Vertical profiles of boundary layer conductance and wind speed in a cotton canopy measured with heated brass surrogate leaves

David A. Grantz*, David L. Vaughn

Department of Botany and Plant Sciences and Air Pollution Research Center, University of California, Riverside, CA 92521, USA

Abstract

Knowledge of single leaf boundary layer conductance (g_b) within extensive canopies is required to scale stomatally regulated gas exchange from leaf to canopy. Fluxes of terpenes and heat, formation of dew, and other processes occurring at the leaf surface may be controlled by g_b. We develop, test, and deploy at five canopy heights, a set of paired, heated and unheated brass surrogate leaves, with realistic 3-dimensional shape and characteristic dimension (d) for cotton (*Gossypium hirsutum* L.) in California. An equation describing heat transfer from a flat plate, enhanced by a factor of 1.15 for complex leaf shape, adequately described g_b of the surrogate leaves. In the field, values of g_b measured with the surrogate leaves near the top of the canopy were closely related to wind speed, as expected from theory. The dependence of g_b on leaf size was apparent at all heights in the canopy using surrogate leaves differing in d. The profile of within-canopy wind speed (u) was determined using the profile of g_b and d of the surrogate leaves. This profile of effective u in the leaf environment was well described by a conventional exponential decay model with an empirically derived wind extinction coefficient ($K = 1.5$). This profile of u was combined with the directly measured profile of d of biological leaves to determine the actual profile of g_b in this canopy. The increasing leaf size toward the middle of the canopy caused actual g_b to decline more steeply than predicted from constant d. With depth in the canopy sunflecks increasingly contributed to unequal radiation interception between paired surrogate leaves and therefore to anomalies in calculated g_b. A simple data filtering protocol, rejecting data outside the range observed at the top of the canopy, is introduced. Data rejection increased appropriately with increasing sunfleck frequency and depth in the canopy. These results extend the applicability of the heated, paired surrogate leaf technique to sheltered positions in dense canopies, and to large-leafed species, allowing direct measurement of an important canopy parameter (g_b) that has typically been estimated or calculated as a residual. ©1999 Elsevier Science B.V. All rights reserved.

1. Introduction

Canopy-atmosphere exchange of trace gases such as ozone, biogenic hydrocarbons, and water vapor may be modeled following an electrical (Ohm's Law) analogy, provided values for all controlling conductances (inverse resistances) are available or can be reliably parameterized. Whereas modern instrumentation allows for accurate measurement of canopy fluxes (F), aerodynamic conductance (g_a) at the canopy scale (Droppo, 1985; Lenschow, 1995), and stomatal conductance (g_s) at the single leaf scale, the determination of aggregate leaf boundary layer conductance (g_b) has remained elusive. Characterization of the profile within dense canopies of distributed, single leaf g_b has not been reported.

* Corresponding author. Present address: Kearney Agricultural Center, 9240 S. Riverbend Avenue, Parlier, CA 93648, USA. Tel.: +1-559-646-6599; fax: +1-559-646-6593
E-mail address: david@uckac.edu (D.A. Grantz)

Efforts to scale physiological measurements to extensive canopy or regional scales are strongly influenced by the magnitude and distributions of g_b as well as of g_a and g_s (Raupach, 1995). In patchy vegetation (e.g., McNaughton, 1994) the classical micrometeorological techniques (e.g., Monteith, 1981) that might allow calculation of g_b by difference (i.e. from F, g_s, g_a and a concentration gradient) break down with increasing surface heterogeneity. Even in extensive, continuous canopies such as cotton (*Gossypium* spp.), calculation of values of g_b by difference may founder on unexpected (e.g., leaf wetness) or unexplained (residual conductance) sources, sinks or modes of transport. These uncertainties confounded our earlier attempts to treat ozone deposition to cotton in the semi-arid San Joaquin Valley (SJV) of central California (Grantz et al., 1997). Cotton is a major crop and a dominant surface cover in the SJV and a significant sink for tropospheric ozone (Grantz et al., 1994). As the SJV air basin exceeds current federal and state air quality standards for ground level ozone, efforts have intensified to characterize, scale, and model these fluxes to and from extensive, commercially managed canopies such as cotton.

In addition to interest in g_b as a component of canopy scale conductance, recent interest in plant leaves as sources of biogenic hydrocarbons (ozone precursors; Chameides et al., 1988), has led to renewed requirements for accurate assessment of the distribution of g_b. This is particularly the case for mono- and sesqui-terpenoids and their oxidation products (Arey et al., 1991; Guenther et al., 1991) which are generally (though see Staudt and Seufert, 1995) emitted from leaf surfaces outside of stomatal control. Cotton emits substantial amounts of terpenoid compounds into the atmosphere (Arey et al., 1991; Winer et al., 1992). Emissions of these materials are expected to be closely related to their leaf temperature-controlled vapor pressures and to g_b (Lerdau et al., 1997; Tingey et al., 1980).

A heated, paired surrogate leaf approach has been described (Leuning and Foster, 1990; Brenner and Jarvis, 1995) and used variously to determine g_b of single leaves located at the exterior surface of an extensive grain canopy (Brenner and Jarvis, 1995), in sparse shrub and tussock grass species (Domingo et al., 1996), in crowns of isolated windbreak trees (Smith et al., 1997), and in a trellised vineyard (Daudet

et al., 1998; with a modified heated, single surrogate leaf protocol). The heated surrogate leaf technique in theory allows continuous, real time measurement of single leaf g_b in place of the more conventional calculation by difference or estimation from empirically parameterized within-canopy wind field models (e.g., Businger, 1975; Massman, 1987).

In the present study we evaluate pairs of alternately heated and unheated, nickel-plated, brass surrogate leaves, molded into the 3-dimensional shape and sizes of cotton leaves, for measurement of vertical profiles of g_b and leaf-effective wind speed in an extensive commercial cotton field in the SJV. This represents the first application of this technique to address the issues of leaf size and canopy insertion level of a large-leafed species in a dense, continuous canopy.

2. Materials and methods

2.1. Construction

The development, manufacture, and application of paired, brass surrogate leaves has been described (Brenner and Jarvis, 1995). Here we constructed two sizes (five pairs each), with characteristic dimensions (d) of 0.10 and 0.15 m to bracket the sizes of mature leaves observed in commercial cotton fields in the SJV. Each surrogate leaf consisted of two layers of 0.15 mm thick brass shim (Goodfellow Corp., Berwyn, PA) individually cut to the lobed outline of actual cotton leaves, then deformed (in pairs) in 3 dimensions to reflect the shape of the actual leaves. Each layer was individually nickel plated, and polished for high reflectance (α) and low emissivity (ε).

The inner surface of each layer was lightly coated with electrically insulating epoxy casting resin. To provide power to the leaves, about 1 m of 0.32 mm diameter nickel-chromium heating wire (Omega Inc., Stamford, CT; temperature sensitivity about $3.5 \times 10^{-3}\ \Omega\,\mathrm{m}^{-1}\,°\mathrm{C}^{-1}$) was arranged uniformly over the surface between the layers and fixed to the surface with minimal cellophane tape. The two layers were joined with a few drops of epoxy glue. To prevent water entry and minimize heat loss, the gap at the edges of the joined layers was sealed with a thin bead of epoxy casting resin. The electrical resistance (r) of the heater wire was determined individually for each

surrogate leaf (range: $r = 7.4$ to $8.6\,\Omega$, $d = 0.10\,\mathrm{m}$; $r = 13.1$ to $15.4\,\Omega$, $d = 0.15\,\mathrm{m}$).

To determine the steady state temperature (T_s) of the surrogate leaves, type T (copper/constantan) thermocouples (0.08 mm diameter) were attached to the exterior lower surface with aluminum foil tape. Thermocouples attached to each surrogate leaf (four each, $d = 0.10\,\mathrm{m}$; six each, $d = 0.15\,\mathrm{m}$) were connected in parallel to a datalogger (21X; Campbell Scientific Inc., Logan, UT) through a thermally insulated analog multiplexer (AM416; Campbell Scientific Inc.). Reference temperature was measured inside the insulated multiplexer enclosure with a thermistor (Model 107; Campbell Scientific Inc.). Independent wiring of each surrogate leaf contrasts with previous designs (e.g., Brenner and Jarvis, 1995; Smith et al., 1997), allowing determination of absolute temperature and providing greater diagnostic power with respect to sun flecks and anomalous values of g_b. The surrogate leaves were attached in pairs to aluminum frames ($0.15 \times 0.30\,\mathrm{m}^2$, $d = 0.10\,\mathrm{m}$; $0.18 \times 0.35\,\mathrm{m}^2$, $d = 0.15\,\mathrm{m}$) with monofilament nylon. Each frame was attached with a ball-joint mount (to allow adjustment of leaf inclination) to a vertical mast.

2.2. Operation

Adjustable electrical power was supplied to the surrogate leaves from a dual voltage regulator connected to several parallel, deep-cycle, 12 V DC lead-acid batteries. Voltage (V) applied to the leaves was recorded every 5 s to calculate power input to the leaves as

$$P = \frac{V^2}{rA} \tag{1}$$

where P is power per unit area ($\mathrm{W\,m^{-2}}$) and A is 2-sided (twice projected) area of the surrogate leaves. To overcome possible differences in incoming short wave radiation incident upon the two surrogate leaves within a pair, power was applied alternately to one member of each pair for 15 min, under datalogger control. 5 min were allowed for T_s to stabilize, then T_s of each surrogate leaf (T_{s1} and T_{s2}, heated and unheated, respectively) was measured every 5 s and averaged over 10 min. Power was then interrupted for 15 min. 10 min were allowed for T_s to stabilize at ambient T_a, then T_{s1} and T_{s2} were again averaged over

5 min to determine an offset temperature between the paired leaves to correct for any inequality in net radiation (Brenner and Jarvis, 1995). The second surrogate leaf in each pair was then heated for 15 min followed by interruption of the power for 15 min and measurement of another offset temperature. All ten sets of leaf replicas of two sizes were operated simultaneously.

The energy budget of the 2-sided surrogate leaves (Leuning and Foster, 1990; Brenner and Jarvis, 1995) can be manipulated to yield leaf boundary layer conductance for heat transfer as

$$g_b = \left(\frac{1}{\rho_a C_p}\right)\left[\left(\frac{P}{(T_{s1} - T_{s2})}\right) - 4\varepsilon\sigma\,(T_{s2}^3)\right] \tag{2}$$

where ρ_a is density of air, C_p is specific heat capacity of air at constant pressure, σ is the Stefan–Boltzman constant, and the final term is a linearized approximation of the long wave radiation balance (Leuning and Foster, 1990). Incoming short wave radiation is not considered explicitly in Eq. (2). This would require a pyranometer sensor on each surrogate leaf, and unrealistically accurate knowledge of thermal inertia in the system. As noted above, the alternate heating protocol is assumed to overcome any differences in incoming radiation (Brenner and Jarvis, 1995). Shortcomings in this assumption due to short-duration sunflecks are addressed experimentally below.

2.3. Laboratory tests

Surrogate leaves were tested on the laboratory bench using an electric fan, with wind (u) varied with fan speed and location. Hot wire anemometers (FMA-603-V, Omega, Stamford, CT) were located at 0.01 m in front of the leading edge of each surrogate leaf, and sampled once per second. Alternative surrogate leaves were constructed as potometers made of two layers of filter paper (Whatman #5; Cole-Parmer, Vernon Hills, IL) enclosing replicate type T thermocouples (0.08 mm). Capillary tubing to provide sufficient distilled water to keep the paper saturated was inserted between the two layers, and connected to a reservoir on an analytical balance for continuous measurement of water loss by evaporation (E). The filter paper surrogate leaves were constructed in the same sizes and 3-dimensional shape as the brass surrogate leaves and suspended in the same aluminum
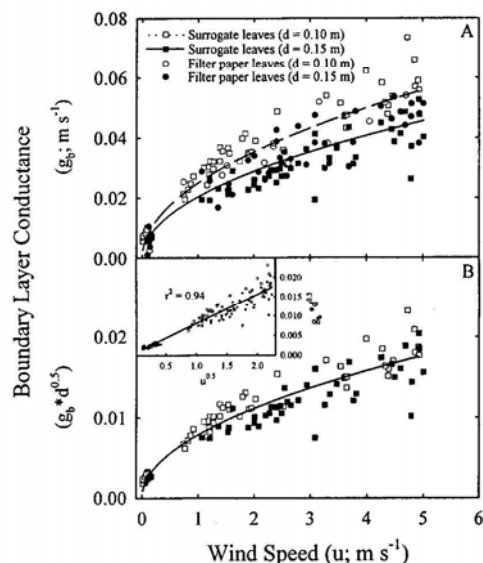
Fig. 1. (A) Relationship (squares) between boundary layer conductance (g_b) and wind speed (u) observed under laboratory conditions for brass surrogate leaves with characteristic dimension, $d = 0.10$ m (open) or $d = 0.15$ m (solid), and (circles) for wetted filter paper surrogate leaves of the same dimensions (open, solid). Predicted relationships (lines) between g_b and u (Eq. (9)) for two-sided leaves of these dimensions (broken, solid lines). (B) Universal relationship between g_b, normalized by leaf dimension ($d^{0.5}$), and u, unifying the data in 1A. (B, inset) The same relationship linearized as a function of $u^{0.5}$.

frames. Boundary layer conductance to water vapor transport ($g_{b,v}$) was determined as

$$g_{b,v} = \frac{E}{[(0.622\rho_a/P_a)(e_{Ts} - e_a)]} \quad (3)$$

where P_a is atmospheric pressure measured in the laboratory (PTA 427; Campbell Scientific Inc., Logan, UT), e_{Ts} is saturation vapor pressure at surrogate leaf temperature and e_a is water vapor pressure in the laboratory atmosphere measured with a chilled mirror hygrometer (Dew 10; General Eastern, Woburn, MA). Conductances for heat (Eq. (2)) and water vapor (Eq. (3)) in the quasi-laminar boundary layer were related by the ratio of the 2/3 power of their diffusion coefficients (0.93; Jones, 1992).

The surrogate leaves of filter paper and of brass described similar relationships of g_b (heat transfer) to u (Fig. 1A), with two distinct relationships for

surrogate leaves with $d = 0.10$ m and $d = 0.15$ m (Fig. 1A). The relationships were modeled with conventional engineering equations for one-sided heat transfer through the boundary layer of a smooth, flat plate (e.g., Schuepp, 1993) as

$$g_{b,plate} = k\left(\frac{Nu}{d}\right) \quad (4)$$

where k is thermal diffusivity of air and the Nusselt number is

$$Nu = ARe^n \quad (5)$$

where A and n vary with the value of the Reynolds number (Re) and the geometry of the surface, with

$$Re = u\frac{d}{\nu} \quad (6)$$

in which ν is the kinematic viscosity of air. For a flat plate with forced convection and laminar boundary layer ($u > 0$; $Re < 2 \times 10^4$) $A = 0.60$ and $n = 0.5$ (Monteith and Unsworth, 1990), so that

$$Nu = 0.60Re^{0.5} \quad (7)$$

and under our conditions

$$g_{b,plate} = 0.60k\nu^{-0.5}\left(\frac{u}{d}\right)^{0.5} \quad (8)$$

The surrogate leaves exhibited g_b in excess of $g_{b,plate}$ (Eq. (8)), as expected (Monteith and Unsworth, 1990), requiring a two-sided scaling factor, 2, and an empirically determined shape enhancement factor, β, so that

$$g_b = 2\beta\left[0.60k\left(\frac{u}{d\nu}\right)^{0.5}\right] \quad (9)$$

The enhancement factor was found by an iterative regression technique to be $\beta = 1.15$. This lies in the range commonly observed (Monteith and Unsworth, 1990; Schuepp, 1993; Smith et al., 1997) and was appropriate for both sizes of surrogate leaves ($r^2 = 0.97$, $d = 0.10$ m; $r^2 = 0.84$, $d = 0.15$ m).

Our choice of $n = 0.5$ (Eqs. (7) and (9)) reflected an a priori assumption of minimally turbulent laminar boundary layer around the surrogate leaves under these conditions, in which case n approaches a theoretical value of 0.5 for diffusion across the boundary layer. This assumption was tested by a process of two

parameter (β and n) curve-fitting and non-linear regression (SigmaPlot, SPSS Inc.). This yielded $n = 0.47$ ($d = 0.10$ m) and $n = 0.52$ ($d = 0.15$ m), confirming laminar boundary layer development under these conditions and supporting the use of $n = 0.5$ for both size classes of surrogate leaves.

Previous studies (Brenner and Jarvis, 1995; Domingo et al., 1996; Smith et al., 1997; Daudet et al., 1998) have deployed surrogate leaves of a single size, while plant canopies exhibit a range of leaf sizes (d) that must be considered in evaluating g_b. As expected from Eq. (9) the large surrogate leaves ($d = 0.15$ m) exhibited lower g_b at all u (Fig. 1A, solid line) than the smaller surrogate leaves ($d = 0.10$ m; Fig. 1A, broken line). Normalization by an appropriate function of d yielded a size-independent boundary layer parameter $g_b * d^{0.5}$ that exhibited a single relationship with u for surrogate leaves of both sizes (Fig. 1B; solid line; $r^2 = 0.94$) and a strong linear relationship with $u^{0.5}$ (Fig. 1B; inset; $r^2 = 0.94$).

2.4. Field measurements

Measurements were obtained in a commercial upland cotton (*Gossypium hirsutum* L. cv. Maxxa) field during September and October 1998. Data are presented for one representative day in October (DOY 281). During this period canopy height was 1.1 m, leaf area index (L) was 2.95, with full ground cover. Rows were 0.91 m apart, oriented north–south.

Plants from five randomly chosen 1.0 m sections of row were excised at ground level and removed to the laboratory in dark plastic bags. Leaves were removed and separated by height in the canopy (five 0.22 m intervals) and measured with a leaf area meter (LI 3100; LICOR, Inc.; Lincoln, NE). The average characteristic dimension, d, of leaves was determined from the number of leaves and total leaf area in each layer, yielding average single leaf area (A_s). These cotton leaves can be visualized as squares with about half of the total area removed to produce lobes. Thus, d was determined as

$$d = (2A_s)^{0.5} \qquad (10)$$

in which the factor of 2 restores the non-lobed area of the square and the square root yields the length of a side (i.e., d).

Wind direction and speed were measured with a vane and cup anemometer (model 3001-5 Wind Sentry set; R.M. Young Co., Traverse City, MI) located at 3.5 m above the ground surface.

Two pairs of brass surrogate leaves were deployed at five heights in the canopy, at 0.11, 0.33, 0.55, 0.77, and 1.0 m above the ground surface (illustrated in Fig. 2). Temperature data were collected continuously from the heated and unheated surrogate leaves, and from cotton leaves and air at the same five heights.

3. Results and discussion

3.1. Within-canopy g_b

Replicate surrogate leaves with characteristic dimension, $d = 0.15$ m, were placed at two heights (Figs. 3A and B) and replicate leaves with $d = 0.10$ m were placed at two additional heights (Fig. 3D and E). A single pair of each size was placed at the intermediate height of 0.55 m for direct comparison (Fig. 3C).

Boundary layer conductance of individual surrogate leaves exhibited a diurnal pattern with peak values occurring near solar noon (Figs. 3A–E). This was most pronounced at the top of the canopy, and declined with depth (cf. Figs. 3A and E). To explore this diurnal pattern the average of the two replicate leaves deployed at 1.0 m (Fig. 4, solid circles) were considered with simultaneous averages of $u^{0.5}$ at 3.5 m (Fig. 4, open squares). A close, though not complete, correspondence in these half-hourly averaged values of wind speed ($u^{0.5}$) and g_b was observed near the top of the canopy (Fig. 4, Figs. 3A and B), but less so at depth (Figs. 3D and E). These data reflect the forced convection that controls g_b in this canopy as both u and g_b vary, even in this low-wind environment. Wind speed and its low frequency variability is sufficiently attenuated at depth in this canopy that only the principal diurnal component of enhanced u near midday is reflected in the diurnal pattern of g_b (Figs. 3D and E). Higher in the canopy, excursions from expected half-hourly g_b are generally associated with similar excursions in u. A contribution of free convection may be reflected in the increase in g_b that precedes the increase in u (e.g., 08:00 to 10:00 PDT; Fig. 4) during the period when canopy warming occurs.
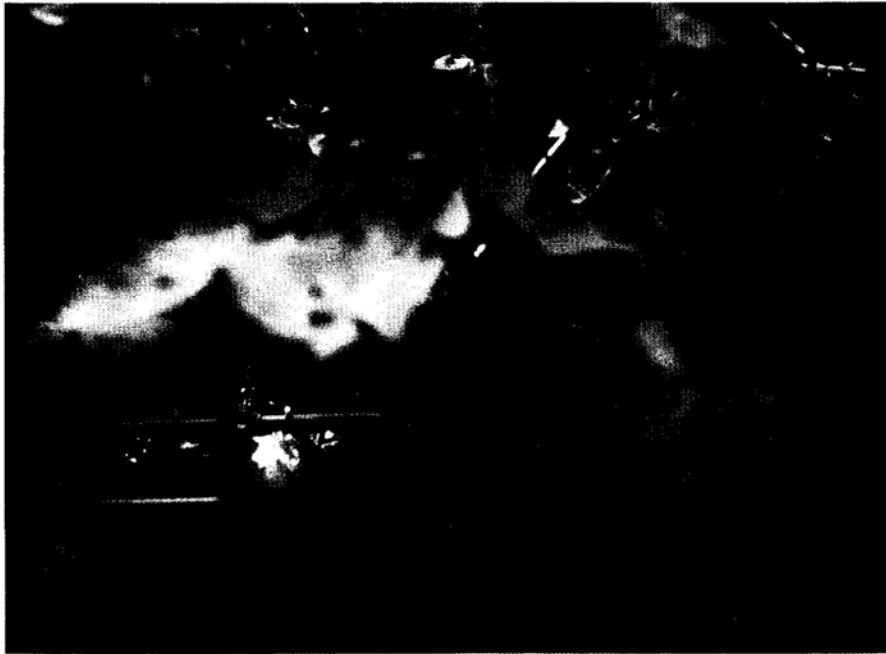
Fig. 2. In situ photograph of a pair of brass surrogate leaves ($d = 0.10$ m) mounted at $z = 0.11$ m in the cotton canopy. Unequal net radiation that violates assumptions of the method is shown by the pronounced sun fleck on one member of a pair of surrogate leaves.

The close correspondence between wind speed and observed boundary layer conductance in the upper strata of the canopy is expected from theory (Jones, 1992). The decline with canopy depth of g_b and of solar radiation make these upper sunlit leaves the most physiologically active in the cotton canopy (e.g., Grantz et al., 1997), dominating canopy-atmosphere exchange.

As observed in the laboratory, g_b of the two sizes of surrogate leaves differed when located at a common height in the canopy (Fig. 3C). Surrogate leaves with $d = 0.15$ m consistently exhibited g_b below that of surrogate leaves with $d = 0.10$ m (cf. Fig. 3C; closed and open circles).

3.2. Sun flecks and data quality

An assumption underlying the heated surrogate leaf technique is that of equal net radiation for each member of a pair. Within plant canopies, increasing with depth, sunflecks induced by leaf shading may cause differential radiation loading between members of a pair, especially if the surface areas are large. The duration of these sunflecks is likely to be variable and may not be apparent in half-hourly average temperature data (e.g., Brenner and Jarvis, 1995). Direct visual observation during deployment of the surrogate leaves repeatedly revealed occasions of full or partial solar irradiation of one member of a pair, while the other remained fully shaded. Such an occasion is illustrated photographically (Fig. 2) for paired surrogate leaves at 0.11 m.

Surrogate leaves at the top of the canopy were fully sunlit and received only diurnally varying radiation in this nearly cloud-free environment. Near the top of the canopy (Fig. 3A) the surrogate leaves provided high quality data, replicate pairs provided similar estimates of g_b, and no temperature anomalies or unexpected changes in offset temperatures were observed. With increasing depth in the canopy the frequency of calculation anomalies in half hourly values of g_b increased. To reduce these errors, heating was alternated between the two paired surrogate leaves and an offset temper-
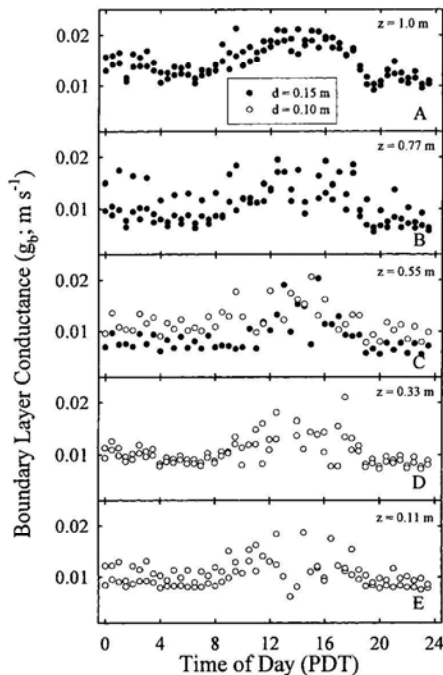
Fig. 3. Diurnal courses of boundary layer conductance (g_b) determined in the cotton canopy with brass surrogate leaves of two sizes. Replicate large surrogate leaves ($d = 0.15$ m) were deployed at two heights in the canopy and small surrogate leaves ($d = 0.10$ m) at two heights, overlapping without replication at mid-canopy. Each data point represents a single half-hourly estimate of g_b.

Fig. 4. Diurnal courses of boundary layer conductance (g_b; circles) determined near the top of the cotton canopy with brass surrogate leaves and of wind speed (u; squares) measured above the canopy. Each data point (circles) represents the mean of two independent half-hourly estimates of g_b from Fig. 3A.

ature (T_{os}) was determined when both were unheated to correct the temperature difference observed when one was being heated (after Brenner and Jarvis, 1995). This protocol, though effective in reducing errors associated with unequal radiation that persisted during the unheated portion of the cycle, does not correct for sunflecks of greater or lesser duration. This remains problematic and has been addressed in various ways (Smith et al., 1997; Daudet et al., 1998).

Brass surrogate leaves in millet (Brenner and Jarvis, 1995) were deployed above the canopy where they were not subject to frequent shading by overlying leaves. Measurements utilizing cylindrical surrogate brass stems (about 2 mm in diameter; Domingo et al., 1996) were not apparently affected by differential solar heating, presumably because of their small radiation cross section. In contrast, for the
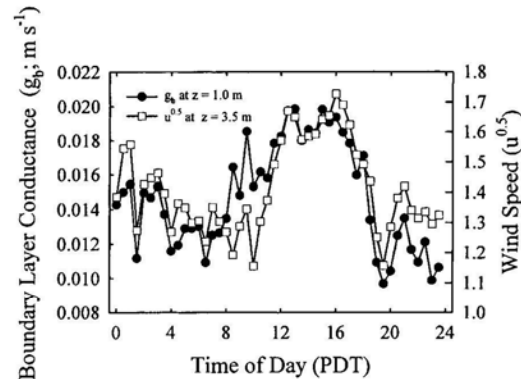
large-leafed grape canopy (*Vitis vinifera* L.; similar in morphology to cotton), a protocol involving a single brass surrogate leaf with concentric heated and unheated areas was developed (Daudet et al., 1998). The surface of the trellised grape canopy may exhibit fewer sunflecks than leaves at depth in the cotton canopy.

In the present study, with explicit consideration of g_b at various depths in the canopy, it became necessary to evaluate objective rules by which to distinguish acceptable from unacceptable data. We tested the protocol of Smith et al. (1997), who used surrogate leaves of intermediate size (61 × 24 mm). In their case, measurements were excluded if offset temperatures observed in sequential unheated periods differed by more than 1.0°C.

Our measurements of the profile within the canopy provided a rigorous test of this data filtering protocol. This filter eliminated considerable data that appeared otherwise to be valid. Most of the observations that were rejected were in the range (0.01 to 0.015 m s^{-1}; Fig. 5) in which most observations occurred, suggesting some degree of randomness. The rejection rate of data also failed to increase with depth in the lower half of the canopy (Fig. 5A, inset), despite the increased frequency of leaf shading-induced sunflecks.

We investigated a more empirical approach, based on the high quality data that were obtained near
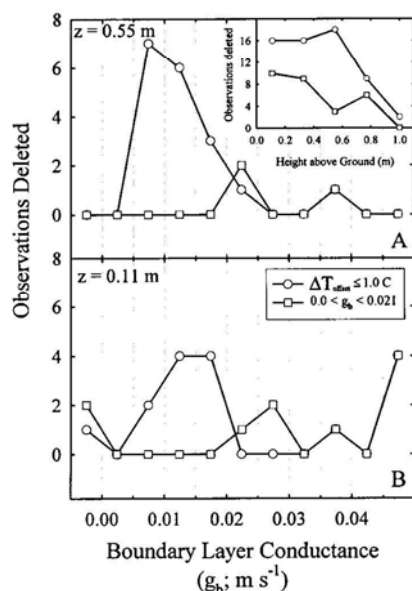
Fig. 5. Distribution of boundary layer conductance (g_b) values rejected by alternative data filtering protocols, based on changes in offset temperature (circles) or on the magnitude of g_b (squares), at two representative heights in the canopy (A) $z = 0.55$ m and (B) $z = 0.11$ m. (5A, inset) The vertical distribution within the cotton canopy of g_b values rejected (out of 96 observations at each height) by the alternative data filtering protocols.

the unshaded top of the canopy (e.g., Fig. 3A). At this height all data in our study lay in the range $0 < g_b < 0.021$ m s^{-1}. We therefore applied a filter that eliminated all data yielding g_b outside of this range, reasoning that $g_b < 0$ m s^{-1} is physically unreasonable and $g_b > 0.021$ m s^{-1} would require wind speed and g_b to increase with depth.

At 0.55 m (Fig. 5A, squares) the new filter eliminated no data in the region of $g_b = 0.01$ m s^{-1}, where the alternative filter (Smith et al., 1997) led to maximal rejection of data (Fig. 5A, circles). A similar situation prevailed at 0.11 m (Fig. 5B). The data remaining in the filtered data set appeared to be internally consistent (Fig. 3) and of reasonable magnitude. In general the new g_b-based filter eliminated only half of the data eliminated by the alternative T_{os}-based filter (Fig. 5A, inset), at all depths in the canopy, and eliminated none at the top of the canopy. Both filtering protocols rejected the larger values of g_b.
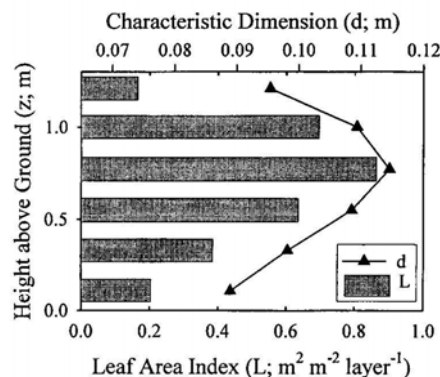

Fig. 6. Vertical distribution within the cotton canopy of leaf area index (L; bars) and mean leaf characteristic dimension (triangles).

With incorporation of this data filter for quality control, the heated, paired brass surrogate leaf technique becomes applicable to large-leafed species such as cotton in dense and extensive canopies with high L. The contrasting requirements of trees in windbreaks (Smith et al., 1997), sparse canopies in semi-arid regions (Domingo et al., 1996) and trellised grape (Daudet et al., 1998) may require somewhat different filtering protocols. In particular, the assumption of a monotonic decline in g_b with depth in the canopy may not pertain to trees with leafless trunk space, nor to trellised vineyards. In such cases it may be possible to deploy a small sun shade to reduce sunflecks while minimally perturbing wind flow in the vicinity of individual surrogate leaves. This latter approach remains to be demonstrated.

3.3. Leaf area index and characteristic dimension

Leaf area index per canopy layer (L) of this cotton canopy exhibited the typical Gaussian distribution observed in cotton (Sassenrath, 1995; Wullschleger and Oosterhuis, 1992) with maximum L at about two-thirds of canopy height (Fig. 6; horizontal bars). Leaf characteristic dimension (d) was also maximal at two-thirds of canopy height (Fig. 6; line and symbols). The actual g_b of individual biological leaves, and the aggregate boundary layer of the canopy, depend on the vertical profile of d, and of L through its effect on u.
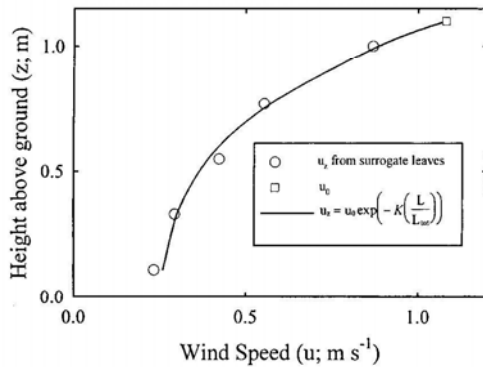
Fig. 7. Vertical profile of wind speed (u) within the cotton canopy determined from measurements of g_b and the relationship (Eq. (9)) between g_b and u (circles), or modeled (line) as an exponential decline with canopy extinction coefficient $K = 1.5$.

3.4. Within canopy wind speed

The mean midday value of g_b decreased with depth in the canopy for a given size of surrogate leaf (cf. Fig. 3A–E). From profiles of g_b and d, and manipulation of Eq. (9), the within-canopy profile of apparent wind speed can be determined. Because these values of wind speed reflect the interaction with leaves in their natural orientation, such values may be superior to within-canopy wind speeds obtained with small omnidirectional anemometers. This is particularly so when such values of u are required for calculation of g_b of biological leaves within the canopy. The wind profile data obtained with the surrogate leaves were well described (not shown; $r^2 = 0.996$) by a classical function of leaf area distribution (e.g., Businger, 1975; Massman, 1987) as

$$u_z = u_0 \exp\left[-K\left(\frac{\Sigma L}{L_{\text{tot}}}\right)\right] \qquad (11)$$

where z is measurement height, u_0 is wind speed at the top of the canopy, ΣL is cumulative leaf area index to each canopy layer, and L_{tot} is total leaf area index. K is an empirically determined canopy wind extinction coefficient, $K = 1.5$. Wind speed was extrapolated upward to the top of the canopy where no surrogate leaves were deployed (Fig. 7, square) with an iterative procedure involving Eq. (11) in which both u_0 and K were fit to u_z. The resulting vertical penetration of

wind into the canopy presented as a function of z (Fig. 7; circles) corresponded closely with that predicted by Eq. (11).

The calculation of u from g_b by manipulation of Eq. (9) assumes a non-turbulent, laminar leaf boundary layer in this dense canopy. Using customary distinctions between laminar and turbulent boundary layer conditions ($Re < 2 \times 10^4$; Monteith and Unsworth, 1990), all of our field measurements were under quasi-laminar boundary layer conditions. For example (Eq. (6)), $Re = 2 \times 10^4$ when $d = 0.15$ m and $u = 2.0$ m s^{-1}, well above the wind speeds observed at the canopy surface (Fig. 7). Although the transition to a turbulent boundary layer may occur at lower u and Re in the boundary layer of rough, 3-dimensional leaves (Brenner and Jarvis, 1995), the convergence to $n = 0.5$ suggests largely laminar boundary layer conditions on the surrogate leaves in this low-wind environment.

3.5. g_b of biological leaves

For leaves of any given characteristic dimension, d, the single leaf boundary layer conductance, g_b, calculated from Eq. (9) declined with depth in the canopy (Fig. 8; squares, triangles) as an implicit function of declining wind speed (Fig. 7). The brass surrogate leaves with $d = 0.10$ m exhibited larger g_b than those with $d = 0.15$ m (Fig. 8; cf. triangles, squares), though
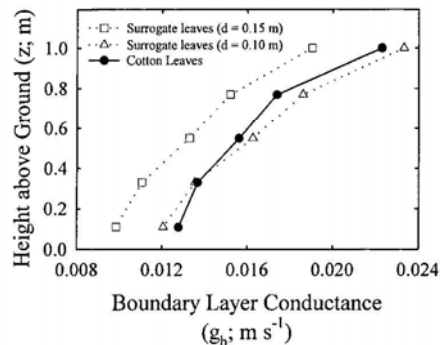

Fig. 8. Vertical profiles of boundary layer conductance (g_b) of the brass surrogate leaves of two characteristic dimensions (open squares, triangles) and g_b of actual cotton leaves determined using Eq. (9) with measured profiles of d and u (from Fig. 7) at each height (solid circles).

with similar profiles. The measured d of actual cotton leaves (Fig. 6; triangles) allows estimation of the error in g_b obtained with a single size of surrogate brass leaf. In this canopy the smaller surrogate leaves (e.g., $d = 0.10$ m; Fig. 8, open triangles) underestimated g_b of biological leaves near the bottom of the canopy and overestimated g_b in the upper canopy. The larger surrogate leaves ($d = 0.15$ m) were not representative of leaves in this canopy, though leaves of this size are observed in SJV cotton.

The values of g_b determined in the upper canopy using the brass surrogate leaf technique (Fig. 8) agreed well with the value of $0.02 \, \mathrm{m\,s^{-1}}$ determined in a similar SJV cotton field as a residual using Ohm's Law (Grantz et al., 1997 and unpublished results). This reflects the dominance of these upper leaves in canopy-atmosphere exchange. Values of g_b for lower leaves are not well represented by these aggregate measures and thus require direct measurements as presented here.

Proper correspondence of the dimensions of surrogate and biological leaves in canopies of interest is required for determination of actual g_b profiles with the paired, heated brass surrogate leaf technique. The vertical distribution of single leaf boundary layer conductance, determined from these direct measurements, may be used with measurements of trace gas fluxes obtained at other scales of biological organization to more fully characterize transport within and above plant canopies.

4. Conclusions

Determination of boundary layer conductance for individual leaves in extensive canopies has been a weak link in the description of surface-atmosphere exchange. Recent developments of heated surrogate leaf protocols have made possible direct measurements of this important parameter. We have developed a technique that allows extension of these protocols to dense canopies of large-leafed species, and have used it in cotton to demonstrate the vertical profile of boundary layer conductances of actual leaves with observed characteristic dimensions. The measured boundary layer conductances also allowed determination of within-canopy wind profiles. Agreement of these profiles with theory supported the validity of the surrogate leaf approach. Characterization of these leaf-effective wind profiles may be superior to other within-canopy wind measurement techniques, particularly for calculation of g_b of biological leaves. These data, and further extensions of the technique, will allow more precise determination of ozone sink strength, photosynthetic and transpirational activity at the canopy scale, and source strength for biogenic hydrocarbons.

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