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Characterization and Improvement of EOS Land Products Using Measurements at AMERIFLUX Grassland and Wheat Sites in the ARM/CART Region: Research Annual Performance Report for Period March 1, 2000- February 28, 2001

E. A. Walter-Shea
University of Nebraska - Lincoln

S. B. Verma
University of Nebraska - Lincoln

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by

Elizabeth A. Walter-Shea and Shashi B. Verma
School of Natural Resource Sciences
Institute of Agriculture and Natural Resources
University of Nebraska
Lincoln, NE 68583-0728

Joseph A. Berry
Department of Plant Biology
Carnegie Institution
Stanford, CA 94305

and

Jeffrey L. Privette
NASA/Goddard Space Flight Center
Greenbelt, MD 20771

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1. INTRODUCTION

Vegetation is important in controlling exchanges of carbon dioxide, water vapor and energy between the atmosphere and the earth's surface. Remote sensing can assist in the estimation of vegetation and its characteristics and thus, provide information needed for predictions of local and regional CO_2 and water vapor fluxes. The project encompasses expertise in areas of remote sensing, mass and energy exchange and physiology/ecology to investigate relations between field measurements and remotely-sensed estimates of leaf area index (LAI), the fraction of absorbed photosynthetically active radiation (FPAR), canopy CO_2 exchange and net primary productivity (NPP) in two key ecosystems (native tallgrass prairie and cultivated wheat), taking advantage of two ongoing AMERIFLUX tower sites in the ARM/CART region in Oklahoma for validation of EOS products, such as surface directional radiance and reflectance, vegetation index, albedo, LAI, FPAR and NPP.

In addition, our study focuses on developing remote sensing algorithms to determine the fraction of incident PAR intercepted by the photosynthetic elements of a canopy (termed the canopy PAR use parameter, Π). In canopies which contain a significant amount of non-green material, Π may differ significantly from FPAR. Tower CO_2 flux measurements will be used together with a model (SiB2) (Sellers et al., 1996) employed in a "pseudo-inverse" mode to determine Π. A sophisticated radiation transport model will be used to analyze these results and to relate this important canopy parameter to spectral reflectance. Thus, in addition to providing information critical to a thorough validation of EOS products, this research should lead to a significant improvement in current and future satellite algorithms and provide a foundation for better estimations of canopy net CO_2 exchange, NPP and ecosystem water and energy balance.

By taking advantage of the facilities and capabilities of the University of Nebraska, Carnegie Institute of Washington and NASA and the ongoing DOE-NIGEC funded research project of Verma and Berry, we will investigate the relations between remote sensing variables and carbon dioxide and water vapor fluxes at a field scale of C_3 and C_4 canopies. We will provide a comprehensive, physically-based scheme which can be applied toward a better estimation of canopy CO_2 exchange and anticipate that the resulting algorithm could provide the Mission to Planet Earth and NASA Ecology Programs with information on CO_2 exchange.

1.1 Goals and Objectives

The goal of the study is two-fold: (1) validation of EOS land surface products and (2) improvement of methods using MODIS, MISR and AVHRR data to yield more accurate estimates of canopy CO_2 exchange and net primary productivity. The following objectives were identified to achieve these goals:

- Test and improve remote sensing methods of estimating the fraction of PAR effectively utilized by the canopy (*i.e.*, the canopy use parameter, Π, which is the fraction of incident PAR intercepted by the photosynthesizing canopy elements) with application to satellite data in two contrasting ecosystems (native tallgrass and wheat) at ongoing AmeriFlux tower sites in the DOE ARM/CART region over the course of three years.

- Test and improve the scheme of integrating remotely-sensed estimates of absorbed light into a mechanistic canopy model (for the C_3 and C_4 vegetation) to yield more accurate estimates of canopy CO_2 exchange from satellite-based canopy reflectance data.

- Rigorously test satellite methods for deriving surface directional radiance, bidirectional reflectance, bidirectional reflectance distribution function (BRDF), albedo, vegetation index, leaf area index (LAI), and the fraction of absorbed photosynthetically active radiation (FPAR).

1.2 Study Area

The research is being conducted at two AmeriFlux tower sites in the DOE ARM-CART region in north central Oklahoma: (a) a wheat site (36.76 N; 96.15 W) near Ponca City, Oklahoma; (b) a native tall grass prairie site (36.95 N; 96.68 W) near Shidler, Oklahoma. The 20km x 20km area surrounding the cultivated wheat site is approximately 75% in wheat and approximately 85% of the 20km x 20km area surrounding the tall grass prairie site is in tall grass prairie. The study takes advantage of year-round measurements of fluxes (eddy covariance) of CO_2, water vapor, sensible heat and momentum at these two sites, along with supporting meteorological variables (funded through an ongoing DOE-NIGEC funded project). The basis of the NASA-funded research are measurements and analyses which build on the strength of the DOE-NIGEC project.

2. ACCOMPLISHMENTS FOR THIS REPORTING PERIOD:

2.1 Canopy and soil reflected radiation measurements and analysis

Ground-based bidirectional reflectance from vegetated surfaces was measured in the solar principal plane (SPP) and in the plane perpendicular to the SPP (PSPP) using a Spectron Engineering SE-590 spectroradiometer (output in the 400-1000 nm range at a 5 nm interval) mounted on a hand-held pointable mast at the two AmeriFlux sites. Reflectance was measured at a variety of view and solar zenith angles during each "field campaign." View zenith angles ranged from 75° to 0° (nadir) at 15° intervals on both sides of nadir in the SPP and PSPP while solar zenith angles of 55° and smaller (depending on time of year) were targeted at a 10° interval. The solar zenith angle desired varied within 5°of the targeted angle defining a "solar zenith angle measurement period." Reflected radiation was measured from two vegetated plots and from a bare soil plot at each site during each solar zenith angle measurement period. Reflected radiation measured from the vegetated and soil plots was bracketed by measurements of reflected radiation from a field reference panel (bidirectional reflectance factor (BRF) was calculated as the ratio of the reflected radiation from the target to the reflected radiation from the panel). The measurement sequence per solar zenith angle typically took approximately 25 minutes. The full complement of canopy reflected radiation measurements during the solar zenith angle measurement period was collected on a single day, from March through May at the wheat site with an approximate 2 week interval schedule and approximately once a month from May through October at the tallgrass prairie site. In addition, soil bidirectional reflected radiation was measured for one day at each site during the current research period; view zenith angles ranged from 60° to 0° (nadir) at 15° intervals on both sides of nadir in the SPP and PSPP while solar zenith angles ranged from 55° to 25°. These data, along with similar data collected in 1998 and 1999, provide 3 years of bidirectional data during the growing season of two different vegetative canopies.

Two Exotech radiometers were installed at the tallgrass prairie for semi-long term, continuous monitoring of incoming and outgoing radiation in four fairly broad spectral bands, a repeat of a similar arrangement in 1999. The Exotech radiometers were mounted at the tallgrass prairie site after the area was burned (mid-April) and remained in the field until late October. The Exotech radiometers were queried every minute in a 10-minute window on the half-hour during daylight hours yielding a data set of incident and reflected radiance values gathered "continuously" for every ½ hour of daylight for nearly every day from mid-April through October at the tallgrass prairie site. A 5-minute average sampling interval was invoked during days of SE-590 canopy bidirectional reflectance factor measurements. The downward pointing Exotech mounted in a nadir direction, was fitted with 15° field of view lenses from which hemispherical reflected flux density was derived. The upward pointing Exotech was fitted with hemispherical lenses so that spectral irradiance was retrieved. Bi-hemispherical reflectances were derived from these data. The intent of the Exotech radiometer measurements was to supplement the "snapshot" spectral data of the SE590 obtained during the field campaigns. The data provide a continuous record of spectral reflectance from green onset through senescence and provides information regarding changes in the prairie spectral characteristics between SE590 data collection times. NDVI calculated from the Exotech data increased with canopy green-up and decreased after the canopy reached its peak LAI (Fig. 1). The decrease in NDVI after the peak LAI was observed in both years of Exotech data collection, 1999 and 2000.

Data have been quality checked with analysis of diurnal effects. Although not tested for significance at this time, some variation between morning and afternoon was detected in the "continuous" Exotech and FPAR data (Fig. 2.). Also noted was a difference in response between the years 1999 and 2000, currently attributed to differences in climatic conditions at the site and canopy architecture.

2.2 Micrometeorological flux measurements and analysis

Fluxes of CO_2, water vapor and energy were measured, using the eddy covariance technique, at the tallgrass prairie and wheat sites. The array of eddy covariance instrumentation includes a three-dimensional sonic anemometer to measure velocity and temperature fluctuations, a krypton hygrometer to measure humidity fluctuations, and a rapid response carbon dioxide sensor to measure CO_2 fluctuations. Supporting micrometeorological measurements include; vertical profiles of mean air temperature, humidity and CO_2 concentration. Solar radiation (incoming and reflected), net radiation, photosynthetically active radiation, soil heat flux, soil temperature, mean wind speed, wind direction and precipitation were also measured.

Real-time (on-line) flux estimates of mass and energy were calculated using computer software developed at the University of Nebraska. All raw data were saved, which allows for data reprocessing and the calculation of spectra and co-spectra. Detailed reprocessing of 2000 data is in progress. The raw data are being processed to determine the proper time delay associated with the closed path CO_2 sensor. Sensor calibration coefficients are being calculated. Proper time delays, calibration coefficients, and quality checked environmental inputs will be used in reprocessing turbulent fluxes and in processing turbulent spectra and co-spectra. Pertinent corrections will be made to fluxes for sensor frequency response (*e.g.*, Moore, 1986) and density effects (Webb *et al.*, 1980).

Comparison among NDVI, FPAR and CO2 flux (Fc) are provided for 1999 and 2000 (Fig. 3).

2.3 Supportive measurements

2.3.1. Fraction of absorbed photosynthetically active radiation (FPAR). The fraction of absorbed photosynthetically active radiation (FPAR) was derived from a set of measurements of incoming, canopy reflected, canopy transmitted and soil reflected PAR values measured throughout the year at each site near the flux towers (scanned every 5 sec from which 30-minute averages are computed). Additionally, the FPAR components were measured using Li-Cor line and point quantum sensors near the canopy reflectance plots during the period of canopy reflectance measurement (scanned every 5 seconds from which 5-minute averages were computed).

FPAR increased as did NDVI (Fig 3) during canopy green-up; unlike NDVI, FPAR remained constant after peak LAI was reached. Accounting for the non-green material influence (see Sec. 2.3.3) on FPAR (i.e., the fraction of PAR absorbed by the green components of the canopy) following Hall et al. (1992) where:

$$FPAR_{green} = \frac{green\ LAI}{total\ LAI} \cdot FPAR. \qquad (1)$$

resulted in a decrease in $FPAR_{green}$ after peak LAI (Fig. 4). The largely non-green leaf component in the canopy affected the reflected signal (and thus NDVI) but had little effect on FPAR, attributed to an increased path length through the canopy as a result of the dense vegetative cover and low sun angles. The fraction of PAR absorbed by the green components of the canopy, $FPAR_{green}$, provides a first approximation of the PAR effectively utilized by the canopy or the canopy PAR use parameter Π, as defined by Sellers et al. (1992). The simple approximation yielded an improved relation between FPAR and NDVI (Fig. 5), regardless of the time of year. However, accounting for the green fraction of the leaf material alone is not a sufficient means of relating remotely-sensed data to plant functioning. Thus, we anticipate Π to differ from FPAR in canopies of high non-green material (see Sec. 2.4.2) and will allow us to derive better techniques for estimating vegetation physiological capacity using remotely sensed data.

2.3.2. Leaf optical properties. Reflected and transmitted radiant energy were measured from four leaves selected from plants of the dominant vegetation species of the canopy at each research site in the vicinity of the canopy reflectance plots. An SE590 spectroradiometer mounted to a Li-COR integrating sphere was used. Leaves remained intact on the plant during the procedure. From the suite of measurements average leaf reflectance and transmittance (adaxial and abaxial surfaces) were derived. In the case of solid components, such as stems and grain heads, only an average reflectance was derived from the suite of measurements from four samples of each canopy element.

2.3.3 Leaf area and biomass measurements. Leaf area is measured directly by harvesting the vegetation (destructive sampling) and using an LI-3100 area meter (LI-COR, Inc., Lincoln, NE) every two weeks. At each site four sampling locations were chosen to provide leaf area and biomass information representative of the tower footprint. At the tallgrass prairie site one 0.33 m x 0.33 m plot was harvested, and at the wheat site 0.5 m of a row (0.145 m row spacing) was harvested at each sampling location on each measurement date. The harvested material was separated into a) green leaves and b) non-green leaves (as well as mulch at the tallgrass prairie site). Biomass was measured on the same samples used in leaf area measurements. Using these measurements, green, dead and total leaf area index (LAI) were calculated. Canopy status at the time of canopy reflectance can be inferred from these data. In addition, LAI and leaf angle distribution in the canopy reflectance and FPAR plots were inferred from measurements of light penetration using a Li-Cor Plant Canopy Analyzer.

2.3.4 *Soil moisture measurements.* A systematic program of soil moisture monitoring was implemented at both sites. Soil moisture was measured with the TDR (time domain reflectometry) method at four depths: 0-0.15 m, 0.15-0.30 m, 0.30-0.60 m, and 0.60-0.90 m.

2.4 Model Studies

2.4.1 *Canopy radiative transfer model.* VEG2 is currently being used to simulate canopy BRFs for the tallgrass and wheat canopies, the results of which are being compared to measured BRFs collected during 1998, 1999 and 2000.

2.4.2 *Inversion of eddy covariance measurements for estimation of canopy structure.* At low incident PAR radiation intensity the rate of CO_2 uptake by physiologically active vegetation (F_c) generally responds linearly to increasing PAR intensity. This is the photosynthetic light response, expressed at canopy level, which can be described as,

$$F_c = R_{eco} - PAR \cdot FPAR \cdot \alpha \cdot \Psi_e \qquad (2)$$

where FPAR is the fractional absorption of incident PAR by chlorophyll, α is the intrinsic quantum yield of electron transport (at 25°C) when CO_2 is abundant in the chloroplast, and Ψ_e represents the influence of temperature and sub-optimal CO_2 and O_2 concentrations on actual quantum yield in C_3 species (Ψ_e=1 in C_4 species). R_{eco} is whole ecosystem respiration rate by soil and plants.

The intrinsic quantum yield (α) at chloroplast level is relatively well known (0.08 and 0.05 mol mol^{-1} for C_3 and C_4 species, respectively). In intact leaves, absorption by leaf material other than the photosynthetic pigments reduces the "apparent" quantum yield to about 0.06 mol mol^{-1} (C_3) and 0.04 mol mol^{-1} (C_4). Since Ψ_e in C_3 species can be estimated to first-order based on leaf temperature, and an assumed CO_2 concentration in the chloroplast (c_i) at low light that is slightly below ambient (e.g. $c_i/c_a = 0.8$), it is possible to obtain "inverse" estimates of FPAR as the slope of the relationship between measured CO_2 flux and incident PAR; these estimates provide a more refined approximation of the canopy PAR use parameter, Π, then obtained using $FPAR_{green}$ (Eq. 1).

Inverse estimates of FPAR were calculated for each day between January 1998 and December 1999 using a seven-day moving window and linear regressions between incident PAR (< 500 μmol m^{-2} s^{-1}) and net ecosystem CO_2 flux (Fig. 6). The standard errors of the inverse FPAR estimates are relatively large, indicating the variability in the measured CO_2 fluxes, but the central tendency is coherent from day to day and week to week. Also shown in Figure 6 are independent measurements of total FPAR made on the sites using light bars.

At the tall-grass prairie site, the measured FPAR corresponds well with the inverse estimates in early season but diverge greatly as the season progresses and physiologically inactive (senescent) leaves become increasingly important in the total interception of the canopy. However, comparison of the inverse FPAR estimates with an approximation of the fractional interception by green leaves, $FPAR_{green}$ (Eq. 1), results in good agreement between the inverse and field measured FPAR throughout each of the three years of measurements. Note that the "field measured" green FPAR, $FPAR_{green}$, is a relatively crude estimate of Π and is likely to underestimate actual absorption by green leaves, since the reflectance and transmittance properties of green and non-green materials are different.

At the wheat site, the inverse estimates underestimate field measured FPAR (when total FPAR is equal to $FPAR_{green}$) during the early part of the season (c.f. Jan-Mar.1998). The reasons for this discrepancy are under investigation, but it is likely to be related to nighttime temperatures that are sufficiently cold (e.g. < 10°C) to cause chilling injury, and resultant reduced quantum efficiency during the following day. Winter wheat is planted in the Fall and growth proceeds slowly through the Fall, Winter and early Spring. Photosynthetic activity during this time is restricted to warmer days. Even on warmer days, if chilling has occurred during the previous night, it may take some hours for the photosystems to recover sufficiently for net photosynthetic uptake to occur. In our inverse analysis, the chilling effect on α and time for recovery from cold-induced photoinhibition are not yet taken into account. This likely results in the underestimation of light interception in the Spring period. This effect is not seen at the tall-grass prairie site, primarily attributed as such because physiological activity, shoot production and growth of the indigenous grassland system are closely tied to temperature increase in the Spring.

Since the inversion technique uses measured CO_2 flux to estimate the amount of PAR absorbed by the canopy, it is inherently a measure of the absorption by photosynthetically active materials in the canopy, rather than a measure of total absorption, and thus an approximation of the canopy PAR use parameter, Π. This approximation is very attractive, since the physiologically active components of plant canopies are primarily responsible for CO_2 and water vapor exchange and the green leaf absorption is in most cases the desired quantity. By contrast it is very difficult, using field measurements of radiation interception and absorption, to separate the fractions absorbed by green and non-green plant materials. Thus it might be argued that the inverse estimation of FPAR provides a more accurate assessment of this structural parameter and a better means of defining Π than can be obtained using direct measurements of light interception.

In the context of the EOS validation study, we will seek to clarify the physiological and structural significance of the inverse FPAR estimation technique and then explore the relationship between inverse FPAR and remotely sensed spectral reflectance and vegetation indices. We expect that inverse FPAR and Π may be more closely, and more linearly, related to indices such as the NDVI and MODIS vegetation indices than are ground measurements of total FPAR or $FPAR_{green}$, as suggested by the lower scatter in $FPAR_{green}$ estimates than with $FPAR_{green}$ and total FPAR (Fig. 7).

2.4.3 *Flux simulations for wheat and tallgrass site.* Model analyses using the SiB2 land surface model have concentrated on long-term simulations of the turbulent fluxes of carbon, water and energy from the tall-grass prairie and wheat sites. Concurrent simulation of the evolution of soil moisture profiles was also a focus since soil moisture retains a much longer historical signature than the canopy fluxes and is thus more liable to drift away from reality during long simulations.

Monthly averages of diurnal measured and simulated CO_2, water and energy exchange over tall-grass prairie were simulated for 1997 and 1998 calendar years (Fig. 8). The most influential parameter in SiB2, the fractional PAR absorption (FPAR), was estimated using the inversion method described in Section 2.4.2. The simulations were further parameterized using field measurements of total leaf area index (LAI), green LAI and soil texture. These simulations thus represent a comprehensive test of the ability of SiB2 to predict fluxes when vegetation structural are reasonably well determined, prior to application of the model using remotely sensed estimates of FPAR and other model parameters. The physiological parameters (photosynthetic capacity and stomatal response to environmental variables) were assigned constant values for C_3 and C_4 species using average values derived from leaf-level gas exchange measurements. The simulations accurately predicted the daily progression of CO_2 fluxes during the two-year period for all months, with two primary exceptions in August of both years.

3. PLANS FOR THE NEXT REPORTING PERIOD

3.1 Quality check of data

3.1.1 Canopy and soil reflected radiation measurements. Checking of the quality of the data will be completed through comparison between SE-590 and Exotech data, analysis of diurnal trends, and comparison of measured and simulated reflectance.

3.1.2 Micrometeorological flux measurements and analyses. Detailed reprocessing of 2000 data will be completed. The reprocessing entails the determination of the proper time delay associated with the closed path CO_2 sensor and sensor calibration. Proper time delays, calibration coefficients, and quality checked environmental inputs are used in reprocessing turbulent fluxes and in processing turbulent spectra and co-spectra. Once processed, the data will be compared with SiB2 simulation results as well as used in the inversion of the SiB2 model for estimating the canopy PAR use parameter Π.

3.2 Modeling studies

3.2.1. Canopy Radiative Transfer Model. The physically-based turbid medium canopy reflectance models, Veg2 and DISORD (Myneni *et al.*, 1995) will be used to simulate canopy reflectance at the research sites. The models will be used to investigate relations between $FPAR_{green}$ estimates, Π, canopy architecture, and leaf conditions with the assumption that the canopy PAR use parameter, Π, is equivalent to the canopy green leaf absorbed PAR fraction. The canopy green leaf absorbed PAR fraction will be derived from canopy reflectance simulations with DISORD.

3.2.2 Inversion of eddy covariance flux measurements for estimation of canopy structure. The inversion of measured CO_2 fluxes to estimate canopy structure will be extended to examine in detail the impact of chilling and drought on the FPAR estimates. We will investigate methods to predict quantum yield responses for the 2000 field season such that realistic inverse FPAR can still be calculated.

The inverse FPAR estimates will be compared to ground measurements of vegetation spectral reflectance at the two field sites. This will allow us to derive better techniques for estimation of vegetation physiological capacity using remote sensing data. We expect that FPAR estimated from the CO_2 flux measurements will be more closely correlated with vegetation index measurements than are ground measurements of FPAR, which are inherently more susceptible to the influence of non-green canopy components.

3.2.3. SiB2 Modeling. Modeling activities with SiB2 in the coming year will concentrate on model-based estimation of structural and physiological parameters at short time-steps (e.g. weekly) using non-linear optimization or Monte Carlo techniques. The Monte Carlo methodology was developed in the first year of this project to investigate parameter sensitivity and could be adapted for semi-automated parameter estimation. Alternatively, we will investigate other non-linear optimization methodologies for this purpose. Once again, these studies will concentrate on estimation of the primary structural parameter (FPAR) and physiological parameter (photosynthetic capacity). This will provide an alternative dataset for comparison with remote sensing measurements and radiative transfer studies.

Comparison of the results for the wheat and tallgrass prairie sites will provide insight into the applicability of the method in rather simple and complex canopies.

4. REFERENCES

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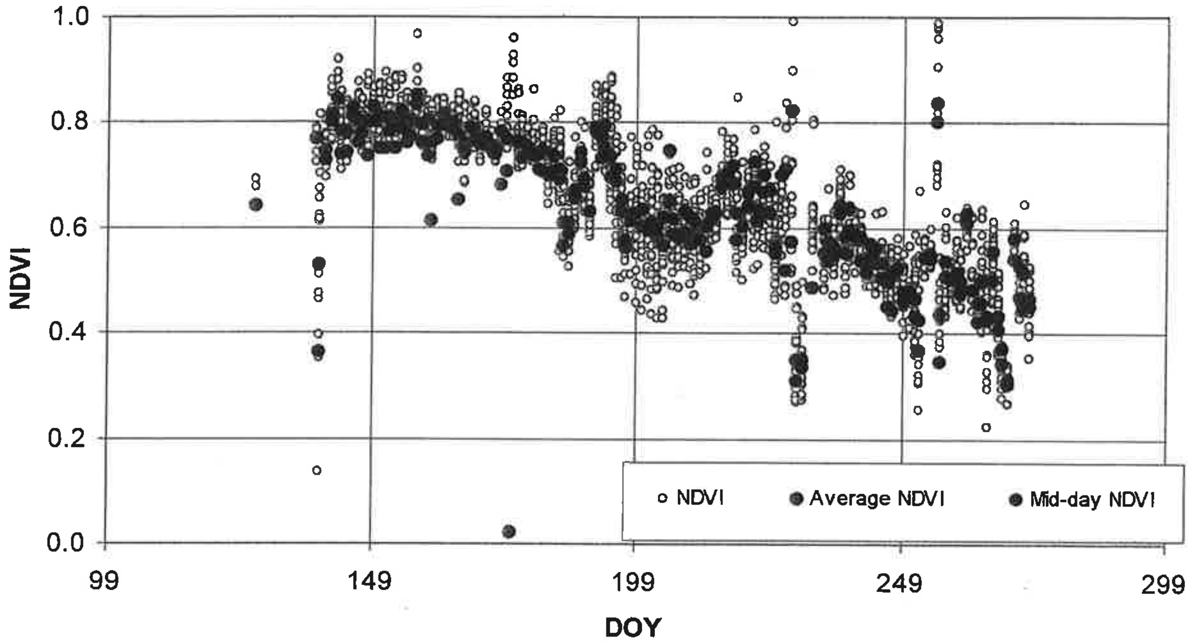
5. FIGURES

Continuous NDVI measurements from Oklahoma Tallgrass (1999)



Continuous NDVI measurements from Oklahoma Tallgrass (2000)

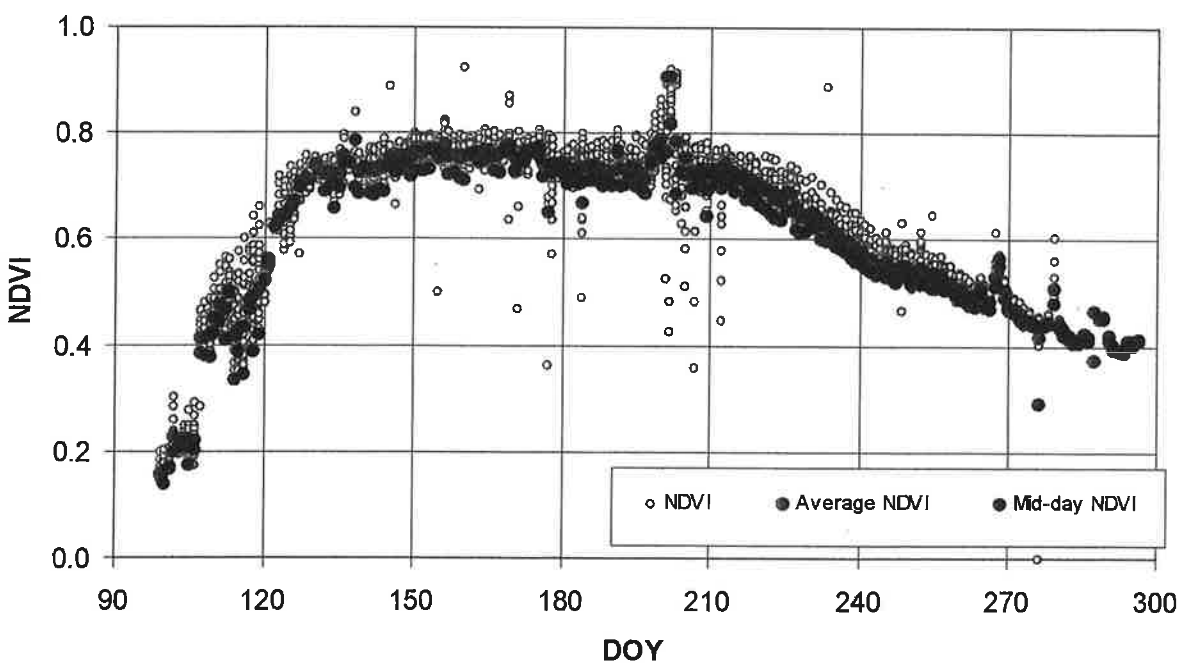


Figure 1. Normalized Difference Vegetation Index (NDVI) from the Exotech "continuous" data as a function of day of year (DOY) from: a) 1999 and b) 2000.

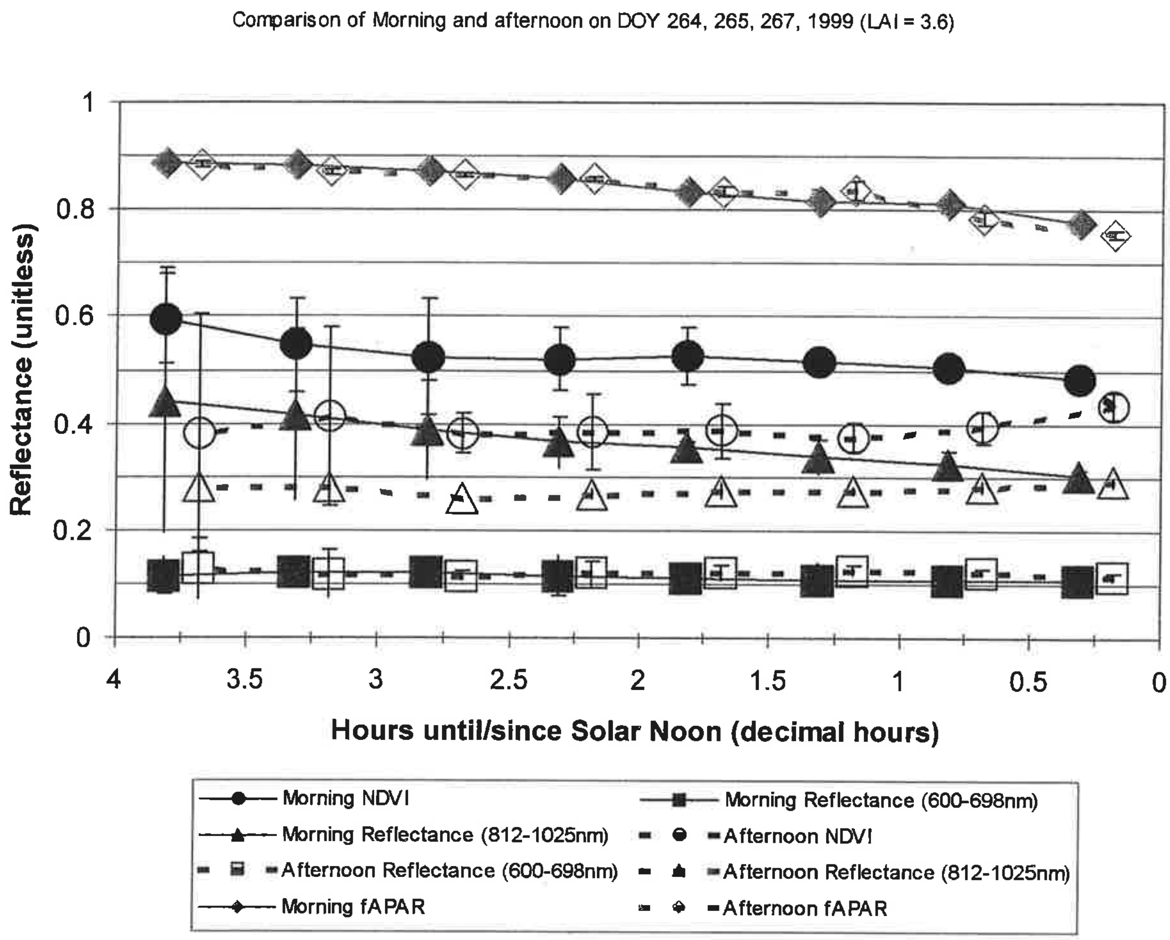
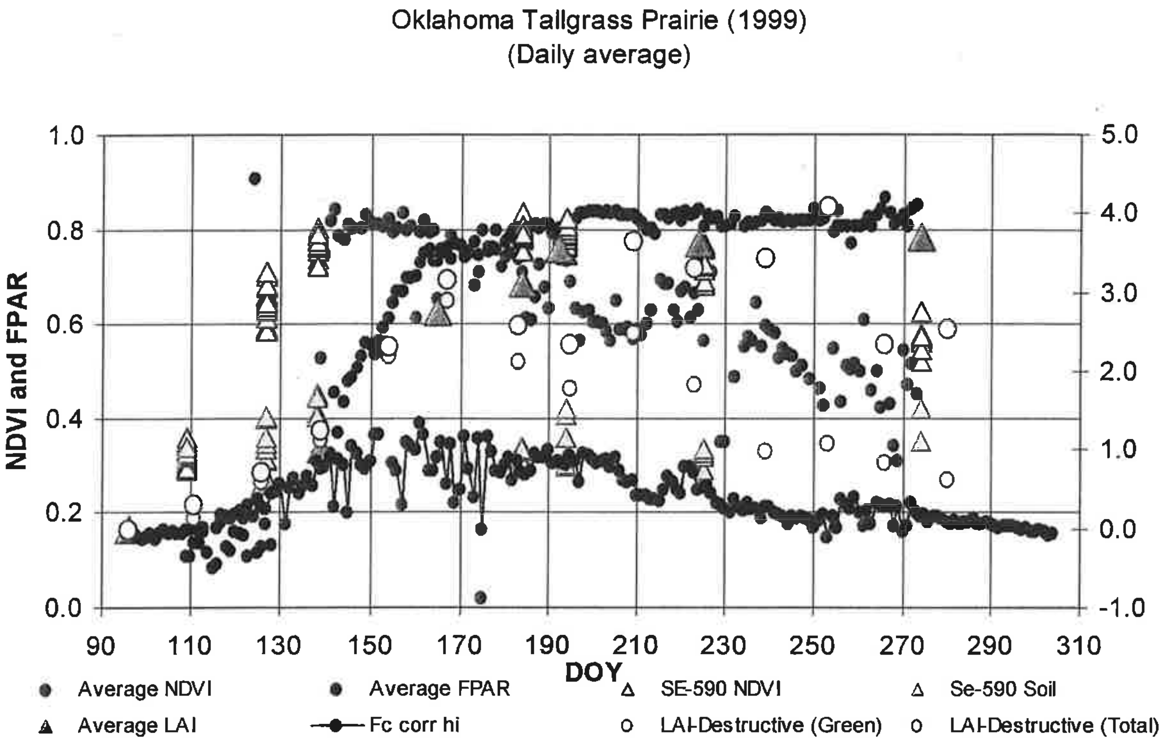


Figure 2. Red and Near-Infrared (NIR) reflectance, NDVI and FPAR as a function of time (as reported as hours before or after solar noon).



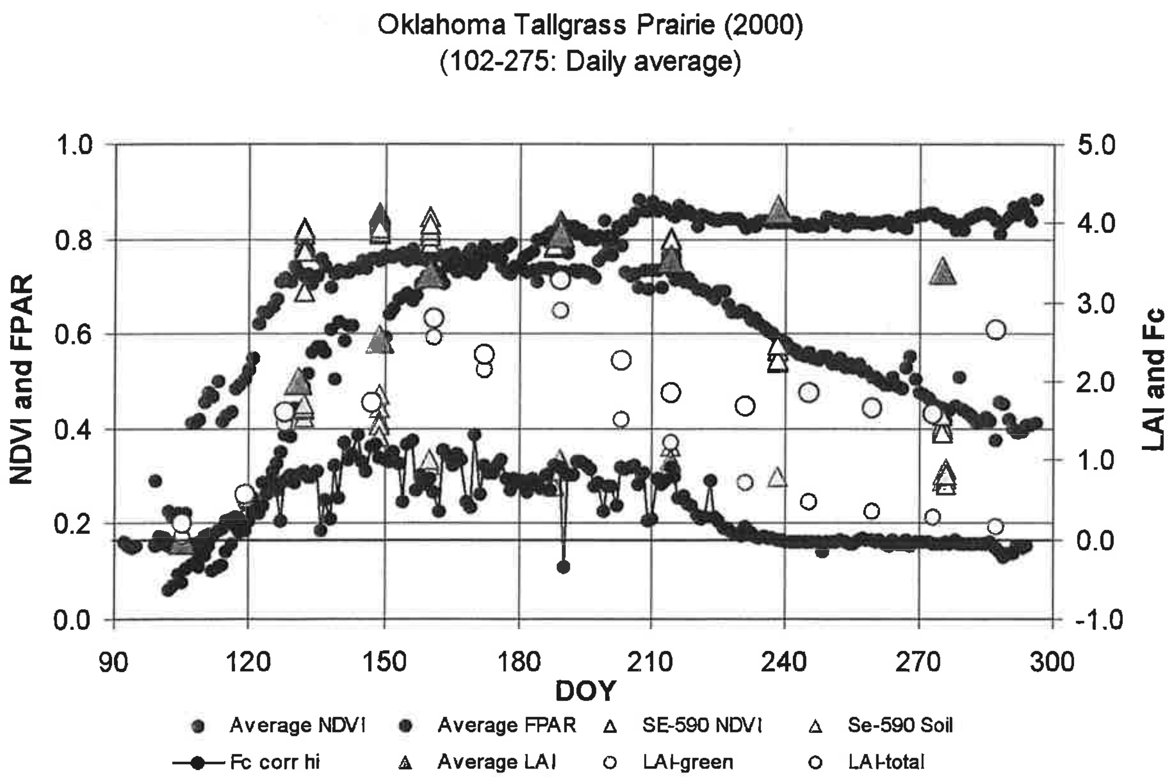
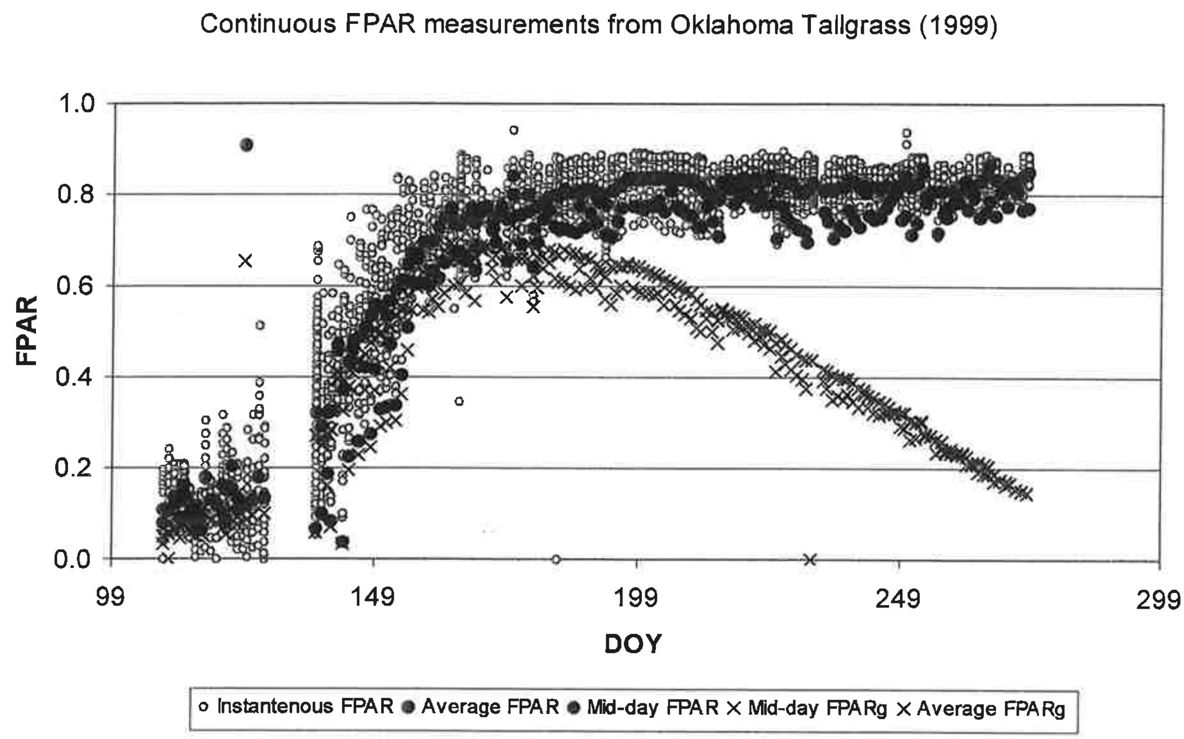


Figure 3. NDVI, FPAR and CO_2 flux as a function of day of year (DOY) for: a) 1999 and b) 2000.



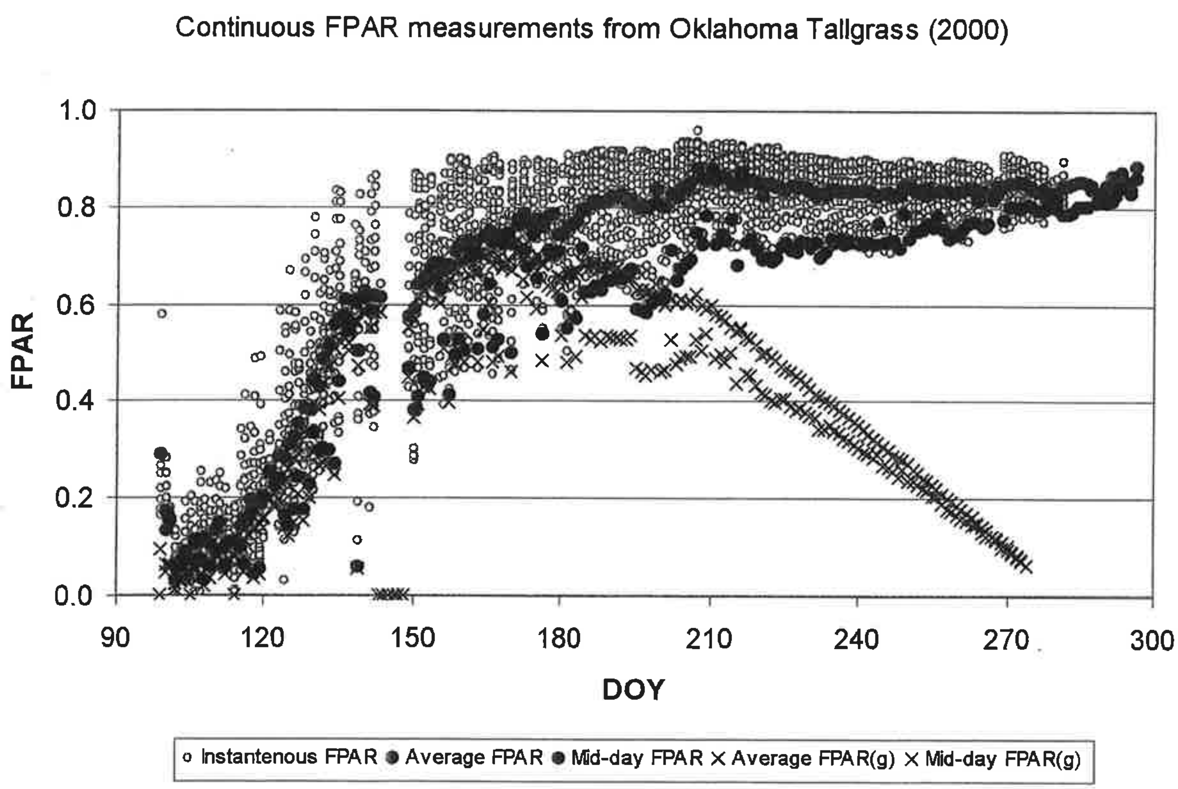
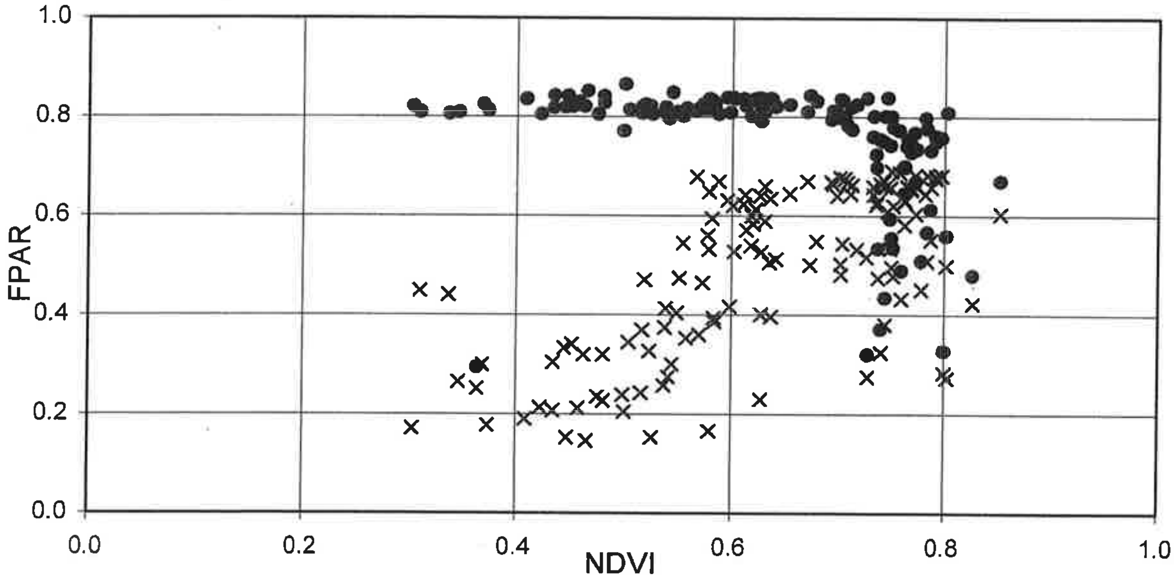


Figure 4. Fraction of absorbed photosynthetically active radiation(FPAR) and FPARgreen (FPARg) attributed to the green portion of the canopy (Eq. 1), as measured every ½ hour for each day in: a) 1999 and b) 2000. The average and midday values of FPAR and FPARg are also given.

a) Relation of FPAR, FPAR(g) and NDVI Oklahoma Tallgrass (1999)



b) Relation of FPAR, FPAR(g) and NDVI Oklahoma Tallgrass (2000)

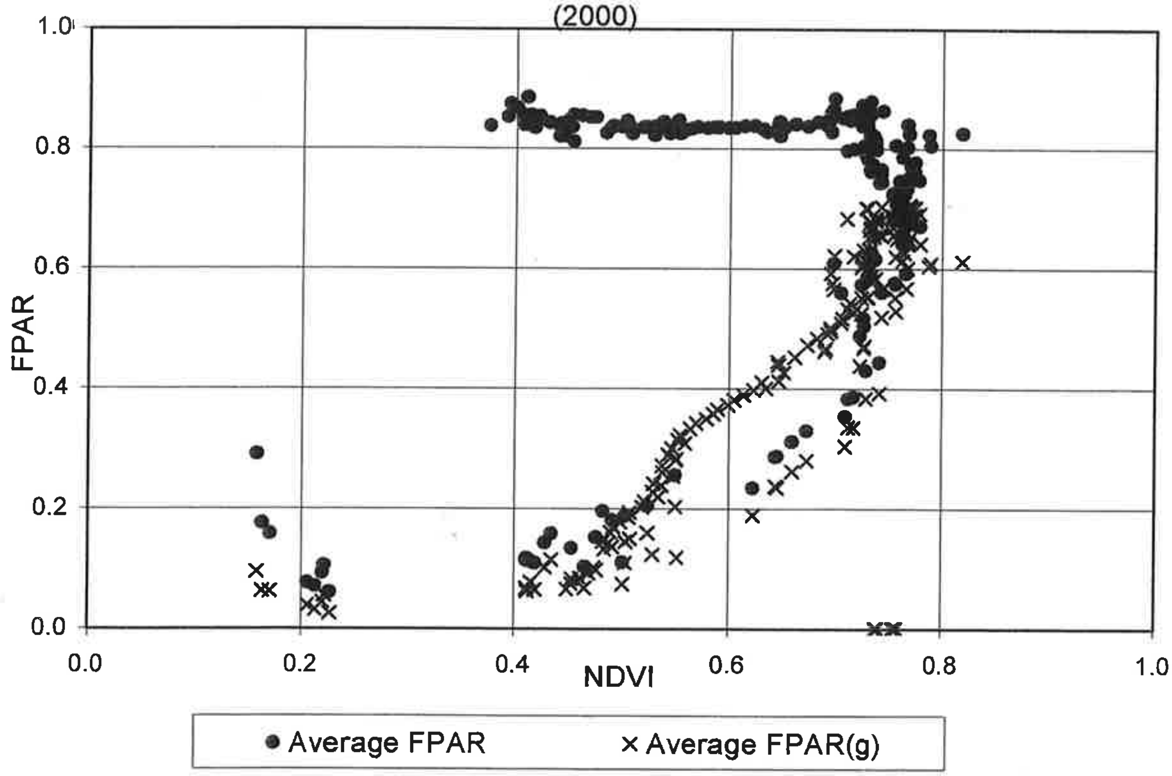


Figure 5. Total FPAR (instantaneous, average and mid-day) and green FPAR (average and Mid-day FPARg) as related to NDVI for: a) 1999 and b) 2000.

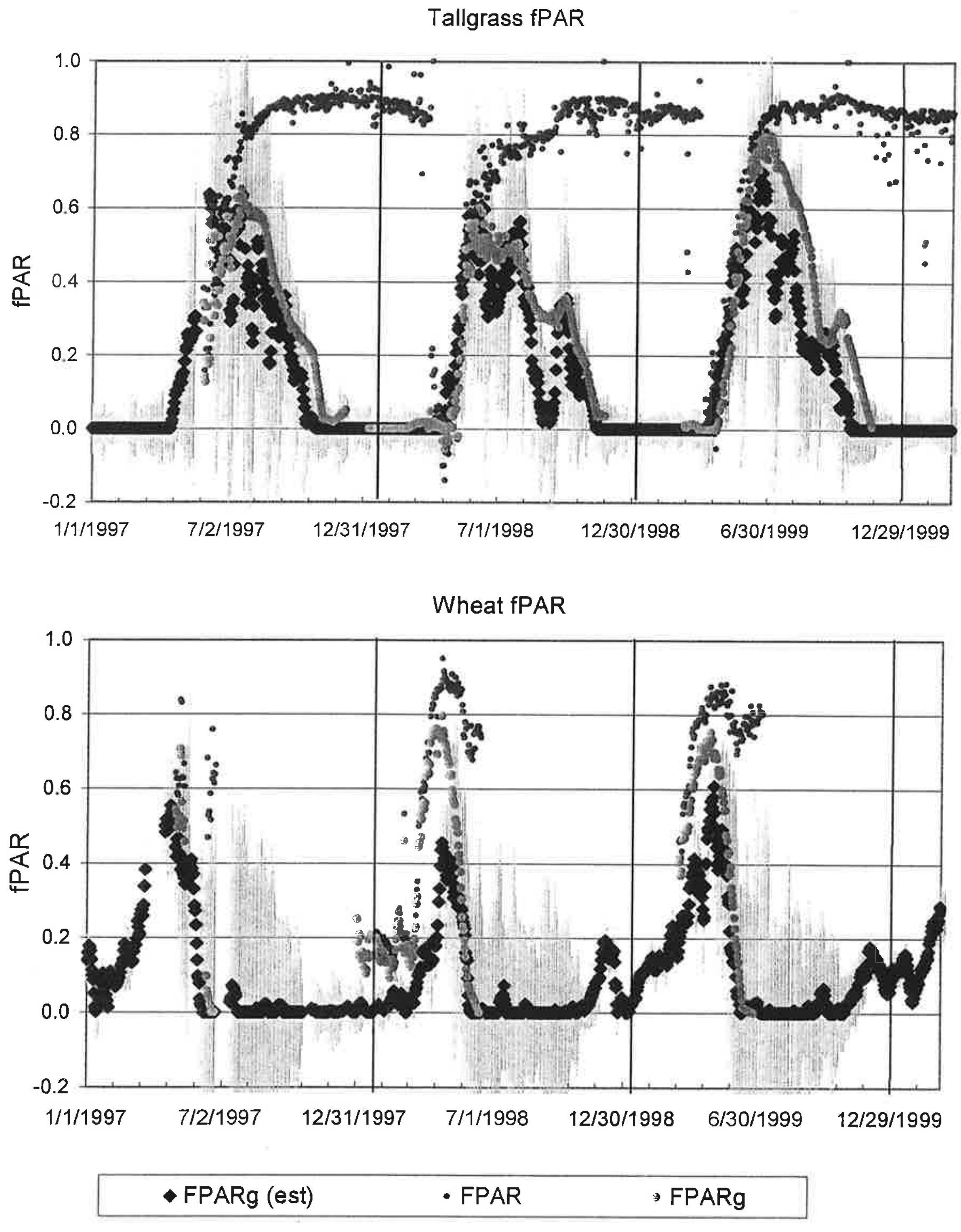


Figure 6. Total FPAR, green FPAR (FPARg) and estimated canopy FPARg an inversion routine (FPAR(PI)) as a function of day of year for 1997 and 1998.

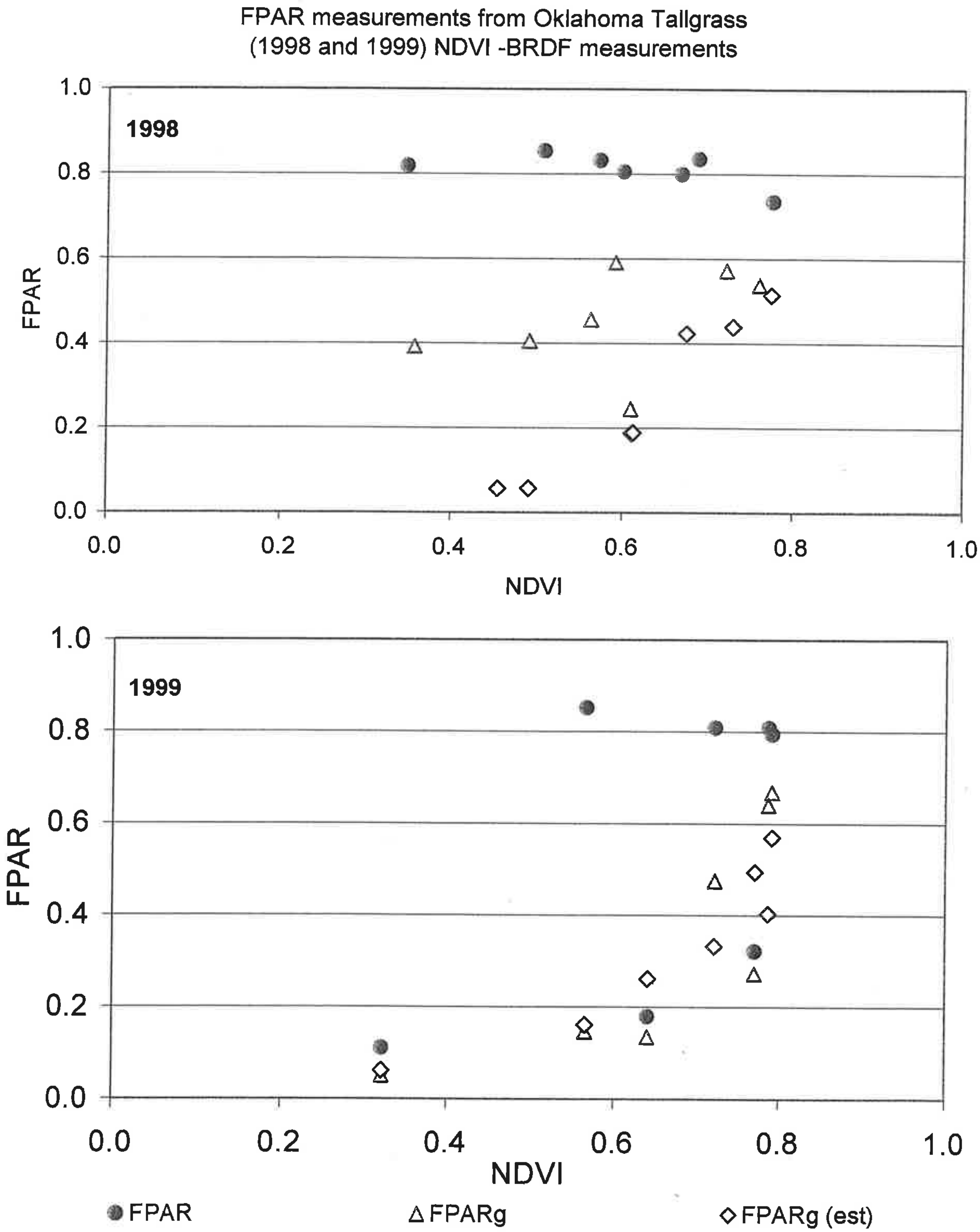


Figure 7. Relation of average total FPAR, green FPAR (FPARg) and estimated FPARg to NDVI for a) 1998 and b) 1999.

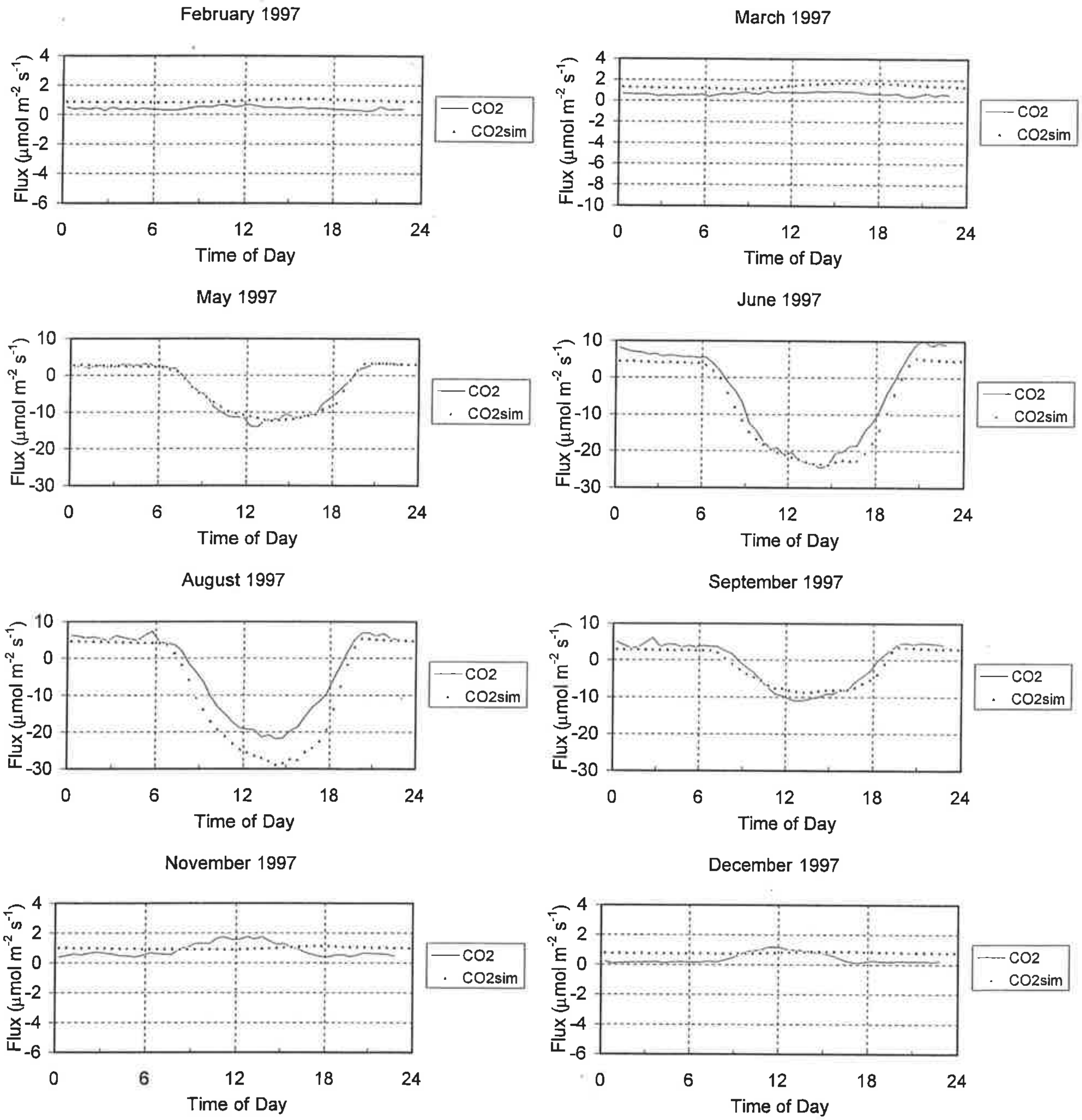


Figure 8a. Monthly average diurnal CO_2 exchange over tall-grass prairie in 1997. Averages were calculated for each 30-minute time period using simulated and measured fluxes from all days of each month.

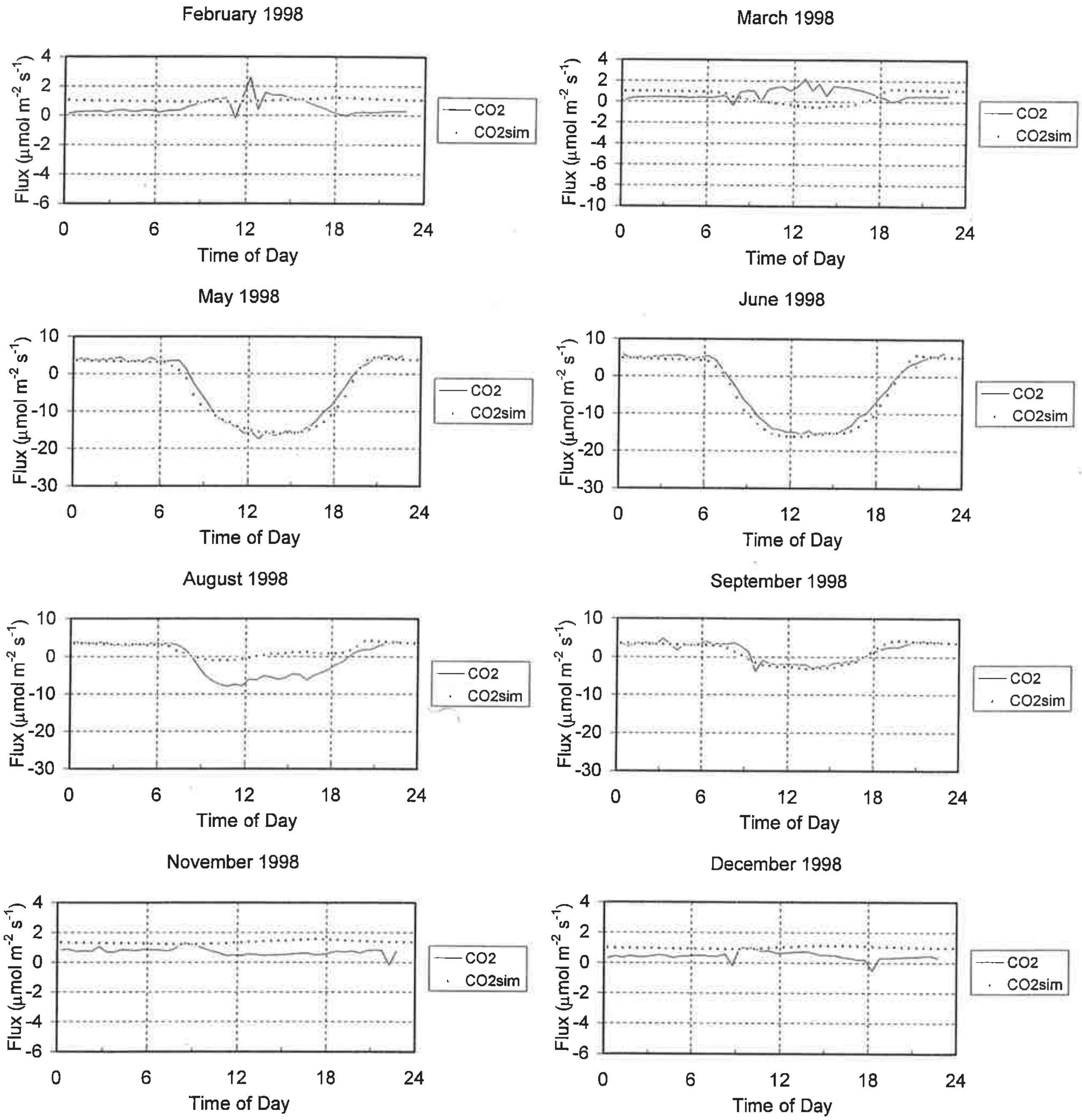


Figure 8b. Monthly average diurnal CO_2 exchange over tall-grass prairie in 1998. Averages were calculated for each 30-minute time period using simulated and measured fluxes from all days of each month.