The Container Tree Nursery Manual

Volume Three
Atmospheric Environment

Chapter 2
Humidity

Contents

3.2.1 Introduction

Maintaining the proper atmospheric humidity in container tree nurseries is important biologically for several reasons: low humidity subjects seedlings to water stress caused by excessive transpiration, proper humidity promotes rapid growth, and excessive humidity promotes the growth of fungal pathogens and other nursery pests such as moss and liverworts. The challenge to the nursery manager is to maintain humidities that are high enough for good seedling growth without encouraging pests (fig. 3.2.1). This chapter introduces the basic concepts of humidity, discusses the ways in which humidity affects seedling growth, and presents optimum levels for container tree nurseries. Cultural methods for modifying humidity and equipment for monitoring humidity levels are also included.

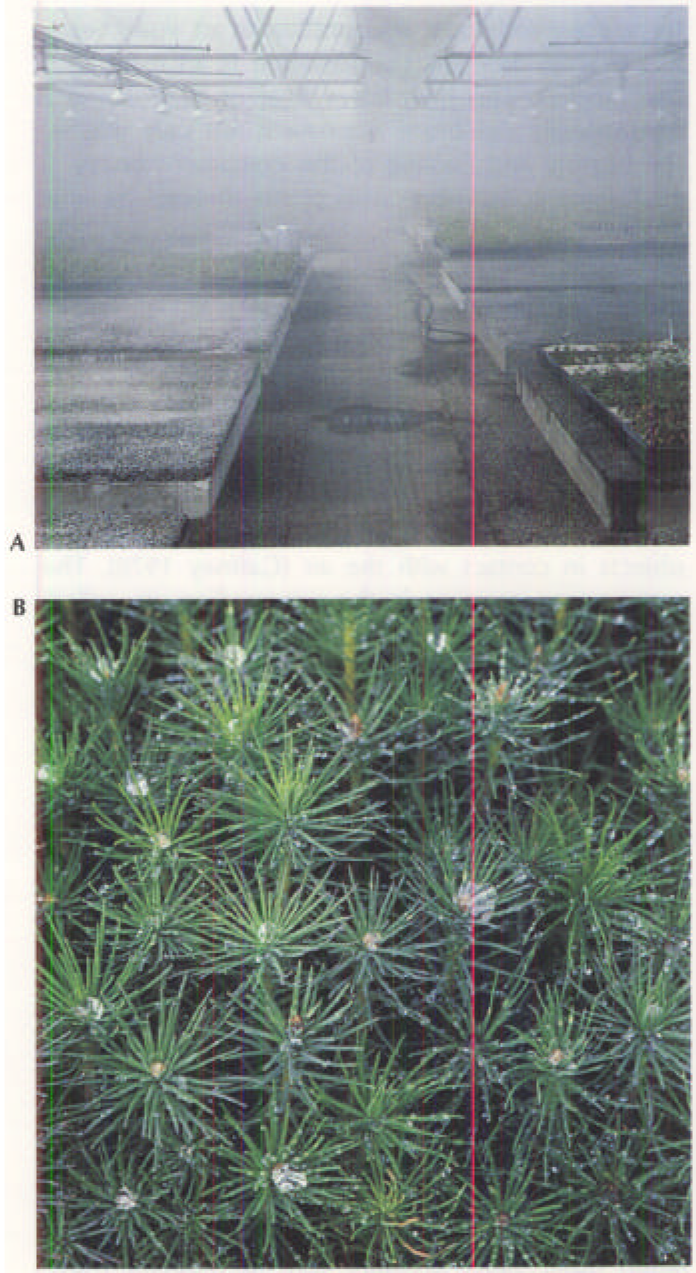


Figure 3.2.1—*Although water vapor is an invisible gas, it can be managed to minimize transpiration, as in this rooting chamber* (**A**), *or if it is mismanaged and allowed to condense on seedling foliage* (**B**), *it can promote disease.*

3.2.1.1 Biophysics of water vapor

In the container nursery environment, water exists in two of its three physical states-invisible water vapor (gas) and liquid. Water vapor is subject to the same physical laws as th e other gases that compose the air, such as nitrogen and oxygen. Moist air can be defined as a two-component mixture of dry air and water vapor. The air and the water vapor simultaneously occupy the same space, but the water vapor acts independently of the other gases. Therefore, the partial pressure of water vapor is solely a function of temperature and is unrelated to the total atmospheric pressure (Gaffney 1978). Air always contains some water vapor, but at any given temperature, it can hold only a finite amount. When this physical limit is reached, the air is **saturated,** and when it is exceeded, condensation occurs.

Water has several unique physical properties that affect the container nursery environment, including the highest known latent heat of evaporation. An extremely large amount of thermal energy (540 cal/g) is required to take liquid water through the phase change from liquid to gas. This is considerably more than the energy required (316 cal/g) to bring 1 g of ice at absolute zero, -273 °C (-460 °F), to the boiling point (Hewitt 1974). The same amount of thermal energy that is used when water evaporates is released when water vapor condenses: **evaporation** is an endothermic process whereas **condensation** is an exothermic process. This high latent heat of evaporation is operationally significant because it not only affects the heating and cooling of the container nursery environment, but also cools plants through transpiration.

3.2.1.2 Definitions and units

Water vapor pressure. The water vapor in a given volume of air exerts a partial pressure (e) that depends on the amount of the water vapor and its temperature. It is useful to think of humidity in terms of a pressure or force that is capable of causing the movement of water vapor to and from objects in contact with the air (Gaffney 1978). The water vapor pressure in the surrounding air, called the **ambient water vapor pressure** (e_a), varies from near zero in cold dry air to over about 8 kPa (0.08 atmospheres) in warm moist air (table 3.2.1). If the ambient vapor pressure is less than the **equilibrium vapor pressure** of liquid water, evaporation occurs. When the atmosphere becomes saturated with water vapor, the **saturation water vapor pressure** (e_s) becomes identical with the vapor pressure of water and net evaporation ceases.

The higher the temperature, the higher the equilibrium water vapor pressure and, in the range of common nursery temperatures, saturation water vapor pressure approximately doubles for each 11 °C (20 °F) increase in temperature (table 3.2.1).

Water vapor pressure deficit. Another important humidity concept is vapor pressure deficit (VPD), which is equal to the difference between the saturation water vapor pressure and the ambient water vapor pressure at the same temperature:

$$VPD = e_s - e_a$$

The VPD is important in horticulture because it represents the evapotranspirational demand of the surrounding atmosphere, as well as the proximity to the **dew point** (when $e_a = e_s$). Therefore, growers can use the VPD to determine whether to irrigate because seedling transpiration will be high or ventilate to avoid condensation.

Table 3.2.1—*Relationship between dew point temperature, saturation vapor pressure, and absolute humidity*

Dew point		Saturation water vapor pressure	Absolute humidity
°C	°F	(kPa)	(mg/l)
−40	−40	0.01	0.2
−35	−31	0.02	0.3
−30	−22	0.04	0.5
−25	−13	0.06	0.7
−20	− 4	0.10	1.1
−15	5	0.16	1.6
−10	14	0.26	2.4
− 5	23	0.40	3.5
0	32	0.60	4.8
5	41	0.86	6.8
10	50	1.21	9.4
15	59	1.68	12.6
20	68	2.31	17.3
25	77	3.13	23.1
30	86	4.19	30.4
35	95	5.42	39.8
40	104	7.28	51.8

Source: Schroeder and Buck (1970).

Water vapor pressure and vapor pressure deficit are expressed in standard pressure units (table 3.2.2). The metric units are pascals (Pa), kilopascals (kPa), and megapascals (MPa), whereas the English units are atmospheres (atm). Older units include bars (b), inches or millimeters of mercury (in. Hg or mm Hg), and pounds per square inch (lb/in^2).

Absolute humidity. The actual amount of water vapor in a given volume of air is the absolute humidity; it is expressed as weight per volume. A direct relationship exists between the dew point, the saturation water vapor pressure, and the absolute humidity because each depends only on the actual amount of water in the air at a given atmospheric pressure (table 3.2.1). Absolute humidity is rarely measured in container tree nurseries, however, and relative humidity is used instead.

Table 3.2.2—*Units used to measure vapor pressure and humidity and their metric and English conversions*

Units	
Metric units	English units
pascals (Pa)	atmospheres (atm)
kilopascals (kPa)	pounds per square inch (psi)
megapascals (MPa)	inches of mercury (in. Hg)
bars (b)	
millimeters of mercury (mm Hg)	
Conversion factors	
Metric to metric	English to English
1 kPa = 10^3 Pa	1 atm = 14.6960 psi
1 MPa = 10^6 Pa	1 atm = 29.921 in. Hg
1 MPa = 10 b	
1 MPa = 7500.62 mm Hg	
Metric to English	English to metric
1 MPa = 9.8962 atm	1 atm = 0.1013 MPa
1 MPa = 145.04 psi	1 atm = 1.0133 b
1 MPa = 295.30 in. Hg	1 atm = 760.0 mm Hg

Source: ASHRAE (1989)

Relative humidity. The most common descriptor of humidity, relative humidity (RH), is also the most practical measurement in container tree nurseries. RH can be defined as the ratio of the amount of moisture in a volume of air to the total amount of moisture that can be held at saturation at a given temperature and atmospheric pressure, and is expressed as a percentage. To compute RH, the ambient water vapor pressure is divided by the saturation water vapor pressure:

$$RH\ (\%) = \frac{e_a}{E_s} \times 100$$

Because both RH and VPD are related to temperature, these humidity indexes can be obtained from handy reference charts when two of the three values are known (table 3.2.3).

Table 3.2.3—*The evapotranspirational demand, as measured by the water vapor pressure deficit, is a function of relative humidity and temperature*

Air temp.		Water vapor pressure deficit (kPa)										
°C	°F	0% RH	10% RH	20% RH	30% RH	40% RH	50% RH	60% RH	70% RH	80% RH	90% RH	100% RH
0	32	0.61	0.55	0.49	0.43	0.37	0.31	0.24	0.18	0.12	0.06	0
5	41	0.87	0.78	0.70	0.61	0.52	0.44	0.35	0.26	0.17	0.09	0
10	50	1.23	1.11	0.98	0.86	0.74	0.62	0.49	0.37	0.25	0.12	0
15	59	1.71	1.54	1.37	1.20	1.03	0.86	0.68	0.51	0.34	0.17	0
20	68	2.33	2.10	1.86	1.63	1.40	1.17	0.93	0.70	0.47	0.23	0
25	77	3.17	2.85	2.54	2.22	1.90	1.59	1.27	0.95	0.63	0.32	0
30	86	4.24	3.82	3.39	2.97	2.54	2.12	1.70	1.27	0.85	0.42	0
35	95	5.63	5.07	4.50	3.94	3.38	2.82	2.25	1.69	1.13	0.56	0
40	104	7.37	6.63	5.90	5.16	4.42	3.69	2.95	2.21	1.47	0.74	0

The vapor pressure deficit should be maintained below the 1.0 kPa line to keep water stress within acceptable limits.

Growers routinely measure RH with psychrometers and hygrothermographs and use this information to control humidity in their growing structures. A **psychrometer** contains two identical thermometers—one that measures the ambient temperature **(dry-bulb temperature)** and another that measures the lowered temperature caused by evaporative cooling **(wet-bulb temperature).** The difference between the two temperatures is the **wet-bulb depression.** The wet and dry-bulb temperatures are used to compute the relative humidity and dew point from psychrometric charts (fig. 3.2.2) or tables (table 3.2.4). The wet-bulb depression is a handy measurement that can be used for several purposes in a greenhouse operation, such as showing the theoretical efficiency of evaporative cooling pads (Hanan and other 1978). (More information on measuring humidity can be found in section 3.2.5.)

Dew point temperature. Saturation occurs when the air is cooled to the point that the saturation vapor pressure exceeds the ambient vapor pressure and condensation occurs-the temperature at which this occurs is called the **dew point.** The practical significance of the dew point is that it is directly related to the amount of water vapor in a volume of moist air (Gaffney 1978). The dew point temperature has direct application to container nursery management because of its relationship to condensation, which occurs when humid air comes in contact with a cooler surface such as the inside of the greenhouse covering or a leaf. Growers manage humidity in their nurseries to minimize condensation, which can cause disease problems.

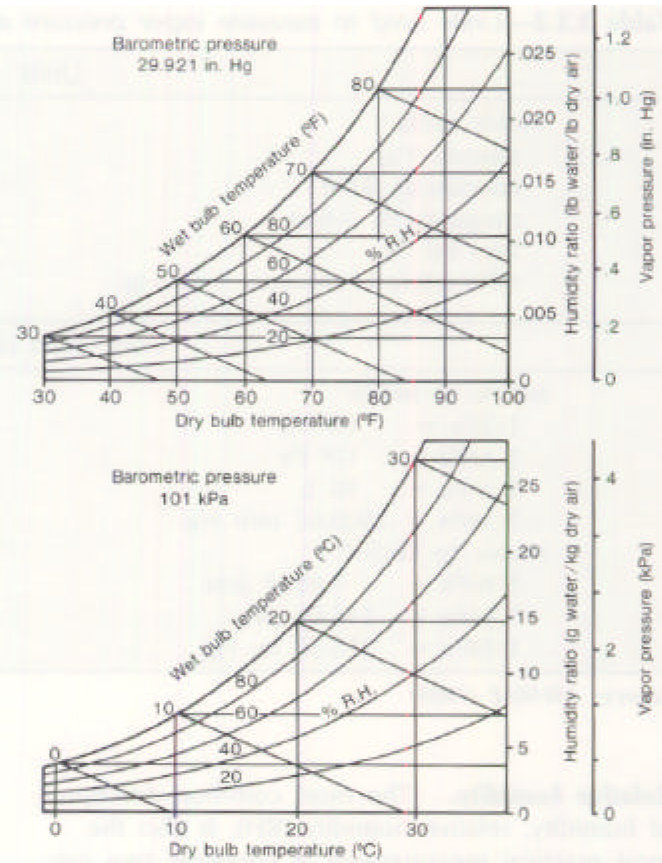


Figure 3.2.2—*A psychrometric chart is a graphical representation of the many functional relationships that exist between the various thermal and physical properties of moist air. When the wet-bulb and dry-bulb temperatures are measured with a psychrometer, these charts can be used to estimate relative humidity. (Modified from Gaffney 1978.)*

Table 3.2.4A—*Relative humidity (%) can be calculated from psychrometric charts, using the wet bulb and dry bulb temperatures from a psychrometer*

Dry-bulb temperatures °C	°F	Wet-bulb temperatures °C / °F	4	6	7	8	9	10	11	12	13	14	16	17	18	19	20	21	22	23	24	26	27	28	29	30	31	32
		°F	40	42	44	46	48	50	52	54	56	58	60	62	64	66	68	70	72	74	76	78	80	82	84	86	88	90
17	62		2	10	17	25	33	42	50	60	69	79	89	100	—	—	—	—	—	—	—	—	—	—	—	—	—	—
18	64		—	5	12	20	27	35	43	52	61	70	80	90	100	—	—	—	—	—	—	—	—	—	—	—	—	—
19	66		—	2	8	15	22	30	37	45	53	62	71	80	90	100	—	—	—	—	—	—	—	—	—	—	—	—
20	68		—	—	5	11	18	24	32	39	47	55	63	72	81	90	100	—	—	—	—	—	—	—	—	—	—	—
21	70		—	—	1	7	14	20	27	34	41	48	56	64	72	81	90	100	—	—	—	—	—	—	—	—	—	—
22	72		—	—	—	4	10	16	22	28	35	42	50	57	65	73	82	91	100	—	—	—	—	—	—	—	—	—
23	74		—	—	—	1	7	12	18	24	30	37	44	51	58	66	74	82	91	100	—	—	—	—	—	—	—	—
24	76		—	—	—	—	4	9	15	20	26	32	39	45	52	59	67	75	83	91	100	—	—	—	—	—	—	—
26	78		—	—	—	—	1	6	11	17	22	28	34	40	46	53	60	67	75	83	91	100	—	—	—	—	—	—
27	80		—	—	—	—	—	4	9	14	19	24	30	35	41	48	54	61	68	76	83	92	100	—	—	—	—	—
28	82		—	—	—	—	—	2	6	10	16	21	26	31	37	43	49	55	62	69	76	84	92	100	—	—	—	—
29	84		—	—	—	—	—	—	4	8	13	17	22	27	33	38	44	50	56	63	70	77	84	92	100	—	—	—
30	86		—	—	—	—	—	—	2	6	10	15	19	24	29	34	40	45	51	57	64	70	77	84	92	100	—	—
31	88		—	—	—	—	—	—	—	4	8	12	16	21	26	30	35	41	46	52	58	64	71	78	85	92	100	—
32	90		—	—	—	—	—	—	—	2	6	10	14	18	22	27	32	37	42	47	53	59	65	71	78	85	92	100

Table 3.2.4B—*Dew point temperatures can be calculated from psychrometric charts, using the wet-bulb and dry-bulb temperatures from a psychrometer*

Dry-bulb temperature °C / °F	Wet-bulb temperatures °C / °F	4	6	7	8	9	10	11	12	13	14	16	17	18	19	20	21	22	23	24	26	27	28	29	30	31	32
	°F	40	42	44	46	48	50	52	54	56	58	60	62	64	66	68	70	72	74	76	78	80	82	84	86	88	90
17		-31	-16	-8	-3	0	3	6	9	11	12	15	17	—	—	—	—	—	—	—	—	—	—	—	—	—	—
62		-23	4	17	26	33	38	43	48	52	55	59	62	—	—	—	—	—	—	—	—	—	—	—	—	—	—
18		—	-21	-12	-6	-1	2	5	8	10	12	14	16	18	—	—	—	—	—	—	—	—	—	—	—	—	—
64		—	-7	11	22	30	36	41	46	50	54	58	61	64	—	—	—	—	—	—	—	—	—	—	—	—	—
19		—	-33	-16	-9	-3	1	3	7	9	11	13	16	17	19	—	—	—	—	—	—	—	—	—	—	—	—
66		—	-28	4	17	26	33	39	44	49	53	56	60	63	66	—	—	—	—	—	—	—	—	—	—	—	—
20		—	—	-21	-11	-6	-1	2	6	8	10	12	15	17	18	20	—	—	—	—	—	—	—	—	—	—	—
68		—	—	-7	12	22	30	37	42	47	51	55	59	62	65	68	—	—	—	—	—	—	—	—	—	—	—
21		—	—	-33	-16	-8	-3	1	4	7	10	12	13	16	18	19	21	—	—	—	—	—	—	—	—	—	—
70		—	—	-29	4	18	27	34	40	45	50	54	57	61	64	67	70	—	—	—	—	—	—	—	—	—	—
22		—	—	—	-21	-11	-5	0	3	6	9	11	13	16	17	19	20	22	—	—	—	—	—	—	—	—	—
72		—	—	—	-6	12	23	31	38	43	48	52	56	60	63	66	69	72	—	—	—	—	—	—	—	—	—
23		—	—	—	-33	-15	-8	-2	1	5	8	10	12	14	17	19	20	22	23	—	—	—	—	—	—	—	—
74		—	—	—	-27	5	19	28	35	41	46	51	55	58	62	65	68	71	74	—	—	—	—	—	—	—	—
24		—	—	—	—	-20	-10	-4	0	3	7	10	12	14	16	18	20	21	22	24	—	—	—	—	—	—	—
76		—	—	—	—	-5	14	24	32	39	44	49	53	57	61	64	67	70	73	76	—	—	—	—	—	—	—
26		—	—	—	—	-30	-14	-7	-2	2	6	9	11	13	16	18	19	21	22	23	26	—	—	—	—	—	—
78		—	—	—	—	-23	7	20	29	36	42	47	52	56	60	63	66	69	72	75	78	—	—	—	—	—	—
27		—	—	—	—	—	-19	-9	-3	1	4	7	10	12	14	17	19	21	22	23	25	27	—	—	—	—	—
80		—	—	—	—	—	-2	15	26	34	40	45	50	54	58	62	65	69	72	75	77	80	—	—	—	—	—
28		—	—	—	—	—	-28	-12	-6	0	3	7	10	12	14	16	18	20	22	23	25	26	28	—	—	—	—
82		—	—	—	—	—	-18	9	22	31	38	44	49	53	57	61	64	68	71	74	77	79	82	—	—	—	—
29		—	—	—	—	—	—	-17	-9	-2	2	5	8	11	13	16	17	19	21	22	24	26	27	29	—	—	—
84		—	—	—	—	—	—	1	17	27	35	41	47	52	56	60	63	67	70	73	76	79	81	84	—	—	—
30		—	—	—	—	—	—	-24	-12	-4	0	3	8	10	12	15	17	19	20	22	23	26	27	28	30	—	—
86		—	—	—	—	—	—	-12	11	24	32	39	45	50	54	59	62	66	69	72	75	78	81	83	86	—	—
31		—	—	—	—	—	—	—	-16	-8	-2	2	6	9	11	13	16	19	20	21	23	25	27	28	29	31	—
88		—	—	—	—	—	—	—	4	19	29	37	43	48	53	57	61	65	68	71	74	77	80	83	85	88	—
32		—	—	—	—	—	—	—	-21	-10	-3	1	5	8	11	13	16	18	19	21	23	25	26	28	29	30	32
90		—	—	—	—	—	—	—	-7	14	26	34	41	47	52	56	60	64	67	71	74	77	79	82	85	87	90

3.2.2 Role of Humidity in Tree Seedling Growth and Development

Atmospheric humidity can affect container tree seedlings directly through its effects on seedling water relations. Controlling humidity is even more critical when plants are being propagated vegetatively by cuttings or grafting. There is also an indirect effect of humidity: many nursery pests thrive in the high-humidity environment that often exists in greenhouses.

3.2.2.1 Seedling growth

Humidity principally affects evapotranspiration rates. Under still conditions, the rate of evaporation from a wet surface is a function of the relative humidity and temperature and is proportional to the vapor pressure deficit. At a constant temperature, the higher the relative humidity, the lower the vapor pressure deficit (table 3.2.3). Under operational conditions, increasing temperature is more of a controlling factor than humidity in determining evapotranspirational demand. For example, when the RH of the air decreases 30% (from 80 to 50%) and the temperature stays at 30 °C (86 °F), the VPD increases 2.5 times; however, if the absolute humidity remains constant and the leaf temperature increases just 10 °C, from 10 to 20 °C (50 to 68 °F), then the VPD increases over 5 times (Kramer 1983).

Under calm conditions, water vapor collects near an evaporating surface, forming a **boundary layer.** If the humidity in the boundary layer approaches saturation, the evaporation rate will almost cease, even though the surrounding air is much drier. Wind removes the boundary layer and replaces it with drier air, thus increasing the evaporation rate (Schroeder and Buck 1970). For example, if the air in the boundary layer was 20 °C (68 °F) with 90% RH, and it was replaced by air at the same temperature and 60% RH, the VPD would increase over fourfold, from 0.23 to 0.93 kPa (table 3.2.3).

Container tree seedlings develop significant boundary layers (fig. 3.2.3) that can significantly lower the evapotranspiration rate in the dense seedling canopy in the typical aggregated containers of a forest tree nursery. Boundary layers are particularly significant in the sheltered environment of an enclosed growing structure where air movement is restricted.

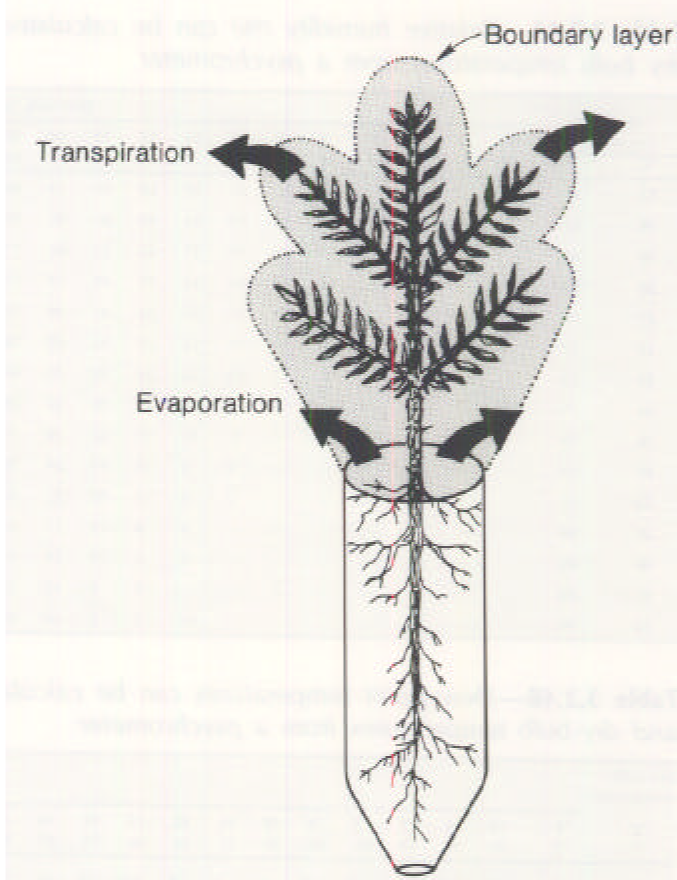


Figure 3.2.3—*Container tree seedlings develop a humid boundary layer within their crowns that restricts evapotranspiration, especially when they are grown in aggregated containers.*

Plants absorb water through their roots from the growing medium and lose it through their leaves into the air through a process called **transpiration,** which is essentially bioregulated evaporation. Although excessive transpirational losses can result in damaging moisture stress, a small amount of transpiration is necessary to move mineral nutrients in the xylem sap from the roots to the leaves (Kramer and Kozlowski 1979). Some transpiration usually occurs as long as water is available to the roots. In intense light, leaves will absorb enough radiant energy to cause a transpirational gradient from the leaf to the air, even at high humidities.

Most of the transpirational water loss occurs through the stomata on the leaves, which must also remain open long enough to absorb sufficient carbon dioxide (C02) for photosynthesis (fig. 3.1.2). Although stomata occupy only about 1 % of the leaf surface area, transpiration rates can approach 50% of the evaporation rate from a free water surface (Kramer and Kozlowski 1979). Stomata remain open as long as their turgor pressure remains high and light levels remain adequate. However, if the rate of water loss exceeds the rate of water uptake, internal moisture stress builds up. If the stress becomes severe, metabolic processes such as photosynthesis are adversely affected. When the moisture stress reaches a critical level, the stomata begin to close and net photosynthesis decreases. With further increase in moisture stress, stomata close further and eventually photosynthesis stops. This series of events may occur regularly on sunny days in many species, even when the seedlings are well watered, because the roots cannot absorb water as fast as the leaves can lose it. For maximum growth, the stomata must remain open as long as possible, and so growers can promote growth by maintaining relatively high humidities in the growing area (fig. 3.2.4). (A more detailed discussion of seedling water relations can be found in volume four of this series.)

A moderate transpiration rate is also beneficial because it cools the leaf and keeps it near the optimum temperature for photosynthesis and other metabolic processes (Clawson and others 1989). Other seedling growth processes, such as cell enlargement, also depend on positive turgor pressure.

3.2.2.2 Vegetative propagation

Although most forest tree seedlings are currently produced from seed, many nurseries also practice some form of vegetative propagation. Tree improvement stock, in particular, is often propagated vegetatively so that the desired genotypes can be maintained. Seed orchard stock is propagated by cuttings or grafting, and genetic test stock can often be produced easier and cheaper with cuttings. Many species that are used for forestry or conservation purposes, such as poplars and willows, are propagated vegetatively.

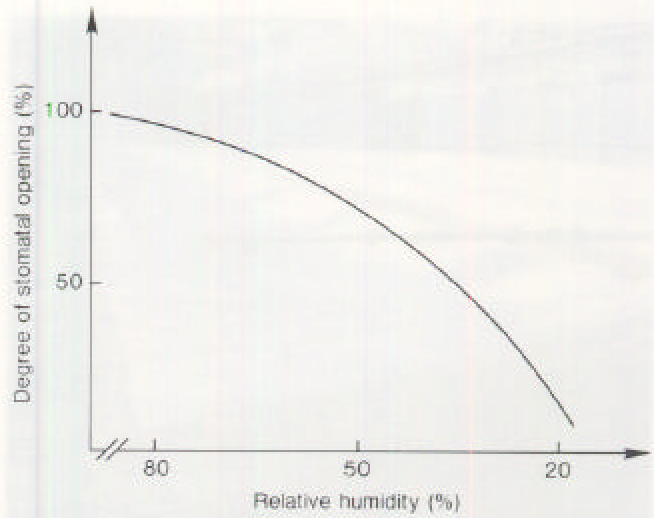


Figure 3.2.4—*Transpiration rate is directly related to the size of the stomatal aperature, which is regulated by guard cells that respond to atmospheric humidity and other environmental stimuli (modified from Jarvis 1980).*

Maintenance of the proper humidity is of particular concern in vegetative propagation. The transpiration rate of cuttings must be kept low for several weeks or even months so that they can maintain enough turgor to produce new roots. Grafted seedlings are often kept under greenhouse conditions because the high humidities reduce the moisture stress on grafted scions (Hartmann and Kester 1983). Special rooting environments are constructed to maintain these higher humidities (fig. 3.2.5).

3.2.2.3 Managing pathogens

It would seem that very high humidities would be desirable in container tree nurseries, but this is not always the case. Nursery pests such as pathogenic fungi, moss, and liverworts are stimulated by high humidities, especially if there is free water present. Cryptogams (moss, algae, and liverworts) thrive in the container nursery environment and can completely cover the top of the container and interfere with seedling growth. In extreme cases, these pests can form a thick plug that completely prevents the infiltration of water and liquid fertilizers (fig. 3.2.6A). Even some insect pests can be related to high humidity environments. Dark-winged fungus gnats can build up damaging populations in greenhouses that have excessive amounts of moss and algae.

Figure 3.2.5—*Some species that are grown for forestry or conservation purposes are most easily propagated by rooting cuttings in specially equipped rooting chambers that maintain a high level of humidity to retard transpiration.*

A

B

Figure 3.2.6—*Prolonged periods of high humidity can cause pest problems, such as excessive growth of algae, moss, or liverworts, which can effectively plug the container opening* (**A**). *Spores of fungal pathogens such as* Botrytis cinerea *require free moisture before they can germinate and cause an infection.* (**B**, *courtesy of F. Dugan.*)

Although most fungi thrive under high humidity, certain plant pathogens particularly favor this environment; the fungal pathogen that causes grey mold is a notable example. The spores of *Botrytis cinerea* require free moisture to germinate and penetrate seedling foliage (fig. 3.2.6B), and high humidities are conducive to the subsequent spread of the fungus. In fact, only 3 hours at temperatures of 15 to 20 °C (59 to 68 °F) and 98% RH promote infection if there is free moisture present. Peterson and others (1988) consider RH values over 90% to be ideal for the germination of *B. cinerea* spores and found that RH within the canopy of Douglas-fir seedlings typically exceeded this threshold at night. Grey mold becomes serious in the fall when cooler temperatures cause moisture to condense on seedling foliage, especially in overly dense seedling canopies. The percentage of time when the RH exceeded 90% in a fiberglass greenhouse increased from 59% in August to 85% in October. (Nursery pests are discussed in detail in volume five of this series.)

3.2.3 Optimum Humidity Levels

It is extremely difficult to set ideal humidity levels for container tree nurseries because relative humidity varies so much with temperature. Optimum humidity levels will change during the growing season for seedlings and will differ for seedlings and cuttings.

3.2.3.1 Seedlings

There have been few controlled experiments to determine optimum humidity levels for plant growth. In one growth-chamber experiment with temperatures of 18 to 24 °C (65 to 75 °F), Krizek and others (1971) showed that 40% RH severely reduced the growth of seedlings of three species of garden flowers (ageratum, petunia, and marigold). Raising the RH to 65% resulted in striking increases in fresh weight, dry weight, leaf area, and height; increasing the RH to 90% produced no further benefits. Similar responses have been reported for loblolly pine (Seiler and Johnson 1984) and cucumber plants (van de Sanden 1985). Besides these few examples, research on the effects of humidity on plant growth is not extensive.

Most of our current knowledge has been obtained through experience and observation in operational container nurseries. In response to a recent survey, container growers reported that their target RH values decreased during the growing season, ranging from 60 to 80% in the establishment phase to 45 to 50% during the hardening phase (table 3.2.5). Several nurseries stated that they did not really have targets for humidity because it is so difficult to control, especially in growing structures that are not fully enclosed, such as shadehouses. Most agreed, however, that high humidities were definitely important during seed germination and emergence.

Establishment phase. Managing the humidity is most critical during the germination period. Seeds are sown on top of the growing medium under a thin covering that must be kept moist so that the seed never dries out. Many nurseries use special mist nozzles during this period to keep the growing medium "moist but not wet" (fig. 3.2.7). Maintaining high relative humidities of 60 to 90% (table 3.2.6) eliminates the need for frequent irrigation, which would keep the growing medium too wet and promote damping-off.

Figure 3.2.7—*Proper water management is critical during the establishment phase. Mist nozzles provide short bursts of water droplets that keep the germinating seed moist and promote rapid and complete emergence. The resultant high humidity also retards transpiration until the root system of the young seedling can get established.*

Because relative humidity varies so much with temperature, it is more effective to manage for vapor pressure deficit. VPD values corresponding to the RH targets (table 3.2.6) should only be considered approximate guidelines, considering the difficulty in precise adjustment of humidity. VPD can be easily calculated by using the RH and temperature measurements from a psychrometer or hygrothermograph (see section 3.2.5 for more information).

Rapid growth phase. *As* soon as the seedlings have established root systems, the relative humidity should be reduced to 50 to 80% (table 3.2.6). This will keep evapotranspiration low, but the surface of the growing medium and the seedling foliage will remain dry. *A* VPD of approximately 1.00 kPa is a reasonable target for this phase; the colored line in table 3.2.3 delineates the combinations of temperature and RH that will keep the evapotranspirational demand below that target.

Table 3.2.5—*Operational targets and ranges for relative humidity for seedlings in their three phases of growth at container tree nurseries*

Crop	State	Growing structure	Relative humidity (%)					
			Establishment		Rapid growth		Hardening	
			Target	Range	Target	Range	Target	Range
Douglas-fir, fir, larch, pine	ID	Fully enclosed	75	50–100	70	50–100	50	30-100
Birch, fir, juniper, larch, maple, oak, pine, spruce, thuja, walnut	MN	Fully enclosed	80	70–90	60	50–70	Ambient	
Cypress, juniper, pine	TX	Fully enclosed	60	40–80	60	40–80	Ambient	
Spruce	ME	Fully enclosed	None	60–80	None	50–70	None	50–70
Douglas-fir, eucalyptus, pine, redwood	CA	Semi-enclosed	70	50–100	55	30–90	45	30-70
Douglas-fir, fir, larch, pine, spruce	MT	Semi-enclosed	None	40–90	None	20–95	None	50-95

Source: Container Nursery Survey

Table 3.2.6—*Optimum relative humidity and vapor pressure deficit (VPD) levels for container tree nurseries*

Growth phase	Relative humidity (%)		Corresponding VPD (KPa) at 25 °C	
	Target	Range	Target	Range
Establishment	80	60–90	0.60	1.3–0.3
Rapid growth	60	50–80	1.20	1.6–0.6
Hardening	Ambient		Ambient	

When temperatures in the growing area become excessive, many nurseries apply a fine mist, often in combination with shade, to cool the seedlings (fig. 3.2.8). Some of the mist evaporates before reaching the ground, thus lowering the air temperature. These mist applications should be relatively brief, however, or the mist will accumulate on the seedling foliage and encourage nursery pests. This warning is particularly important to heed immediately after routine irrigation. Free surface moisture keeps the air nearly saturated within the seedling crown and promotes foliar diseases such as grey mold. Scheduling irrigations early in the day allows time for the moisture on the seedling foliage to evaporate. A critical period for humidity control in a greenhouse is when the seedling crowns close. During this period, adequate air circulation must be maintained throughout the greenhouse to lower humidity around the seedlings; air circulation is even effective during periods of high humidity because the moving air creates a vapor pressure gradient from the foliage to the atmosphere.

Figure 3.2.8—*Brief irrigations, or mists, can provide cooling when temperatures become excessive in the growing area. Applications must be brief, however, or high humidity will cause condensation, which drips onto the crop and causes waterlogged growing media* (**arrows**).

Hardening phase. The cultural objectives of this phase are slowing height growth, promoting bud set, and hardening the seedlings to environmental stresses. Lowering humidity to ambient levels during this period (table 3.2.6) causes seedlings to undergo a mild moisture stress. This can be difficult in completely enclosed greenhouses, however, because the cooler temperatures during late summer and fall promote high humidities and often condensation, especially at night. For this reason, many nurseries move their seedlings from the greenhouse at the beginning of the hardening phase, and others remove the covering, unless outside conditions are too stressful (table 3.2.5). Shelterhouses are particularly beneficial during this period because their sides can be raised to promote good cross ventilation (fig. 3.1.12B).

3.2.3.2 Vegetative propagation

Significantly higher humidities are required for all types of vegetative propagation than for seedling culture. With all types of cuttings, the normal water supply has been completely severed and water stress can quickly become severe. The problem is critical with softwood cuttings, which have leaves that are still transpiring, and hardwood cuttings, which root slowly. Because the production of new roots requires positive turgor pressure, plant moisture stress must be minimized by keeping the ambient vapor pressure at nearly the same level as that in the plant (Hartmann and Kester 1983). Maintaining relative humidity values as close to 100% as possible is desirable (fig. 3.2AA); once cuttings have rooted, they are gradually hardened to ambient conditions by allowing humidities to decrease. Newly grafted plants also benefit from highly humid environments until the grafts have taken and normal internal water relations have resumed.

3.2.4 Modifying Humidity in Container Nurseries

Most container tree nurseries are not designed with specific equipment for controlling humidity, but utilize existing heating, ventilation, and irrigation equipment to maintain humidities within the desired range. The type of growing structure has an overriding effect because some greenhouses hold humidity better than others.

3.2.4.1 Growing structures

Fully enclosed structures are better for maintaining a given humidity level because they inhibit air exchange with the outside environment. All greenhouses leak air to some degree, and so the tighter the structure, the less the variation in humidity can be expected (Hanan and others 1978). It is difficult to keep humidity high in semi-enclosed greenhouses (such as shelterhouses), which have roll-up sides that cannot be tightly sealed. This design feature is a definite advantage, however, when the objective is to dehumidify the environment rapidly.

The type of greenhouse covering is also important. Plastic tarp (polyethylene or "poly") coverings fit more snugly and have fewer seams than rigid panels, and so they allow less air exchange. Well-insulated growing structures, such as those with double-polyethylene coverings and thermal blankets, will have higher humidities (Aldrich and Bartok 1989). However, because of their poor insulation, single-layer polyethylene-covered greenhouses often develop condensation on their inside surfaces, which can lead to drip problems (Mastalerz 1977). There are also differences in transparency to sunlight between different coverings, which would affect internal temperatures and therefore relative humidity levels. For a 4-month period in the late summer and fall in British Columbia, the RH in fiberglass growing structures was significantly higher than that in plastic-covered structures, and this variation was not solely due to differences in temperature (fig. 3.2.9). These differences were culturally important because humidity-related disease losses were 8 times higher in the fiberglass house than in the polyethylene-covered structure (Peterson and others 1988).

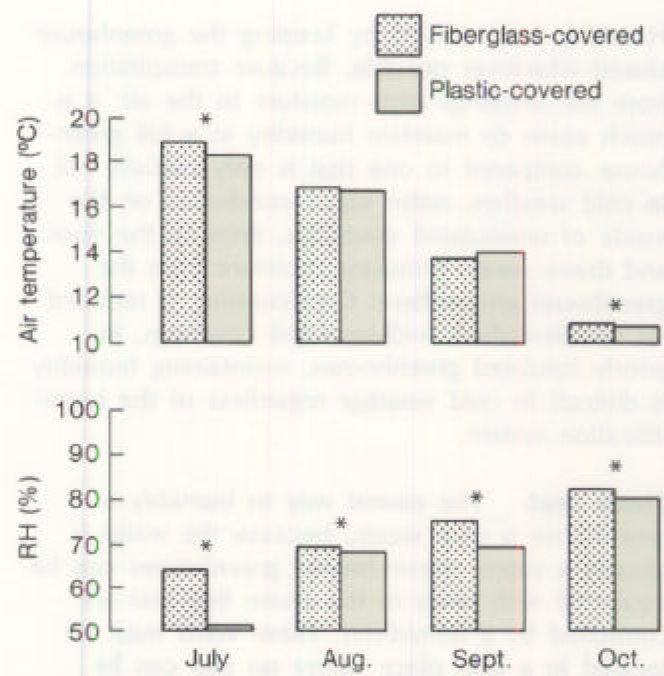


Figure 3.2.9—*The type of covering can affect the temperature and relative humidity (RH) in the greenhouse environment. Fiberglass greenhouses have significantly higher humidities during late summer and early fall when grey mold can become a problem. *Significant at P=0.05. (Adapted from Peterson and others 1988.)*

3.2.4.2 Humidification

Humidification is used operationally to retard evapotranspiration under the following conditions:

1. During the establishment phase, when seeds, germinants, cuttings, and new grafts require conditions that are "moist but not wet."
2. At times during the growing season when the outside air is much colder than in the green house because cold air contains less moisture.
3. In arid climates, where the outside air is often hot and dry.

Humidification is most commonly needed in arid climates during cold weather when relatively dry air is brought into the greenhouse and heated, which further lowers the RH. Whereas dehumidification relies on the heating and ventilation systems to dissipate atmospheric moisture, humidification requires conservation of moisture and addition of water vapor to the greenhouse atmosphere.

Humidity is conserved by keeping the greenhouse closed whenever possible. Because transpiration from the seedlings adds moisture to the air, it is much easier to maintain humidity in a full greenhouse compared to one that is only partially full. In cold weather, water vapor condenses on the inside of uninsulated coverings, drips to the floor and drains away, removing moisture from the greenhouse atmosphere. Condensation is reduced on double-walled, well-insulated coverings. In poorly insulated greenhouses, maintaining humidity is difficult in cold weather regardless of the humidification system.

Steam heat. The easiest way to humidify a greenhouse is with steam, because the water is already a vapor. Steam-heated greenhouses can be equipped with vents in the steam line that are controlled by a humidistat. **These vents must be located in a safe place where no one can be scalded** and where the water vapor will be quickly distributed throughout the greenhouse.

Fog and mist. Humidity can also be added by spraying fine droplets of water into the air (fig. 3.2.10). The difference between fog and mist is in the size of the droplet. Mist droplets are large enough to settle out in a few seconds and will wet the surfaces on which they land. Fog droplets are almost invisibly small and will remain suspended for several minutes, during which most will evaporate. Properly applied, fog will not wet foliage. With either fog or mist, it may be necessary to shade the greenhouse to maintain the desired high humidity.

There are two basic types of nozzle used to produce fog or mist. The impact nozzle directs a stream of water against a surface, breaking the water into droplets. The centrifugal nozzle spins the water into an orifice, which achieves the same thing. Because of the high surface tension of water, the smaller the droplet, the more energy is required to produce it. This energy may come from several sources. Mist nozzles generally operate satisfactorily at the standard domestic water pressure of 300 to 450 kPa (45 to 65 pounds per square inch). Fog nozzles require a booster pump

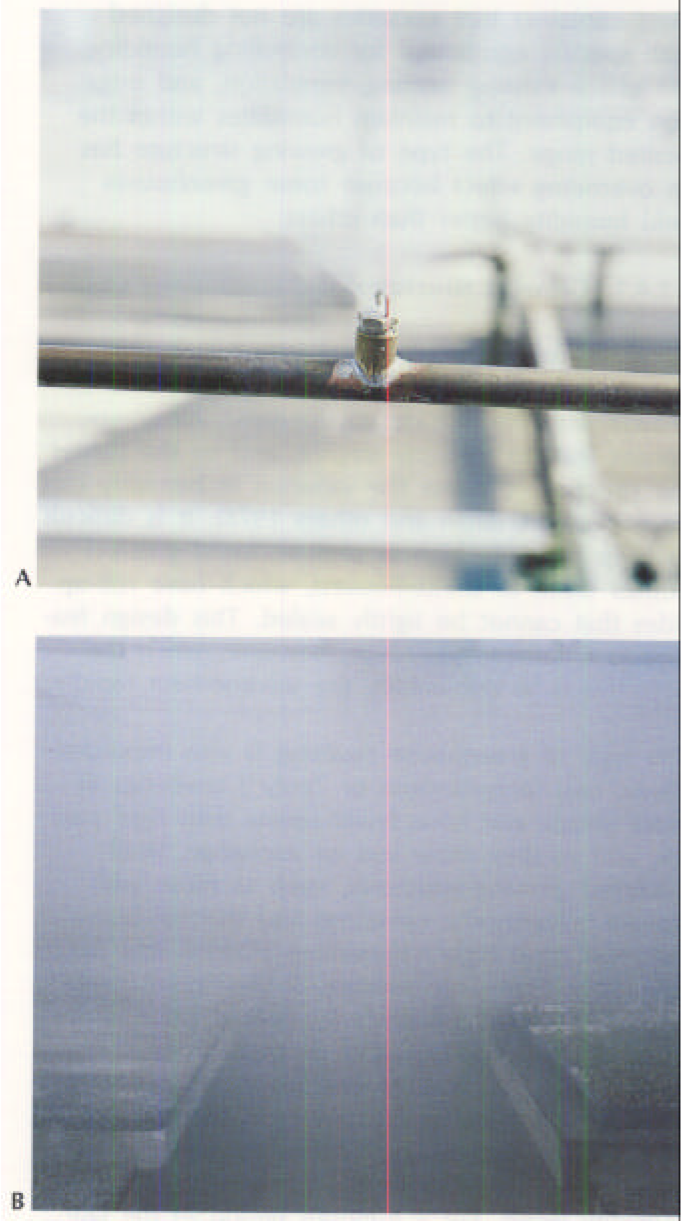


Figure 3.2.10—*Both misting and fogging systems can be used to humidify the container nursery environment. Mist nozzles* (**A**) *produce fine water droplets that settle on the seedling foliage, whereas fogging systems produce water particles small enough to remain suspended in the air* (**B**).

to raise the pressure to 2,700 to 10,000 kPa (400 to 1,500 pounds per square inch). Another fogging system uses an electric motor to spin a wheel that has orifices on its rim. Centrifugal force raises the water pressure at the orifice, and a fan is often used to distribute the fog. A third type uses com- air to shear the water into fog.

The choice of system will depend on the type of crop, climate, greenhouse ventilation system, cultural objectives, and water quality (Weed 1989). Mist systems are cheaper to operate and will wet the foliage beneath them. This may be beneficial because leaf temperatures will be reduced and the mist can deliver mineral nutrients or pesticides to the crop. However, excessive misting can leach nutrients, leave mineral deposits, encourage growth of algae, and promote fungal diseases (Hartmann and Kester 1983). Fog systems cost more to install and operate but have proven superior for control of humidity. They are especially useful in vegetative propagation and can be used outdoors for frost protection (Gordon 1989).

Because fog and mist nozzles have tiny orifices, the water must pass through very fine pore filters to remove any suspended particles that might clog the orifice (fig. 3.2.1 1 A). Fogging or misting with saline water will deposit salts on the foliage (fig. 3.2.1 1 B). These deposits not only are unsightly, but also may cause salt burn and inhibit photosynthesis. This problem can be particularly serious in vegetative propagation systems because of the frequent applications. Fertilizers and pesticides that contain suspended particles should not be applied with a fog system. (Irrigation water quality and filtration are discussed in detail in volume four of this series.)

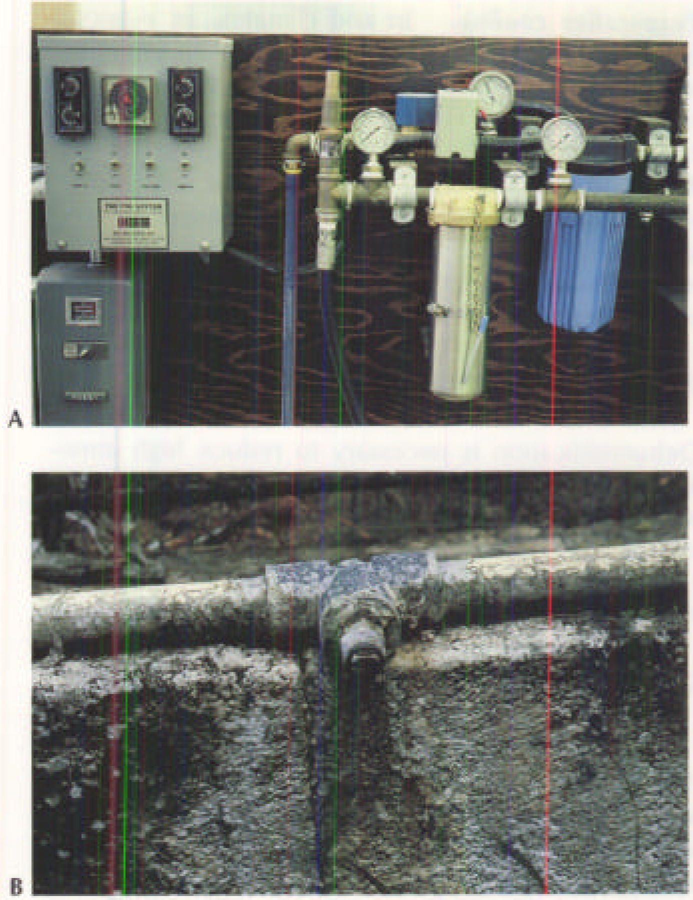


Figure 3.2.11—*Irrigation water that will be used for misting or fogging must be filtered or otherwise treated to remove suspended solids* (**A**) *and saline water must be treated to prevent plugged nozzles or "scale deposits"* (**B**).

Irrigation. Standard irrigation nozzles can also be used to humidify a greenhouse if they are turned on for brief intervals. However, this must be monitored carefully, because over-irrigation can result in suboptimal leaf temperatures, wet foliage, and saturated growing media-conditions that can promote fungal diseases. Overhead mobile irrigation booms are particularly effective for humidification because they provide even coverage and irrigation intervals can be easily controlled (Garzoli 1988). Some growers have outfitted mobile booms with multiple spray heads, one of which is a misting nozzle (fig. 3.1.22B). The effectiveness of cooling with irrigation was found to be short-lived, however, as the increase in RH lasted less than 1 hour (Mastalerz 1977). No matter what type of irrigation system is used, the water should be filtered to remove suspended solids that can cause problems.

Evaporative cooling. In arid climates, an evaporative cooling system (fig. 3.1.19) can be an effective means of humidification during warm weather. Hanan and others (1978) report that evaporative cooling will typically raise the RH to about 70 to 80% and that the cool, humid air flow will also reduce the VPD. Evaporative cooling systems should not be used as a principal source of humidity, however, but rather as a beneficial effect of temperature control.

3.2.4.3 Dehumidification

Dehumidification is necessary to reduce high atmospheric humidity and prevent problems such as excessive condensation. High humidity most often occurs under the following conditions:

1. After irrigation, especially when the growing area cannot be immediately ventilated.
2. In climates with perennially high atmospheric humidity.

Ventilation and heating. The simplest and easiest way to dehumidify the growing environment is to ventilate with drier or warmer air. When the outside air is drier, growers can simply activate the ventilation system whenever the greenhouse humidity rises above the target level (fig. 3.2.12). If ventilation alone is not effective, then a combination of heating and ventilation will be, even when the outside air is very humid. Often, when conditions require dehumidification, the outside air is cool enough that the heating system automatically switches on when the vents open. It is also possible to switch the ventilation and heating systems jointly to guarantee effective dehumidification. In addition to lowering the ambient RH, the flow of warmer air over the foliage can effectively prevent condensation and eliminate temperature stratification in the greenhouse (Aldrich and Bartok 1989). High ventilation rates with very dry air can result in seedling water stress, however (Hanan and others 1977).

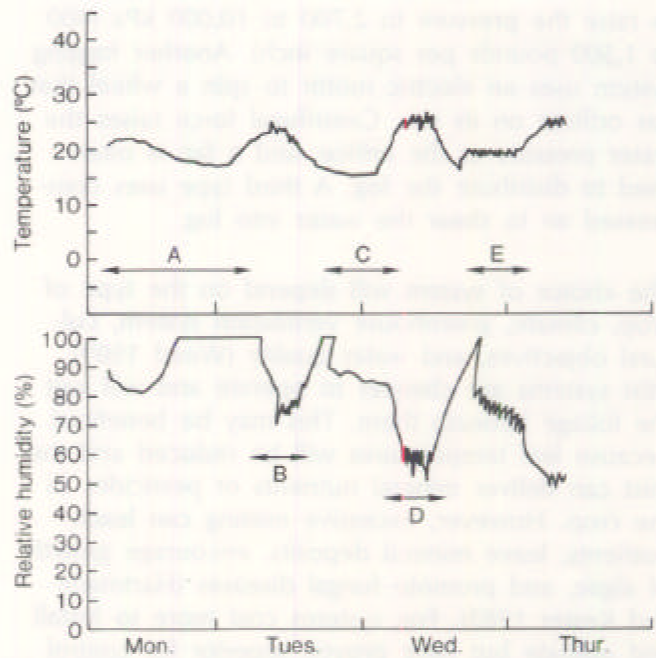


Figure 3.2.12—*This hygrothermograph chart illustrates how dehumidification can be accomplished. Monday* (**A**) *is overcast and humid, and no attempt is made to control the humidity, which rises to 100% by 6 pm and remains there all night. Tuesday* (**B**) *is warmer and partly sunny, and the rising temperature alone reduces the humidity during the day. In the evening the humidity again rises to 100%, but at 8 pm fan ventilation begins* (**C**). *If the outside air is less humid than inside the greenhouse, humidity may be reduced even if the outside air is cooler. Wednesday* (**D**) *is sunny, and the humidity drops considerably, but again rises to 100% by 8 pm. This time* (**E**) *the decondensate cycle comes on (both heating and ventilation) and lowers the humidity dramatically.*

Dehumidifying the seedling canopy. Perforated ventilation or heating tubes are often located under raised benches so that air is forced up through the seedlings, effectively dehumidifying the microenvironment within the canopy (fig. 3.1.27B). The warm air not only dries the foliage but also raises the temperature of the root plug, which can be beneficial, especially during winter months (Hallett 1982). Peterson and Sutherland (1989) found that underbench ventilation with cool air took 11 hours longer to dry the seedlings than ventilation with heated air, but concluded that cool air ventilation was better for lowering the germination potential of the grey mold fungus.

The seedling canopy can also be dehumidified with fans, which can be moved into place after irrigation or directly mounted on the irrigation boom (fig. 3.2.13). One grower has successfully used a portable leaf blower to dry the foliage after irrigation.

Overhead radiant heaters (fig. 3.1.28) reduce the humidity within the seedling canopy and effectively eliminate condensation on foliage. The thermal radiation warms objects rather than the surrounding air, thus decreasing RH without increasing air flow around the seedlings, which would increase evapotranspiration rates.

Figure 3.2.13—*Immediately after irrigation, fans can be used to increase the air flow over the seedling foliage and evaporate unwanted surface moisture.*

3.2.5 Humidity Monitoring and Control Systems

It is relatively difficult to measure humidity compared to the other atmospheric variables. Relative humidity is the only measure of humidity that is routinely monitored in container tree nurseries, although new computer systems can calculate vapor pressure deficit.

3.2.5.1 Humidity

Any instrument that measures humidity is called a **hygrometer.** A **psychrometer** is a common type of hygrometer that consists of two adjacent temperature sensors: a dry-bulb sensor that measures ambient temperature and a wet-bulb sensor that is covered with an absorbent cloth. This cloth is wetted with distilled water and both sensors are ventilated with air moving at a rate of at least 3.5 m/s (12 feet per second) until the wet-bulb temperature reaches a steady state. The difference in temperature between wet-bulb and dry-bulb sensors is known as the **wet-bulb depression.**

Two types of psychrometers are commonly used in container nurseries. The **sling psychrometer** (fig. 3.2.14) is whirled manually in a circular motion until the wet-bulb temperature stabilizes. With the **aspirated psychrometer,** the thermometers remain stationary and air is drawn across the bulbs with a small fan. Charts and tables are available for converting the wet and dry-bulb temperature to relative humidity or dew point (fig. 3.2.2 and table 3.2.4). Psychrometers have a precision of 0.3 to 3.0% and an effective range of -18 to 260 °C (0 to 500 ° F). Because the wet-bulb depression is so slight, psychrometers are less accurate at low temperatures, and special psychrometric charts are necessary under subfreezing conditions (ASHRAE 1989). Also, errors caused by a dirty wet-bulb, or less than optimum ventilation, always result in a reduced wet-bulb depression reading, which in turn, produces an elevated RH reading. However, psychrometers remain a useful way of measuring RH under greenhouse conditions.

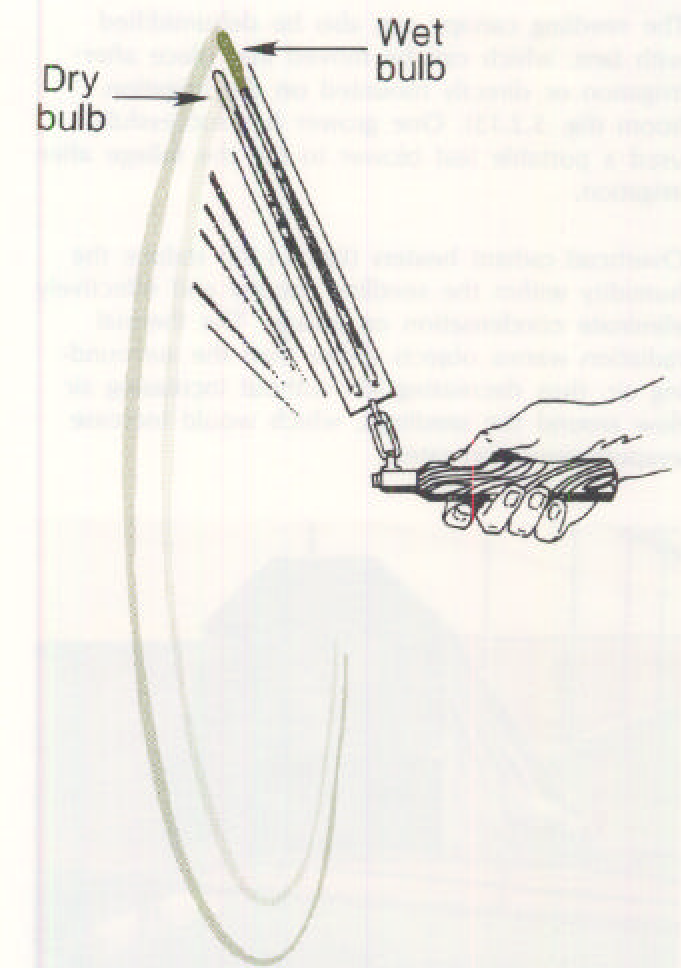


Figure 3.2.14—*A sling psychrometer contains two thermometers: the "dry-bulb," which measures ambient conditions, and the "wet-bulb," which is covered with a wet cloth and measures the lower temperature resulting from evaporative cooling. The difference between these two readings gives the wet-bulb depression. The psychrometer is whirled with a circular motion until the wet-bulb temperature stabilizes. Both thermometers are quickly read, and the relative humidity can be determined from psychrometric charts (see figure 3.2.2) or tables (see table 3.2.4). (Adapted from Schroeder and Buck 1970.)*

The other instrument that is commonly used to monitor humidity in container tree nurseries is the hygrothermograph (fig. 3.1.31C), which measures both air temperature and relative humidity (fig. 3.2.12). Because proteins in hair (keratin) change length with changes in humidity, human hair is often used in hygrothermographs. Hygrothermographs are precise within 3% RH, but their accuracy decreases at extreme humidities and they are slow to respond to changes (ASHRAE 1989). They have the advantage of continually recording RH values to show diurnal and daily trends. A good approach is to install a shaded hygrothermograph to provide a permanent record of RH, and then occasionally check the instrument with a sling psychrometer.

Electrical RH sensors offer improved accuracy and are durable and compact. They also feature digital readout capability, which makes them easy to use. The two most widely used electrical RH sensors, the Dunmore element and the Pope cell, both use wire grids in a substrate containing a hygroscopic salt. The electrical resistance of the substrates declines as the humidity of the surrounding air rises. Although they are accurate and quick to respond, both of these RH sensors are highly sensitive to contamination, which reduces their useful lifetime in a container nursery application (Gaffney 1978).

A new environmental control system can measure VPD around plant foliage. The computer uses sensors to measure leaf temperature and the temperature and RH of the air. Because the air within the stomata is always near saturation under normal nursery conditions, the VPD of the leaf can be determined from its temperature. The computer system calculates VPD every few seconds and uses an accumulated value to estimate plant water use and schedule irrigation (Barrett 1990).

The basic device for controlling humidity is the humidistat, which has a relative humidity sensor connected to an electrical switch (fig. 3.2.15). Humidistats can be wired to close when humidities rise, switching on a dehumidification system, or when humidities fall, triggering a humidification cycle. Likewise, dehumidification can be programmed into a decondensate stage on the environmental control panel, which synchronizes the opening of vents and triggers the heating system, and can be operated either manually or automatically (fig. 3.2.16). Computer-assisted environmental control systems are able to monitor electric hygrometers continuously and generate permanent records of relative humidity and other related climatic variables. (Environmental control systems are discussed in more detail in volume one of this series.)

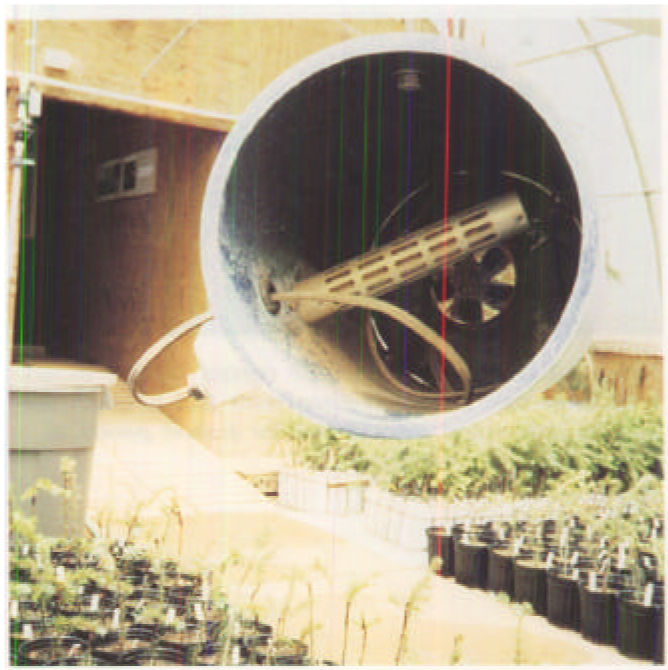


Figure 3.2.15—*Misting systems can be controlled with a humidistat, which senses relative humidity. A humidistat must be shielded from direct exposure to moisture.*

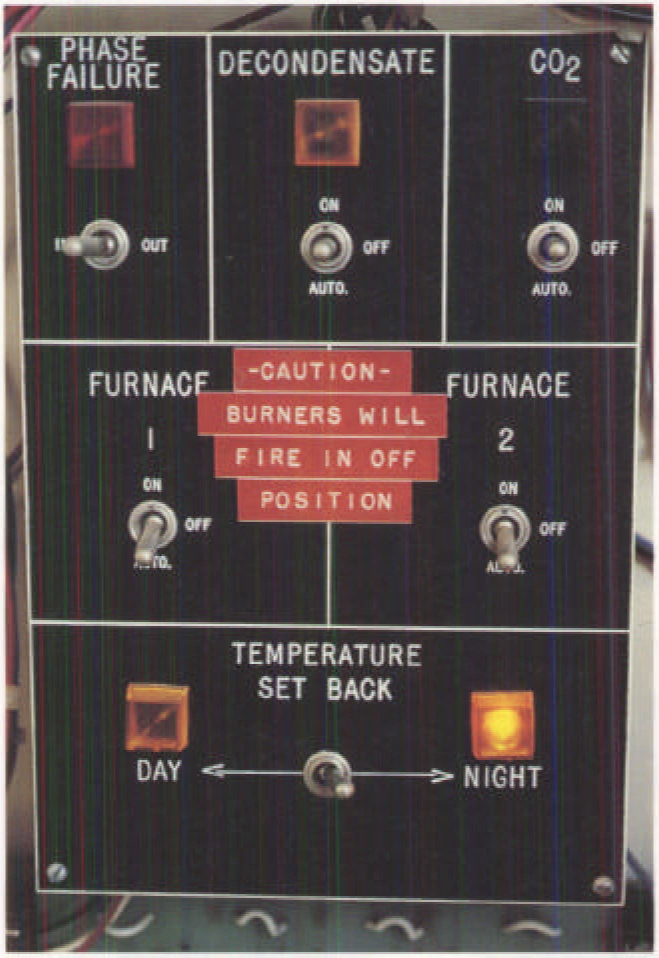
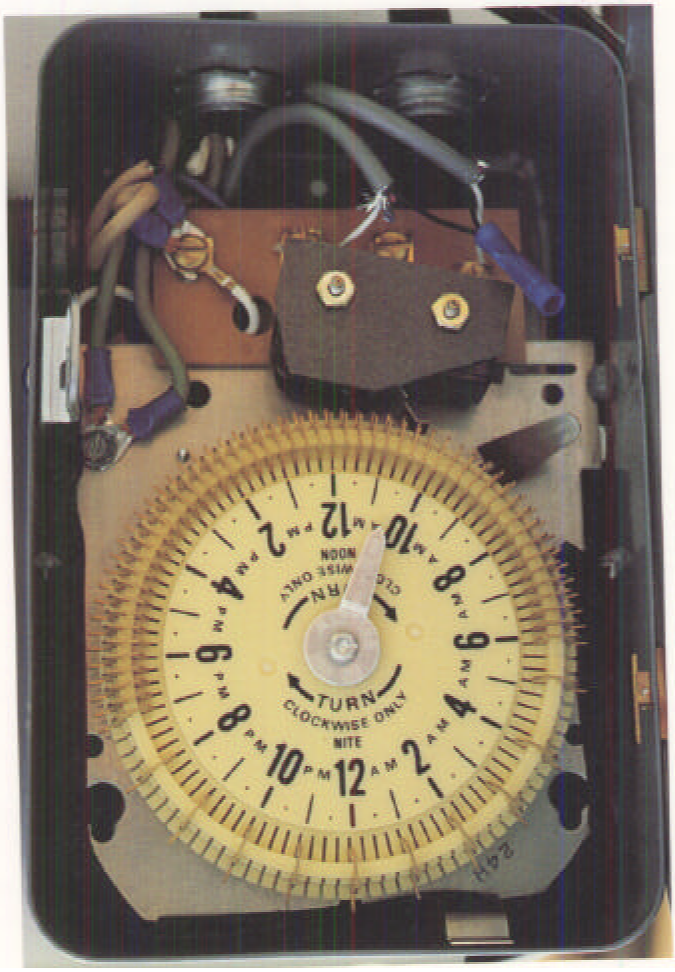


Figure 3.2.16—Some greenhouse control systems include a decondensate stage that open vents and turns on the heating system and exhaust fans for a short period to dehumidify the greenhouse.

3.2.5.2 Fog and mist

Three basic types of mist controllers are available: time clocks, mechanical sensors such as the "artificial leaf," and computer-assisted control equipment that monitors humidity or radiant energy. With time controllers, the grower sets the hours of operation and the duration of the mists on a mechanical clock (fig. 3.2.17A/B). These relatively simple and inexpensive controls are often wired in series to provide intermittent mist during certain hours. The artificial leaf is another inexpensive control system consisting of a square of wire gauze on one end of a balance arm (fig. 3.2.17C). When the mist that has settled on the leaf becomes heavy enough, the balance arm tips, triggering a mercury switch to shut off the mist system. After the water evaporates from the leaf, the balance arm rises again to the "on" position. Thus, the misting cycle is repeated at intervals that are determined by the evaporation rate in the growing area.

Fogging requires more sophisticated electronic controls. New environmental computers monitor humidity and other factors, such as solar radiation, and integrate this information to activate the fog system.



A


C

B

Figure 3.2.17—*Several different mist control systems are available, including mechanical clocks (**A** and **B**) and the "artificial leaf" (**C**).*

3.2.6 Conclusions and Recommendations

Atmospheric humidity in container tree nurseries is biologically important because it affects seedling water relations and the growth of fungal pathogens. The principal influence of humidity is on evapotranspiration rates. When the air is still, the rate of evaporation from a wet surface is a function of relative humidity and temperature and is proportional to the vapor pressure deficit. At a constant temperature, the higher the relative humidity, the lower the vapor pressure deficit, and the less the plant moisture stress. When the vapor pressure deficit increases, the seedlings come under greater stress, which results in stomatal closure and a reduction in net photosynthesis. For maximum growth, the stomata must remain open as long as possible. Growers can promote growth by maintaining relatively high humidities in the growing areas.

It is difficult to maintain optimum humidity levels for container tree nurseries because relative humidity varies so much with temperature. Ideal humidity levels also change during the growing season depending upon the seedlings' stage of development. High relative humidities are most important during seed germination and seedling emergence. Target relative humidity during the establishment phase is 80%, with a range of 60 to 90%, and during the rapid growth phase the target RH drops to 60%, with a range of 50 to 80%. During the hardening phase, outside ambient relative humidities are usually acceptable.

Except for vegetative propagation, very high relative humidities (90 to 100%) are not desirable because growth of pathogenic fungi, moss, algae, and liverworts is stimulated under these conditions and can result in a lowering of seedling quality or even in mortality.

Most container nurseries are not designed with specific equipment for controlling humidity, but utilize existing heating, ventilation, and irrigation equipment to maintain humidities within the desired ranges.

3.2.7 Literature Cited

Aldrich, R.A.; Bartok, J.W. Jr. 1989. Greenhouse engineering. Ithaca, NY: Cornell University, Northeast Regional Agricultural Engineering Service. 203 p.

ASHRAE, 1989. ASHRAE Handbook: fundamentals. Atlanta, GA: American Society of Heating, Refrigerating, and Air Conditioning Engineers, Inc. 792 p.

Barrett, J. 1990. Plants and water 101: understanding VPD. Grower Talks, September 1990: 48-52.

Clawson, K.L.; Jackson, R.D.; Pinter, P.J. Jr. 1989. Evaluating plant moisture stress with canopy temperature differences. Agronomy Journal 81:858-863.

Gaffney, J.J. 1978. Humidity: basic principles and measurement techniques. HortScience 13(5):551-555.

Garzoli, K. 1988. Greenhouses. Canberra, Australia: Australian Government Publishing Service. 185 p.

Gordon, I. 1989. Fogging systems for propagation. International Plant Propagators' Society Combined Proceedings 38:84-86.

Hallett, R.D. 1982. Contrasting approaches to containerized seedling production. 3. The Maritime Provinces. In: Scarratt, J.B.; Glerum, C.; Plexman, C.A., eds. Proceedings, Canadian Containerized Tree Seedling Symposium. COJFRC Symposium Proceedings O-P-10. 1981, Sept. 14-16. Toronto, ON. Sault Ste. Marie, ON: Canadian Forestry Service, Great Lakes Forest Research Centre: 129-138.

Hanan, J.J.; Holley, W.D.; Goldsberry, K.L. 1978. Greenhouse management. New York: SpringerVerlag. 530 p.

Hartmann, H.T.; Kester, D.E. 1983. Plant propagation: principles and practices Englewood Cliffs, NJ: Prentice-Hall. 727 p.

Jarvis, P.G. 1980. Stomatal response to water stress in conifers. In: Turner, N.; Kramer, P., eds. Adaption of plants to water and high temperature stress. Oxford: Blackwell: 105-122.

Kramer, P.J. 1983. Water relations of plants. New York: Academic Press. 489 p.

Kramer, P.J.; Kozlowski, T.T. 1979. Physiology of woody plants. New York: Academic Press. ft 1 1 n

Krizek, D.T.; Bailey, W.A.; Klueter, H.H. 1971. Effects of relative humidity and type of container on the growth of F, hybrid annuals in controlled environments. American Journal of Botany 58:544-551.

Mastalerz, J.W. 1977. The greenhouse environment. New York: John Wiley and Sons. 629 p.

Peterson, M.J.; Sutherland, J.R.; Tuller, S.E. 1988. Greenhouse environment and epidemiology of grey mould of container-grown Douglas-fir seedlings. Canadian Journal of Forestry Research 18(8):974-980.

Peterson, M.J.; Sutherland, J.R. 1989. Grey mould control by seedling canopy humidity reduction through under-bench ventilation and styroblock aeration. FRDA Rep. 077. Victoria, BC: Canadian Forestry Service and BC Ministry of Forests. 16 p.

Schroeder, M.J.; Buck, C.C. 1970. Fire weather: a guide for application of meteorological information to forest fire control operations. Agric. Handbk. 360. Washington, DC: USDA Forest Service. 229 p.

Seiler, J.R.; Johnson, J.D. 1984. Abnormal needle morphology in loblolly pine induced by low humidity. HortScience 19(4):521-522.

Van de Sanden, P.A.C.M. 1985. Effect of air humidity on growth and water exchange of cucumber seedlings: preliminary report. Acta Horticulturae 174:259-267.

Weed, J. 1989. A look at fog cooling systems. Greenhouse Manager 8(6):110-113.