Chapter 15

Guidelines for Measurement and Reporting of Environmental Conditions

Donald T. Krizek, John C. Sager, and Theodore W. Tibbitts

Contents

The environmental conditions employed in growth chambers should be reported in detail sufficient to allow either comparison of the results with similar experiments in other laboratories or effective duplication of experiments within the same laboratory at a later date. The following guidelines are presented to assist investigators to achieve these objectives. The guidelines also will alert investigators to factors of the environment that could be important in their experiments but that they do not measure.

These guidelines were first published in 1972 (HortScience 7:239) and during the next decade were published in many different plant science journals and publications by various members of the growth chamber group. They were developed initially by the American Society of Horticultural Science Growth Chamber Working Group. Now the responsibility for revisions is assumed by the USDA North Central Regional Committee on Controlled Environment Use and Technology (NCR-101). The following guidelines were developed for the American Society of Agricultural Engineers Environment of Plant Structures Committee and published as ASAE Engineering Practice 411 originally in 1982 with a last revision in February 1992 (EP 411.2). Updates are scheduled every 5 years. The following guidelines incorporate some recent modifications and corrections not found in the 1992 revision. The following sections duplicate the ASAE Engineering Practice 411.2 format.

Readers are directed to Section 7 for the summary of the measurement and reporting guidelines that are recommended in conducting and publishing growth chamber research.

Section 1: Purpose and Scope

1.1 The purpose of this Engineering Practice is to set forth guidelines for the measurement of environmental parameters that characterize the aerial and root environment in a plant growth chamber.

1.2 This Engineering Practice establishes criteria that will promote a common basis for environmental measurements for the research community and the commercial plant producer.

1.3 This Engineering Practice promotes uniformity and accuracy in reporting data and results in the course of conducting plant experiments.

Section 2: Introduction

2.1 The aerial environment is characterized by the following parameters: air temperature, atmospheric composition including moisture and carbon dioxide concentration, air velocity, radiation, and the edge effects of wall/floor on these parameters.

2.2 The root environment is characterized by the following parameters: medium composition and quantity, nutrient concentrations, water content, temperature, pH, electrical conductivity, and oxygen concentration.

2.3 Measuring and reporting these various parameters will be covered in the sections that follow. The definitions of the parameters indicate the symbol and units in the format (symbol, units). Measurements should be made that accurately represent the mean and range of the environmental parameters to which the plants are exposed during the experimental period, to indicate the temporal variations, both cyclic and transient, and the spatial variations over the separate plants in the chamber.

2.4 The definitions, measurement techniques, and reporting procedures provide criteria and promote uniformity in measuring and reporting environmental parameters, but these guidelines should not be used to select the environmental parameters applicable to a particular experiment. Other parameters may be applicable to a particular experiment or special environments such as elemental concentration in hydroponic solutions, pollutant concentration in air quality research, and spectral quality ratios in photobiology.

2.5 When measurements are made, the chamber should be operating with containers and plants located in the chamber. Provision should be made to take all measurements with minimum disturbance to the operating environment.

Section 3: Definitions

3.1 **Radiation:** The emission and propagation of electromagnetic waves or particles through space or matter.

3.1.1 **Radiant energy** (Q_e, J): The transfer of energy of radiation.

3.1.2 **Energy flow rate** ($\o_e$, W): The rate of flow of energy, a fundamental radiometric unit; also called radiant power.

3.1.3 **Spectral distribution:** A functional or graphic expression of the relation between the spectral energy flux, spectral photon flux, or fluence rate per unit wavelength, and wavelength.

3.1.4 **Spectral energy flow rate** ($\o_{e,\lambda}$, $W{\cdot}nm^{-1}$): The radiant energy flow rate per unit wavelength interval at wavelength λ.

3.1.5 **Energy flux** (E_e, $W{\cdot}m^{-2}$): The radiant energy flow rate per unit plane (flat) surface area; also called irradiance.

3.1.6 **Spectral energy flux** ($E_{e,\lambda}$, $W{\cdot}m^{-2}nm^{-1}$): The radiant energy flow rate per unit plane surface per unit wavelength interval at wavelength λ.

3.1.7 **Energy fluence** (F_e, J·m^{-2}): The radiant energy dose time integral per unit spherical area.

3.1.8 **Spectral energy** fluence ($F_{e,\lambda}$, J·m^{-2}nm^{-1}): The energy fluence per unit wavelength interval at wavelength λ.

3.1.9 **Energy fluence rate** ($F_{e,t}$, W·m^{-2}): The radiant energy fluence per unit time. The same as radiant energy flux (irradiance) for normal incident (perpendicular) radiation on a plane surface.

3.1.10 **Spectral energy fluence rate** ($F_{e,t,\lambda}$, W·m^{-2}nm^{-1}): The radiant energy fluence rate per unit wavelength interval at wavelength λ.

3.1.11 **Photon** (unit = q; i.e., one photon): A quantum (the smallest, discrete particle) of electromagnetic energy with an energy of hc/λ (h = Planck's constant; c = speed of light; λ = wavelength). Its energy is expressed in joules (J).

3.1.12 **Photon flow rate** ($ø_p$, q·s^{-1} or mol·s^{-1}): The rate of flow of photons.

3.1.13 **Photon flux** (E_p, q·m^{-2}· s^{-1} or mol·m^{-2}· s^{-1}): The photon flow rate per unit plane surface area; sometimes also called photon flux density to emphasize the unit area.

3.1.14 **Spectral photon flux** ($E_{p,\lambda}$, q·m^{-2}· s^{-1}· nm^{-1} or mol·m^{-2}·s^{-1}·nm^{-1}): The photon flux per unit wavelength interval at wavelength λ.

3.1.15 **Photon fluence** (F_p, q·m^{-2} or mol·m^{-2}): The photon dose time integral per unit spherical area.

3.1.16 **Photon fluence rate** ($F_{p,t}$, q·m^{-2}· s^{-1} or mol·m^{-2}· s^{-1}): The photon fluence per unit time. The same as photon flux for normal incident radiation.

3.1.17 **Spectral photon fluence rate** ($F_{p,t,\lambda}$, q·m^{-2}·s^{-1}·nm^{-1} or mol·m^{-2}·s^{-1} · nm^{-1}): The photon fluence rate per unit wavelength interval at wavelength λ.

3.1.18 **Light:** Visually evaluated radiant energy, with wavelengths approximately ranging between 380 and 780 nm, based on the sensitivity of the human eye.

3.1.19 **Illuminance** (E_v , lx): The luminous flux (light incident per unit area).

NOTE: (a) Radiation instruments that measure illuminance are not recommended. They should only be used along with recommended radiation instruments for historical comparison. (b) Conversion factors from illuminance to radiation are spectrally sensitive and thus unique for each specified source.

3.1.20 **Photosynthetically active radiation** (*PAR*, q·m^{-2}·s^{-1}, mol·q·m^{-2} · s^{-1}, or W·m^{-2}): The radiation in the wavelength range of 400-700 nm. Measured as the photosynthetic photon flux (*PPF*), in quanta· m^{-2}·s^{-1}, or mol·m^{-2}· s^{-1} or photosynthetic irradiance, (*PI*), in W·m^{-2} for the specified waveband, λ_1-λ_2 (400-700 nm).

3.1.21 **Photomorphogenic radiation** (q·m^{-2}·s^{-1}, mol·m^{-2}·s^{-1}, or W·m^{-2}): The radiation with wavelengths approximately ranging between 300-800 nm contributing to photomorphogenic responses (i.e., phototropism, flowering, reproduction, elongation, dormancy) in relation to the relative quantum efficiency of the spectral quality of the radiation in several discrete spectral regions. Measured as the photon flux in average quanta·m^{-2}·s^{-1}, or in energy flux in W·m^{-2} for the specified waveband, λ_1-λ_2.

NOTE: The specfic responses to photomorphogenic radiation must be biologically quantified and carefully measured for each response spectrum (action spectrum).

3.2 **Temperature:** The thermal state of matter with reference to its tendency to transfer heat. A measure of the mean molecular kinetic energy of that matter.

3.2.1 **Temperature, dry bulb** (T, °C): The temperature of a gas or mixture of gases indicated by an accurate thermometer protected from or corrected for radiation effects.

3.2.2 **Temperature, wet-bulb** (T_w, °C): Wet-bulb temperature is the temperature indicated by a wet-bulb sensor of a psychrometer constructed and used according to instructions.

3.2.3 **Temperature, dewpoint** (T_d, °C): The temperature of an air mass at which the condensation of water vapor begins as the temperature of the air mass is reduced. Also, the temperature corresponding to saturation vapor pressure (100% relative humidity) for a given air mass at constant pressure.

3.3 **Atmospheric moisture:** The water vapor component of the mixture of gases of the atmosphere.

3.3.1 **Water vapor density** (P_r, $g{\cdot}m^{-3}$ or Pa): The ratio of the mass of water vapor to a given volume of air, also called absolute humidity. It may also be measured as partial pressure. (Water vapor pressure).

3.3.2 **Relative humidity** (H_r, percent): The ratio of the mol fraction of water vapor present in the air to the mol fraction of water vapor present in saturated air at the same temperature and barometric pressure. It approximates the ratio of the partial pressure or density of the water vapor in the air to the saturation pressure or density of water vapor at the same temperature.

3.3.3. **Water vapor deficit** (e_d, Pa): The difference between saturation water vapor pressure at ambient temperature and actual vapor pressure at ambient temperature.

3.4 **Air velocity** (V, $m{\cdot}s^{-1}$): The time rate of air motion along a directional vector.

3.5 **Carbon dioxide concentration** ($[CO_2]$, $\mu mol{\cdot}mol^{-1}$ or Pa): The carbon dioxide component of the mixture of gases of the atmosphere. Current expression of units of equivalent gas concentration are $\mu mol{\cdot}mol^{-1}$, parts per million (ppm), or $\mu L{\cdot}L^{-1}$, but they do not express standard temperature and pressure, *STP*, correction. Use of partial pressure, Pa, is preferred in nonstandard atmospheres.

3.6 **Watering** (volume, L): The addition of water to the substrate specified as to the source, the times, the amount, and the distribution method.

3.7 **Substrate:** The media comprising the root environment specified as to type, amendments, and its dimensions (container size).

3.8 **Nutrition:** The organic and inorganic nutrient salts necessary for plant growth and development. Formula and/or macro and micro nutrients are specified within the substrate as $mol{\cdot}m^{-3}$ or $mol{\cdot}kg^{-1}$ within liquid solution as $mol{\cdot}L^{-1}$.

3.9 **Hydrogen ion concentration** (*p*H units): The hydrogen ion concentration measured in the substrate or liquid media over a range of 0 to 14 *p*H units.

3.10 **Electrical conductivity** (λ_c, $mS{\cdot}m^{-1}$): The electrical conductivity within the solid or liquid media.

3.11 **Accuracy:** The extent to which the readings of a measurement approach the true values of a single measured quantity.

3.12 **Precision:** The ability of the instrument to consistently reproduce a value of a measured quantity.

Section 4: Instrumentation

4.1 **Radiation.** Sensors should be cosine corrected and constructed of material of known stability, known response curve, and low temperature sensitivity. Such relationships should be specified and available for each sensor. By definition fluence measurements can only be taken with spherical sensors and cannot be derived from measurements taken with any plane-surface sensors. The sensitivity and linearity over the spectral response and irradiance range should be specified by calibration or direct transfer from a calibrated instrument. Spectral measurements should be made with a bandwidth of 20 nm or less in the 300-800 nm waveband.

4.2 **Temperature.** Sensors should be shielded with reflective material and aspirated (≥ 3 $m \cdot s^{-1}$) for air measurements.

4.3 **Atmospheric moisture.** Measurement should be made by infrared analyzer, dewpoint sensor, or psychrometer (shielded and aspirated at ≥ 3 $m \cdot s^{-1}$).

4.4 **Air velocity.** Sensor should have a range of 0.1 to 5.0 $m \cdot s^{-1}$.

4.5 **Carbon dioxide.** Measurement should be made by an infrared analyzer with a range of 0 to 1000 $\mu mol \cdot mol^{-1}$ or greater.

4.6 **Hydrogen ion concentration.** Sensor should have a range of 3.0 to 10.0 *p*H units.

4.7 **Electrical conductivity.** Sensor should have a range of 1 to 10^{-2} $mS \cdot m^{-1}$ (1-100 mho resistance).

4.8 **Expected instrument precision and measurement accuracy.** Table 1 gives these percentages, which indicate full scale precision or accuracy. Further definition of these requirements can be found in North Central Regional 101 Committee on Growth Chamber Use (1986).

Table 1. Expected Instrument Precision and Measurement Accuracy

Parameter	Instrument precision	Measurement accuracy of reading
Radiation		
Flux	± 1 %	± 10 %
Spectral flux	± 1 %	± 5 %
Temperature		
Air	± 0.1 °C	± 0.2 °C
Soil or liquid	± 0.1 °C	± 0.2 °C
Atmospheric moisture		
Relative humidity	± 2 %	± 5 %
Dewpoint temperature	± 0.1 C	± 0.5 °C
Water vapor density	± 0.1 g◊m^{-3}	± 0.1 $g \cdot m^{-3}$
Air velocity	± 2 %	± 5 %
Carbon dioxide	± 1 %	± 3 %
*p*H		
H^+ concentration	± 0.1 *p*H	± 0.1 *p*H
Electrical conductivity		
Salt concentration	± 5 %	± 5 %

Section 5: Measurement Technique

5.1 **Photon and energy flux.** Measurements should be taken over the top of the plant canopy to obtain the average, maximum, and minimum readings, and at least at the start and end of each study and biweekly if studies extend beyond 14 days.

5.2 **Spectral photon or energy flux.** A measurement should be taken at the center of the growing area, at least at the start and end of each study.

5.3 **Air temperature.** Measurements should be made at the top of the plant canopy at least daily, 1 h or more after each light and dark period begins, to obtain average, maximum, and minimum data. Continuous measurements are recommended.

5.4 **Soil and liquid temperatures.** Measurements should be made at the center of the containers in the growing area, obtaining average, maximum, and minimum readings at the middle of the light and dark periods at the start of the experiment. Continuous measurements during the entire study are recommended.

5.5 **Atmospheric moisture.** Measurements should be made at the top of the plant canopy in the center of the growing area daily, 1 h or more after each light and dark period. Continuous measurements are recommended.

5.6 **Air velocity.** Measurements should be taken at the top of the plant canopy, at the start and end of the studies. Obtain average, maximum, and minimum readings over the plants. If instantaneous devices are utilized, 10 consecutive readings should be taken at each location and averaged.

5.7 **Carbon dioxide.** Measurements should be taken at the top of the plant canopy continuously during the period of the study. A time-sharing technique that provides a periodic measurement (at least hourly) in each chamber can be utilized.

5.8 **Watering.** The quantity of water added to each container or average per plant at each watering should be measured. Soil moisture should be measured to provide the range between waterings.

5.9 **Nutrition.** Measurement of nutrients added to a volume of medium or concentration of nutrients added in liquid culture should be obtained at each addition.

5.10 **Hydrogen ion concentration.** The *p*H of the liquid solutions in a nutrient culture system should be monitored daily and before each *p*H adjustment. The *p*H of the solution extracted from solid media should be measured at the start and end of studies and before and after each *p*H adjustment.

5.11 **Electrical conductivity.** Conductivity of the liquid solutions in a nutrient culture system should be monitored daily during the course of each study. Conductivity of the solution extracted from solid media should be measured at the start and end of each study.

SECTION 6: REPORTING

6.1 Photon or energy flux. Report the average and range over the containers at the start of the study, and the decrease or fluctuations from the average over the course of the study. The source of radiation and the measuring instrument/sensor should be reported. Illuminance should not be reported except for historical comparison in conjunction with other radiation measurements.

6.2 **Spectral photon or energy flux.** Report the spectral distribution (graphical) and the integral (photon or energy flux) at the start of the study. The source of radiation and the measuring instruments should be reported.

6.3 **Air temperature.** Report the average daily readings with extremes over the growing area for the light and dark periods with the range of variations over the course of the study.

6.4 **Soil and liquid temperatures.** Report the average readings at the start of the study for the light and dark periods.

6.5 **Atmospheric moisture.** Report the daily average moisture level for both light and dark periods with the range over the course of the study.

6.6 **Air velocity.** Report the average and range over containers at the start and end of the study.

6.7 **Carbon dioxide.** Report the mean of hourly average concentrations and range of average readings over the period of the study.

6.8 **Watering.** Report the frequency of watering, source, and amount of water added daily to each container, and/or the range in soil moisture content between waterings.

6.9 **Substrate.** Report the type of soil and amendments, or components of soilless substrate, and container dimensions.

6.10 **Nutrition.** Report the nutrients added to solid media. Report the concentration of nutrients in liquid additions and in liquid culture solution along with the amount and frequency of all additions.

6.11 **Hydrogen ion concentration.** Report the average and range in *p*H over the period of the study.

6.12 **Electrical conductivity.** Report the average and range in conductivity over the period of the study.

Section 7: Synoptic Table

7.1 Table 2 is a synoptic table of the material presented in the previous section.

Table 2. Guidelines for Measuring and Reporting Environmental Parameters for Plant Experiments in Growth Chambers*

		Measurements		
Parameter	**Units**[a]	**Where to take**	**When to take**	**What to report**
Radiation				
Photon flux, λ_1 - λ_2 nm, with cosine correction or ***Energy flux*** (Irradiance)[b], λ_1 - λ_2 nm with cosine correction	$\mu mol \cdot m^{-2} \cdot s^{-1}$ (λ_1 - λ_2 nm) or $W \cdot m^{-2}$ (λ_1 - λ_2 nm)	At top of plant canopy. Obtain maximum and minimum over plant growing area.	Minimum measurement: at start and finish of each study and biweekly if studies extend beyond 14 d.	Average ($\pm$ extremes) over containers at start of study. Percent decrease or fluctuation from average over course of the study. Source of radiation and instrument/sensor.
Spectral photon flux λ_1 - λ_2 nm, in <20 nm bandwidths with cosine correction or ***Spectral energy flux (Spectral irradiance)*** λ_1 - λ_2 nm, in <10 nm bandwidths with cosine correction	$\mu mol \cdot m^{-2} \cdot s^{-1} \cdot nm^{-1}$ (λ_1 - λ_2 nm) or $W \cdot m^{-2} \cdot nm^{-1}$ (λ_1 - λ_2 nm)	At top of plant in center of growing area.	Minimum measuremenr: at start and end of each study.	Spectral distribution of radiation with integral (λ_1 - λ_2) at start of study. Source of radiation and instrument/sensor.
Photosynthetic photon flux, PPF,[c] λ_{400} - λ_{700} nm with cosine correction or ***Photosynthetic irradiance, PI,***[c] λ_{400} - λ_{700} nm with cosine correction	$\mu mol \cdot m^{-2} \cdot s^{-1}$ (λ_{400} - λ_{700} nm) or $W \cdot m^{-2}$ (λ_{400} - λ_{700} nm)	At top of plant canopy. Obtain maximum and minimum over plant growing area.	Minimum measurement: at start and finish of each study and biweekly if studies extend beyond 14 d.	Average ($\pm$ extremes) over containers at start of study. Percent decrease or fluctuation from average over the course of the study. Source of radiation and instrument/sensor.
Temperature				
Air Shielded and aspirated ($\geq 3\ m \cdot s^{-1}$) device	°C	At top of plant canopy. Obtain maximum and minimum over plant growing area.	Minimum measurement: measure once daily during each light and dark period at least 1 h after light change. Desirable: continuous measurement.	Average of once daily readings (or hourly average values) for the light and dark periods of the study with $\pm$ extremes for the variation over the growing area.
Soil and liquid	°C	In center of container. Obtain maximum and minimum over plant growing area.	Minimum: measure at the middle of the light and dark periods at the start of the study. Desirable: continuous measurement.	Light and dark period readings at the start of the study (or hourly average values of 24 h if taken).

(continued)

Table 2. *(continued)*

Parameter	Units[a]	Measurements: Where to take	When to take	What to report
Atmospheric Moisture Relative humidity (RH) with aspirated psychrometer, dewpoint hygrometer, or IRGA or	%RH, dewpoint temperature, or $g \cdot m^{-3}$ or	At top of plant canopy in center of plant growing area.	Minimum: once during each light and dark period at least 1 h after light changes. Desirable: continuous measurement.	Average of daily readings for both light and dark periods, with range of daily variation during studies.
Vapor deficit, *VPD* or vapor difference	kPa or $g \cdot m^{-3}$			
Air Velocity	$m \cdot s^{-1}$	At top of plant canopy. Obtain maximum and minimum readings over growing area.	At start and end of studies. Take 10 successive readings at each location and age.	Average reading and range over containers at start and end of the study.
Carbon Dioxide		At top of plant canopy	Minimum: hourly measurements. Desirable: continuous measurement.	Mean of hourly average concentrations and range of average concentrations over the period of the study.
Mole fraction	$\mu mol \cdot mol^{-1}$			
Partial pressure	Pa			
Concentration	$mol \cdot m^{-3}$			
Watering	liter (L)		At times of water additions.	Frequency of watering. Amount of water added and/or range in soil moisture content between waterings.
Substrate			At beginning of studies.	Type of soil and amendments. Components of soilless substrate. Water retention capacity. Container dimensions.
Nutrition	Soil media $mol \cdot m^{-3}$ or $mol \cdot kg^{-1}$ Liquid culture $mol \cdot L^{-1}$.		At times of nutrient additions.	Nutrients added to solid media. Concentration of nutrients in liquid additions and solution culture. Amount and frequency of solution addition and renewal.
***p*H**	*p*H units	In saturated media, extract from media or in solution of liquid culture.	Start and end of studies in solid media. Daily in liquid culture. Before each *p*H adjustment.	Mode and range during studies.
Electrical conductivity	$mS \cdot m^{-1}$[d] (millisiemens per meter)	In saturated media, extract from media or in solution of liquid.	Start and end of studies in solid media. Daily in liquid culture.	Average and range during studies.

*USDA North Central Regional (NCR 101) Committee on Controlled Environment Technology and Use, June 1978; Revised by ASAE Environment of Plant Structures Committee, Oct. 1978; Revised by NCR 101 Committee, March 1993.

[a] Report in other subdivisions of indicated units if more convenient.

[b] The energy flux (irradiance) is also commonly reported in $J \cdot m^{-2} \cdot s^{-1}$ (equals $W \cdot m^{-2}$)

[c] Referred to as photosynthetically active radiation (*PAR*) for general usage.

[d] $mS \cdot m^{-1} = 10\ \mu mho \cdot cm^{-1}$.

SECTION 8: BIBLIOGRAPHY

American Society for Horticultural Science Working Group on Growth Chambers and Controlled Environments. 1980. Guidelines for measuring and reporting the environment for plant studies. HortScience 15(6):719-720.

ASAE. 1988. ASAE Engineering Practice: ASAE EP285.7, Use of SI (Metric) Units. American Society of Agricultural Engineers, St. Joseph, MI 49085.

ASAE. 1985. ASAE Engineering Practice: ASAE EP402, Radiation Quantities and Units. American Society of Agricultural Engineers, St. Joseph, MI 49085.

Bell, C. J. and D. A. Rose. 1981. Light measurement and the terminology of flow. Plant, Cell and Environment 4:89-96.

Bickford, E. D. and S. Dunn. 1972. Lighting for Plant Growth. The Kent State University Press, Kent, Ohio.

Biggs, W. W. and M. C. Hansen. 1979. Instrumentation for biological and environmental sciences. LI-COR Inc. Lincoln, Nebraska.

C.I.E. 1970. International Lighting Vocabulary. Publ. No. 17. *Commission Internationale de l'Eclairage*, Paris, France.

Downs, R. J. 1975. Controlled Environments for Plant Research. Columbia University Press, New York, NY.

Downs, R. J. 1988. Rules for using the international systems of units. HortScience 12(5):811-812.

Geist, J. and E. Zalewski. 1973. Chinese nomenclature for radiometry. Applied Optics 12:435-436.

Holmes, M. G. and L. Fukshansky. 1979. Phytochrome photoequilibrium in green leaves under polychromatic radiation: a theoretical approach. Plant, Cell and Environment 2:59-65.

Holmes, M. G., W. H. Klein and J. C. Sager. 1985. Photons, flux, and some light on philology. HortScience 20(1):29-31.

IES Lighting Handbook. 1981. Fifth edition. Illuminating Engineering Society of North America, New York, NY.

Incoll, L. D., S. P. Long and M. R. Ashmore. 1977. SI units in publications in plant science. Current Advances in Plant Science 9(4):331-343.

Kerr, J. P., G. W. Thurtell and C. B. Tanner. 1967. An integrating pyranometer for climatological observer stations and mesoscale networks. Journal of Applied Meterology 6:688-694.

Kozlowski, T. T. editor. 1968 and 1976. Water Deficits and Plant Growth. Vol. 1, Development, Control and Measurements. Vol. 4, Soil Water Measurement, Plant Responses and Breeding for Drought Resistance. Academic Press, New York, NY.

Krizek, D. T. 1982. Guidelines for measuring and reporting environmental conditions in controlled-environment studies. Physiol. Plant. 56:231-235.

Krizek, D. T. and J. C. McFarlane. 1983. Controlled-environment guidelines. HortScience 18(5):662-664 and Erratum 19(1):17.

19.Langhans, R. W., editor. 1978. A Growth Chamber Manual. Cornell University Press, Ithaca, NY.

LI-COR. 1982. Radiation measurements and instrumentation. Publ. No. 8208-LM. LI-COR, Lincoln, Nebraska.

McCree, K. J. 1972. Test of current definitions of photosynthetically active radiation against leaf photosynthesis data. Agricultural Meteorology 10:443-453.

McFarlane, J. C. 1981. Measurement and reporting guidelines for plant growth chamber environments. Plant Science Bulletin 27(2):9-11.

Mohr, H. and E. Schäfer. 1979. Guest Editorial—Uniform terminology for radiation: A critical comment. Photochemistry and Photobiology 29:1061-1062.

Monteith, J. L. 1984. Consistency and convenience in the choice of units for agricultural science. Experimental Agriculture 20(2):105-117.

NBS Technical Note 910-2. 1978. Self-Study Manual on Optical Radiation Measurements, Part 1-Concepts. United States Government Printing Office, Washington, DC.

Norris, K. H. 1968. Evaluation of visible radiation for plant growth. Annual Review of Plant Physiology 19:490-499.

North Central Regional 101 Committee on Growth Chamber Use. 1986. Quality assurance procedures for environmental control and monitoring in plant growth facilities. Biotronics 15:81-84.

Percival Manufacturing Co. 1981. Guidelines: Measuring and Reporting Environment for Plant Studies. Available as a plastic card.

Rosenberg, N. J. 1974. Microclimate: The Biological Environment. John Wiley & Sons, New York, NY.

Rupert, C. S. and R. Latarjet. 1978. Toward a nomenclature and dosimetric scheme applicable to all radiations. Photochemistry and Photobiology 28:3-5.

Salisbury, F. B. and C. W. Ross. 1991. Plant Physiology. Fourth edition. Wadsworth Publishing Co., Belmont, California.

Šesták, Z., J. Čatský and P. G. Jarvis, editors. 1971. Plant Photosynthetic Production, Manual of Methods. Junk, The Hague, Netherlands.

Slatyer, R. O. 1967. Plant-Water Relationships. Academic Press, New York, NY.

Spomer, L. A. 1980. Guidelines for measuring and reporting environmental factors in controlled environment facilities. Commun. Soil Science and Plant Analysis 11(12):1203-1208.

Spomer, L. A. 1981. Guidelines for measuring and reporting environmental factors in growth chambers. Agronomy Journal 73(2):376-378.

Thimijan, R. W. and R. D. Heins. 1983. Photometric, radiometric, and quantum light units of measure: A review of procedures for interconversion. HortScience 18(6):818-821.

Tibbitts, T. W. and T. T. Kozlowski, editors. 1979. Controlled Environment Guidelines for Plant Research. Academic Press, New York, NY.

Tooming, K. G. 1977. Solar Radiation and Yield Formation (Solnechnaya radiatsiya i formirovanio urozhaya) Gidrometeoizdat, Leningrad.

Zelitch, I. 1971. Photosynthesis, Photorespiration and Plant Productivity. Academic Press, New York. NY.