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SURFACE ENERGY BALANCE, EVAPOTRANSPIRATION, AND SURFACE COEFFICIENTS DURING NON-GROWING SEASON IN A MAIZE-SOYBEAN CROPPING SYSTEM

L. O. Odhiambo, S. Irmak

ABSTRACT. Surface energy balance components, including actual evapotranspiration (ET), were measured in a reduced-till maize-soybean field in south central Nebraska during three consecutive non-growing seasons (2006/2007, 2007/2008, and 2008/2009). The relative fractions of the energy balance components were compared across the non-growing seasons, and surface coefficients (K_c) were determined as a ratio of measured ET to estimated alfalfa (ET_r) and grass (ET_o) reference ET (ET_{ref}). The non-growing season following a maize crop had 25% to 35% more field surface covered with crop residue as compared to the non-growing seasons following soybean crops. Net radiation (R_n) was the dominant surface energy balance component, and its partitioning as latent heat (LE), sensible heat (H), and soil heat (G) fluxes depended on field surface and atmospheric conditions. No significant differences in magnitude, trend, and distribution of the surface energy balance components were observed between the seasons with maize or soybean surface residue cover. The cumulative ET was 196, 221, and 226 mm during the three consecutive non-growing seasons. Compared to ET_{ref} , the cumulative total measured ET was 61%, 63%, and 59% of cumulative total ET_o and 43%, 46%, and 41% of cumulative total ET_r during the three consecutive seasons. The type of residue on the field surface had no significant effect on the magnitude of ET. Thus, ET was primarily driven by atmospheric conditions rather than surface characteristics. The coefficient of determination (R^2) for the daily ET vs. ET_r data during the three consecutive non-growing seasons was only 0.23, 0.42, and 0.42, and R^2 for ET vs. ET_o was 0.29, 0.46, and 0.45, respectively. Daily and monthly average K_c values varied substantially from day to day and from month to month, and exhibited interannual variability as well. Thus, no single K_c value can be used as a good representation of the surface coefficient for accurate prediction of ET for part or all of the non-growing season. A good relationship was observed between monthly total measured ET vs. monthly total ET_{ref} . The R^2 values for monthly total ET vs. monthly total ET_{ref} data ranged from 0.71 to 0.89 for both ET_r and ET_o . Using pooled data for monthly total ET vs. monthly total ET_{ref} , R^2 was 0.78 for ET_r and 0.80 for ET_o . The slopes (S) of the best-fit line with intercept for the monthly total ET vs. monthly total ET_{ref} data were consistent for all three non-growing seasons, with $S = 0.45 \pm 0.05$ for ET_r and $S = 0.62 \pm 0.08$ for ET_o . The parity in R^2 and S across the three non-growing seasons suggests that the same regression equation can be used to approximate non-growing season ET for field surfaces with both maize and soybean crop residue covers. Considering the extreme difficulties in measuring ET during winter in cold and windy climates with frozen and/or snow-covered conditions, the approach using a linear relationship between monthly total ET vs. monthly total ET_{ref} appears to be a good alternative to using a surface coefficient to approximate non-growing season monthly total ET. The conclusions of this research are based on the typical dormant season conditions observed at the research location and may not be generally transferable to other locations with different climatic and surface conditions.

Keywords. Dormant season, Evapotranspiration, Non-growing season, Reference evapotranspiration, Surface coefficient, Surface energy balance.

In the Midwestern U.S., maize (*Zea mays* L.) and soybean (*Glycine max* (L.) Merrell) are the predominant crops mostly grown in rotation. In this region, the non-

growing season, also referred to as the dormant period, is the period during which no maize or soybean crop is planted in the fields due to cold winter temperatures. The non-growing season occurs between the first killing frost of autumn and the last killing frost of spring (October to April). The field surface conditions during this period are characterized by the presence of plant residue, periods of frost and frozen conditions, cessation of active plant growth, and periods of snow and/or ice cover. The field surface conditions during the non-growing season have the potential to affect the magnitude of individual components of the surface energy balance, including actual evapotranspiration (ET). The total amount of incoming solar radiation during this period of the year (October to April) is substantially reduced due to the large solar zenith angles and

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short day lengths, which can impact the surface energy balance and residue cover interactions. Horton et al. (1996) provide a comprehensive review of how crop residue on the soil surface affects components of the surface energy balance. The shortwave reflectivity (α) of light-colored residue is considerably greater than that of a dark-colored soil surface, thereby reducing the amount of solar radiation that becomes available at the soil surface for ET [i.e., latent heat (LE)], sensible heat (H), or soil heat (G) fluxes (Aase and Tanaka, 1991; Hares and Novak, 1992; Bristow, 1988; Horton et al., 1994; Bussiere and Cellier, 1994; Sauer et al., 1997, 1998a). Residue on the soil surface also blocks the incoming radiation that would otherwise reach the soil and affects vapor transfer and loss of heat by conduction, convection, and evaporation (Horton et al., 1994; Steiner, 1994). Sauer et al. (1998b) measured all surface energy balance components of a maize residue-covered field during the non-growing season on snow-free days. They found that on overcast days with a dry surface 42% to 75% of the available energy was consumed by LE , and on continuous sunny days with a dry surface less than 21% of the available energy was partitioned into LE . Sauer et al. (1998a) found that on wet surfaces during snow-free periods, less energy was partitioned into LE on sunny days than on overcast days (<19% on sunny days vs. >38% on overcast days). Snow cover with its high α also reduces the amount of solar radiation that becomes available at the soil surface for LE or G . Sauer (1998a) measured the surface energy balance of a maize residue-covered field during melting of the snow cover. They found that the net radiation and snowmelt/storage terms dominated the energy balance during the snowmelt period, and peak LE and G fluxes were below 100 W m^{-2} .

During the non-growing season, ET occurs predominantly by evaporation from exposed soil surfaces, intercepted water by crop residue, and from snow and/or ice cover. Total non-growing season ET can be relatively small as compared to the yearly water balance, but knowledge of the ET processes during the dormant period is necessary for developing strategies for conserving water in the soil and root zone, and for estimating the effectiveness of non-growing season precipitation in recharging the soil water storage for the subsequent growing season. Furthermore, quantifying ET losses during non-growing season and determining how ET impacts surface runoff and groundwater recharge which is essential for modeling the hydrologic water balance and also for better understanding of the transport process of agricultural chemicals that may occur during the non-growing season. Lewan (1993) measured ET from bare soil and cover crop surfaces during winter in southwestern Sweden and found no difference in ET between bare soil and cover crop surfaces. Lewan (1993) also found that total ET during the non-growing season was 75% of winter precipitation. Hatfield et al. (1996) measured ET over three fields with different crop covers during winter in central Iowa using a Bowen ratio system. They found that daily ET ranged from less than 1 mm d^{-1} to over 3 mm d^{-1} , and the evaporative fraction ranged from 40% to 90%. Prueger et al. (1998) conducted a three-year study in central

Iowa to evaluate the partitioning of available energy to ET during the non-growing season by measuring micrometeorological parameters used for estimating surface energy balance components. They found that energy partitioning at the surface over rye, oats, and bare soil during the non-growing period is driven by climate, snow, residue cover, and available energy. They also observed that seasonal ET totals from mid-October through late February ranged from 118 to 205 mm for the three-year study. In a more recent study, Hay and Irmak (2009) evaluated non-growing season evaporative losses in relation to available energy and precipitation of a maize residue-covered subsurface drip-irrigated field as part of the Nebraska Water and Energy Flux Measurement, Modeling, and Research Network (NEBFLUX; Irmak, 2010). They measured the evaporative losses using a Bowen ratio energy balance system (BREBS) on an hourly basis and averaged over 24 h for three consecutive non-growing periods. They found that ET was about 50% of the available energy for wet seasons and about 41% of the available energy for dry seasons. Seasonal cumulative ET ranged from 133 to 167 mm and exceeded precipitation by 21% during the dry season. The ratios of ET to precipitation were 0.85, 1.21, and 0.41 during the three consecutive years. ET was approximately 50% of ET_o and 36% of ET_r in both the first and second year, whereas ET was 32% of ET_o and 23% of ET_r in the third year. Overall, measured ET during the dormant season was generally most strongly correlated with radiation terms, particularly R_n , surface albedo, incoming shortwave radiation, and outgoing longwave radiation. Suyker and Verma (2009) evaluated the contributions of non-growing season ET to annual ET totals. They found that non-growing season ET ranged from 100 to 172 mm and contributed 16% to 28% of the annual ET in irrigated/rainfed maize and 24% to 26% in irrigated/rainfed soybean. They found that the amount of crop residue on the soil surface explained 71% of the variability in non-growing season ET totals.

A major drawback in determining ET during the non-growing season is the lack of robust surface coefficients (K_c), which could be used to predict ET from calculated reference (potential) evapotranspiration (ET_{ref}) (i.e., $ET = K_c \times ET_{ref}$). Because estimating ET during the non-growing season is characterized by non-crop surface conditions, the coefficient might be more appropriately referred to as a "surface" coefficient rather than "crop" coefficient; however, the usage and application would be the same. Crop coefficients (K_c) developed for the growing season cannot be used to estimate ET during the non-growing season due to the field surface conditions, which are significantly different from the field surface during the growing season. Very few studies have been conducted to determine K_c values for the non-growing season. Wright (1991, 1993) conducted a series of wintertime measurements of ET using the dual precision weighing lysimeter systems at Kimberly, Idaho. The lysimeter measurement surfaces included clipped fescue grass and bare soil conditions of disked wheat stubble, disked alfalfa, disked bare soil, dormant alfalfa, and winter wheat. Wright (1991) found that the K_c for an alfalfa-reference surface based on the ASCE standardized Penman-Monteith equation (ASCE, 2005) rarely reached 1.0

during winter. However, the mean K_c approached or exceeded 0.80 for periods having nearly continuous distributions of precipitation. Hay and Irmak (2009) measured average surface coefficients over the three seasons as 0.44 and 0.33 for grass- and alfalfa-reference surfaces, respectively. Using geometric mean K_c values to calculate ET using a $K_c \cdot ET_{ref}$ approach over the entire non-growing season yielded adequate predictions, with overall root mean square deviations of 0.64 and 0.67 mm d⁻¹ for ET_o and ET_r , respectively. Estimates of ET using a dual crop coefficient approach were good on a seasonal basis but performed less well on a daily basis.

While the aforementioned studies provide important information on surface energy balance, ET, and surface coefficients during the non-growing season in agricultural fields, there is a need for more research on fields with different surface conditions due to the great diversity in cropping patterns, climatic and soil conditions, and management practices. The objective of this research was to measure and compare the surface energy balance components and evapotranspiration in a ridge-tilled maize-soybean rotation field during three consecutive non-growing seasons, and also to determine how the magnitudes of individual energy balance components and ET change during the period. Non-growing season K_c values were determined from the relationships between the measured ET and estimated ET_{ref} .

MATERIALS AND METHODS

STUDY SITE

Field measurements for this research were conducted on a 14.5 ha subsurface drip irrigation (SDI) field located at the University of Nebraska-Lincoln/Institute of Agriculture and Natural Resources, South Central Agricultural Laboratory near Clay Center, Nebraska (40° 34' N, 98° 8' W, 552 m above mean sea level). The climate of the area is sub-humid with warm and dry summers and very cold and windy winters with average temperatures usually below 0°C. The warmest month of the year is usually July with an average maximum temperature of 30°C, while the coldest month of the year is January with an average minimum air temperature of -10°C. The annual average precipitation is about 700 mm. Rainfall is not evenly distributed throughout the year. The wettest month of the year is usually May with an average rainfall of 120 mm. The soil in the research field is classified as Hastings silt loam, which is well drained soil with a 0.5% slope. The particle size distribution is 15% sand, 62.5% silt, and 20% clay with 2.5% organic matter content. The soil field capacity (θ_{fc}) is 0.34 m³ m⁻³, the permanent wilting point (θ_{wp}) is 0.14 m³ m⁻³, and the saturation point (θ_{sat}) is 0.51 m³ m⁻³. In 2007, the field was planted with soybean after a maize crop the previous year; in 2008, the field was again planted with soybean. The field was under ridge tillage with crop residue evenly spread on the soil surface after harvest (Irmak, 2010).

ESTIMATING SURFACE RESIDUE COVER

Several methods are accepted for estimating the amount

of crop residue on the soil surface (Morrison et al., 1993). They include the line-transect method, photo-comparison method, remote sensing methods, and calculation methods based on measured grain yield. Generally, researchers have observed that the amount of crop residue can be estimated from measured grain yield. For example linear relationships between the amount of crop residue and grain yield have been reported for small grains (McCool et al., 2006) and corn (Linden et al., 2000), such that grain yield has been used to predict residue yield (Johnson et al., 2006). In this research, the percentage of the field surface covered with crop residue was estimated using a procedure based on the relationship between measured crop yield, crop residues produced, and residue decay over winter (Odhambo and Irmak, 2012). Wortmann et al. (2008) approximated that 1 ton of residue (at 10% moisture) is produced with 1.02 ton of maize grain yield and 0.82 ton of soybean. The amount of crop residue left on the soil surface after winter weathering was determined from tables of typical percent residue remaining after winter weathering developed by Shelton et al. (2000). The residue remaining on the soil surface during the 2006/2007 non-growing season was from a maize crop harvested in October 2006. The yield of the 2006 maize crop was 11.6 ton ha⁻¹, and the amount of residue produced at harvest was estimated at 11.4 ton ha⁻¹. About 90% of maize residue remains after winter weathering (Shelton et al., 2000). The residue remaining on the surface during the 2007/2008 and 2008/2009 non-growing seasons was from soybean crops that were harvested in October 2007 and October 2008. The yield of the 2007 soybean crop was 4.7 ton ha⁻¹ (Irmak et al., 2014), and the amount of residue produced at harvest was estimated at 5.7 ton ha⁻¹. The yield of the 2008 soybean crop was 4.9 ton ha⁻¹ (Irmak et al., 2014), and the amount of residue produced at harvest was estimated at 6.0 ton ha⁻¹. About 75% of soybean residues remain after winter weathering (Shelton et al., 2000). The fraction of the soil surface covered with crop residue (C_r) was estimated as a function of the mass of residue (Gregory, 1982), which is expressed as:

$$C_r = 1 - \exp(-A_m M) \quad (1)$$

where M is total residue mass (ton ha⁻¹), and A_m is an empirical parameter that converts mass to an equivalent area and varies with residue characteristics and randomness of distribution. Reported values of A_m for maize and soybean are 0.32 and 0.20, respectively (Gregory, 1982).

SURFACE ENERGY BALANCE COMPONENTS

The energy balance components at the field surface were measured using a BREBS (Radiation and Energy Balance Systems, REBS, Inc., Bellevue, Wash.), which was installed inside the field. The BREBS has been used extensively and successfully to determine ET above various vegetation surfaces, yielding ET values that compare well with data from other techniques (Lafleur and Rouse, 1990; McGinn and King 1990; Ham et al. 1991; Kjølgaard et al. 1994; Verma et al. 1976; Bausch and Bernard 1992; Irmak 2010). The energy balance equation is written as:

$$R_n = LE + H + G + Q \quad (2)$$

where R_n is net radiation (positive downward), LE is latent heat flux (positive upward), H is sensible heat flux (positive upward), G is soil heat flux (positive downward), and Q is the residual of the closure of the energy balance. The energy fluxes are expressed in $W\ m^{-2}$. In the following sections, each term in the energy balance equation is described, showing the measurement equipment and parameters that were measured or calculated.

Net Radiation at Field Surface

Net radiation (R_n) is the difference between incoming total hemispherical radiation and outgoing total hemispherical radiation. R_n was measured directly using a Q*7.1 net radiometer, manufactured by Radiation and Energy Balance Systems (REBS). Frequent care and maintenance were used to ensure that the radiometer was level and that the transparent polyethylene shields on the net radiometer did not become less translucent due to UV radiation as a result of aging or scouring from wind-driven particles.

Soil Heat Flux and Soil Temperature

Soil heat flux (G) is the heat transferred from the surface downward via conduction to warm the subsurface. A temperature gradient must exist between the surface and the subsurface for heat transfer to occur. G was measured using three REBS HFT-3.1 heat flux plates installed in the soil below the net radiometer at a depth of 0.05 to 0.06 m below the soil surface. In close proximity to each heat flux plate, soil thermocouple probes (REBS STP-1) were installed 0.05 to 0.06 m below the soil surface to measure the temporal change in temperature of the soil layer above the HFT-3. The G measurements were adjusted for soil temperature and moisture as measured by three REBS SMP1 R soil moisture probes installed in the same location as the soil temperature sensors and soil heat flux plates (Irmak, 2010).

Sensible and Latent Heat Fluxes

Sensible heat flux (H) above a field surface is the heat energy transferred between the surface and air when there is a temperature gradient between the surface and the air above. Latent heat flux (LE) at the field surface is the quantity of heat absorbed or released by water undergoing a change of state, such as ice changing to water or water to vapor (evaporation), at constant air temperature and pressure. Both H and LE were determined from measured R_n , G , and air temperature (T) and specific humidity (q) gradients at two levels. T and q were measured using two platinum resistance thermometers and monolithic capacitive humidity sensors (REBS models THP04015 and THP04016, respectively) with resolutions of $0.0055^\circ C$ for temperature and 0.033% for relative humidity. The BREBS used an automatic exchange mechanism that physically exchanged the air temperature (T) and relative humidity (q) sensors at two heights above the canopy every 15 min. The lower exchanger sensors level was raised to a height of 2 m above the field surface, and the distance between the upper and lower exchanger sensors level was kept at 1 m throughout the non-growing season. Using the classical equations of the turbulent diffusion of heat and water, and assuming that the transfer coefficients of heat and water vapor are equal, Bowen (1926) and Tanner (1960) showed that:

$$\beta = \frac{c_p \Delta T}{\lambda \Delta q} \quad (3)$$

where β is Bowen ratio, c_p is specific heat of air for constant pressure, λ is latent heat of vaporization of water, q is specific humidity, ΔT is the gradient of air temperature at the two levels of measurement, and Δq is the gradient of specific humidity at the two levels of measurement. H and LE are then estimated from:

$$H = \frac{\beta}{1+\beta}(R_n - G) \quad (4)$$

$$LE = \frac{1}{1+\beta}(R_n + G) \quad (5)$$

The BREBS and other datasets used in this research are part of the Nebraska Water and Energy Flux Measurement, Modeling, and Research Network (NEBFLUX; Irmak, 2010) that operates eleven BREBS and eddy covariance systems over various vegetation surfaces. Detailed description of the microclimate measurements, including LE , H , G , R_n , and other microclimatic variables (e , T , q , wind speed (u), α , and soil temperature) are presented in Irmak (2010).

REFERENCE (POTENTIAL) EVAPOTRANSPIRATION DURING NON-GROWING SEASON

The reference surface during the non-growing season in winter is characterized by a vegetative cover (grass or alfalfa) that changes from active growth to dormant or dead vegetative cover, snow cover, and freezing soil conditions. As the winter period nears the end, snowmelt increases the soil moisture, the soil warms up, and the vegetative cover begins to become active again. This reference surface condition during the non-growing season bears a stark contrast with the standardized hypothetical reference for calculating ET_{ref} , which consists of a surface of green, well-watered grass (or alfalfa) of uniform height, actively growing and completely shading the ground. While it is recognized that ET_{ref} equations do not represent measurable quantities of ET from reference surfaces during most of the non-growing season, the calculated ET_{ref} may be useful as an evaporative index and was used in this research to calculate non-growing season surface coefficients. The weather data needed for calculating ET_{ref} were collected at a weather station about 500 m from the research field. The weather station was maintained on natural grass cover without irrigation but somewhat meeting the reference condition criteria. The ASCE Committee on Evapotranspiration in Irrigation and Hydrology recommended that two crops be adopted as approximations for ET_{ref} (ASCE, 2005). The symbols and definitions given are: $ET_o = ET_{ref}$ for a short crop having an approximate height of 0.12 m (similar to grass), and $ET_r = ET_{ref}$ for a tall crop having an approximate height of 0.50 m (similar to alfalfa). Grass-reference (potential) evapotranspiration (ET_o) and alfalfa-reference evapotranspiration (ET_r) were calculated using the Penman-Monteith equation (Monteith, 1965) with a fixed canopy resistance (ASCE, 2005):

$$ET_{ref} = \frac{0.408\Delta(R_n - G) + \gamma \frac{C_n}{T + 273}(e_s - e_a)u_2}{\Delta + \gamma(1 + C_d u_2)} \quad (6)$$

where Δ is the slope of the saturation vapor pressure at mean air temperature curve ($\text{kPa } ^\circ\text{C}^{-1}$), R_n and G are the net radiation and soil heat flux density ($\text{MJ m}^{-2} \text{d}^{-1}$ for daily data or $\text{MJ m}^{-2} \text{h}^{-1}$ for hourly data), γ is the psychrometric constant ($\text{kPa } ^\circ\text{C}^{-1}$), T is daily or hourly mean temperature ($^\circ\text{C}$), u_2 is the mean wind speed at 2 m height (m s^{-1}), and $e_s - e_a$ is the vapor pressure deficit (kPa). The coefficients in the numerator (C_n) and the denominator (C_d) are given specific values depending on the calculation time step and the reference crop. The output units from equation 4 are in mm d^{-1} for the daily time step and in mm h^{-1} for the hourly time step. For the daily data, R_n is input in $\text{MJ m}^{-2} \text{d}^{-1}$ and G is assumed to be zero. For the hourly calculations, G is assumed equal to 10% of R_n when $R_n \geq 0$, and G is assumed equal to 50% of R_n when $R_n < 0$. The coefficients used in the ET_{ref} equation were $C_n = 900$ and $C_d = 0.34$ for ET_o and $C_n = 1600$ and $C_d = 0.38$ for ET_r . In this research, ET_{ref} was calculated based on an hourly time step and then summed to daily values.

CALCULATION OF SURFACE COEFFICIENTS DURING NON-GROWING SEASON

Crop or surface coefficients (K_c) are generally defined as empirical ratios of ET to ET_{ref} (Wright, 1981):

$$K_c = ET / ET_{ref} \quad (7)$$

where K_c is a dimensionless surface coefficient for a particular field surface and soil moisture condition, ET is actual evapotranspiration from the field surface, and ET_{ref} is reference evapotranspiration. ET during the non-growing season is predominantly in the form of evaporation from the field surface and includes evaporation from soil profile and residue surfaces, and sublimation from ice and snow surfaces. K_c calculated using $ET_{ref} = ET_r$ and $ET_{ref} = ET_o$ are denoted by K_{cr} and K_{co} , respectively, and are considered to represent surface coefficients. The dual K_c method (Wright, 1981) divides the K_c value into a “basal” crop coefficient (K_{cb}) representing crop transpiration plus evaporation from the soil surface by diffusive evaporation, and an “evaporation” coefficient (K_e) representing evaporation from the soil surface. This method would not bring significant improvement to the estimated K_c values for a non-growing season with no crops on the field, as K_{cb} tends to be relatively small (≤ 0.1) and approaches zero when there is snow cover on the surface or when the soil surface is frozen. Furthermore, the dual K_c method requires daily calculation time steps, which is suitable for day-to-day irrigation management but not for water balance studies during the non-growing season.

RESULTS AND DISCUSSION

FIELD SURFACE CONDITIONS

The research field had virtually no active plant or weed growth during the non-growing seasons. As an example, figure 1 shows the changes in field surface conditions over

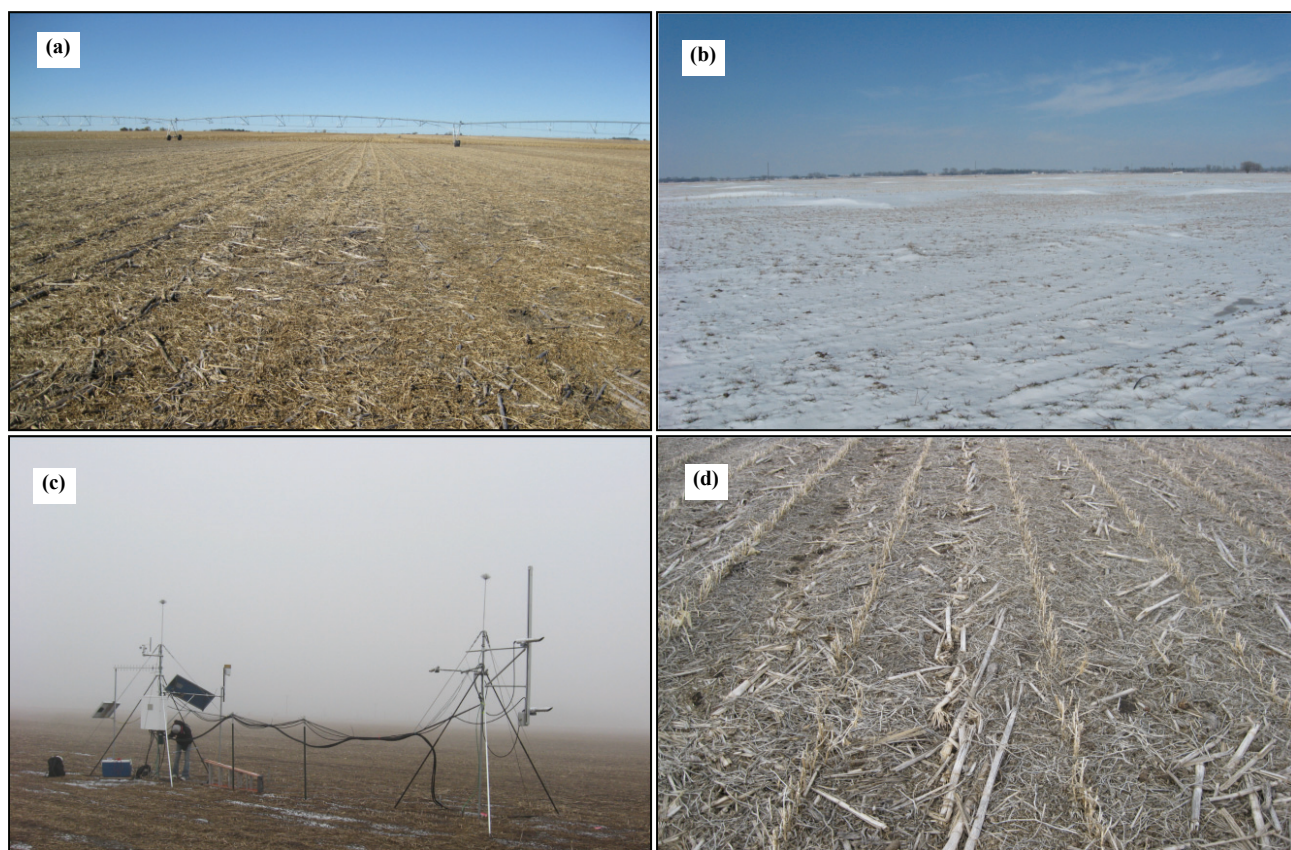


Figure 1. Change in field surface conditions during the 2007/2008 non-growing season (a) immediately after crop harvest, (b) during snow cover, (c) during snow melt, and (d) toward the end of the non-growing season.

Table 1. Estimated amount of crop residue remaining on the soil surface at the beginning and end of the non-growing seasons and the estimated fraction of soil surface covered with residue.

Non-Growing Season	Crop	Yield (ton ha ⁻¹)	Residue at Start of Season ^[a]		Residue at End of Season ^[a]	
			<i>M</i>	<i>C_r</i>	<i>M</i>	<i>C_r</i>
2006/2007	Maize	11.6	11.4	0.97	10.3	0.96
2007/2008	Soybean	4.7	5.7	0.68	4.3	0.58
2008/2009	Soybean	4.9	6.0	0.70	4.5	0.59

^[a] *M* = total mass of crop residue on soil surface (ton ha⁻¹), and *C_r* = fraction of soil surface covered with crop residue (%).

the non-growing season in 2007/2008 following harvest of the soybean crop that was planted after maize. Even though the field was devoid of weeds, it had significant amounts of surface residue that underwent very little change over the winter. Table 1 shows the estimated amounts of crop residue remaining on the soil surface at the beginning and end of the non-growing seasons and the estimated fraction of soil surface covered with residue for the entire research period. The soil surface during the 2006/2007 non-growing season was 97% covered with maize residue immediately after harvest. Maize residue is less fragile and is little affected by winter weathering. The percentage of the soil surface covered by maize residue was reduced by winter weathering by only 1% (i.e., to 96%). Since a soybean crop results in less residue than maize; during the 2007/2008 and 2008/2009 non-growing seasons an estimated 68% and 70%, respectively, of the soil surface was covered with soybean residue. Soybean residue is fragile, and the percentage of the soil surface covered in 2007/2008 and 2008/2009 was reduced to 58% and 59%, respectively, by winter weathering. These results show that the soil surface

after maize during the 2006/2007 non-growing season had as much as 25% to 35% more field surface covered by crop residue as compared to 2007/2008 and 2008/2009 non-growing seasons, which followed soybean.

METEOROLOGICAL PARAMETERS

The meteorological parameters observed in this research were air temperature (*T*), solar radiation (*R_s*), wind speed (*WS*), vapor pressure deficit (VPD, estimated), precipitation, snow cover depth, and soil temperature measured at 0.06 m depth. The monthly means of *T*, *R_s*, *WS*, and VPD were compared with the long-term (1983-2009) monthly means as presented in figure 2. The long-term monthly mean *T* fell from about 10.9°C at the beginning of October, reached a minimum value of -3.6°C in January, and then increased to about 9.1°C by the end of April (early spring). Similarly, the long-term mean monthly *R_s* fell from about 11.3 MJ m² d⁻¹ at the beginning of October to a minimum value of 6.7 MJ m² d⁻¹ in December and then increased to 17.7 MJ m² d⁻¹ at the end of April. The *WS* (fig. 2c) is adjusted for the measurement height of 2 m. The long-term monthly mean *WS* increased from 3.3 m s⁻¹ at the beginning of October to 4.6 m s⁻¹ at the end of April. The monthly means of *WS* for 2008/2009 were higher than the long-term averages.

The VPD (fig. 2d) is defined as the difference between the ambient (actual) vapor pressure and the saturation vapor pressure of the water present in the atmosphere at a given temperature. Because VPD has a nearly straight-line relationship with the rate of evapotranspiration, it is a strong measure of the evaporative demand of the atmosphere

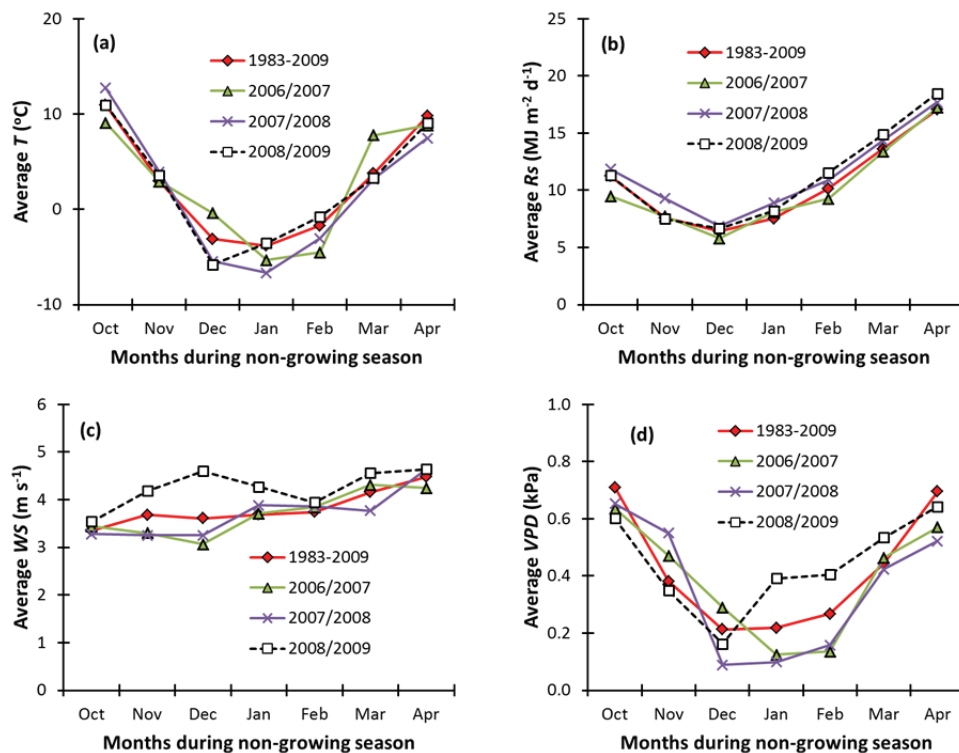


Figure 2. Weather data during the research period vs. long-term trends: (a) average monthly air temperature (*T*), (b) monthly total incoming solar radiation (*R_s*), (c) average monthly wind speed (*WS*) adjusted for measurement height of 2 m, and (d) average monthly vapor pressure deficit (VPD).

above the field surface. The 2006/2007 and 2007/2008 non-growing seasons exhibited a lower atmospheric evaporative demand than the 26-year averages for December, January, and February, whereas the atmospheric evaporative demand for the 2008/2009 non-growing season was higher than the long-term normal for January, February, and March. Past studies have indicated that one unit change in VPD can result in as much as 10% to 30% change in the estimated reference (potential) ET (Saxton, 1975; Sadler and Evans, 1989; Yoder et al., 2005; Irmak et al., 2006). In the present research, the largest difference in VPD between the 2006/2007, 2007/2008, and 2008/2009 non-growing seasons and the long-term averages was less than 0.25 kPa; hence, the seasonal differences in VPD could not have contributed substantially to the differences in ET. The T , R_s , WS , and VPD in each of the three dormant periods were similar in trend and magnitude to the long-term averages, indicating that all three periods studied were representative of the typical non-growing season weather conditions expected at the research location.

Figure 3 shows the precipitation distribution as well as cumulative precipitation during the non-growing seasons. In 2006/2007, very little precipitation occurred early in the season, and most of the precipitation occurred in the second half of the season, with peaks in mid-February and late April. Total cumulative precipitation during the 2006/2007

non-growing season was 418 mm. In 2007/2008, significant amounts of precipitation occurred early October, early to mid-December, mid- to late February, and late March through April. Total cumulative precipitation during the 2007/2008 non-growing season was 497 mm. The 2008/2009 non-growing season was different in that it started with high amounts of precipitation, followed by a dry or minimal precipitation period, but frequent amounts of precipitation until late March and late April when considerable amounts of precipitation occurred. The 2008/2009 non-growing season was relatively dry as compared to the non-growing seasons in 2006/2007 and 2007/2008. Total cumulative precipitation during the 2008/2009 non-growing season was 360 mm.

The snow depths presented in figure 4 are estimated snow cover depths at Clay Center, Nebraska, reported by the local National Weather Service (NWS) office. The data were compiled by NWS using reports from local law enforcement, volunteer spotters, and cooperative observers. The 2006/2007 non-growing season had 23 days with snow cover on the field surface, concentrated between mid-January and mid-February. The 2007/2008 non-growing season had 55 days with snow cover on the field surface, concentrated between early December and early February. The 2008/2009 non-growing season had 24 days with snow cover on the field surface, concentrated between mid-

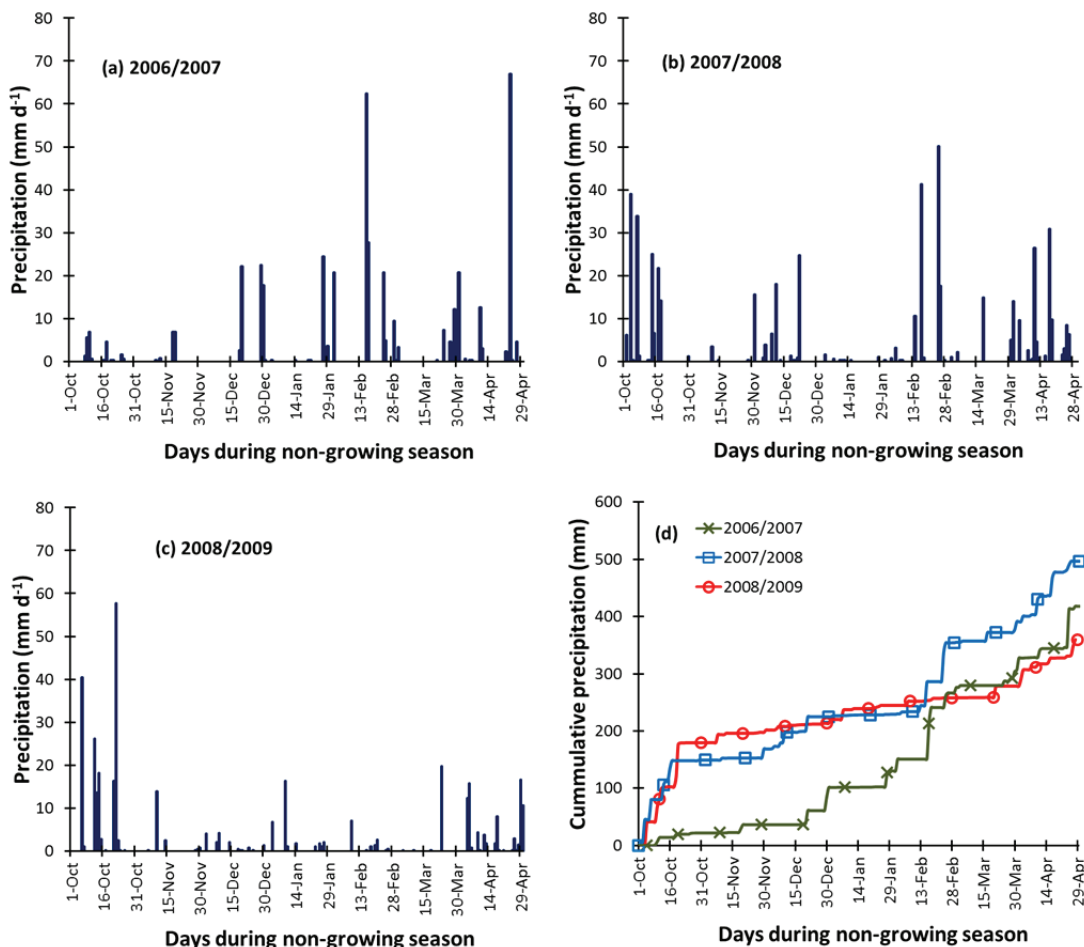


Figure 3. Daily precipitation amounts and distribution during the non-growing seasons in (a) 2006/2007, (b) 2007/2008, and (c) 2008/2009, and (d) cumulative precipitation during the three non-growing seasons.

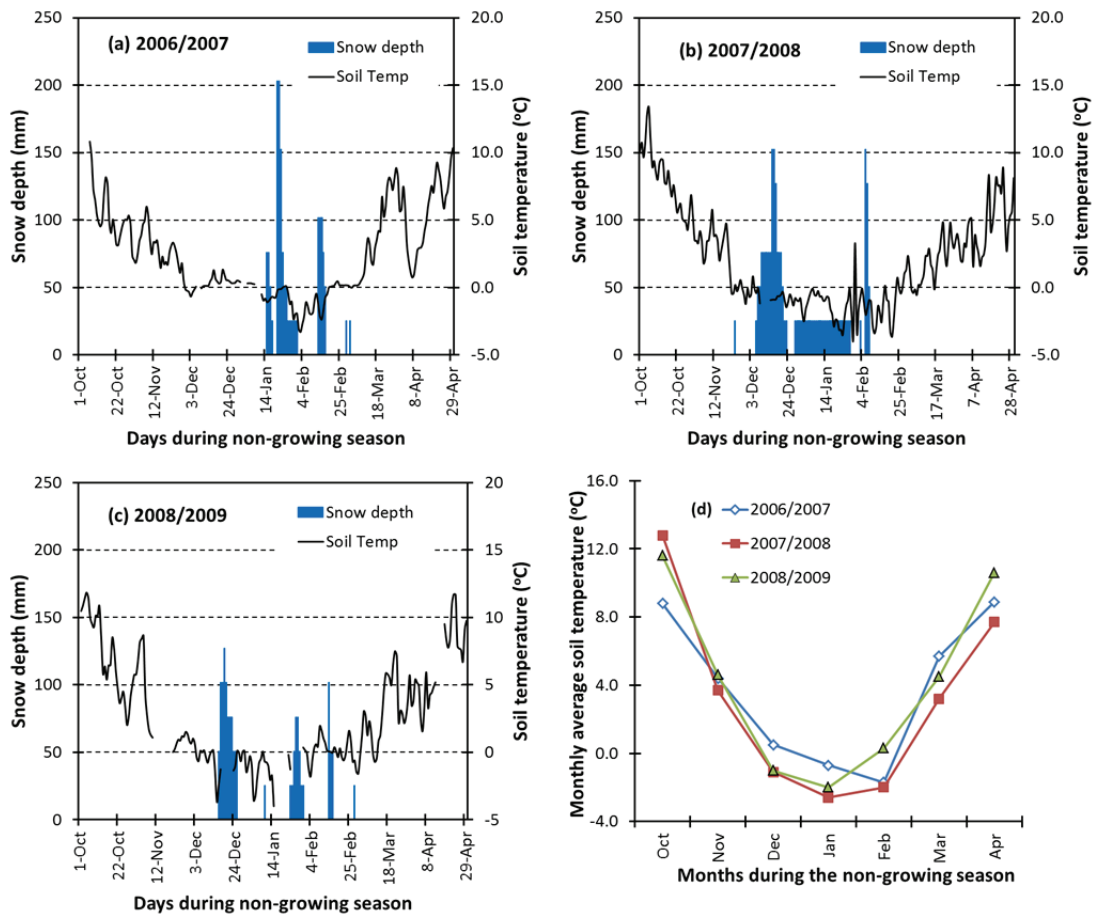


Figure 4. Snow cover depth on the experimental field surface and soil temperature variation during the non-growing seasons in (a) 2006/2007, (b) 2007/2008, and (c) 2008/2009, and (d) monthly average soil temperature compared between the three non-growing seasons.

December and mid-February. Figure 4d shows that the soil temperature measured at 0.06 m below the soil surface gradually decreased from 8°C or 13°C in October to below 0°C in December and January and then gradually increased to about 8°C or 10°C in April. There was only a slight difference in interannual soil temperature changes between the three consecutive non-growing seasons.

SURFACE ENERGY BALANCE COMPONENTS

Figure 5 shows daily variation of R_n , LE , H , and G during the three consecutive non-growing seasons. Gaps in the data are days when the measuring equipment malfunctioned due to ice formation on the instrumentation and/or other issues, or days when maintenance was being performed on the BREBS. The period from October to late December is a transition from summer to winter when day length becomes shorter and the total incoming solar radiation gradually decreases. The shortening of day length runs from the summer solstice (longest day of the year), which occurs on June 21 or 22, to the winter solstice (shortest day of the year), which occurs on December 21 or 22. The period from late December to mid-March is usually associated with freezing temperatures and snowfall at the research location. The period from mid-March to April is a transition from winter cold to summer, during which the day length and total incoming solar radiation gradually increase. The transition from winter to summer runs from the

vernal equinox (day and night equal in length), which occurs on March 20 or 21, to the summer solstice.

R_n is a positive value when incoming shortwave radiation exceeds outgoing radiation, allowing the field surface to absorb energy. When the outgoing radiation is greater than the incoming radiation, R_n becomes negative. Daily values of R_n during the non-growing season ranged from -20.5 to 168.8 $W m^{-2}$ with a mean of 48.5 $W m^{-2}$ in 2006/2007, from -31.1 to 175.7 $W m^{-2}$ with a mean of 47.4 $W m^{-2}$ in 2007/2008, and from 28.2 to 162.6 $W m^{-2}$ with a mean of 54.3 $W m^{-2}$ in 2008/2009. The 2006/2007 non-growing season had six days with negative R_n values in January 2007, while the 2007/2008 non-growing season had 44 days with negative R_n values occurring in early December 2007, late January 2008, and mid-February 2008. The 2008/2009 non-growing season had 13 days with negative R_n , which occurred in late December and mid-February. R_n is distributed (partitioned) as LE , H , and G components, depending on the field surface and atmospheric conditions, and their interactions. When evaporation is taking place from the field surface, there is a positive LE flux. A positive LE flux is upward (away from the field surface), indicating that the surface is losing energy to the air above. Sometimes there is also condensation of water vapor present in the atmosphere to a liquid form on the field surface. During the condensation process, the LE flux is negative, indicating that it is converted to H flux, which

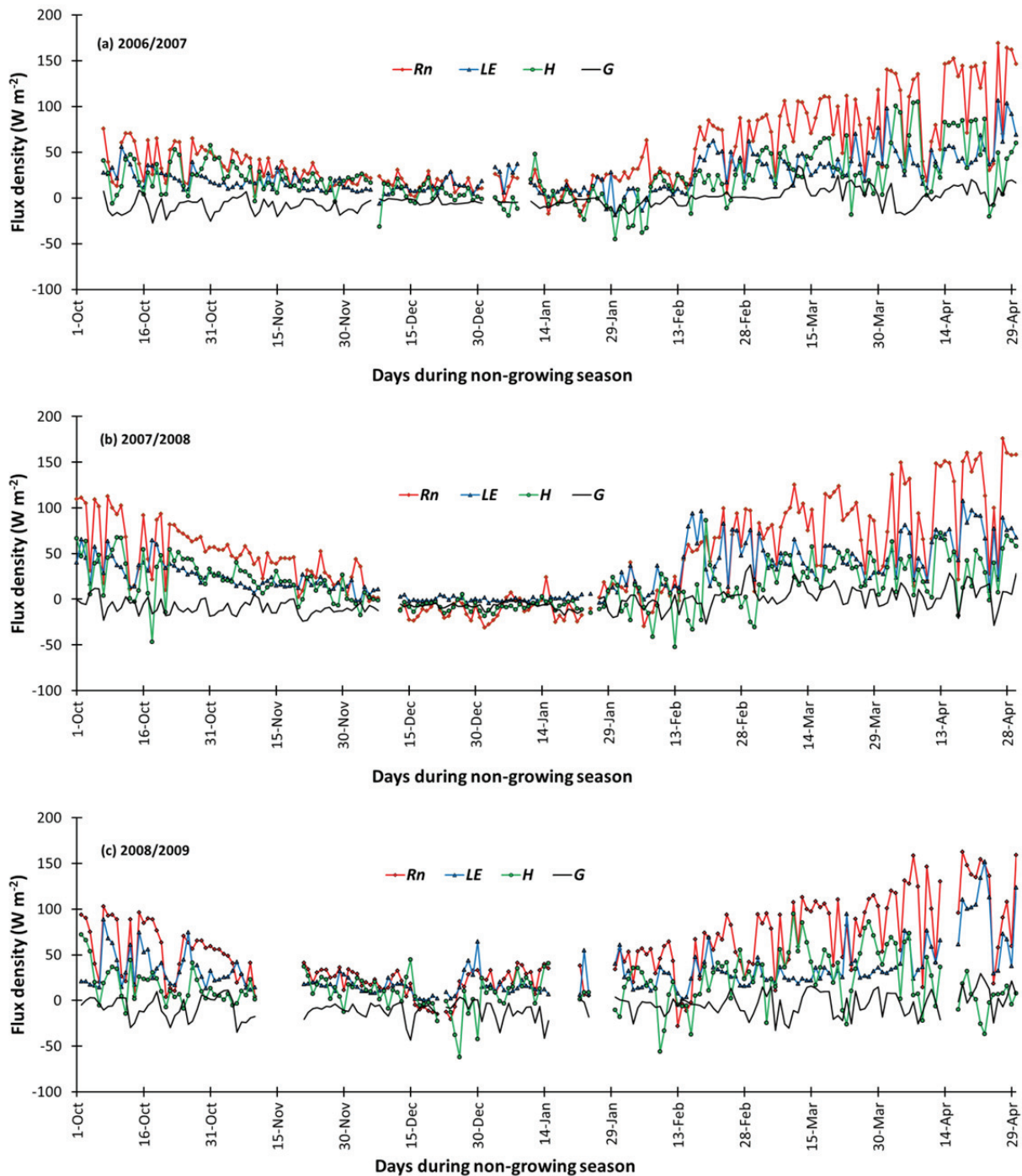


Figure 5. Surface energy balance components measured in the experimental field during the non-growing seasons: (a) 2006/2007, (b) 2007/2008, and (c) 2008/2009. R_n = net radiation, LE = latent heat flux (actual evapotranspiration), H = sensible heat flux, and G = ground heat flux. Gaps in the data are days when the measuring equipment malfunctioned or when maintenance was being performed.

causes an increase in the temperature of the air. Daily values of LE during the non-growing season ranged from -19.4 to 106.2 W m^{-2} with a mean of 24.9 W m^{-2} in 2006/2007, from -4.8 to 107.3 W m^{-2} with a mean of 28.9 W m^{-2} in 2007/2008, and from 0.6 to 151.8 W m^{-2} with a mean of 31.6 W m^{-2} in 2008/2009. The 2006/2007 non-growing season had seven days with negative LE values occurring in late January 2007, the 2007/2008 non-growing season had 29 days with negative LE values occurring between early December 2007 and mid-February 2008, and the 2008/2009

non-growing season had no days with negative LE values.

Heat is initially transferred into the air by conduction as air molecules collide with those of the field surface. As the air warms, it circulates upward via convection. When the surface is warmer than the air above, heat is transferred upward into the air as a positive H flux. The transfer of heat increases the air temperature but cools the surface. If the air is warmer than the surface, heat is transferred from the air to the surface, creating a negative H flux. If heat is transferred out of the air, the temperature of the air decreases

and the surface temperature increases. These processes exhibit much complexity during the winter, especially in Nebraska where the interactions of extremely cold air with the surface are very dynamic due to high wind speeds that result in abrupt changes in the air-surface temperature interactions due to wind chill, thereby resulting in abrupt changes in H . Daily values of H during the non-growing season ranged from -44.9 to 104.9 W m^{-2} with a mean of 21.5 W m^{-2} in 2006/2007, from -52.6 to 86.0 W m^{-2} with a mean of 15.2 W m^{-2} in 2007/2008, and from -62.3 to 95.0 W m^{-2} with a mean of 16.9 W m^{-2} in 2008/2009. The 2006/2007 non-growing season had 37 days with negative H values, most of which occurred between mid-December 2006 and early February 2007. The 2007/2008 non-growing season had 73 days with negative H values, mostly occurring between late November 2007 and early March 2008. The 2008/2009 non-growing season had 41 days with negative LE values, mostly occurring between mid-December 2008 and mid-February 2009. Similar to the heat transfer principles with H , heat is transferred downward when the surface is warmer than the subsurface, resulting in positive G flux. If the subsurface is warmer than the surface, then heat is transferred upward (negative G flux). Daily values of G during the non-growing season ranged from -27.3 to 35.5 W m^{-2} with a mean of -2.5 W m^{-2} in 2006/2007, from -43.2 to 29.3 W m^{-2} with a mean of -6.4 W m^{-2} in 2007/2008, and from -28.5 to 37.4 W m^{-2} with a mean of -3.2 W m^{-2} in 2008/2009. Over 65% of the days in all the three non-growing seasons had negative G values

when heat was transferred from the air to the field surface.

For better visualization of the trends, variations, and relative magnitudes of the surface energy balance components during the non-growing seasons, the energy balance components were averaged at monthly time steps (fig. 6). The averaging of monthly intervals retained a good temporal resolution of the data. In the 2006/2007 non-growing season, the monthly averages of R_n and LE ranged from 10.9 to 110.5 W m^{-2} and from 10.2 to 51.2 W m^{-2} , respectively. Thus, the monthly averages of R_n and LE were positive during the entire non-growing season. The monthly average H ranged from -2.3 to 53.5 W m^{-2} and was positive for all months except January. The monthly average G ranged from -9.8 to 8.4 W m^{-2} , was negative from October to February due to cold soil temperatures, and then became positive in March and April as the surface soil temperatures increased. In the 2007/2008 non-growing season, the monthly averages of R_n and H ranged from -6.6 to 111.2 W m^{-2} and from -6.0 to 35.4 W m^{-2} , respectively. Average monthly R_n and H were positive for all months except December and January. The monthly average LE ranged from 1.0 to 62.4 W m^{-2} , making LE positive during the entire season. The monthly average G ranged from -10.7 to 6.6 W m^{-2} , was negative from October to February, and then became positive in March and April. In the 2008/2009 non-growing season, the monthly averages of R_n , LE , and H were all positive for the entire season and ranged from 12.2 to 110.4 W m^{-2} , from 15.1 to 69.0 W m^{-2} , and from 1.4 to 39.7 W m^{-2} , respectively. Monthly average G ranged from -

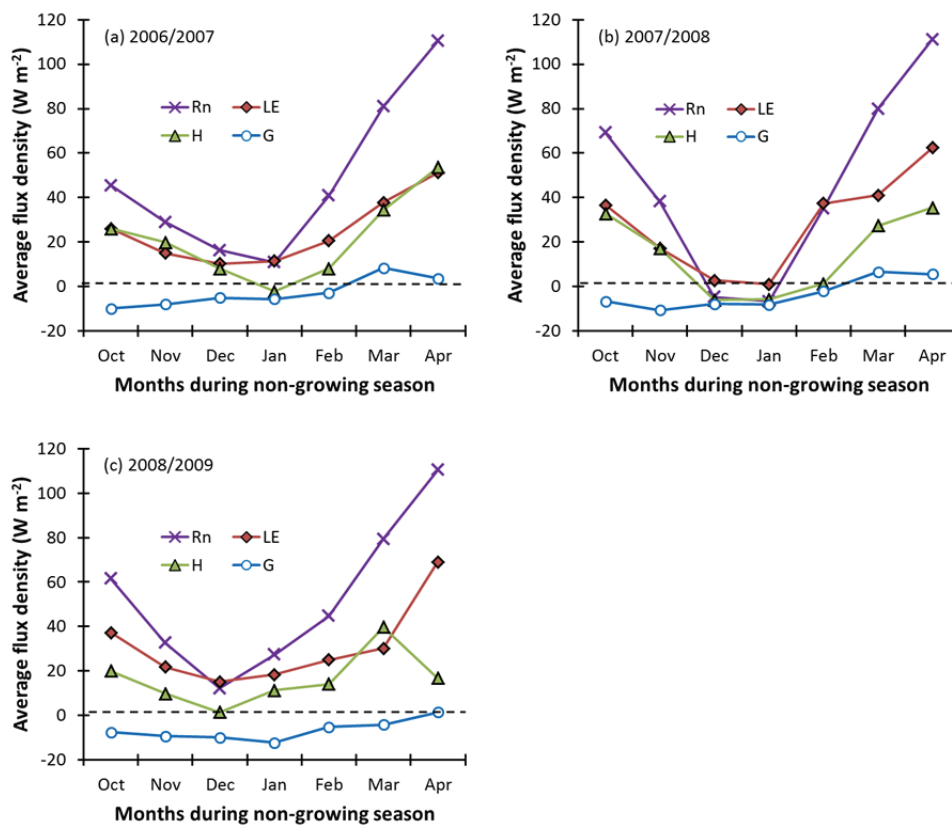


Figure 6. Monthly averages of surface energy balance components measured in the research field during the non-growing seasons: (a) 2006/2007, (b) 2007/2008, and (c) 2008/2009. R_n = net radiation, LE = latent heat flux (actual evapotranspiration), H = sensible heat flux, and G = ground heat flux.

12.2 to 1.5 W m⁻² and was negative from October to March and positive only in April. These results show that R_n was the dominant surface energy balance component throughout the non-growing seasons, except in 2007/2008 when it was less than LE in December and January. The occurrence of negative or low positive values of R_n , LE , and H corresponded with periods of snow cover on the field surface. Based on monthly averages, more energy was used for LE than for H and G during the non-growing seasons, and H , in general, was higher than G . In addition, based on monthly averages, more heat was transferred from the subsoil to warm the field surface, creating a negative G flux from October to February in 2006/2007 and 2007/2008 and from October to March in 2008/2009. No significant differences in magnitude, trend, and distribution of the surface energy balance components were observed between the field surface when over 90% of the surface was covered with maize residue (2006/2007) and the field surface when only about 60% of the surface was covered with soybean residue (2007/2008 and 2008/2009).

HOURLY DISTRIBUTION OF ENERGY FLUXES

Hourly distribution of surface energy fluxes under a range of ambient conditions representing fresh residue in fall, weathered residue in spring, snow-covered surface in winter, frozen soil without snow cover in winter, thawing soil in early spring, and wet field surface after rainfall are shown in figure 7. In all cases, except on very cloudy days, R_n was the dominant surface energy balance component during daytime. Figure 7a represents an interval in the fall season of 2006 where the soil surface was 97% covered with fresh maize residue. The soil temperature at 0.05 to 0.06 m depth gradually decreased from 7.3°C on October 9 to 4.8°C on October 12. Small amounts of rainfall occurred on October 9 and 10, and both days were cloudy with low R_s . On October 9, almost all R_n was used for LE , and G was negative, indicating that heat was transferred from the subsoil to warm the air above the field surface. October 11 was sunny and followed a cloudy wet day with 6.9 mm of rainfall. More energy was used for LE as compared to H on October 11, while on October 12 the field surface had dried and hence more energy was used for H than for LE . Figure 7b represents the interval around the winter solstice (shortest day of the year) in 2006. This interval had no precipitation events, but the soil surface was probably wet following a 22.5 mm rainfall on December 20. During the interval, T ranged from -0.3 to -4.2°C, RH ranged from 82% to 100%, WS ranged from 1.4 to 4.8 m s⁻¹, soil temperature at 0.06 m depth ranged from 0.5 to 1.3°C, and daily average R_n gradually increased from 3.2 to 55.2 W m⁻². The amounts of energy used during daytime for LE and H were approximately equal, and G was very small compared to the other energy balance components. The interval in figure 7c represents late winter in 2007 when about 60% of the field surface was covered with soybean residue. There was no precipitation or snow cover during this interval, but it closely followed a five-day period with snow cover on the field surface. The soil temperature at 0.06 m depth ranged from 0.1°C to 0.4°C. On February 20 and 21, relatively more energy was used during daytime for LE than for

H , and on February 22 and 23 approximately equal amounts of energy were used during daytime for LE and H .

Figure 7d represents the interval in winter when the field surface had accumulated 76 to 152 mm of continuous snow cover. The magnitude of R_n , LE , H , and G were small as compared to values at other intervals and ranged from -70.0 to 30.0 W m⁻². Hourly mean values for R_n , LE , H , and G were -17.8, -7.5, 0.1, and -8.1 W m⁻², respectively, with more energy used during daytime for LE than for H . The interval in figure 7e is in the fall season of 2008 when about 70% of the soil surface was covered with fresh soybean residue. October 11 was dry, but October 12, 13, and 14 had considerable rainfall in the amounts of 26.2, 13.7, and 18.1 mm, respectively. October 11, 12, and 14 were cloudy with mean daytime R_s of 132.8, 87.0, and 53.0 W m⁻², respectively, and October 13 was sunny with mean daytime R_s of 289.5 W m⁻². R_n was the dominant component in the interval, and as expected for wet surface conditions, more energy was used for LE than for H . Figure 7f represents the conditions in early spring of 2009 when about 59% of the field surface was covered with weathered soybean residue (soil temperature at 0.06 m was gradually increasing), and the interval was preceded by rainfall event (8.1 mm) on October 18. A significant amount of daytime energy was consumed in heating the soil; on April 21 and 22, more daytime energy was used for G than for H . These results show that the magnitude and relative amounts of R_n , LE , H , and G are influenced by cloudiness and day of the year, which determines the amount of R_s , surface wetness and temperature, and snow cover.

RELATIONSHIP BETWEEN ACTUAL AND REFERENCE (POTENTIAL) EVAPOTRANSPIRATION

Daily values of measured actual ET and daily values of ET_r and ET_o during three non-growing seasons are correlated in figures 8a to 8c. A general trend is observed in which ET , ET_r , and ET_o gradually decreased from October, reached minimum values around December to January, and then gradually increased from February through April. Both ET_r and ET_o were generally higher than ET , but there were also a few days, especially in the 2007/2008 season, when ET was greater than ET_r and/or ET_o . Figures 8d to 8f show the seasonal cumulative ET , ET_r , and ET_o during the three seasons. The cumulative ET , ET_r , and ET_o were 196, 442, and 321 mm, respectively, in the 2006/2007 non-growing season; 221, 478, and 350 mm, respectively, in the 2007/2008 non-growing season; and 226, 533, and 384 mm, respectively, in the 2008/2009 non-growing season. Total cumulative ET was 61%, 63%, and 59% of total cumulative ET_o in 2006/2007, 2007/2008, and 2008/2009, respectively. Total cumulative ET was 43%, 46%, and 41% of total cumulative ET_r in 2006/2007, 2007/2008, and 2008/2009, respectively. These results show that the differences in type and amount of maize and soybean residue on the field surface had no effect in the way residue cover influenced the ET process to satisfy the atmospheric evaporative demand. Thus, the evaporative losses were primarily driven by atmospheric conditions rather than surface characteristics. The maximum differences in seasonal cumulative ET , ET_r , and ET_o between the three non-growing seasons were 30, 111, and 63 mm, respectively. The

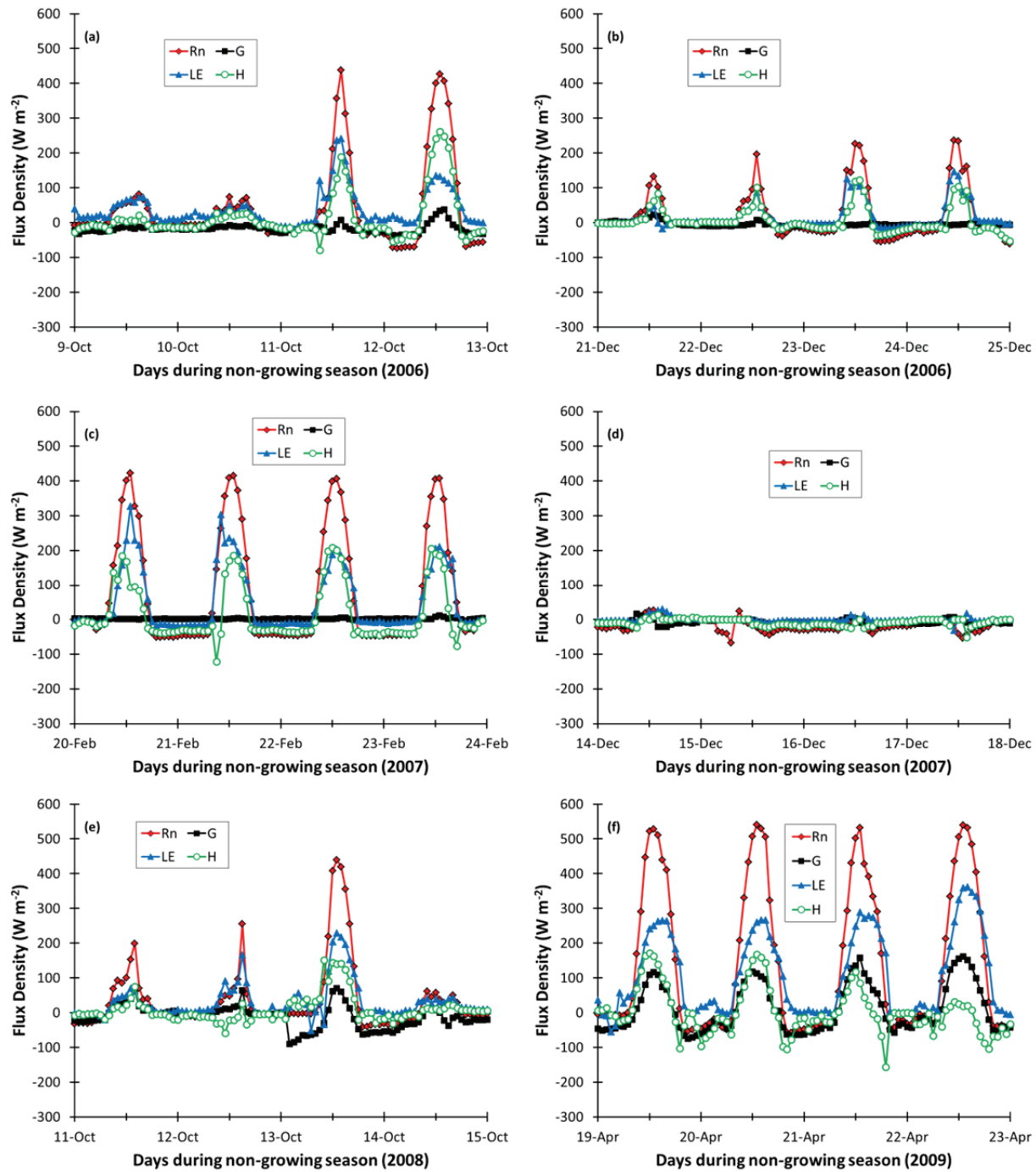


Figure 7. Hourly distribution of surface energy fluxes under a range of ambient conditions representing: (a) fresh maize residue, (b) around winter solstice and wet surface, (c) late winter frozen soil with no precipitation or snow, (d) snow cover in winter, (e) fresh soybean residue and some rainfall, and (f) period in early spring preceded by slight rainfall.

2008/2009 non-growing season had the highest cumulative ET, ET_r , and ET_o values, and the 2006/2007 non-growing season had the lowest cumulative ET, ET_r , and ET_o values. Total cumulative ET was 53%, 45%, and 63% of total cumulative non-growing season precipitation in 2006/2007, 2007/2008, and 2008/2009, respectively.

Since measurement of actual ET in winter is an extremely difficult task, to explore the potential feasibility of using ET_{ref} to estimate ET, regression plots between daily ET vs. ET_r and ET vs. ET_o are presented in figure 9. The intercept

and slope (S) of the best-fit line and coefficients of determination (R^2) are summarized in table 2. The intercept for the ET vs. ET_r data ranged from 0.271 to 0.438, and the intercept for the ET vs. ET_o data ranged from 0.355 to 0.478. The intercept for pooled data (all three non-growing seasons) was 0.334 for the ET vs. ET_r data and 0.434 for the ET vs. ET_o data. When the calculated ET_{ref} was zero, the measured ET values ranged from zero to a small value of less than 0.5 mm d^{-1} . S ranged from 0.243 to 0.328 for

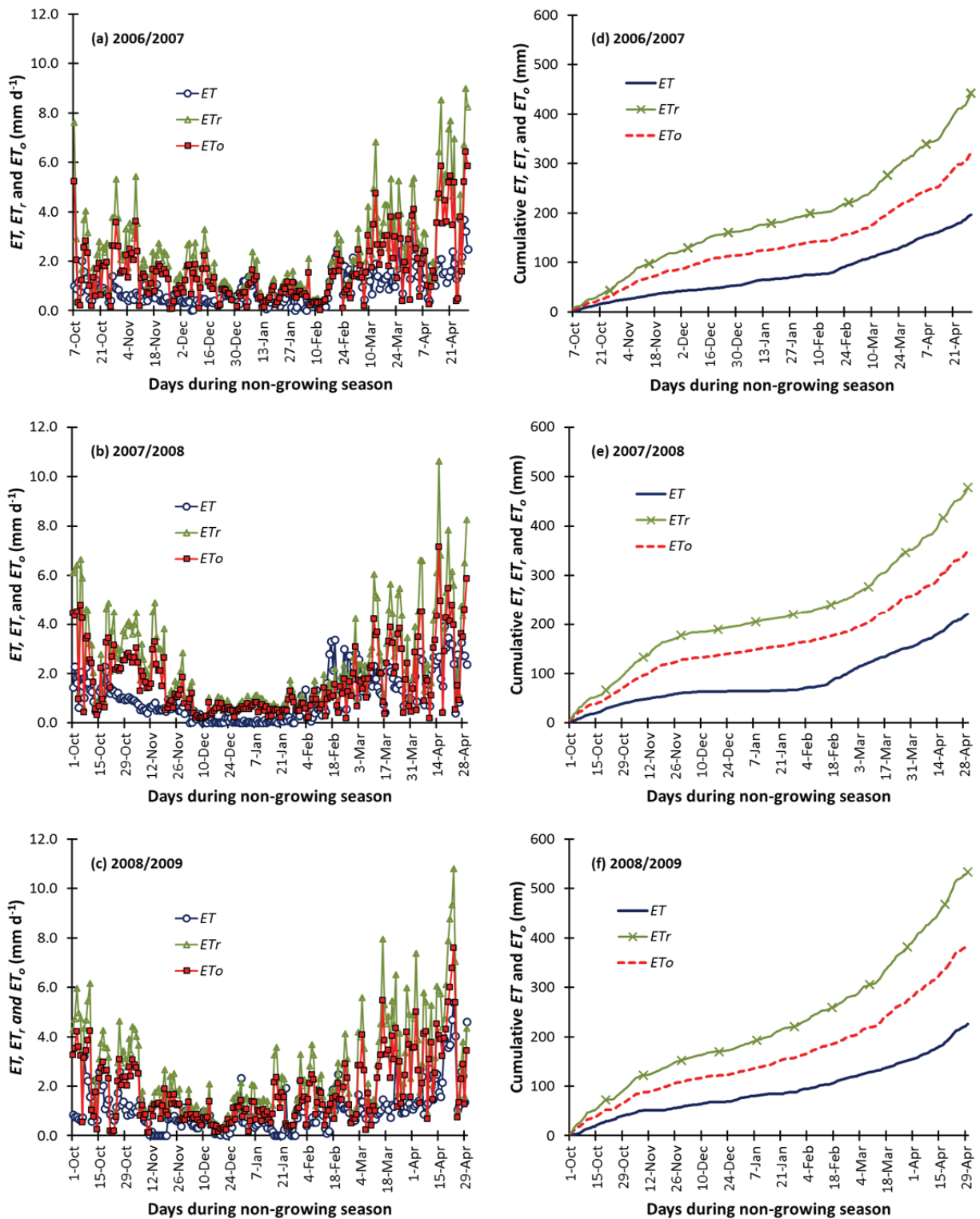


Figure 8. (a-c) Comparison of actual evapotranspiration (ET) and alfalfa- and grass-reference evapotranspiration (ET_r and ET₀) estimated using the ASCE standardized Penman-Monteith equation for the three non-growing seasons and (d-f) seasonal cumulative ET, ET_r, and ET₀.

the ET vs. ET_r data and from 0.254 to 0.405 for ET vs. ET₀, and the *S* for the pooled data was 0.299 for ET vs. ET_r and 0.296 for ET vs. ET₀. The values of *S* indicate that ET was less than ET_{ref}. The R² values for the ET vs. ET_r data ranged from 0.39 to 0.45 with a value of 0.44 for the pooled data, and R² for the ET vs. ET₀ ranged from 0.43 to 0.47 with a value of 0.46 for the pooled data. In all cases,

the intercept was positive, indicating that estimates of ET on days with low ET_{ref} were high, and this resulted in some very high *K_c* values. The low R² values indicate a weak linear relationship between daily values of ET to ET_r and ET₀, suggesting that calculated daily ET_{ref} values are not suitable for accurately predicting daily ET values during for the non-growing season. Some studies have suggested us-

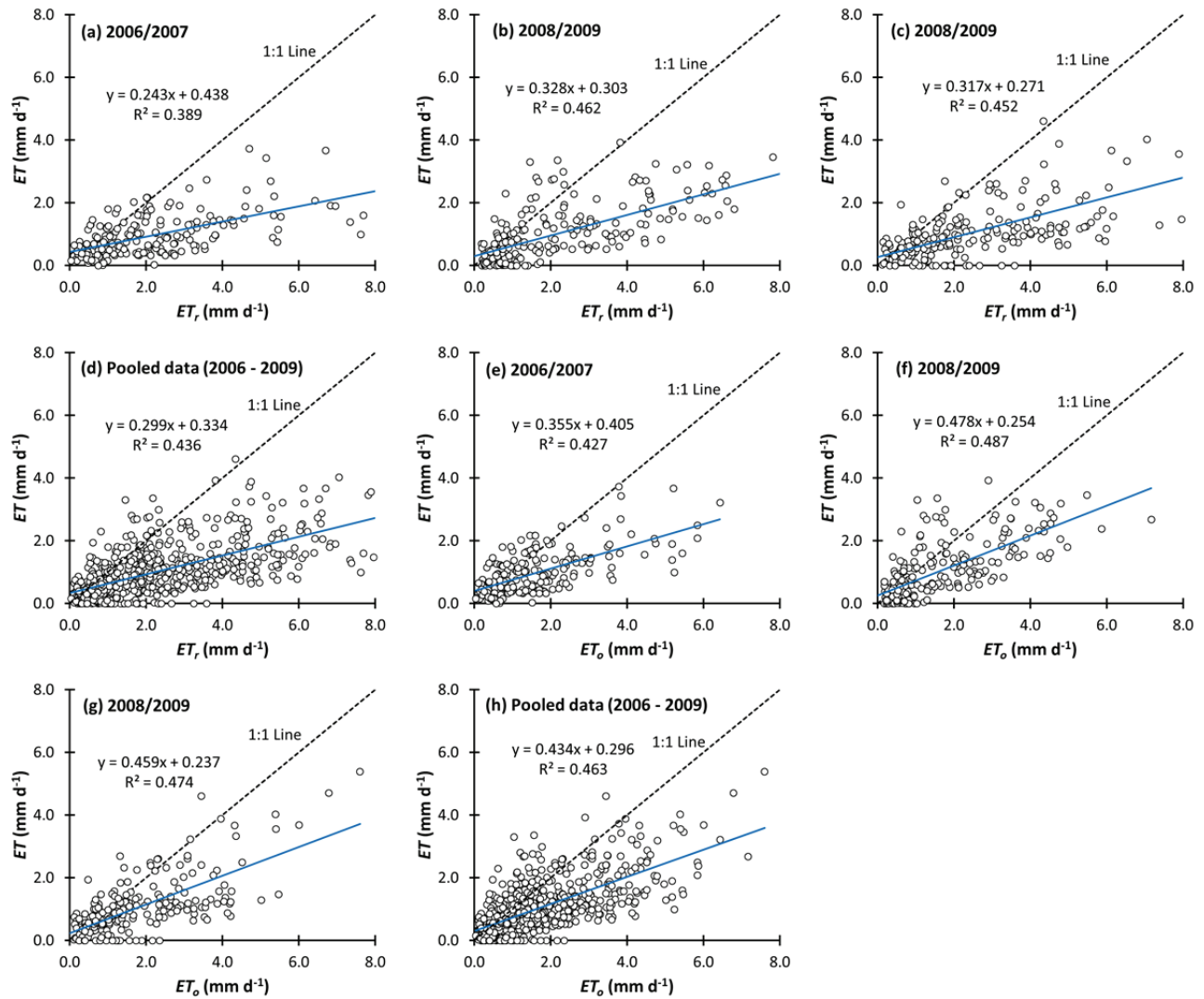


Figure 9. (a-d) Relationships between daily ET and ET_r values and (e-h) regression plots between daily ET vs. ET_o values.

ing the average daily K_c values for the entire non-growing season, but such an approach has the potential to considerably overestimate daily ET.

Regression plots of monthly total ET and monthly total ET_r and ET_o are presented in figure 10. The intercept, S , and R^2 are summarized in table 3. The intercept ranged from 2.909 to -3.147 for the ET vs. ET_r monthly data and from 2.970 to -2.632 for the ET vs. ET_o monthly data. For the pooled monthly data, the intercept was -0.318 for ET vs. ET_r and -0.559 for ET vs. ET_o. S for the monthly ET vs. ET_r data ranged from 0.398 to 0.474, and S for the pooled data was 0.448. S for the monthly ET vs. ET_o data ranged from 0.546 to 0.670, and S for the pooled data was 0.621.

Table 2. Intercept, slope (S), and coefficient of regression (R^2) of measured evapotranspiration (ET) vs. calculated reference evapotranspiration (ET_r and ET_o) with day data.

Non-Growing Season	ET vs. ET _r			ET vs. ET _o		
	Intercept	S	R^2	Intercept	S	R^2
2006/2007	0.438	0.243	0.39	0.355	0.405	0.43
2007/2008	0.303	0.328	0.42	0.478	0.254	0.49
2008/2009	0.271	0.317	0.45	0.459	0.237	0.47
Pooled data (2006-2009)	0.334	0.299	0.44	0.434	0.296	0.46

These S values between different seasons were within narrow ranges of 0.448 ± 0.050 for ET vs. ET_r and 0.621 ± 0.075 for ET vs. ET_o, which show that the slopes of the best fit lines were relatively consistent. The R^2 values for monthly ET vs. ET_r data ranged from 0.71 to 0.88, and R^2 for the pooled data was 0.78. The R^2 values for monthly ET vs. ET_o data ranged from 0.73 to 0.89, and R^2 for the pooled data was 0.80, indicating a very strong linear relationship between the total monthly values of ET and ET_o, suggesting a better relationship that can be used to predict ET from ET_r or ET_o. The close similarity in the values of S between the three non-growing seasons indicates that the relationship between ET vs. ET_o and ET_r does not have substantial interannual variation. Thus, we suggest that regression equations determined from pooled data for the three non-growing seasons can be used to approximate monthly ET from monthly ET_{ref} during the non-growing season under conditions similar to the study area and are given as:

$$ET_{month} = 0.448 \times ET_{r-month} - 0.318 \quad (8)$$

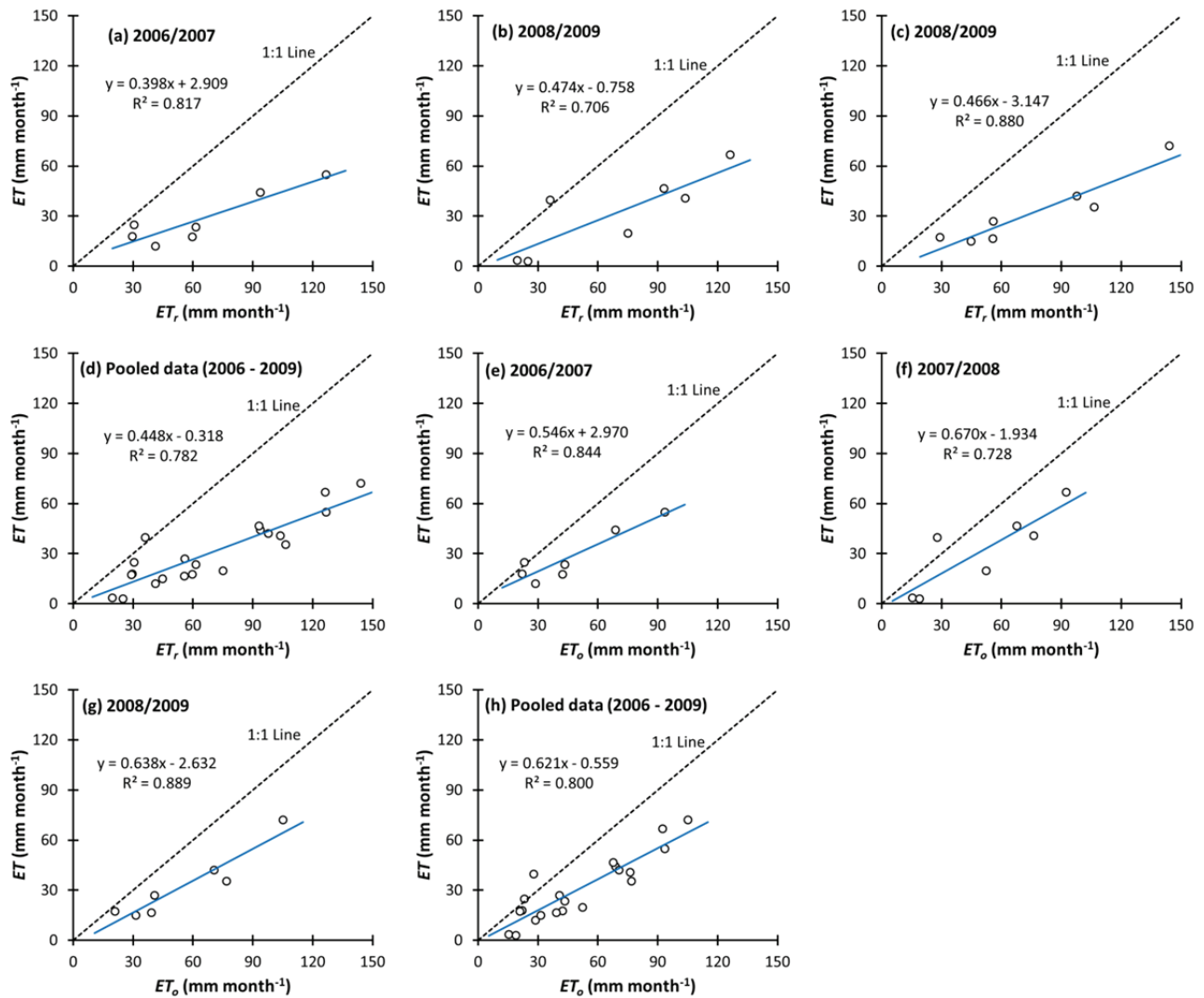


Figure 10. Relationships between monthly total ET values and monthly total ET_r and ET_o values.

Table 3. Intercept, slope (S), and coefficient of regression (R^2) of measured evapotranspiration (ET) vs. calculated reference evapotranspiration (ET_r and ET_o) with monthly data.

Non-Growing Season	ET vs. ET_r			ET vs. ET_o		
	Intercept	S	R^2	Intercept	S	R^2
2006/2007	2.909	0.398	0.82	2.970	0.546	0.84
2007/2008	-0.758	0.474	0.71	-1.934	0.670	0.73
2008/2009	-3.147	0.466	0.88	-2.632	0.638	0.89
Pooled data (2006-2009)	-0.318	0.448	0.78	-0.559	0.621	0.80

$$ET_{month} = 0.621 \times ET_{o-month} - 0.559 \quad (9)$$

where ET_{month} is total monthly values of ET (mm), $ET_{r-month}$ is total monthly values of ET_r (mm), and $ET_{o-month}$ is total monthly values of ET_o (mm).

NON-GROWING SEASON SURFACE COEFFICIENTS

Figures 11a to 11f show the changes in daily surface coefficients (K_{cr} and K_{co}) over the course of three seasons. Unlike the growing season, in which K_c depends on the growth and development of a crop canopy, non-growing season K_c values varied widely from day to day because of the frequent and erratic changes in surface wetness, freez-

ing of soils, snow cover, air temperature, wind speed, and net solar radiation. These changes in climatic and soil surface conditions affect both measured ET and calculated ET_{ref} in different ways. Because of the unpredictability and frequency of changes that affect daily ET and ET_{ref} , the surface coefficients during the non-growing season cannot be based on a time scale as the crop coefficient. Daily K_{cr} values ranged from 0.01 to 5.22 with a mean of 0.73 in the 2006/2007 non-growing season, from 0.01 to 3.66 with a mean of 0.57 in the 2007/2008 non-growing season, and from 0.01 to 5.34 with a mean of 0.57 in the 2008/2009 non-growing season. Daily K_{co} values ranged from 0.01 to 6.50 with a mean of 0.94 in the 2006/2007 non-growing season, from 0.01 to 3.87 with a mean of 0.75 in the 2007/2008 non-growing season, and from 0.01 to 6.24 with a mean of 0.84 in the 2008/2009 non-growing season. Spikes in the daily K_c values were associated with very low ET_r and ET_o values. Because of wide fluctuations in daily K_c values, there is no single K_c value that can be used for a part or all of the non-growing season.

Figures 11g and 11h show the monthly K_{cr} and K_{co} values as computed from averaging daily values of ET, ET_r ,

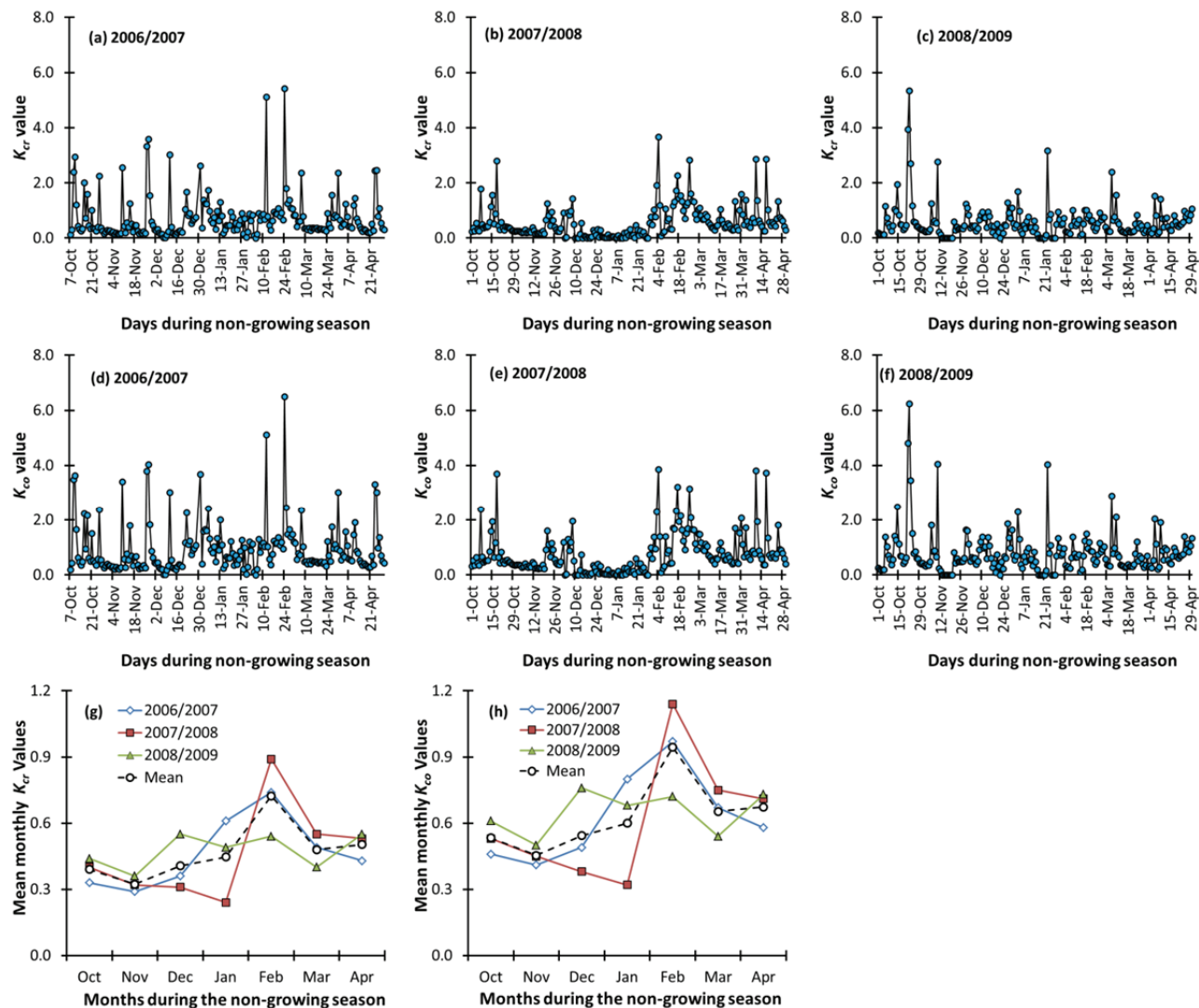


Figure 11. (a-f) Changes in daily K_{cr} and K_{co} values over the course of non-growing seasons and (g-h) monthly K_{cr} and K_{co} values computed from monthly averages of ET_c , ET_r , and ET_o .

Table 4. Monthly K_{cr} and K_{co} values computed from monthly averages of ET_c , ET_r , and ET_o .

Month	K_{cr}				K_{co}			
	2006/2007	2007/2008	2008/2009	Mean	2006/2007	2007/2008	2008/2009	Mean
October	0.33	0.40	0.44	0.39	0.46	0.53	0.61	0.53
November	0.29	0.32	0.36	0.32	0.41	0.45	0.50	0.45
December	0.36	0.31	0.55	0.41	0.49	0.38	0.76	0.54
January	0.61	0.24	0.49	0.45	0.80	0.32	0.68	0.60
February	0.74	0.89	0.54	0.72	0.97	1.14	0.72	0.94
March	0.49	0.55	0.40	0.48	0.67	0.75	0.54	0.65
April	0.43	0.53	0.55	0.50	0.58	0.71	0.73	0.67
Maximum	0.74	0.89	0.55	0.72	0.97	1.14	0.76	0.94
Minimum	0.29	0.24	0.36	0.32	0.41	0.32	0.50	0.45
Mean	0.46	0.46	0.48	0.47	0.63	0.61	0.65	0.63

and ET_o . The monthly K_{cr} and K_{co} values as calculated for the three non-growing seasons are summarized in table 4. Monthly K_{cr} values ranged from 0.24 to 0.89, and K_{co} ranged from 0.32 to 1.14. Even with monthly K_c , the values can still vary widely between different years. The greatest variations in K_c occurred in December, January, and February, which are the coldest months of the non-growing season at the research location. Both K_{cr} and K_{co} , however, showed a general trend in which the values increased from the beginning of the season in October, reached a peak value in February, and

then decreased toward the end of the season. Thus, because the K_c values varied substantially within the non-growing season and between years, no single K_c value was identified from the monthly data that can be used as a good representation of the surface coefficient for the entire non-growing season. The approach of using a strong linear relationship of monthly ET vs. monthly ET_r or ET_o could be a good alternative to using surface coefficients to predict non-growing season total monthly ET . Unlike crop coefficients, which are needed for estimating day-to-day crop water requirements,

K_c values for estimating non-growing season ET are needed for determining seasonal groundwater recharge and surface runoff. Thus, estimating ET using a linear regression equation for total monthly data may be sufficient for approximating the non-growing season ET.

SUMMARY AND CONCLUSIONS

This research measured and compared surface energy balance components including actual evapotranspiration (ET), which represented surface evaporation losses, in a ridge-till maize-soybean rotation field during non-growing seasons and also determined the non-growing season surface coefficients. The research was performed in south central Nebraska during three consecutive non-growing seasons (2006/2007, 2007/2008, and 2008/2009). The surface energy balance components [net radiation (R_n), soil heat flux (G), sensible (H) and latent (LE) heat fluxes] were measured using a Bowen ratio energy balance system. The 2006/2007 non-growing season had maize residue, and the 2007/2008 and 2008/2009 non-growing seasons followed soybean crops. The non-growing season following the maize crop had more crop residue (96%) after harvest as compared to the other two non-growing seasons following soybean crops, which had an average of 68% of the field surface covered with residue. The meteorological parameters observed during the three seasons were similar in trend and magnitude to the 26-year long-term averages, indicating that all three seasons were representative of the typical non-growing season weather conditions that can be expected at the research location. R_n was the dominant surface energy balance component, and its partitioning into LE , H , and G components depended on the field surface and atmospheric conditions. No significant differences in magnitude, trend, and distribution of the surface energy balance components were observed between the seasons with maize and soybean surface residue cover.

Measured cumulative total ET was 61%, 63%, and 59% of cumulative total ET_o in 2006/2007, 2007/2008, and 2008/2009, respectively. Cumulative total ET was 43%, 46%, and 41% of cumulative total ET_r in 2006/2007, 2007/2008, and 2008/2009, respectively. Differences in type and amount of maize or soybean residue on the field surface had no significant influence on ET. Thus, the evaporative losses during the non-growing seasons were primarily driven by atmospheric conditions rather than by surface characteristics for these experimental conditions. The cumulative ET was 53%, 45%, and 63% of cumulative non-growing season precipitation in 2006/2007, 2007/2008, and 2008/2009, respectively. The R^2 values for the daily ET vs. ET_{ref} data during the 2006/2007, 2007/2008, and 2008/2009 non-growing seasons were low (0.23 to 0.42 for ET_r and 0.29 to 0.46 for ET_o), indicating a weak linear relationship between daily values of ET to ET_r and ET_o . The low R^2 values suggest that using daily ET_{ref} values to predict daily ET values for a non-growing season would not provide accurate estimates.

The K_c values obtained as a ratio of measured ET to ET_{ref} using daily and monthly average data varied widely

from day to day and from month to month. Thus, because the K_c values varied substantially within the non-growing season and between years, depending on the weather conditions, no single K_c value was identified that can be used as a good representation of the surface coefficient for accurate prediction of ET for part or all of the non-growing season. The approach of using strong linear relationships developed between monthly ET vs. monthly ET_{ref} could be an alternative to using a surface coefficient to predict monthly or total non-growing season ET. The R^2 values for monthly ET vs. monthly ET_{ref} data ranged from 0.71 to 0.89 for both ET_r and ET_o . Using pooled data for ET vs. ET_{ref} , R^2 was 0.78 for ET_r and 0.80 for ET_o . The S value for the monthly ET vs. monthly ET_{ref} data was consistent for all three non-growing seasons, with $S = 0.448 \pm 0.050$ for ET_r and $S = 0.621 \pm 0.075$ for ET_o . These results suggest that maize and soybean crop residues do not have significant difference in influencing surface energy balance during the non-growing season. The results also show that the relationship between the monthly ET vs. monthly ET_{ref} data can be exploited to provide a more consistent and robust method to predict non-growing season ET from ET_{ref} in reduced-tillage fields with a maize-soybean rotation in the climatic conditions of south central Nebraska.

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