COMPONENTS OF SURFACE ENERGY BALANCE IN A TEMPERATE GRASSLAND ECOSYSTEM[1]

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(Received in final form 1 December, 1989)

Abstract. Eddy correlation measurements were made of fluxes of moisture, heat and momentum at a tallgrass prairie site near Manhattan, Kansas, U.S.A. during the First ISLSCP[2] Field Experiment (FIFE) in 1987. The study site is dominated by three C_4 grass species: big bluestem (*Andropogon gerardii*), indiangrass (*Sorghastrum nutans*), and switchgrass (*Panicum virgatum*). The stomatal conductance and leaf water potential of these grass species were also measured.

In this paper, daily and seasonal variations in the components of the surface energy balance are examined. The aerodynamic and canopy surface conductances for the prairie vegetation are also evaluated.

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. Grasslands are also believed to play an important role in the global budget of heat and moisture. Very little information on the surface energy balance in grasslands is currently available. A better understanding of the energy exchange processes, particularly evapotranspiration, is necessary for studies of global climate.

Several models have been proposed to estimate actual evapotranspiration 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 surface and the atmosphere. Thus, knowledge of how canopy surface conductance responds to environment and soil water deficit in grasslands is critical in evaluating the relative importance of surface and atmospheric control of energy partitioning in this ecosystem.

In this paper we present results of measurements, made as a part of FIFE, to study the surface energy balance components over a tallgrass prairie site near the Konza Prairie Long Term Ecological Research (LTER) site near Manhattan, Kansas. Diurnal and seasonal behaviour of the aerodynamic and canopy surface conductances is described. Results are compared with available information over agricultural and forest vegetation.

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[1] Published as Paper No. 8987, Journal Series, Nebraska Agricultural Research Division.

[2] ISLSCP: International Satellite Land Surface Climatology Project (for details, see *Sellers et al.*, 1988).

Boundary-Layer Meteorology **51**: 401–417, 1990.

2. Materials and Methods

2.1. SITE AND VEGETATION

Measurements were made during May to October, 1987 over a tallgrass prairie 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 prairie was burned on 16 April 1987 to improve the mix of grasses and forbs. The experimental area was not grazed in 1986 and 1987.

Percent species composition at the study site was estimated by employing a modified step-point method (Owensby 1973). The vegetation is dominated by three warm season C_4 grasses: big bluestem (*Andropogon gerardii*), indiangrass (*Sorghastrum nutans*) and switchgrass (*Panicum virgatum*). Numerous other grasses, sedges, forbs and woody plants constitute the remainder of the plant community (Table I).

2.2. PLANT AND SOIL MEASUREMENTS

Plant growth was monitored on a regular basis by measuring plant height and leaf area. Leaf area index (LAI) was measured with a portable area meter (LI-COR, Inc., Lincoln, NE, Model LI-3000). Stomatal conductance (g_s) and leaf water potential (ψ_L) in the three dominant grasses were measured hourly on four upper 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 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.

TABLE I

Percent species composition at the experimental site (flowering stage, 1987) estimated by the modified step-point method (Owensby 1973)

Species	%
Andropogon gerardii (C_4)	27.1
Sorghastrum nutans (C_4)	22.2
Panicum virgatum (C_4)	16.6
Sporobolus asper (C_4)	7.0
Schizsachyrium scoparium (C_4)	4.7
Bouteloua gracilis (C_4)	4.3
Dichanthelium oligosanthes (C_3)	4.0
Agropyron smithii (C_3)	1.2
Other grasses	2.4
Sedges	6.3
Forbs and woody plants	4.2

2.3. MICROMETEOROLOGICAL MEASUREMENTS

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), a Krypton hygometer (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). 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).

2.3.2. *Supporting Measurements*

Net radiation (R_n) was measured with a net radiometer (Radiation Energy Balance System, Beaverton, OR) located at 2.0 m above 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.

2.4. THEORETICAL CONSIDERATIONS

2.4.1. *Aerodynamic and Canopy Surface Conductance*

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

$$g_a = 1/r_a\,, \tag{1}$$

where the aerodynamic resistance (r_a) is given by

$$r_a = r_{am} + r_b\,. \tag{2}$$

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

$$r_{am} = \bar{U}/u_*^2\,, \tag{3}$$

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; Wesley and Hicks, 1977; Verma *et al.*, 1986, for further details) is approximated by

$$r_b = (2/ku_*)(\kappa/D_v)^{2/3}\,, \tag{4}$$

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):

$$r_c = [(s/\gamma)\beta - 1]r_a + (\beta + 1)(\rho C_p/\gamma)(D/A)\,, \tag{5}$$

where s is the slope of the saturated vapor pressure-temperature curve, γ is the psychrometric constant, β is the Bowen ratio ($= H/\mathrm{LE}$), H and LE are sensible and latent heat fluxes,[3] respectively, ρ is the density of air, C_p is the specific heat of air and D is vapor pressure deficit, and A ($= R_n + G$) is available energy, R_n is net radiation and G is soil heat flux.

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

$$\mathrm{LE} = \Omega[sA/(s + \gamma)] + (1 - \Omega)/(\rho C_p D/\gamma r_c)\,, \tag{6}$$

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:

$$\Omega = [1 + \gamma(r_c/r_a)/(s + \gamma)]^{-} \tag{7}$$

3. Results and Discussion

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) (Figure 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 m^3 m^{-3},

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[3] Fluxes directed toward the surface are positive, while those directed away from the surface are negative.

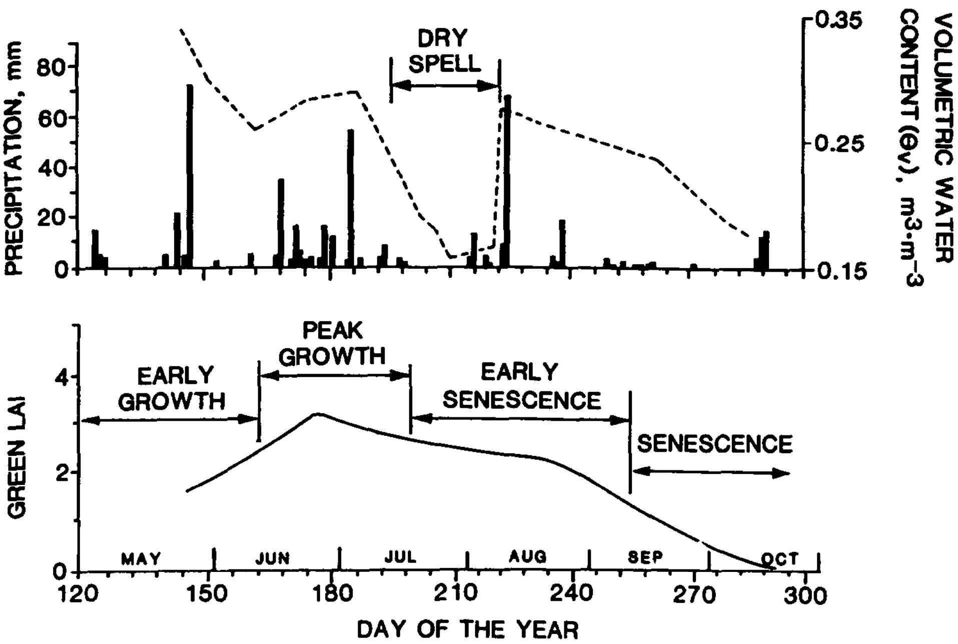

Fig. 1. Seasonal precipitation, soil water content, and green leaf area index.

except during the dry period when θ_v decreased to 0.16 $m^3 m^{-3}$ and moisture stress conditions prevailed (Figure 1).

Seasonal changes in green LAI are also shown in Figure 1. The green LAI reached its maximum of about 3.2 toward the end of June, and gradually decreased later in the growing season.

3.2. Diurnal variations

3.2.1. *Energy Balance Components, Stomatal Conductance and Leaf Water Potential*

Figures 2a and 2b show typical diurnal patterns[4] 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 II). Midday (1230–1430 h) R_n averaged about 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 about 57 and 63 W m^{-2}, respectively.

The magnitude of midday LE on 11 July averaged about 402 W m^{-2} ($0.67R_n$) while on 30 July it was 208 W m^{-2} ($0.35R_n$). Even though the evaporative demand

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[4] Central standard time is shown in figures and tables.

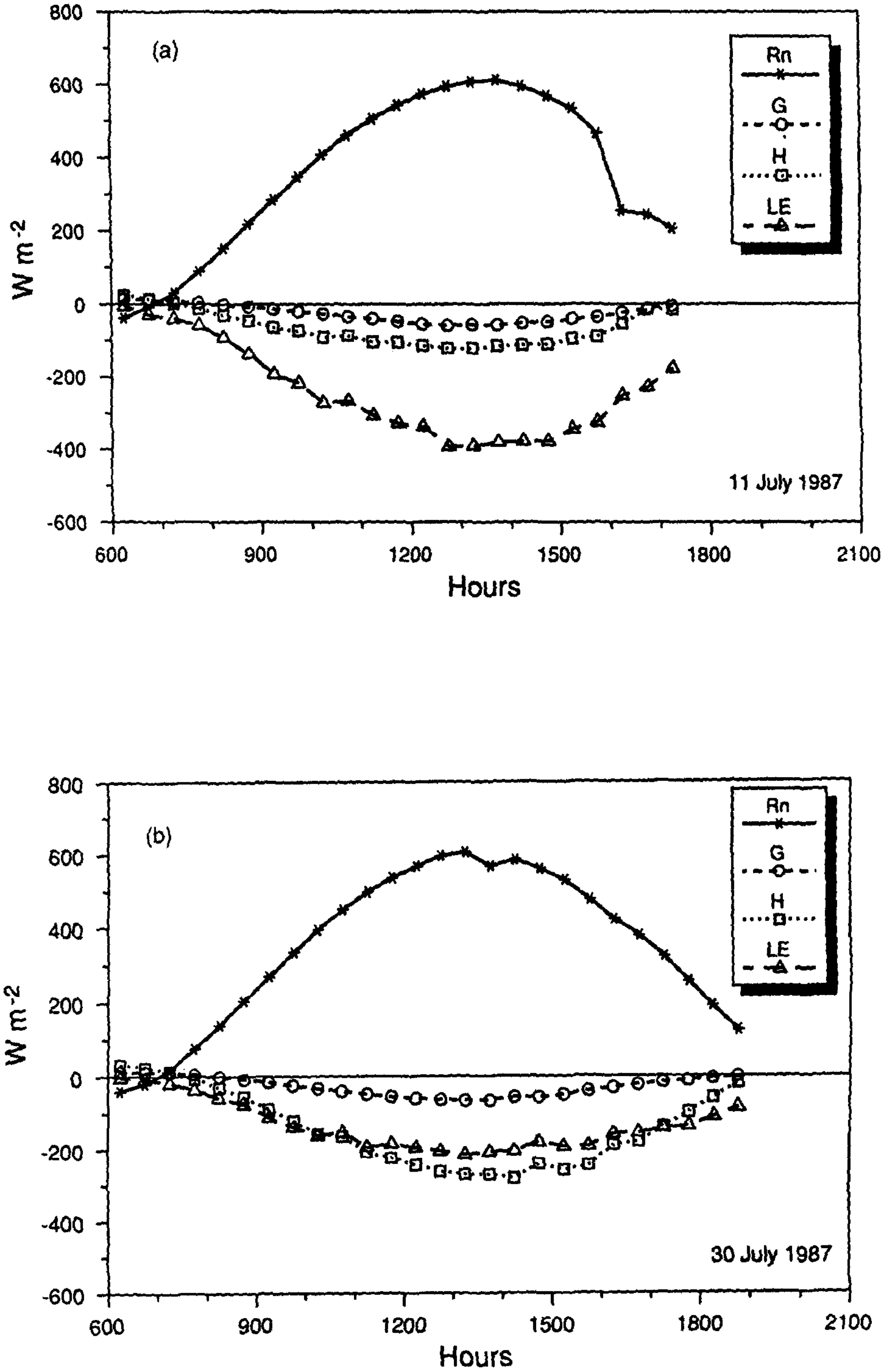

Fig. 2. Diurnal variation of the energy balance components on (a) 11 July 1987 and (b) 30 July 1987.

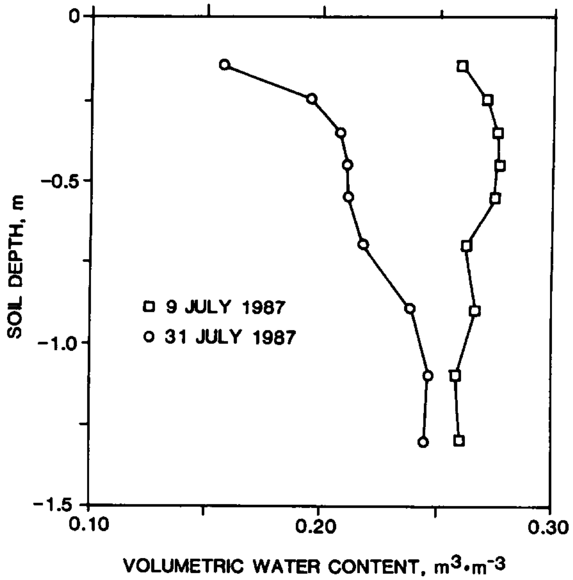

Fig. 3. Profiles of volumetric soil water content on 9 and 31 July 1987.

TABLE II

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

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 (Figure 3) and by high vapor pressure deficit (Table II) encountered on 30 July.

Figures 4a and 4b 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 big bluestem and indiangrass 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 switchgrass on 30 July were also substantially lower than those on 11 July. Switchgrass, however, maintained higher ψ_L throughout the day. This is probably due to a somewhat different physiological drought tolerance mechanism in switchgrass. Knapp (1984) also observed that switchgrass usually

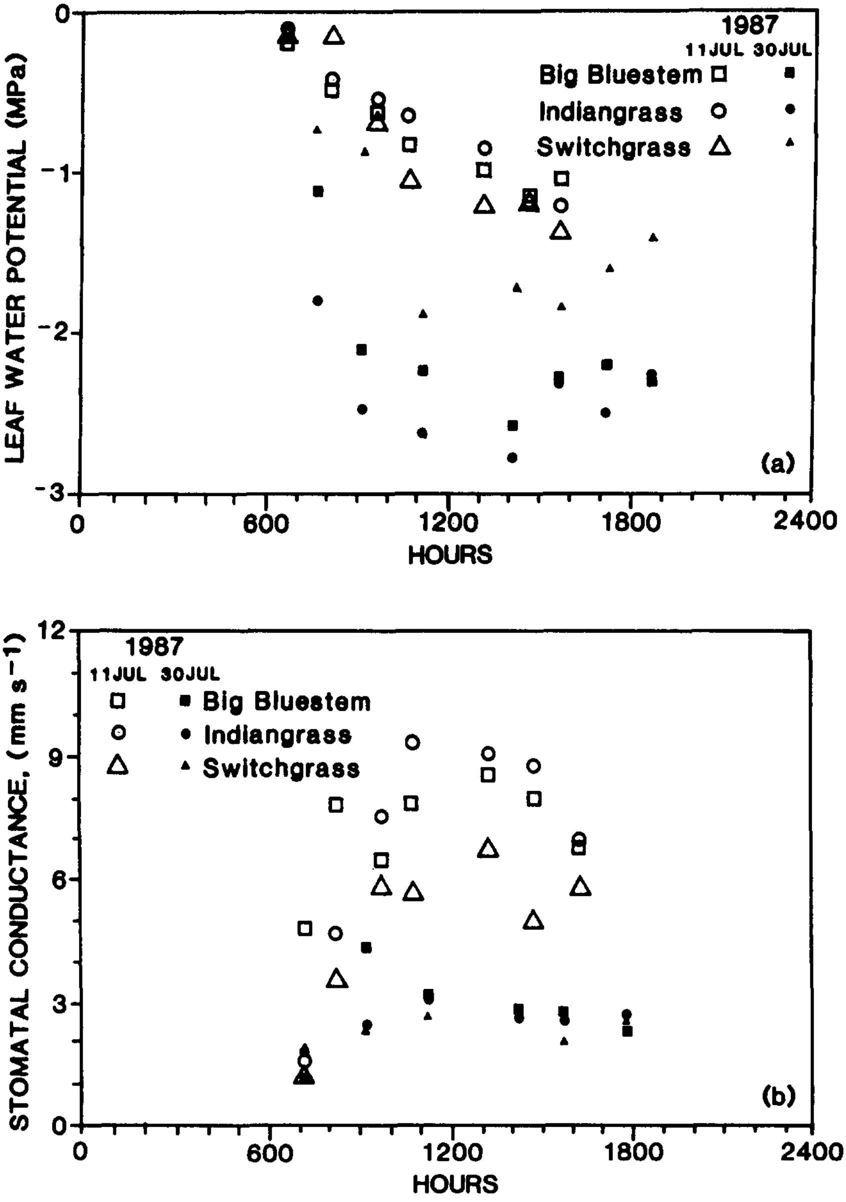

Fig. 4. Diurnal patterns of (a) leaf water potential and (b) stomatal conductance on 11 and 30 July, 1987.

maintained higher predawn and midday leaf water potentials than big bluestem and little bluestem throughout the season.

Stomatal conductance of the three dominant grasses on 11 July followed diurnal patterns of R_n (Figure 4b) and averaged about 8 mm s^{-1} during midday. On 30

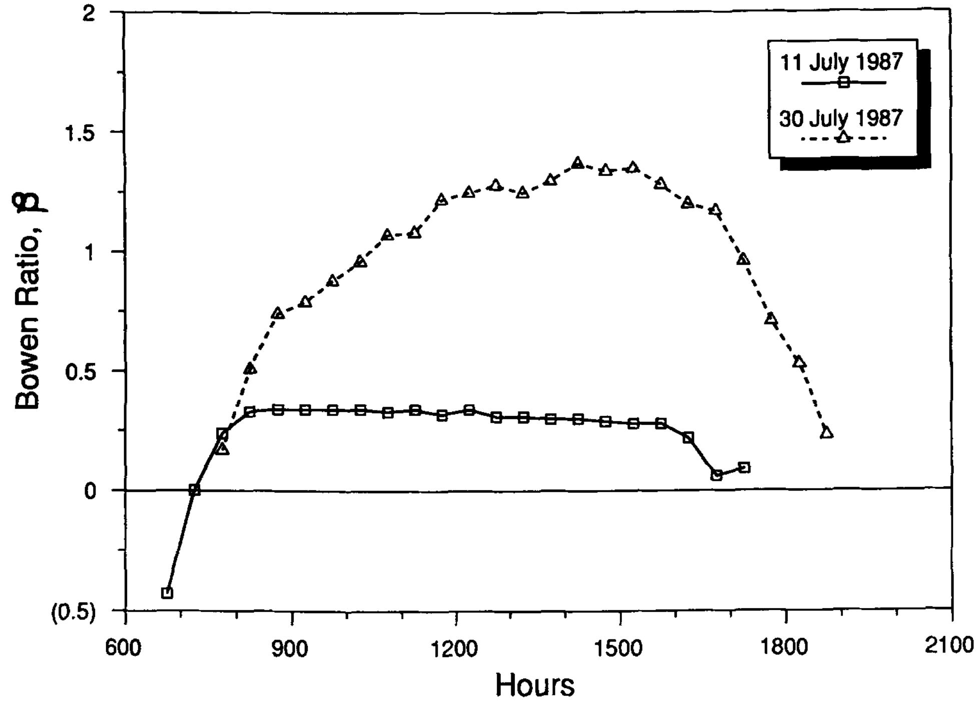

Fig. 5. Diurnal patterns of the Bowen ratio on 11 and 30 July, 1987.

July, midday g_s averaged about 3 mm s^{-1}. The diurnal patterns of g_s, especially for big bluestem which was the most dominant species, did not seem to follow that of R_n. The g_s values for big bluestem reached a peak in the early morning and then decreased thereafter. The lower stomatal conductance on 30 July resulted in lower LE throughout the day. Accordingly, a greater portion of R_n was partitioned to H and G on 30 July as compared to those on 11 July (Table II).

Energy partitioning can also be described in terms of the Bowen ratio, β (Figure 5). On 11 July, β remained relatively constant (about 0.31) during the day. On 30 July, however, β increased rapidly from 0.17 to 1.37 with a midday average of 1.30.

3.2.2. *Aerodynamic (g_a) and Canopy Surface (g_c) Conductances*

Figure 6a shows diurnal trends of g_a for 11 and 30 July 1987. The midday averages of g_a on these two days were 48 and 36 mm s^{-1}, respectively. The difference in midday g_a can be attributed to different wind speeds encountered on two days (see Table II). The dependence of g_a on wind speed is clearly shown in Figure 6b. For $\bar{U} > 1.5$ m s^{-1} there is a strong linear relationship between g_a and $\bar{U}$.

Figure 7 shows diurnal behaviour of g_c calculated from measured LE using the Penman–Monteith equation (Equation (5)). Diurnal variation of g_c on 11 July followed a pattern similar to that of R_n. The g_c value was least (about 1.0 mm s^{-1})

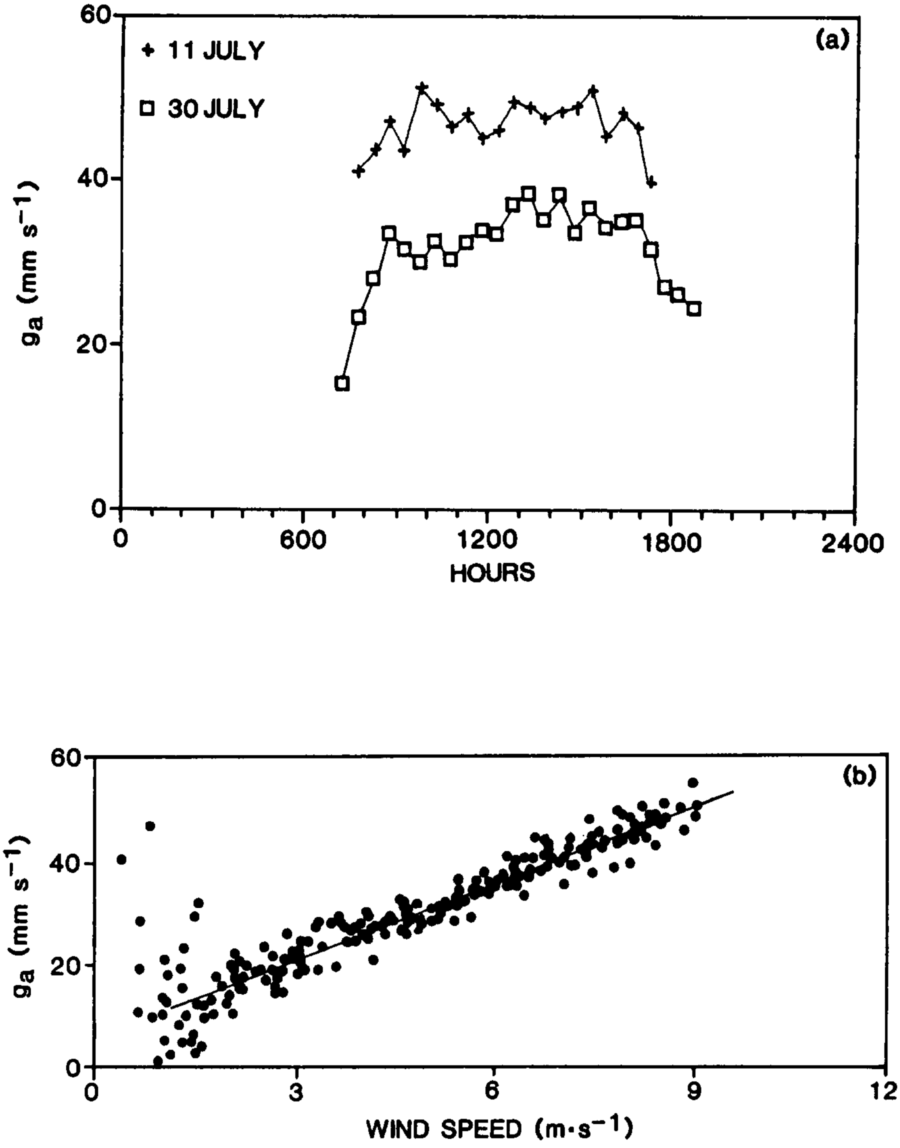

Fig. 6. (a) Diurnal patterns of the aerodynamic conductance on 11 and 30 July 1987. (b) The relationship between aerodynamic conductance and mean wind speed, June and July 1987.

near sunrise, and reached its maximum of 13.1 mm s^{-1} during midday. On 30 July g_c reached a peak of 3.4 mm s^{-1} in the early morning and decreased thereafter to a minimum value of 1.5 mm s^{-1} near sunset. As seen in Figure 4b, porometer measurements of g_s of individual leaves on 11 and 30 July showed diurnal patterns very similar to those of g_c. These observations substantiate the physiological significance of g_c, as has been pointed out in earlier studies (e.g. Monteith 1981).

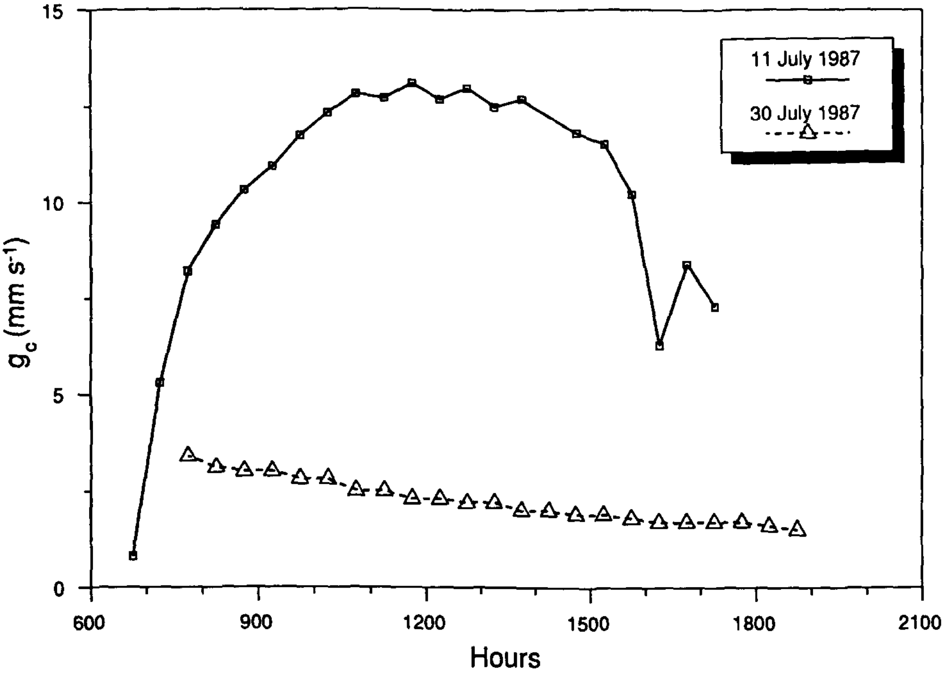

Fig. 7. Diurnal patterns of the canopy surface conductance on 11 and 30 July, 1987.

3.3. SEASONAL VARIATIONS

3.3.1. *Energy Balance Components*

Figure 8 shows seasonal changes in R_n, LE, H and G. The midday R_n on clear days ranged from 600 to 630 W m^{-2} in June and July, reaching the maximum values around summer solstice. It gradually decreased and averaged about 400 W m^{-2} in October. The midday G decreased with season from 150 W m^{-2} (0.27R_n) in May to 39 W m^{-2} (0.10R_n) in October. This decrease can be attributed to increasing total plant cover (green and brown vegetation) in the early part of the measurement period and to the depletion of soil water during senescence (Figure 1).

During the most vigorous stage of vegetation growth (June and July), the magnitude of midday LE ranged from 211 to 460 W m^{-2} (0.58–0.83R_n). When soil water was limiting during the dry spell (from late July to early August), LE fell below 210 W m^{-2} ($<$0.45R_n). After the dry spell, LE recovered to its early season magnitude with midday values ranging from 311 to 440 W m^{-2}. In September LE decreased rapidly with plant senescence and ranged from 17 to 98 W m^{-2} (0.08–0.22R_n) in October.

The magnitude of midday H in June and July ranged from 50 to 140 W m^{-2} (0.10–0.23R_n), reaching up to 290 W m^{-2} (0.52R_n) during the dry period. As plants senesced in October, a greater portion of R_n was dissipated in terms of

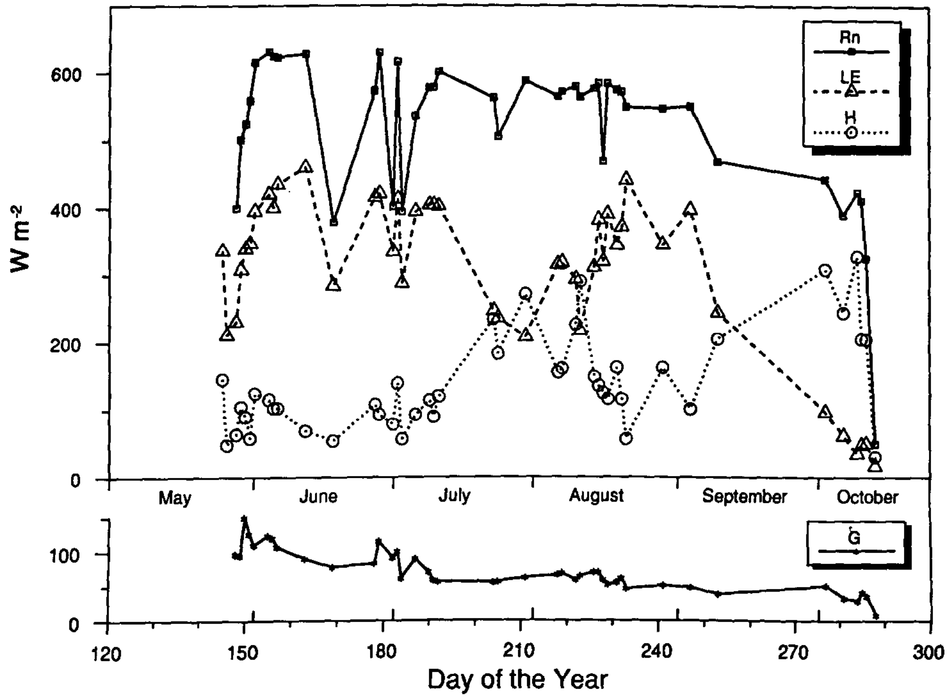

Fig. 8. Seasonal variation in midday (1230–1430 hr) magnitudes of energy balance components in 1987.

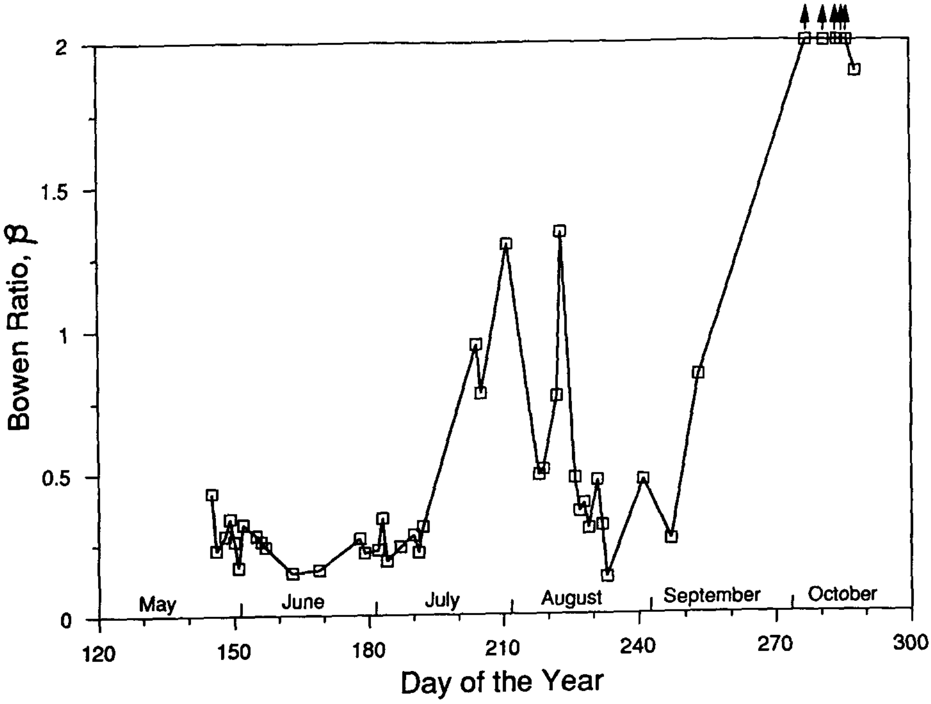

Fig. 9. Seasonal variation in midday values of the Bowen ratio in 1987.

sensible heat. The magnitude of H during this month ranged from 205 to 328 W m^{-2} (0.63–0.78R_n).

During the period of June–July, midday β ranged from 0.15 to 0.43, with an average of 0.26 (Figure 9). During the dry spell, midday β ranged from 0.77 to 1.34 with an average of 1.03. A brief recovery in mid August-mid September was due to frequent rainfall (see Figure 1). Values in excess of 2.0 were not uncommon in October.

3.3.2. *Aerodynamic (g_a) and Canopy Surface (g_c) Conductances*

Seasonal variation in the midday g_a is shown in Figure 10a. The values of g_a ranged from 7.2 to 56.5 mm s^{-1} with seasonal average of 30 mm s^{-1}. As mentioned above, the day to day variation in g_a is directly related to the variation in wind speed (Figure 6b).

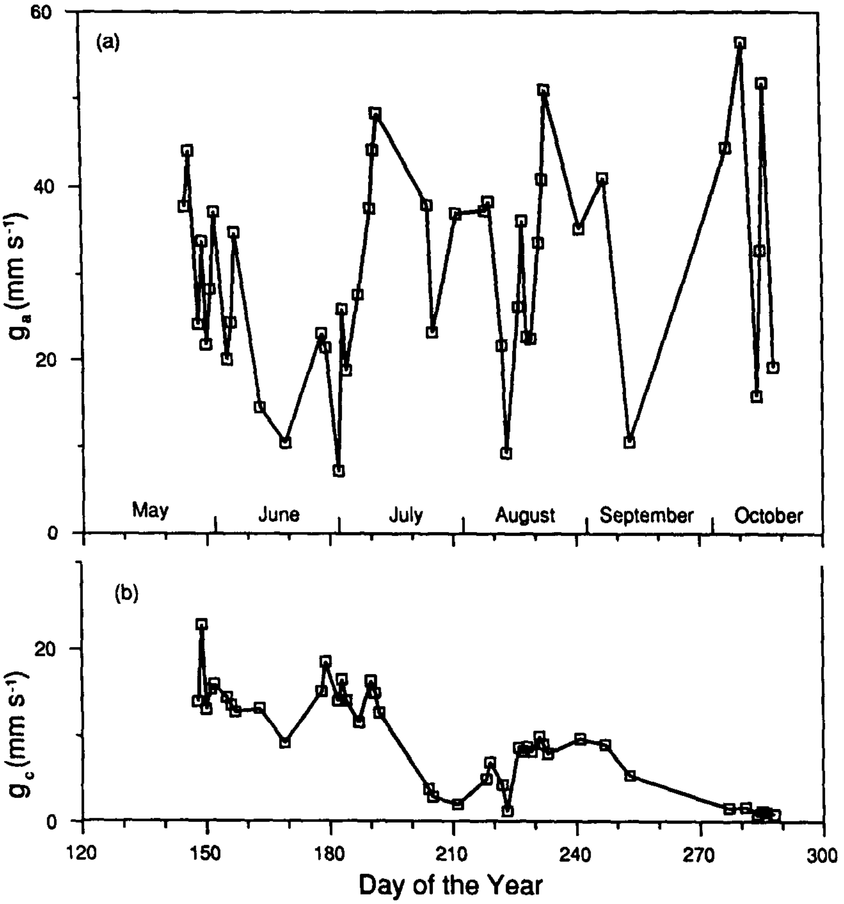

Fig. 10. Seasonal variation in midday values of (a) aerodynamic conductance and (b) canopy surface conductance in 1987.

Figure 10b shows the seasonal behaviour of g_c. During the period of most vigorous plant growth (June and July) with no moisture stress, the midday g_c averaged about 15.0 mm s^{-1}. The dry spell during later July produced much lower value of g_c, with the average of 3.0 mm s^{-1}. With ample rainfall in mid August, prairie vegetation began to recover from the moisture stress, resulting in an increase of g_c. In late August, midday g_c averaged about 9.0 mm s^{-1}. Later in the season, the rapidly decreasing green LAI of the senescing prairie vegetation (Figure 1) caused a decrease in g_c. In October the midday g_c averaged about 1.3 mm s^{-1}.

3.4. COMPARISON WITH OTHER TYPES OF VEGETATION

The midday LE (0.58 to $0.83R_n$) observed in this grassland ecosystem (dominated by C_4 grasses) is somewhat lower than the reported LE values from agricultural crops (0.7 to $0.9R_n$) such as soybean (Baldocchi, 1982), grain sorghum (Anderson, 1983), winter wheat and Barley (Kim *et al.*, 1989) for a similar range of vapor pressure deficit ($0 < D < 2$ kPa), and with no moisture stress and advection of sensible heat. Ripley (1974) reported LE values of about $0.5R_n$ for a shortgrass prairie (dominated with C_3 grasses) at Matador, Canada. On the other hand, our measured LE values are higher than those (0.2 to $0.55R_n$) from coniferous (Stewart and Thom, 1973; Jarvis *et al.*, 1976) and deciduous forests (Verma *et al.*, 1986) in temperate latitudes.

The difference in LE/R_n values can be explained partly in terms of a surface-atmospheric coupling parameter (McNaughton and Jarvis, 1983). When the soil water was not limiting, the coupling parameter, Ω (see Equations (6) and (7)) for the grassland studied here ranged from 0.51 to 0.99 with the average of about 0.72.[5] As McNaughton and Jarvis have pointed out, a large value of Ω ($\approx$ 0.7–0.8 for grasslands and agricultural crops) would indicate that the surface vapor pressure deficit approaches an equilibrium value so that LE is determined mainly by R_n and responds to only a small extent to regional advective conditions. On the other hand, a small value of Ω ($\approx$0.2), as is generally the case for forests, would indicate that the regional vapor pressure deficit is imposed on the vegetation by vigorous turbulent mixing.

The difference in LE rates can also be examined in terms of the canopy surface conductance values (larger values of g_c would cause higher LE rates). The values of g_c for the tallgrass prairie studied here (10–25 mm s^{-1}) are smaller than those for the agricultural crops (20–50 mm s^{-1}) cited above and larger than those for forests (5–20 mm s^{-1}) (see Jarvis, 1981; Verma *et al.*, 1986).

Values of g_a observed in this study (7–57 mm s^{-1}) are very similar to those for agricultural crops (20–50 mm s^{-1}), but lower than for forests (100–330 mm s^{-1} for coniferous forests – Jarvis, 1981; 45–70 mm s^{-1} for a deciduous forest – Verma *et*

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[5] Paw U and Gao (1988) suggest that caution is necessary when applying the coupling parameter concept due to an error in using a linearized Penman-Monteith form, especially when $\Omega \geqslant 0.8$. However, this error would be relatively small for the results reported here.

al., 1986). The differences in these values of g_a are probably due to differences in prevailing wind speed regimes and aerodynamic roughness of the vegetation.

In the absence of water stress and advection of sensible heat, daytime values of β (0.1 to 0.4) from this study are similar to those found over agricultural crops. On the other hand, values of β over forests reported in the literature range from 0.1 to 4. Smaller canopy surface conductance values observed over forests partially explain the larger Bowen ratio. Small values of ambient vapor pressure deficit may have also contributed to those results (Jarvis *et al.*, 1976).

4. Summary and Conclusions

Eddy fluxes of latent heat (LE) and sensible heat (H) measured over a tallgrass prairie in northeastern Kansas during a six-month period in 1987 are reported here. During the period of most vigorous plant growth (June–July) with favorable soil moisture, midday LE averaged about $0.69R_n$ (where R_n is net radiation) and the Bowen ratio (β) was about 0.25. Daily patterns of LE and H followed that of R_n.

The canopy surface conductance (g_c, computed from the Penman–Monteith equation) followed the diurnal pattern of R_n, as did the stomatal conductance of individual leaves (measured with a steady-state porometer). The miday averages of the aerodynamic and canopy surface conductances were about 30 and 15 mm s^{-1}, respectively.

A dry spell encountered in late July caused depletion of soil water, resulting in substantial decrease in g_c (midday value ≈ 3.0 mm s^{-1}). Like that of the stomatal conductance of the individual leaves, the diurnal pattern of g_c during this period did not respond to R_n. Midday LE was reduced to $0.40R_n$ and β averaged about 1.03.

Significant seasonal variation was found in energy partition and canopy surface conductance. Both R_n and LE reached their peak values (about 630 and 460 W m^{-2}, respectively, on clear days) in June and then decreased later in the season. The magnitude of LE dropped sharply during the dry spell and increased again after rainfall in mid August. It rapidly decreased in September and October with plant senescence. The soil heat flux (G) reached a peak ($\approx$ 150 W m^{-2}) in late May and then decreasd later as a result of increasing plant cover.

Canopy surface conductance showed a seasonal pattern generally similar to that of LE. With rainfall (in mid August) following the dry spell, g_c recovered to only 50 to 60 percent of the early season magnitude whereas LE recovered almost fully.

Acknowledgements

This study was supported by the National Aeronautics and Space Administration under Grant #NAG5.890 and by the National Science Foundation under Grant TM-8519026. Messrs. H. D. Earl and Sheldon Sharpe provided valued assistance in maintenance of instruments and data acquisition systems. Mr. James Hines assisted in data computation. We wish to express our appreciation to Mr. Robert Clement for his valuable help in data collection and processing. We thank Dr. James Stubbendieck for his help in estimating species composition; Mrs. Sharon Kelly for the stenographic work; and Drs. Max D. Clegg and Elizabeth A. Walter-Shea for their review of this manuscript.

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