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PREVIEW

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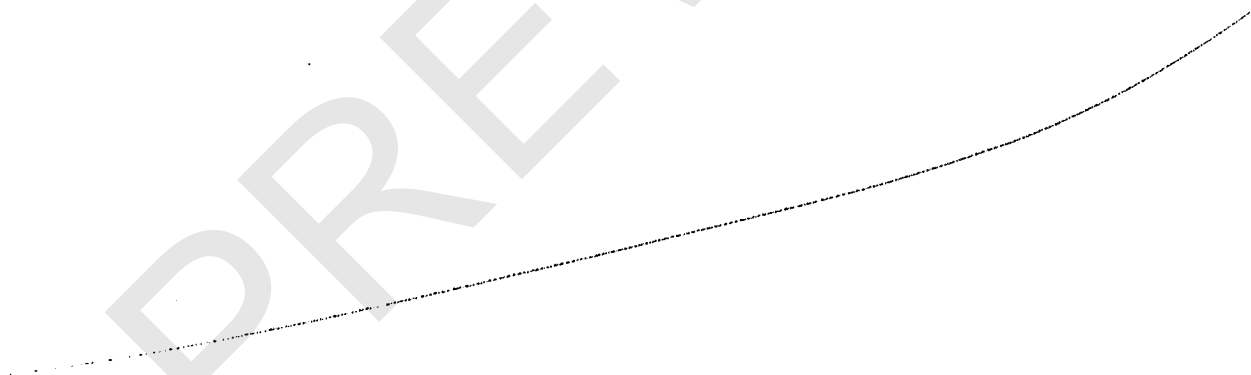
Kim, Joon, Ph.D.

The University of Nebraska - Lincoln, 1990

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PREVIEW



**CARBON DIOXIDE AND ENERGY EXCHANGES
IN A TEMPERATE GRASSLAND ECOSYSTEM**

by

Joon Kim

A DISSERTATION

**Presented to the Faculty of
The Graduate College in the University of Nebraska
In Partial Fulfillment of Requirements
For the Degree of Doctor of Philosophy**

Major: Agronomy

Under the Supervision of Professor Shashi B. Verma

Lincoln, Nebraska

May, 1990

DISSERTATION TITLE

Carbon Dioxide and Energy Exchanges in a

Temperate Grassland Ecosystem

BY

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CARBON DIOXIDE AND ENERGY EXCHANGES IN A TEMPERATE GRASSLAND ECOSYSTEM

Joon Kim, Ph.D.

University of Nebraska, 1990

Adviser: Dr. Shashi B. Verma

A micrometeorological study was conducted from May to October in 1987 to evaluate the surface exchanges of carbon dioxide and energy at a temperate grassland site in northeastern Kansas. The fluxes of CO₂ (F_c), latent heat (LE), sensible heat (H) and momentum were measured using the eddy correlation technique. Pertinent microclimatic, plant and soil variables were also monitored through the season. The prairie was dominated by three C₄ grass species: *Andropogon gerardii*, *Sorghastrum nutans*, *Panicum virgatum*.

The energy partitioning was controlled mainly by net radiation (R_n) and by soil water availability. On sunny days with no moisture stress, about 58 to 83% of R_n was consumed in evapotranspiration during midday. The midday canopy surface conductance averaged about 15 mm s⁻¹. Under moisture stress conditions the magnitude of midday LE/ R_n ranged from 0.35 to 0.45 whereas the canopy surface conductance was less than 3 mm s⁻¹.

Considerable daily and seasonal variability of CO₂ flux was observed. The midday F_c reached a seasonal peak of 1.3 mg m⁻² (ground area) s⁻¹ in early July and was near zero during a dry period in late July. The dependence of the daytime F_c on pertinent controlling variables (e.g., light, temperature, vapor pressure deficit, soil water availability, and canopy surface conductance) was investigated. The magnitude of nocturnal F_c (soil plus plant respiration) averaged 0.4 mg m⁻² s⁻¹ under well-watered conditions and was about 0.2 mg m⁻² s⁻¹ during the dry period.

A leaf stomatal conductance model was developed for the major grass species in this ecosystem, and was scaled up to a canopy level using a canopy radiative transfer model. Comparisons with field measurements indicated that the model provided reasonable estimates of canopy stomatal conductance for well-watered conditions. The modelled half-hourly values of LE agreed well (generally within 5%) with those measured, under these conditions.

A biochemical leaf photosynthesis model was adapted to the major grass species studied here, and was scaled up to a canopy level. Comparisons with field measurements showed that the model realistically simulated the magnitudes and the diurnal variations of canopy photosynthesis under well-watered conditions. Although the modelled canopy photosynthesis overestimated the measured values by 0.2-0.3 mg m⁻² s⁻¹ under moisture stress conditions, the model did simulate the diurnal patterns adequately.

PREVIEW

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Finally, I dedicate this work to my wife Haeok and to my son Jeehyun. They have patiently and willingly made do without a husband and father for days and even weeks at a time while I pursued this degree. I am eternally grateful to my family for their love and support of me over the years.

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CHAPTER 1

INTRODUCTION

The subject of vegetation-atmosphere relationships has been actively investigated for the last three decades. Most of the prior micrometeorological work concentrated on evapotranspiration and water use efficiency of agricultural crops. To further the understanding of biophysical controls on surface-atmosphere exchange in global-scale studies, increasing attention has been given to natural vegetation characterized by mixed communities of plants (e.g., forests, grasslands, swamps, etc.). Rapid advances in instrumentation and data acquisition systems and interdisciplinary efforts among scientists have allowed important insights into atmosphere-biosphere interactions in various terrestrial ecosystems.

Grasslands are biological communities characterized by mixed vegetation dominated by grasses. Grasslands constitute almost 24% of global plant cover and, therefore, play an important role in the global distribution of energy, heat, moisture and carbon dioxide. Yet, little information on the surface exchange of mass and energy in grasslands is currently available.

Stomata are small pores in the leaf epidermis, through which most of the water and CO₂ exchange occurs. The role of the stomata in controlling vegetation-atmosphere interactions at large scales (i.e., canopy to global scale) has only recently been recognized. Several investigations have focused on modelling the stomatal response at the individual leaf level. There is a need to develop procedures for "scaling-up" leaf level models to produce canopy stomatal conductance.

Vegetation in the terrestrial biosphere depends on photosynthesis to convert light energy to carbohydrates. While considerable progress has been made in understanding morphological, physiological and biochemical aspects of photosynthesis at the chloroplast or leaf level, much less is known at the canopy level. Global atmospheric CO₂ studies and models have generally lacked reliable information on canopy CO₂ exchange in terrestrial

ecosystems, including grasslands.

In view of the proceeding, a micrometeorological study* was conducted at a temperate grassland site in northeastern Kansas during a six-month period in 1987. The primary objectives of this dissertation research were:

- 1) to evaluate the diurnal and seasonal changes in the surface energy budget components and canopy surface and aerodynamic conductance of the grassland;
- 2) to evaluate the diurnal and seasonal variations in daytime and nocturnal CO₂ fluxes and examine their dependence on pertinent environmental variables;
- 3) to develop a model of leaf stomatal conductance of major grass species, to scale the model up from a leaf to a canopy level, and to test this model in estimating evapotranspiration; and
- 4) to adapt an appropriate leaf photosynthesis model for the grassland vegetation, scale the model up to a canopy level and test it against measured data.

The following chapters (Chaps. 2-5) will deal, sequentially, with the above mentioned primary objectives. The final chapter (Chap. 6) presents an overall summary and conclusions from this study.

*These measurements were made as a part of the First ISLSCP (International Satellite Land Surface Climatology Project) Field Experiment (FIFE) (for details, see *Sellers et al.* 1988).

CHAPTER 2

COMPONENTS OF SURFACE ENERGY BALANCE

2.1. Introduction

Grasslands cover a major part of both the western hemisphere and the global land mass. The production of food for the human population relies heavily on the productivity of grassland ecosystems. The North American grassland, which extends from Saskatchewan to Mexico and from the Rockies to the Mississippi river, may be primarily divided into the tallgrass prairie, mixed grasslands and the shortgrass prairie (Clements and Shelford, 1939). Generally, tall grasses and forbs occupy the eastern portion and moister habitats while shorter vegetation occupies western and drier habitats (Bazzaz and Parrish, 1982).

Grasslands play an important role in the global budget of heat and moisture. Little information on the surface energy balance in grasslands is currently available. A better understanding of the energy exchange processes, particularly evapotranspiration (ET), is necessary for studies of global climate, hydrology and grassland management.

Several models have been proposed to estimate actual ET since Monteith's derivation of the combination equation (Monteith 1965). These models require information on aerodynamic and canopy surface conductances, derived either from direct measurements or estimated from sub-models (e.g., Stewart 1983). Inclusion of canopy surface conductance provides an important link between vegetative surfaces and the atmosphere. Thus, knowledge of how canopy surface conductance responds to its environment and soil water deficits in grasslands is critical in evaluating the relative importance of surface and atmospheric control of energy partitioning in this ecosystem.

Results on the surface energy balance components over a tallgrass prairie site near Manhattan, Kansas are presented in this chapter. Diurnal and seasonal behaviour of the aerodynamic and canopy surface conductances is described. Results are compared with available information over agricultural and forest vegetation.

2.2 Materials and Methods

2.2.1 Site and Vegetation

Measurements were made during May to October, 1987 over a tallgrass prairie near the Konza Prairie Long Term Ecological Research (LTER) site near Manhattan, Kansas (39°03' N, 96°32' W, 445 m above m.s.l.). Soil at the experimental site is predominantly Dwight silty clay loam (Typic Natrustolls). The soil bulk density averaged about 1.15 Mg m⁻³ for the top 0.30 m. The prairie was burned on 16 April 1987 to improve the botanical composition of grasses and forbs. The experimental area was not grazed by domestic livestock in 1986 and 1987.

Percent species composition at the study site was estimated by employing a modified step point method (Owensby 1973). The vegetation was dominated by three warm season C₄ grasses: *Andropogon gerardii* (big bluestem), *Sorghastrum nutans* (indiangrass) and *Panicum virgatum* (switchgrass). Numerous other grasses, sedges, forbs and woody plants constitute the remainder of the plant community (Table 2.1).

Table 2.1 Species composition (%) at the experimental site (flowering stage, 1987) estimated by the modified step-point method (Owensby 1973).

Species	%
<i>Andropogon gerardii</i> (Big bluestem) (C ₄)	27.1
<i>Sorghastrum nutans</i> (Indiangrass) (C ₄)	22.2
<i>Panicum virgatum</i> (Switchgrass) (C ₄)	16.6
<i>Sporobolus asper</i> (Tall dropseed) (C ₄)	7.0
<i>Schizachyrium scoparium</i> (Little bluestem) (C ₄)	4.7
<i>Bouteloua gracilis</i> (Blue grama) (C ₄)	4.3
<i>Dichanthelium oligosanthos</i> (Scribner panicum) (C ₃)	4.0
<i>Agropyron smithii</i> (Western wheatgrass) (C ₃)	1.2
Other grasses	2.4
Sedges	6.3
Forbs and woody plants	4.2

2.2.2 Plant and Soil Measurements

Plant growth was monitored on a regular basis by measuring plant height, leaf width and leaf area. Leaves from eight 0.18 m² area were harvested and fed through an area meter (LI-COR, Inc., Lincoln, NE, Model LI-3000) to measure leaf area index (LAI). Stomatal conductance (g_s) and leaf water potential (ψ_L) in the three dominant grasses were measured hourly on four, fully expanded sunlit leaves with a steady-state porometer (LI-COR, Inc., Lincoln, NE, Model LI-1600) and a pressure chamber (Precision Machine Co., Lincoln, NE), respectively.

The surface soil water content (0–0.1 m) was monitored gravimetrically almost every day and subsurface water content (0.1–1.4 m) was measured with a neutron probe (Campbell Pacific Nuclear Corp., Pacheco, CA, Model 503) on a weekly basis. The neutron probe was calibrated at the field site prior to the experiment.

2.2.3 Micrometeorological Measurements

2.2.3.1 Eddy Correlation Measurements

Fluxes of sensible heat (H), latent heat (LE) and momentum were measured using the eddy correlation technique (see e.g., Kaimal 1975; Kanemasu *et al.* 1979; Verma *et al.* 1989). The instrumentation included: a one-dimensional sonic anemometer, a fine wire (0.025 mm) thermocouple (Campbell Scientific, Logan, Utah), a three-dimensional sonic anemometer (Kaijo Denki Co., Model DAT-310), and a Krypton hygrometer (Campbell Scientific, Logan, Utah) with 5 mm path length. These instruments were installed on a horizontal boom at 2.25 m above ground. The data were low pass filtered using 8-pole Butterworth active filters with 12.5 Hz cutoff frequency. The data were sampled at 20 Hz. Sampling, recording, and near real-time processing of the data were done [including coordinate rotation employing the velocity signals measured with the three-dimensional sonic anemometer in a procedure described by Wesely (1970)] with an IBM PC-AT microcomputer (details are available in

previous reports--e.g. Verma *et al.* 1986; 1989). Fluxes were obtained from covariances computed over 30 minute averaging periods. Covariance values were corrected for the effects of spatial separation of sensors following Moore (1986). The latent heat flux was corrected for the variation in air density due to simultaneous transfers of water vapor and sensible heat following Webb *et al.* (1980).

2.2.3.2 Supporting Measurements

Net radiation (R_n) was measured with a net radiometer (Radiation Energy Balance System, Beaverton, OR) at a height of 2.0 m above the ground. Seven heat flow transducers (REBS, Model HFT-1) were installed at a depth of 50 mm. Platinum resistance thermometers (0.2 m long), buried at an angle of 15 degrees, were used to measure an average soil temperature from the surface to a depth of 50 mm. Soil heat fluxes were corrected for differences in thermal conductivity among calibration medium, transducer and soil following a method described by Philip (1961). Surface soil heat flux (G) was estimated by employing a combination method (Kimball *et al.* 1976). Mean air temperature and humidity were measured with an aspirated ceramic wick psychrometer at 2.25 m above ground. Mean horizontal wind speed was measured with a three-cup anemometer (Cayuga Development, Ithaca, NY, Model WP-1) at 2.25 m above ground. An IBM PC-AT microcomputer was used to record and process the half-hourly data on a real time basis.

2.2.4 Theoretical Considerations

2.2.4.1 Aerodynamic and Canopy Surface Conductance

The aerodynamic conductance (g_a) for transfer of heat/water vapor was estimated as:

$$g_a = 1/r_a \quad (2.1)$$

where the aerodynamic resistance (r_a) is given by

$$r_a = r_{am} + r_b \quad (2.2)$$

The term, r_{am} is the aerodynamic resistance for momentum transfer, and is given by

$$r_{am} = \bar{U}/u_*^2 \quad (2.3)$$

where \bar{U} is the mean horizontal wind speed at a height z and u_* is the friction velocity. The excess resistance term, r_b (see Thom, 1972; Wesely and Hicks, 1977; Verma et al., 1986, for further details) is approximated by

$$r_b = (2/ku_*)(\kappa/D_v)^{2/3} \quad (2.4)$$

where k is von Karman's constant, κ is the thermal diffusivity, and D_v is the molecular diffusivity of water vapor.

The canopy surface conductance ($g_c = 1/r_c$) was obtained from the Penman-Monteith equation (Monteith, 1965) following Jarvis *et al.* (1976):

$$r_c = [(s/\gamma)\beta - 1]r_a + (\beta + 1)(\rho C_p/\gamma)(D/A) \quad (2.5)$$

where s is the slope of the saturated vapor pressure-temperature curve, γ is the psychrometric constant, β is the Bowen ratio ($=H/LE$), ρ is the density of air, C_p is the specific heat of air, D is vapor pressure deficit, and A ($=R_n + G$) is available energy.

McNaughton and Jarvis (1983) have written the Penman-Monteith equation in the form

$$LE = \Omega[sA/(s + \gamma)] + (1 - \Omega)(\rho C_p D/\gamma r_c) \quad (2.6)$$

where Ω is a coupling parameter ($0 < \Omega < 1$) that indicates the relative importance of the equilibrium evapotranspiration and imposed evapotranspiration and is defined by:

$$\Omega = [1 + \gamma(r_c/r_a)/(s + \gamma)]^{-1} \quad (2.7)$$

2.3 RESULTS AND DISCUSSION

2.3.1 Soil Moisture and Plant Growth

Rainfall was generally ample from May to September, except for three weeks from late July to early August (dry period) (Fig. 2.1). The soil (0 - 0.3 m layer) volumetric water content (θ_v) was variable depending on the frequency and the amount of rainfall. From May to September, θ_v was generally above $0.25 \text{ m}^3 \text{ m}^{-3}$, except during the dry period when θ_v reduced to $0.16 \text{ m}^3 \text{ m}^{-3}$ and moisture stress conditions prevailed (Fig. 2.1).

Seasonal changes in green LAI are also shown in Figure 2.1. The green LAI reached its maximum of about 3.2 toward the end of June, and gradually decreased later in the growing season.

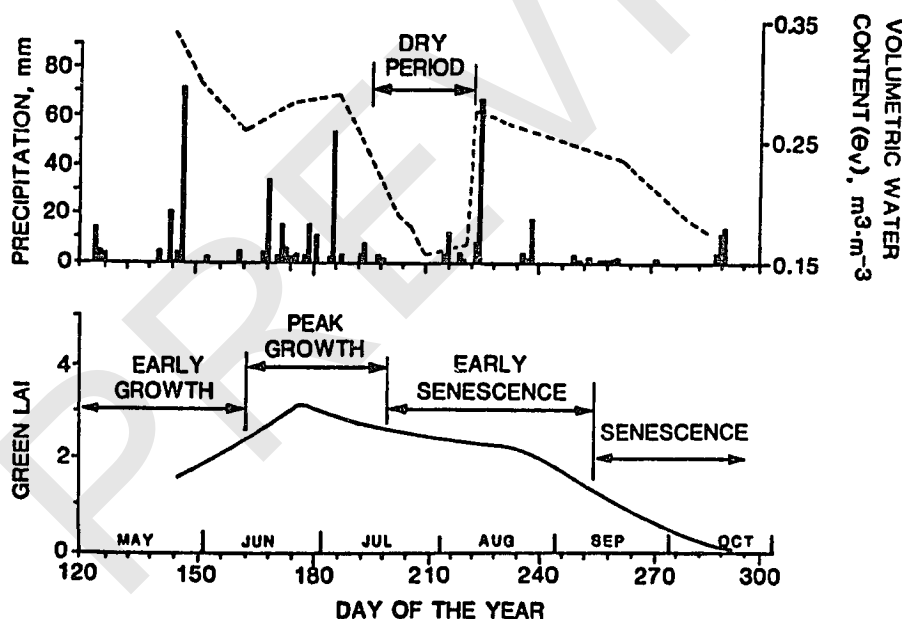


Figure 2.1 Seasonal precipitation, soil water content (0-0.3 m), and green leaf area index during the growing season in 1987.

2.3.2 Diurnal Variations

2.3.2.1 Energy Balance Components

Figures 2.2(a) and 2.2(b) show typical diurnal patterns* of the energy balance components** on a day with favorable soil moisture (11 July 1987) and on a day with moisture stress (30 July 1987). The atmospheric evaporative demand (air temperature and vapor pressure deficit) was moderate on 11 July, but was much higher on 30 July (Table 2.2). Midday (1230–1430 h) R_n averaged 601 and 587 $W m^{-2}$ on 11 and 30 July, respectively. Diurnal patterns of LE, H and G followed that of R_n . The magnitude of midday G on 11 and 30 July averaged 57 and 63 $W m^{-2}$, respectively.

The magnitude of midday LE on 11 July averaged 402 $W m^{-2}$ (0.67 R_n) while on 30 July it was 208 $W m^{-2}$ (0.35 R_n). Even though the evaporative demand was much higher on 30 July, LE was substantially reduced, because of partial stomatal closure. This was likely due to reduced leaf turgor caused by a decrease in water uptake in the root zone (Fig. 2.3) and by high vapor pressure deficit (Table 2.2) encountered on 30 July.

Table 2.2 Midday (1230–1430 hrs) magnitudes of mean air temperature (\bar{T}), vapor pressure deficit (\bar{D}), wind speed (\bar{U}), LE/R_n , H/R_n , and G/R_n on 11 and 30 July 1987. Values of green leaf area index (LAI) are also included.

	\bar{T} (°C)	\bar{D} (kPa)	\bar{U} ($m s^{-1}$)	LE/R_n	H/R_n	G/R_n	LAI
11 July	31	1.8	8	0.67	0.21	0.09	2.8
30 July	37	4.3	6	0.35	0.48	0.11	2.6

*Central daylight savings time is shown in figures and tables.

**Fluxes directed toward the surface are positive, while those directed away from the surface are negative.

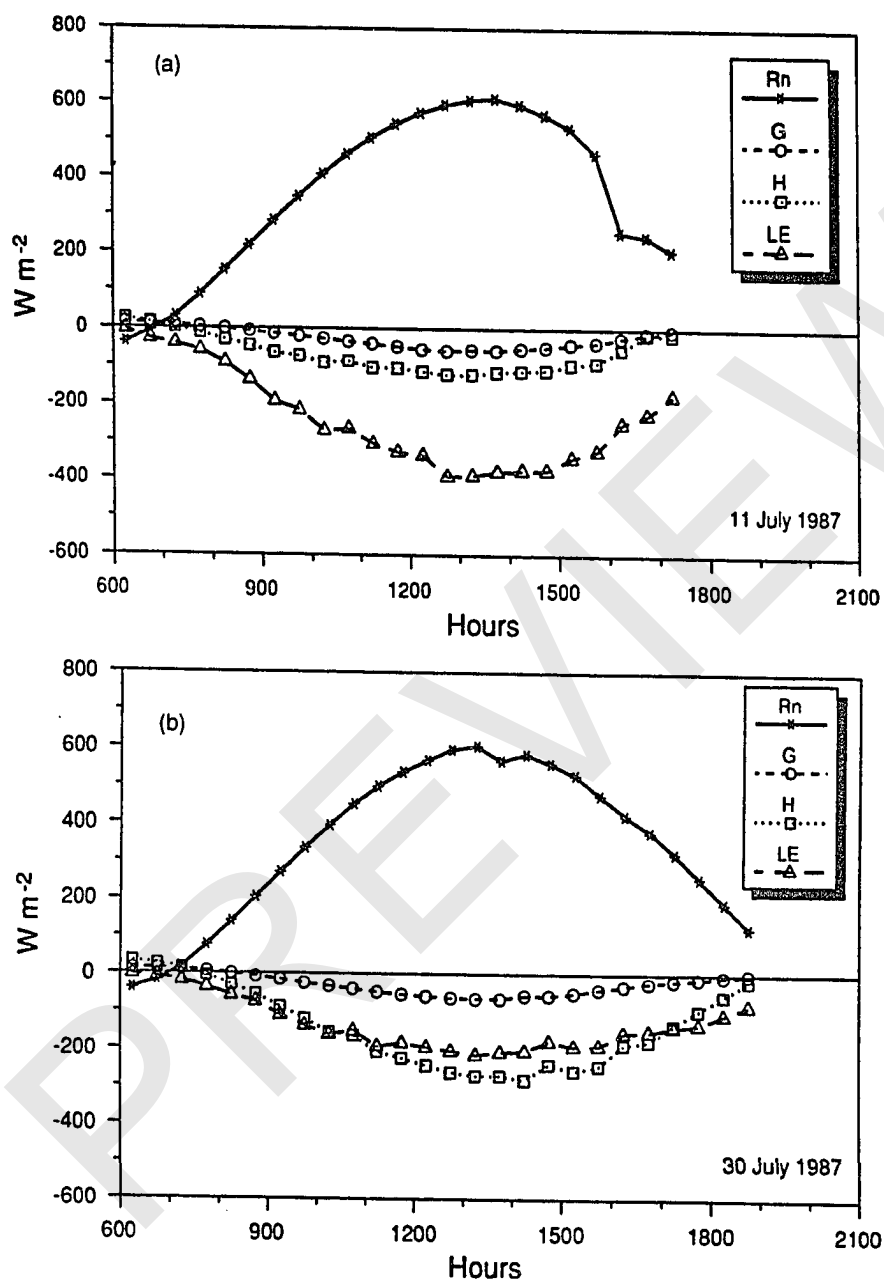


Figure 2.2 Diurnal variation of the energy balance components on (a) 11 July 1987 and (b) 30 July 1987.

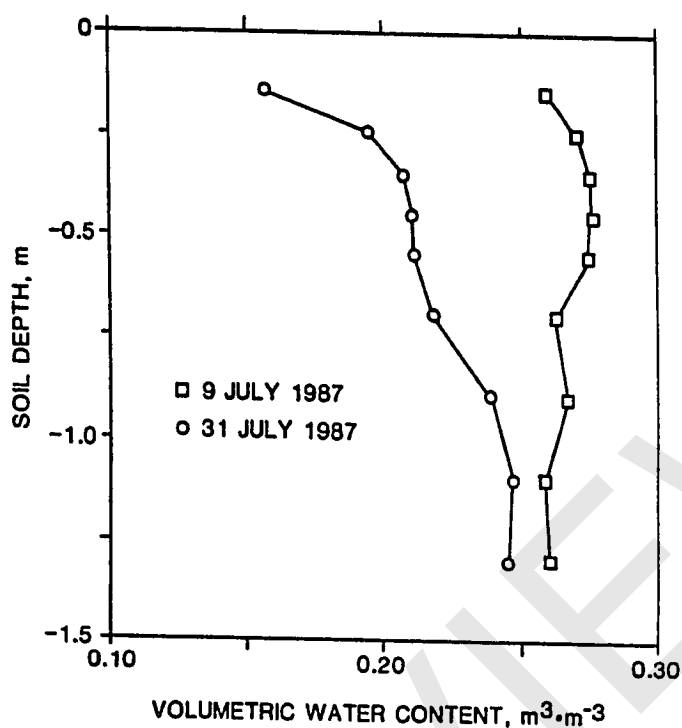


Figure 2.3 Profiles of volumetric soil water content on 9 and 31 July 1987.

Figures 2.4(a) and 2.4(b) show the diurnal patterns of leaf water potential (ψ_L) and stomatal conductance (g_s , measured with a steady-state porometer), respectively, for the three dominant grass species on these two days. On 11 July ψ_L of all three grasses decreased gradually and reached minima of around -1.2 MPa at 1500 h. On 30 July, however, ψ_L of *Andropogon gerardii* and *Sorghastrum nutans* decreased very rapidly in the morning and stayed below -2.0 MPa for most of the day (from 0900 to 1900 h). The ψ_L values of *Panicum virgatum* on 30 July were also substantially lower than those on 11 July. *Panicum virgatum*, however, maintained higher ψ_L throughout the day, compared to *Andropogon gerardii* and *Sorghastrum nutans*. This is probably due to a somewhat different physiological drought tolerance mechanism in *Panicum virgatum*. Knapp (1984) also observed that switchgrass usually maintained higher predawn and midday leaf water potentials than *Andropogon gerardii* and *Schizachyrium scoparium* throughout the season.