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Guidelines for measuring and reporting environmental conditions in controlled-environment studies

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Guidelines for measuring and reporting environmental conditions in plant growth chambers are presented in tabular form. These guidelines are recommended by the North Central Region (NCR–101) Technical Committee on Growth Chamber Use, a committee formed under the Cooperative Research Program of the State Agricultural Experiment Stations (SAES) and the United States Department of Agriculture (USDA). Recommendations on location and frequency of measurements as well as suggested format and units of measurement are listed for each environmental parameter. The adoption of these standardized guidelines should greatly improve the uniformity of research conducted in controlled environments and facilitate comparison of experimental results obtained in studies conducted in different laboratories on a world-wide basis.

Additional key words – Environmental measurements, experimental design, plant growth chambers, phytotronics, reporting guidelines, SI units of measurements, standardization.

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Plant growth chambers and other controlled-environment facilities are widely used in physiological and biochemical research to provide a reproducible environment for growing plants, plant tissues, or plant cells (Hudson 1957, Went 1957, Evans 1963, Downs 1975, Downs and Hellmers 1975, Kramer 1978, Langhans 1978). Articles published in Physiologia Plantarum and in other plant science journals frequently report the use of some type of controlled-environment facility. Until recently, however, little effort was made to standardize cultural methods (Krizek et al. 1975, Tibbitts 1978), measurement procedures (Tibbitts and Kozlowski 1979, ASAE 1982, Sager 1982), or reporting units (Krizek 1970, ASHS 1972, Shibles 1976, Berry et al. 1977, Incoll 1977, Gates 1980, ASA 1981, Bell and Rose 1981, ASAE 1982, Sager 1982) in controlled-environment experiments.

Detailed and complete measurements are needed because of the vast differences in growth chamber design, maintenance procedures, surrounding environmental conditions, and cultural practices in each facility (Downs 1975, Downs and Hellmers 1975, Krizek et al. 1975, Langhans 1978, Tibbitts 1978). Despite careful efforts to control the environment, these differences may cause significant differences in irradiance patterns, airflow patterns, atmospheric composition (CO_2, O_2, moisture), temperature patterns, and other environmental factors which may affect experimental results (Tibbitts et al. 1976). Inadvertent environmental stresses caused by atmospheric contaminants, radiation stress (ultraviolet, visible, or infrared radiation), excessive vibration, and inadequate water and nutrient supply may also adversely affect the results obtained (Tibbitts et al. 1977, Ormrod and Krizek 1978, 1979).

Proposed guidelines for reporting environmental conditions in controlled-environment studies were published initially in 1970 (Krizek) by the American Society for Horticultural Sciences (ASHS) Working

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Tab. 1. Proposed guidelines for measuring and reporting the environment for plant studies.*

Parameter	Typically used unit	Measurements		
		Where to take	When to take	What ro report
Radiation:				
PAR (Photosynthetically active radiation) a) Photosynthetic photon flux density (PPFD) 400–700 nm with cosine correction. or b) Photosynthetic Irradiance 400–700 nm with cosine correction	µmol s^{-1} m^{-2}** or µE s^{-1} m^{-2} W m^{-2}	At top of plant canopy. Obtain average over plant growing area.	At start and finish of each study and biweekly if studies extend beyond 14 days.	Average over containers at start of study. Decrease or fluctuation from average over course of study. Wavebands measured.
Total irradiance With cosine correction. Indicate bandwidth.	W m^{-2}	At top of plant canopy.	At start of each study.	Average over containers. Wavebands measured.
Spectral distribution a) Spectral photon flux density $\lambda_1 - \lambda_2$ nm in <20 nm bandwidths with cosine correction. or b) Spectral irradiance (Spectral energy flux density) $\lambda_1 - \lambda_2$ in <20 nm bandwidths with cosine correction.	µmol s^{-1} m^{-2} nm^{-1} (λ_1–λ_2 nm) (quanta) or W m^{-2} nm^{-1} ($\lambda_1 - \lambda_2$ nm)	At top of plant in center of growing area.	At start of each study as a minimum.	Spectral distribution of radiation with integral ($\lambda_1 - \lambda_2$) at start of study. Source of radiation and instrument/sensor.
Illuminance*** 380–780 nm with cosine correction.	klx	At top of plant canopy.	At start of each study.	Average over containers. Wavebands measured.
Temperature:				
Air Shielded and aspirated ($\geq$ 3 m s^{-1}) device.	°C	At top of plant canopy. Obtain average over plant growing area.	Hourly over the period of the study. (Continuous measurement advisable).	Average of hourly average values for the light and dark periods of the study with range of variation over the growing area.
Soil or liquid	°C	In center of container.	Hourly during the first 24 h of the study. Start immediately after watering (monitoring over the course of the study advisable).	Average of hourly average values for the light and dark periods for the first day or over entire period of the study if taken. Location of measurement.

Atmospheric moisture:				
Shielded and aspirated (≥3 m s^{-1}) psychrometer, dew point sensor or infrared analyzer.	% RH, dewpoint temperature, or g m^{-3}	At top of plant canopy in center of plant growing area.	Once during each light and dark period, taken at least 1 h after light changes. Monitoring over the course of the study advisable.	Average of once daily readings for both light and dark periods with range of diurnal variation over the period of the study (or average of hourly values if taken).
Air velocity:	m s^{-1}	At top of plant canopy. Obtain maximum and minimum readings over plant growing area.	At start and end of studies. Take 10 successive readings at each location and average.	Average and range of readings over containers at start and end of the study.
Carbon dioxide:	mmol m^{-3}	At top of plant canopy.	Hourly over the period of the study.	Average of hourly average readings and range of daily average readings over the period of the study.
Watering:	1	–	At times of additions.	Frequency of watering. Amount of water added per day and/or range in soil moisture content between waterings.
Substrate:	–	–	–	Type of soil and amendments. Components of soilless substrate. Container dimensions.
Nutrition:	Solid media: mol m^{-3} or mol kg^{-1} Liquid culture: µmol or mmol 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.
pH:	pH units	In saturated media, extract from media, or solution of liquid culture.	Start and end of studies in solid media. Daily in liquid culture and before each pH adjustment.	Mode and range during study.
Electrical Conductivity:	dS m^{-1}**** (decisiemens per meter)	In saturated media, extract from media, or solution of liquid culture.	Start and end of studies in solid media. Daily in liquid culture.	Average and range during study.

* Proposed by the North Central Region Committee (NCR-101) on Growth Chamber Use.

** The first is preferred because it follows the SI convention. However, since 1 Einstein = 1 mol of photons, the values are equivalent. It is inaccurate to report that "radiation values are xx.x µmol s^{-1} m^{-2}". This is wrong for the same reason that reporting mol kg^{-1} is wrong without associating that value and units with the element (i.e., K was 300 mol kg^{-1}). Thus, "the PPFD was 320 µmol s^{-1} m^{-2}" is correct since it specifically associates a definition (i.e., photons within a certain waveband) with the value and units.

*** Report with PAR reading *only* for historical comparison.

**** 1 dS m^{-1} = 1 mmho cm^{-1} (millimho per centimeter).

Group on Growth Chambers and Controlled Environments in an attempt to improve the uniformity of research conducted in plant growth chambers and to permit an intercomparison of studies conducted in different laboratories. These were subsequently revised in 1972 (ASHS) and 1977 (Berry et al.). During the next two years the guidelines were expanded by the North Central Region (NCR-101) Committee on Growth Chamber Use, a committee formed under the Cooperative Regional Research Program of the State Agricultural Experiment Stations (SAES) and the United States Department of Agriculture (USDA), to include recommended procedures for making environmental measurements (Tibbitts and Kozlowski 1979, ASAE 1982, Sager 1982). This committee is comprised of agricultural engineers, agronomists, botanists, horticulturists, plant physiologists, and soil scientists from agricultural experiment stations and government laboratories throughout the United States and Canada.

The expanded guidelines were formally presented in 1979 (Tibbitts and Kozlowski) at a Controlled Environments Working Conference held at Madison, Wisconsin. The conference was jointly sponsored by the NCR-101 Committee on Growth Chamber Use, the American Society of Agricultural Engineers' Committee on Environment and Plant Structures, the ASHS Working Group on Growth Chambers and Controlled Environments, and the University of Wisconsin Biotron. Following the workshop, the guidelines were refined, reviewed and published along with the entire proceedings of the conference (Tibbitts and Kozlowski 1979). Since that time some additional modifications have been made based on further evaluation. These changes have received the support of the NCR-101 Committee.

These guidelines, presented in Tab. 1, reflect the current thinking of many scientists, engineers, and manufacturers. They provide recommendations on types of instruments, location and frequency of measurement, and suggested format and units that should be used in reporting environmental conditions in each study.

The recommendations on location and frequency of measurements are intended primarily for those experiments in which plant responses are observed in intervals of several days rather than on a daily basis, and where the investigator is interested in relating total growth to the environment as a whole, rather than in analyzing the effects of a single environmental factor on some aspect of growth.

The NCR-101 Committee on Growth Chamber Use recognizes that not all laboratories will have the necessary instrumentation to make all of the recommended measurements. In these cases an investigator will have to compromise and settle for a careful description of experimental methods and environmental facilities (e.g. manufacturer, type, wattage, and voltage of lamp.).

The use of SI units (CIE 1970, Burström 1972, Geist and Zalewski 1973, Incoll et al. 1977, Krizek 1979, ISO 1980, 1981, NBS 1981) has been recommended in all cases. It is anticipated that these guidelines will be continually updated as instrumentation is improved and greater precision in environmental measurement and control is demanded by researchers.

Scientists are encouraged to utilize the sample paragraph that was published with the 1977 guidelines (Berry et al. 1977). The adoption of standardized measurement and reporting guidelines by researchers and adherence to these suggestions by journal reviewers and review editors will significantly enhance the uniformity of environmental research and will greatly aid in making a comparison of data obtained in studies conducted in different laboratories on a world-wide basis. We encourage all readers of Physiologia Plantarum to adopt these guidelines and welcome your comments and suggestions for evaluation and possible inclusion in future, revised versions.

Comments and suggestions may be sent to Donald T. Krizek, Plant Stress Laboratory, Plant Physiology Institute, U.S. Department of Agriculture, ARS, Beltsville, MD 20705, USA, or to other members of the NCR-101 Committee on Growth Chamber Use: Richard J. Gladon, Iowa State University, Ames, Iowa; R. Bruce Curry, Ohio Agricultural Research and Development Center, Wooster, Ohio; R. J. Downs, North Carolina State University, Raleigh, North Carolina; Murray Duysen, North Dakota State University, Fargo, North Dakota; Jerry D. Eastin, University of Nebraska, Lincoln, Nebraska; P. Allen Hammer, Purdue University, West Lafayette, Indiana; Thamon Hazen, Iowa State University, Ames, Iowa; Robert W. Langhans, Cornell University, Ithaca, New York; Keith J. McCree, Texas A&M University, College Station, Texas; J. Craig McFarlane, Environmental Protection Agency, Corvallis, Oregon; Robert A. Norton, Washington State University, Mount Vernon, Washington; Boyd W. Post, USDA Cooperative States Research Service, Washington, D. C.; Ralph P. Prince, University of Connecticut, Storrs, Connecticut; L. Art Spomer, University of Illinois, Urbana, Illinois; and T. W. Tibbitts, University of Wisconsin, Madison, Wisconsin.

References

ASA (American Society of Agronomy) 1981. SI unit usage in the Society publications. – Agronomy News, pp. 1–9, May–June.

ASAE (American Society of Agricultural Engineers) 1982. ASAE Engineering Practice: ASAE EP411, Guidelines for Measuring and Reporting Environmental Parameters for Plant Experiments in Plant Growth Chambers. – *In* 1982 Agricultural Engineers Yearbook, pp. 406–409, ASAE, St. Joseph, Michigan.

ASHS (American Society for Horticultural Sciences Committee on Growth Chamber Environments) 1972. Guidelines for reporting studies conducted in controlled environment chambers. – HortScience 7: 239.
Bell, C. J., & Rose, D. A. 1981. Light measurement and the terminology of flow. – Plant Cell Environ. 4: 89–96.
Berry, W. L., Hammer, P. A., Hodgson, R. H., Krizek, D. T., Langhans, R. W., McFarlane, J. C., Ormrod, D. P., Poole, H. A. & Tibbitts, T. W. 1977. Revised guidelines for reporting studies in controlled environment chambers. – HortScience 12: 309–310.
Burström, H. G. 1972. Tentative Recommendations of Terminology, Symbols and Units in Plant Physiology. International Association for Plant Physiology (IAPP), 24 pp., Carl Bloms Boktryckeri AB, Lund.
C.I.E. (Commission Internationale 'de l'Eclairage) 1970. International Lighting Vocabulary. Publ. No. 17., Paris. 359 pp.
Downs, R. J. 1975. Controlled Environments for Plant Research. – Columbia University Press, pp. 175, New York.
– & H. Hellmers. 1975. Environment and the Experimental Control of Plant Growth. – Academic Press, New York. 145 pp.
Evans, L. T. 1963. Environmental Control of Plant Growth. – Academic Press, New York, pp. 449.
Gates, D. M. 1980. Radiation laws, units and definitions. – *In* Biophysical Ecology. (D. M. Gates, ed.), Springer-Verlag, New York, pp. 75–95,
Geist, J. & Zalewski, E. 1973. Chinese restaurant nomenclature for radiometry. – Appl. Optics 12: 435–436.
Hudson, J. P. 1957. Control of the Plant Environment. Proc. Fourth Easter School in Agricultural Science, Univ. of Nottingham. – Butterworth's London. 240 pp.
Incoll, L. D., Long, S. P. & Ashmore, M. R. 1977. SI units in publications in plant science. – Current Adv. Plant Sci. 28: 331–343.
ISO (International Organization for Standardization) 1980. International Standard. ISO 31/6. Quantities and Units of Light and Related Electromagnetic Radiations, 2nd ed. Ref. No. 150 31/6–1980 (E), 15 pp., Switzerland.
– 1981. International Standard. ISO/DIS 31/6–1980 (E) Erratum. Quantities and Units of Light and Related Electromagnetic Radiations 1 p., Switzerland.
Kramer, P. 1978. The use of controlled environments in research. – HortScience 13: 447–451.
Krizek, D. T. 1970. Proposed guidelines for reporting studies conducted in controlled environemt chambers. – HortScience. 5: 390.
– 1979. Carbon dioxide: guidelines. – *In* Controlled Environment Guidelines for Plant Research. (T. W. Tibbitts and T. T. Kozlowski, eds), pp. 241–258, Academic Press, New York.
– , Langhans, R. W., Tibbitts, T. W., Larson, R. A., Berry, W. L., McFarlane, J. C., Ormrod, D. P. & Hammer, P. A. 1975. Standardization of controlled environment research. – *In* Phytotronics III, Phytotronics in Agricultural and Horticultural Research (P. Chouard and N. deBilderling, eds), pp. 222–229. Gauthier-Villars, Paris.
Langhans, R. W. 1978. Growth Chamber Manual: Environmental Control for Plants. – Cornell University Press, Ithaca, pp. 222, New York.
NBS (National Bureau of Standards) 1981. The International System of Units (SI). NBS Special Pub. 330, pp. 48, Washington, DC.
Ormrod, D. P. & Krizek, D. T. 1978. Plant stress studies in controlled environments. – HortScience. 12: 310–311.
– & Krizek, D. T. 1979. Environmental stresses in controlled environments. – Phytotronics Newslett. 19: 41–51.
Sager, J. C. 1982. Guidelines for measuring and reporting environmental parameters for plant experiments in growth chambers. – ASAE Paper No. 82–4056, 8 pp., ASAE Environment of Plant Structures (SE-303) Committee. St. Joseph, Michigan.
Shibles, R. 1976. Terminology relating to photosynthesis. – Crop Sci. 16: 437–439.
Tibbitts, T. W. 1978. Standardization of controlled environment research. – HortScience 13: 451–458.
– & Kozlowski, T. T. 1979. Controlled Environment Guidelines for Plant Research. – Academic Press, New York, pp. 413.
– , McFarlane, J. C., Krizek, D. T., Berry, W. L., Hammer, P. A., Hodgson, R. H., & Langhans, R. W. 1977. Contaminants in plant growth chambers. – HortScience 12: 310–311.
– , McFarlane, J. C., Krizek, D. T., Berry, W. L., Hammer, P. A., Langhans, W. R., Larson, R. A. & Ormrod, D. P. 1976. Radiation environment of growth chambers. – J. Am. Soc. Hortic. Sci. 101: 164–170.
Went, F. W. 1957. The Experimental Control of Plant Growth, 343 pp., Chronica Botanica Co., Waltham, Mass.

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