The Container Tree Nursery Manual

Volume Three
Atmospheric Environment

Chapter 4
Carbon Dioxide

Contents

3.4.1 Introduction

Carbon dioxide (CO_2) is a colorless, odorless gas. Because it exists in relatively small amounts in the ambient atmosphere, CO_2 is considered to be the principal limiting factor of photosynthesis under some growing conditions. In horticulture, carbon dioxide was the last of the limiting growth factors to be culturally managed. Initial experiments with CO_2 enrichment were discouraging because elevated levels of CO_2 produced a phytotoxic response, which was probably due to the presence of toxic gaseous contaminants. In 1918, the beneficial effects of CO_2 enrichment for plant growth were firmly established, but commercial application did not become widespread until the mid-1960's (Bauerle and others 1986, Hicklenton 1988).

Carbon dioxide enrichment is not widely practiced in container tree nurseries. Only 17% of the nurseries in the United States and Canada reported CO_2 management programs (Container Nursery Survey). The lack of interest should not be interpreted to mean that CO_2 is not important to tree seedling culture, as many research studies have shown that increased COZ levels definitely accelerate photo synthetic rates (Kramer and Kozlowski 1979).

3.4.1.1 Carbon dioxide in the environment

Two familiar gases make up 99% of the earth's atmosphere by volume-nitrogen (78%) and oxygen (21 %)-whereas carbon dioxide concentrations currently average only 0.035% (350 ppm). This was not always the case, however, as CO_2 was more common than oxygen in the primitive atmosphere. The rapid development of plant life quickly utilized this CO_2 and released oxygen, which made possible the evolution of larger and more advanced organisms. The CO_2 level of the earth's atmo sphere appears to have stabilized at its lowest level (280 ppm) in the mid-1800's. Since that time, the industrial revolution has resulted in a gradual increase in ambient CO_2 concentrations. Massive deforestation and combustion of fossil fuels has caused the atmospheric CO_2 level to increase 1 to 2 ppm per year. This trend is unlikely to change in the near future (Hicklenton 1988). The concern over "global warming" has resulted in many new research studies of the effects of higher CO_2 levels on tree growth in the past few years, and much of this work has been done on forest tree seedlings (see section 3.4.2.2).

The ambient COZ_2 level around a nursery can vary from 200 to 400 ppm, depending on location; higher values can be found in industrial areas, due to combustion of fossil fuels, and in low wet areas, such as swamps and river bottoms, where plant materials are decomposing (Nelson 1985). Carbon dioxide concentration measured in weight per unit volume also decreases with elevation, decreasing about 40% from sea level to 4,500 m (14,800 feet) (Kramer and Kozlowski 1979).

3.4.1.2 Definitions and units

Carbon dioxide levels can be described and measured in several different ways. Because it is a gas, CO_2 can be described in pressure units but these are not widely used for horticultural purposes. Plant physiologists measure photosynthesis by the amount of CO_2 consumed per unit volume, expressed either by weight in milligrams per liter (mg/l) or by volume in microliters per liter (µl/l). Pallas (1986) provides a thorough discussion of units that are used in scientific research. However, for operational nursery work, concentration units—percentage (%) or parts per million (ppm)—are the simplest and most appropriate way to measure CO_2.

3.4.2 Role of Carbon Dioxide in Tree Seedling Growth and Development

Carbon is one of the 16 nutrients that are essential for plant growth. About 40% of the dry weight of a typical plant is composed of carbon. Plants obtain this carbon from the CO_2 in the air through the stomata in the leaves (fig. 3.1.2). The normal ambient CO_2 level of approximately 350 ppm is considered to be adequate for "normal" growth, although plants have the capacity to utilize much greater amounts. This capacity apparently stems back to primitive times when CO_2 levels were 10 to 100 times higher than the present time (Nelson 1985).

3.4.2.1 Carbon dioxide and photosynthesis

Plants consume CO_2 during photosynthesis and give it off through respiration; during daylight hours these processes occur simultaneously (fig. 3.3.5). When the ambient CO_2 level reaches the **compensation point,** the point at which photosynthesis and respiration are equal, the seedling will not grow but only maintain itself. In greenhouses, this situation only occurs on cool, bright days when vents remain closed. At CO_2 levels above the compensation point, which is 40 to 60 ppm for most commonly grown seedlings, net photosynthesis is positive, as long as other critical factors are not limiting (Ludlow and Jarvis 1971, Higginbotham and others 1985).

Carbon dioxide levels follow a typical diurnal pattern in a closed greenhouse environment (fig. 3.4.1). At night, green plants release CO_2 through respiration and so concentration in a closed greenhouse rises to over 400 ppm; however, at dawn, photosynthesis begins and the concentration drops rapidly. The CO_2 concentration becomes critically low in a greenhouse on a cool, cloudy day when ventilation is not required; in a greenhouse with only two air exchanges per hour or less, the CO_2 concentration often drops below 200 ppm and limits photosynthesis (Holley 1965). Environmental measurements inside a greenhouse showed that the average daily CO_2 concentration varied significantly during the month of February and reached its lowest level when the outside temperature was cold and the vents remained closed (fig. 3.4.2). Under calm conditions, CO_2 levels can even be limiting in dense

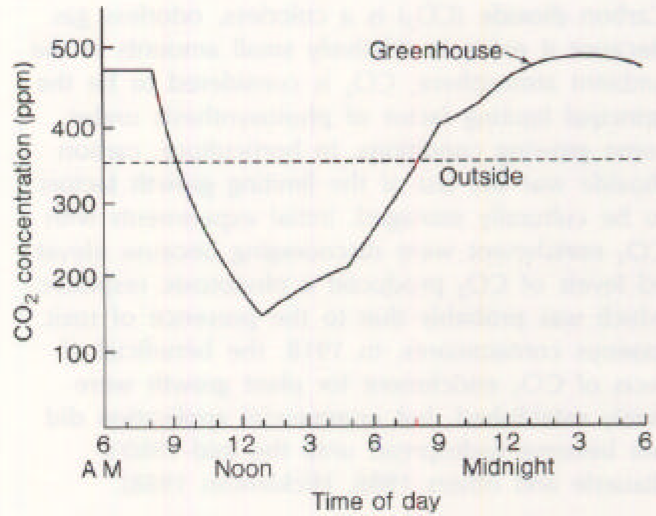


Figure 3.4.1—*Carbon dioxide levels in a closed greenhouse follow a typical diurnal pattern, building up overnight due to plant respiration and then dropping rapidly early in the morning when the photosynthetic rate is greatest (modified from Aldrich and Bartok 1989).*

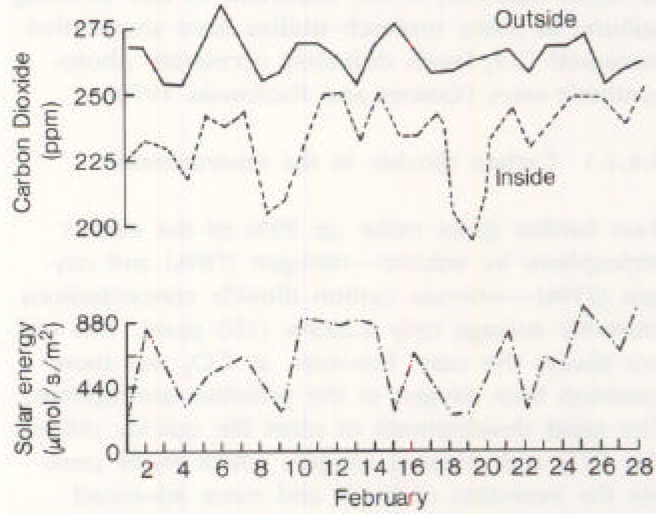


Figure 3.4.2—*During the winter, average daily CO_2 levels inside a greenhouse remain significantly lower than ambient levels because of the relatively few hours of ventilation. Note that the inside CO_2 levels are highest on sunny days when the vents remain open longer. (Modified from Hanan and others 1978.)*

crops grown in open fields, resulting in a 10 to 20% decrease in photosynthetic rate (Chang 1968).

As CO_2 concentrations are enhanced above ambient levels, the photosynthetic rate increases because high concentrations increase the diffusion gradient from the ambient air, through the stomata, to the mesosphyll cells where the chloroplasts use CO_2 in photosynthesis. Photorespiration, which occurs at high light levels and causes loss of CO_2, is also suppressed by high concentrations of CO_2, which further increase net photosynthesis (Tinus *1975,* Pearcy and others *1987).*

3.4.2.2 Growth response to carbon dioxide enrichment

Seedling growth rate increases when the net photosynthate is exported from the leaves, where photosynthesis takes place, to the meristems, where growth occurs. There are numerous studies on the beneficial effects of enhanced CO_2 on tree seedling growth. The height, stem diameter, and total volume of ponderosa pine seedlings increased with increasing CO_2 concentration, although two seed sources had different patterns of growth response (Surano and others 1986). Tolley and Strain (1984) found increased shoot height, leaf area, and biomass for loblolly pine and sweetgum seedlings and reported that the growth response of sweetgum was greater than loblolly pine. Lodgepole pine seedlings grown in enhanced CO_2 levels produced more leaf growth and shoot height than did controls. Analysis of the biomass partitioning showed that root growth was particularly stimulated (fig. 3.4.3). The authors concluded that the combination of increased leaf area and root production could shorten the nursery production period.

There is an upper limit to the stimulatory effect of increased CO_2 concentrations on many plants. High concentrations of CO_2 can cause stomatal closure, which automatically reduces the amount of CO_2 entering the leaf. In addition, faster growth caused by a higher concentration of CO_2 usually results in a shortage of another factor that limits photosynthesis and therefore growth.

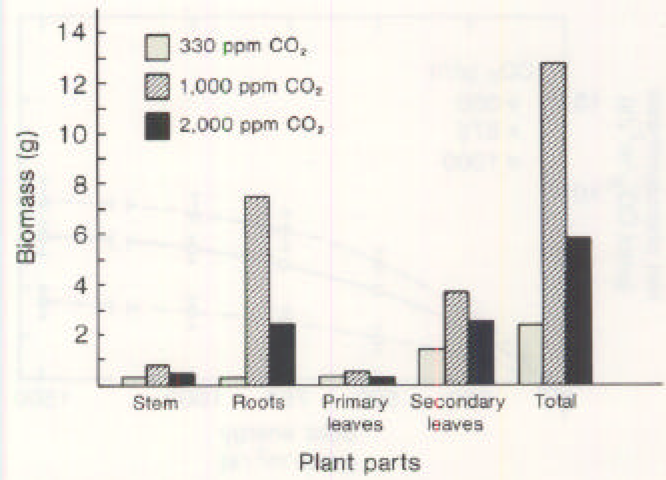


Figure 3.4.3—*After 5 months, the biomass of entire lodgepole pine seedlings and also the various components was highest in seedlings supplemented with 1,000 ppm CO_2. The biomass of the root system and secondary needles shows the greatest increase to the enhanced CO_2 environment. (Adapted from Higginbotham and others 1985.)*

3.4.2.3 Interaction of carbon dioxide with other factors

The physiological effects of CO_2 must not be considered alone, for they are highly interrelated to the effects of other factors limiting to plant growth, especially light, temperature, water, and mineral nutrients (Blackman 1905*).* As the CO_2 concentration changes and the photosynthetic rate varies, the optimum levels of the other environmental factors also change.

Light. Photosynthesis, as measured by CO_2 utilization, increases linearly with light until the light saturation point is reached. As long as the other factors are not limiting, the light saturation point becomes progressively greater as light intensities and CO_2 concentration increase (fig. 3.4.4). In fact, high CO_2 levels can, to a degree, compensate for low light intensity (Tolley and Strain 1984), which often occurs on cloudy winter days. When such conditions occur, supplemental photosynthetic lighting is sometimes used to promote crop growth; CO_2 enrichment is essential in obtaining the full benefits from the additional light (Hicklenton 1988). (See chapter 3 in this volume for more information on light effects on photosynthesis.)

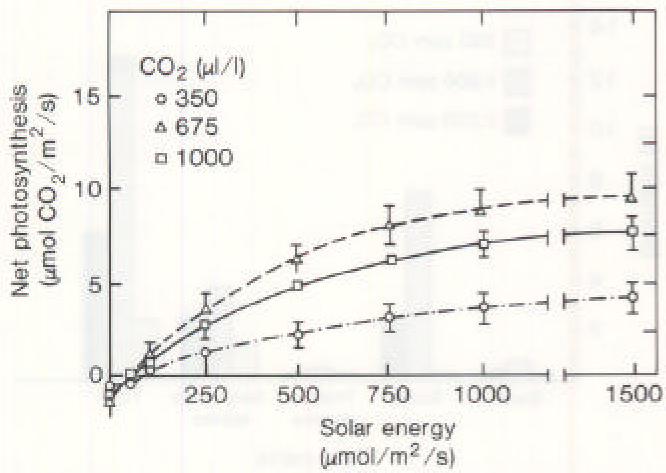


Figure 3.4.4—*The effects of supplemental CO_2 on photosynthesis are greatly dependent on light intensity. These sweetgum seedlings reached light saturation at progressively higher light intensities when CO_2 levels were artificially enhanced.*

Solar radiation also has a direct effect on the temperature regime in a closed greenhouse environment. Because sunlight is converted to thermal radiation in a greenhouse, the amount of sunlight directly influences the need for cooling by ventilation. Thus, the average daily light level has a direct relationship with the CO_2 concentration in a greenhouse during winter (fig. 3.4.2).

Temperature. For many plant species, the optimum temperature for photosynthesis increases when the CO_2 concentration is enhanced. Therefore, the greenhouse vents can remain closed longer-keeping the temperature about 3 to 6 °C (5 to 10 ° F) warmer than otherwise-which in turn prolongs the seedlings' exposure to high CO_2 (Nelson 1985). Likewise, tolerance for higher temperature means that shading is less likely to be needed. High CO_2, more light, and higher temperature therefore act synergistically up to the point where other problems limit growth.

When stomata close at high CO_2 levels, evapotranspiration ceases, and plants may become damaged by the high foliar temperatures. For example, Surano and others (1986) found that transpirational cooling was much reduced when ponderosa pine seedlings were grown in enhanced CO_2 levels in special growth chambers and needle temperature approached 45 °C (114 °F). Reduced transpiration was accompanied by an increase in ethylene production, which may be indicative of heat stress. Stomatal response to high CO_2 varies between species: for example, stomatal opening of lodgepole pine seedlings was unaffected by CO_2 concentrations up to 2,000 ppm (Higginbotham and others 1985). Because small seedlings are so sensitive to heat, stomata[closure may lead to heat injury in container nurseries with enriched CO_2 levels.

Water and mineral nutrients. The rapid growth rates of plants grown in enhanced CO_2 levels result in an increase in water and mineral nutrient uptake (Hicklenton 1988). Seedling water use will increase because the larger foliage has a greater transpirational surface. However, because stomata begin to close at higher CO_2 levels, the efficiency of water use by the seedlings should also increase. This was apparently the case in an experiment with radiata pine where water-stressed seedlings had a greater growth response than those supplied with adequate water (Conroy and others 1986).

The increased growth resulting from the higher photosynthetic rate will also create a demand for more mineral nutrients, but the uptake is not consistent for all nutrients. In Virginia pine, uptake of nitrogen and calcium increased during CO_2 enrichment, but uptake of phosphorus and potassium was unaffected (Luxmore and others 1986). Aspen and white spruce seedlings responded differently to enhanced CO_2 and nitrogen fertilization. Root, stem, and leaf biomass of aspen were greater at high and low nitrogen levels, whereas only leaf mass of white spruce was significantly increased and only at high nitrogen levels. However, the increased growth rate of the aspen seedlings did not persist, because mineral nutrient deficiencies were caused by rapid growth (Brown and Higginbotham 1986). A similar response was noted with sweet chestnut seedlings: leaves grown under enhanced CO_2 became prematurely chlorotic, which was attributed to nutrient dilution resulting from the rapid growth rate (Mousseau and Enoch 1989).

Growers who supply extra CO_2 to their crops will have to be aware of these potential problems and make appropriate adjustments to their cultural regimes. In general, growers who fertilize with every watering should have no problems, but those who fertilize intermittently may need to fertilize more often or with higher concentrations of nutrients.

3.4.3 Optimum Carbon Dioxide Levels

The optimum CO_2 level will depend on the crop species and the stage of seedling development. Most ornamental greenhouses try to maintain CO_2 concentrations between 600 to 1,500 ppm (Freeman 1985). Research trials with tree seedlings have shown positive growth responses at 1,000 ppm or below. Sionit and Kramer (1986) provide a comprehensive listing of the responses of woody plants to CO_2 enrichment. Carbon dioxide levels in excess of 1,500 ppm have not resulted in any additional growth, although most research has been done at light intensities equivalent to 20 to 30% of full sunlight and therefore may not accurately predict what will happen in a greenhouse. Phyto toxicity may occur above 2,500 ppm in some species (table 3.4.1).

3.4.3.1 Establishment phase

There is some question whether enhancing CO_2 levels during seed germination and early establishment is beneficial. Younger plants have slightly higher optimal requirements for CO_2 than older plants (Chang 1968), but the small surface area of the cotyledons and primary needles means less photosynthetic capacity. Most research trials begin supplementing CO_2 several weeks after the seedlings became established. However, Yeatman (1970) found a definite positive response when germinants of four conifer species were grown under increased CO_2 at two different light levels (fig. 3.4.5). In all cases, supplementing the CO_2 levels to 900 ppm was found to produce larger seedlings at 3 weeks after germination, but response to further CO_2 enrichment was variable.

Table 3.4.1—*Effects of carbon dioxide levels on plants and workers in container tree nurseries*

Response	Carbon dioxide concentration (ppm)
Plant effects	
Negative growth	< 100
CO_2 compensation point	50– 100
Reduced growth rate	100– 350
Ambient CO_2 Level	350
Enhanced growth rate	350–1,000
Marginal benefits	1,000–2,500
Possibility of adverse effects	> 2,500
Human effects	
Worker exposure limit	5,000
Headaches and listlessness	> 5,000
Loss of consciousness and death	> 80,000

Source: Compiled from numerous sources.

3.4.3.2 Rapid growth phase

Seedlings show the most response to CO_2 enrichment in the rapid growth phase and the treatment usually begins about 1 month after sowing. Campagna and Margolis (1989) supplied enhanced CO_2 levels for black spruce seedlings at different stages of development and found a significant growth response during the first 3 months of the growing season, when the seedlings had the greatest amount of active photosynthetic surface. Lodgepole pine seedlings showed an increasing response in both shoot height and leaf surface area (fig. 3.4.6) throughout a 5-month growing season (Higginbotham and others 1985). A 1,000 ppm CO_2 level was more effective than a higher concentration. Ponderosa pine and blue spruce seedlings grown for 1 year in 1,200 PPM CO_2 were 50 to 70% heavier than seedlings grown in 325 ppm (Tinus 1972).

3.4.3.3 Hardening phase

The benefits of CO_2 enrichment decline during the hardening phase. Black spruce seedlings grown in enhanced CO_2 during late summer showed no increase in height growth or biomass, although seedlings treated earlier in the growing season had significant growth responses (Campagna and Margolis 1989). An enriched CO_2 environment may actually be detrimental to development of seedling cold hardiness. Black spruce seedlings grown under elevated CO_2 levels hardened more slowly than control seedlings and subsequently suffered greater frost injury (Margolis and Vezina 1990). Enhanced CO_2 levels prolong the succulence of seedlings, which makes them more susceptible to cold injury

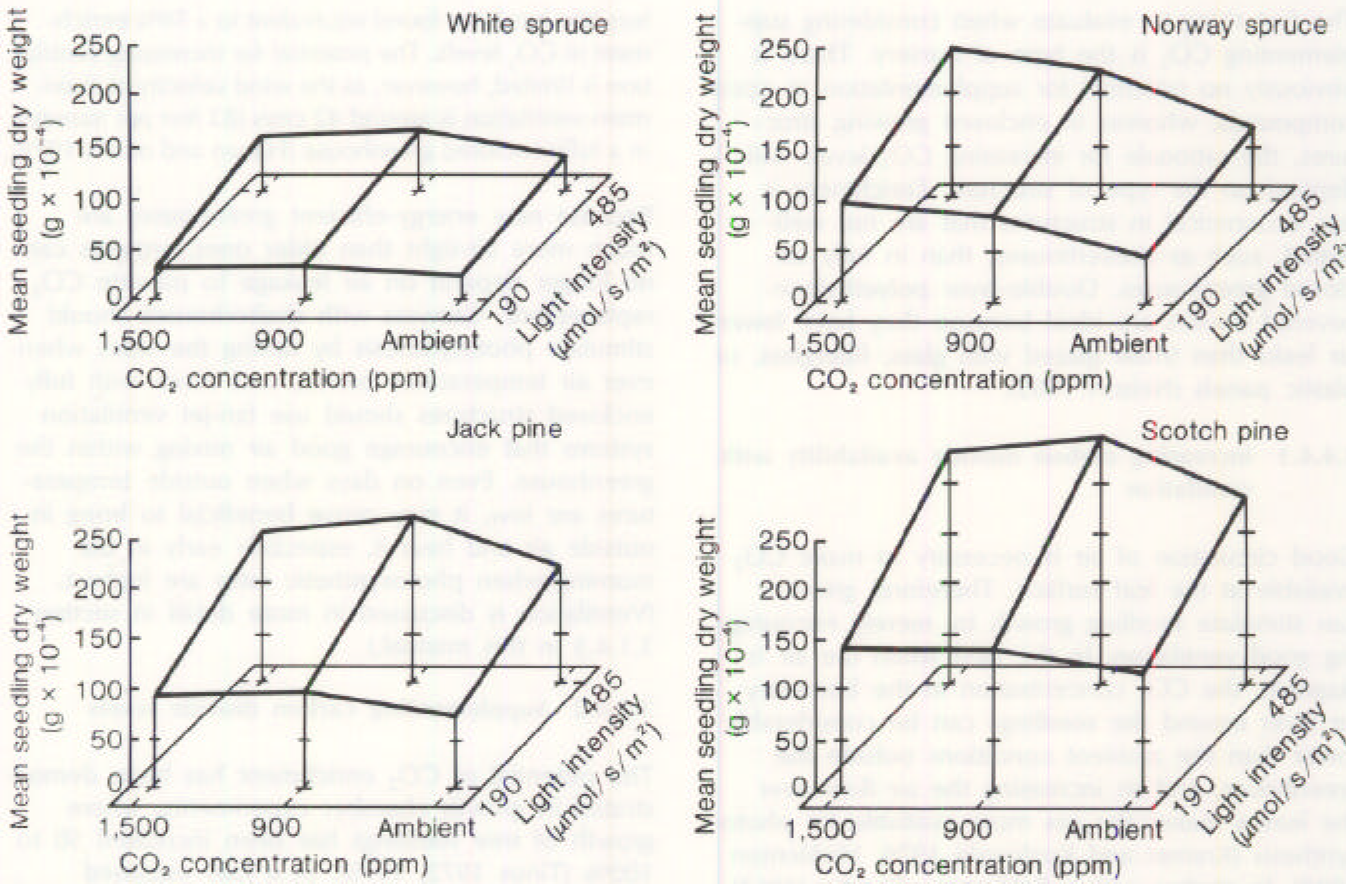


Figure 3.4.5—*Even 3-week-old conifer germinants showed a positive response to CO_2 enrichment in spite of the fact that the highest light level tested was only about 27% of full sunlight (modified from Yeatman 1970).*

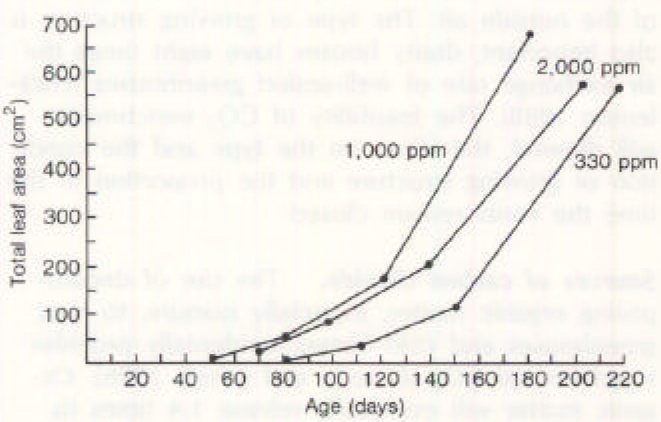


Figure 3.4.6—*The beneficial effects of enhanced CO_2 levels can actually accelerate over the growing season because larger leaves produce more photosynthate, which is used for increasingly more growth (adapted from Higginbotham and others 1985).*

and other stresses. Enhanced CO_2 retards leaf abscission in deciduous hardwoods and may stimulate budbreak and renewed growth. Therefore, container nursery managers should terminate CO_2 treatment before beginning the stress treatments used to initiate dormancy.

3.4.4 Modifying Carbon Dioxide in Container Tree Nurseries

The first thing to evaluate when considering supplementing CO_2 is the type of nursery. There is obviously no potential for supplementation in open compounds, whereas in enclosed growing structures, the rationale for increasing CO_2 levels will depend on the type of structure. Enrichment is less economical in structures that are not well-sealed, such as shelterhouses, than in fully enclosed greenhouses. Double-layer polyethylene covered houses are ideal because they have fewer air leaks than those glazed with glass, fiberglass, or plastic panels (Nelson *1985).*

3.4.4.1 Increasing carbon dioxide availability with ventilation

Good circulation of air is necessary to make CO_2 available at the leaf surface. Therefore, growers can stimulate seedling growth by merely encouraging good ventilation. In the light when the air is stagnant, the CO_2 concentration in the boundary air layer around the seedlings can be considerably lower than the ambient conditions outside the greenhouse, and so increasing the air flow over the leaves makes the gas more available for photo synthesis (Kramer and Kozlowski 1979, Hicklenton 1988). In studies with a field crop, Gaastra (1963) demonstrated that increasing the wind velocity over the leaf surface can significantly increase photosynthesis (table 3.4.2). In a greenhouse, an air flow rate of 50 cm/s (99 feet per minute), which is fast but feasible, has been found equivalent to a 50% enrichment in CO_2 levels. The potential for increasing ventilation is limited, however, as the wind velocity at maximum ventilation is around 42 cm/s (83 feet per minute) in a fully enclosed greenhouse (Hanan and others 1978).

Table 3.4.2—*The effect of wind velocity on the photosynthetic rate of leaves*

Wind velocity (cm/s)	Photosynthetic rate (mm^3 $CO_2/cm^2/h$)
10	79
16	88
42*	101
100	109
300	114
1000	118

* Typical greenhouse ventilation rate with fan and pad system.
Source: Gaastra (1963).

Because new energy-efficient greenhouses are much more air-tight than older ones, growers can no longer depend on air leakage to provide CO_2 replacement. Growers with shelterhouses should stimulate photosynthesis by raising the sides whenever air temperatures permit, and those with fully enclosed structures should use fan-jet ventilation systems that encourage good air mixing within the greenhouse. Even on days when outside temperatures are low, it may prove beneficial to bring in outside air and heat it, especially early in the morning when photosynthetic rates are highest. (Ventilation is discussed in more detail in section 3.1.4.3 in this manual.)

3.4.4.2 Supplementing carbon dioxide levels

The potential of CO_2 enrichment has been demonstrated in growth chamber experiments, where growth of tree seedlings has been increased 50 to 100% (Tinus 1972, 1976). In a fully enclosed greenhouse the response will be somewhat less because it is necessary to ventilate when air temperatures exceed optimum levels and it becomes impossible to maintain CO_2 levels much above that of the outside air. The type of growing structure is also important; drafty houses have eight times the air exchange rate of well-sealed greenhouses (Hicklenton 1988). The feasibility of CO_2 enrichment will depend, therefore, on the type and the condition of growing structure and the proportion of the time the vents remain closed.

Sources of carbon dioxide. The use of decomposing organic matter, especially manure, to heat greenhouses and cold-frames incidentally provides supplemental CO_2 (Bauerle and others 1986). Organic matter will eventually release 1.4 times its weight of CO_2 (Hanan and others 1978). Although these materials are cheap and readily available, they are rarely used in modern container nursery facilities because of problems with sanitation and disposal. Another serious drawback is the impossibility of controlling the decomposition rate and therefore the CO_2 concentration in the greenhouse. The potential has been demonstrated for forest nurseries, however, as white fir seedlings grown above an organic mulch were significantly taller than controls (Montano and others 1977). Hicklenton (1988) provides a good discussion of the possible applications for supplying CO_2 through controlled decomposition.

In modern container nurseries, there are two realistic options for supplying CO_2: injection of pure CO_2 and combustion of carbon fuels.

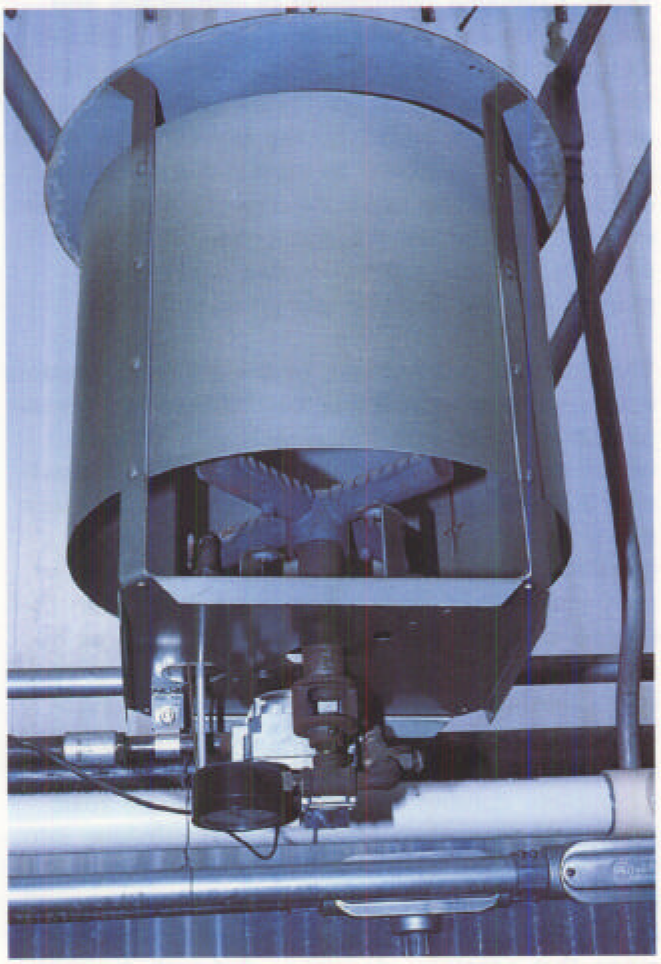
Pure carbon dioxide. The safest method of supplying CO_2 in greenhouses is to inject pure CO_2 from pressurized liquid tanks (Hicklenton 1988). The pressurized gas is distributed along the length of the greenhouse through perforated pipes. Hanan and others (1989) estimated an average CO_2 usage of 10 to 26 kg/m^2 (2 to 5 pounds per square foot) of greenhouse space for flower crops. Although effective, the major drawback of this method is the expense. In recent years, however, the higher costs and uncertain future of fossil fuels have made pure CO_2 more economically attractive (Nelson 1985).

Combustion of carbon fuels. Complete combustion of any carbon compound will produce CO_2 Kerosene was the first fuel to be used in greenhouses for CO_2 generation, although its cost and concerns about sulfur dioxide phytotoxicity have made it unpopular in many parts of the world. Propane and natural gas are more commonly used in commercial greenhouses, and the difference is primarily one of cost and availability. Both sources are pure enough, and thus are generally considered the most economical source of generating CO_2.

Carbon dioxide generators that burn propane or natural gas are commercially available (fig. 3.4.7). The CO_2 production rate is controlled by modulation of the burner, and approximately 15 burners per hectare (6 per acre) should generate 1,000 PPM CO_2 in a well-sealed greenhouse. The gas consumption of these generators is quite low—2 m^3/hr (70 cubic feet per hour) (Hicklenton 1988). Complete combustion of natural gas and propane requires adequate oxygen and produces CO_2 and water; propane produces proportionally less water than natural gas (Sheldrake (1964). Considerable heat is added by the burner: from 4,000 to 5,000 kcal/kg (8,000 to 10,000 Btu per pound) of fuel, depending upon the type of fuel and the efficiency of the burner. If excessive heat is a problem, burners can be located outside the greenhouse and the flue gas piped in.

The principal disadvantage of these CO_2 generators is that leaks or incomplete combustion can release phyto toxic gases into the greenhouse. Propane, which can contain a significant amount of propylene, is more of a concern because propylene can produce damage that is similar to ethylene (Abeles 1973). Natural gas is mainly a mixture of methane, ethane, and propane, but it too can contain potentially harmful contaminants, such as hy drogen sulfide, propylene, and ethylene, but in levels that are generally too low to cause problems. The burner flame should always be adjusted to a uniform blue color; traces of yellow indicate incomplete combustion, which can release toxic gases such as carbon monoxide and ethylene into the greenhouse environment (Hicklenton 1988). Carbon monoxide is dangerous to humans as well as to plants, and ethylene is a potent plant hormone that promotes dormancy and leaf abscission (Abeles 1973).

Exhaust gases from greenhouse heating systems that use propane or natural gas are another potential source of CO_2, but they are available only when heating is required. Scrubbed stack gas from industrial or electric generating plants also produces waste CO_2, as do fertilizer factories and some food processing plants. The practicality of these sources depends on the location of the greenhouse. The major benefit is that they are essentially free, and there is also the potential for utilizing waste heat from the source. Exhaust gases have the same potential problems as propane or natural gas, and incomplete combustion is more common and more difficult to detect than with the readily visible flames of CO_2 generators (Hicklenton 1988).



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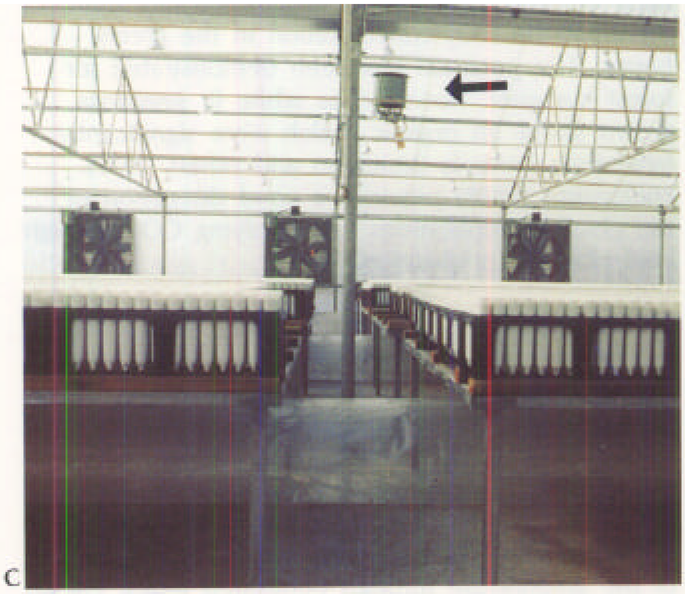

C

Figure 3.4.7—*Carbon dioxide generators burn propane or natural gas and produce heat and water vapor in addition to CO_2 (**A**). Some models (**B**) contain fans to increase the distribution of CO_2 in the greenhouse. If the generator itself does not have a fan, operating an air circulation system, such as a fan jet, is beneficial (**C**).*

Designing a carbon dioxide enrichment system. It is only practical to supply CO_2 in well-sealed greenhouses. Even though polyethylene is permeable to CO_2 greenhouses covered with polyethylene film are very air tight compared to glass or fiberglass structures.

Calculating carbon dioxide requirements. The quantity of CO_2 to supply depends on the amount used by the crop plus the leakage from the greenhouse. Specific calculations to determine the proper size of generator for a given size and type of greenhouse can be found in Aldrich and Bartok (1989), but table 3.4.3 provides a typical example. Calculations for fuel use and amount of heat generated are also described in the same reference.

Distribution within the greenhouse. Once a CO_2 generator has been installed, it is necessary to mix the gas with the greenhouse air to provide a uniform concentration at the crop level. This should not be a problem during cold days when the heating system creates normal convection currents, but Hicklenton (1988) reports that CO_2 levels are typically higher in the immediate vicinity of the gener-

Table 3.4.3—*Calculations for designing a CO_2 enrichment system for a greenhouse*

Given:

Double-layer polyethylene-covered greenhouse (L × W × H)
= 58.5 m × 29.2 m × 2.7 m (192 ft × 96 ft × 9 ft)

Air leakage = 0.5 air changes per hour

CO_2 target = 1,000 ppm

Ambient CO_2 level = 300 ppm

Plant use rate
= 0.0009 m^3 of CO_2 per hour per m^2 of crop (0.003 ft^2 of CO_2/h/ft^2)

Step 1. Determine plant use for greenhouse:

Plant use = plant use rate × greenhouse floor area
Plant use = 0.0009 m^3/hr/m^2 × 1,708 m^2
Plant use = 1.5 m^3 of CO_2/h
(55.3 ft^3 of CO_2/h)

Step 2. Determine leakage loss from greenhouse:

Leakage loss = greenhouse volume × air changes per hour × 0.000001 × (CO_2 target − ambient level)
Leakage loss = 4,610 m^3 × 0.5 × 0.000001 × 700
Leakage loss = 1.6 m^3 of CO_2/h (58 ft^3 of CO_2/h)

Step 3. Calculate CO_2 requirement:

CO_2 requirement = plant use + leakage loss
CO_2 requirement = 1.5 m^3 of CO_2/h + 1.6 m^3 of CO_2/h
CO_2 requirement = 3.1 m^3 of CO_2/h (113 ft^3 of CO_2/h)

Source: Aldrich and Bartok (1989).

ator. Carbon dioxide generators should be mounted with air circulation and fire safety in mind (fig. 3.4.7C). Some brands contain fans to ensure that the CO_2 is distributed horizontally across the greenhouse (fig. 3.4.713). Special vertical fan tube systems can be used to move CO_2 down to the crop level.

If pure CO_2 is injected from a point source, it must be distributed throughout the greenhouse. Some growers use fans to induce horizontal flow; others distribute the pressurized gas through finely perforated tubing installed along the length of the greenhouse at the crop level. Hicklenton (1988) discusses some common applications of injecting pure CO_2 in horticultural greenhouses.

Potential problems with combustion systems.
Several potentially dangerous gases can result from improperly designed or maintained CO_2 burners (table 3.4.4). Certain compounds, such as carbon monoxide and ethylene, are produced by incom-

Table 3.4.4—*Chemical pollutants produced from carbon dioxide generation*

Pollutant (chemical symbol)	Maximum allowable concentration (ppm)
Carbon monoxide (CO)	500
Nitrogen dioxide (NO_2)	20
Ammonia (NH_3)	10
Formaldehyde (HCHO)	0.7
Sulfur dioxide (SO_2)	0.2
Ozone (O_3)	0.2
Ethylene (C_2H_4)	0.05

Source: Compiled from numerous sources.

plete combustion (Scarratt 1985). Sulfur dioxides result from burning high-sulfur fuel. The following fuels were suggested for CO_2 generation because of their low sulfur content (Kretchman and Howlett 1970): propane, 0.01 % sulfur; natural gas, 0.02% sulfur; and kerosene, 0.02% sulfur.

A good way to ensure complete combustion is to provide a direct supply of outside air to the burner. An air intake area of 1 cm^2 for every 80 kcal (1 square inch for every 2,000 Btu) of burner capacity should provide sufficient air for complete burning. The burner should be properly adjusted. If the flame is yellow, and especially if it is smokey, it may produce harmful products of partial combustion; if the flame is short and very turbulent, there is likely to be some gas that escaped unburned into the greenhouse. For a further discussion of combustion-generated pollutants that can be produced by CO_2 generators, see Hicklenton (1988) and Hand (1986).

3.4.5 Carbon Dioxide Monitoring and Control Systems

3.4.5.1 Measuring carbon dioxide levels

Once the generators have been adjusted to produce the desired levels, most nurseries do not monitor CO_2 levels continuously, but check them occasionally. Small hand-pump CO_2 testers with reasonable accuracy are available for around $200; the air is pumped through a glass tube that contains a CO_2-sensitive chemical that changes color as an air sample is drawn through it (Pallas 1986) (fig. 3.4.8A).

A more sophisticated and expensive ($1,400) monitor, the infrared gas analyzer, is popular because of its accuracy and precision (fig. 3.4.813). These analyzers can measure CO_2 continuously and can interface directly with environmental computer systems (Pallas 1986). Nurseries that do not have infrared gas analyzers may be able to have samples tested at a nearby university or agricultural research station. Samples can be taken by filling a clean inner tube with greenhouse air using a bicy cle pump. Butyl rubber is highly impermeable to

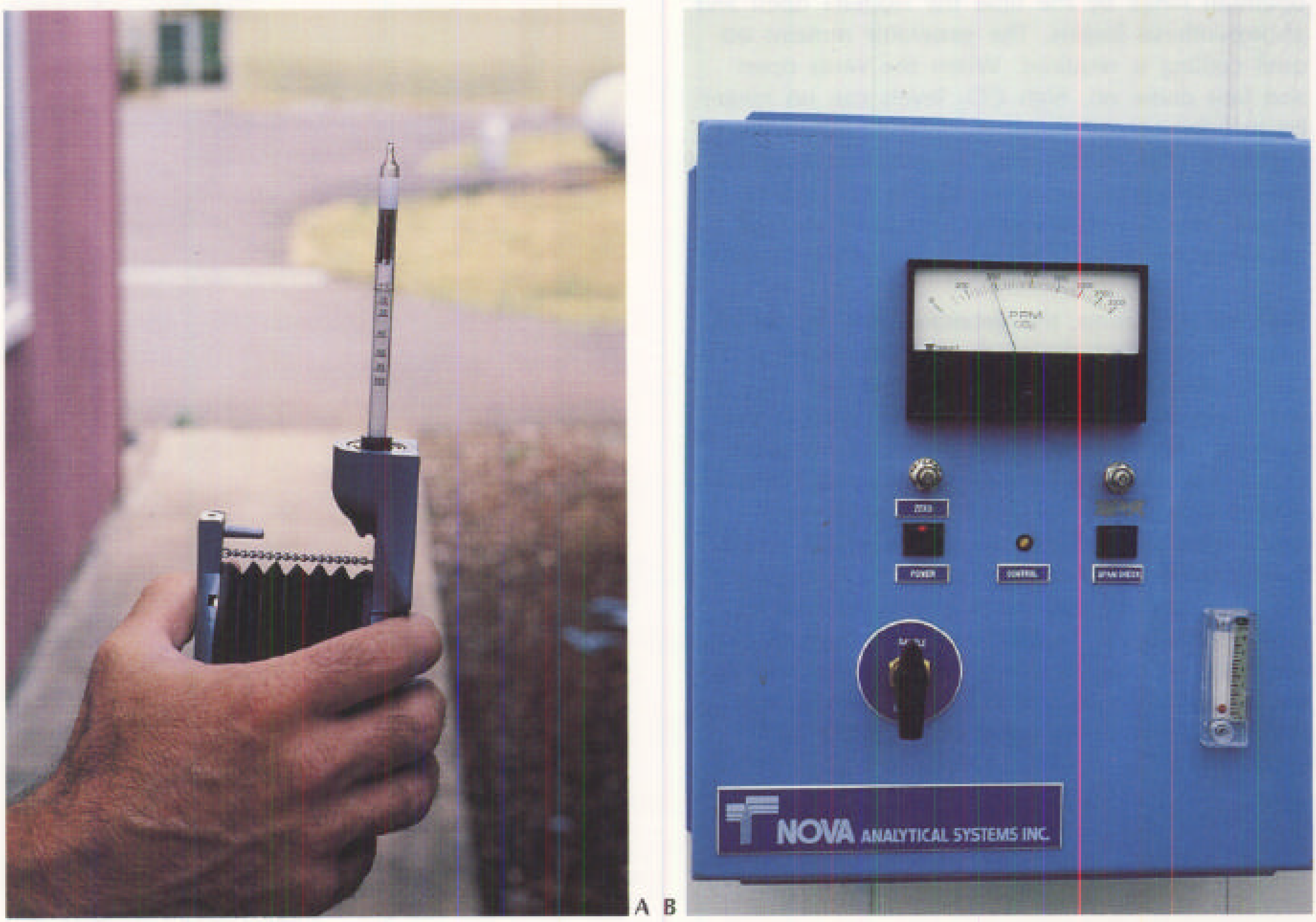

Figure 3.4.8—*Hand pump CO_2 testers* (**A**) *operate by forcing air through a glass tube that is filled with reactive chemicals. The CO_2 concentration is measured by the distance of the color change down the tube. More sophisticated and expensive infrared gas analyzers precisely monitor CO_2 levels and provide constant feedback to the generators* (**B**).

CO_2, and such samples should be good for days. Do not use plastic bags, unless the samples can be analyzed in a matter of minutes. Be sure no human breath is mixed with the sample.

3.4.5.2 Carbon dioxide control systems

A simple and inexpensive CO_2 control system uses a photocell or time clock that is connected to the thermostat that controls the first stage of cooling. The generator comes on at dawn or about 1 hour before, boosting the CO_2 concentration into the optimum range by the time the stomata open and photosynthesis begins. The generator remains on until cooling is required. When the vents open and fans come on, high CO_2 levels can no longer be maintained and the thermostat shuts off the generator. The system may be activated again in the late afternoon when ventilation for cooling ceases. The time clock would normally shut off the generator about one-half hour before sunset.

With these systems, the generator may be on all day in winter; but during the warmer seasons, it is usually possible to raise the CO_2 level for only a few hours in the early morning and again in the evening. This relatively short period of increased CO_2 is still effective because the stomata typically close during midday because of normal water stress, even if the plants are well watered. Under these conditions, photosynthesis is most rapid in the early morning and has a secondary peak in the late afternoon. In addition, the enhanced CO_2 will keep the stomata partly closed, which will delay the midday moisture stress and perhaps prevent the dip in photosynthesis (Pettibone and others 1970).

The best way to control CO_2 concentration is to use an automatic feedback system that continuously measures CO_2 concentration and adds CO_2 as needed. Many microcomputer control systems use infrared gas analyzers and a system of solenoid valves to regulate the CO_2 concentration in the greenhouse to within 100 ppm. These systems are expensive ($3,000 to 10,000), but new models are durable and have a proven record in operational greenhouses. Pallas (1986) and Hicklenton (1988) provide an excellent review of CO_2 measurement and control systems and their suppliers.

3.4.6 Conclusions and Recommendations

Carbon dioxide is commonly the most limiting factor to photosynthesis in the natural environment, and this situation is exacerbated in greenhouses that restrict air exchange, especially in cool weather when vents are closed. Although CO_2 levels are not currently managed in most container tree nurseries, numerous research studies have demonstrated the benefits from doing so.

Growers can insure that their crops get enough CO_2 in two ways: first, by encouraging adequate ventilation during periods when photosynthesis is greatest, and second, by direct supplementation. Fully controlled greenhouses should supplement CO_2 levels to 1,000 ppm, and even growers with semicontrolled growing structures can increase photosynthesis and growth by promoting good air exchange during cool weather, especially during early morning hours. Nurseries that grow crops during winter months are particularly well-suited for CO_2 enrichment, especially at high latitudes where supplemental photosynthetic lighting is also used.

Carbon dioxide enrichment has been shown to increase the growth rate of many forest tree seedlings, but species variation should be expected. Enhanced CO_2 levels will give the best results early in the growing season and can even help during the establishment phase. Because it may inhibit dormancy and cold hardiness, CO_2 supplementation should be stopped at the beginning of the hardening phase. The accelerated seedling growth rates that are experienced will cause an increased demand for mineral nutrients and water, and so growers must adjust their fertilization and irrigation schedules when CO_2 enrichment is used. Likewise, crops grown under high CO_2 can tolerate higher temperatures and benefit from higher light intensities. Shorter crop rotations can be expected.

The practicality and economics of CO_2 enrichment must be calculated for each individual container nursery but, considering that annual operating costs are only \$1 to \$2 per m^2 (\$0.10 to \$0.15 per square foot), more growers should consider this cultural practice (Freeman 1985).

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Table A.1—*Conversion factors for a range of typical container nursery temperatures (Celsius to Fahrenheit)*

Celsius to Fahrenheit (°C × 9/5) + 32 = °F							
°C	°F	°C	°F	°C	°F	°C	°F
100	**212**	**60**	**140**	**20**	**68**	**−20**	**−4**
98	208	58	136	18	64	−22	−8
96	205	56	133	16	61	−24	−11
94	201	54	129	14	57	−26	−15
92	198	52	126	12	54	−28	−18
90	**194**	**50**	**122**	**10**	**50**	**−30**	**−22**
88	190	48	118	8	46	−32	−26
86	187	46	115	6	43	−34	−29
84	183	44	111	4	39	−36	−33
82	180	42	108	2	36	−38	−36
80	**176**	**40**	**104**	**0**	**32**	**−40**	**−40**
78	172	38	100	−2	28		
76	169	36	97	−4	25		
74	165	34	93	−6	21		
72	162	32	90	−8	18		
70	**158**	**30**	**86**	**−10**	**14**		
68	154	28	82	−12	10		
66	151	26	79	−14	7		
64	147	24	75	−16	3		
62	144	22	72	−18	0		
60	**140**	**20**	**68**	**−20**	**−4**		

Table A.2—*Conversion factors for a range of typical container nursery temperatures (Fahrenheit to Celsius)*

Fahrenheit to Celsius ($(°F - 32) \times 5/9 = °C$)									
°F	°C	°F	°C	°F	°C	°F	°C	°F	°C
212	100								
210	**99**	**160**	**71**	**110**	**43**	**60**	**16**	**10**	**−12**
208	98	158	70	108	42	58	14	8	−13
206	97	156	69	106	41	56	13	6	−14
204	95	154	68	104	40	54	12	4	−16
202	94	152	67	102	39	52	11	2	−17
200	**93**	**150**	**65**	**100**	**38**	**50**	**10**	**0**	**−18**
198	92	148	64	98	37	48	9	− 2	−19
196	91	146	63	96	36	46	8	− 4	−20
194	90	144	62	94	34	44	7	− 6	−21
192	89	142	61	92	33	42	6	− 8	−22
190	**88**	**140**	**60**	**90**	**32**	**40**	**4**	**−10**	**−23**
188	87	138	59	88	31	38	3	−12	−24
186	86	136	58	86	30	36	2	−14	−26
184	84	134	57	84	29	34	1	−16	−27
182	83	132	56	82	28	32	0	−18	−28
180	**82**	**130**	**54**	**80**	**27**	**30**	**− 1**	**−20**	**−29**
178	81	128	53	78	26	28	− 2	−22	−30
176	80	126	52	76	24	26	− 3	−24	−31
174	79	124	51	74	23	24	− 4	−26	−32
172	78	122	50	72	22	22	− 6	−28	−33
170	**77**	**120**	**49**	**70**	**21**	**20**	**− 7**	**−30**	**−34**
168	75	118	48	68	20	18	− 8	−32	−36
166	74	116	47	66	19	16	− 9	−34	−37
164	73	114	46	64	18	14	−10	−36	−38
162	72	112	44	62	17	12	−11	−38	−39
160	**71**	**110**	**43**	**60**	**16**	**10**	**−12**	**−40**	**−40**

Index of Common and Scientific Names

Trees

Other Plants

Pathogens