\$36

6 Irrigation

6.1 Before sowing

Irrigation is sometimes required prior to sowing. Soil fumigations with compounds such as chloropicrin and methyl bromide are less effective when soil moisture is low (Munnecke et al. 1982). The target soil moisture for coarse soils is 75% of field capacity (Cordell 1989). When the moisture level is low, managers will irrigate dry fields to increase soil moisture. In the past, irrigation was also used to reduce the emission of certain compounds produced during fumigation such as with metam sodium and dazomet (Barnard et al. 1994; Wang et al. 2006). Irrigation is also applied prior to testing solar fumigation (Salerno et al. 2000).

6.2 Germination phase

Seedbeds should be kept uniformly moist during germination (Sudworth 1900) and sometimes pine seedlings were irrigated only during the germination period (Shirley and Meuli 1939). Some managers begin irrigating at 3 AM and may irrigate four times a day during emergence (Morby 1982). Irrigating before dawn is preferred as distribution is more uniform when the wind is calm. Some managers apply about 14 mm week⁻¹ after sowing (Hilszczanska 2004), and when added to 11 mm week⁻¹ of rain, this equals the amount recommended by Wakeley (1954).

In April, some consider 20 mm week⁻¹ as overwatering (Mexal and Khadduri 2011). However, there is a belief that it's better to overwater pine seedbeds than to

underwater them during the germination phase (McDonald 1978; Cawse and Martyn 1981). For example, irrigating 3 times per day in one greenhouse resulted in 4 more seedlings per tray (i.e., a potential value increase of \$2.40) than irrigating every other day (Pinto et al. 2009).

On non-fumigated soil, post emergence damping-off can occur when high soil temperatures occur in the presence of soil pathogens (Roth and Riker 1943). An example of inadequate irrigation occurred on non-fumigated soil after seeds were sown on April 24, 2007. Soil temperatures exceeded 40.5°C on May 11 and 13 (between noon and 5:30 PM). Irrigation was reduced to conserve water and damping-off occurred on May 15th (Figure 4). In 1980, nine managers reported seedling losses due to drought, but only one manager reported a loss in 2012 (Starkey et al. 2015).



Figure 4. At this nursery in 2007 the February-May rainfall was 310mm below normal which was the lowest level recorded over 126 years. The water level in the irrigation reservoir reached a record low level. To conserve water irrigation frequency was reduced and, as a result, seedlings died when soil temperatures reached lethal levels. Pine seeds were sown on April 24th and the photo above was taken on the morning of May 16th.

6.2.1 Mulch

In one study (Jackson and South 2011), applying a bark mulch increased the number of plantable seedlings by 35 m⁻² (Figure 5). Applying a mulch after sowing can reduce soil temperatures and reduce the loss of soil moisture (Bristow 1988). Prior to 1970, managers who mulched seedbeds would ensure seedlings received about 25 mm week⁻¹ of water (rain+ irrigation) until early September (Wakeley 1954; May et al. 1961). As some mulches introduced weed seeds into the nursery beds, managers began favoring weed-free mulches. In 1980, about 98% of nurseries in the SUSA used a mulch (Boyer and South 1984a) and now about 35% use a mulch. Most managers in the SUSA now apply a soil adhesive (Figure 6) to stabilize the soil surface and reduce loss of seed during rainstorms (Starkey et al. 2015; Rentz 2019). Although use of a soil stabilizer increases seed efficiency, seedbeds without a mulch require more irrigation. When supplied with the same rate of irrigation, seedlings growing on mulched beds tend to be larger than those on non-mulched beds. Without a mulch, pine seedlings now might receive twice as much water (e.g., 54 mm per week of rain + irrigation).



Figure 5. After sowing *Pinus taeda* seed (April 20, 2020), a thin layer of pine bark mulch was applied within the roped area. The same amount of irrigation was applied to all treatment plots. Plantable seedlings were 194 m⁻² on the mulched area and 175 m⁻² on the non-mulched area (Jackson and South 2011). Some managers in the SUSA apply soil adhesive after sowing and then follow by applying a thin layer of bark mulch.



Figure 6. Several managers apply a soil adhesive to seedbeds soon after sowing. At this nursery, standing water occurs when areas not treated with a soil adhesive form a crust that reduces water infiltration and reduces seed efficiency. A rectangular irrigation layout (12.2 m x 17.7 m) is used at this nursery in Alabama.

6.3 Height growth phase

After the germination phase (6-8 weeks after sowing), some managers increase the irrigation rate and apply 100% more water per day (Stoekeler and Jones 1957). As soil temperatures rise, evapotranspiration rates increase and the need for irrigation increases (Mexal and Khadduri 2011). In North America, irrigation applications are greatest in July and August with some container-seedlings receiving 15 mm day⁻¹. The amount applied during three months before the fall equinox can amount to 60 to 80% of the total volume applied to the crop.

Irrigation should be frequent and uniform to ensure seedlings are not adversely affected by moisture stress (Wallich and Stevens 2003). The amount of rainfall plus irrigation (April to September) can exceed OPE by 25% or more (Tables 7

and 8). To ensure all seedbeds are moist, managers apply more irrigation than recommended using OPE theory. For example, when using OPE, pine seedbeds may receive less than 300 mm during the first six months after sowing (van den Driessche 1969; Day 1984; Prévost 1989; Papadopol 1990). Most nursery managers do not follow OPE theory.

Table 7. Estimated irrigation for container-grown seedlings grown at a density of 554 m⁻² in 110 cc volume cells (3.8 cm x 3.8 cm x 12 cm). During germination in April, smaller nozzles are used to provide 3.18 mm of water per hour. Larger nozzles are used in May to provide 6.35 mm of water per hour. At the Westervelt Nursery in Alabama (32°55'N, 87°51'W), the center pivot covers 1.28 ha with 1.409 million cells. Open-pan evaporation means (1956-1979; Demopolis, AL) are provided as a comparison.

Month	Irrigations	Irrigation	Irrigation	Rain	Normal rain	Open-pan evaporation
2019	#	Hours day ⁻¹	mm	mm	mm	mm
April	16	1	51	172	122	142
May	12	1	76	105	107	165
June	16	2	203	96	107	179
July	31	1.9	381	112	127	178
Aug	31	2.3	457	179	102	169
Sep	30	1.1	203	4	91	131
Oct	24	1	152	269	94	104
Nov	12	1	76	88	124	69
Dec	6	1	38	154	119	56
Jan-2020	4	1	25	197	137	61
Total	182		1664	1377	1130	1254

Table 8. Irrigation at a bareroot southern pine nursery in 2019. On a typical day, seedlings received no more than one hour of irrigation (i.e., 6.35 mm). In this year, rainfall exceeded 220 mm in April and May and was lowest in August and September. Open-pan evaporation means (1948-1979; State University, MS) are provided as a comparison.

Month	3-7AM	9-11AM	1-4PM	4-7PM	Days irrigated	Irrigation	Rain	Normal rain	Open-pan evaporation
					#	mm	mm	mm	mm
April	12min	12min	12min	12min	5	25	223	131	152
May	12min	12min	12min	12min	5	25	284	131	184
June	15min	15 min		15min	27	128	98	129	193
July	20min	20min	20min		20	127	183	111	197
Aug	30min			30min	24	152	8	85	185
Sep	60min				12	76	7	79	146
Oct	60min				8	50	115	120	114
Nov	60min				4	25	54	135	76
Dec					0	0	37	157	57
				total	105	610	1009	1079	1304

6.3.1 Cooling

When irrigation is adequate, pine seedlings (RCD < 2.7 mm) do not die when air temperatures reach 44 to 50°C (Ameye et al. 2012; Carlson et al 2004). However, without irrigation soil surface temperatures can exceed 48°C and injury can occur (Engstrom and Stoeckeler 1941; Barnard 1990; Helgerson 1990). The increased transpirational demand created by high temperatures coupled with low soil moisture

can damage roots by embolism formation. A lack of moisture is a greater stressor of pine than high air temperatures (Bauweraerts et al. 2014). Although mortality is rare, embolisms in roots do not repair (Choat et al. 2015; Choat et al. 2019), reducing seedling growth and water transport. To no avail, nursery managers attempted to boost growth with extra irrigation and fertilization. Sometimes managers are puzzled as to the cause of these stunted seedlings (eg., Belluschi 1968). In the past when some nurseries did not sell seedlings, it was not considered economical to install overhead irrigation to reduce this type of injury (Engstrom and Stoeckeler 1941).

When air temperature reaches 45°C during midday, maximum needle temperatures may reach 60°C when soil moisture is low (Kolb and Robberecht 1996). As a result, seedling mortality can occur in July. Data indicate that when soil moisture is adequate, high transpiration rates keep seedlings cool and this reduces the risk of mortality (Kolb and Robberecht 1996). For this reason, some managers irrigate bareroot seedlings two or three times a day in July. Irrigating pines three times in a greenhouse can reduce temperatures by 1.5°C at noon (Pinto et al. 2009). Some nurseries in the Western USA irrigate seedlings when soil temperatures in July reach 35°C (Thompson 1984) or 38°C (Morby 1982; Adams 1983) and container nurseries in the SUSA irrigate when temperatures reach 34°C (Starkey et al. 2015). Irrigation is used to reduce water stress levels and avoid potential xylem cavitation. When the canopy begins to shade the soil, the risk of xylem cavitation injury declines. The risk of injury also declines as seedlings get older (Bates and Roeser 1924).

6.3.2 Weeds

Irrigation will increase weed biomass in fallow fields, but it can also reduce weed biomass when the larger crop canopy shades out weeds (Burnside and Colville 1964). Water from wells can be weed free but irrigation from surface waters introduce weed seeds.

For some herbicides, moisture is a requirement for best results (Buchanan 1969). Even when effective herbicides keep weed populations low, frequent hand weeding is required to keep resistant weeds from producing seed. At some nurseries, weeding times were cut in half when irrigation was applied before weeding (Engstrom 1949).

6.3.3 Disease

Irrigation affects the development of certain disease organisms (Dumroese and James 2005), especially when using untreated recycled water (Werreset al. 2007; Stewart-Wade 2011; Machado et al. 2013). The root disease *Macrophomina* may peak late in the growing season when soil temperatures are high and where dry soils occur due to a reduction in irrigation (Vaartaja and Bumbieris 1967; Barnard and Gilly 1986). *Macrophomina* was a more common problem in the past when soil fumigation was omitted and irrigation was withheld to purposely induce water stress (Barnard 1997). Although root dieback caused by uninucleate *Rhizoctonia* cannot be avoided merely by reducing irrigation (Lilja et al. 1998), irrigation can reduce mortality caused by *Diplodiapinea* (Stanosz et al. 2001). Irrigating early in the morning may help reduce the incidence of *Rhizoctonia* blight (Starkey and Enebak 2012). Too little soil oxygen can increase the occurrence of *Fusarium* and *Pythium* (Juzwik et al. 1999). Not reusing irrigation water can be part of an integrated pest management program.

6.3.4 Foliar injury

Application of some agrochemicals can cause foliar burn on pines seedlings. For this reason, irrigation is often applied after treatment to dilute the chemical and reduce the risk of cosmetic injury. Potassium chloride fertilizer can cause burn when granules are not washed from needles but injury should not be a problem when irrigation rinses it from foliage (Landis et al. 1989). Some pesticides contain petroleum distillates that injure young cotyledons when residues are not washed from seedlings.

6.3.5 Replication effect

Differences in irrigation distribution (Savory 2005; Lamhamedi et al. 2006; Overton 2014; Durlo et al. 2018b) affect pine seedling growth and sometimes the effect can be seen in aerial imagery (Figure 3). In several nursery trials, the location of replications affected seedling growth more than experimental treatments. Although several factors might cause seedlings in one replication to grow 50% more than in another (McNabb 1985), a 47% increase in irrigation (Overton 2014) could account for some of the extra growth.

6.3.6 Two schools of thought

Two schools of thought exist regarding summer irrigation. Managers who irrigate in July and August to increase root growth are from the NO WILT school and in North America most reside below latitude 43°N. During a week with no rainfall in August, SUSA managers might irrigate 4 to 13 mm day⁻¹. In contrast, those from the WILT school withhold irrigation in the summer to set terminal buds and reduce height and diameter growth. Although seed efficiency and root mass are important for all managers, those from the WILT school are more concerned with the “physiological well-being of the crop” (Lavender and Cleary 1974; McDonald 1978; Lavender 1984; Hubbel 2015).

6.3.7 Wilt

In the first half of the 20th century, The Wind River Nursery (Carson, Washington) was established in 1909 to produce seedlings for planting on national forests. Seedlings grown there might receive 43 mm week⁻¹ of rain. However, some claimed these seedlings would not be suitable for planting on sites that normally receive one-eighth that amount of rain. Therefore, in hopes of improving outplanting survival, a nursery was established at Bend, Oregon where rain averaged only 5.7 mm week⁻¹ (Engstrom 1949). The belief at that time was that bareroot seedlings receiving just 3 mm week⁻¹ of rain in the summer would result in better survival and growth in the forest. In fact, some believe plants subjected to periodic wilting attained a greater resistance to drought than plants provided with an abundant moisture supply (Shirley and Meuli 1939; Stoeckeler and Jounes 1957). As a result, some managers were told to stop irrigation in the summer (Stoeckeler and Slabaugh 1965) and in doing so the soil became hard and dry enough to wilt seedlings and reduce root growth.

Lavender and Cleary (1974) created a graph indicating 99% survival in February for properly stressed seedlings and only 25% survival for non-stressed seedlings. This graph explains why some believe that withholding irrigation during the summer will impart a long-term (8 month) effect on seedling physiology sufficient to

improve seedling survival after outplanting. However, no data were presented to support this hypothetical model.

Several researchers adopted a philosophy of stressing seedlings in the summer to more closely mimic seedlings in nature. Irrigation was reduced in May (Zaerr et al. 1981), June (Lavender and Cleary 1974; Morris and Greenwood 1977), July (Wenny and Dumroese 1987; van den Driessche 1991; Sloan 1992), August (Stoeckeer and Sabaugh 1965; Lavender and Cleary 1974; Hennessey and Dougherty 1984), and September (Wakeley 1954). As a result, bareroot seedlings were short and did not require the use of black-out cloth or top-pruning to improve the ratio of roots to shoots. The practice of stressing container-grown seedlings began in the 1970's (Lavender and Cleary 1974; Hahn 1983) and now most WILT advocates grow seedlings in greenhouses. Some believe survival increases when roots of container-grown pine seedlings are brown and suberized at time of outplanting.

Pressure chambers are sometimes used to determine when to resume irrigation (Morby 1982; Semerci et al. 2017; Grossnickle et al. 2020). A generic recommendation was to withhold irrigation in mid-July until the plant water potential (PWP) reached either -1.0 MPa before dawn (Morby 1982) or perhaps -1.7 MPa at mid-day (Lavender and Cleary 1974). In one study, net photosynthesis was reduced by 40% when seedlings reached -1.6 MPa (Cleary 1971). The recommendation for bareroot *Pinus taeda* in September-October was to irrigate only when the predawn values reached -0.75 MPa (Hennessey and Dougherty 1984). Since pressure-chamber readings can vary with user, equipment and environment, the best irrigation regime at one nursery cannot and should not be used at another nursery (Morby 1982). Therefore, one should expect PWP recommendations to vary among researchers and among nursery managers. Since the duration of the stress is just as important as the mid-day level reached on a particular day, it seems odd that few researchers have investigated this topic.

Pressure-chambers are used at nurseries in Washington and Oregon where rainfall in July averages less than 5 mm week⁻¹ (Wallich and Stevens 2003). Sometimes they were used before lifting to check that seedlings were not under too much stress. Stressing 2-0 bareroot seedlings to -1.5 MPa in July and August (Elkton, Oregon) produced stock that was not plantable (Zaerr et al. 1981) and in Arkansas, irrigating when predawn PWP reached -0.36 MPa resulted in cull *Pinus taeda* seedlings (Morris and Greenwood 1977).

The use of water stress in the nursery is not always successful in improving seedling survival in the field (Williams et al. 1988; Sloan 1992; Grossnickle 2012; Espinoza et al. 2020). When pine seedlings are weakened by too much stress, they may be more susceptible to drought (Shirley and Meuli 1939). When this occurs, sometimes the claim is made that the stress was not done correctly or that seedlings received too much rain. Since it is difficult to repeat any particular level of water stress in bareroot nurseries, some use growth chambers to stress seedlings (Meier et al. 1992; Blake and Li 2003).

Recommendations for using pressure chambers on container seedlings vary. Without any data, one recommendation (Hodgson 2011) was to irrigate container-grown pine seedlings after they temporarily wilt (at midday about -2.5 MPa) (Figure 7). Others irrigate after 40% of the crop wilts when midday PWP is about -1.2 to -1.7 MPa (Grossnickle et al. 2020) or -1.7 to -1.8 (Lavender and Cleary 1974). It may take several days for irrigated seedlings to recover after they wilt (Brix 1962).



Figure 7. Wilted *Pinus taeda* seedlings at the Pelton Nursery in British Columbia, Canada (122°38'N, 49°14'W), (photo by Jol Hodgson).

6.3.8 No wilt

Bareroot seedlings require abundant water, well distributed throughout the growing season to achieve target size (Olson 1930) and irrigation should not be withheld to the point of preventing normal growth (Wakeley 1954). Some believe well-watered stock has a slightly higher potential for outplanting survival in late summer than properly hardened stock (Lavender and Cleary 1974; Villar-Salvador et al. 2013) which may be due to a greater root growth (Bayley and Kietzka 1996; Villar-Salvador et al. 1999). Currently, managers from the NO WILT school rely mostly on experience and visual clues to determine when to irrigate seedlings during the summer and many top-prune pine seedlings since outplanting seedlings with greater height can result in lower survival on droughty sites (Grossnickle 2012). The appearance of the seedlings and soil moisture content are the principle guides for irrigation. Irrigating during August or September can increase the size of apical buds (Clements 1970) and can also increase bud break after outplanting (Guehl et al. 1993). Trials show that stressing bareroot pine seedlings (by irrigating when PWP reaches -0.46 MPa) can reduce root mass by 28% to 56% (Table 9).

Many managers weigh container trays to determine when to irrigate seedlings (Juntunen and Rikala 2001; Dumroese et al. 2015) and some increase the trigger weight as seedlings gain mass over time (Dumroese et al. 2012; Figure 8). For this

paper, we use the managers method of calculating media moisture content (Dumroese et al. 2015). Some managers keep media moist (85% g/g) and produce seedlings with an average RCD of 5.7 mm while others irrigate less (55% g/g) to produce seedlings with a 4.6 mm RCD (Kildisheva et al. 2017).

Table 9. Morphological data for bareroot *Pinus taeda* seedlings that were not top-pruned in 1975. Seedlings at the OK nursery were irrigated in August when predawn water potential was below -0.46 MPa and AR seedlings were irrigated when PWP reaches -0.36 MPa (Morris and Greenwood 1977). In theory, harvested seedlings that average 3 mm RCD should have more than 50% culls (when a cull is defined as < 3.2 mm RCD). RCD = root-collar diameter; RMR = root dry mass ratio (i.e., root dry mass/seedling dry mass).

Nursery	Irrigation	RCD	Height	Shoot	Root	Root dry mass ratio
		mm	cm	g	g	
AR	Normal	3.7	14	1.9	0.53	0.22
	Stressed	3.0	12	1.3	0.74	0.36
OK	Normal	4.7	34	4.3	0.92	0.18
	Stressed	3.0	20	1.4	0.40	0.22

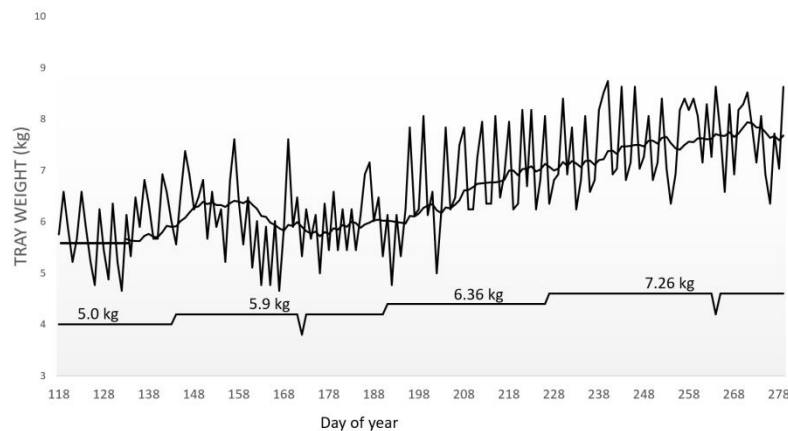


Figure 8. At the Cal-Forest Nursery in California (41°28'N, 122°49'W), *Pinus ponderosa* seed were sown on April 28 (day 118) and irrigation was stopped on October 19 (day 292) (data provided by Tom Jopson). During the growing season, the trigger weight for irrigation increased from 5 kg in May to 7.26 kg in October. Assuming a Styroblock 8 trays at field capacity have an average weight of 6.66 kg, then a 75% trigger value was used in May (i.e., 5 kg/6.66 kg). Assuming a fully saturated tray with seedlings (in September) weighs 8.66 kg, then perhaps 90 green seedlings weigh 2 kg. When seedlings have a dry mass of 9.2 g and a green mass of 22.2 g, then the moisture content would be about 140%.

The point of zero turgor (i.e., wilting) can be physiologically detrimental to the seedling and cellular damage can result if wilting is persistent (Cleary 1971; Lopushinsky 1990). To avoid wilting seedlings, irrigation may be applied after undercutting seedlings (Kissee et al. 1985; Dierauf 1995). In several cases where irrigation was delayed after undercutting, seedlings became stunted and the production of culls increased. When cavitation occurs, 1-0 seedlings do not respond well to subsequent irrigation and fertilization. Some pine seedlings die when soil is maintained at 3% (g/g) soil moisture (Abdollahi et al. 1993) or when container media is maintained at 30% (v/v) water content (Lilja et al. 1998). In some regions, six days of no irrigation in a greenhouse can turn needles brown (Jones et al. 2014).

Proper planting of seedlings with larger roots and shorter shoots increases outplanting survival (Rose et al. 1997; South and Mitchell 1999; South et al. 2005; Grossnickle 2012; Villar-Salvador 2012). Studies with bareroot seedlings indicate reducing irrigation in the summer or fall does not increase survival on sites with >80% survival (Table 10). Managers at the Stone Nursery in Oregon realized that good root growth in the nursery was important for survival in the field (Riley and Steinfeld 2005). Instead of allowing seedlings to cavitate during the summer, managers irrigated to keep seedlings above -1.2 MPa predawn. The NO WILT school believes sunsuberized roots take up more water after transplanting than suberized (brown) roots (Chung and Kramer 1975; Carlson 1986).

Table 10. Trials at bareroot nurseries where seedlings received rainfall and all treatments were outplanted in the field. Values in parentheses for root-collar diameter (RCD) and survival represent moisture stress treatments. Average heights were 15 cm, 18 cm, 25 cm, and 30 cm for *Pinus nigra*, *Pinus ponderosa*, *Pinus echinata*, and *Pinus nigra* spp. *laricio*, respectively. Studies are listed in order of survival. Reducing irrigation can reduce the production of plantable seedlings without affecting outplanting survival (Minko 1976; Williams et al. 1988; Dierauf and Chandler 1991).

Species	Season of irrigation treatments	Root collar diameter (mm)	Survival	Survival statistically significant ($\alpha=0.05$)	Reference
<i>Pinus radiata</i>	Summer-fall	5.4 vs (4.0)	?? vs (??)	No	Minko 1976
<i>Pinus contorta</i>	Summer	4.29 vs (3.77)	99% vs (99%)	No	Sloan 1992
<i>Pinus taeda</i>	Fall	4.8 vs (4.4)	99% vs (97%)	No	Williams et al. 1988
<i>Pinus taeda</i>	Summer-fall	4.10 vs (3.83)	96% vs (94%)	No	Dierauf and Chandler 1991
<i>Pinus taeda</i>	Summer-fall	3.50 vs (3.36)	94% vs (95%)	No	Dierauf and Chandler 1991
<i>Pinus elliotii</i>	Fall-winter	3.3 vs (3.6)	94% vs (91%)	No	McNabb 1985
<i>Pinus taeda</i>	Summer	1.9 vs (1.4)	93% vs (92%)	No	Walsh 1954
<i>Pinus ponderosa</i>	Summer	?? vs (??)	92% vs (92%)	No	Sloan 1992
<i>Pinus echinata</i>	Summer-fall	?? vs (??)	89% vs (88%)	No	Chapman 1944
<i>Pinus ponderosa</i>	Summer-fall	3.3 vs (3.1)	88% vs (88%)	No	Brewster and Larsen 1925
<i>Pinus nigra</i>	Fall	?? vs (??)	84% vs (79%)	No	Kaushal and Aussenac 1989
<i>Pinus nigra</i>	Summer-fall	?? vs (??)	83% vs (67%)	?	Guehl et al. 1993
<i>Pinus elliotii</i>	Fall	?? vs (??)	81% vs (73%)	No	Personal files
<i>Pinus taeda</i>	Summer-fall	4.18 vs (3.29)	79% vs (83%)	No	Dierauf and Chandler 1991
<i>Pinus taeda</i>	Summer-fall	3.93 vs (3.84)	68% vs (69%)	No	Dierauf and Chandler 1991
<i>Pinus taeda</i>	Summer-fall	3.94 vs (4.00)	67% vs (69%)	No	Dierauf and Chandler 1991
<i>Pinus taeda</i>	Summer-fall	3.83 vs (3.68)	64% vs (70%)	No	Dierauf and Chandler 1991
			85% vs (84%)		Mean

Although some from the WILT school recommend irrigating when soil tension reaches -75 kPa (Thompson 1984), some managers of sandy soils irrigate to keep soil at or above -10 kPa during the summer (Figure 9). Although it was once a common practice, most managers no longer stop irrigating seedlings (either container or bareroot) after the fall equinox. Managers attempting to increase the outplanting performance of bareroot seedlings by withholding irrigation should establish a protocol, document soil moisture-irrigation amounts, and proceed with caution (Weatherly 2019).

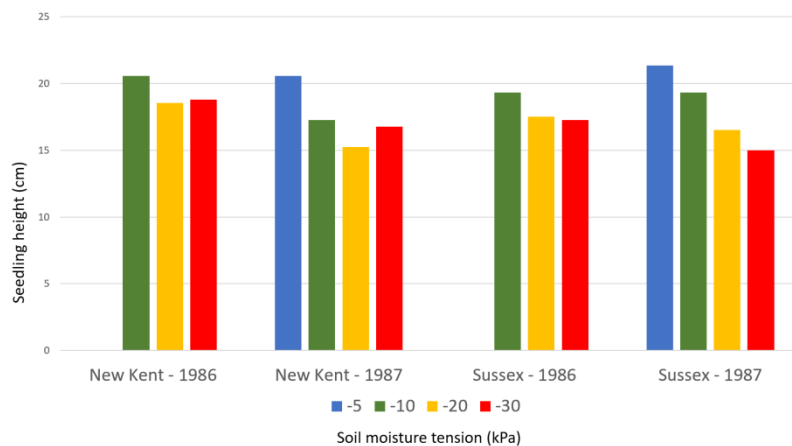


Figure 9. Irrigation treatments applied at two nurseries in Virginia over a three-year period (Dierauf and Chandler 1991). Irrigating when soil values reached -10 kPa (6 cm depth) during the summer increased height growth and reduced production of cull seedlings. In 1987, weekly irrigation rates averaged 16 mm (-5 kPa) and 4 mm (-30 kPa) at the Sussex Nursery (36°51'N, 77°10'W). All seedbeds in 1986 and 1987 were top-pruned around August 1st, August 25th and September 15th.

A target RCD of 5 mm for bareroot *Pinus taeda* seedlings is used by most growers (South et al. 2016) and a 7 mm target is used when *Pinus palustris* seedlings are grown outside in containers. Many contend that survival of pines is greater when well-balanced seedlings have larger roots (Carlson 1986; South et al. 2005; Grossnickle 2012). As a result, some organizations set 3.5 mm as the minimum RCD for container-grown pines that are sold to the public. In contrast, some researchers grow and test greenhouse-grown pines with < 3.5 mm RCD and roots smaller than 0.4 g (Seiler 1984; Timmer and Armstrong 1989; Miller and Timmer 1994; Bayley and Kietzka 1996; Hubbel 2015; Moser et al. 2015; Shi et al. 2018; Robakowski et al. 2020). It is difficult to demonstrate differences in survival when root mass is large enough and shoot height is short enough to minimize mortality after transplanting.

In July and August, many container-grown and bareroot seedlings receive more than 15 mm of rainfall and most nursery managers apply more irrigation during these months. As a result, bareroot seedbeds in some regions are wetter than -25 kPa during the summer (Stoekeler and Aamodt 1940; Retzlaff and South 1984; Dierauf and Chandler 1991). When seedlings are grown in containers under a roof, withholding irrigation can reduce RCD by 15% (Figure 10). In one trial (Atala et al. 2012), withholding 0.36 kg of water seedling⁻¹ reduced RCD by 20% (3.5 vs 4.4 mm).

Long nights and chilling (not drought) increase freeze tolerance of pine seedlings. Therefore, when container-grown pines are outplanted in October (Lavender and Cleary 1974; Ruehle et al. 1981; Pickens 2012; Luoranen and Rikala 2013; Luoranen 2018), there is no need to attempt to drought-stress seedlings in hopes the seedlings will be able to better tolerate a freeze in December. For some pines, a 4- or 5-mm RCD seedling is relatively tolerant to a -5°C freeze (Kildisheva et al. 2017). Without any hypothesis testing, simply saying something is true does not make it true.

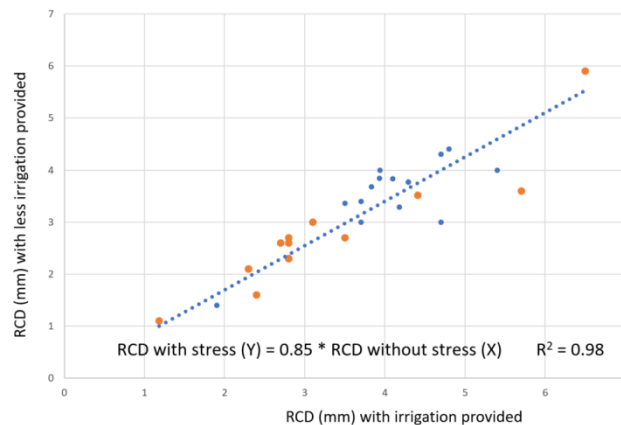


Figure 10. The effect of withholding irrigation on the average root-collar diameter (RCD) of pine seedlings (orange dot = container seedlings; blue dot = bareroot seedlings). Each dot represents one research trial with no top-pruning to control height. Eighteen trials (out of 29) produced seedlings with an average RCD of < 4.0 mm.

6.4 Root growth phase

About 3 weeks before the fall equinox, some managers begin to reduce the weekly irrigation rate as evapotranspiration decreases. In September, outside nurseries might irrigated with half the amount applied in August. Height growth slows and root growth increases (Boyer and South 1988; Brisette and Tiarks 1991; Sung et al. 1997). At some nurseries, root mass of pine seedlings will double during the last three months of the year (Figure 11). In the SUSA, about 20% of container seedlings are shipped or planted before the end of September (Starkey et al. 2015) and, although not a common practice, bareroot seedlings can be outplanted successfully in moist soil in October. Although some recommend ceasing irrigation about 6 weeks prior to first expected -3°C freeze (Engstrom and Stoeckeler 1941), for pines, chilling-photoperiod has a greater effect on freeze tolerance than does moisture stress (Shirley and Meuli 1939; Mexal et al. 1979; Menzies and Holden 1981).

Some managers use soil tensiometers to monitor soil moisture and to train staff in irrigation practices. After developing a soil moisture retention curve for each nursery field, soil moisture values can be estimated from soil tension values (Stoeckeler and Aamodt 1940; Ursic 1961; Retzlaff and South 1985). In some years, rainfall is sufficient to keep soil tension (at 10 cm depth) above -25 kPa (Stoeckeler and Aamodt 1940; Retzlaff and South 1984). Even at the 25 cm level, soil tension at some sandy nurseries will exceed -65 kPa all year long (Figure 12). Allowing the soil to periodically dry to below -40 kPa in August, September and October is done in hopes of producing more fibrous root system.

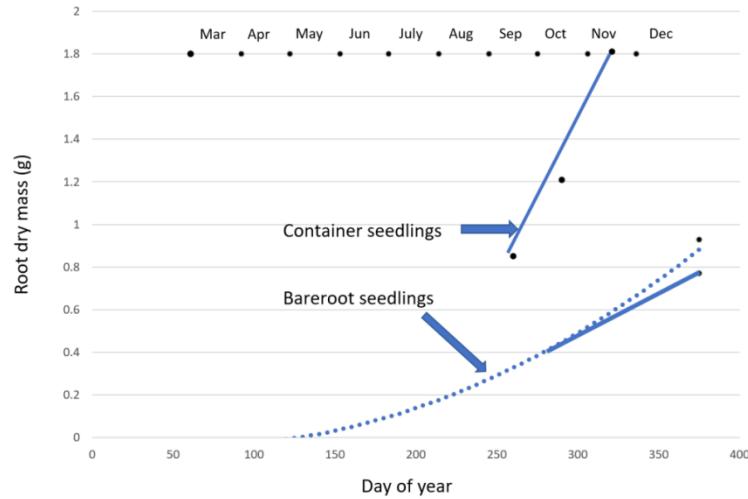


Figure 11. In some years, stopping irrigation on day 254 (September 11) will reduce root growth of bareroot *Pinus taeda* seedlings (Williams et al 1988). On day 375, root mass of irrigated seedlings was 20% greater than seedlings irrigated only once to wash fertilizer off seedlings. At some locations, *Pinus taeda* seedlings grown outside in containers (Starkey and Enebak 2016) may reach the same root biomass four months earlier than bareroot seedlings.

Soil tension at the 25 cm depth

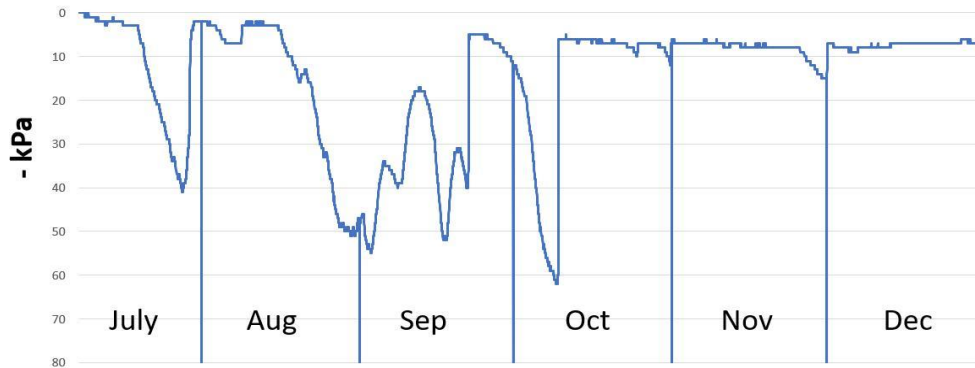


Figure 12. Many managers irrigate seedlings based on experience, feeling soil and touching seedlings. A few managers record soil moisture levels every 30 minutes at three soil levels. This graph illustrates how moist nursery soil (25 cm depth) can be after mid-October.

6.4.1 Overirrigation

For this paper, overirrigation occurs when: (1) there is a 5% reduction in one or more of the following: seed efficiency, profits, root dry mass; (2) when seedlings are culled because they were not properly top-pruned and are too tall; (3) when lenticles form on the root and lower stem; when anaerobic conditions turn roots black. Therefore, overirrigation did not occur when top-pruned seedlings received 16 mm of

irrigation week⁻¹ (Figure 9) but seedlings were overirrigated when root mass is reduced (Stoekeler and Jones 1957; p 70) or when seedlings grew too tall (Minko 1976). Without an economic analysis, simply saying overwatering occurred does not make it true.

When oxygen levels remain low for extended periods, growth of seedlings in containers is reduced (Trautmann and Iyer 1967; Heiskanen 1993; Table 11). In some cases, excessive rainfall will reduce root-growth potential and can kill seedlings once outplanted (South and Carey 1999; South and Starkey 2010). At sandy nurseries, nursery managers typically do not apply irrigation at rates and frequencies that reduce soil oxygen levels. When growing in containers containing well drain potting mix, pine seedlings grow well with five irrigations per week; 90% container capacity (Timmer and Miller 1991).

Although opinions suggest that inexperienced managers apply more irrigation than is necessary (Toumey and Korstian 1942; Cawse and Martyn 1981; Mexaland Khadduri 2011; Dumroese and Haase 2018), water-production function data supporting these views are lacking. For example, for some sandy nurseries, irrigating when soil dries to -5 kPa does not qualify as overirrigation (Figure 9). Likewise, keeping container media between -1 and -5 kPa can increase RCD (Dumroese et al. 2011) and therefore does not qualify as overirrigation. In fact, irrigating every 2 days (vs. every 5 days) might increase crop value by 4% (due to an additional 6 pine seedlings per 160 cavities).

Table 11. Too much irrigation can reduce the mass (g) of pine seedlings.

Species	Plant part	Sufficient water	Overwatered	Reduction	Reference
Containers		g	g	%	
<i>Pinus contorta</i>	Root	1.13	0.92	18	Minore 1970
<i>Pinus densiflora</i>	Shoot	0.26	0.15	42	Beon and Bartsch 2003
<i>Pinus echinata</i>	Root	13.40	11.10	17	Zak 1961
<i>Pinus elliotii</i>	Shoot	1.33	0.53	60	Pessin 1938
<i>Pinus palustris</i>	Shoot	1.90	1.26	33	Pessin 1938
<i>Pinus sylvestris</i>	Shoot	1.76	0.91	48	Heiskanen 1995
<i>Pinus sylvestris</i>	Shoot	0.14	0.10	28	Repo et al. 2016
<i>Pinus taeda</i>	Root	7.00	5.00	28	Zak 1961
Bareroot					
<i>Pinus elliotii</i>	Shoot	3.02	2.71	10	McNabb 1985
<i>Pinus elliotii</i>	Shoot	2.54	2.35	7	May et al. 1961
<i>Pinus taeda</i>	Shoot	1.55	1.15	25	Retzlaff and South 1984

6.4.2 Freeze protection

Irrigation can be used to protect pine seedlings from freeze injury (Figure 13). There are several types of freezes (McDonald 1984) and three types of freeze injury. Preacclimation injury occurs before seedlings have been exposed to a sufficient amount of chilling temperatures (<8°C and >-0.1°C) while acclimation injury occurs after pines have been acclimatized by long nights and low temperatures (South 2007). Deacclimation injury occurs when a freeze event occurs after warm weather causes a resumption of cell division (Warmund et al. 2008). Irrigation can protect seedlings

from preacclimation and deacclimation injury (Allison 1972; McDonald 1984; Rose and Haase 1996; Snyder and Melo-Abreu 2005; Landis et al. 2015) but protection is unlikely when an acclimation freeze keeps soil frozen from January 10 to February 7 (Skilling and Slayton 1970; Landis et al. 2015).



Figure 13. Irrigation was used to protect a Texas source of *Pinus taeda* seedlings during a preacclimation freeze at Magnolia, Arkansas. The high temperature was 22°C on November 10, 2019 and below freezing temperatures started on November 12 and reached a low of -8°C on November 13. The irrigation was applied continuously for 50 hours (Photo by Robert Catrett).

Bareroot nursery managers in Washington and Oregon are more likely to irrigate conifers during freezing temperatures than managers in Arizona and New Mexico. This is due, in part, to growing genotypes that are more sensitive to a -5°C freeze (Gerhold 1965) in combination with a 25% chance of a preacclimation freeze event in the more northern states (Allison 1972). For example, irrigation was used during a preacclimation freeze at the Webster Nursery at Olympia, Washington. Below freezing temperatures started on November 22, 2010 and lasted until about 10 a.m. on November 25. Starting on the morning of November 23, crews worked in shifts for 34 hours tending to sprinklers and water lines to keep them from freezing. Two shifts of workers were out in temperatures that dropped at one point to -10°C. The work continued until 1:30 a.m. November 24 when the system started to freeze. The irrigation was applied continuously for 36 hours and then the pipes were drained to reduce damage to the equipment. Freezing temperatures continued for another 30 hours. After the ice thawed, seedlings were inspected and no injury was observed (Personal communication John Trobaugh).

Preacclimation freeze can injure some container-grown seedlings that are grown outdoors (Rikala and Repo 1997; Sword et al. 1999; South 2007). Irrigation has been used to reduce freeze injury, but the approach varies with nursery manager. Some managers saturate plugs the day before the freeze while others will irrigate seedlings for 1 to 2 hours during the coldest period. Sometimes when irrigation is applied throughout a freeze event, container plugs will remain saturated for an

extended period while ice slowly melts. For this reason, various other methods can be used to reduce the need to freeze-protect container seedlings using irrigation. These methods include (1) outplanting seedlings before the first killing freeze; (2) packing and storing seedlings before December 15; (3) growing cold-sensitive species at nurseries in frost-free zones; (4) applying shade cloth (Menzies et al. 2001); and (5) moving seedlings inside greenhouses or into protected shelters. One forest company has a goal of planting all container seedlings by mid-October.

There is a low risk of injury when seeds are sown after the predicted last spring freeze. Many SUSA nurseries sow seed in mid-April to avoid windy days in March and late freezes in early April (Suckling 1986). If temperatures reach -1°C when new seedlings are in the umbrella stage, cotyledons may turn purple without any serious long-term effects. When a late freeze is predicted (e.g., April 6-10, 2007) then some managers of container nurseries irrigate cells to ensure full saturation the evening before the freeze. The size of the pumping station determines how many seedlings can be protected from a freeze (Allison 1972). As a result, most bareroot nurseries in the SUSA are unable to protect their entire crop from a preacclimation freeze.

6.4.3 Undercutting/wrenching/pruning

In southern pine nurseries, the time of undercutting with a thin horizontal blade (15 cm depth is typical) depends on seedling size, and may occur from August to October (Kainer and Duryea 1990). Undercutting does little to disturb the topsoil, while wrenching (at the same depth) lifts the soil with the intent of lowering soil bulk density (Starkey 2002). Wilting can occur when irrigation is withheld for 2 to 4 hours after undercutting (Kissee et al. 1985; Dierauf 1995) or wrenching (Venator and Mexal 1981). To avoid PWP levels reaching -1.6 MPa (Kissee et al. 1985), most managers apply irrigation soon after undercutting or wrenching.

When soil is dry, the undercutting blade can wear quickly or break, so some managers irrigate 2 to 4 hours prior to undercutting (Weatherly 2019). Likewise, irrigation for 1 to 2 hours, the day before lateral pruning a field, helps the blades to penetrate to a depth of 20 to 25 cm (Weatherly 2019).

6.4.4 Lifting

When seedbeds are too dry, irrigation is applied to assist in machine lifting of bareroot seedlings. When soil conditions are not optimal, machine lifting can reduce survival after outplanting (Greene and Danley 2001). When lifting at some nurseries, the predawn values range from -1.4 MPa to -1.8 MPa (Rose et al. 1991; McGrath and Duryea 1994). After seedlings are placed in cool storage, the PWP values might return to -0.3 MPa (Balaneves and Menzies 1990). At container nurseries, trays are irrigated to container capacity before root-plugs are placed in cool storage (Wenny and Dumroese 1987).

At time of lifting, the PWP can affect growth after seedlings are transplanted into the field. Pine seedlings under more stress than -1 MPa (mid-day) will likely grow less the first year after transplanting (Cleary and Zaerr 1980; Balneaves and Menzies 1990). Since the root growth potential (RGP) of seedlings can decline when seedlings dry out in storage, evaluating PWP of bareroot pine seedlings might be a relatively quick way to check seedling quality before outplanting (Cleary and Zaerr 1980; Tinus

1996; Vallas-Cuesta et al. 1999; Mena-Petite et al. 2001). Unless mishandling has occurred, it is rare that seedlings at reforestation sites in Canada have PWP values less than -0.5 MPa (Simpson 1986).

6.4.5 Water-production function

The relationship between nursery yield and water use is called the water-production function (WPF). WPF research is common in agronomy (Sammis and Wu 1986; Nakayama et al. 1991; NRCS 1997) but rare for bareroot nurseries that produce three-fourths of the seedlings in the USA (Haase et al. 2019). The goal of developing a WPF is to understand how irrigation rates affect seedling growth (e.g., Johnson 1960; Hatzistathis 1973; Retzlaff and South 1984), seed efficiency, plantable seedling production, profits, and outplanting survival (Williams et al. 1988; South et al. 1989; Shi et al. 2020). When a WPF predicts increasing irrigation frequency will increase RCD by 1 mm (Kildisheva et al. 2017), then crop value might increase by more than \$13,000 ha⁻¹ (Table 2). A WPF for height growth of *Pinus radiata* seedlings (Minko 1976) is: height = -62.5cm + (1397 cm x sm)-(4438 cm x sm x sm) (where sm = average soil moisture g/g). Another WPF indicates that doubling irrigation to 42 mm week⁻¹ can increase height of *Fagus* seedlings by 9 cm (Figure 14). Without WPFs, some researchers guess at how much irrigation should be applied in nurseries by estimating evapotranspiration rates (Prévost et al. 1989; Durlo et al. 2018a). Without conducting an economic analysis, they often assume that nursery managers overwater seedlings during months when rainfall exceeds estimates of potential evapotranspiration. In contrast, once the WPF is known, recommended irrigation rates might double (Foster and Coffelt 2005).

7 Survival and outplanting

On average, reducing RCD by withholding irrigation in the summer or fall does not increase survival of bareroot pine seedlings (Table 10). Even assuming Type II statistical errors, withholding irrigation may increase survival by just 1% to 6% when survival of control seedlings is less than 80% (Dierauf and Chandler 1991). Some people believe drought stressing in the nursery (which will reduce root mass) can increase mortality of seedlings outplanted in September (Lavender and Cleary 1974; Villar-Salvador et al. 2013).

Field tests with container-grown seedlings indicate that reducing RCD by stressing seedlings does not, on average, increase survival when seedlings in the field receive rain (Table 12). However, when seedlings are smaller than 3 mm, an increase in survival might occur 20% of the time. Greenhouse managers who choose to wilt small seedlings might apply 1,000 mm of irrigation (April-August) while others may apply 1,200 mm to their container trays.

Table 12. Root-collar diameter (RCD) and survival for container-grown pine seedlings exposed to two irrigation treatments. Survival tests were either conducted outside with rain or under a roof. Values in parentheses for RCD and survival represent the lower irrigation treatment. Survival results are listed in order of survival by test location (# at least a 6% difference).

Species	RCD (mm)	Survival after lifting	Survival statistically significant ($\alpha=0.05$)	Reference
Survival test outside				
<i>Pinus banksiana</i>	2.8 vs (2.3)	100% vs (100%)	No	McClain 1986
<i>Pinus cooperi</i>	2.9 vs (??)	99% vs (99%)	No	Prieto et al. 2004
<i>Pinus taeda</i>	?? vs (??)	96% vs (98%)	No	Seiler 1984
<i>Pinus halepensis</i>	2.5 vs (??)	94% vs (92%)	No	Villar-Salvador et al. 1999 (PC)
<i>Pinus tabuliformis</i>	2.7 vs (2.6)	93% vs (88%)	No	See table 4
<i>Pinus radiata</i>	3.5 vs (2.7)	92% vs (42%)#	Yes	Espinoza et al. 2020
<i>Pinus patula</i>	2.8 vs (2.6)	80% vs (81%)	No	Bayley and Kietzka 1996
<i>Pinus banksiana</i>	2.8 vs (2.3)	80% vs (79%)	No	McClain 1986
<i>Pinus patula</i>	2.8 vs (2.6)	76% vs (83%)#	No	Bayley and Kietzka 1996
<i>Pinus patula</i>	2.8 vs (2.7)	76% vs (71%)	-	Unpublished Nicky Jones
<i>Pinus nigra</i>	3.3 vs (??)	75% vs (75%)	No	Biel et al. 2004
<i>Pinus sylvestrius</i>	5.7 vs (3.6)	64% vs (71%)#	Yes?	Kulac et al. 2015
<i>Pinus patula</i>	2.8 vs (2.6)	62% vs (65%)	No	Bayley and Kietzka 1996
<i>Pinus halepensis</i>	2.3 vs (2.1)	58% vs (61%)	No	Royo et al. 2001
<i>Pinus patula</i>	3.1 vs (3.0)	36% vs (43%)#	Yes	Jones et al. 2014
<i>Pinus patula</i>	3.1 vs (3.0)	27% vs (18%)#	-	Unpublished Nicky Jones
		76% vs (74%)		Mean for outside trials
Survival test under roof				
<i>Pinus pinea</i>	?? vs (??)	100% vs (100%)	No	Villar-Salvador et al. 2013
<i>Pinus halepensis</i>	?? vs (??)	100% vs (87%)	Yes	Vallas Cuesta et al. 1999
<i>Pinus occidentalis</i>	2.4 vs (1.6)	98% vs (99%)	No	St John 2018
<i>Pinus contorta</i>	2.3 vs (2.1)	93% vs (98%)	No	van den Driessche 1991
<i>Pinus contorta</i>	2.3 vs (2.1)	92% vs (97%)	No	van den Driessche 1991
<i>Pinus contorta</i>	?? vs (??)	86% vs (92%)#	Yes	van den Driessche 1992
<i>Pinus contorta</i>	2.3 vs (2.1)	73% vs (89%)#	Yes	van den Driessche 1991
<i>Pinus pinea</i>	?? vs (??)	62% vs (67%)	No	Villar-Salvador et al. 2013
<i>Pinus pinea</i>	?? vs (??)	53% vs (33%)#	Yes	Villar-Salvador et al. 2013
<i>Pinus occidentalis</i>	2.4 vs (1.6)	36% vs (64%)#	No	St John 2018
		77% vs (76%)		Mean for under roof trials

8 Decline effect

“Many scientifically discovered effects published in the literature seem to diminish with time” (Schooler 2011). When studies are repeated, the magnitude of the treatment response may be less than expected, based on the initial published results. The “decline effect” was discovered in research into parapsychology but the phenomenon also occurs in biology. For example, South (1998) reported on 30 top-pruning studies installed from 1949 to 1979. As it turned out, the initial 1949 study reported a 55% increase in survival, while none of the subsequent studies reported an increase of 37% or more. This phenomenon also exists with irrigation research.

Lavender and Cleary (1974) assumed a 75% increase in survival if properly hardened bareroot seedlings were planted on a moderate site in February. However, subsequent studies have detected no significant increase in survival (Table 10). Likewise, Rook (1973) was perhaps the first to test the effect of irrigation rate on RGP of greenhouse-grown stock. His study suggested RGP (on day 18) was increased 300% by withholding irrigation. Thus far, subsequent irrigation studies have not duplicated that level of response in either absolute or relative terms (Figure 15).

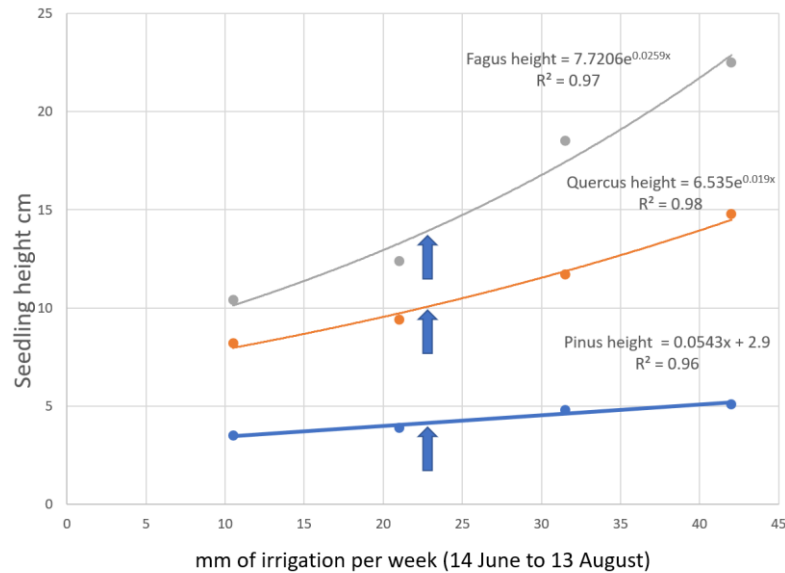


Figure 14. Three water-production functions for greenhouse-grown seedlings growing in 430 ml containers (Robakowski 2020). Seedlings were grown under controlled conditions in an unheated tunnel at the Rogoziniec Forest Nursery in Poland (52°18'N 15°46'E). Seeds of *Pinus sylvestris*, *Quercus petraea* and *Fagus sylvatica* were sown in late May and irrigation was applied from 14 June to 13 August. The blue arrows indicate the approximate height of seedlings assuming a hypothetical irrigation rate equal to the open-pan evaporation (Bogawski and Bednorz 2014). When growing container seedlings in a greenhouse, some researchers say that 25 to 45 mm week⁻¹ is overirrigation.

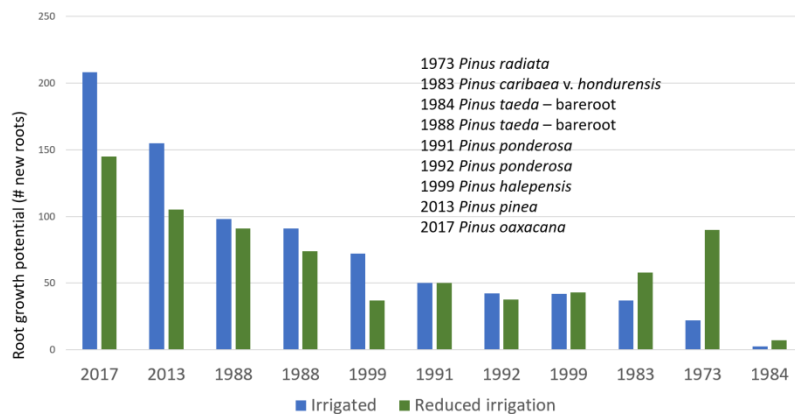


Figure 15. Reducing irrigation decreased ($\alpha = 0.05$) RGP in three trials (1999, 2013, 2017) and increased RGP in three trials (1973, 1983, 1984). Studies listed are: Rook (1973), Abod and Sandi (1983), Hennessey and Dougherty (1984), Williams et al. (1988), van den Driessche (1991), van den Driessche (1992), Vallas-Cuesta et al. (1999), Villar-Salvador (1999), Villar-Salvador (2013), Ávila-Angulo et al. (2017). Values were estimated for 1991 and 1992 as treatment means were not published.

9 Terminology

Poor terminology is often used to describe irrigation regimes. The term “mild drought stress” is meaningless without supporting data. In one case, authors said “mild” water stress treatment showed a 15% increase in diameter growth (Tran et al. 2018). Other subjective terms [*adequate, as needed, better, frequently, growing season, hardening fertilizer, misted, overirrigated, proper irrigation, sparingly, standard, sufficiently dormant, well defined*] are not useful to those seeking to replicate the trial. In one paper, outplanting meant transplanting seedlings in a ventilated greenhouse (Timmer and Miller 1991). Typically, precise terms like “600 mm of irrigation” are omitted in favor of vague words like “medium irrigation”. Due to failure to document irrigation totals and seedling densities, a number of peer-reviewed papers were not listed in Table 5.

Some recommend hardwood seedlings be watered (irrigation+rainfall) with twice the amount used for pine seedlings (Davey and McNabb 2019), but what does this terminology really mean? When pines (200 m²) and hardwoods (100 m²), are provided with 600 mm of irrigation plus 400 mm of rain in a bareroot nursery, then each hardwood seedling receives 10 kg of water, which is indeed twice the amount for pines. But which species grew larger? In one study, hardwoods outgrew pines when both were irrigated at similar rates (Figure 14). To date, there are no scientific data to show the amount of water (kg) needed to produce a 10-g *Quercus* seedling is twice the amount needed to produce of a 10-g pine seedling. In general, the amount of irrigation research conducted in container nurseries is far greater than in bareroot nurseries.

10 Conclusions

- (1) Some greenhouse and outdoor nursery managers document how much irrigation water (kg seedling⁻¹) they apply to pine seedlings.
- (2) When *Pinus taeda* seedlings in the SUSA are outplanted in early October (with the root-collar planted 10 cm below the soil surface), there is no need to drought stress seedlings to increase tolerance to a late -5°C October freeze.
- (3) For *Pinus taeda*, the amount of irrigation currently applied per rain-free week in the summer is about twice that applied during the middle of the 20th century.
- (4) Although several authors believe it is true, so far data do not suggest drought stressing bareroot pine seedlings in the nursery increases survival ($\alpha = 0.05$) in reforestation sites.
- (5) Temporarily withholding irrigation in greenhouses can reduce seedling RCD and, unless seedlings have been overwatered, reducing irrigation does not increase the average RCD of pine seedlings.
- (6) Cavitation decreases the hydraulic conductance of pine stems, and too much can reduce seedling survival and growth.
- (7) Using open-pan evaporation to limit the amount of irrigation (i.e., irrigation is not greater than open-pan evaporation) for container-grown pines will result in reduced growth in a rain-free greenhouse.
- (8) Some researchers do not realize that withholding irrigation in nurseries can reduce nursery profits.
- (9) When Type II statistical errors exist, some researchers recommend reducing the total amount of irrigation.

11 Recommendations for researchers

- (1) Develop water-production functions for pine nurseries (i.e., seedling dry mass = $x + a \times \text{kg H}_2\text{O seedling}^{-1}$).
- (2) Record and report irrigation amounts (kg m^{-2}) and rainfall amounts by month; 1 kg m^{-2} is equivalent to 1 mm of rain.
- (3) Record initial seed spacing ($\#\text{m}^{-2}$), plantable seedling density ($\#\text{m}^{-2}$), and cull seedling density ($\#\text{m}^{-2}$) for each nursery treatment.
- (4) Publish this information even when experimental treatments do not involve irrigation.
- (5) Since most nursery trials have low statistical power (i.e., Type II errors are common), publish all variable means regardless of P-values.
- (6) Publish tables and graphs that “stand alone” (do not require returning to methods section to decode unnecessary abbreviations).
- (7) Instead of guessing at how treatments might affect reforestation efficiency, researchers should evaluate seedling performance by outplanting seedlings (either outside or outside under a rain shelter).
- (8) Grow plantable seedlings first, and then, if you have to, apply stress treatments.
- (9) Do not use vague and misleading terminology, and do not make recommendations based on results from outplanting cull seedlings. Do not assume the frequency of fertilization has no effect on seedling growth or the total amount of nitrogen applied per seedling.
- (10) Do not use relative growth rates in order to hide absolute growth values from readers.
- (11) Do not use pseudo-replication and do not confound treatments with tree planter.
- (12) Do not make recommendations to experienced nursery managers when you have no supporting data.
- (13) For irrigation trials, do not use the term “seedlings” to describe stem cuttings, fascicle cuttings, explants, emblings, stecklings, or ramets.
- (14) Be skeptical. Be aware of the “decline effect.” Do not believe irrigation myths are true.

12 Acknowledgments

The authors thank members of the Southern Forest Nursery Management Cooperative and various nursery managers for providing feedback on operational use of irrigation. We thank Wenhui Shi for providing data for table 4 and Tom Jopson for data for figure 8. We thank Eric Hinesley, John Mexal and Sarah White for reviews of earlier drafts of this manuscript. Thanks to Jol Hodgson, Alex Steepe, Robert Catrett, John Trobaugh, Tom Jopson, Steve Grossnickle, Mike Coyle, Tom Starkey, Wenhui Shi, Joshua Bennicoff, Pedro Villar-Salvador, and Tom Stevens for providing comments or photographs.

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