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Progress Report

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by

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1. SUMMARY OF ACTIVITIES

During the past several months we have concentrated on further analysis of our field measurements of carbon dioxide and water vapor fluxes. These data were examined in conjunction with reflectances obtained from a helicopter mounted Modular Multiband Radiometer (MMR) at our grassland study site (#16) during 1987. These measurements are representative of the canopy scale $(10\text{-}100\ \mathrm{m})^2$ and provide a good basis for investigating the hypotheses/relationships potentially useful in remote sensing applications.

All of the micrometeorological data collected at site 916 during FIFE-89 have been processed and fluxes of CO_2, water vapor and sensible heat have been calculated. Soil CO_2 fluxes were estimated using the relationships developed at our site by Norman *et al.* (1991). Employing these soil CO_2 flux values, in conjunction with our micrometeorological measurements, canopy photosynthesis is being estimated.

A biochemical model of leaf photosynthesis was adapted to the prairie vegetation. The modeled leaf photosynthetic rates were scaled up to the canopy level. Further tests are underway employing our measurements made during FIFE-89. This model and a multiplicative stomatal conductance model are also used to calculate canopy conductance. Further evaluation of these calculations, using the FIFE-89 data, is in progress.

Our future plans include completion of these tests of our canopy photosynthesis and conductance models against our FIFE-89 measurements. Our FIFE-87 and FIFE-89 data will also be used to examine the contribution of this temperate grassland in northeastern Kansas as a source and sink for atmospheric CO_2 under a wide range of meteorological and soil moisture conditions.

2. DETAILS OF WORK PERFORMED

2.1 Photosynthesis and Stomatal Conductance Related to Reflectance on the Canopy Scale

2.1.1 Introduction

In recent years many researchers (*e.g.*, Monteith, 1977; Tucker *et al.*, 1981; Asrar *et al.*, 1984; Sellers, 1985, 1987) have investigated the relationships between linear combinations of reflected visible and near infrared radiation known as vegetation indices, and biophysical quantities, such as the leaf area index, biomass, and the amount of photosynthetically active radiation (PAR) absorbed by the canopy. Two vegetation indices commonly used are:

$$\textit{Simple Ratio Vegetation Index (SR)} = R_N/R_V \tag{1}$$

and

$$\textit{Normalized Difference Vegetation Index (NDVI)} = (R_N - R_V)/(R_N + R_V)\ , \tag{2}$$

where R_N and R_V are upwelling radiances or surface reflectances in the near-infrared and visible-red spectral regions, respectively.

Canopy conductance (g_c) and canopy photosynthesis (P_c) can be described using two simple multiplicative relationships (see Jarvis, 1976; Sellers, 1987):

$$g_c = g_c^* \ (PAR) \cdot [f(T) \cdot f(D) \cdot f(\theta_s)] \tag{3}$$

$$P_c = P_c^* \ (PAR) \cdot [f(T) \cdot f(D) \cdot f(\theta_s)] \tag{4}$$

where $g_c^*(PAR)$ and $P_c^*(PAR)$ are the unstressed values of g_c and P_c, regulated only by vegetation type, health and density and the amount of incoming PAR. The stress factors f(T), f(D), and $f(\theta_s)$ account for the effects of temperature (T), ambient vapor pressure deficit (D) and extractable soil water (θ_s). The "stress factors" f(x) vary between unity (optimal conditions) and zero (unfavorable conditions shutting down photosynthesis and transpiration). The stress factors operating on g_c and P_c are assumed to be identical and invariant within the canopy for a given set of environmental conditions. In this study, canopy level flux data and the leaf stomatal conductance of the dominant grass species measured at the site were used to obtain the functional forms of the expressions for the stress factors (see Appendix A). The derived coefficients for these stress factors are independent of the time-varying leaf area index.

The terms g_c^* and P_c^* are dependent on the vegetation canopy and the incident PAR flux. Prior analyses (*e.g.*, Sellers, 1987) have indicated that g_c^* and P_c^* should increase almost linearly with PAR and, therefore, $\partial g_c^*/\partial PAR$ and $\partial P_c^*/\partial PAR$ can be treated as conservative surface properties. Put simply, a bare soil surface should show no change in conductance or "photosynthesis" with increasing PAR and so its associated partial derivatives of g_c^* and P_c^* would be zero. A thickly vegetated surface, on the other hand, would exhibit a strong sensitivity to PAR (non-zero partial derivatives of g_c^* and P_c^*).

The theoretical study of Sellers (1987) proposed that for ideal conditions SR should be near-linearly related to the absorbed PAR (APAR) and to the derivatives of g_c^* and P_c^* with respect to PAR:

$$SR \propto APAR, \frac{\partial g_c^*}{\partial PAR}, \frac{\partial P_c^*}{\partial PAR} \tag{5}$$

The relationship described in Eq. (5) should hold where (a) the canopy consists of spatially uniform cover of green leaves, (b) the reflectance of the background and understory in the chlorophyll absorption band is approximately equal to that of the overlying vegetation and (c) the wavebands of the sensing instrument are configured so that the perceived scattering coefficients of the leaves conform to:

$$\omega_N = 1 - \left[\frac{G(\mu)}{2\mu}\right]^2 (1 - \omega_\pi) , \tag{6}$$

where ω_N and ω_π are the leaf scattering coefficients in the near infrared and PAR wavelength intervals, respectively, $G(\mu)$ is the relative projected area of leaf elements in the direction of $\cos^{-1}\mu$ and μ is the cosine of the zenith angle of the incident radiation flux (see Sellers, 1987).

During 1987, the First ISLSCP Field Experiment (FIFE) was conducted in a 15 km x 15 km area near Manhattan, Kansas. In this paper we report on an analysis of the surface flux and surface reflectance measurements made at a prairie site in the FIFE study area. The fluxes of water vapor and carbon dioxide were measured using the micrometeorological eddy correlation technique (see *e.g.*, Kaimal, 1975; Kanemasu *et al.*, 1979; Verma, 1990), and the reflectance measurements were made with a helicopter-mounted Barnes Modular Multiband Radiometer (MMR). The effective narrow-band visible and near-infrared scattering coefficients for Landsat TM bands 3 and 4, which correspond to the bands on the helicopter MMR, were calculated to be 0.12-0.18 and 0.95-0.97 respectively for individual grass leaves from the data of Walter-Shea (personal communication) collected during FIFE. For calculations involving the penetration of broad-band PAR (0.4 - 0.7 μm) into the canopy we have assumed[1] $\omega_\pi = 0.2$, following the calculation of Sellers (1987). Equation (6) is, therefore, approximately satisfied for a spherical leaf angle distribution ($G(\mu)=0.5$) and so we might expect that Eq. (5) should hold reasonably well for the prairie site being studied here. The purpose of this paper is to test the hypothesis represented in this equation with the field measurements collected in this study. The data presented here are representative of canopy scale and, therefore, can be considered as a test case for investigating the use of Eq. (5) for remote sensing applications.

2.1.2 Materials and Methods

2.1.2.1 Site

The study was conducted in 1987 at a tallgrass prairie site (39° 03' N, 96° 32' W, 445 m above m.s.l., FIFE site #16) near Manhattan, Kansas. The soil is predominantly Dwight silty clay loam (Typic Natrustolls). The vegetation is dominated by three C_4 grass species: big bluestem (*Andropogon gerardii*), indiangrass (*Sorghastrum nutans*) and switchgrass (*Panicum virgatum*). The prairie was burned in the spring of 1987. The experimental area had been lightly grazed for several years, but was not grazed in 1986 and 1987.

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[1] Values of ω_π derived from the observations of E. A. Walter-Shea (personal communication) vary from 0.17 to 0.19.

2.1.2.2 Micrometeorological Measurements

Fluxes of carbon dioxide, water vapor, sensible heat and momentum were measured with eddy correlation sensors mounted 2.25 m above the ground. The sensors included: a three-dimensional sonic anemometer (Kaijo Denki Co., Tokyo, Japan, Model DAT-310), one-dimensional sonic anemometers (Kaijo Denki Co., Tokyo, Japan, Model DAT-110; Campbell Scientific, Logan, Utah, Model CA27), fine wire (0.025 mm) thermocouples (Campbell Scientific, Logan, Utah, Model 127), a Lyman-alpha hygrometer (A.I.R., Inc., Boulder, CO, Model LA-1) with a 5 mm path length and a rapid response CO_2 sensor with a 200 mm path length (Bingham *et al.*, 1978; Anderson *et al.*, 1984). Net radiation, PAR, soil heat flux, air temperature and humidity were also measured. Details on the instrumentation and procedure can be found in Kim and Verma (1990a & b). The configuration of the flux instrumentation indicates that an area extending up to $(100\ m)^2$ upwind of the instrumentation would have the strongest (~70%)influence on the measured flux (see *e.g.* Schuepp *et al.*, 1990).

2.1.2.3 Plant and Soil Measurements

Stomatal conductance was measured on selected leaf blades of tillers of big bluestem, indiangrass and switchgrass, employing a steady-state porometer. The surface soil water content (0-0.1 m) was monitored gravimetrically almost every day and the subsurface water content (0.1-1.4 m) was measured with a neutron probe on a weekly basis. Leaf area index was measured generally every two weeks.

2.1.2.4 Reflectance Measurements

Measurements of surface reflectance were made with a helicopter-mounted MMR from 230 m above the ground. The MMR has eight spectral channels, however only two channels were used in the analysis: 0.63 - 0.68 μm (MMR3 or visible-red) and 0.75 - 0.88 μm (MMR4 or near infrared). A second MMR was positioned on the surface to measure reflected radiance from a Barium Sulfate reference panel as a measure of irradiance. These reference panel measurements were made at one minute intervals starting thirty minutes before the helicopter missions and ending 20 to 30 minutes after the helicopter left the FIFE study area. The reference panel was calibrated using procedures outlined in Jackson *et al.* (1987), and the MMR was calibrated using procedures described in Markham *et al.* (1988), thus allowing determination of absolute radiance from the MMR voltage responses.

A minimum of 25 and a maximum of 150 measurements were taken over the study site within 100 m of the flux station during each mission. Two to five minutes were required to obtain these measurements. Data were collected under clear sky conditions one or two times a day. The sampled areas within the site were usually concentrated upwind of the micrometeorological flux sensors. The vegetation across the site was fairly uniform, with little variation in topography.

The raw digital count values from the MMR were converted to sensor radiances using the calibration data taken prior to the experiment. The sensor radiances were then corrected for atmospheric effects using an atmospheric correction algorithm developed for FIFE by Fraser *et al.* (1989) based on the Dave (1978) algorithm that includes the effects of multiple scattering in the atmosphere and between the atmosphere and the surface. Aerosol optical depths were determined from a Sun-tracking photometer, operating in discrete bands in the 380 - 1020 nm region (Wrigley *et al.*, 1990 and Halthore *et al.* 1990) during the helicopter data acquisition. Gaseous absorption terms (CO_2, O_3, H_2O, etc.) were calculated using Lowtran-7 (Kniezys, 1988) from radiosonde atmospheric water-vapor profiles taken simultaneously with the helicopter data acquisition. The SR was then calculated for the site using the average site reflectance in MMR3 and MMR4.

2.1.2.5 Estimating Canopy Conductance

Canopy stomatal conductance (g_c) can be estimated from the surface conductance, g_c(PM) [canopy conductance and surface conductance are roughly equivalent as the soil evaporation tends to zero - see *e.g.*, Monteith, 1965; Thom, 1975; Baldocchi *et al.*, 1991, Kim and Verma, 1991]. Values of $g_c(PM) = 1/r_c(PM)$ were calculated from the measured fluxes employing the Penman-Monteith equation (Monteith, 1965; Jarvis *et al.*, 1976):

$$r_c(PM) = [(s/\gamma)\beta - 1]\, r_a + (\beta + 1)\, (\rho C_p/\gamma)\, (D/A)\ , \tag{7}$$

where s is the slope of the saturated vapor pressure-temperature curve, γ is the psychrometric constant, β is the Bowen ratio (=H/λE), H is the sensible heat flux, λE is the latent heat flux, ρ is the density of air, C_p is the specific heat of air, D is the vapor pressure deficit, A ($=R_n + G$) is the available energy, G is the soil heat flux and r_a is the aerodynamic resistance to water vapor/heat transfer. The resistance, r_a can be given by:

$$r_a = r_{am} + r_b\ , \tag{8}$$

where r_{am} is the aerodynamic resistance to momentum transfer (see Appendix B for details). The term r_{am} can be expressed as:

$$r_{am} = \overline{U}/u_*^2\ , \tag{9}$$

where $\bar{U}$ is the mean horizontal wind speed at a reference height z and u_* is the friction velocity. The excess resistance term, r_b (see *e.g.*, Thom, 1972; Wesely and Hicks, 1977), is approximated by:

$$r_b = (2/ku_*)\, (\kappa/D_v)^{2/3}\ , \tag{10}$$

where k is von Karman's constant, κ is the thermal diffusivity and D_v is the molecular diffusivity of water vapor. Friction velocity data from the three-dimensional sonic anemometer signals were used to compute r_a. Values of g_c(PM) were calculated using r_a and measured fluxes of R_n, G, H and λE in Eq. (7).

2.1.2.6 Calculation of Canopy Photosynthesis (P_c)

The eddy correlation measurement of atmospheric CO_2 flux (F_c) provides the sum of canopy and soil CO_2 fluxes. An estimation of soil CO_2 flux is necessary for computation of canopy photosynthesis (P_c). Soil CO_2 flux was not directly measured in this study. However, our nocturnal F_c data provided information on the respiratory release of CO_2 from plant and soil. Plant respiration (R_d) was estimated by the following relationship (Polley *et al.*, 1991):

$$R_d = R_d\ (@\ 25°C)\ [\exp\ \{E_1\ (T_\ell - 25)/(298\ R\ T_k)\}]\ L_T \tag{11}$$

where E_1 is the activation energy =45,000 J mol^{-1}, T_ℓ and T_k are the leaf temperature in °C and °K, respectively, R is the gas constant, and L_T is the leaf area index. In our computations, the air temperature near the top of the canopy was used to approximate the leaf temperature. Following Polley *et al.* (1991), a value of 1.55 μ mol m^{-2} (leaf area) s^{-1} was used for R_d (@ 25°C). Plant respiration, estimated by Eq. (11), was subtracted from the nocturnal F_c to obtain (nocturnal) soil CO_2 flux. The soil CO_2 flux values were then adjusted to the daytime soil temperature (0-50 mm) using a Q_{10} factor of 2 (Kucera and Kirkham, 1971) to calculate the daytime soil CO_2 flux. The daytime soil CO_2 flux was used in conjunction with the F_c to estimate canopy photosynthesis (P_c). To minimize the effect of changing soil moisture and photosynthate on soil CO_2 flux, the nocturnal F_c data used here were generally limited to those from the preceding or the following nights.

2.1.3. Results and Discussion

2.1.3.1 Soil Moisture and Plant Growth

A seasonal picture of soil moisture and plant growth at the study site is presented in Fig. 1. Except for a three-week period in late July-early August, precipitation was generally ample during the study period. During the dry period, the extractable soil water, θ_e (0-1.4 m), reached as low as 25% and moisture stress conditions prevailed. Values of green leaf area index (LAI) and stages in the annual life cycle of the prairie vegetation are also included in Fig. 1.

2.1.3.2 Seasonal Variations in Canopy Surface Conductance, Canopy Photosynthesis and Simple Ratio Vegetation Index

In Fig. 2, an overall seasonal pattern[2] of canopy conductance, computed from our measured surface fluxes using Eqs. (7-10), is presented. During the most vigorous stage of plant growth (June and July), the midday g_c averaged about 15.0 mm s^{-1}. The dry period during late July-early August produced much lower value of g_c with an average of 3 mm s^{-1}. With ample rainfall in mid-August, the vegetation began to recover from moisture stress, resulting in an increase in g_c. In mid-late August, the midday g_c averaged about 9.0 mm s^{-1}. Later in the season g_c decreased as the prairie vegetation senesced. In October the midday g_c averaged about 1.3 mm s^{-1}.

The seasonal variation[3] of canopy photosynthesis (P_c) is given in Fig. 3. The midday P_c reached a seasonal peak of about 1.5 mg m^{-2} (ground area) s^{-1} during June-early July, the most vigorous stage of plant growth. There was a drastic reduction in P_c during the dry period. The value of P_c reached a minimum of near zero around 30 July, a day with severe moisture stress. The soil moisture conditions improved during mid-August, and the midday P_c increased to about 0.75 mg m^{-2} s^{-1}. The photosynthetic rates diminished rapidly as the vegetation senesced. The midday value of P_c in early to mid-October was about 0.1 mg m^{-2} s^{-1}.

The days on which SR was measured are indicated on Figs. 2 and 3. The seasonal progression of SR for the study site is shown in Fig. 4. Values of SR were high, ranging from 8.5 to 9.4, in June-early July when the plants were growing vigorously. During the early senescence stage which followed the dry period in late July-early August (see Fig. 1), the SR values reduced to 5.1-6.2. The lowest values (≈ 2) of SR were observed during mid-October toward the end of the senescence period.

2.1.3.3 Simple Ratio Vegetation Index, Related to Unstressed Canopy Conductance and Unstressed Canopy Photosynthesis

The procedure described in Appendix A was employed to define the form and coefficients for the stress factors, f(x), used in Eqs. 3 and 4. Measured values of D and θ_s were used to calculate

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[2] Details of these results have been reported in Kim and Verma, 1990a.

[3] Details of these results have been reported in Verma *et al.*, 1991.

the stress factors f(D) and $f(\theta_s)$. The values of g_c and P_c were then divided by the stress factors to estimate g_c^* and P_c^* (see Eqs. 3 and 4). Plots of g_c^* and P_c^* against PAR are shown in Figs. 5 and 6. Estimates of $\partial g_c^*/\partial PAR$ and $\partial P_c^*/\partial PAR$ were obtained by applying simple linear fits to these data (only afternoon data were used in estimating $\partial g_c^*/\partial PAR$ to minimize confounding effects of rapid time rate of change in soil evaporation). The values of $\partial g_c^*/\partial PAR$ and $\partial P_c^*/\partial PAR$ are shown in Table 1. The correlation coefficient (r^2) was generally quite high, except on 4 June, 11 August and 8 October. Because of rain on 2 and 3 June, our analysis of data on 4 June is subject to problems arising from a rapid rate of change in soil evaporation. 11 August was a day with the driest soil moisture conditions of all the days during June-August when g_c^* and P_c^* were computed. Our empirical approach to calculate the stress factors under such severe moisture stress conditions is not adequate. The low r^2 on 8 October is likely because the canopy conductance and photosynthetic rates diminished rapidly as vegetation senesced in October.

On five days (16 and 17 August and 7, 10 and 13 October), the canopy photosynthesis and conductance measurements were not available. The $\partial g_c^*/\partial PAR$ and $\partial P_c^*/\partial PAR$ values on 16 and 17 August were interpolated from the values on 15 and 20 August. On 7, 10 and 13 October, the values of $\partial g_c^*/\partial PAR$ and $\partial P_c^*/\partial PAR$ were assumed to be the same as those on 8 October.

In Figs. 7 and 8, SR is plotted against $\partial g_c^*/\partial PAR$ and $\partial P_c^*/\partial PAR$, respectively. As indicated above, the data included in these two figures are from a range of soil moisture and meteorological conditions and cover different stages in the annual life cycle of the prairie vegetation (Table 1). The data from 4 June-11 July are from a period when the soil water was not limiting and the plants were growing vigorously. The data point from 11 August is during the dry period, when severe moisture stress conditions prevailed. With about 67 mm of rainfall on 13 August, the soil water conditions improved significantly. The data collected during 15-20 August represent the improved soil water conditions. The data during 7-13 October are from the senescence period.

Whereas the SR and canopy biophysical variables ($\partial g_c^*/\partial PAR$, $\partial P_c^*/\partial PAR$) track each other fairly well, the same cannot be said of the reported green LAI values and these three quantities. One reason[4] may be that the canopy was much less lush in August than in June-July, but the bulk of the foliage was still classified as "green" rather than brown in August. This would explain the lower SR values in August (in spite of larger values reported for green LAI) and also the lower values of $\partial g_c^*/\partial PAR$ and $\partial P_c^*/\partial PAR$.

A linear regression of all of the SR-$\partial P_c^*/\partial PAR$ data yielded a r^2 of 0.41 (Fig. 8). Similarly, a linear regression of all the data in the SR-$\partial g_c^*/\partial PAR$ relationship (Fig. 7) resulted in $r^2 = 0.56$. Our representation of the effect of moisture stress on g_c^* and P_c^* is inadequate on 11 August when extreme dry soil moisture conditions prevailed. Also, as mentioned above, the value of $\partial g_c^*/\partial PAR$ on 4 June was probably affected by problems associated with a rapid change in soil evaporation. Excluding the data points on 4 June and 11 August a linear regression of the SR-$\partial g_c^*/\partial PAR$ data (solid line shown in Fig. 7) resulted in $r^2 = 0.69$. Similarly, excluding the data point on 11 August, a linear regression of the SR-$\partial P_c^*/\partial PAR$ data (solid line shown in Fig. 8) yielded $r^2 = 0.57$.

Even though there is some scatter in the data, Figs. 7 and 8 seem to support the hypothesis suggested by Sellers (1987) that there should be near-linear relationships between the simple ratio vegetation index (SR) and the response of the unstressed canopy conductance and the photosynthetic capacity to the incident PAR (Eq. 5). The data scatter in Figs. 7 and 8 could have resulted from several simplifying assumptions used in the analysis presented above. First, there was no allowance for soil evaporation in the calculation of g_c(PM); it was assumed that all of the latent heat flux was due to canopy transpiration. Second, the soil respiration was not measured directly, but was estimated using empirical relationships. Third, the expressions used to calculate the environmental stress factors are empirical and need further evaluation.

The scatter in Figs. 7 and 8 is consistent with expectations given the experimental methodologies and simple analytical tools we have applied. Further work is needed to address the problems outlined above to bring us closer to the goal of using satellite data to provide information on energy and mass exchanges in various terrestrial ecosystems.

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[4] To estimate LAI, leaves of eight $0.18 m^2$ area were harvested. The harvested foliage was divided into live and dead components, and then fed through an area meter. However, this procedure took no account of changes in the greenness/lushness of live vegetation and in August the leaves were less green than in June/July.

2.1.4. Summary and Concluding Remarks

The surface fluxes of carbon dioxide and water vapor were measured employing the micrometeorological eddy correlation technique during FIFE in 1987. Concurrent measurements were also made of reflectance using a helicopter-mounted Barnes MMR, from which the simple ratio vegetation index (SR) was calculated. Both of these data sets provide information on the grassland canopy at a comparable scale, $(10\text{-}100\ \mathrm{m})^2$.

Using our data, both on the leaf level (*e.g.*, stomatal conductance of the three dominant species) and the canopy level (*e.g.*, water vapor flux), empirical relationships for the environmental stress factors, f(D) and $f(\theta_s)$, were developed to account for the effect of ambient vapor pressure deficit (D) and extractable soil water (θ_s). These factors were then used in conjunction with the measured surface fluxes to compute unstressed canopy conductance (g_c^*) and unstressed canopy photosynthesis (P_c^*).

The derivatives ($\partial g_c^*/\partial PAR$ and $\partial P_c^*/\partial PAR$) of unstressed canopy conductance and unstressed canopy photosynthesis are dependent on the amount and type of green vegetation, and therefore, should be amenable to remote sensing. The analysis of Sellers (1987) indicated that $\partial g_c^*/\partial PAR$ and $\partial P_c^*/\partial PAR$ should be near-linearly related to SR and the first order, preliminary analysis of data presented in this paper seems to support this hypothesis. However, before such relationships can be employed in satellite remote sensing applications, more work is needed. Future studies should include: (a) adequate allowance of soil evaporation in calculating canopy conductance, (b) direct measurement of soil respiration, (c) further development and evaluation of environmental stress functions and (d) more frequent measurements of canopy reflectance under similar illumination conditions.

2.2 Further Data Processing and Analyses

All of the eddy correlation data collected at site 916 during 1989 have been processed and fluxes of energy and mass have been calculated. Supporting meteorological, soil water and plant growth data have also been computed.

Soil CO_2 flux has been estimated using the relationships developed at our site by Norman *et al.* (1991). Employing these estimates in conjunction with our eddy correlation measurements during FIFE-89, canopy photosynthesis of the prairie vegetation is being estimated. A biochemical model of leaf photosynthesis was applied to the tallgrass prairie. The modeled photosynthetic rates of individual leaves were scaled up to the canopy level using a radiative transfer model. The FIFE-89 data are now being used to further test the canopy photosynthesis model. This model as well as a "multiplicative" stomatal conductance model are employed to evaluate canopy conductance. Further tests of these models using the FIFE-89 data are underway.

3. JOINT STUDIES WITH OTHER FIFE INVESTIGATORS

The following includes a list of major joint studies presently underway:

- Relating surface fluxes to reflectance values measured by the helicopter-mounted multiband radiometer (MMR)—with Dr. C. Walthall, University of Maryland, College Park, MD, Drs. P. Sellers and F. Hall, NASA-Goddard Space Flight Center, Greenbelt, MD.
- Comparison of canopy surface conductance at two contrasting sites within the FIFE study area—with Dr. J. B. Stewart, Institute of Hydrology, Wallingford, Oxon, United Kingdom.
- Intercomparison of rapid response CO_2 sensors—with Dr. M. Wesely, Argonne National Laboratory, Argonne, IL and Dr. J. Moncrieff, University of Edinburgh, Edinburgh, U.K.

4. SCIENTIFIC PUBLICATIONS AND PRESENTATIONS STEMMING FROM GRANT NAG5-890

The following scientific publications and presentations stem from our work on Grant No. NAG5-890.

Journal Articles

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5. RESEARCH PLANS

Estimation of canopy photosynthesis during the measurement period in FIFE-89 will be completed. Further testing of canopy photosynthesis model, presently underway, will be completed in the next few months. Results from the 1989 stomatal conductance measurements will be incorporated into a multiplicative canopy conductance model. This model will also be further tested with FIFE-89 data.

Our micrometeorological measurements during FIFE-87 and FIFE-89 will be used to calculate daily net ecosystem CO_2 exchange. These results will be used to examine the contribution of this temperate grassland as a source and sink for atmospheric CO_2 under a wide range of meteorological and soil moisture conditions.

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7. APPENDICES

APPENDIX A

The procedure employed to derive the stress factors f(T), f(D) and f(θ_s) (see Eqs. 3 and 4) is described here.

Leaf stomatal conductance (g_l) can be described in terms of a simple multiplicative model (see *e.g.*, Jarvis, 1976; Kim and Verma, 1991):

$$g_l = g_l{*}(PAR) \cdot [f(T) \cdot f(D) \cdot f(\theta_s)], \qquad \text{(A-1)}$$

where g_l^*(PAR) is the unstressed value of leaf stomatal conductance. Similarly, leaf photosynthesis can be estimated as:

$$P_l = P_l^*(PAR) \cdot [f(T) \cdot f(D) \cdot f(\theta_s)] \ , \qquad \text{(A-2)}$$

where P_l^*(PAR) is the unstressed value of leaf photosynthesis. The stress factors f(T), f(D) and f(θ_s) account for the effect of temperature (T in C), ambient vapor pressure deficit (D in kPa) and extractable soil water (θ_s in %). Values of θ_s were computed as the ratio of actual to total soil moisture held with a water potential between -1/30 and -1.5 MPa.

Equations (A-1) and (A-2) can be integrated ("scaled up") to provide estimates of canopy stomatal conductance (g_c) and canopy photosynthesis (P_c);

$$g_c = F(\Sigma) \int_o^{L_T} g_l^*(PAR) dL = g_c^*(PAR) \cdot F(\Sigma) \qquad \text{(A-3)}$$

and

$$P_c = F(\Sigma) \int_0^{L_T} P_\ell^*(PAR)dL = P_c^*(PAR) \cdot F(\Sigma) \; , \qquad \text{(A-4)}$$

where $F(\Sigma) = f(T) \cdot f(D) \cdot f(\theta_s)$ and L_T = total leaf area index. We assume that the stress factors are independent of leaf area index.

There appears to be a wide range of temperature optima for the grass species in the experimental area (Knapp, 1985) and, therefore, the effect of changes in T was assumed to be negligible (*i.e.*, $f(T) \approx 1$). The response of the unstressed leaf stomatal conductance to PAR was estimated using a hyperbolic relationship (*e.g.*, Monteith, 1965):

$$g_\ell^*(PAR) = (a_1 PAR\downarrow)/(a_2 + PAR\downarrow) \; , \qquad \text{(A-5)}$$

where PAR↓ is the normal (relative to the leaf) flux density of incident PAR, and a_1 and a_2 are empirically derived constants[5]. The leaf stomatal conductance data of the three dominant species (big bluestem, indiangrass and switchgrass) measured at the site were used to evaluate parameters a_1 and a_2 for each of the three species (see Kim and Verma, 1991 for details). Averaged values of these parameters ($\bar{a}_1$ = 19.7 mm s^{-1} and $\bar{a}_2$ = 441 μEi m^{-2} s^{-1}) were used here to yield a canopy level relationship for the mixed vegetation.

Using f(T) = 1 and Eq. (A-5), Eq. (A-3) can be rewritten as:

$$g_c = \left[\int_0^{L_T} \left(\frac{\bar{a}_1 PAR\downarrow}{\bar{a}_2 + PAR\downarrow} \right) dL \right] f(D) \, f(\theta_s) \; . \qquad \text{(A-6)}$$

Substituting the Ross-Goudriaan function (see *e.g.*, Sellers, 1985, Table 3, p. 1351), Eq. (A-6) can be simplified to:

---

[5] The parameter, a_1, represents the asymptotic value of g_ℓ^* when PAR→∞, and can be considered as the maximum stomatal conductance under optimal conditions; and a_2 defines the curvature of the response to PAR.

$$g_c = \frac{\overline{a_1}}{k_*}\left[\ln \frac{\mu \overline{a_2} + G(\mu)\, PAR_o}{\mu \overline{a_2} + G(\mu)\, PAR_o\, e^{-k_* L_T}}\right] f(D)\, f(\theta_s) \,, \qquad \text{(A-7)}$$

where k_* = extinction coefficient for PAR $= (1 - \omega_*)^{1/2}\, G(\mu)/\mu$, $\omega_* \simeq 0.2$, $G(\mu) \simeq 0.5$ (for spherical leaf distribution) and PAR_o = PAR flux above the canopy.

A curvilinear reduction in canopy conductance with increasing vapor pressure deficit (D) was assumed (*e.g.*, Lohammar *et al.*, 1980):

$$f(D) = 1/(1 + a_3\, D) \,, \qquad \text{(A-8)}$$

where a_3 is a constant. The response of canopy conductance to θ_s (extractable soil water) was estimated using a negative exponential relationship (*e.g.*, Stewart, 1988; Kim and Verma, 1991):

$$f(\theta_s) = 1 - \exp(-a_4 \theta_s) \,, \qquad \text{(A-9)}$$

where a_4 is a constant.

As discussed in Sec. 2.5, g_c was computed from our half-hourly measurements of fluxes of net radiation, soil heat, sensible heat and latent heat. Values of μ and k_* were calculated every half hour. The stress functions f(D) and $f(\theta_s)$ were then evaluated by fitting (nonlinear least squares) these data (g_c, μ, k_*, PAR_o, L_T) to Eq. A-7:

$$\begin{aligned} a_3 &= 0.2031 \pm 0.0536 \\ a_4 &= 0.0144 \pm 0.0017 \qquad \text{(A-10)} \\ &(r^2 = 0.788) \end{aligned}$$

(These values were derived from 450 half-hour g_c data points collected during 20 days distributed throughout the season.)

Thus, the following stress factors were used in this study:

$$f(D) = 1/(1+0.2031D) \tag{A-11}$$

and

$$f(\theta_s) = 1 - \exp(-0.0144\theta_s) \tag{A-12}$$

where D is the air vapor pressure deficit measured at 2.25 m above ground and θ_s is the daily value of extractable soil water over the primary root zone (0 to 1.4 m depth).

These derived stress factors were applied to the estimates of g_c and P_c, computed from flux observations, to calculate values of g_c^* and P_c^* (see Sec. 3.3). Note that while values of L_T were used to derive the coefficients given in Eqs. (A-11) and (A-12), the coefficients and the forms of stress factors are independent of the time-varying leaf area index.

APPENDIX B

Heat (or water vapor) transfer in the immediate vicinity of a vegetated surface is primarily controlled by molecular diffusion. Momentum, however, is transferred to a large extent by pressure forces, which have no analog in heat (or water vapor) transfer. Transfer of momentum in aerodynamically rough flows (*e.g.*, over a vegetated surface) is primarily independent of molecular viscosity. Therefore, the transfer of heat (or water vapor) to or from a vegetated surface encounters greater aerodynamic resistance than does the transfer of momentum (Owen and Thomson, 1963; Chamberlain, 1966, 1968; Thom, 1972; Verma, 1989). Accordingly, an "excess resistance" term, r_b is defined:

$$r_a = r_{am} + r_b \qquad \text{(B-1)}$$

where r_{am} and r_a are the aerodynamic resistance to transfer of momentum and sensible heat/water vapor.

The terms r_{am} and r_a can be obtained from:

$$\tau = \rho \frac{\overline{U}}{r_{am}} \qquad \text{(B-2)}$$

and

$$H = \rho\, C_p \frac{T_m - \overline{T}}{r_a} , \qquad \text{(B-3)}$$

where τ ($=\rho\, u_*^2$) is the momentum flux, u_* is the friction velocity, $\overline{U}$ and $\overline{T}$ are the mean horizontal wind speed and air temperature at a reference height. The term T_m represents an effective surface temperature. Equation (B-2) can be rewritten as:

$$r_{am} = \overline{U}/u_*^2 . \qquad \text{(B-4)}$$

Owen and Thomson (1963) proposed a dimensionless parameter B^{-1} (sublayer Stanton number) to express the difference between r_a and r_{am}:

$$B^{-1} = r_a^+ - r_{am}^+ , \qquad \text{(B-5)}$$

where r_a^+ and r_{am}^+ are nondimensionless resistances given by:

$$r_a^+ = r_a\, u_* \qquad \text{(B-6)}$$

and

$$r_{am}^{+} = r_{am}\, u_{*} \;. \tag{B-7}$$

Several investigations (*e.g.*, Garratt and Hicks, 1973; Brutsaert, 1984) suggest that for surfaces with densely spaced permeable roughness elements, as a first approximation k B^{-1} can be assumed to be of the order of 2 for scalars whose Schmidt (S_c) or Prandtl (P_r) number is of the order of 0.6 to 0.8 (k is von Karman's constant). Therefore, the excess resistance term, r_b, can be expressed as:

$$r_b = (2/ku_*)\,(S_c/P_r)^{2/3} = (2/ku_*)\,(\kappa/D_v)^{2/3} \;. \tag{B-8}$$

The factor $(S_c/P_r)^{2/3}$ is incorporated to account for the fact that the basic information was derived from heat transfer observations primarily (Wesely and Hicks, 1977). The term κ represents the thermal diffusivity and D_v represents the molecular diffusivity of water vapor.

APPENDIX C

Table 1. Values of $\partial g_c^{\bullet}/\partial PAR$ and $\partial P_c^{\bullet}/\partial PAR$.

Date (1987)	$g_c^{\bullet}$ *vs* PAR		$P_c^{\bullet}$ *vs* PAR	
	$(\partial g_c^{\bullet}/\partial PAR)$x1000 (mm s^{-1}/μEi $m^{-2}s^{-1}$)	r^2	$(\partial P_c^{\bullet}/\partial PAR)$x1000 (mg $m^{-2}s^{-1}/\mu$Ei $m^{-2}s^{-1}$)	r^2
June 4	14.0	0.590	1.01	0.845
June 5	9.4	0.976	1.23	0.951
June 6	8.6	0.964	1.19	0.927
July 11	10.8	0.887	1.24	0.966
August 11	0.2	0.002	0.14	0.029
August 15	8.2	0.961	1.16	0.961
August 16*	8.6	---	1.18	---
August 17*	9.1	---	1.19	---
August 20	10.3	0.955	1.24	0.923
October 7*	2.5	---	0.44	---
October 8	2.5	0.438	0.44	0.683
October 11*	2.5	---	0.44	---
October 13*	2.5	---	0.44	---

*Estimated data (see text for details).

Table 2. Information of annual life cycle stage, green leaf area index, extractable soil water (θ_s: 0-1.4 m depth), midday (averaged during 1230-1430 hrs, central daylight savings time) mean air temperature (T) and vapor pressure deficit (D) and photosynthetically active radiation (PAR) on selected days when reflectance and flux measurements were available. T and D were measured at 2.25 m above ground.

Date	Day Number	Annual Life Cycle Stage	θ_s (%)	Green LAI	T (C)	D (KPa)	PAR (μEi m^{-2} s^{-1})
June 04	155	Early Growth	79.3	1.86	25.4	1.88	2052
June 05	156	Early Growth	77.7	1.90	27.1	1.91	2048
June 06	157	Early Growth	76.2	1.94	27.8	2.11	2050
July 11	192	Peak Growth	68.4	2.79	31.0	1.85	1971
Aug. 11	223	Early Senescence	24.8	2.44	32.6	2.87	1844
Aug. 15	227	Early Senescence	54.4	2.39	33.7	2.35	1888
Aug. 16	228	Early Senescence	54.2	2.38	30.8	1.57	1887
Aug. 17	229	Early Senescence	54.0	2.37	31.4	2.71	1885
Aug. 20	232	Early Senescence	53.4	2.28	32.8	2.35	1860
Oct. 07	280	Senescence	30.7	0.30	15.9	1.71	1351
Oct. 11	284	Senescence	29.8	0.20	11.6	0.97	1450
Oct. 13	286	Senescence	32.5	<0.20	22.7	2.13	1165

APPENDIX D

LIST OF FIGURES

Fig. 1. Seasonal precipitation, extractable soil water (0-1.4 m depth) and green leaf area index (after Kim and Verma, 1991).

Fig. 2. Seasonal variation in midday (1230-1430 h, central daylight savings time) values of canopy conductance, (after Kim and Verma, 1990a). The days on which SR was measured are indicated with arrows.

Fig. 3. Seasonal variation in midday (1230-1430 h, central daylight savings time) values of canopy photosynthesis (after Verma *et al.*, 1991). The days on which SR was measured are indicated with arrows.

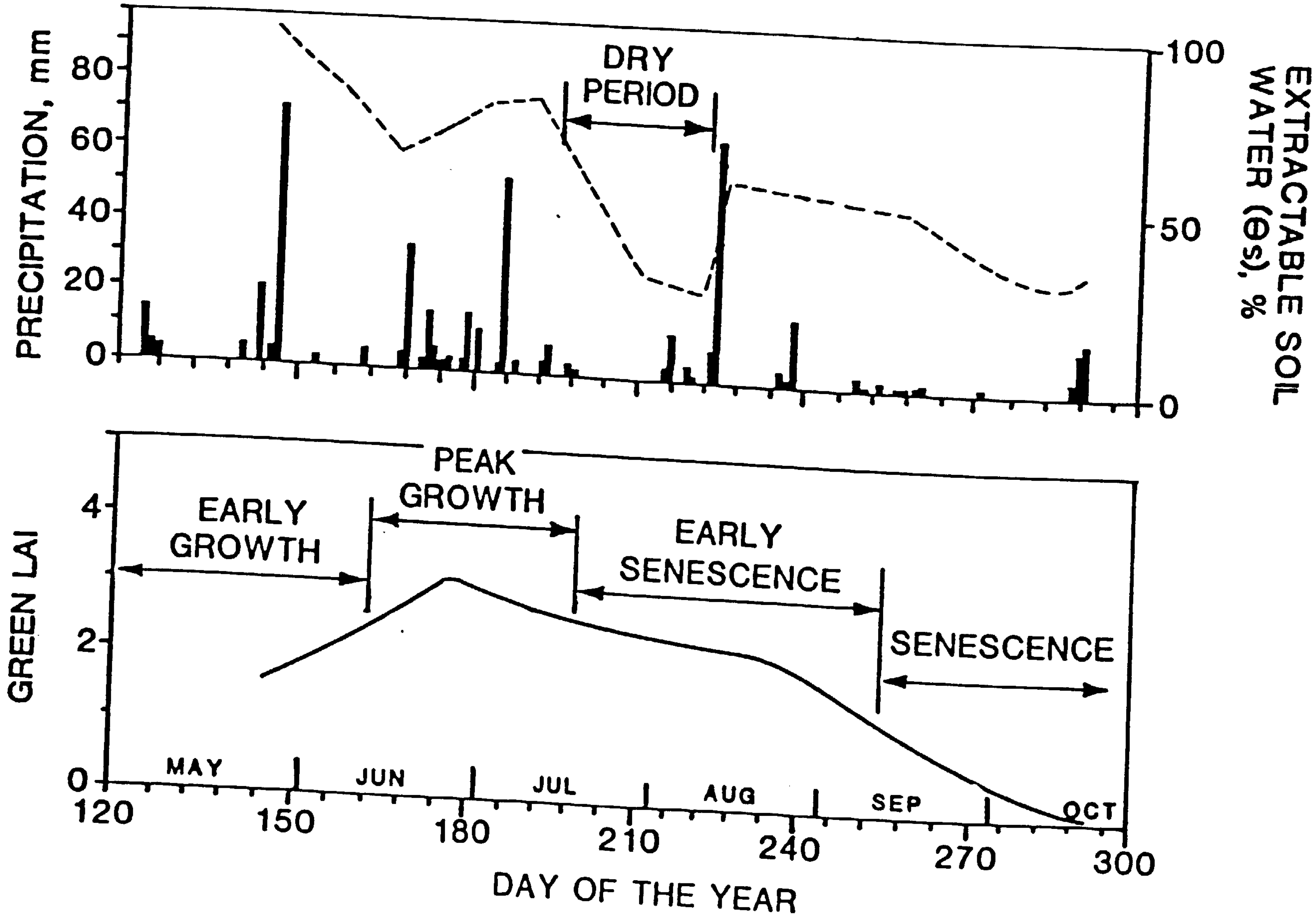
Fig. 4. Seasonal variation in the simple ratio vegetation index (SR).

Fig. 5. Unstressed canopy conductance (g_c^*) as a function of the photosynthetically active radiation (PAR). Only afternoon data were used to minimize confounding effects. Estimates of $\partial g_c^*/\partial PAR$ were obtained by applying simple linear fits to these data.

Fig. 6. Unstressed canopy photosynthesis (P_c^*) as a function of the photosynthetically active radiation (PAR). Estimates of $\partial P_c^* /\partial PAR$ were obtained by applying simple linear fits to the data.

Fig. 7. Simple ratio vegetative index (SR) as a function of the derivative ($\partial g_c^*/\partial PAR$) of the unstressed canopy conductance with respect to the photosynthetically active radiation (PAR). The correlation coefficient (r^2) for the linear regression is 0.56 for all data and 0.69 for the data set excluding 4 June and 11 August. The solid line represents the linear regression of the data set excluding 4 June and 11 August.

Fig. 8. Simple ratio vegetative index (SR) as a function of the derivative ($\partial P_c^*/\partial PAR$) of the unstressed canopy photosynthesis with respect to the photosynthetically active radiation (PAR). The correlation coefficient (r^2) for the linear regression is 0.41 for all data and 0.57 for the data set excluding 11 August.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EXTRACTABLE SOIL WATER (θs), %
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0
DRY PERIOD
GREEN LAI
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2
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EARLY GROWTH
PEAK GROWTH
EARLY SENESCENCE
SENESCENCE
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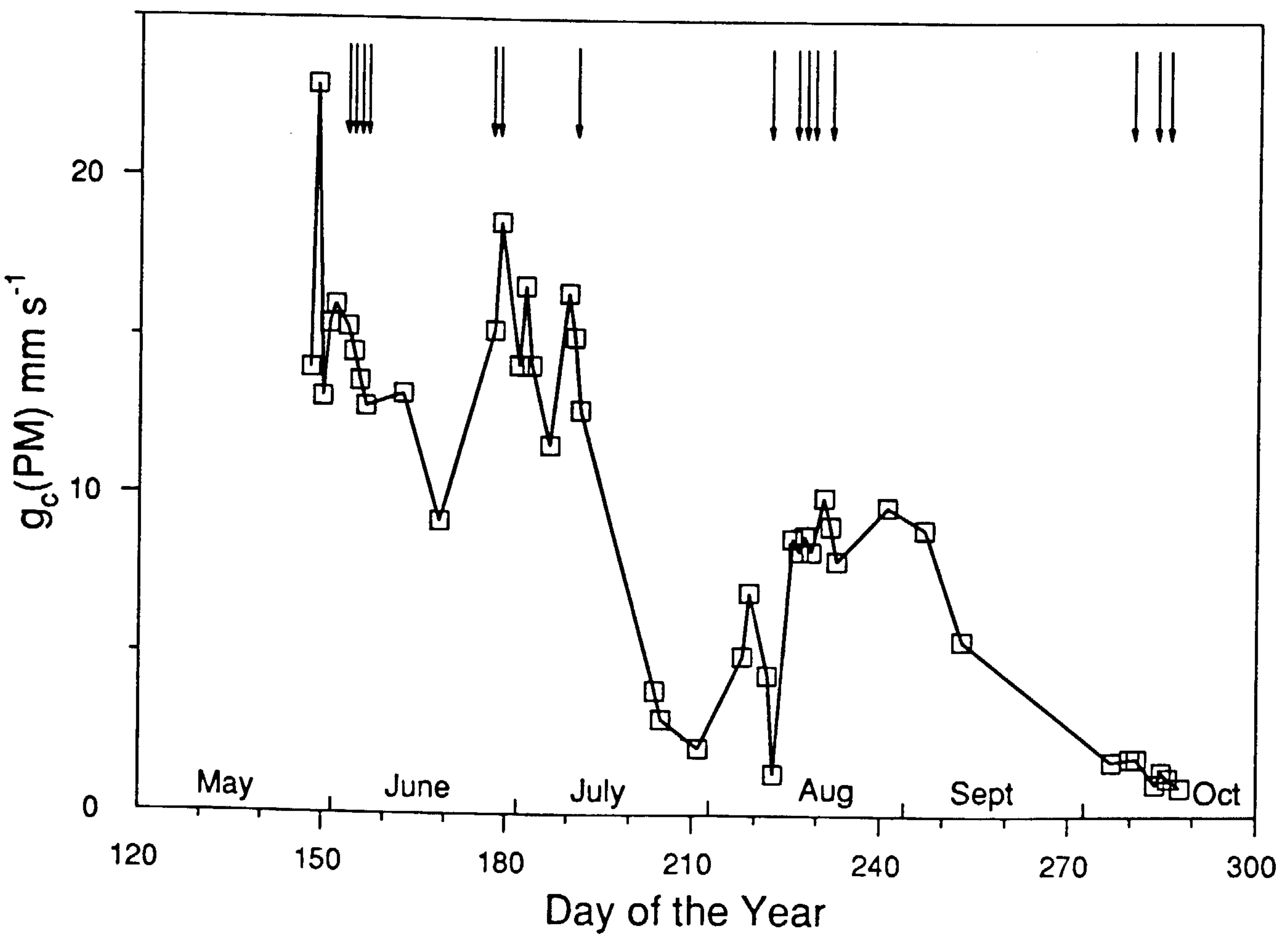
DAY OF THE YEAR

Figure 1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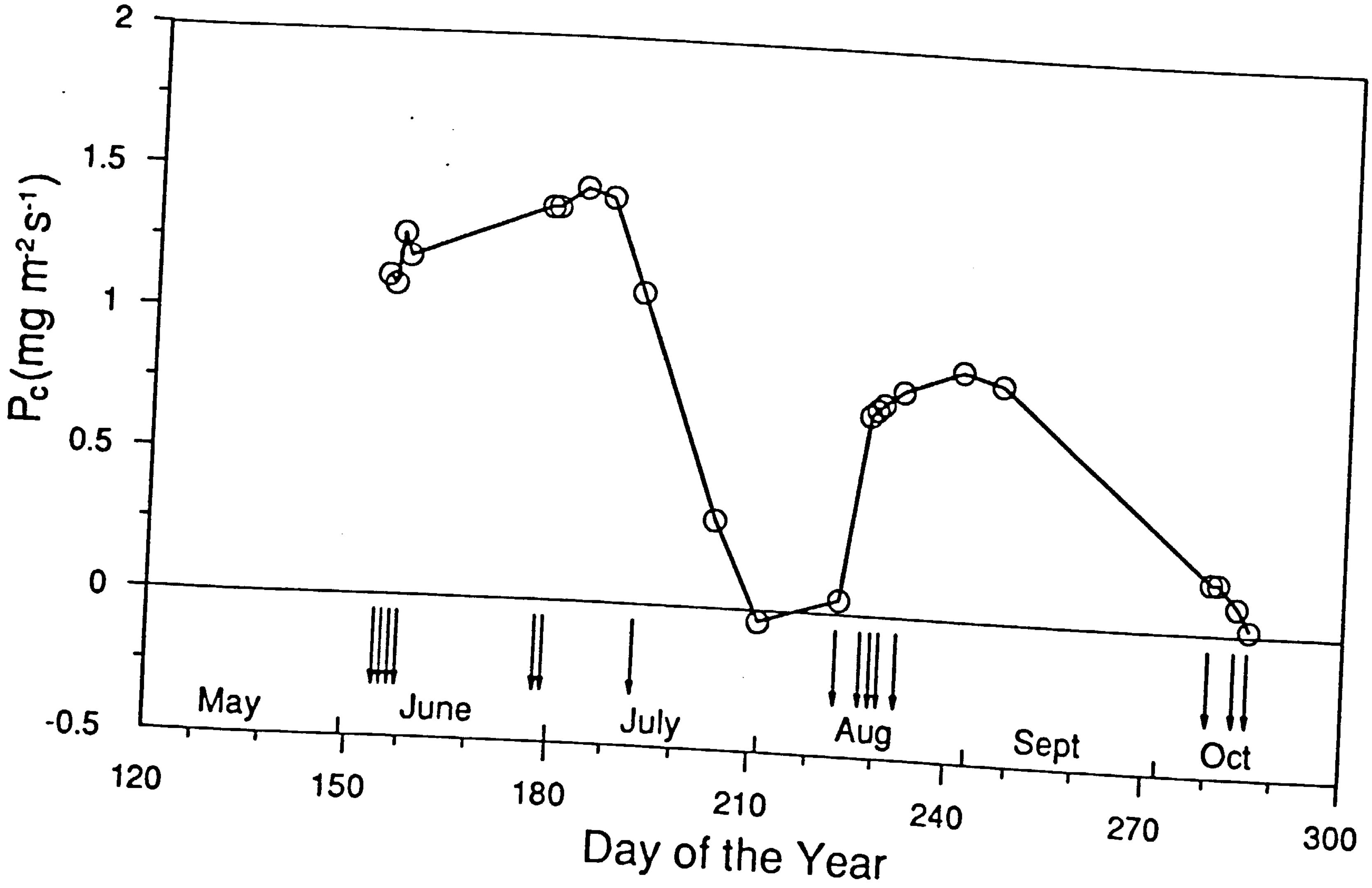
Day of the Year

Figure 2


P_c(mg m^{-2}s^{-1})
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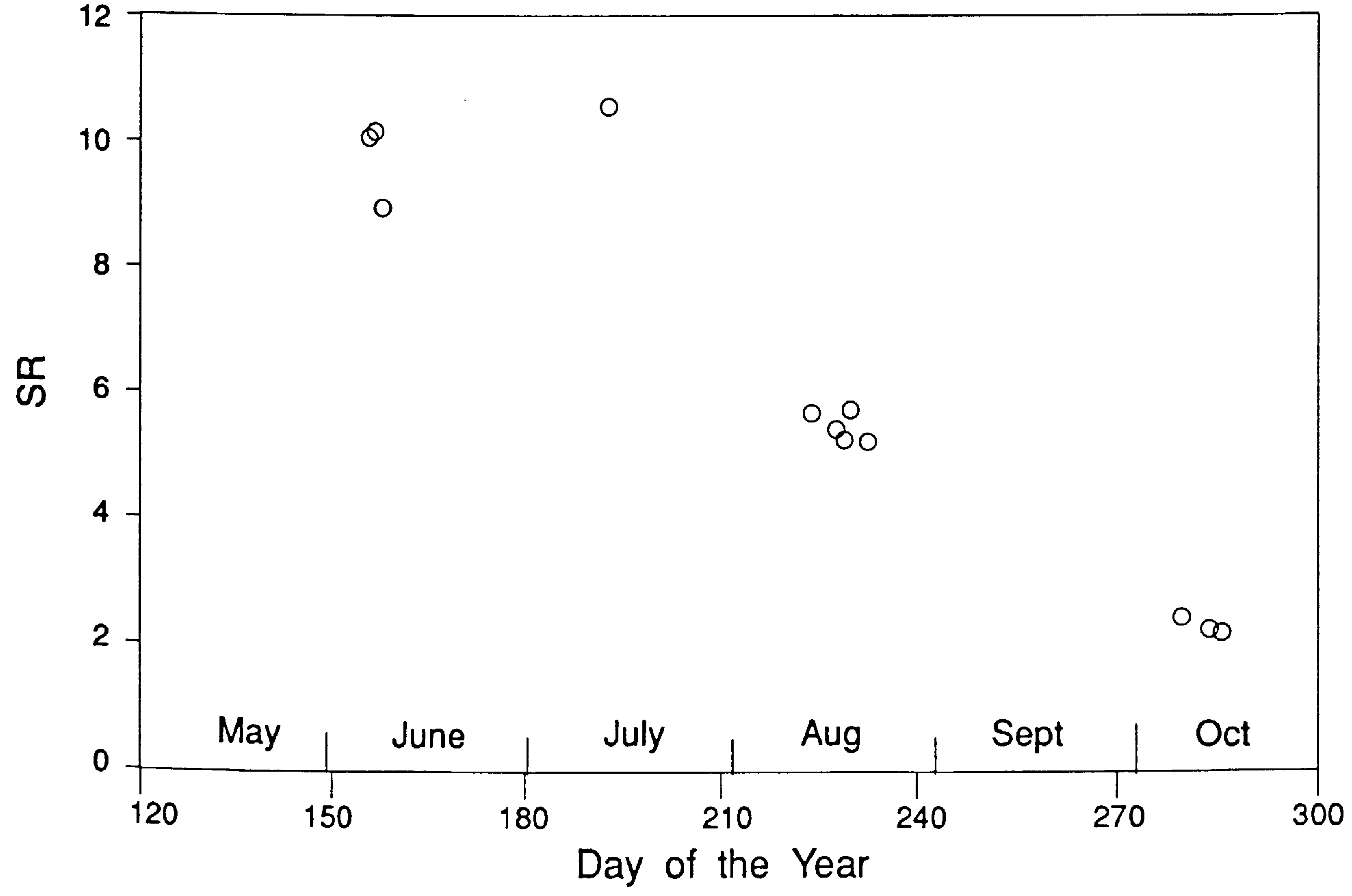
Day of the Year

Figure 3


12
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6
4
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Day of the Year

Figure 4

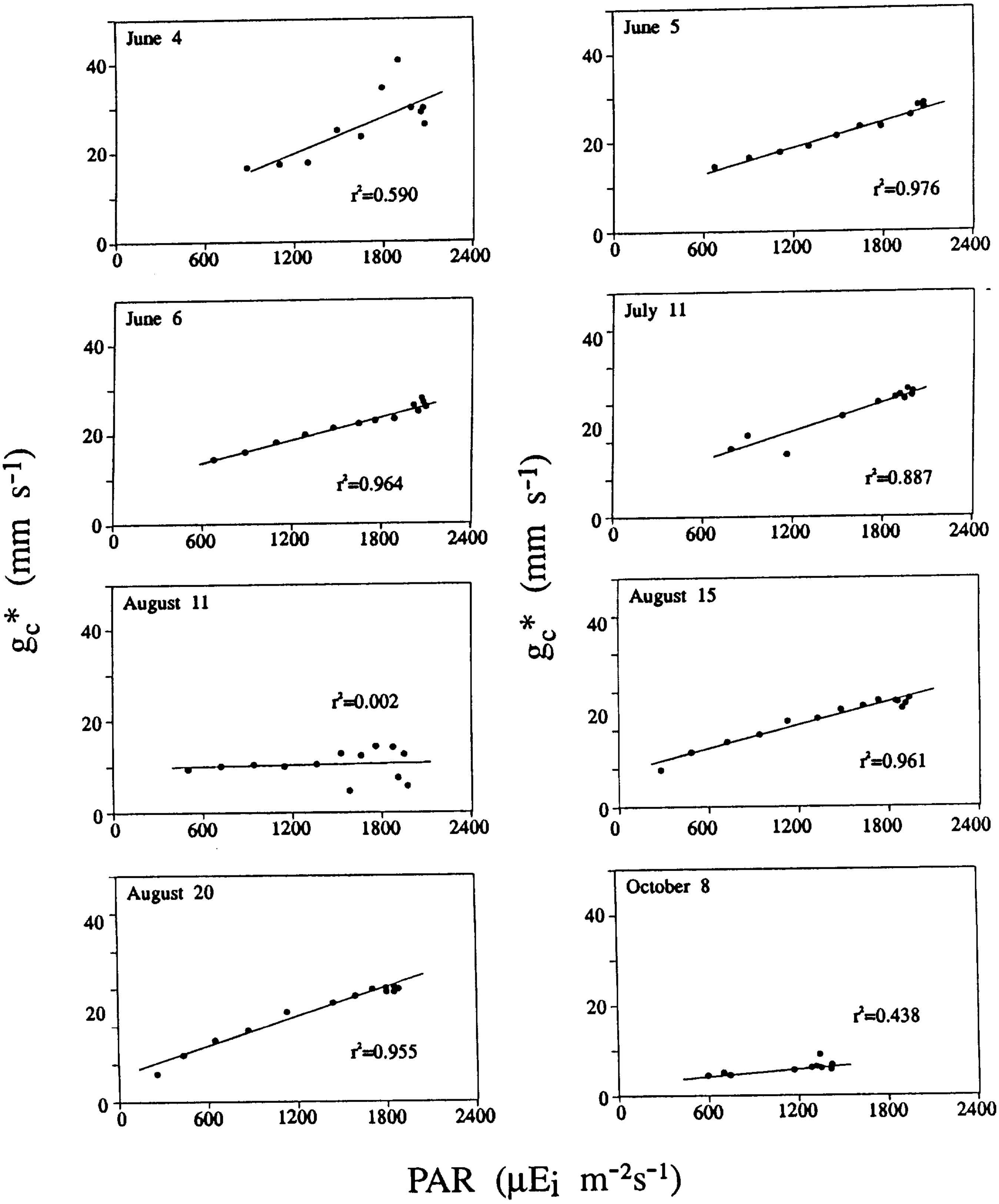

June 4
r²=0.590
June 5
r²=0.976
June 6
r²=0.964
July 11
r²=0.887
August 11
r²=0.002
August 15
r²=0.961
August 20
r²=0.955
October 8
r²=0.438
0
20
40
0
600
1200
1800
2400
g_c^* (mm s^{-1})
PAR (μEi m^{-2}s^{-1})

Figure 5

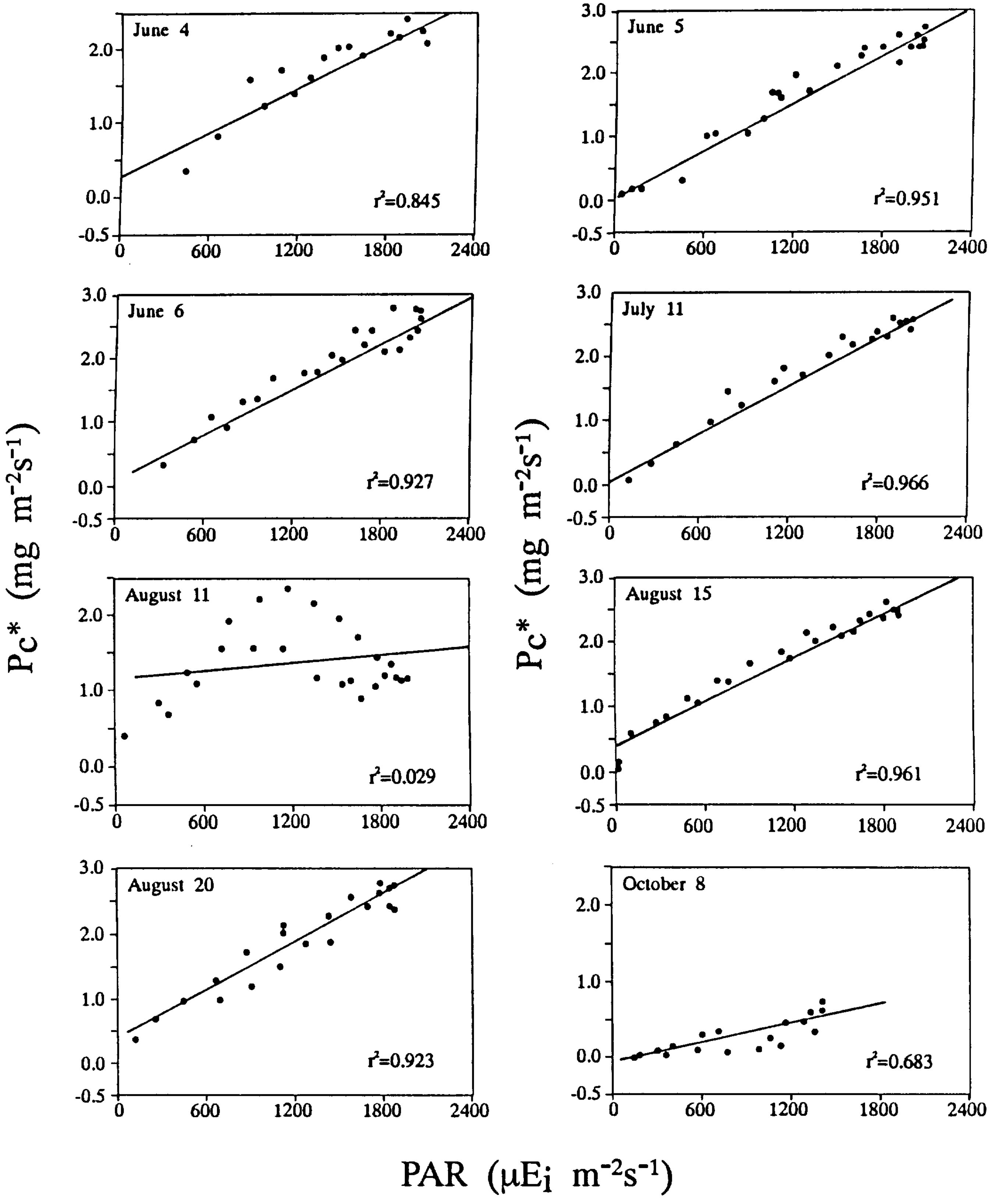

June 4
r²=0.845
June 5
r²=0.951
June 6
r²=0.927
July 11
r²=0.966
August 11
r²=0.029
August 15
r²=0.961
August 20
r²=0.923
October 8
r²=0.683
-0.5
0.0
1.0
2.0
3.0
0
600
1200
1800
2400
Pc* (mg m-2s-1)
PAR (μEi m-2s-1)

Figure 6

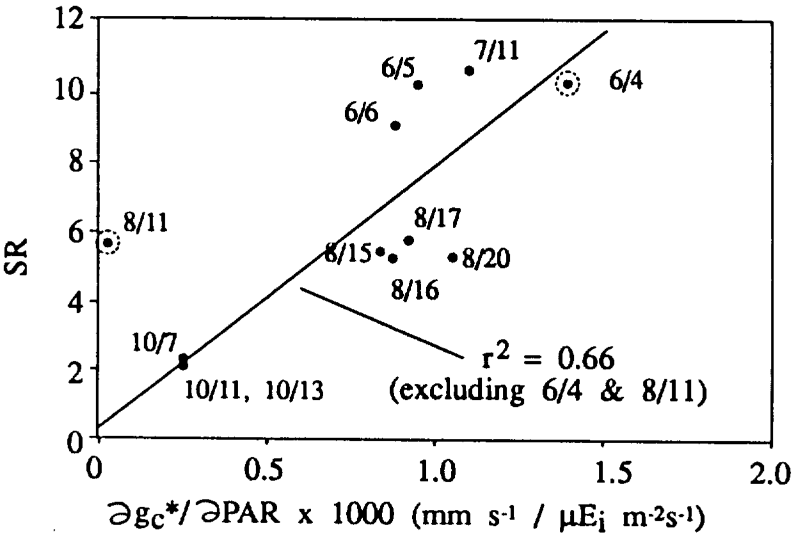
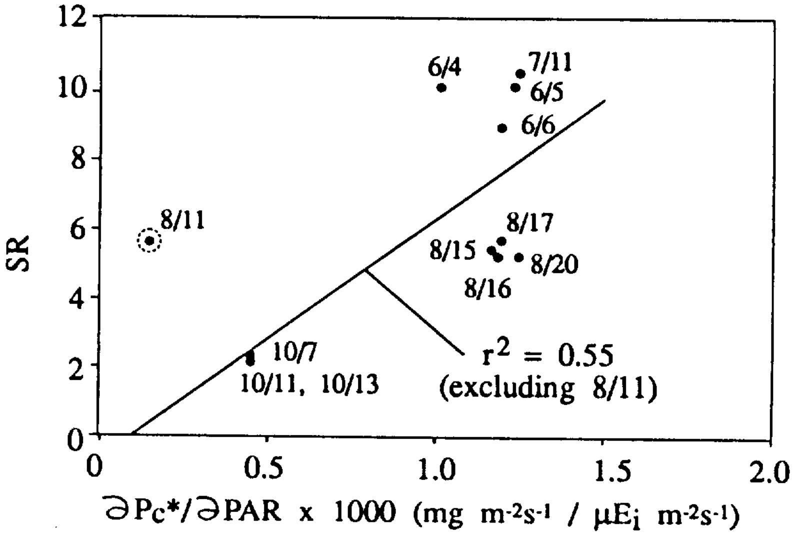

12
10
8
6
4
2
0
SR
0
0.5
1.0
1.5
2.0
∂gc*/∂PAR x 1000 (mm s-1 / μEi m-2s-1)
6/5
7/11
6/4
6/6
8/11
8/17
8/15
8/20
8/16
10/7
10/11, 10/13
r2 = 0.66
(excluding 6/4 & 8/11)

Figure 7



12
10
8
6
4
2
0
SR
0
0.5
1.0
1.5
2.0
∂Pc*/∂PAR x 1000 (mg m-2s-1 / μEi m-2s-1)
6/4
7/11
6/5
6/6
8/11
8/17
8/15
8/20
8/16
10/7
10/11, 10/13
r2 = 0.55
(excluding 8/11)

Figure 8