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Korthals, R. L.
USDA-Meat Animal Research Center

Knight, S. L.
Department of Horticulture University of Illinois

Christianson, L. L.
Department of Horticulture University of Illinois

Spomer, L. Art
Department of Horticulture University of Illinois

出版情報：BIOTRONICS. 23, pp.113-119, 1994-12. Biotron Institute, Kyushu University
バージョン：
権利関係：

BIOTRONICS **23**, 113–119, 1994

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R. L. KORTHALS,* S. L. KNIGHT,** L. L. CHRISTIANSON,*** and L. ART SPOMER**

**USDA–Meat Animal Research Center, POB 166, Clay Center, NE 68933*
***Department of Horticulture, University of Illinois, Urbana, IL 61801–4778*
****Department of Agricultural Engineering, University of Illinois, Urbana, IL 61801*

(Received September 6, 1994; accepted September 12, 1994)

KORTHALS R. L., KNIGHT S. L., CHRISTLANSON L. L. and SPOMER L. ART *Chambers for studying the effects of airflow velocity on plant growth.* BIOTRONICS **23**, *113–119, 1994. Three plant growth chambers were developed for studying the effect of airflow velocity on plant growth and development. Airflow delivery design was based on ASHRAE Standard 51–1985 (1)* for fan testing. Each chamber consisted of five sections— a supply fan section plus two short and one long airflow settling sections preceding the plant growth section— in linear sequence along the airflow path. They delivered measured horizontal air velocities of 0.4, 0.8, and 1.5 m s^{-1} to plants growing in an otherwise normal greenhouse environmental setting. Experiments conducted with soybean plants (*Glycine max* L. 'Carlon') to test these chambers indicated that their relatively simple design adequately provided the set airflow without otherwise constraining plant growth.

Key words: Airflow velocity; growth chamber; wind; thigmomorphogenesis; soybean (*Glycine max* L. 'Carlon').

INTRODUCTION

Airflow is a prevalent environmental factor in horticultural research and production areas. Actual airflow velocities measured in greenhouses span a range from zero to nearly 2 m s^{-1}. Similar velocities occur in growth chambers. The overall intent of this project is to investigate the significance of variation in airflow on crop growth and development— thereby promoting its optimal control in horticultural research and production and improving interpretation of plant response within these growing situations. The first step in accomplishing this goal is to develop relevant testing methodology.

Most horticultural and other controlled environment research and production systems rely on airflow as the main vector supplying humidity, temperature control, and carbon dioxide to the plant canopies. Although airflow has been shown to affect plant growth and development (and thereby crop yield) in various direct and indirect ways, it is almost never measured or controlled— even in otherwise highly-managed research environments. Consequently, little

is known about the contribution of airflow to horticultural or other plant science research results or crop yield. The overall purpose of this project is to investigate the significance of defferent airflow rates on plants in horticultural growing situations.

Airflow affects plant growth directly through energy and mass transfer (*2, 7, 8, 9*). The significant heat energy and carbon dioxide, oxygen, and water vapor exchanged directly between the plant structure and surrounding atmosphere is directly affected by air movement. In addition, latent heat exchanged through the processes of water evaporation (transpiration) from and condensation onto plant surfaces is also directly affected by air movement.

The heat energy exchange promoted by airflow helps determine leaf temperature— thereby affecting growth and development through moderation of metabolic processes. Mechanical energy in the form of stem and leaf movement stimulates thigmomorphic growth responses (decreased plant height, increased stem thickness, decreased internode deistance). In addition, airflow motivated leaf and stem movement often promotes tissue abrasion or other mechanical injury and affects stomatal opening.

Airflow promotes gas exchange through bulk movement of gases to and from the canopy and by reducing the boundary layer of stagnant air surrounding plant surfaces. Gas exchange directly affects net photosynthesis through supply of carbon dioxide and oxygen utilized as raw materials during photosynthesis and respiration. Increasing airflow within a canopy can enhance net photosynthesis in the same way as enriching canopy carbon dioxide concentration. In research, this interaction between carbon dioxide concentration and airflow can lead to conflicting and confusing results. In production, airflow might substitute for carbon dioxide enhancement, especially in situations where the growing area can not be contained. Water vapor exchange directly affects growth by determining leaf water balance and indirectly by contributing to leaf thermal balance (latent heat loss).

In general, the greater the airflow velocity, the greater the effects of airflow on plant growth. However, responses are not linear over the range of airflow normally experienced, but tend toward a maximum or optimum. Observed greenhouse airflow velocities within the plant canopy ranging from 0.15 to 1.70 m s^{-1} caused variation in zinnia (*Zinnia elgans*) stem and leaf height, width, and dry mass (*6*). An air velocity of 0.5 to 0.7 m s^{-1} was reported as optimum for plant growth under controlled conditions (*3*) ; however, there are minimal data to support this conclusion. Some researchers have even suggested air velocities as high as 1.5 m s^{-1} can be used without detrimental effects to most plants (*3*). This inconsistency in response can be attributed to species canopy and physiological differences, interaction with other environmental factors, or inaccurate control or measurement of air flow.

This paper describes the design and testing of growth chambers designed to investigate the significance of airflow on horticultural and other crops in otherwise typical crop growing environments.

MATERIALS AND METHODS

Chambers

Three different modular chambers were constructed to provide airflows of 0.4, 0.8, and 1.5 m s^{-1}. The design of airflow delivery was based on ASHRAE Standard 51–1985 for fan testing (*1*). Individual chambers were located in the University of Illinois Plant Sciences Laboratory greenhouse. Each consisted of a linear array of five different sections along the airflow path in the following sequence— one fan (762 mm long), two short (152 mm) settling, one long (610 mm) settling, and one (760 mm) plant growing section. An interior cross–section of 762×762 mm was maintained along the flow path (Figure 1).

Airflow is introduced into the chambers by a fan at the entrance to the fan section. A 305 mm diameter axial fan supplied 14.6 m^3 min^{-1} airflow for one chamber and 610 mm diameter axial fans supplied 28.3 or 52.3 m^3 min^{-1} for the other two. Fan performances were tested according to the ASHRAE Standard 51–1985 for fan testing (*1*) using the BESS Lab fan test chamber in the Department of Agricultural Engineering. Accuracies are ±1% of the measured flow. All settling sections consisted of a settling screen located at the upstream entrance followed by an open flow volume. The settling screen in the first section following the fan was constructed from 9.5 mm thick plywood perforated with 50 mm diameter holes uniformly spaced across the chamber cross section. Airflow rate was controlled in this section by changing the total number of holes in the settling screen. For example, screens with 36, 49, and 64 holes provided for this study three different treatments of— low, medium, and high airflow

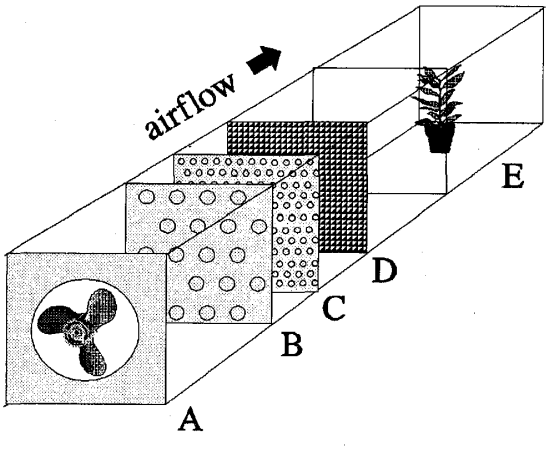

Fig. 1. Diagram of experimental controlled airflow plant growth chamber consisting of a linear sequence of five sections along the airflow path—one fan (762 mm long), two short settling (152 mm), one long settling (610 mm), and one plant growing section (760 mm). Fan (A) pushes air through the three settling screens [50 mm holes (B), 6 mm holes on 14 mm centers (C), and 65% open nylon mesh (D)] defining the fan and settling sections and into a plant growing chamber covered with clear polyethylene film (E). An interior cross–section of 762×762 mm is maintained along the flow path.

rates, respectively. The screen in the second settling section consisted of 65% open nylon shade cloth stretched tightly across the entrance. The third settling screen was fabricated from a 14 ga. steel sheet with 3 mm diameter holes on 4 mm centers uniformly distributed over the chamber cross section to produce 44 % open space. The 610 mm path between the last screen and the entrance to the plant growing section allowed full development of airflow patterns. The growing section consisted of a cube enclosed on three sides by 4 mil clear polyethylene plastic film stretched on wood frames (50×50 mm members).

The chambers were placed in the glasshouse with their long axis oriented North–South to ensure optimal exposure of the plants to solar radiation. The glasshouse was oriented East–West. Aseembled chamber components were elevated approximately 100 mm above the concrete greenhouse floor. This located the bottom of the chamber airflow path at the top of the plant containers, thereby minimizing container interference with the airflow pattern. The plant containers rested directly on the concrete greenhouse floor to prevent transmission of fan vibration to the plants through the chamber structure.

The chambers described herein produced measured plant growing section airflow velocities of 0.4, 0.8, and 1.5 m s^{-1}±0.05 m s^{-1} for the low, medium, and high airflow treatments. Airflow was measured with TSI omnidirectional anemometers calibrated for low air velocity measurements. These flow rates represented the average of 27 measurements, one at the center of each cube comprising a 3×3×3 matrix within the cube-shaped growing sections. The airflows produced by each chamber remained consistent throughout the period of the study.

In addition to ambient solar radiation, two 1,000 W high pressure sodium lamps (Phillips C1000S52) located 0.98 m above and equal distance from the three chambers supplied supplemental photosynthetic photon flux (PPF) between 0900 and 1700 hours. Mean supplemental PPF levels were approximately 180 μmol m^{-2} s^{-1} with a maximum standard deviation of 79 μmol m^{-2} s^{-1} as based on 9 instantaneous measurements made with a LiCor LI-190SB quantum sensor at the center of each square in a horizontal 3×3 grid across the bottom of the empty chamber (at pot level). The greenhouse environment was computer monitored and controlled. Temperature control set points were 27℃ day (0900–1700) and 24℃ night ±0.5℃ (1700–0900), coinciding with the supplemental photoperiod. Cooling was effected primarily by fan-ventilation with the incoming air passing through evaporative pads on the North wall, along the long axis of the chambers (same direction as chamber airflow), then out through large exhaust fans on the South wall. Heating was supplied through hot water fin tube heat exchangers just above the floor on the South wall. Air was recirculated within the greenhouse during heating. Chamber relative humidity was not controlled and varied from over 90% to about 40% during the plant growth experiments.

Plant experiments.

Soybeans (*Glycine max* L. 'Carlon') were germinated in six, 152 mm dia

plastic pots containing approximately 3,000 cm^3 of 1 : 2 : 1 (by volume) soil : peat : perlite growing media. Experimental treatments were initiated 5 days following seedling emergence. Four seeds were planted in each pot, and all but one were harvested after two weeks of airflow treatments. Each container was irrigated once daily with 90 ml of water supplied from an automatic trickle system. Soil mineral nutrition was provided by incorporating 6 g of 20–20–20 time-release fertilizer (Osmocote) into the growing media prior to germination. Pest control consisted of biweekly topical alcohol applications.

Plant experiments consisted of three replications each of low (0.4 m s^{-1}), medium (0.8 m s^{-1}), and high (1.5 m s^{-1}) airflow velocity treatments. The experimental design was a completely randomized block with mean comparisons for differences between pairs within the three different treatments. The growth parameters— plant height, width, stem diameter, and node number were measured after 2 and 4 weeks of treatment. Stem diameter was measured at the soil line with a digital caliper immediately after harvest. The dry masses of harvested leaves, stems, and roots were determined after drying to a constant mass in a forcedventilation electric oven at 75℃. Second order polynomial curves were fitted to trait versus velocity data to esimate optimal velocity for each trait.

RESULTS AND DISCUSSION

Following two weeks of treatment, plants in the medium airflow velocity were at least 10% taller and 14% more massive (shoots) than plants in the other treatments (Figure 2). Reduced plant growth in the low airflow probably mirrors a lower canopy net photosynthetic rate. In this treatment, less airflow through the canopy could reduce canopy and leaf carbon dioxide exchange due to decreased bulk air flow and increased leaf boundary layer thickness (decreased diffusion). High airflow can also decrease canopy net photosynthesis.

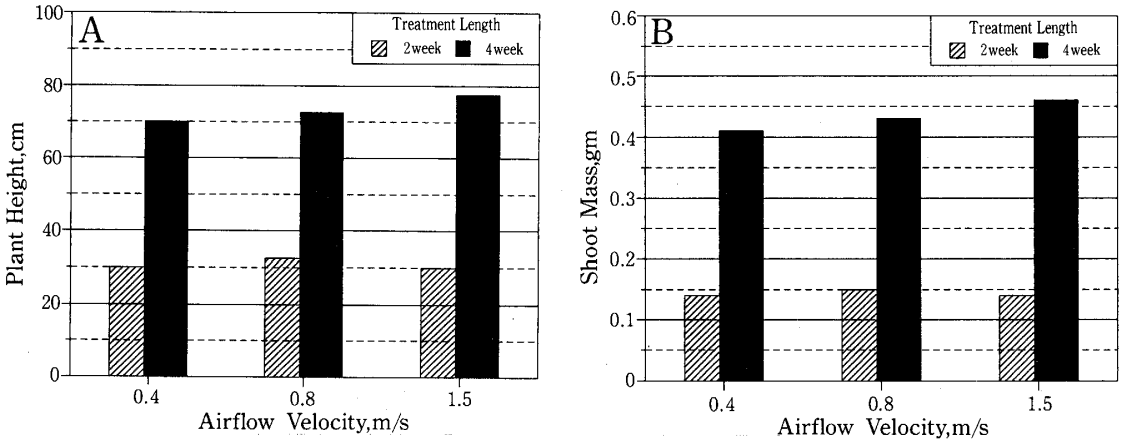

Fig. 2. Soybean plant height (A) and shoot mass (B) following two and four weeks exposure to the airflow treatments of 0.4, 0.8, or 1.5 m s^{-1}. Similar letters indicate statistically similar response (1% level).

Stomatal closure caused by leaf desiccation or mechanical stress is a plausible cause in this case. The prevalence of mechanical stress is confirmed by the downwind leaf orientation observed in the high airflow treatment (*5*). The smaller leaves also observed on plants in that treatment may be symptoms of either desiccation or mechanical stress.

Over the next two weeks the relative plant growth responses changed somewhat. Cumulative growth was still the least in the low airflow treatment; however, it was the greatest in the high airflow. The growth ranking in the low airflow treatment after four weeks merely reflected its difference from the medium airflow treatment at two weeks. Actual plant growth in low airflow during the second two weeks nearly matched the medium treatment (Figure 2). Both treatments may have approximated a closed crop canopy by two weeks thereby maximizing PPF interception and equlizing their canopy net photosynthesis and subsequent vegetative growth. In the high airflow treatment, however, a closed crop canopy was likely reached only after development of a taller canopy because of the generally greater canopy openness resulting from its downwind leaf orientation. Plant node number increased 160 % between weeks 2 and 4 in the high treatment whereas the increase was only 144 and 147% in the low and medium treatments. The greater increase in node number presumably mirrors the greater general growth increase in the high airflow treatments rather than resulting from any sort of developmental response.

Analysis of trait versus velocity at two and four weeks for height, width, node number, and stem leaf and whole plant mass indicates optimal airflow velocities for plant vegetative of 0.8 and 1.0 m s^{-1} respectively for this study environment (Table 1). These values are slightly higher than the optimum of about 0.5 m s^{-1} for a number of plant species reported by Crace (*3*).

The difficulty in interpreting results from such studies originates with the general complexity and dynamic nature of the plant–atmosphere interaction. For example, as the canopy grows, many changes occur including average leaf exposure to the airflow, stomatal response and gas exchange, general

Table 1. Estimated optimal airflow velocity (m s^{-1}) for soybeans (*Glycine max* L. 'Carlon') vegetative growth based on fitted parabolic curves of trait versus velocity.

	2 wks		4 wks	
	max velocity m s^{-1}	R^2	min. velocity m s^{-1}	R^2
height (cm)	0.95	0.028	>1.5	0.003
width (cm)	0.80	0.020	—	—
nodes (no.)	0.80	0.185	1.0	0.001
mass (g)				
stem	0.95	0.075	>1.5	0.021
leaf	0.90	0.106	1.1	0.023
plant	0.090	0.082	1.35	0.032

photosynthetic response, exposure to PPF, and airflow itself. This complexity is increased by natural and imposed variations in airflow within typical growing systems. Much of the complexity of the plant–atmosphere interaction can be avoided if the scale of control and observations is reduced— for example, to the level of a single leaf. However, interpretation becomes more complex because the behavior of a single leaf cannot merely be extrapolated to an intact canopy. Likewise, it would be best to grow the crop through to harvest to determine the effect of airflow on speciffic yields.

The effects of airflow treatments on soybean vegetative growth observed in this study support the importance of characterizing and controlling airflow in plant experiments conducted in greenhouse, growth chamber, or other controlled environment conditions. Future experiments should concentrate on better environmental control in the chambers and more thorough characterization of the intracanopy airflow environment and its relationship to extracanopy airflow. Specifically, additional studies are required to determine exactly the range of airflow velocities characteristic to agricultural production areas, and to determine exactly how this range of airflow velocity affects plant growth and development. In addition, chambers with larger growing surfaces would permit plant experiments under more typical planting and canopy densities which would create gradient airflows within the canopy more typical of those in production situations.

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