GUIDELINES FOR MEASURING AND REPORTING ENVIRONMENTAL PARAMETERS IN GROWTH CHAMBERS

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INTRODUCTION

These measurement and reporting guidelines are a revision of guidelines developed by the USDA North Central Regional (NCR-101) Committee on Controlled Environment Technology and Use. The original impetus for the development of guidelines came from the American Society for Horticultural Science Growth Chamber Working Group in the 1970s (2,3,4,6). The guidelines were openly discussed and published in the proceedings of an international conference held at Madison WI in 1979 (9). Over the years, updates and other recommendations as quality assurance guidelines (7), have been published in Biotronics and in a number of other plant science journals. The guidelines in recent years have been adopted by the American Society of Agricultural Engineers Environment of Plant Structures Committee and published as ASAE Engineering Practice 411.3 (1). This most recent ASAE update has been included in Units, Symbols and Terminology for Plant Physiology by the Oxford University Press (8) and in the Growth Chamber Handbook published by the Iowa State University Press (5).

These guidelines are developed for routine studies. Any unusual or special modifications to the growing system should also be noted.

INSTRUMENTATION

Radiation. Sensors should be cosine corrected and constructed of materials of known stability and response and have low temperature sensitivity. These characteristics should be specified and available for each sensor. The sensitivity and linearity over the spectral range should be specified. For routine studies, spectral measurements should be made using a bandwidth of 2 nm or less over the range of 300-800 nm. For specialized ultraviolet or infrared studies, the wavelength range should be extended. Radiation instruments most commonly have flat-surface sensors with cosine correction to provide hemispherical measurements. By definition, fluence measurements can be taken only with spherical sensors and should not be derived from measurements taken with flat-surface sensors.

Temperature. Sensors should be shielded with reflective material and aspirated ($\geq 3\ m \cdot s^{-1}$) for air temperature measurements. Sensors should be moisture insulated for soil measurements.

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

Air velocity. Measurements should be made by thermal transfer (hot wire) or wave propagation (ultrasonic) sensors within a range of 0 to 5.0 $m \cdot s^{-1}$.

Carbon dioxide. Measurement should be made by an infrared analyzer with a range of 0 to 1000 $\mu mol \cdot mol^{-1}$ or greater range provided they have the required sensitivity.

Hydrogen ion concentration. Sensor should have a range of 3.0 to 10.0 pH units.

Electrical conductivity. Sensor should have a range of 1 to 100 $mS \cdot m^{-1}$ (10-1000 $\mu mhos \cdot cm^{-1}$).

Dissolved oxygen. Required to maintain an optimum root environment in liquid culture studies. Sensors should have a range of 0-20 $mg \cdot L^{-1}$ with automatic temperature compensation. It is important to maintain the proper solution flow rate around the sensing element.

Expected instrument precision and accuracy of reading. Table 1 gives the expected instrument precision and accuracy of reading for each parameter.

Table 1. Expected Instrument Precision and Accuracy of Reading

Parameter	Precision	Accuracy
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 %
Dew-point temperature	± 0.1 °C	± 0.5 °C
Water vapor density	± 0.1 $g \cdot m^{-3}$	± 0.1 $g \cdot m^{-3}$
Air velocity	± 2 %	± 5 %
Carbon dioxide	± 1 %	± 3 %
pH		
H^+ concentration	± 0.1 pH	± 0.1 pH
Electrical conductivity		
Salt concentration	± 5 %	± 5 %
Dissolved oxygen	± 0.1 $mg \cdot L^{-1}$	± 0.2 $mg \cdot L^{-1}$

Instrument calibration. Researchers should have access to both within-lab calibrators for frequent checking and reference calibrators for annual or biannual calibration of their regularly utilized instruments. It is anticipated that the within-lab calibrators would be available at the facility for checking at the start of each research study, whereas the reference calibrators could be at the facility or be accessed by shipping the regularly utilized instruments to be calibrated at a central service location. Table 2 provides guidelines for type and accuracy of calibration instruments.

Table 2. Type and accuracy of instruments for calibration of environmental sensors.

Parameter	Within-Lab Calibration		Reference Calibration	
	Type	Accuracy	Type	Accuracy
Radiation				
Flux	Duplicate photon sensor and meter[y]	<±5% of full scale	Lamp traceable to a national bureau of standards[z]	<±5% of full scale
Spectral	None	N/A	Lamp traceable to a national bureau of standards[z]	<±5% of full scale
Temperature	Duplicate sensor and meter[y]	<±0.2°C	Precision Hg thermometer in water bath	<±0.05°C
Atmospheric moisture	Psychrometer, dew point instrument, or infrared analyzer	<±5% RH	Constant humidity chamber	<±2% RH
Carbon dioxide	Cylinders of span concentration of CO_2 in N_2	<±2% of full scale	Cylinders of span and 50% of span concentrations calibrated against a standard from a bureau of standards	<±1% of full scale
Air velocity	Omni-directional hot wire anemometer	<±5% of full scale	Calibrated wind tunnel	<±2% of full scale
Dissolved oxygen	Distilled water at 25°C rapidly bubbled with high purity O_2	<± 0.2 $mg \cdot L^{-1}$	Potentiometric titration	<± 0.05 $mg \cdot L^{-1}$

[y]Sensor and meter similar to the regular measurement instruments.
[z]In the United States by the National Institute of Standards and Technology.

MEASUREMENT

Photon ($\mu mol \cdot m^{-2} \cdot s^{-1}$) **and energy flux**. ($W \cdot m^{-2}$). Measurements should be taken at the top of the plant canopy to obtain average, maximum, and minimum readings, at the start and end of each study and biweekly if studies extend beyond 14 days. Continuous monitoring of the lighting system is recommended.

Spectral photon ($\mu mol \cdot m^{-2} \cdot s^{-1} \cdot nm^{-1}$) **or energy flux** ($W \cdot m^{-2} \cdot nm^{-1}$). A measurement should be taken at the top of the plant canopy in the center of the growing area, at least at the start and end of each study.

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

Soil and liquid temperatures (°C). Measurements should be made at the center of the container grouping 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 are recommended.

Atmospheric moisture (% RH), **Dewpoint temperature** (°C), **Water vapor deficit** (kPa), **Water vapor density** ($g \cdot m^{-3}$), **Humidity ratio** ($kg \cdot kg$ dry air^{-1}). 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 transition. Continuous measurements are recommended.

Air velocity ($m \cdot s^{-1}$). Measurements should be taken at the top of the plant canopy at the start of the study. Obtain average,

maximum, and minimum readings over the plants. If instantaneous devices are uilized, ten consecutive readings should be taken at each location and averaged.

Carbon dioxide ($\mu mol \cdot mol^{-1}$), (pa), or ($mol \cdot m^{-3}$). 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.

Watering (L). 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 of water potential between waterings.

Nutrition ($mol \cdot m^{-3}$), ($mol \cdot kg^{-1}$), or ($mol \cdot L^{-1}$) Quantity of nutrients added to a volume of medium or concentration of nutrients added in liquid culture should be reported at each addition.

Hydrogen ion concentration (pH units). The pH of the liquid solutions in a nutrient culture system should be monitored at least once daily and before and after each pH adjustment. The pH of the solution extracted from solid media should be measured at the start and end of studies and before and after each pH adjustment.

Electrical conductivity ($mS \cdot m^{-1}$). 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.

Dissolved oxygen. ($mg \cdot L^{-1}$ or ppm) The dissolved oxygen concentration should be monitored at least daily with continuous measurement recommended. Liquid samples should be measured immediately after the samples are taken.

REPORTING

Photon or energy flux. Report the average and range at the top of the containers or plant canopy for the period of the study. The source of radiation and the measuring instrument/sensor should be reported. Illuminance (measurement of irradiance for human vision) should not be reported except for historical comparison in conjunction with other radiation measurements.

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.

Air temperature. Report the daily average and range at the top of the containers or plant canopy for the period of the study for both light and dark periods.

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

Atmospheric moisture. Report the average moisture level for the period of the study for both light and dark periods.

Air velocity. Report the average and range over the containers or the plant canopy at the start of the study. Indicate whether air flow is up, down, or horizontal.

Carbon dioxide. Report the average concentration and range for both light and dark periods of the study.

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. Specify when waterings are made to excess.

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

Nutrition. Report the nutrients added to solid media. Report the concentration of nutrients in liquid culture solutions and in liquid additions along with the frequency of additions to liquid cultures.

Hydrogen ion concentration. Report the average and range in pH of the nutrient solution (or growing medium) for the period of the study.

Electrical conductivity. Report the average and range in conductivity of the nutrient solution (or growing medium) for the period of the study.

Dissolved oxygen. Report the average and range of dissolved oxygen concentrations for the period of the study.

Table 3 is a summary table of the material presented in the Measurement and Reporting sections.

Table 3. Summary of Guidelines for Measuring and Reporting Environmental Parameters for Plant Experiments in Growth Chambers

Parameter	Units[a]	Measurements		
		Where to take	**When to take**	**What to report**
Radiation				
Photosynthetic photon flux, (PPF)[c] (400 - 700 nm)	$\mu mol \cdot m^{-2} \cdot s^{-1}$	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 days.	Average (± range) over containers. Source of radiation and instrument/sensor.
Photon flux	$\mu mol \cdot m^{-2} \cdot s^{-1}$ (nm waveband)	At top of plant canopy. Obtain maximum and minimum over plant growing area.	Minimum measurements: at start and finish of each study and biweekly if studies extend beyond 14 days.	Average (± range over containers. Source of radiation and instrument/sensor.
Energy flux (Irradiance)[b],	$W \cdot m^{-2}$ (nm waveband)			
Spectral photon flux in ≤2 nm bandwidths	$\mu mol \cdot m^{-2} \cdot s^{-1} \cdot nm^{-1}$	At top of plant canopy in center of growing area.	Minimum measurement: at start and end of each study.	Spectral distribution of radiation at start of study. Source of radiation and instrument/sensor.
Spectral energy flux (Spectral irradiance) in ≤2 nm bandwidths	$W \cdot m^{-2} \cdot nm^{-1}$			
Temperature **Air**	°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 ± range of 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.

Atmospheric moisture **Relative humidity** (RH) or **Dew point temperature** or **Vapor deficit**, (VPD) or **Water vapor density** or **Humidity ratio**	% RH °C kPa $g \cdot m^{-3}$ $kg \cdot kg$ dry air^{-1}	At top of plant canopy in center of 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.
Air velocity	$m \cdot s^{-1}$	At top of plant canopy. Obtain maximum and minimum readings over growing area.	At start of studies. Take 10 successive readings at each location and average.	Average reading and range over containers at start of the study.
Carbon dioxide **Mole fraction** or **Partial pressure** or **Concentration**	$\mu mol \cdot mol^{-1}$ Pa $mol \cdot m^{-3}$	At top of plant canopy.	Minimum: hourly measurements. Desirable: continuous measurement.	Average and range of concentrations.
Watering	liter (L)		At times of water additions.	Frequency of watering, source and 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. Container dimensions.
Nutrition **Solid media** **Liquid culture**	$mol \cdot m^{-3}$ or $mol \cdot kg^{-1}$ $mol \cdot L^{-1}$		At times of nutrient additions	Nutrients added to soil media. Concentration of nutrients in liquid additions and solution culture. Amount and frequency of solution addition and renewal.
pH	pH units	Extract from media or in solution of liquid culture.	Start and end of studies in solid media. Daily in liquid culture. Before each pH adjustment.	Average and range during studies.
Electrical conductivity	$mS \cdot m^{-1}$ (milliSiemens per meter)[d]	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.
Dissolved oxygen	$mg \cdot L^{-1}$	In center of liquid containers	Daily. Desirable: continuous measurements in container with largest plant(s).	Average of daily or hourly readings with ± range of variation over the growing period.

[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 and described as photosynthetic photon flux density (PPFD) by many journals, professional societies and manufacturers of quantum sensors.
[d] $mS \cdot m^{-1} = 10\ \mu mho \cdot cm^{-1}$.

REFERENCES

1. American Society of Agricultural Engineers. (1999) Guidelines for measuring and reporting environmental parameters for plant experiments in growth chambers. ANSI/ASAE EP 411.3. Pages 687-691 *in ASAE Standards 1999 46th Edition.* ASAE. St. Joseph, MI.
2. American Society for Horticultural Science Committee on Growth Chamber Environments. (1972) Guidelines for reporting studies conducted in controlled environment chambers. *HortScience* **7**, 239.
3. American Society for Horticultural Science Special Committee on Growth Chamber Environments. (1977) Revised guidelines for reporting studies in controlled environment chambers. *HortScience* **12**, 309-310.
4. Growth Chamber Working Group of the American Society for Horticultural Science. (1980) Guidelines for measuring and reporting the environment for plant studies. *HortScience* **15**, 719-720.
5. Krizek, D. T., Sager J. C. and Tibbitts, T. W. (1997) Guidelines for measurement and reporting of environmental conditions. Pages 207-216 *in* R.W. Langhans and T. W. Tibbitts (eds.) *Plant Growth Chamber Handbook.* North Central Regional Research Publication 340. Iowa State University, Ames, IA.
6. Krizek, D. T. (1970) Proposed guidelines for reporting studies conducted in controlled environment chambers. *HortScience* **5**, 390.
7. 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.
8. Sager, J. C., Krizek, D. T. and Tibbitts, T. W. (1996) Guidelines for measuring and reporting environmental parameters for plant experiments in growth chambers. Pages 202-215 *in* F. B. Salisbury (ed.) *Units, Symbols, and Terminology for Plant Physiology*. Oxford University Press, NY.
9. Tibbitts, T. W. and Kozlowski, T. T. (eds.) (1979) *Controlled Environment Guidelines for Plant Research.* Academic Press, New York, NY.