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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, 1999- February 29, 2000.

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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, 1999 - February 29, 2000

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TABLE OF CONTENTS

page

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 Research Team Workshop

A workshop was held in Lincoln, NE June 21-22, 1999 in which all team members and support personnel attended. The objectives of the workshop were to provide updates of field research and analysis components and to identify ways to improve the research efforts. Each team presented a brief report on the current research status and preliminary results (Shashi Verma: Atmospheric Fluxex, Betty Walter-Shea: Canopy Reflectance; Joe Berry: Ecophysiology; Niall Hanan: SiB2 Modeling; Jeff Privette: EOS Core Sites and DISORD). A major issue identified was that of real time access to flux data in evaluating the SiB2 model. The flux team agreed to make available the "day check file" (real time preliminarily processed data from the previous day) to team members via an FTP site. Simulated fluxes based on these preliminary data will be made available to the team via the FTP site. Also, the model are to be adjusted to get the best fit which gives us a "pseudo inversion" of the model in estimating Π. Another estimate of Π (the slope of the light response which is an estimate of the Canopy PAR Use Parameter Π) will be made available as well.

Additional issues from the workshop which are to be (or have been) addressed include:
- Investigation of the relations between canopy reflectance and:
  1. LAI
  2. FPAR (total and green)
  3. fractional cover
  4. wind speed and direction (Exotech data should help us here)
- Identification of the optimal wavebands to use in the relations (possibly using principal components analysis)
- Providing the following data on the FTP site (most of which will be provided once a month since data retrieval is on a monthly basis):
  1. Exotech reflectance for all 4 bands and NDVI through time as a function of solar zenith

    angles 45 and 60°
    2. FPAR
    3. LAI
- Providing on the FTP site information on the:
    1. Overflights for SeaWIFS, AVHRR, Landsat
    2. Location of CIMEL sunphotometer

As a follow-up mechanism to the workshop and to maintain contact with team members, an exploding e-mail address was established. Simply by sending a message to the e-mail address, the message is sent to all team members. This seemed to be the simplest means of setting up a communication of all announcements regarding research findings, data problems or concerns.

2.2 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. 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°.

In addition, 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. 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 June through September (initial data logging problems prevented data collection until June) 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 peak greenness through senescence and provides information regarding changes in the prairie spectral characteristics between SE590 data collection times.

As FPAR increased, NDVI increased through the green-up period of vegetation growth (Fig. 1a). The relationship fell apart after the time of green peak LAI (Fig. 3c) (from DOY 169 through DOY 274). The largely non-green leaf component in the canopy affected the reflected signal (and thus NDVI) but had little effect on FPAR (Fig. 2). The fraction of PAR absorbed by the green components of the canopy, as represented here as $FPAR_{green}$ (a first approximation of the PAR effectively utilized by the canopy or the canopy PAR use parameter Π) was approximated following an approach similar to that of Hall et al., 1992 where:

$$FPAR_{green} = \frac{green\ LAI}{total\ LAI} \cdot FPAR.$$

The simple approximation yieled an improved relation between FPAR and NDVI (Fig. 1b). However, results indicate that accounting for the green fraction of the leaf material alone is not sufficient in relating remotely-sensed data to plant functioning. Thus, we expect Π to differ significantly from FPAR in canopies of high non-green material.

2.3 Micrometeorological flux measurements and analysis

Fluxes of CO_2, water vapor and energy were measured, using the eddy covariance technique, at two AmeriFlux tower sites (tallgrass prairie and wheat) in north central Oklahoma. 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 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). Some preliminary results, based on real-time observations during January -December, 1999 are included below.

2.3.1 Tallgrass Prairie. Year-round measurement of midday (10:00 - 1430 hours local time) CO_2 flux (F_c), latent heat flux (LE), photosynthetically active radiation (PAR) and net radiation (R_n) during 1999 are shown in Fig. 1. Also shown are measured values of green leaf area index, volumetric soil water content (0-0.9 m depth), and precipitation. During the period of January through March, midday averaged F_c ranged between zero and -0.06 mg m^{-2} s^{-1} (F_c less than zero indicates CO_2 loss and F_c greater than zero indicates CO_2 uptake). The midday averaged LE was 40 to 200 W m^{-2} for clear days and 10 to 50 W m^{-2} for very cloudy/overcast days. The site was burned on April 6 (day 96). Approximately 15 days after the burn (day 111), the prairie began showing an uptake of CO_2, when the green leaf area index was 0.1. The LE values at this time (days 96 -113) ranged between 150 and 320 W m^{-2} for clear days and 55 to 120 W m^{-2} for cloudy days. The prairie began showing a steady rise in F_c from day 119 onward, increasing to a seasonal maximum of 1.35 mg m^{-2} s^{-1} by June 10 (day 161). The green leaf area reached its seasonal maximum of 2.9 on June 1 (day 167). The midday average LE between May and mid-June (days 120 to 170) ranged between 240 and 390 W m^{-2} for clear days. The value of F_c began declining shortly after the seasonal green leaf area maximum was reached. As green leaf area declined, F_c ranged typically between 1.2 and 0.6 mg m^{-2} sec^{-1}. The midday LE ranging between 200 and 350 W m^{-2}. A dry period set in after July 10 (day 191). The soil moisture declined to around 0.14 m^3 m^{-3}. There were some infrequent rains, but these did not improve the soil moisture condition. The values of F_c, LE and green LAI all declined noticeably. By September 10 (day 253), F_c was reduced to 0.10 mg m^{-2} sec^{-1}. A series of brief rains in mid to late September (days 251 - 274) buoyed up the canopy activity, as the F_c levels rose temporarily to between 0.20 and 0.40 mg m^{-2} s^{-1} on clear days and the green leaf area index rebounded to 1.1. With the onset of senescence at the end of September (day 274) the decline in F_c continued, coinciding with the second steady decline in soil moisture. The F_c changed sign by early November (day 301), indicating a loss of CO_2. The soil moisture was again replenished by an early November rain, then declined more gradually. The prairie was a source of CO_2 for the remainder of 1999.

2.3.2 *Wheat.* The winter wheat was in its semi-dormant growth stage during the early part of January (days 1 – 11), having midday average F_c values very close to zero. Around January 12 (day 12) the value of F_c (Fig 2a) began to increase steadily and reached about 0.3 mg $m^{-2}s^{-1}$ by early March (day 62) as the wheat moved out of its semi-dormant state and began growing. Between January 14 and March 3 (days 14 – 62) the green leaf area increased from 0.5 to 1.5. The value of LE (Fig 2b) was less than 80 W m^{-2} in January (days 1 – 32) and rose to between 80 and 170 W m^{-2} by February 3 (day 34). During most of March (days 60 to 80), F_c and LE leveled-off briefly and the green LAI declined slightly to 1.3. The value of F_c did not begin to increase again until after March 21 (day 80). From then on, the canopy activity continued to rise with the wheat crop in anthesis, and F_c reached its seasonal maximum of 1.14 mg m^{-2} s^{-1} on day 123. The LE maximum of 390 W m^{-2} nearly coincided with the maximum in F_c. The green leaf area mimicked the pattern of F_c, and reached its seasonal maximum of 4.7 at the end of the month (day 119). Then, F_c declined quite rapidly, reaching values on the order of 0.15 mg m^{-2} s^{-1} by the end of May (day 151). Green LAI had also declined linearly to 0.1 by June 11 (day 162). Midday F_c changed from positive to negative on June 5 (day 156). After this time, F_c ranged between zero and -0.15 mg m^{-2} s^{-1} until planting in October. LE remained high, between 370 and 150 W m^{-2}. Green leaf area index reduced to negligible values by June 25 (day 176). The field was harvested on June 28 (day 179) and immediately tilled. There was a short period around day 280 where F_c was positive due to volunteer growth, which was tilled under. Midday LE remained between 130 and 300 W m^{-2} for the month of July and had declined to between 30 and 80 W m^{-2} in late August and early September (days 235 to 247). The field tillage events produced days of high LE due to the turning of the soil. Also, a large CO_2 loss (-0.4 mg m^{-2} s^{-1}) followed the only significant precipitation event in August (day 215). Rains in early and mid September caused the midday average LE to rise up to around 200 W m^{-2}, and remain at that level into early October. The field was planted on October 22 (day 294). The LE after planting was fairly steady around 50 W m^{-2}, until precipitation on days 302 and 303 helped it to rise up again to around 150 W m^{-2} for a brief period. Plants emerged on November 1 (day 305). The CO_2 flux became positive around November 9 (day 313) when the canopy began to show significant growth. The value of F_c ranged between 0.15 and 0.20 mg m^{-2} s^{-1} from mid-November through the end of December.

2.4 Supportive measurements

2.4.1. 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). In addition, a hand-held line quantum sensor was used to measure FPAR at each canopy reflectance plot and near the FPAR plot at approximately solar noon on days when canopy reflectance was measured.

The dynamics and contrasts of FPAR throughout the growing season and between years is represented by mid-day values of FPAR at the tallgrass prairie site in 1998 and 1999 (Fig. 2).

2.4.2. 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.

2.4.3 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.

2.4.4 Soil moisture measurements. A systematic program of soil moisture monitoring has been 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.

2.5 Model Studies

2.5.1 Canopy radiative transfer model. DISORD is currently being installed with the intent of having graduate student Ms. Kham Nang becoming familiar with the program, running simulations of canopy BRFs for the tallgrass and wheat canopies and comparing these to measured BRFs collected during 1998 and 1999.

2.5.2 SiB2 Model. Over the past year we have worked on preparing data sets for modeling and on model development. Our goal with this work is to analyze the response of net ecosystem CO_2 exchange over a range of conditions. Assuming that the leaf-scale physiological parameters of the model, SiB2, are properly selected, the simulated rate of net CO_2 exchange will be largely determined by the canopy PAR use parameter, Π. This model parameter, Π, is a key parameter used in the radiation transport subroutines to calculate the flux of absorbed photons and in the photosynthesis subroutine to calculate the physiological capacity of the canopy for enzymatic fixation of CO_2. In turn, these determine the rates of CO_2 uptake under light limiting and light saturating conditions, respectively. The value of Π is normally obtained from remote sensing or from direct measurement of the leaf area index and optical properties of leaves of the canopy-based on theoretical considerations developed with idealized canopies. Our hypothesis is that we can use the observed measurements of net CO_2 exchange obtained in this study together with the model to find values of Π which provide the best fit to the observations of net CO_2 exchange obtained by eddy correlation measurements in the field with a real grassland canopy. At the same time, we are collecting information on canopy phenology, leaf area index, optical properties and spectral reflectance. This approach provides an independent means for estimating Π. Ideally, these two independent means of estimating this key parameter should lead to the same answer. This provides an important opportunity to validate the theoretical basis of estimating the canopy integration factor, and we expect this work to test and improve the algorithms used to provide biophysical boundary conditions for land surface models such as SiB2 from remote sensing platforms.

3. ANTICIPATED ACCOMPLISHMENTS FOR THE NEXT REPORTING PERIOD

3.1 Continuation of canopy and soil reflected radiation measurements

Canopy and soil reflectance characterization will resume at the wheat site presumably in March (and continuing through June) and at the tallgrass prairie site presumably in April (and continuing through October), concluding the final year of field research. The Exotech radiometers will be mounted at the tallgrass prairie for near continuous nadir canopy reflectance (throughout green-up through senescence) and the SE-590 will be used to gather intensive bidirectional reflectance information on biweekly to monthly intervals (weather dependent).

3.2 Micrometeorological flux measurements and analyses

Detailed eddy covariance measurements of fluxes of CO_2, water vapor, sensible heat and momentum will be continued year-round at the tallgrass and wheat sites. Concurrent measurements of supporting information (e.g., solar radiation, net radiation, photosynthetically active radiation, soil heat flux, mean air and soil temperatures, mean vapor pressure, mean horizontal wind speed, wind direction and precipitation) will be made at the two sites. Flux and supporting data collected at the two sites will be processed and results will be analyzed to quantify the diurnal, seasonal and annual net ecosystem exchange of carbon dioxide and water vapor.

3.3 Biophysical measurements

Soil moisture will be monitored with a TDR (time-domain reflectometer) sensor at each site. Soil surface CO_2 flux will be measured, in an ongoing collaborative study (C. Rice, Kansas State University), with a portable gas exchange system connected to a stainless steel measurement chamber. Seasonal course of leaf area index (LAI) will be determined at both sites. These measurements will be made directly by harvesting the vegetation (destructive sampling) and using an LI-3100 area meter (LI-COR, Inc., Lincoln, NE). Green and total leaf area and dry weight will be determined at each sampling date. Leaf optical properties and “instantaneous” values of FPAR will be determined from measurements made during the canopy reflectance “field campaigns.”

3.4 Modeling studies

We will work closely with graduate student Kham Noam Nang in using the physically-based turbid medium canopy reflectance model, DISORD (Myneni *et al.*, 1995) to simulate canopy reflectance at the research sites in preparation of using the model in investigating relations between **Π**, canopy architecture, and leaf conditions. It is our assumption that the canopy PAR use parameter, **Π**, is equivalent to the canopy green leaf absorbed PAR fraction which we will derive from canopy reflectance simulations with DISORD.

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5. FIGURES

Figure 1. The "instantaneous" fraction of photosynthetically active radiation absorbed (FPAR) by the tallgrass prairie vegetation and by the green portion of the vegetation only ($FPAR_{green)}$ as a function of NDVI derived from the Exotech and SE-590 Spectroradiometers during the 1999 growing season.

Figure 2. Mid-day values of the fraction of photosynthetically active radiation absorbed by the tallgrass prairie vegetation as a function of day of year during the 1998 and 1999 growing seasons.

Figure 3. a) Midday net carbon exchange (Fc) and photosynthetically active radiation (PAR), b) midday latent heat flux (LE), and net radiation (Rn), c) green leaf area index, and d) volumetric soil water content (0-0.9 m depth) and daily precipitation. The TDR Soil moisture probe was replaced at the site on day 126. Therefore, the soil moisture data for days 126-143 were questionable, indicated by the dashed line.

Figure 4. a) Midday net carbon exchange (Fc) and photosynthetically active radiation (PAR), b) midday latent heat flux (LE), and net radiation (Rn), c) green leaf area index, and d) volumetric soil water content (0-0.9 m depth) and daily precipitation. The TDR Soil moisture probe was removed following harvest and not installed again until after planting. Periodic field tillage made continuous measurements with the device difficult, because of the settling time needed to get reliable data.

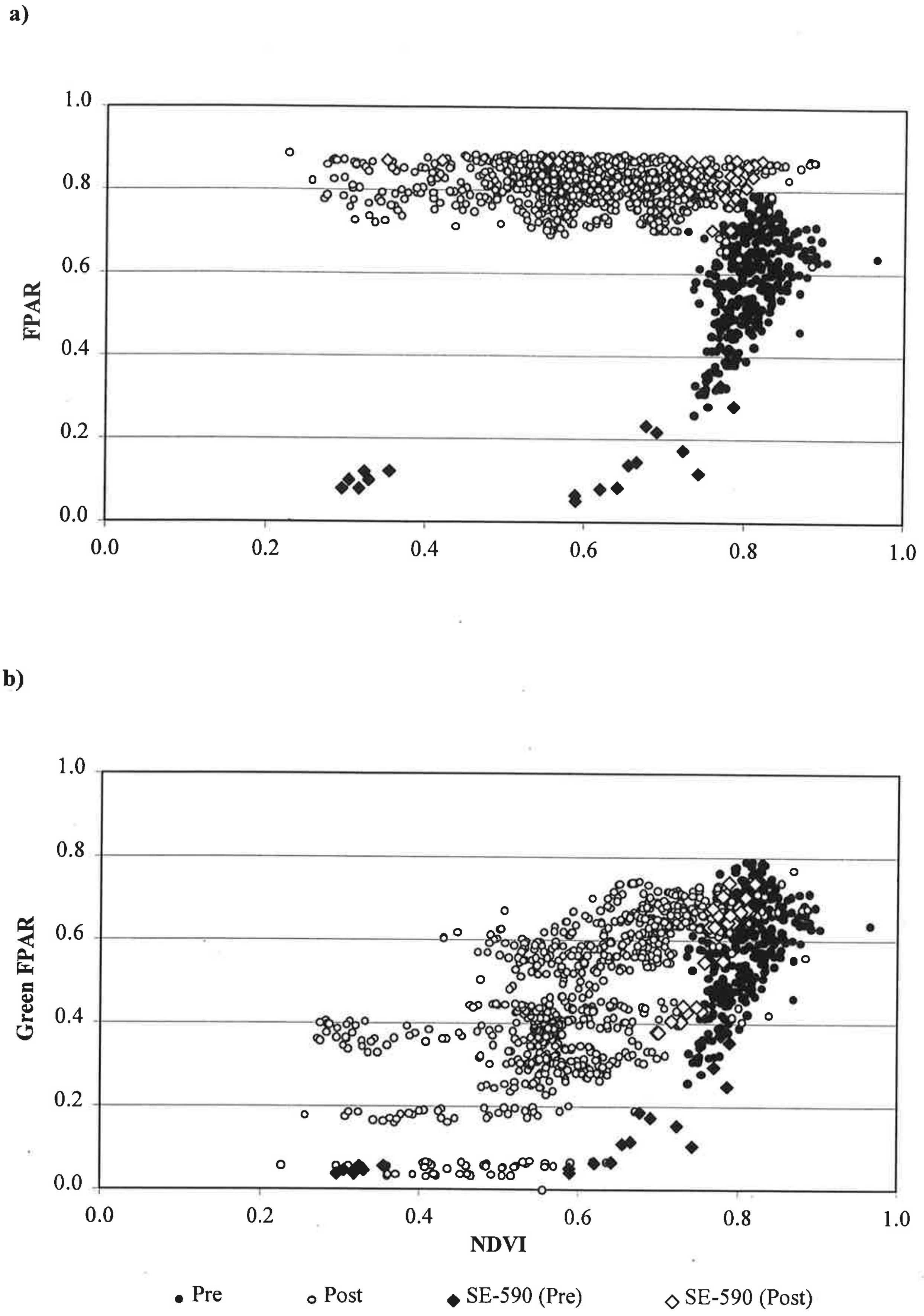

Fig. 1. The "instantaneous" fraction of photosynthetically active radiation absorbed (FPAR)by the tallgrass prairie vegetation and by the green portion of vegetation only ($FPAR_{green}$) as a function on NDVI derived from the Exotech and SE-590 Spectroradiometers during the 1999 growing season.

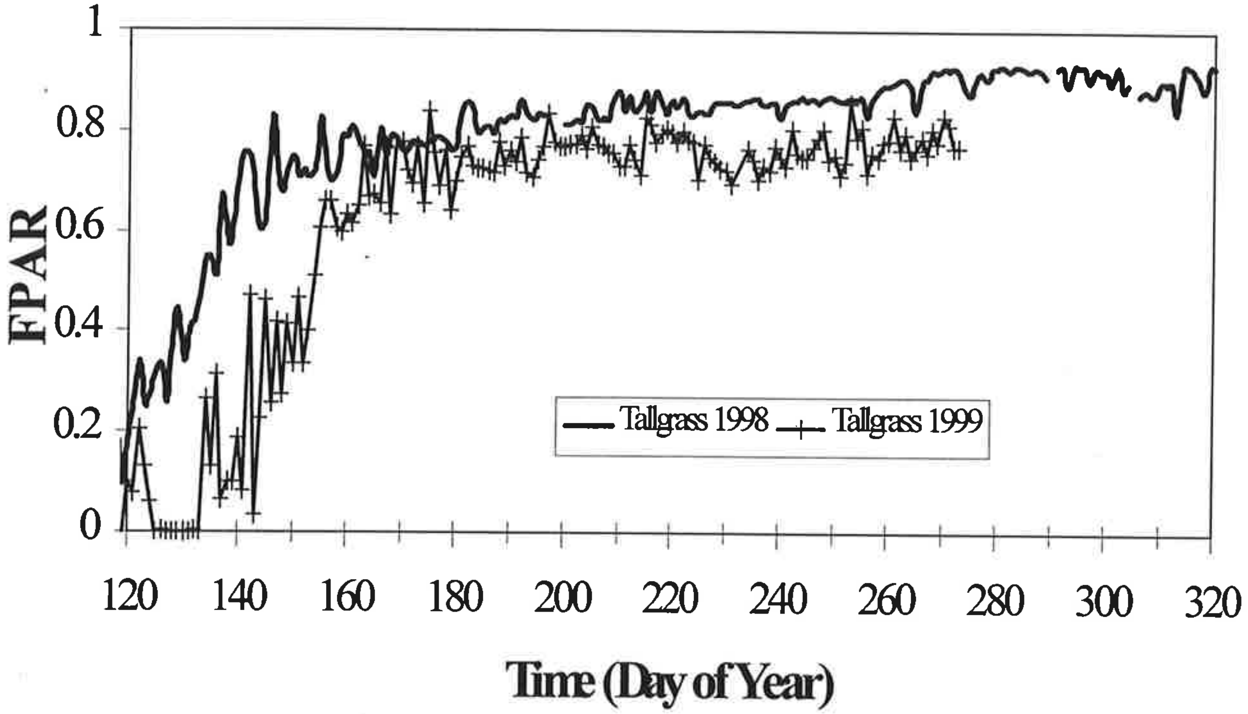

Fig. 2. Mid-day values of the fraction of photosynthetically active radiation absorbed by the tallgrass prairie vegetation as a function of day of year during the 1998 and 1999 growing seasons.

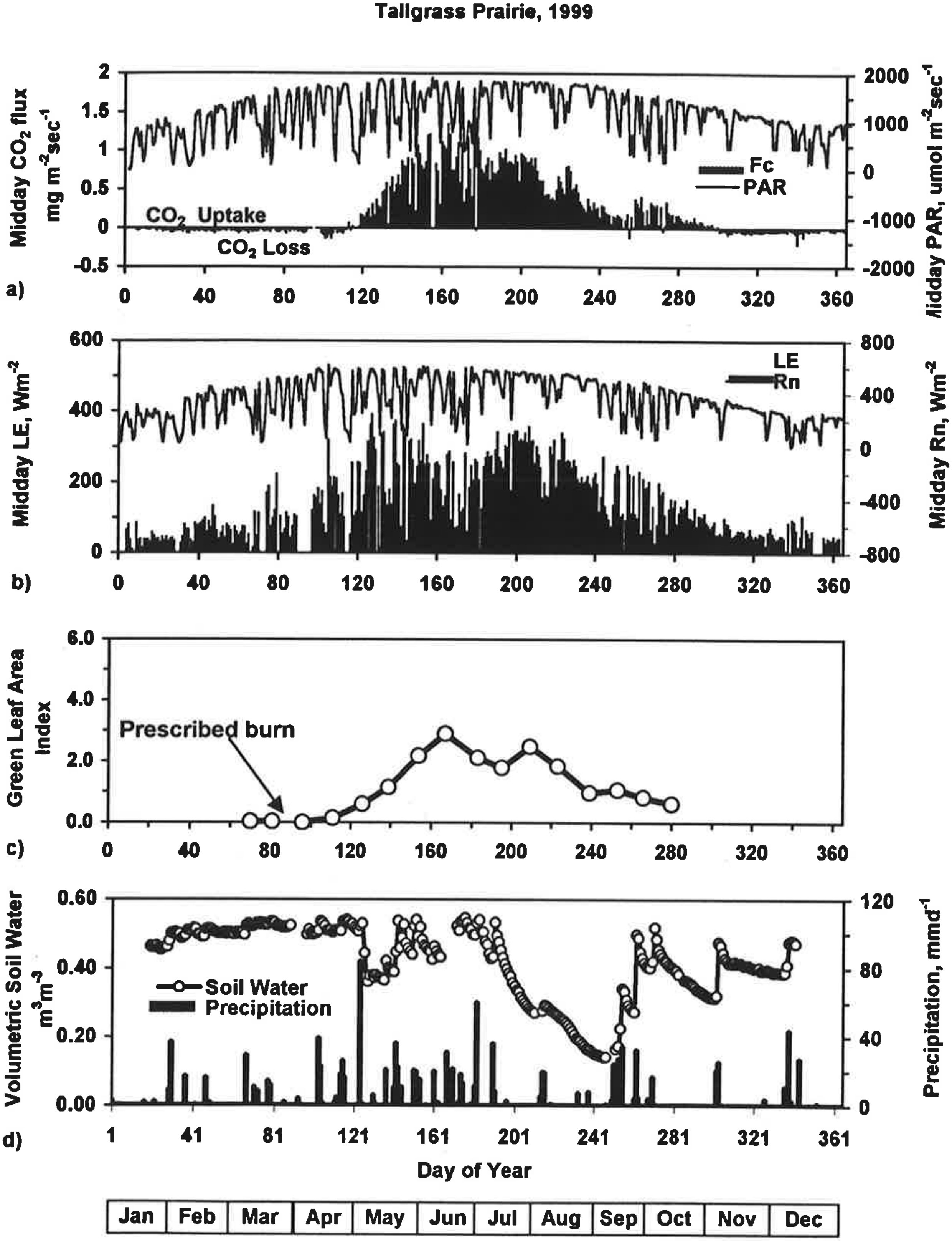

Figure 3. a) Midday net carbon exchange (F_c) and photosynthetically active radiation (PAR), b) midday latent heat flux (LE), and net radiation (R_n), c) green leaf area index, and d) volumetric soil water content (0 - 0.9 m depth) and daily precipitation. The TDR soil moisture probe was replaced at the site on day 126. Therefore the soil moisture data for days 126 -143 were questionable, indicated by the dashed line.

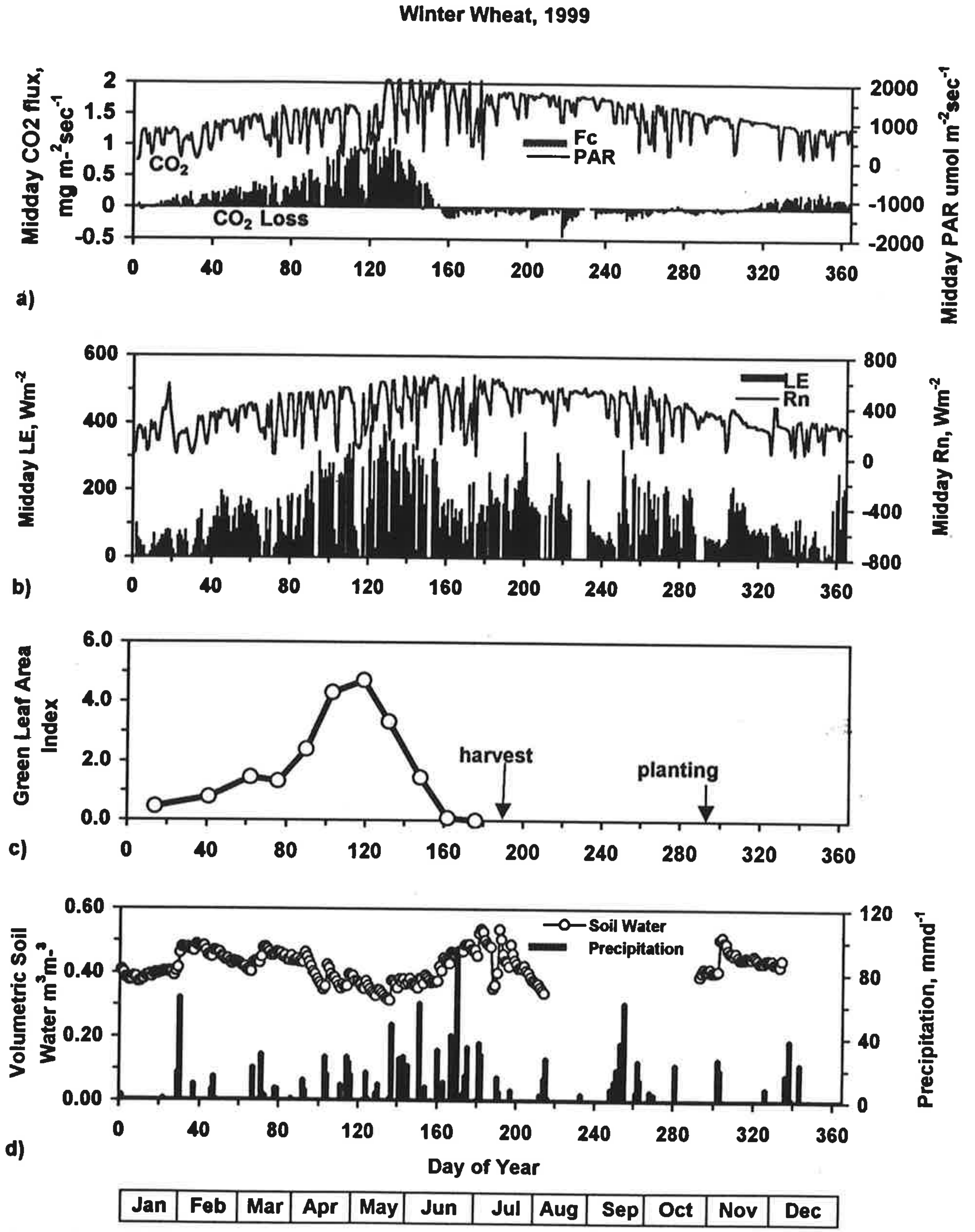
Winter Wheat, 1999

Figure 4. a) Midday net carbon exchange (F_c) and photosynthetically active radiation (PAR), b) midday latent heat flux (LE), and net radiation (R_n), c) green leaf area index, and d) volumetric soil water content (0 - 0.9 m depth) and daily precipitation. The TDR probe was removed following harvest and not installed again until after planting. Periodic field tillage made continuous measurement with the device difficult, because of the settling time needed to get reliable data.