

# Analyses of assumptions and errors in the calculation of stomatal conductance from sap flux measurements

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**Summary** We analyzed assumptions and measurement errors in estimating canopy transpiration ( $E_L$ ) from sap flux ( $J_S$ ) measured with Granier-type sensors, and in calculating canopy stomatal conductance ( $G_S$ ) from  $E_L$  and vapor pressure deficit ( $D$ ). The study was performed in 12-year-old *Pinus taeda* L. stands with a wide range in leaf area index ( $L$ ) and growth rate. No systematic differences in  $J_S$  were found between the north and south sides of trees. However,  $J_S$  in xylem between 20 and 40 mm from the cambium was 50 and 39% of  $J_S$  in the outer 20-mm band of xylem in slow- and fast-growing trees, respectively. Sap flux measured in stems did not lag  $J_S$  measured in branches, and time and frequency domain analyses of time series indicated that variability in  $J_S$  in stems and branches is mostly explained by variation in  $D$ . Therefore,  $J_S$  was used to estimate transpiration, after accounting for radial patterns. There was no difference between  $D$  and leaf-to-air vapor pressure gradient, and  $D$  did not have a vertical profile in stands of either low or high  $L$  suggesting a strong canopy–atmosphere coupling. Therefore,  $D$  estimated at one point in the canopy can be used to calculate  $G_S$  in such stands. Given the uncertainties in  $J_S$ , relative humidity, and temperature measurements, to keep errors in  $G_S$  estimates to less than 10%, estimates of  $G_S$  should be limited to conditions in which  $D \geq 0.6$  kPa.

**Keywords:** air temperature, air vapor pressure deficit, leaf temperature, leaf-to-air vapor pressure deficit, relative humidity, time lags.

## Introduction

Stomata respond to environmental variation, regulate water loss and carbon dioxide gain, and thus biosphere–atmosphere exchange of mass and energy. From porometry measurements, leaf conductance ( $g_s$ ) can be calculated with Fick's law as:

$$g_s = \frac{E_L}{\delta_w}, \quad (1)$$

where  $E_L$  is transpiration per unit leaf area ( $\text{mol m}^{-2} \text{s}^{-1}$ ), and

$\delta_w$  ( $\text{mol mol}^{-1}$ ) is the water vapor pressure gradient between the substomatal cavity and the air near the leaf surface (Percy et al. 1989). Mean  $g_s$  of the canopy ( $\langle g_s \rangle$ ;  $\text{mol m}^{-2} \text{s}^{-1}$ ) (Sellars et al. 1997, Baldocchi and Meyers 1998, Pataki et al. 1998a), can be obtained from measurements of  $g_s$  at several levels in the canopy, together with the vertical distribution of leaf area, and models describing stomatal responses to environmental gradients within the canopy (Jarvis 1995). However, variation among porometric measurements of  $g_s$  is large (Jarvis 1995, Hinckley et al. 1998). Leverenz et al. (1982) calculated that, in a uniform monospecific Norway spruce canopy, the number of sample leaves needed to produce an estimate within 10% of the mean at each time step may exceed 150 even if sampling is stratified by major sources of variation.

Recently,  $\langle g_s \rangle$  has been approximated from sap flux ( $J_S$ ) measurements scaled to  $E_L$  (Köstner et al. 1992, Arneth et al. 1996, Granier et al. 1996, Martin et al. 1997, Oren et al. 1998, Pataki et al. 1998a, 1998b, Phillips and Oren 1998, Oren et al. 1999a). When leaf and air temperature are similar, a condition that occurs for small leaves exposed to a sufficiently high wind speed (Herbst 1995, Martin et al. 1999), the bulk air vapor pressure deficit ( $D$ ) can be used as an approximation of  $\delta_w$  for calculating  $g_s$  (Monteith and Unsworth 1990). Under such conditions, calculation of  $\langle g_s \rangle$  from sap-flux-scaled  $E_L$  (hereafter,  $G_S$ ) can be simplified as suggested by Monteith and Unsworth (1990):

$$G_S = \frac{K_G(T_A)E_L}{D}, \quad (2)$$

where  $G_S$  is mean canopy stomatal conductance to water vapor ( $\text{m s}^{-1}$ ),  $K_G$  is the conductance coefficient as a function of temperature ( $115.8 \pm 0.4236 \text{ kPa m}^3 \text{ kg}^{-1}$ )—accounting for temperature effects on the psychrometric constant, latent heat of vaporization, specific heat of air at constant pressure, and the density of air—and  $T_A$  is bulk air temperature ( $^{\circ}\text{C}$ ). Phillips and Oren (1998) showed that errors associated with lumping the temperature-dependent physical coefficients into  $K_G$  are negligible.

Because sap-flux-scaled  $G_S$  is the product of measurements representing relatively large leaf areas, it is subject to certain sources of error. These include errors in estimating  $E_L$  and  $\delta_w$  because of systematic and random variations and instrument limitations. This study was designed to generate a conditional sampling scheme aimed at keeping the effect of measurement errors in the estimate of  $G_S$  to within 10% of the measurement error-free estimate.

#### Errors in estimating $E_L$

Sap-flux-scaled  $E_L$  may represent water uptake rather than transpiration if the quantity of water discharged from storage in the plant into the transpiration stream in the morning is large relative to uptake, and the quantity recharged by uptake late in the day is large relative to transpiration (Granier et al. 1996, Phillips et al. 1996, Loustau et al. 1998, Phillips and Oren 1998). To assess if  $J_S$  can be used to calculate  $G_S$  in this stand, we evaluated the effect of stem water storage capacity on  $E_L$  by comparing a time series of stem  $J_S$  measured with Granier-type sensors with branch  $J_S$  measured with Kučera-type sensors (Cienciala et al. 1994) in the top and bottom branches of the canopy.

Increasingly, sap flux in the hydroactive xylem is estimated with Granier-type sensors (Granier 1987), which measure the maximum temperature difference between heated and unheated probes during times of zero flux ( $\Delta T_M$ ) as a baseline. Temperature difference ( $\Delta T$ ) is also measured during the day as water carries heat away from the probe. Deviation from the baseline is used to estimate water flux. Granier-type sensors may be sensitive to temperature gradients in the stem creating an apparent temperature difference (Goulden and Field 1994, Köstner et al. 1998). This error can be large when fluxes are low, and trees are small (Granier 1987). Additional errors, even in large trees, may be caused by uncertainties in the baseline position (i.e.,  $\Delta T_M$ ). Therefore, we quantified the effect of uncertainties in  $\Delta T_M$  on estimates of diurnal time courses of  $J_S$ .

#### Errors in estimating $\delta_w$

Calculation of  $D$  requires measurements of relative humidity of bulk air ( $R_H$ ), and  $T_A$ , and calculations of  $\delta_w$  require additional measurements of leaf temperature ( $T_L$ ; °C). It is often assumed that a single sensor is sufficient to represent  $D$  in the canopy (Köstner et al. 1992, Granier et al. 1996, Martin et al. 1997, Oren et al. 1998, Pataki et al. 1998a, 1998b). For well-coupled canopies at sufficiently high wind speeds,  $D$  approximates  $\delta_w$  (Jarvis and McNaughton 1986, Martin et al. 1999), and thus a single  $R_H$ – $T_A$  sensor can be used to calculate  $G_S$ . In this study, we analyzed the effects of measurement errors on values of  $\delta_w$  and  $D$  and, in turn, on the calculation of  $G_S$ . We also tested the assumption that  $D$  does not vary horizontally and vertically by performing: (1) concurrent measurements in nearby stands with twofold difference in leaf area index ( $L$ ) and an adjacent opening, and (2) rapid measurements along a vertical transect within the canopy.

## Material and methods

### Study site and treatments

The Southeast Tree Research and Education Site (SETRES) was established in 1992 in a stand of *Pinus taeda* L. planted in 1984 in the Sandhills of North Carolina (35° N, 79° W) on an infertile, well-drained, sandy, siliceous, thermic Psammentic Hapludult soil (Wakulla series). Mean annual precipitation is 1210 mm with occasional growing season water deficits. Three treatments were established in addition to a control (C): irrigated (I), fertilized (F), and a combination of irrigation and fertilization (IF). Nutrient treatments have been maintained since March 1992 and irrigation treatments since April 1993. The treatments have resulted in peak  $L$  of 1.8, 1.9, 3.3, and 3.6 and basal areas of 14, 14, 20, and 25 m<sup>2</sup> ha<sup>-1</sup> for trees in the C, I, F, and IF treatments, respectively. For details of nutrition and irrigation treatments see Albaugh et al. (1998) and Murthy et al. (1996).

Stem  $J_S$  and associated environmental variables were measured from August 1996 to January 1999. During this period, short measurement campaigns were carried out to evaluate potential sources of error.

### Sap flux measurements

We measured  $J_S$  in stem xylem of eight trees in a 6-m diameter plot and in branch xylem in a subset of three trees within each treatment (Ewers et al. 1999). Measurements on the north side of stems (1.4 m above ground) were made with Granier-type sensors at two depths: the outer 20 mm of the xylem ( $J_{S_{out}}$ ) in eight trees, and, to account for radial patterns in  $J_S$ , the next 20 mm of the xylem ( $J_{S_{in}}$ ) in a subset of five trees. The  $J_S$  (m<sup>3</sup> H<sub>2</sub>O m<sup>-2</sup> s<sup>-1</sup>) is calculated based on the empirical equation (Granier 1987):

$$J_S = 119 \times 10^{-6} \left( \frac{\Delta T_M - \Delta T}{\Delta T} \right)^{1.231} \quad (3)$$

We calculated mean  $J_S$ , weighting  $J_{S_{out}}$  by the sapwood area represented in that xylem band and  $J_{S_{in}}$  by the sapwood area internal to the outer band (Ewers et al. 1999), assuming that  $J_{S_{in}}$  represents sap flux in the xylem between 20 and 40 mm from the cambium. On average, sapwood area inside the outer 20-mm band was 15% of the total. On June 12–24, 1998, to evaluate whether scaling must account for a systematic circumferential variance in flux, we installed sensors to measure  $J_{S_{out}}$  on the south side of stems of a subset of five trees in C and IF, and compared these with measurements made on the north side. Trees in the C and IF treatments were chosen because they represented the highest and lowest  $L$  and differed in sapwood characteristics (Ewers et al. 1999).

We evaluated time lags between water uptake and transpiration by measuring xylem flux with Kučera-type sensors (Cienciala et al. 1994), based on the heat balance method, in upper branches of 6–12 mm diameter and lower branches of 12–18 mm diameter. Branch measurements were made from

July 23 to August 8, 1998. To avoid thermal gradients from direct radiation, all sensors were shielded. Analyses of daily water use were performed on daily sums of  $J_s$  from 0500 to 0500 h, corresponding approximately to the time of zero flow, and therefore include nighttime recharge (Phillips and Oren 1998).

To calculate  $E_L$  ( $\text{kg H}_2\text{O m}^{-2} A_L \text{ s}^{-1}$ ),  $J_s$  ( $\text{kg H}_2\text{O m}^{-2} A_s \text{ s}^{-1}$ ) for either branches or stems is combined with sapwood area ( $A_s$ ;  $\text{m}^2$ ) and leaf area ( $A_L$ ;  $\text{m}^2$ ) as follows (Pataki et al. 1998b):

$$E_L = J_s \frac{A_s}{A_L} \quad (4)$$

### Environmental measurements

Values of  $\delta_w$  were calculated from  $R_H$ ,  $T_L$ , and  $T_A$  based on equations adapted from Goff and Gratch (1946):

$$V_s = 0.611e^{(17.27T_L)/(T_L + 237)}, \quad (5)$$

$$\delta_w = \left( \left( \frac{R_H}{100} \right) V_s \right) - V_s, \quad (6)$$

where  $V_s$  is saturated water vapor pressure (kPa). Here,  $\delta_w$  is in kPa and can be converted to mole fractions used in Equation 1 by dividing by atmospheric pressure. The value of  $D$  is calculated from Equations 5 and 6, where  $T_A$  is substituted for  $T_L$ .

During most of the study period, an  $R_H$ - $T_A$  probe (Vaisala HMP 35C, Campbell Scientific, Logan, UT) was positioned at the center of each plot at 2/3 distance from the bottom of the canopy (sensor height/stand height,  $z/h = 0.79$ – $0.83$ ). During August 2–28, 1997, additional measurements of  $T_L$  were made in each treatment by infrared thermometry (Everest Interscience, Palo Alto, CA) based on an emissivity of 0.97 (Gates 1965, Gay and Knoerr, 1975). We used these measurements to test the validity of replacing  $D$  with  $\delta_w$  for calculating  $G_s$ . We also used the measurements to assess the effect of horizontal variability in  $L$  on  $D$ . On July 23 and August 5, 1998, the effect of the vertical distribution of leaf area on the  $D$  profile was evaluated by raising and then lowering the sensor 1 m  $\text{min}^{-1}$  during the midday plateau in the diurnal pattern of  $D$ .

Photosynthetic photon flux density ( $Q$ ) above the canopy was monitored with a quantum sensor (LI-190s, Li-Cor, Lincoln, NE). Xylem flux and all environmental sensors were sampled every 30 s (DL2, Delta-T Devices, Cambridge, U.K.). Thirty-minute mean values were recorded during the study, except for branch  $J_s$  for which 15-min averages were recorded.

### Structural measurements

At the end of the study, branches monitored for sap flux were harvested. No heartwood was visible in upper or lower branches, but the pith was clearly discernible from the sapwood. Branch sapwood area was determined by subtracting the bark and heartwood areas from the branch cross-sectional

area at the midpoint of sensor length. From each branch, five fascicles were selected randomly from current- and previous-year foliage. The length and width of each needle were measured to  $\pm 1$  and  $\pm 0.005$  mm, respectively. Projected leaf area was determined by multiplying the width of each needle by its length and then summing the area for the fascicle. Needles were then oven-dried for at least 24 h at 65 °C, weighed, and their specific leaf area ( $\text{cm}^2 \text{g}^{-1}$ ) determined. The remaining needles of each age class were also oven-dried. Total leaf area of each branch was obtained by multiplying leaf mass in each age class by the respective specific leaf area and summing the area of both age classes.

Heartwood was not present in any stems of any treatments as expected for *P. taeda* of this age (cf. Megraw 1985). Therefore, sapwood area for each tree was calculated from diameter at sensor height. Bark thickness was measured in each tree and differed among treatments (Ewers et al. 1999). After correcting for bark thickness, sapwood area per unit of ground area was calculated by summing the area of all trees in the plot and dividing by plot area. Sapwood area was 9.0, 9.0, 15.2, 21.9  $\text{m}^2 \text{ha}^{-1}$  for trees in the C, I, F, and IF treatments, respectively (Ewers et al. 1999). Leaf area of each tree was calculated from allometric relationships derived from winter biomass harvests at the site (Albaugh et al. 1998). Leaf area estimates for each tree were corrected for seasonality based on relative increase in leaf area from winter to the sampling period as determined with a leaf area meter (Li-Cor, LAI-2000) and litterfall at the stand level (Ewers et al. 1999). The  $A_s:A_L$  ratio was calculated for each tree based on estimates of leaf area and sapwood area. To estimate stand  $L$  (projected), “winter equivalent” leaf area of each tree in each subplot was estimated from its diameter and the treatment specific allometric relationships as above (Albaugh et al. 1998, Ewers et al. 1999). Leaf area measurements of all individuals in each subplot were summed, divided by the plot area (133  $\text{m}^2$ ) and corrected for seasonal leaf area dynamics.

### Statistical analyses

All statistical analyses were made with SAS procedures GLM, ARIMA and SPECTRA (Version 6.12, SAS Institute, Cary, NC). Nonlinear curve fits were performed in SIGMAPLOT (Version 4.5, SPSS, San Rafael, CA). Time lags were evaluated by time series analyses performed both in the time and frequency domain according to Brocklebank and Dickey (1986).

## Results

### Errors in estimates of $J_s$ caused by baseline placement

Occasionally, an apparently stable  $\Delta T_M$  became unstable in early morning when sap flux began. We chose the most unstable behavior found among all trees as an example in Figure 1. Relatively stable  $\Delta T_M$  (defined as the portion of  $\Delta T_M$  that varies within the narrow range of 0.02 mV for at least 2 h) is plotted alongside unstable  $\Delta T_M$  (defined as the  $\Delta T_M$  connecting the

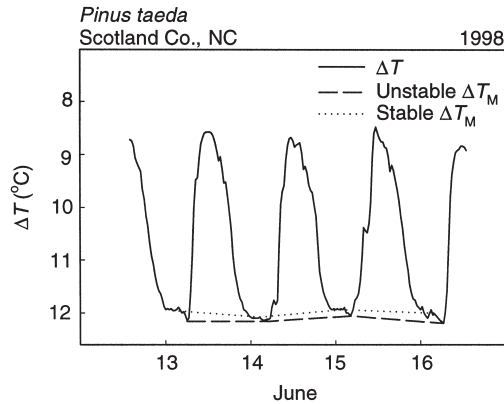


Figure 1. Time series of the temperature difference ( $\Delta T$ , °C) between heated and unheated Granier-type sensors of sap flux ( $J_S$ ). The solid line is the actual decline in  $\Delta T$  with increasing sap flux. The dotted line represents the stable maximum temperature difference between the two sensors, which is assumed to occur near zero flux ( $\Delta T_M$ ). The dashed line represents the unstable  $\Delta T_M$ . See text for definitions of stable and unstable  $\Delta T_M$ .

greatest temperature differences). The maximum difference between stable and unstable  $\Delta T_M$  values occurred on June 16 and amounted to 0.1 °C, a small fraction of the mean  $\Delta T_M$  of

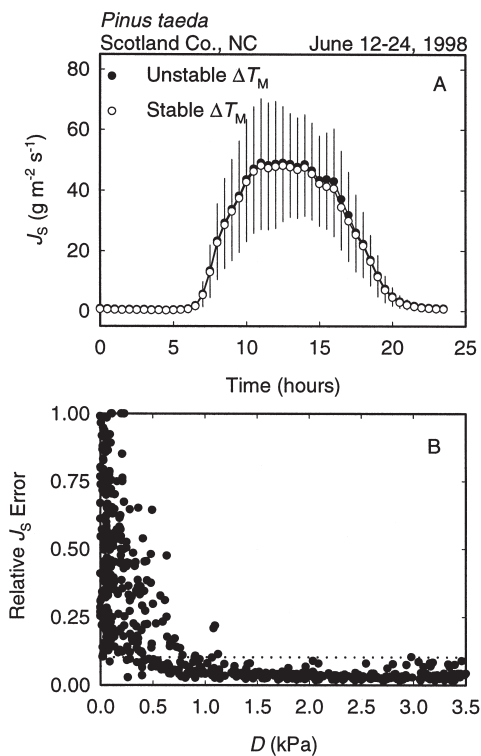


Figure 2. (A) Time-averaged sap flux ( $J_S$ ) over 12 days based on stable and unstable maximum temperature difference near zero flux ( $\Delta T_M$ ) as shown in Figure 1. The bars are 1 SE over time ( $n = 12$ ). (B) Difference in  $J_S$  calculated based on stable and unstable  $\Delta T_M$  as a fraction of  $J_S$  calculated for a stable  $\Delta T_M$  in relation to vapor pressure deficit ( $D$ ). The dotted line represents a 10% error.

12 °C.

The effect of the difference between stable and unstable  $\Delta T_M$  (Figure 1) on the absolute value of  $J_S$  was very small (Figure 2A). However, even a small error in  $\Delta T_M$  placement may cause large errors in estimates of  $G_S$  under conditions of low sap flux. The effect of  $\Delta T_M$  placement on errors in  $J_S$  (and thus  $E_L$  and  $G_S$ ) was assessed by normalizing the difference between  $J_S$  estimated with stable and unstable  $\Delta T_M$  by the values obtained with the stable  $\Delta T_M$ , and relating this relative error in  $J_S$  to  $D$  (Figure 2B).

#### Azimuthal and radial patterns in stem $J_S$

The  $J_{S_{out}}$  in south-facing sensors was a constant proportion of  $J_{S_{out}}$  in north-facing sensors along the entire range of  $D$ , but was highly variable at low  $D$  (Figure 3). In both the C and IF stands, the ratio of  $J_S$  measured toward the south relative to that measured toward the north was unity (paired  $t$ -test  $P = 0.88$ ), even after reducing the variability by selecting data corresponding to  $D \geq 0.6$  kPa. Therefore, the daily sum of  $J_S$  was similar in both directions ( $P = 0.86$ ). Furthermore, the ratio of north to south  $J_S$  was similar in both stands ( $P = 0.50$ ).

We quantified the fertilization-induced increases in  $L$  and growth rate on the radial change in  $J_S$  between the outer 20 mm and the next 20 mm in the xylem. In both the C and IF stands, the  $J_{S_{in}}/J_{S_{out}}$  ratio was constant with respect to  $D$ . However, the daily sums of  $J_{S_{in}}$  and  $J_{S_{out}}$  differed ( $P = 0.001$ ). In the slow-growing C stand,  $J_{S_{in}}$  was 50% of  $J_{S_{out}}$  ( $P = 0.008$ ; Figure 3), whereas  $J_{S_{in}}$  was only 39% of  $J_{S_{out}}$  ( $P = 0.003$ ; Figure 3) in the fast-growing IF stand.

#### Water uptake versus transpiration

The magnitude of  $J_S$  in branches and stems was similar in all treatments. Diurnal patterns of  $J_S$  in stems and lower and up-

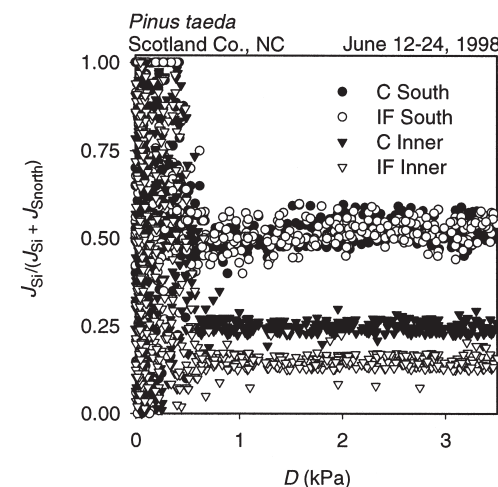


Figure 3. Quotient of sap flux in four positions ( $J_{S_i}$ ; where  $i$  represents southward, outer or inner sensor) over the sum of  $J_{S_i}$  and  $J_S$  measured toward the north ( $J_{S_{north}}$ ) in control (C) and irrigated + fertilized (IF) stands in relation to vapor pressure deficit ( $D$ ).



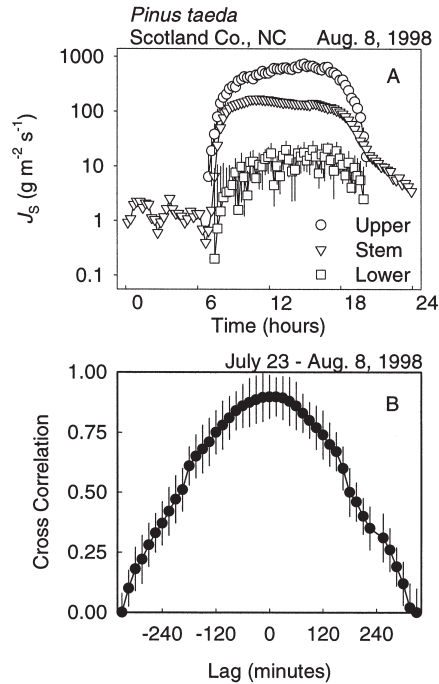


Figure 4. (A) Semi-log plot of diurnal course of sap flux ( $J_s$ ) in upper and lower branches and stems of trees in the control (C) stand. (B) Cross correlation coefficient between stems and branches in the control stand plotted as a function of lag in minutes. Bars in both (A) and (B) are 1 SEM ( $n = 3$ ).

per branches of control trees are shown in Figure 4A. Stem  $J_s$  values were intermediate between  $J_s$  values of the upper and lower branches. Stem  $J_s$  continued until 2300 h, whereas  $J_s$  of

upper and lower branches reached zero flux at 1900 h (effect masked by log scale in Figure 4A).

The lag between  $E_L$  and  $J_s$  was analyzed by time series analysis of  $J_s$  measured in stems and branches. The dependence of  $J_s$  at one time point on the previous point (autoregressive coefficient) was lower in branches than in stems (Table 1) indicating greater variability between consecutive measurements because there is less buffering by stored water in branches than in stems. In addition,  $J_s$  of all branches and stems was correlated to  $D$  without a lag (Table 1), whereas  $J_s$  lagged two hours behind  $Q$ . In all cases, the cross-correlation between stem sensors and  $D$  was uniformly high (Table 1). Because neither branch nor stem  $J_s$  showed a lag with  $D$ , branch  $J_s$  did not lag stem  $J_s$  in any treatment (Figure 4B).

#### Effect of errors in measurements of $R_H$ and $T_A$

Measurement errors in  $T_A$  were small relative to measurement errors in  $R_H$  (Figure 5A). According to the manufacturer's specifications, measurement errors in  $R_H$  are  $\pm 2\%$  below 90%  $R_H$  and  $\pm 3\%$  above 90%  $R_H$ . The combined effect of measurement errors in  $R_H$  and  $T_A$  is shown in Figure 5B. Errors in measurement of  $R_H$  at 1300 h on June 13 caused an error in  $D$  of 5.9%, corresponding to 0.19 kPa. A 0.7 °C error in temperature measurements caused an error of 3.9%.

The time-averaged mean of half-hourly  $D$  over a 6-day period, calculated based on a  $\pm 2\%$  measurement error below 90%  $R_H$  and  $\pm 3\%$  above 90%  $R_H$ , showed a fairly constant absolute difference (Figure 6A). Because the large errors in  $R_H$  measurement during periods of high  $R_H$  would have caused  $R_H$

Table 1. Autoregression and cross correlation coefficients with vapor pressure deficit ( $D$ ) in control, irrigated, fertilized, and irrigated + fertilized stands (C, I, F, IF) for the north side and south side of stems and branches in the upper and lower crown. The SEM is one standard error of the mean,  $n = 5$  for stem sensors and  $n = 3$  for branch sensors. Different letters indicate significant differences at  $\alpha = 0.05$  based on least significant differences.

Treatment	Sensor position	Autoregression coefficient (SEM)	Cross correlation coefficient with $D$ (SEM)
C	Stem north	0.64(0.05)a	0.91(0.03)a
C	Stem south	0.62(0.05)a	0.93(0.04)a
I	Stem north	0.63(0.04)a	0.94(0.04)a
F	Stem north	0.79(0.07)b	0.89a(0.06)
IF	Stem north	0.73(0.12)b	0.93(0.03)a
IF	Stem south	0.72(0.15)b	0.90(0.04)a
C	Upper Branch	0.40 (0.08) c	0.76(0.15)a
C	Lower Branch	0.41 (0.11) c	0.87(0.09)a
I	Upper Branch	0.39 (0.11) c	0.85(0.15)a
I	Lower Branch	0.46 (0.07) c	0.79(0.13)a
F	Upper Branch	0.28 (0.05) d	0.86(0.17)a
F	Lower Branch	0.33 (0.05) c	0.85(0.10)a
IF	Upper Branch	0.51 (0.14) ac	0.86(0.12)a
IF	Lower Branch	0.59 (0.09) ac	0.54(0.10)b

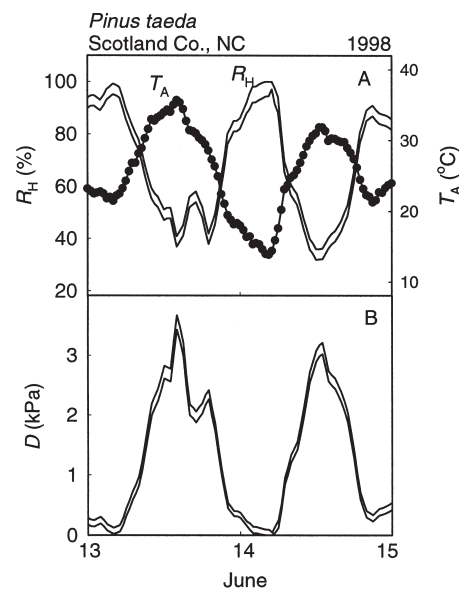


Figure 5. (A) Relative humidity ( $R_H$ ) shown as two solid lines representing the highest and lowest  $R_H$  associated with measurement error. Measurement errors in bulk air temperature ( $T_A$ ) were too small to be discerned. (B) Vapor pressure deficit ( $D$ ) calculated from the  $R_H$  and  $T_A$  values in Panel A. The two lines represent the highest and lowest  $D$  values resulting from measurement error.

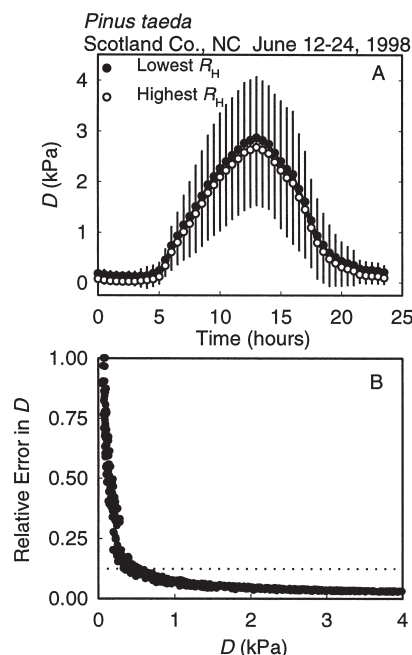


Figure 6. (A) Time-averaged vapor pressure deficit ( $D$ ) over 12 days calculated using the mean relative humidity  $\pm$  measurement error shown in Figure 5A. Bars represent 1 SEM across all days ( $n = 12$ ). (B) The difference between the two  $D$  estimates at each measurement as a fraction of the lower estimate in relation to  $D$ .

to be greater than 100% especially at nighttime, we set these  $R_H$  values to 100%. Similarly, the highest value of the lower estimate of  $R_H$  cannot exceed 97%. These limits predictably affected the error analysis at high  $R_H$  values. Even when using the actual data (without generating a time average), the error increased to above 10% at  $D < 0.6$  kPa (Figure 6B), a  $D$  value that is typically exceeded for 12 h on a sunny day at this site.

#### Vertical gradients of $R_H$ , $T_A$ , and $D$

We evaluated the assumption that there is a negligible vertical gradient in  $R_H$  and  $T_A$  in well-coupled stands representing a twofold difference in  $L$  under conditions of both dry soil surface and during a period of continuous irrigation. The measurements were contrasted with those taken in a nearby opening. There was no vertical gradient in  $R_H$  with depth in the canopy regardless of  $L$  and the values of all stands were similar to the value found in the opening (Figure 7A). The effect of irrigation was noticeable only lower in the profile where it directly impacted the sensor at 2.8 m (Figure 7B). The vertical profile of  $T_A$  generally showed similar responses to those of  $R_H$  except that  $T_A$  was 1 °C lower during the cooler, unirrigated day than in the opening and 2 °C lower during the warmer, irrigated day (Figures 7C and 7D). The high  $T_A$  near the soil surface of the fertilized stands may reflect their location near a large opening that may have provided heat through advection to the space between the soil surface and the base of the canopy at 2 m in the two high- $L$  plots.

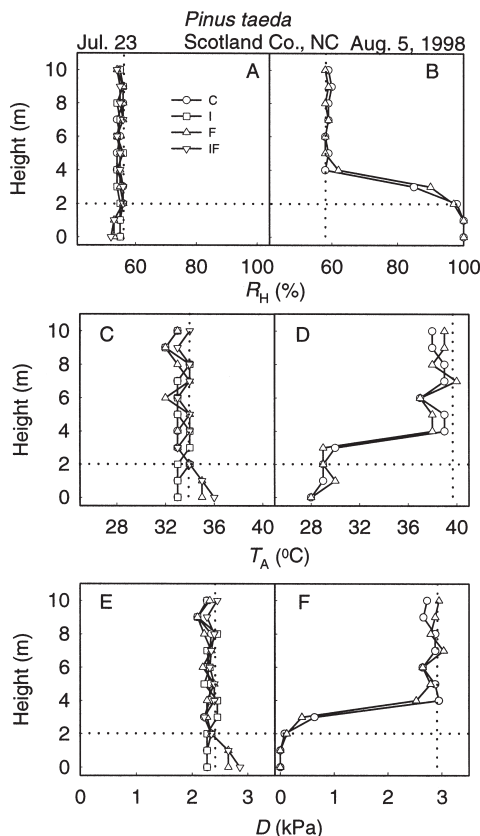


Figure 7. Vertical profiles of relative humidity ( $R_H$ ), bulk air temperature ( $T_A$ ) and vapor pressure deficit ( $D$ ) in control, irrigated, fertilized, and irrigated + fertilized (C, I, F, IF, respectively) plots. Values in (A), (C), and (E) were obtained when irrigation was not applied. Values in (B), (D), and (F) were obtained in plots C and F during a time of a continuous irrigation to a height of 2.8 m. Vertical lines represent the corresponding value taken from a sensor located in a nearby clearing. Horizontal lines represent the mean height of the lowest foliage.

#### Difference between $D$ and $\delta_w$

There was a linear relationship between  $T_L$  and  $T_A$  ( $P = 0.002$ ,  $R^2 = 0.99$ ) with a slope of unity and an intercept of 0.03 °C ( $P = 0.01$ , Figure 8A). The difference between  $T_L$  and  $T_A$  reached a maximum of 0.1 °C at 12 °C  $> T_A > 33$  °C. In early morning, dew formation on the  $T_A$  sensor probably depressed its temperature below the true  $T_A$ , and during midday hours of high radiation load  $T_L$  was probably slightly greater than  $T_A$ .

The relationship between  $D$  and  $\delta_w$  was close to unity regardless of whether the measurement error in  $R_H$  was considered (Figure 8B). The largest difference observed between  $\delta_w$  and  $D$  was 0.27 kPa at  $\delta_w = 4.42$  kPa, a difference of 6%.

#### Diurnal distribution of errors in $G_s$

Diurnal patterns of  $J_s$  in stems and branches of the C stand during one clear day and one cloudy day with early morning showers were converted to  $G_s$  estimates (Figure 9). The random variability among individuals is shown as SE either in as-

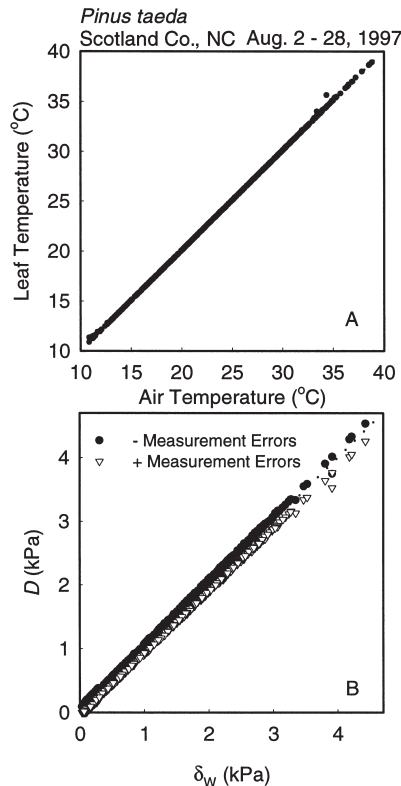


Figure 8. (A) Leaf temperature ( $T_L$ ) plotted as a function of air temperature ( $T_A$ ). (B) Vapor pressure deficit ( $D$ ) plotted as a function of leaf-to-air vapor pressure deficit ( $\delta_W$ ). The uncertainty caused by errors in relative humidity measurements was incorporated into both the  $D$  and  $\delta_W$  estimates.

sociation with the means of  $J_S$  (Figures 9A and 9B), or for clarity above the means of  $G_S$  (Figures 9C–H). Variability was higher among branches ( $n = 3$ ) than among stems ( $n = 8$ ) and was highest in the upper branches (Figure 9C–F) owing to the asynchronous high frequency fluctuation in branch  $J_S$  during the day. The effect of using high and low estimates of  $D$  (i.e., reflecting low and high estimates of  $R_H$ ) is shown by the difference between the lines representing low and high  $G_S$ , respectively (Figure 9C–H). The difference between the low and high estimates of  $D$  contributed most to the difference in estimates of  $G_S$  in the early morning and late afternoon of the clear day. For  $G_S$  estimated from stem  $J_S$ , additional large errors were introduced by baseline uncertainties (Figures 9G and 9H). The errors were particularly large in the early morning and evening hours when the combined effect of measurement errors in  $J_S$  and  $D$  produced estimates of  $G_S$  that ranged from 0 to 100  $\text{mmol m}^{-2} \text{s}^{-1}$ . During the night before the cloudy day, a stable baseline was not attained (Figure 9H). Although the uncertainty in  $G_S$  caused by the unstable baseline began to decrease with increasing  $J_S$  in the morning,  $R_H$  and its associated errors increased in mid-morning because of rains, causing the uncertainty in estimates of  $G_S$  to remain high until noon. In addition to errors in estimating  $G_S$  caused by measurement errors

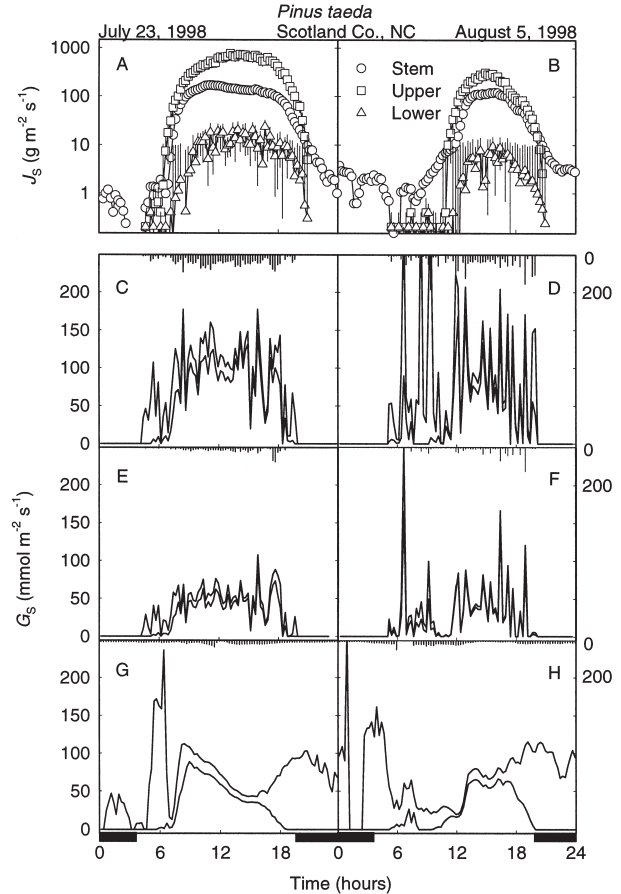


Figure 9. Semi-log plot of diurnal courses of sap flux ( $J_S$ ) measured with Granier-type sensors in stems, and Kučera-type sensors in top and bottom branches in the control stand during a clear day (A) and a rainy day (B). Bars are 1 SEM ( $n = 3$ ). Diurnal courses of sap-flux-scaled canopy stomatal conductance ( $G_S$ ) for the same days as in (A) and (B) are shown for upper branches in (C) and (D), lower branches in (E) and (F), and for the stems in (G) and (H). The two lines each represent high and low estimates of  $G_S$  incorporating measurement errors that affect vapor pressure deficit ( $D$ ) in branches and both  $D$  and  $J_S$  in stems. The descending bars are 1 SEM ( $n = 3$ ), and the scale is shown on the right-side y-axis. Nighttime hours are shown at the bottom.

in  $J_S$  and  $D$ , stem recharge with water during the night produced artificial nighttime  $G_S$  values (Figures 9G and 9H).

Errors in  $G_S$  calculated from measurements of  $J_S$  in branches decreased to less than 10% at  $D \geq 0.6$  kPa, whereas errors in  $G_S$  calculated from measurements of  $J_S$  in stems decreased to the same value at  $D \geq 1.0$  kPa (Figure 10A). Measurement errors in Kučera-type sensors were not assessed, and the difference in  $D$  above which similar errors in  $G_S$  are produced by both sensors may change if this error is included.

## Discussion

We evaluated the effects of measurement errors in  $J_S$ ,  $R_H$ , and  $T_A$  on estimates of  $E_L$  and  $\delta_W$ . We also evaluated the impact of

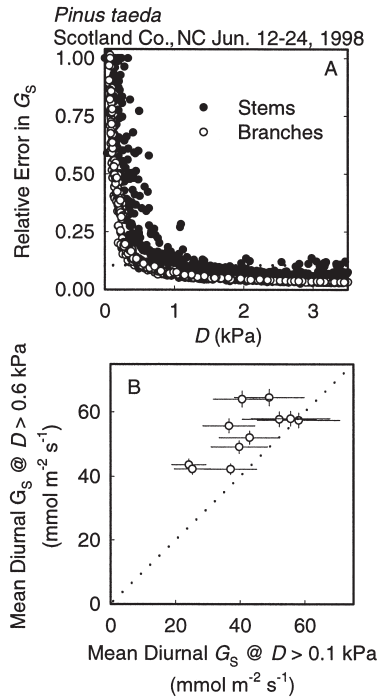


Figure 10. (A) Difference between the high and low estimates of sap-flux-scaled canopy stomatal conductance ( $G_s$ ), shown in Figure 9, as a fraction of the lower estimate in relation to vapor pressure deficit ( $D$ ). Error in  $G_s$  estimates based on stem  $J_s$  include errors in  $J_s$  and  $D$ , whereas those based on branch  $J_s$  include only errors in  $D$ . (B) Mean diurnal  $G_s$  calculated using values of  $D \geq 0.1$  kPa (after Phillips and Oren 1998), in relation to mean diurnal  $G_s$  calculated using values of  $D \geq 0.6$  kPa.

spatial variation in  $J_s$  (both radially and azimuthally) on  $E_L$ , and the assumption that  $D$  at one position in the canopy can be used as a surrogate for  $\delta_w$  to calculate  $G_s$ . All of these errors, systematic variations, and assumptions are inherent to many recent studies in which sap flux is used to estimate  $G_s$  (Köstner et al. 1992, Granier et al. 1996, Martin et al. 1997, Pataki et al. 1998a, 1998b, Oren et al. 1999a).

#### Estimating $E_L$ from sap flux measurements

Use of sap flux measurements to estimate  $E_L$  is problematic because of the potential effects of baseline error in  $J_s$  measurements, systematic spatial variation in  $J_s$ , and a lag between water uptake and transpiration caused by water storage in the stem. Typically, a stable  $\Delta T_M$  is realized sometime at night, and is reached at a later hour as soil dries (Phillips et al. 1996). Goulden and Field (1994) used a small  $\Delta T_M$  value (2.2 °C) and found that temperature gradients in the afternoon can cause relatively large  $\Delta T_M$  shifts in trees of similar size. In this study,  $\Delta T_M$  was large (12 °C, Figure 1) and thermal gradients never exceeded 0.01 °C (Ewers et al. 1999), thus making our setup less sensitive to thermal gradient. The error in  $J_s$  caused by uncertainties in  $\Delta T_M$  can be high at low  $D$ , corresponding to early

morning, late afternoon, and nighttime (Figure 2B). The relative error in  $J_s$  was less than 10% at  $D \geq 0.6$  kPa and stabilized at approximately 4% at  $D \geq 1$  kPa.

Scaling of sap flux in small xylem patches to the entire stem is based on quantifying circumferential and radial patterns in xylem sap flux (Granier et al. 1996, Phillips et al. 1996, Čermák and Nadezhdina 1998, Oren et al. 1998). In *Taxodium distichum* (L.) L. Rich., sap flux on the north side of trees was 64% of that in directions 120° from the north (Oren et al. 1999b). We found no difference in  $J_s$  between the north and south sides of trees (Figure 3). Although fertilization increased  $L$  from 1.8 to 3.6, the resulting light and radiation differences did not produce azimuthal changes in  $J_s$ , perhaps reflecting low variation among measurements made near the base of crowns (Loustau et al. 1998).

Inner, juvenile xylem in *P. taeda* stands of similar age and moderate growth rate showed a 45% decline in  $J_s$  relative to the outer, mature wood (Phillips et al. 1996). The radial decrease in  $J_s$  was 50% in the slow-growing C stand and 39% in the fast-growing IF stand (Figure 3), reflecting changes in wood properties and growth rate in response to fertilization (Ewers et al. 1999). It appears that  $J_s$  decreases with depth more in fast-growing trees than in slow-growing trees. We conclude that measurements in the outer xylem alone should not be used in comparative studies among individuals and stands growing at different rates, especially when the sapwood includes juvenile wood.

Calculating  $G_s$  from  $J_s$  requires corrections for the lag between water uptake and transpiration (Schulze et al. 1985, Granier et al. 1996, Martin et al. 1997). Commonly, the lag is estimated from a formal or informal time series analysis of environmental variables and  $J_s$  (Diawara et al. 1991, Granier and Loustau 1994, Phillips et al. 1997). Time lags between  $J_s$  in stems and environmental variables range from 0 to 3.5 h and are not clearly related to tree size or measurement distance below the crown (Schulze et al. 1985, Köstner et al. 1992, Granier et al. 1996, Loustau et al. 1996, Martin et al. 1997, Phillips et al. 1997). Alternatively, one can measure  $J_s$  simultaneously in branches and in the stem and estimate the lag between the resulting time series (Meinzer et al. 1997). The use of  $J_s$  in branches is justified when the branches are considered to represent the entire crown and store negligible amounts of water.

Sap flux in branches began about the same time as sap flux in the stem, but ceased earlier in the evening as transpiration stopped; whereas water uptake for stem recharge continued (Figures 4A and 9A). Time series analysis indicated that water storage in branches is much less than in the stem (Table 1). However, both time and frequency domain analyses indicated that  $J_s$  in stems did not lag either  $J_s$  in branches or  $D$  (Figure 4B, Table 1). Although this justifies using  $J_s$  in stems and branches to calculate  $G_s$  without lag, the observed nighttime uptake in stems (Figures 4A and 9A) indicates that  $G_s$  calculated from  $J_s$  in stems may be underestimated early in the morning and overestimated late in the afternoon. Phillips and Oren (1998) proposed a conditional sampling approach designed to select times when these errors are small.



### Estimating $\delta_w$

Estimates of  $G_s$  suffer not only from errors in estimating  $J_s$  (Figure 2B) and stem recharge (Figures 4A and 9A) but also from errors in estimating the driving force for transpiration. Errors in the driving force may originate from measurement errors of  $T_L$ ,  $T_A$ , and  $R_H$ , and from systematic variation along the canopy profile. Castellvi et al. (1996) found that  $R_H$  estimated from mean daily dewpoint temperature, mean daily  $T_A$ , and diurnal pattern of  $T_A$  had an error of up to 9% compared with  $R_H$  measured with the more accurate but less automated dewpoint hygrometer. Given patterns in  $T_A$  and  $R_H$  found in this study (Figure 5A), the largest measurement errors in  $T_A$  translated to a maximum error in  $D$  of 3.9%. However, errors in measurement of  $R_H$  may cause large errors in  $D$ , exceeding 10% when  $D < 0.6$  kPa (Figures 5B, 6A and 6B).

In well-coupled stands when wind speed is sufficiently high (Martin et al. 1999),  $T_L$  is often assumed to be similar to  $T_A$ , justifying the use of  $D$  as a proxy for  $\delta_w$  for calculating  $G_s$  (Köstner et al. 1992, Granier et al. 1996, Martin et al. 1997, Oren et al. 1998). We did not evaluate the effect of errors in estimates of emissivity on the measurement of  $T_L$  with an infrared thermometer, but these errors can be large (Gay and Knoerr 1975). Provided that the emissivity used in this study is correct,  $T_L$  was indistinguishable from  $T_A$  (Figure 8A) justifying the use of  $D$  as a surrogate for  $\delta_w$  (Figure 8B).

In most studies,  $D$  is calculated for one position within or above the canopy (Köstner et al. 1992, Granier et al. 1996, Martin et al. 1997, Oren et al. 1998, Pataki et al. 1998a, 1998b). This assumes that vertical gradients in  $T_A$  and  $R_H$  are small and their effects on  $G_s$  estimates are negligible. Temperature gradients may be as high as 5 °C in shrub canopies and 17 °C in pasture (Tappeiner and Cernusca 1996), both of which are less aerodynamically turbulent than many coniferous and some broadleaf forests. In coniferous and other forests with high canopy roughness, the air within the canopy is considered well mixed with the air above the canopy, at least during daytime when the mechanical production of turbulent kinetic energy is high (Oke 1995). This should result in a relatively weak gradient of  $D$  within the canopy.

In forests where aerodynamic turbulence is low, the simplification of Equation 2 cannot be used and a radiative term must be added (Monteith and Unsworth 1990). Furthermore, multiple measurements of  $D$  would be needed in a vertical array to measure the vertical gradients of  $D$  that result in forests of low aerodynamic conductance. Aerodynamic conductance in all stands at our study site was estimated to be 33-fold higher than total canopy conductance (Ewers et al. 1999). This difference is reflected in the similarity observed between  $D$  in an opening and  $D$  inside stands differing twofold in  $L$  and the absence of a vertical gradient in  $D$  (Figure 7). This is similar to findings in a *Pinus sylvestris* L. stand ( $L = 2.8$ , height = 12 m), where  $D$  changed vertically only at an aerodynamic conductance of 0.001 kPa m<sup>-1</sup> (Joss and Graber 1996). At our study site, a gradient in  $D$  below the canopy was found only under conditions caused by irrigation or a nearby large opening (Figures 7E and 7F). Thus, the assumption that a single  $R_H$ - $T_A$  sen-

sor is sufficient to provide an estimate of  $D$  throughout the canopy is valid for *P. taeda* and similar forests.

### Conditional sampling approaches for calculating $G_s$

Analysis of measurement errors indicated that, to estimate  $G_s$  within 10% of error-free values, data should be selected for  $D \geq 0.6$  to 1.0 kPa (Figure 10A). Phillips and Oren (1998) employed a statistically based conditional sampling approach to reduce the errors in estimating  $G_s$ . This statistical approach removed from the analysis rain days, all values of  $G_s$  corresponding to times in which  $D < 0.1$  kPa, and all days with less than 12  $G_s$  values after applying the second criterion. Based on these selection criteria, an acceptable agreement was obtained between the mean of the remaining half-hour data and a mean daily  $G_s$  ( $\langle G_s \rangle$ ) computed directly from the daily sum of  $J_s$  and the daily mean daytime  $D$ . Phillips and Oren (1998) anticipated that the mean of diurnal  $G_s$  values will be lower than  $\langle G_s \rangle$  because, unlike  $\langle G_s \rangle$ ,  $G_s$  does not incorporate the water that is transpired during the day but taken up during the night. Based on the criteria for conditional sampling obtained here (i.e.,  $D \geq 0.6$  kPa), mean diurnal  $G_s$  values were generally greater than  $\langle G_s \rangle$ , and there was no difference between use of  $D \geq 0.6$  kPa or  $D \geq 1.0$  kPa as a filter ( $P > 0.5$ ). As a result, the  $G_s$  calculated as recommended here was higher than that calculated as suggested by Phillips and Oren (1998; Figure 10B); however, the means estimated by two approaches converged for days of high conductance.

The conditional sampling method proposed here does not exclude rain days and is not limited by a requisite minimum number of points for estimating  $G_s$ , unlike the statistically based approach proposed in Phillips and Oren (1998). However, the statistically based approach permits use of data when  $D$  is low (i.e.,  $D \geq 0.1$  kPa). Environmental conditions may dictate which approach is used to calculate  $G_s$  (e.g., the statistically based approach may be more suitable in moist environments where a large proportion of the data would be excluded at  $D < 0.6$  kPa). Nevertheless, the approach developed here limits the data to the range in which estimates of  $G_s$  have a lower uncertainty (Figure 10A).

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