Seasonal and Interannual Varialbility in Evapotranspiration of Native Tallgrass Prairie and Cultivated Wheat Ecosystems, by G.G. Burba, S.B. Verma

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Seasonal and interannual variability in evapotranspiration of native tallgrass prairie and cultivated wheat ecosystems

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Abstract

Year-round measurements of evapotranspiration (ET) were made, using the eddy covariance technique, in tallgrass prairie and winter wheat ecosystems in north-central Oklahoma during 1996–2000. Seasonal and interannual variability in water vapor flux was examined in terms of relevant controlling variables. During the growing season, the daily ET was 3.5–5.0 mm day^{-1} for the prairie and 2.5–7.0 mm day^{-1} for wheat. Annual ET ranged 640–810 mm for the prairie, and 710–750 mm for wheat. "Non-growing" season ET was about 25% of the annual ET in the prairie (during November–April) and about 50% of the annual ET in wheat (during July–February). Differences in ET between the two ecosystems and the corresponding interannual variability were related mostly to the effects of soil moisture stress and variations in green foliage area, while the weather parameters had a smaller impact. The ET model of Priestley and Taylor (1972) [Priestley, C.H.B., Taylor, R.J., 1972. On the assessment of surface heat flux and evaporation using large-scale parameters. Mon. Weather Rev. 100, pp. 81–92.] was modified to incorporate the effects of soil moisture and foliage area, and tested against field measurement. The modification improved the prediction of ET significantly as compared to the original model. On average, the overestimation of the actual ET by the original model reduced from 47 to 9% at the prairie site, and from 20 to 4% at the wheat site. Improved performance of the modified Priestley–Taylor model over a wide range of environmental conditions makes it potentially a practical tool for predicting ET in grasslands and agricultural systems.

Keywords: Water vapor flux; Latent heat flux; Grasslands; Winter wheat; Priestley–Taylor parameter

1. Introduction

Evapotranspiration (latent heat flux) is an essential component of the energy and water budgets in grassland and agricultural ecosystems (e.g. Knapp, 1985; Verma et al., 1989; Hunsaker et al., 2000). Understanding the processes that affect evapotranspiration in these and other communities at different temporal scales and under a variety of environmental conditions is important in modeling ecosystem production (Williams et al., 2004), the water balance of terrestrial ecosystems (Yunusa et al., 2004), and atmospheric circulation (Heijmans et al., 2004).

Many micrometeorological studies have examined the variability in evapotranspiration in relation to weather parameters, and have provided a number of relevant models and empirical equations (e.g. Penman, 1948; van Bavel, 1966; Priestley and Taylor, 1972). In earlier research, the use of soil moisture and canopy conditions was limited, which may have led to the poor performance of some weather-based evapotranspiration models, especially when used on a long-term basis. Recent studies have begun to recognize the role of the soil moisture and canopy characteristics (e.g. phenology, leaf

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area index) in accurate prediction of evapotranspiration (e.g. Shuttleworth and Wallace, 1985; Massman, 1992; Stannard, 1993). Most investigations have, however, been limited to growing seasons. Furthermore, very few studies have examined multi-year variability in ET of grassland and agricultural ecosystems. Such information is critical for an accurate assessment of the overall water balance of these systems. Here we report results on evapotranspiration and energy fluxes from a study conducted during 1996–2000 in tallgrass prairie and winter wheat ecosystems. Our main objective is to examine the seasonal and interannual variability in evapotranspiration in terms of relevant controlling factors (weather variables, soil moisture, and foliage area). We also take advantage of our soil moisture and foliage area information to modify the evapotranspiration model of Priestley and Taylor (1972), and test the modification against our measurements in a wide range of environmental conditions.

2. Materials and methods

2.1. Study sites

Our study was conducted at a native tallgrass prairie site (36°56′N, 96°41′W, elevation 350 m) and a cultivated wheat site (36°45′N, 97°05′W, elevation 310 m) in north-central Oklahoma during the period from early August 1996 through early April 2000. The prairie site (about 500 m × 500 m), located 69 km north-east of Ponca City, OK is surrounded by rolling hills occupied by stretches of grazed and ungrazed tallgrass prairie 1–6 km long. To improve pasture quality, the tallgrass prairie was burned during the spring of every year, except 1996 because of the dry conditions and a burning ban in the region. The site was not grazed during the entire study. The species composition at the tallgrass prairie site was determined with the help of Professor J. Stubbendiek (University of Nebraska) in the fall of 1997. The prevailing vegetation at the study site was true grasses, which occupied over 83% of the site. Forbs comprised about 13% of the vegetation, and grass-like plants occupied 4% of the area. Most plants at the site were warm season (C_4) species, and reached their peak activity in the mid-late summer, except forbs, which were active in the late spring. Soil consisted of clay loam of Wolco–Dwight complex (thermic Pachic Argiustolls and mesic Typic Natrustolls), with a 1–2 m layer of dense clay below the depth of 0.6 m, underlined by limestone bedrock.

The wheat site (also about 500 m × 500 m) was located about 16 km to the north of Ponca City, OK. The site was planted in wheat during mid-fall of every year and was harvested in the late spring. Soils consisted of Typic and Pachic Argiustolls of Poncreek and Kirkland complexes, with silt loam and silty clay loam in the upper horizons, and heavy clay below 0.6 m. Lower horizons were carbonated due to limestone bedrock.

2.2. Flux and supporting micrometeorological measurements

The eddy covariance method was used to measure fluxes of sensible and latent heat (e.g. Baldocchi, 2003). The sensors included an omnidirectional three-dimensional sonic anemometer (R3, Gill Instruments Ltd., Lymington, UK), and a krypton hygrometer (Campbell Scientific, Logan, UT), located 4.5 m above the soil surface. Further details on the eddy covariance instrumentation are described in Suyker and Verma (2001) and Suyker et al. (2003). Net radiation (Rn) was measured 3.5 m above the soil surface (Radiation Energy Balance Systems, Beaverton, OR, model Q7). Mean air temperature and humidity were measured at the height of 4.5 m (Vaisala Inc., Woburn, MA, model Humitter 50Y). Mean horizontal wind speed (U) and wind direction were measured at 4.5 m (Met One, Grants Pass, OR, model 010C). Mean soil temperature (T_s) was measured with nine resistance thermometer (RTD) bars (0.1 m long). In addition, six thermistors were installed at different depths. These variables were measured every 5 s and averaged over 30 min. The soil heat flux (G_s) was calculated from the values measured with heat flux plates (Radiation Energy Balance Systems, Beaverton, OR, model HFT 1) installed 0.05 m below the surface and the rate of the change in the average temperature of the top 0.05 m of the soil (e.g. Kimball et al., 1976). To examine the "energy budget closure", we calculated linear regressions between the hourly values of $H + \mathrm{LE}$ and $\mathrm{Rn} + G$ measured at both sites during our study (excluding winter months and periods of rain). Here H and LE are fluxes of sensible and latent heat, and $G = G_s$ (soil heat flux) + G_c (estimated canopy heat storage) + G_m (estimated heat stored in the mulch). The regression slopes ranged from 0.89 to 0.94 (with r^2 ranging from 0.83 to 0.96), implying a reasonably good closure of the energy budget in our study.

2.3. Soil moisture measurements

Soil moisture was measured with Moisture Point Sensors (Environmental Sensors Inc., Victoria, B.C.;

model MP-917; Hook and Livingston, 1995). Time domain reflectometer (TDR) probes were installed at five locations at the prairie site and at four locations at the wheat site. These probes were sampled weekly. In addition, at each site, a centrally located probe collected soil moisture data at four depths (0–0.15, 0.15–0.30, 0.30–0.60, and 0.60–0.90 m) continuously throughout the year, at 2 h intervals. TDR measurements were verified against gravimetric sampling, conducted by Professor B. Carter (Department of Plant and Soil Sciences, Oklahoma State University). Overall, the TDR measurements were within 5% of results obtained gravimetrically for each horizon. On some occasions, when the readings of soil moisture after heavy rains exceeded the soil porosity level (about 50%), the values were set to 50% (the precision of the instrument was low under full saturation).

2.4. Foliage area measurements

At the prairie site, the aboveground biomass and foliage area index (FAI) were measured by harvesting the vegetation (destructive sampling) from four locations at approximately 2-week intervals. At each sampling location, a 0.33 m × 0.33 m plot was harvested. The samples were separated into green, non-green, and mulch components. Each sample was weighed, processed through a foliage area meter (LI-COR Inc., Lincoln, NE, model LI-3100), and reweighed after drying in an oven. At the wheat site, the above ground biomass and FAI were also measured at 2-week intervals. Foliage area at the wheat site was measured at four locations, with 0.5 m of a row sampled in each area. Canopy was separated into green leaves and non-green matter, and then the green, dead and total foliage area indices were calculated. The field was photographed every 2 weeks for visual determination of the wheat growth stage.

3. Results and discussion

3.1. General weather conditions

Relevant information on weather parameters at the prairie and wheat sites are given in Table 1. Mean annual values of incoming shortwave radiation (R_s) and net radiation (Rn) were similar in all years (year-to-year differences did not exceed 5%). The year 1997 was slightly cooler and more humid than 1998 and 1999. The total annual precipitation in 1997 was similar to that in 1998, but slightly smaller than in 1999.

3.2. Soil moisture and foliage area

The annually averaged soil moisture content was similar at both sites in all years, but the distributions during the summer months were quite different (Fig. 1A). There was no soil moisture stress in 1997. However, the summers of 1998 and 1999 experienced moisture stress. Severity of the moisture stress in a given year was determined by the number of days when soil moisture was below a "moisture stress threshold" (assumed here as 50% of the extractable soil water, which corresponded to the volumetric soil moisture of 0.31 in the top 0.9 m soil layer), and by the minimum soil moisture value in that soil layer. The summer of 1998 at the prairie site had a total of 83 days of the moisture stress, and had the minimum volumetric soil moisture of 0.09, and thus was characterized to experience a "severe moisture stress". The summer of 1999 had a total of 45 days of the moisture stress, and had a minimum volumetric soil moisture of 0.14, and thus was said to have experienced "mild moisture stress". Since wheat was harvested in late June, the canopy did not experience any moisture stress.

Foliage area (Fig. 1B) was also substantially different between the sites due to differences in

Table 1
Annually integrated values of incoming solar radiation (R_s), net radiation (Rn) and precipitation, and mean values of air temperature (T_a), soil temperature (T_s), vapor pressure deficit (D), and wind speed (U)

Parameter	Units	Prairie site			Wheat site		
		1997	1998	1999	1997	1998	1999
R_s (incoming solar radiation)	MJ year^{-1}	5634	5668	5973	5617	5758	5998
Rn (net radiation at 4.5 m)	MJ year^{-1}	3105	2952	3017	3185	2864	2891
Precipitation	mm year^{-1}	1104	1193	1213	1231	1202	1342
T_a (air temperature at 4.5 m)	°C	14.5	15.9	15.5	13.2	15.5	15.9
T_s (soil temperature at 0.1 m)	°C	15.1	16.8	15.4	14.9	16.8	16.6
D (vapor pressure deficit at 4.5 m)	kPa	4.6	6.4	7.6	5.7	7.8	7.3
U (wind speed at 4.5 m)	m s^{-1}	3.9	4.1	4.2	3.8	4.3	4.3

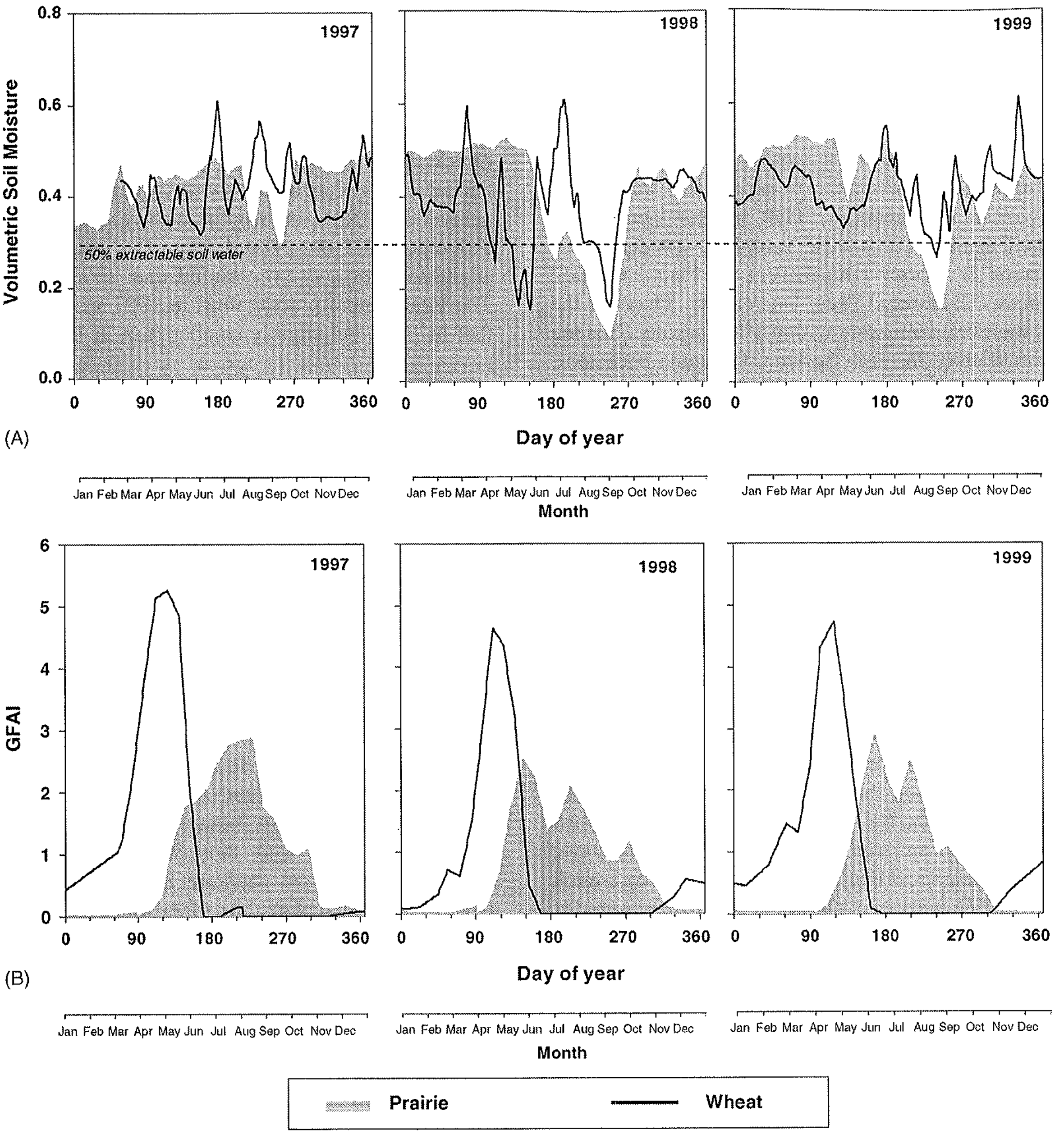

Fig. 1. (A) Volumetric moisture and (B) green foliage area index (GFAI) information at the prairie and wheat sites.

physiology (C_3, wheat; C_4, tallgrass prairie) and phenology. Wheat reached its peak green foliage area index (GFAI) of about 5 in May of each year, and rapidly senesced by early June. On the other hand, the prairie reached its peak GFAI of about 3 in August of 1997 (a year with no moisture stress), and senesced by late October. Moisture stressed periods in summer of 1998 and 1999 led to multiple peaks in GFAI and an earlier start of senescence.

3.3. Annual distributions of evapotranspiration in the two ecosystems

Fig. 2A and B shows the daily averaged values of equilibrium evapotranspiration, $ET_{eq} = s(Rn + G)/(s + \gamma)$ for 3 years at both study sites (e.g. Slatyer and McIlroy, 1961; s is the slope of the saturation vapor pressure–temperature curve and γ is the psychometric constant = 0.66 kPa °C^{-1}). On clear days, ET_{eq} ranged

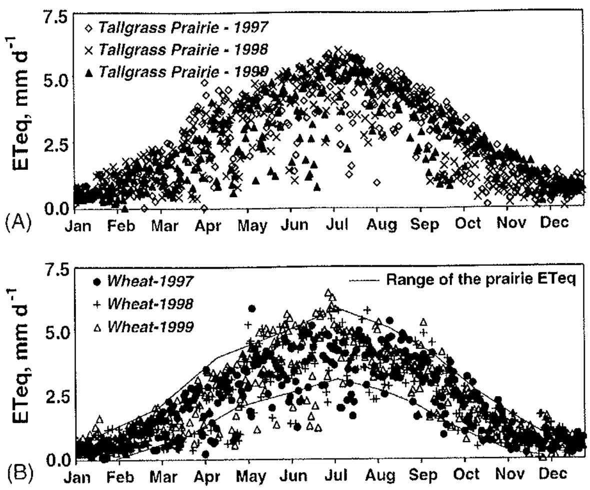

Fig. 2. Annual distributions of equilibrium evapotranspiration (ET_{eq}) at the prairie (A) and wheat sites (B). The solid curves in (B) represent the range of ET_{eq} from the prairie site.

from about 0.6 mm day^{-1} in winter to about 5 mm day^{-1} in mid-summer at both sites. With generally similar atmospheric conditions, as expected, ET_{eq} values were also quite similar in the 3 years of our study. In contrast, the actual ET values at the two sites were quite different (Fig. 3A–C). The differences in ET

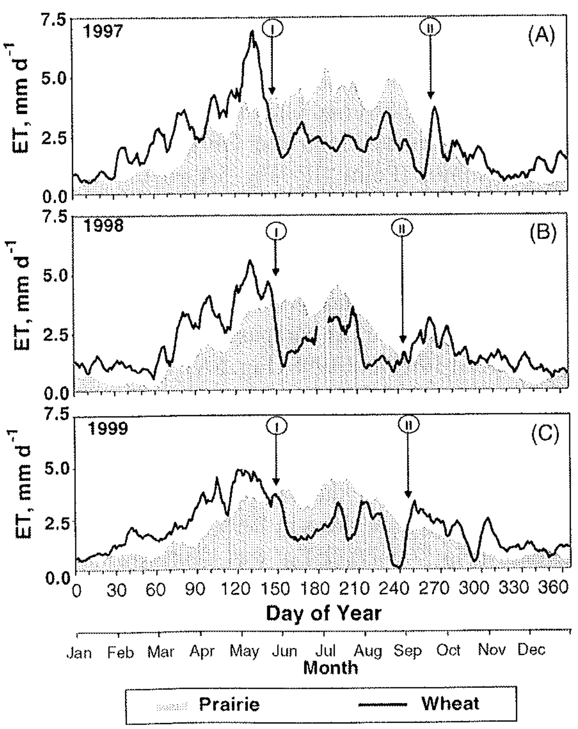

Fig. 3. Annual distributions of evapotranspiration (ET) at the prairie and wheat sites in: (A) 1997, (B) 1998, and (C) 1999. Points (I) and (II) are discussed in the text.

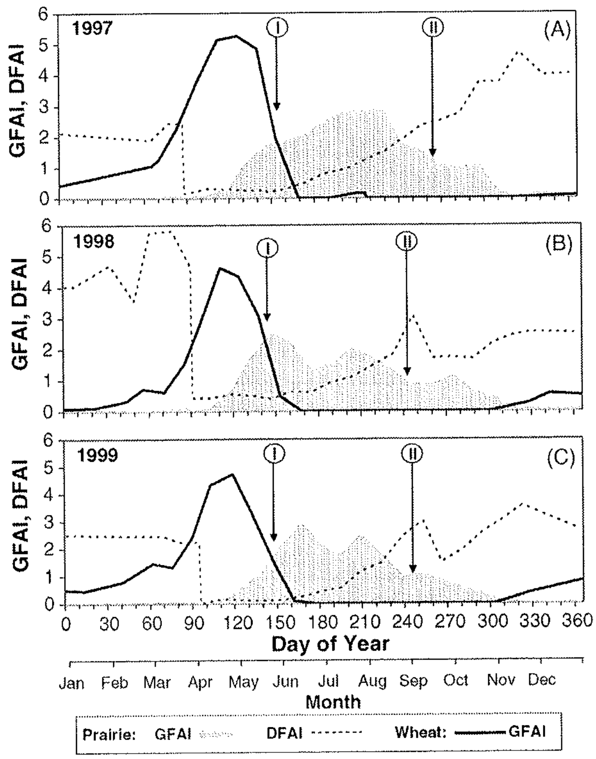

Fig. 4. Distributions of green foliage area index (GFAI) and dead foliage area index (DFAI) at the prairie and wheat sites in: (A) 1997, (B) 1998, and (C) 1999. Points (I) and (II) are discussed in the text.

of the two ecosystems in the 3 study years can be attributed primarily to the differences in vegetation growth and soil moisture conditions. ET at the wheat site was higher by 10–60% in all years from the beginning of the year until early June, as compared to the prairie. Later, the wheat ET was lower by 7–65% until mid-late September, and generally higher again for the remainder of the year. This feature was primarily related to the differences in vegetation phenology of the two ecosystems (Fig. 4A–C). Cool-season (C_3) wheat canopy developed much earlier in the year than the warm season (C_4) prairie. An examination of the seasonal distribution of ET and foliage area allows us to make two observations. First, during all 3 years, the prairie ET began to exceed the wheat ET in late May to early June (denoted by point "I" in Fig. 3) at the time when the prairie green foliage area index (GFAI) became larger than the wheat GFAI (denoted by point "I" in Fig. 4). Secondly, during early fall in all 3 years, the prairie ET became smaller than the evaporation from the bare wheat field (denoted by point "II" in Fig. 3) when the dead foliage area index (DFAI) at the prairie site was approximately twice the GFAI. This may have been related to the fact that, as the prairie

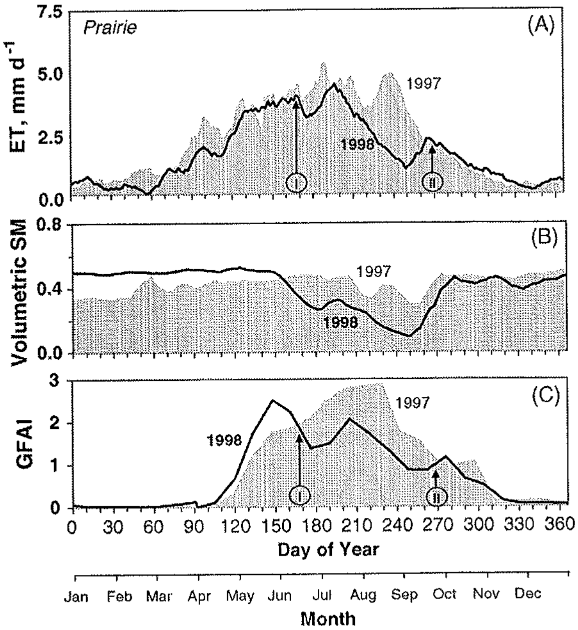

Fig. 5. (A) Prairie evapotranspiration, ET during 1997 and 1998, (B) volumetric soil moisture, and (C) green foliage area index (GFAI). Points (I) and (II) are discussed in the text.

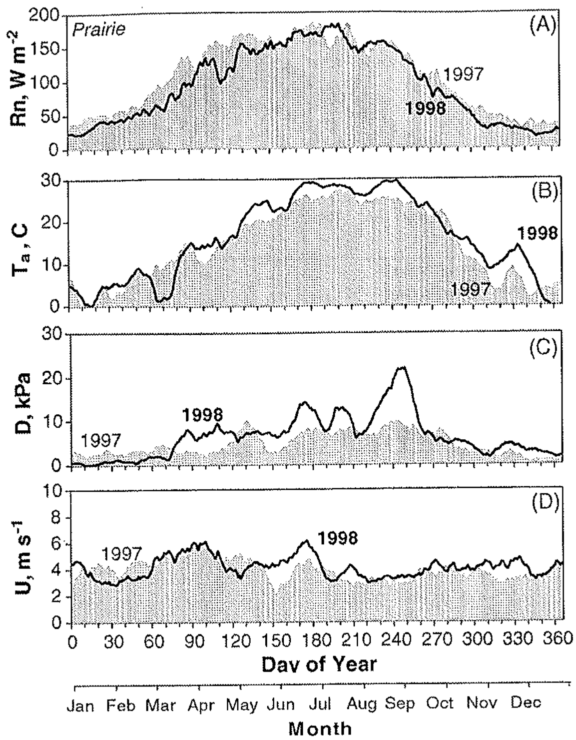

Fig. 6. Key weather parameters at the prairie site in 1997 and 1998: (A) net radiation, Rn, (B) air temperature, T_a, (C) vapor pressure deficit, D, and (D) wind speed, U.

transpiration decreased rapidly with the decreasing GFAI, the increasing dead stand provided substantial resistance to the radiative and water vapor exchange between the soil and the atmosphere. During the respective growing seasons the daily ET ranged from 3.5 to 5.0 mm day^{-1} for the prairie and from 2.5 to 7.0 mm day^{-1} for wheat.

3.4. Interannual variability in evapotranspiration

3.4.1. Prairie ET

To facilitate the discussion of the interannual variability in ET, the results from 2 years were compared at a time (1997 versus 1998; 1998 versus 1999). Weekly averaged evapotranspiration values for 1997 (ET_{97}) and 1998 (ET_{98}) at the prairie site are shown in Fig. 5A. During the first half of the year, differences in ET were relatively small: ET_{97} was generally a little larger than ET_{98}, mostly due to a larger Rn (Fig. 6A), with the exception of early January when colder temperatures in 1997 may have led to a slightly lower ET. During summer (DOY 170–270), ET_{98} was significantly lower (by about 3.3 mm day^{-1}) than ET_{97} (Fig. 5A), despite the higher evaporative demand in 1998 (higher air temperature, T_a; vapor pressure deficit, D; wind speed, U; Fig. 6). The ET differences were primarily related to a severe moisture stress experienced in 1998 resulting in reduced GFAI (Fig. 5C). The ET_{98} values became lower than ET_{97} immediately after GFAI in 1998 became lower than that in 1997 (denoted by point "I" in Fig. 5A and C). Differences between ET_{97} and ET_{98} diminished soon after GFAI from these 2 years became similar (Point "II", Fig. 5A and C) as a result of precipitation and associated increase in soil moisture.

Weekly averaged evapotranspiration values for 1998 (ET_{98}) and 1999 (ET_{99}) are presented in Fig. 7A. Differences of ET during these 2 years were smaller throughout the year, as compared to the differences in ET between 1997 and 1998 (Fig. 5A). In 1999, moisture stress occurred during July through September (Fig. 7B), reducing GFAI and leading to some decrease in ET_{99}. However, this decrease in ET was smaller than in 1998, because of the shorter duration and smaller severity of moisture stress in 1999 (Fig. 7B). During the autumn (Fig. 7A–D), ET_{99} was slightly smaller than ET_{98} in accordance with lower SM and GFAI (in spite of higher Rn).

The effect of moisture stress can be further examined via a relationship between the ET/Rn ratio and the soil moisture. When volumetric soil moisture was greater than 0.31 (the moisture stress threshold; 50% of the extractable soil water), it did not seem to noticeably affect the ET/Rn values (data not shown here). For such

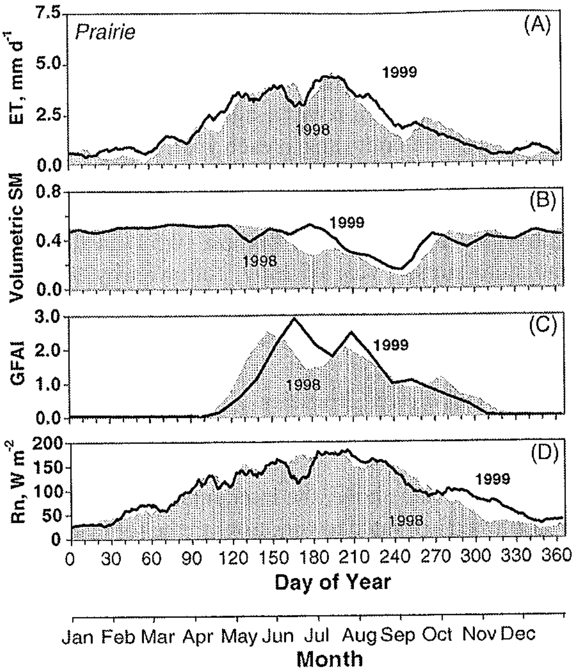

Fig. 7. (A) Prairie evapotranspiration, ET in 1998 and 1999, (B) volumetric soil moisture, (C) green foliage area index, GFAI, and (D) net radiation, Rn.

periods, GFAI was an important factor controlling the ET/Rn ratio in a near-linear relationship (Fig. 8A). However, during periods of soil moisture stress (volumetric soil moisture less than 0.31) in 1998 and 1999, the ET/Rn ratio was controlled by soil moisture. The relationship was near-logarithmic for all ranges of

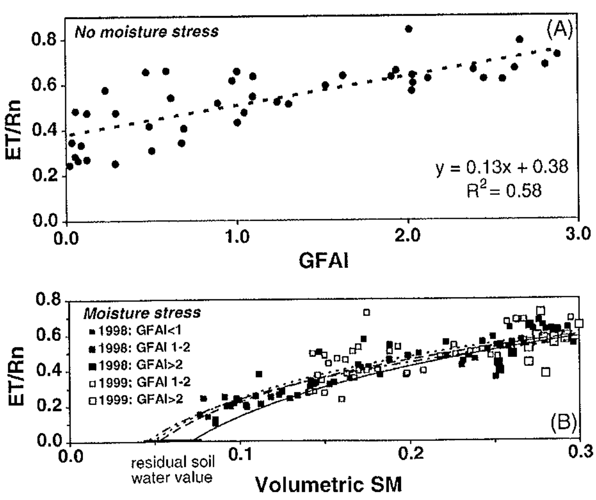

Fig. 8. Ratio of evapotranspiration to net radiation (Rn) at the prairie site in 1997–1999 as a function of: (A) green foliage area index (GFAI) for the period with no moisture stress, and (B) daily volumetric soil moisture (no curve was fitted for the moisture stress period in 1998 when GFAI > 2 because of insufficient data).

GFAI (Fig. 8B). The best fit ($r^2 = 0.73$) was obtained during the period with GFAI < 1 in 1998, followed by the period with GFAI of 1–2 ($r^2 = 0.62$ in 1998 and $r^2 = 0.51$ in 1999), and then by the period with GFAI > 2 in 1999 ($r^2 = 0.24$), perhaps indicating a decrease in the level of the control of the ET/Rn ratio by soil moisture for a "greener" canopy. The ET/Rn versus soil moisture relationship for both years extrapolated to the point of "residual soil moisture" (defined as the soil moisture level when evapotranspiration ceases: Smith and Diekkruger, 1992) value of 0.045–0.08 (Fig. 8). This is consistent with the value of the residual soil moisture of approximately 0.05–0.07 reported for a variety of soils in several ecosystems (e.g. Brooks and Corey, 1964; Vertessy and Elsenbeer, 1999).

3.4.2. Wheat ET

The interannual variability in ET of wheat was smaller than that of the prairie, primarily because of the absence of the moisture stress during its growing season (Fig. 9). In 1997 and 1998, GFAI seemed to have some effect on ET during the first half of the year: ET_{97} was generally larger than ET_{98} due to larger GFAI regardless of variations in soil moisture (Fig. 9A–C). After senescence, the effect of soil moisture became important: the largest difference in soil evaporation between 1997 and 1998 was observed during the moisture stress period in May and June (Fig. 9B). In 1998 and 1999, GFAI were similar and differences in ET were small throughout the year.

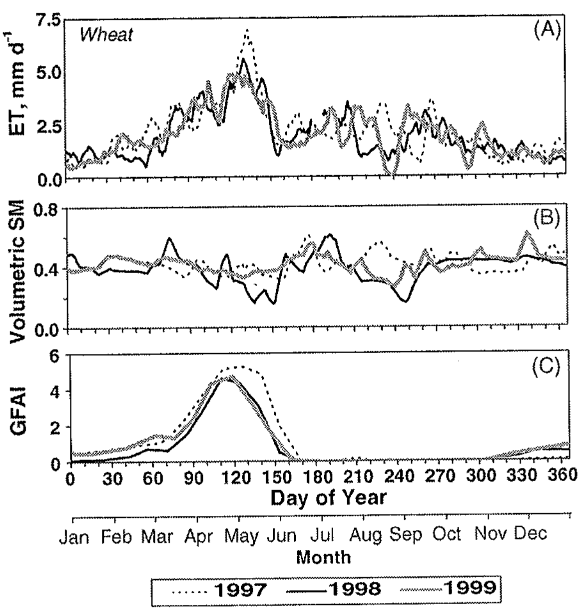

Fig. 9. (A) Evapotranspiration (ET) of wheat in 1997, 1998, and 1999, (B) volumetric soil moisture, and (C) green foliage area, GFAI.

3.5. Annually integrated evapotranspiration

The annually integrated evapotranspiration values at the prairie site were 807, 637, and 692 mm in 1997, 1998, and 1999, respectively (Table 2). At the wheat sites, the corresponding ET sums were 750, 714, and 742 mm. At the prairie site, the year (1997) with the highest ET had the smallest total precipitation. The distributions of precipitation (not the annual total) and soil moisture played a key role: in 1997, a large fraction of the total precipitation occurred during the summer (with the periods of high evaporative demand: high Rn, T_a, D), which resulted in no moisture stress, and promoted ET. In 1998 and 1999, however, more precipitation occurred during fall, winter, and spring, while the summer ET was reduced due to moisture stress. As a result, at the prairie site, the ratio of annual ET to precipitation was the highest (0.76) in 1997, and lower (0.53–0.57) in 1998 and 1999. Evapotranspiration during the "non-growing season" (November–April) was about 25% of the annual ET of the prairie.

At the wheat site, most of the water loss occurred in the spring (outside the summer period of high evaporative demand) when the GFAI was large. The wheat ET was 61, 59, and 55% of annual precipitation in 1997, 1998, and 1999, respectively. The annual ET at the wheat site was lower than that at the prairie site in the "non-moisture stress" year of 1997, and it was significantly higher than the prairie ET in the drier years of 1998 and 1999 (Table 2). The non-growing season (July–February) ET of wheat was about 50% of its annual ET. The significantly higher contribution of the non-growing season ET in wheat as compared to the prairie is likely related to its timing (a large portion of the non-growing period for winter wheat occurs during the summer months with high evaporative demand).

Evapotranspiration was a significant consumer of the solar energy at both sites in each year. At the wheat site, the portion of Rn consumed in ET was 0.54–0.58 (Table 2). At the prairie site, however, the portion of Rn consumed in ET was the highest (0.59) in the "non-moisture stress" year of 1997, followed by the "mild moisture stress year" of 1999 (0.52) and then by the "severe moisture stress" year of 1998 (0.49).

3.6. Modifying the Priestley–Taylor model of evapotranspiration

As discussed above, the interannual variability in ET was primarily related to variations in the foliage area and soil moisture conditions. Including these two factors can potentially improve weather-based models of evapotranspiration, such as the Priestley–Taylor model (1972). The Priestley–Taylor model, used for predicting evapotranspiration for well-watered conditions, employs atmospheric parameters to compute evapotranspiration as follows (Priestley and Taylor, 1972; Slatyer and McIlroy, 1961): $ET = \alpha ET_{eq} = \alpha s(Rn + G)/(s + \gamma)$, where ET is the actual evapotranspiration, ET_{eq} is the equilibrium evapotranspiration, and α is a coefficient. Based on the information from a range of "well-watered green canopies", Priestley and Taylor recommended 1.26 as the value of α, which has been used in many studies (e.g. Lhomme, 1988; McAneney and Itier, 1996; Bidlake, 2002). However, a growing number of recent studies report values of α different from 1.26 (Stannard,

Table 2
Annually integrated values of net radiation, evapotranspiration (latent heat flux), precipitation, and related information at the prairie and wheat sites

		1997	1998	1999
Prairie site				
Rn (net radiation)	MJ year^{-1}	3105	2952	3017
ET (evapotranspiration)	MJ year^{-1}	1824	1440	1564
	mm year^{-1}	807	637	692
Growing season (May–October)	mm	610	486	496
Precipitation	mm year^{-1}	1104	1193	1213
ET as a percentage of precipitation (%)		73	53	57
ET as a percentage of Rn (%)		59	49	52
Wheat Site				
Rn (net radiation)	MJ year^{-1}	3143	2869	2878
ET (evapotranspiration)	MJ year^{-1}	1694	1614	1677
	mm year^{-1}	750	714	742
Growing season (March–June)	mm	409	360	357
Precipitation	mm year^{-1}	1231	1202	1342
ET as a percentage of precipitation (%)		61	59	55
ET as a percentage of Rn (%)		54	56	58

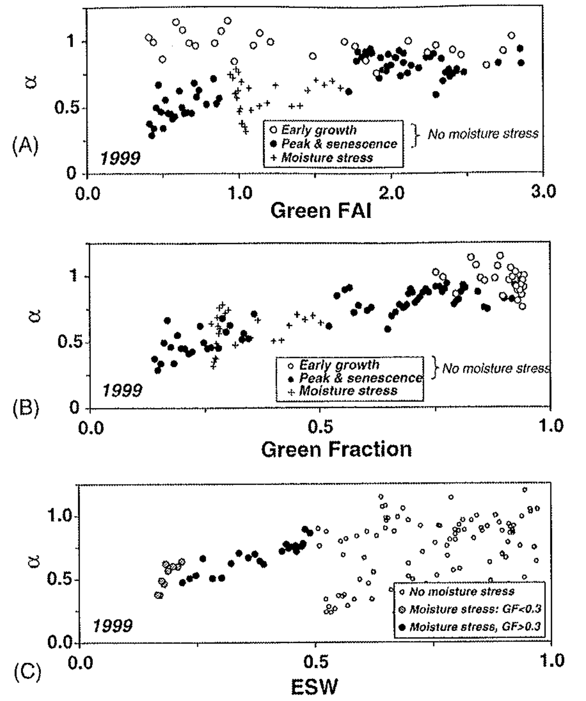

Fig. 10. Relationship between the Priestley–Taylor coefficient α and: (A) green foliage area index, GFAI, (B) green fraction, GF, and (C) extractable soil water, ESW at the prairie site in 1999.

1993; Baldocchi, 1994; Pereira, 2004), likely due to the effects of canopy and soil moisture conditions.

Therefore, we attempted a modification in the Priestley–Taylor model to account for variations in foliage area and soil moisture. This modification was first developed using our data in 1999 (a year with "mid-range" soil moisture and weather conditions among the 3 years studied) at the prairie site, and then tested during other years at the prairie site and during all years at the wheat site. Fig. 10A demonstrates the relationship between the Priestley–Taylor α (calculated by applying Priestley–Taylor equation to our measurements) and GFAI during the growing season in 1999 at the prairie site. In general, α increased from 0.25 to 1.1 with increasing GFAI in periods of no moisture stress during peak growth and senescence. However, during early growth, α ranged between 0.78 and 1.23, and did not seem to depend on GFAI. Also, during periods of moisture stress, α was not closely related to GFAI. The value of α in 1999 was below the conventional value of 1.26, as also observed by Kristensen and Jensen (1975) for early and peak growth in barley, sugar beets, and grass.

The value of α is influenced not only by the green foliage area (which promotes transpiration), but by the dead foliage area as well (which provides a physical barrier to evaporation). To account for these effects, a variable called the "green fraction", GF (GF = GFAI/TFAI, where TFAI is the total foliage area) is considered here: α plotted versus GF (Fig. 10B) displayed a better relationship as compared to the data in Fig. 10A. With increasing GF, the value of α increased non-linearly, reaching a value of 1.23 for the fully green canopy (GF = 1). Data during the early growth and moisture stress periods seemed to fit well within the overall relationship between α and GF. For active green canopies or GF = 1, α is expected to be around 1.26 (e.g. Davis and Allen, 1973; Jury and Tanner, 1975; Stewart and Rose, 1977). Also α should be near zero for the dead canopy (GF = 0). So, a power relationship was assumed to account for variations in GF (for conditions of no moisture stress):

$$\alpha_{GF} = 1.26(\mathrm{GF})^{b}, \qquad (1)$$

where α_{GF} is the Priestley–Taylor α adjusted for the green fraction (GF) and b is a variable parameter.

Coefficient α at the prairie site is plotted against the extractable soil water (ESW: top 0.9 m of the soil; Fig. 10C). In the absence of moisture stress, α does not show any clear relationship to ESW and is primarily related to GF (Fig. 10B). However, in the presence of moisture stress (ESW $\leq$ 0.5), a decrease in ESW seems to lead to a decrease in the value of α for all GF. As was

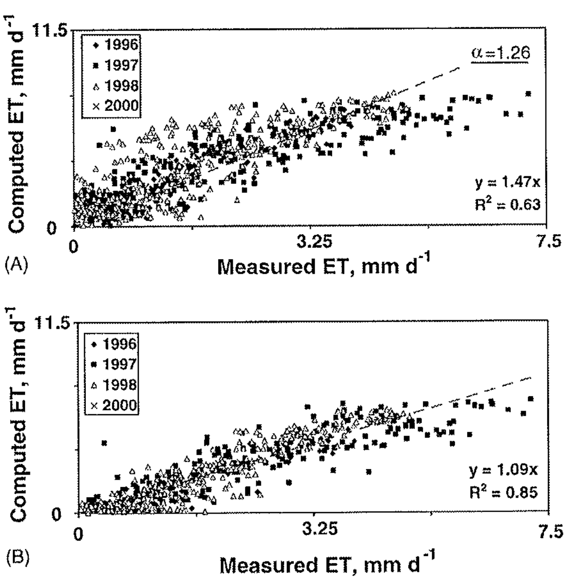

Fig. 11. Daily evapotranspiration at the prairie site computed using the Priestley–Taylor model with: (A) conventional α = 1.26 and (B) α adjusted for green fraction and extractable soil water for 1996, 1997, 1998, and 2000. Data from year 1999 were used to develop the adjustment for α, and are excluded here.

Table 3
Comparison of the slope, root mean square error (RMSE), and r^2 of the evapotranspiration values calculated using the Priestley–Taylor model with conventional $\alpha = 1.26$, and with α adjusted for green fraction and extractable soil water for: (A) the prairie site and (B) wheat site; d is the slope of the linear relationship between the computed ET and measured ET

Year	ET with $\alpha = 1.26$			ET with adjusted α		
	Slope, d	r^2	RMSE (mm day^{-1})	Slope, d	r^2	RMSE (mm day^{-1})
A						
1997	1.53	0.84	1.5	0.96	0.85	0.9
1998	1.30	0.66	2.0	1.02	0.80	0.8
1999	1.64	0.62	1.6	1.15	0.87	0.8
Total	1.47	0.63	1.7	1.09	0.85	0.8
B						
1997	1.14	0.23	1.7	1.05	0.62	1.0
1998	1.21	0.11	1.8	0.83	0.21	1.2
1999	1.36	0.20	2.0	1.20	0.66	1.1
Total	1.20	0.24	1.8	1.04	0.53	1.1

Only complete years of data are presented for proper comparison.

done in Eq. (1), applying logical constraints (e.g. $\alpha = 1.26$ at ESW = 1 and $\alpha = 0$ at ESW = 0) leads to a relationship of the following type:

$$\alpha_{\mathrm{ESW}} = 1.26(\mathrm{ESW})^c, \quad (2)$$

where α_{ESW} is the Priestley–Taylor α adjusted for extractable soil water (ESW) and c is a variable parameter. Similar types of non-linear relationships were observed by Crago and Brutsaert (1996) for Konza prairie and by Flint and Childs (1991) for a forest clear-cut in Oregon.

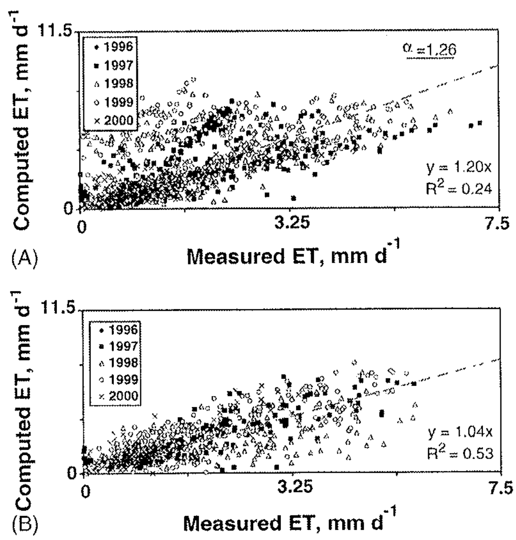

Fig. 12. Daily evapotranspiration at the wheat site computed using the Priestley–Taylor model with: (A) conventional $\alpha = 1.26$ and (B) α adjusted for the green fraction and extractable soil water for 1996–2000.

As indicated above, this modification to the Priestley–Taylor model (Eqs. (1) and (2)) was calibrated using 1 year (1999) of data from the prairie site. Eq. (1) was used under non-limiting moisture conditions (ESW > 0.5: the canopy green fraction becomes the primary influence), and Eq. (2) was used under conditions of moisture stress (ESW $\leq$ 0.5: the influence of ESW dominates). Applying Eqs. (1) and (2) to the 1999 data from the prairie site yielded $b = 0.5$ and $c = 0.5$. Performance of the adjusted α for other years at the prairie site is shown in Fig. 11 and in Table 3. For 1997, 1998, and parts of 1996 and 2000, using the conventional value of $\alpha = 1.26$ (the original Priestley–Taylor model) at the prairie site led to an overestimation of the actual ET by about 47%. In contrast, the use of the modified model improved the prediction significantly (the overestimation reduced from 47 to 9%; the RMSE reduced by about a factor of 2, and the r^2 increased from 0.63 to 0.85). Considerable improvement was also observed at the wheat site (Fig. 12, Table 3B).

4. Summary and conclusions

A micrometeorological study was conducted in two ecosystems (tallgrass prairie and winter wheat) in the north-central Oklahoma during 1996–2000. The annual ET of the tallgrass prairie ranged between 637 and 807 mm. The distribution of precipitation (not the total annual precipitation) played a crucial role in determining the annual ET. The ratio of annual ET to annual precipitation ranged from 0.53 to 0.73.

The annual ET of winter wheat was between 714 and 750 mm. The annual wheat ET was lower than the prairie ET during 1997 (a year with no moisture stress). However, the annual ET in wheat during the drought years was significantly higher than in the prairie (714 versus 637 in 1998 and 742 versus 692 in 1999). The ratio of annual ET to precipitation ranged between 0.55 and 0.64.

In the prairie, the fraction of the net radiation consumed in evapotranspiration was highest (0.59) in 1997 (a year with no moisture stress), followed by the "mild moisture stress" year of 1999 (0.52) and the "severe moisture stress" year of 1998 (0.49). In wheat, the fraction was 0.53–0.58 in all years.

Overall, at both sites, the inter-annual variability in ET in 1997, 1998, and 1999 could be primarily explained by the variations in soil moisture and vegetation growth. The Priestley–Taylor model of ET was modified to include such effects (varying soil moisture and foliage area). Substantial improvement in predicting ET, for a wide range of conditions, was achieved as a result of the modification.

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