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ABSTRACT

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Title: Investigating the Importance of Land Cover on Evapotranspiration

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ABSTRACT

Land surface properties influence weather and climate. More specifically, different vegetative surfaces partition latent, sensible, and ground heat fluxes differently. A current limitation in atmospheric modeling is the lack of detailed surface-to-atmosphere interactions over heterogeneous surfaces. Research in this field will improve both short-term forecasts and long-range climate modeling. The objective of this research was to investigate (1) the importance of land surface characteristics such as soil moisture and plant health on evapotranspiration, and (2) the differences in evapotranspiration between natural ecosystems (prairie) and current ecosystems (crop) in the Midwest. This was accomplished through analysis of two data sets: (1) continuous long-term surface energy balance data from two Kansas prairies, and (2) discrete surface energy balance measurements from corn, soybean, winter wheat, and prairie sites in northern Illinois during the 2003 growing season. Results showed that surface characteristics of soil moisture and plant health have strong effects on latent heat flux, Bowen ratio, and resulting evapotranspiration. Highest evapotranspiration occurred when high available energy interacted with high soil moisture and robust plant health. Distinct differences were found between evapotranspiration from natural land surfaces and current agricultural land surfaces. Peak summertime evapotranspriation was approximately 1 mm/m^2 higher during an eight-hour day with current vegetation. This

difference applied over a large geographic area, and combined with other meteorological factors, could explain a substantial amount of dew point temperature increases observed across the Midwest over the last century. This human-induced increase in water vapor during mid-summer has consequences. More available energy may lead to more intense thunderstorms with a greater potential for damage. Additionally, higher water vapor levels act to intensify extreme heat waves by raising the apparent temperature, leading to higher heat stress. Application of this knowledge could lessen human suffering and loss during future high heat events that are augmented by higher water vapor levels.

NORTHERN ILLINOIS UNIVERSITY

INVESTIGATING THE IMPORTANCE OF LAND COVER ON EVAPOTRANSPIRATION

A THESIS SUBMITTED TO THE GRADUATE SCHOOL
IN PARTIAL FULFILLMENT OF THE REQUIREMENTS
FOR THE DEGREE
MASTER OF SCIENCE

DEPARTMENT OF GEOGRAPHY

BY
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Certification:	In accordance with departmental and Graduate School policies, this thesis is accepted in partial fulfillment of degree requirements.

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Date

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CHAPTER 1

INTRODUCTION

A critical component of the earth-atmosphere system is the interrelationship between land surface and the overlying atmosphere. Energy balance at the Earth's surface largely controls local climate. Solar radiation drives the energy balance system and is the dominant surface energy input, in addition to longwave radiation emitted from the atmosphere. Net surface energy is distributed into sensible heat flux, latent heat flux, and heat transfer to the ground. Sensible heat flux involves transfer of heat to the atmosphere by conduction or convection. Latent heat flux is energy stored in evaporation of water, and released in condensation. Energy is also transferred from the surface to the ground by thermal conduction.

Since various land surfaces have differing properties, the feedbacks of heat, momentum, and moisture to the atmosphere are not uniform across the globe. The U.S. government has invested millions of dollars into researching the differences among land surfaces and their effects on the atmosphere. A better understanding of the influences of surface characteristics will have benefits ranging from more accurate mesoscale modeling for short-term weather prediction to improved long-range climate modeling.

An example of how critical land cover is to our weather occurred during a July 1995 heat wave in Chicago, Illinois, which killed over 500 people. Meteorological analysis of this event by Kunkel et al. (1996) showed this was the most extreme Chicago heat event in the last half of the 20th century due to unusually high dew point values.

Indeed, the highest dew point readings in the entire United States during this event were found in the upper Midwest, suggesting the high water vapor levels were enhanced through regional processes instead of advecting into the region from a large, warm body of water such as the Gulf of Mexico. Recent research suggests regional enhancement of dew point temperatures may be driven by wet soils from recent precipitation and evapotranspiration (hereafter ET) from crops (Mahmood and Hubbard, 2002; Changnon et al., 2003; Sandstrom et al., 2004; Zangvil et al., 2004). The importance of land surface and its effect on weather and climate should not be underestimated.

To better understand the partitioning of sensible heat, latent heat, and moisture fluxes over various vegetative surfaces, two data sets were collected and analyzed: (1) a long-term set of continuous measurements from two central Kansas prairies, and, (2) a set of discrete measurements from one growing season from four typical vegetative Midwestern land uses: corn, soybean, winter wheat, and prairie.

Long-term continuous measurements of surface energy budget as well as other surface characteristic data were acquired from the Atmospheric Boundary Layer Experiment (ABLE), provided by Argonne National Laboratories, for two fields located in central Kansas. These data were collected continuously for four years over ungrazed prairie, and three years over grazed prairie. The value of these data lies in the continuous nature of the measurements, which extended over several years. To better understand fluxes over different surfaces, additional data were required.

To obtain measurements over four different vegetative surfaces, field data were collected during the summer of 2003 in northern Illinois. Measurements were taken several times over each field (corn, soybean, winter wheat, prairie) during this growing season. These data allow for direct comparison of ET between human-induced agricultural ecosystems and a natural prairie ecosystem. Energy and moisture flux differences between natural and crop ecosystems would indicate an anthropogenic land use change that affects weather and climate. Since cropland is today's dominant Midwestern land use, this research area deserves study.

The objectives of this work are to investigate (1) the importance of land cover to ET and (2) the differences between natural ET and production of ET from human-induced ecosystems, and possible implications. This thesis is composed of six chapters: Chapter 1 introduces the research topic and explains its importance in scientific research. Chapter 2 provides a review of relevant background literature. Chapter 3 describes data collection and sites. Chapter 4 describes data analysis. Chapter 5 discusses major findings in the analysis. Finally, Chapter 6 concludes with a summary of the work and implications of the research results.

CHAPTER 2

BACKGROUND

Land Cover Effects on the Atmosphere

Terrestrial ecosystem dynamics influence atmospheric processes. Terrestrial ecosystem-to-atmosphere interactions include exchanges of heat, moisture, gases, aerosols, and momentum between land surfaces and the air above. These feedbacks represent a dynamic coupled system that is dependent on interactions between the two media. Variations in land surface properties cause horizontal variations in the surface energy budget. Studies have shown this variation can influence the amount of precipitation and its distribution (Pielke et al., 1998).

For over 20 years atmospheric general circulation models have demonstrated the sensitivity of global-scale atmospheric circulation and surface climate to changes in land surface conditions. Pielke et al. (1998) compared changes in land surface simulations to a control model. This approach shows the influence of terrestrial vegetation on climate. Recent approaches to studying these interactions involve the calculation of latent and sensible heat fluxes and integration from individual leaves to canopies to model grid cells. These land surface models capture some effects of nonlinear interactions between climate and ecosystems (Pielke et al., 1998). Terrestrial ecosystem dynamics are influential on Earth’s climate system.

Stohlgren et al. (1998) presented evidence that land-use practices in the Colorado Plains influence regional climate and vegetation in adjacent natural areas. Regional Atmospheric Modeling System (RAMS) simulations projected that modifications to natural vegetation in the plains, due to agriculture and urbanization, would reduce summer temperatures and increase stream flow in nearby mountains. As observational data supported the model simulation, the authors concluded that effects of land-use practices on regional climate may overshadow changes usually associated with increases in CO_2 and other greenhouse gases.

Pielke et al. (1999) investigated the influence of anthropogenic landscape changes on weather in south Florida. The period from July and August 1973 was examined for the region using observed data and RAMS. Three separate experiments were performed using a: 1973 landscape, 1993 landscape, and 1900 landscape (representing a natural surface). Reductions in rainfall were 9% and 11% for the 1973 and 1993 landscapes, respectively, when compared with model results from the 1900 landscape. Observational data were consistent with these trends. A reduction in evaporation from the Everglades is one possible cause of this rainfall reduction.

Surface energy budget components were investigated along a sharp boundary between agricultural and native vegetation in Australia (Esau and Lyons, 2002). A vermin-proof fence in Western Australia separated native woodland with lower ground shrubs from agricultural wheat fields. Averaged latent and sensible heat fluxes measured across the vermin-proof fence showed a sharp contrast. Lower sensible heat flux and higher latent heat flux were found over agricultural vegetation than native vegetation. Model calculations also showed significant horizontal heat and moisture flux from the agricultural to the native vegetation area. As a result of this heat and moisture flux, increased cloud formation and increased rainfall was noted over the native vegetation. Clearing for agriculture changed land surface characteristics which led to the redistribution of surface energy components and changes in the partitioning between sensible and latent heat fluxes. Clearly, changes in land use have an effect on weather and climate.

Midwestern Land-Use Change

The landscape of the North American Midwest underwent a rapid transition during the 19th and 20th centuries. Since the mid-1800s the landscape of the Midwest has been almost completely converted to agricultural fields. Ramankutty and Foley (1999) outlined the social circumstances that allowed this massive conversion to take place. The Homestead Act of 1862 provided 160 acres of government land free of charge to anyone who would cultivate that land for five years. This led to a rapid settling of those lands, especially after the Civil War. Building of canals and expansion of railroads allowed for quick transport of goods to market. Dryland farming in the Midwest and Great Plains began in the 1880s. At this time corn and wheat belts developed and were later pushed westward by rising land costs. The government passed a reclamation act in 1902 to provide irrigation resources to small farmers. This aided in agricultural development of the Midwest. Between the 1930s and 1950s more government-sponsored irrigation projects led to agricultural development in states further west. In the 1940s overall crop acreage began to stabilize in the U.S. However, in the last half of the 20th century technologic advances in farming equipment, pesticides, fertilizers, and plant genetics led to an increase in production like never before.

In addition to a historical view of agricultural land increase, Ramankutty and Foley modeled crop coverage from 1850 to 1990. By 1870 farms had crossed the Mississippi River and continued pushing west to the Rockies by 1910. From 1930 to 1950 expansion occurred mainly in Canada, but during this time agriculture intensified across the Midwest. By 1990, 80 to 100 percent of land was used for farming from eastern South Dakota and Nebraska, east through Iowa, Illinois, Indiana, and western Ohio.

Prairie/grassland and forest are the principal ecosystems that were replaced by cropland in North America. About 1.68 million km^2 of prairie/grassland and 1.40 million km^2 of forest have been cleared since 1850. During that time, cropland increased by over 2.0 million km^2. The majority of land surface in northern Illinois is now covered by corn and soybeans from mid-May through September. Corn and soybeans are the principal crops grown in northern Illinois and much of the surrounding region. Together they comprise 92% of all cropland and 70% of all land surfaces in northern Illinois (Univ. of Illinois, 2000). This massive conversion has affected many natural processes in the region.

Differences Between Crop and Natural ET

Brye et al. (2000) examined how land-use change from natural prairie to managed agricultural fields altered water budget components. Data were collected from a restored prairie and corn fields in south-central Wisconsin from June 1995 through January 1998. Weighing lysimeters were used to measure ET throughout the period. The prairie site was found to have significantly less drainage than the managed fields due to interception of precipitation by a residue later. ET data showed that the prairie began to transpire sooner than corn in the spring by six weeks and later into the fall by three weeks. This allowed for higher annual ET in the prairie site. However, during summer an actively growing corn crop produced about 10% more ET than prairie. These results suggest that conversion of prairie to agricultural fields has altered the hydrologic cycle by increasing drainage, increasing summertime ET, and decreasing annual ET.

While direct field measurements of crop ET are sparse, several studies have examined crop water use through the growing season. Al-Kaisi (2000) developed relationships between actual ET (hereafter AET) and potential ET (hereafter PET) for both corn and soybeans in Iowa. AET is attained by multiplying PET by a crop coefficient. This coefficient is the ratio between AET of the crop at certain growth stages and PET. A coefficient value of one would indicate the particular crop releases as much water through ET as an open water surface. The development stage of each crop has a large effect on ET. Corn produces highest ET values near mid-July and reaches a maximum coefficient of 0.8. Soybeans reach maximum ET slightly later in the season and have a larger coefficient value of up to 1.1. Annual total water use for each crop is approximately equal, from 21-22 inches in the central corn belt.

Rhoads and Yonts (1991) presented information on corn water use. Many factors affect crop water demand. Textural characteristics of soil type affect water storage capacity. Storage capacity ranges from 1.0” ft^{-1} for fine sand to 2.0” ft^{-1} for sandy clay loam. Root development is also an important factor. At tassel stages, root depth averages 2 feet, while by beginning dent root depth reaches 4 feet. This greatly affects the crops’ ability to remove water from the soil. Most importantly, growth stage of the crop dictates water demand. Within the first few weeks of planting, weekly ET averages near 0.5”. This value steadily increases to over 2” per week during pollination when sufficient soil moisture is present. Additionally, Hill (1993) and Ritchie (1994) examined how corn and soybean plants develop, respectively. Various plant growth stages require vastly different amounts of water, with corn generally requiring more water earlier in the season. The growth stages dictate when these crops will produce maximum ET, given adequate soil moisture.

Mahmood and Hubbard (2002) examined changes in the surface hydrologic cycle across Nebraska as a result of human-induced land use changes. Specifically, corn has replaced prairie in most of the area, and irrigation is common, especially in the central and western portions of Nebraska. A soil/water balance model was applied to three locations representing the east-to-west declining precipitation gradient in the area. Results for several variables were produced for rainfed corn, irrigated corn, and grass.

ET was found to be much higher for corn than grass, as much as 3 mm day^{-1} for a portion of the growing season. ET for irrigated corn was greatest and remained high later into the growing season than rainfed corn or grass. For McCook, Nebraska annual ET for irrigated corn was 36% higher than grass, and rainfed corn was 2% higher than grass. This irrigation resulted in an additional 50 million m^3 of water released into the air over 19,000 acres during the growing season. Simulations for Clay Center, Nebraska resulted in 100 million m^3 of excess water put into the atmosphere over a growing season compared to a natural grass surface. The impacts of land use on the atmosphere are significant. How this increase in water vapor over the Midwest has affected weather in a detectable manner is important.

Increased Midwestern Water Vapor Levels

Research by Bonan (1997) explored effects of land use on the climate of the U.S. Much of the evergreen, deciduous, and mixed forests of the eastern United States have been replaced with crops. Likewise, grasslands in the central U.S. have been replaced with crops. Results from a general circulation model coupled with a land surface model showed that the climate of the U.S. is different with current vegetation compared to climate with natural vegetation. Several climate shifts are caused by modern vegetation. Those notable to the central U.S. are: (1) cooling of up to 2° C during the summer, and, (2) moistening of the lower atmosphere by 0.5 to 1.5 g/kg in spring and summer. This moistening in the Midwest of up to 1.5 g/kg is a result of increased latent heat flux where crops have replaced natural vegetation (Bonan, 1997). Model simulations for several variables compared current vegetation with natural vegetation in the north-central U.S. Of note is a decrease in sensible heat, increase in latent heat, increase in infiltration, and increase in soil water during the summer months as a result of modern vegetation. The author states these climate changes were caused by an increase in surface albedo and reductions in surface roughness, leaf and stem area index, and stomatal resistance as a result of land use practices.

Numerous studies have examined dew point and surface humidity trends across the entire U.S. A study by Robinson (2000) assessed data from 178 stations from 1951-1990. Results showed increased dew points of about 1° C per 100 years in spring and autumn; slightly less in summer. The 1961-2000 period saw 1-2° C per 100 year increases. Rates of increase were higher in day than night, especially in summer. Increases during calm conditions were similar in magnitude to overall average changes. This suggests that the local hydrologic cycle is important in driving these changes (Robinson, 2000). Changes could also be attributed to the moisture content of incoming air masses.

On a more regional scale, Sandstrom et al. (2004) presented results of a central U.S. summer extreme dew point climatology. Data were examined for 68 stations in the central U.S. to determine changes in the occurrence of summertime dew point values greater than 22° C. Data were excluded if changes in equipment, station location, or instrument height produced statistically significant changes in the record. Results showed that much of the Midwest experienced a consistent increase in the frequency of extreme dew point values over time, while extreme values along the Gulf of Mexico coast were generally unchanged. This suggests that increases were not strictly the result of advection from the Gulf of Mexico; rather, regional enhancement played a larger role. Authors suggested the moisture source was related to ET from corn and soybeans, which nearly doubled in total acreage from 1950-2000. Additionally, during the last half of the 20th century, crop row width decreased, allowing for higher plant density per acre (Changnon et al., 2003).

Sparks et al. (2002) examined warm season surface dew points in northeastern Illinois. Records from Chicago O'Hare and Rockford airports were examined since 1959. The record was divided into two periods: 1959-1979, and 1980-2000. Results indicated that the occurrence of dew point values ≥ 24° C were much greater in the later period. The number of hours per year with a dew point of 24° C or higher for both Chicago and Rockford were more common for both locations since 1980. Interestingly, the three highest hourly dew point totals occurred at Rockford, and 13 of the 21 years from 1980-2000 saw higher totals at Rockford. While not statistically significant, these trends reveal more extreme values in the rural setting of Rockford than a more urban landscape in Chicago. ET from agricultural fields would locally be more significant at Rockford than Chicago. Authors speculated that causes of the overall increasing trend were regional enhancement from increased available soil moisture and increased ET rates from crops.

Extreme heat waves in Chicago were found more dangerous in the late 20th century as a result of increased water vapor levels (Changnon et al., 2003). The authors analyzed Chicago's 13 most intense heat waves that ran for three days or longer since 1928. Events were randomly distributed throughout the century, with the most severe in 1936 and 1995. Average dew points during the events showed an interesting trend. The five highest average hourly dew point events occurred since the mid-1980s. The lowest five dew point events occurred in or before 1971. The authors investigated possible causes of this trend and concluded that rainfall prior to the events and increased ET due to agricultural advances were likely causes of higher dew point levels. The authors determined that since the mid-1960s soybean acreage in the central U.S. has doubled. During the same time corn acreage remained relatively steady. Even without an acreage increase in corn, technologic advances in farm equipment, irrigation, hybrids, fertilizers, and pesticides allowed for higher plant density, greater yields, and possibly higher ET.

At least three documented dew point measuring instrument changes occurred during the last half of the 20th century. The first change included a replacement of sling psychrometers with lithium chloride hygrothermometers (HO-61) primarily used in the 1960s. Chilled mirror dew point hygrothermometers (HO-83) were introduced in the early to mid-1980s. A modification to the HO-83 units took place during the installation of the ASOS (Automated Surface Observing System) from the mid-1990s until 2000 (Gaffen and Ross, 1999; Robinson, 2000; Sparks et al., 2002; and Changnon et al., 2003). No shifts in the mean dew point values at the time of instrument changes were detected by Gaffen and Ross (1999) or Robinson (2000).

Impacts of increased water vapor levels are numerous. The human body cools itself through a process that evaporates moisture from the skin surface to the surrounding air. During high temperatures, when the body increases efforts to cool, higher atmospheric water vapor levels reduce the body’s ability to cool. This leads to higher heat stress and an increased potential for illness or death during heat events. Similarly, outdoor animals such as livestock are at greater risk of harm during such times. Energy demand related to air conditioning use is high during heat events. Those cooling systems that rely on evaporative cooling to operate are less effective in a high-moisture environment. Finally, increased thunderstorm frequency and intensity could result from higher water vapor levels. Increased low-level moisture assists in the initiation of deep convection. These convective events often occur as organized structures termed Mesoscale Convective Systems that can produce damaging wind, hail, and flooding rain.

CHAPTER 3

DATA COLLECTION AND SITES

Kansas Data

To determine the importance of land surface conditions on ET, a continuous data set was obtained from the Atmospheric Boundary Layer Experiment (ABLE) site located east of Wichita, Kansas, on the lower Walnut Watershed, at coordinates 37°N, 97°W (Figure 1).

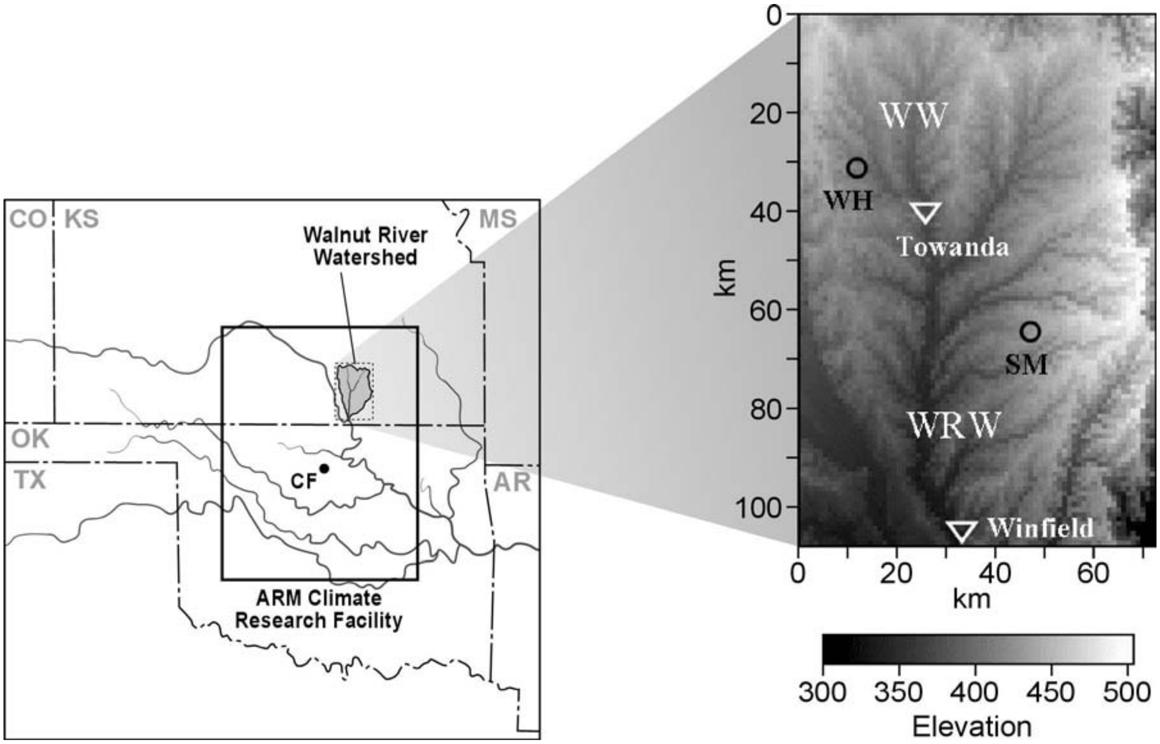

Figure 1. Kansas site locations with WH representing Whitewater and SM representing Smileyberg.

The watershed has an area of approximately 5,000 km^2, and is located within the Atmospheric Radiation Measurement Climate Research Facility. Average annual rainfall in the watershed varies from 76 cm in the west to 86 cm in the east. Daily average temperatures vary from 32° F in the winter to 79° F in the summer (www.kwo.org/Org_People/walnut.htm). Data were obtained for every half hour from 2000-2003 at Whitewater (ungrazed prairie) and 2000-2002 at Smileyberg (grazed prairie). To derive sensible and latent heat fluxes two different techniques were used: Bowen ratio for Whitewater and Eddy correlation for Smileyberg.

There are distinct differences between these techniques: Bowen ratio is an indirect measurement technique where gradients, which are a reflection of the effects of transport mechanisms, are measured; Eddy correlation is a direct measurement technique where physical measurements of transport mechanisms are captured. The
Bowen ratio technique is the same method used in collection of northern Illinois data and described later. The Eddy correlation technique is based on the statistical correlation of vertical wind speed with another quantity such as temperature or water vapor. The transport characteristics of eddies in the surface layer determine the effectiveness of this technique (Cook, 2004). Because this is a statistical technique where the sample represents the total population of eddies, a sufficiently long averaging period of eddies that develop over the desired surface is necessary. For these reasons, the horizontal advection of air parcels with differing characteristics than those desired (such as eddies that develop over a surface other than that being studied), reduces the effectiveness of this technique.

For both methods, provided data consisted of day, time, temperature, relative humidity, wind speed, net radiation, ground heat flux, and soil moisture. Soil moisture was measured at a depth of 2.5 cm, representing the 0-5 cm average soil moisture value. NDVI data were manually collected periodically throughout the growing seasons. Latent and sensible heat values for every half hour were computed and provided.

Several corrections were made to the raw data. First, erroneous data and spikes were removed and replaced through linear interpolation. Then, missing data were replaced by linear interpolation or extrapolation of data from days with similar environmental conditions. Next, the half hourly data were averaged into a daily average value for each variable for ease in analysis, and daily average ET values were computed from latent heat values. Now, fair analysis within each site was possible.

The effects of soil moisture, available energy (net radiation minus ground heat flux), and plant health (NDVI) on ET were analyzed. After this analysis, an additional analysis examined the effects of soil moisture and NDVI on Bowen ratio. Finally, an analysis of annual differences within and between Whitewater and Smileyberg was conducted. Due to differences in climate between Kansas and Illinois, and different measurement techniques and instrumentation, comparisons across geographic regions was not performed. However, the same physical mechanisms that drive ET and affect Bowen ratio in Kansas do the same in Illinois. With high-quality, continuous data available, the importance of surface conditions such as NDVI and soil moisture on ET could be examined from this data set.

Northern Illinois Data

To determine the effects of modern vegetation (agriculture) on ET, a field experiment was conducted during the summer of 2003 in northern Illinois. Data were collected from principal crops in the region: corn, soybean, and winter wheat. Data were also collected from a field site representing natural land cover: prairie.

The corn (Zea mays) field site was located approximately four miles east of Colona, Illinois (Figure 2, number 1), 41º 28’ N, 90º 19’ W, 600 feet above mean sea level. The 130-acre field was planted on 5 May with Pioneer 32K61 seed at a density of 30,000 seeds per acre (Minneart, 2003). Soil type varied from sandy clay to clay, as it was located in the Green River valley.

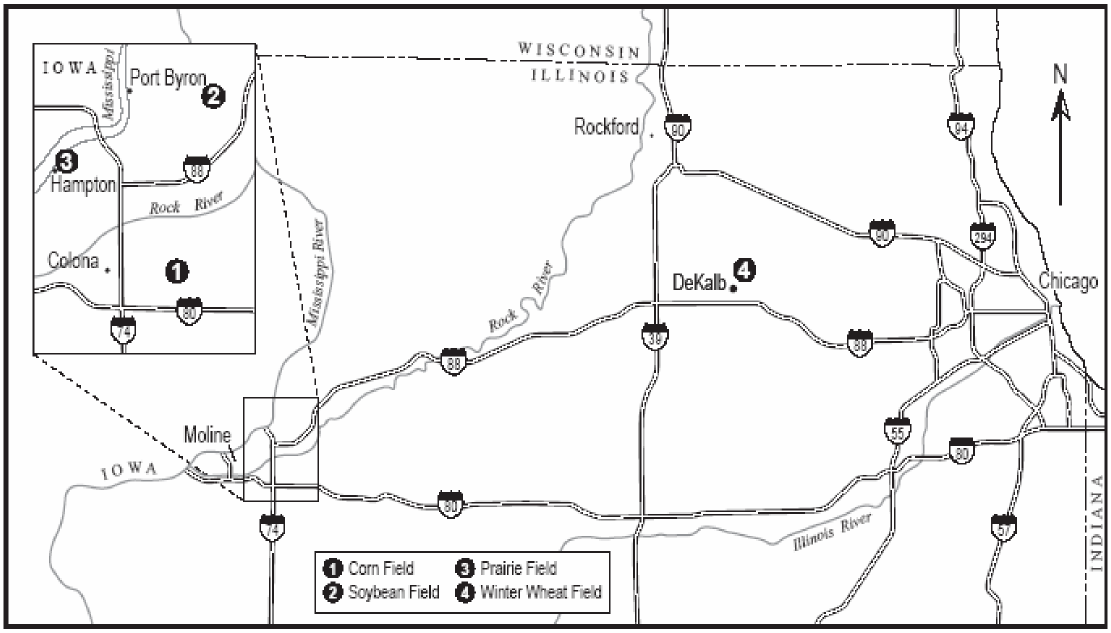

Figure 2. Northern Illinois field locations.

The soybean (Glycine max) field was located approximately six miles east of Port Byron Illinois (Figure 2, number 2), 41º 37’ N, 90º 19’W, 700 feet above mean sea level. This 140-acre field was planted on 14 May with Garst 2603 seed at a density of 200,000 seeds per acre (DeKlerk, 2003). Soil type was clay loam, located on a bluff east of the Mississippi river.

The winter wheat field was located approximately two miles northeast of DeKalb, Illinois (Figure 2, number 4), 41° 90’N, 88° 75’ W, 880 feet above mean sea level. This 30 acre field was planted in the fall at a seed density of 100 lbs. per acre. The crop was harvested on 14 July.

The natural prairie site was located in Hampton, Illinois (Figure 2, number 3), 41º 33’ N, 90º 24’ W, 680 feet above mean sea level. This location was approximately 0.5 miles south of the Illiniwek Forest Preserve. The preserve contains thousands of acres of forest and hundreds of acres of prairie. The chosen prairie was 21 acres, surrounded by hundreds of acres of forest.

Field measurement of ET was obtained through use of a Bowen ratio energy balance system (hereafter BREB) (Tanner, 1960). This system measures net radiation, ground heat flux, and temperature and humidity gradients above a surface. Combining these data with energy balance equations provided the elements for calculating ET (Kjelgarrd et. al., 1994). Relatively accurate energy balance measurements can be obtained through use of a BREB system (Tanner, 1960).

Equations

For a BREB measurement, surface energy input is in the form of shortwave solar radiation (K↓) and longwave radiation from the atmosphere (L↓). Radiant energy fluxes from the surface are in the form of reflectance (K↑) and longwave radiation emitted from earth (L↑). The following equation quantifies the radiation budget at Earth's surface:

$$Q^* \text{ (net radiation)} = (K\downarrow + L\downarrow) - (K\uparrow + L\uparrow) \tag{2.1}$$

Therefore, Q* is the resulting surplus or deficit of energy at the surface. If Q* is positive, energy is being used to heat the ground (G), to heat the air in the form of sensible heat (H), and used to evaporate water from the surface (Le). IF Q* is negative, energy is given from the surface to the atmosphere, resulting in surface cooling and condensation. Net radiation provides energy for warming the atmosphere and ground, and can be expressed as:

$$Q^* = H + G + Le \tag{2.2}$$

Instruments used in BREB systems are able to directly measure Q* and G. Partitioning of the residual energy into H and Le are derived from the BREB measurements. The BREB system helps quantify how Q* is partitioned into H and LE:

$$H = \beta Le, \tag{2.3}$$

$$Le = (Q^*-G) / (1+ \beta), \tag{2.4}$$

where the Bowen ratio (β) (Bowen, 1926) is the ratio of the vertical flux of sensible heat (H) to the vertical flux of latent heat (Le),

$$\beta = H / Le, \text{ or,} \qquad (2.5)$$

$$\beta = \{Ca\ (dT)\} \ / \ \{1/(Rv/T_{avg})\ (de)\}, \qquad (2.6)$$

Ca = heat capacity of dry air

dT = temperature difference between two levels in degrees Kelvin

Rv = gas constant for water vapor

T_{avg} = average temperature between two levels in degrees Kelvin

de = vapor pressure difference in hecto-Pascals (hPa)

Now, Le can be computed:

$$Le = (Q^* - G) / (1 + \beta) \qquad (2.7)$$

So, Le can be found using (2.7) and sensible heat (H) can be found as the residual of (2.5) with Q* and G known.

Use of BREB to partition sensible and latent heat fluxes assumes that the exchange coefficients are equivalent. Also, fluxes must be constant with increasing height in the boundary layer (Oke, 1987). These conditions are met on days with clear skies and light winds, when horizontal advection is small and the boundary layer is unstable. Under proper conditions with the measurements of Q*, G, and temperature and water vapor gradients in (2.6), latent and sensible heat can be accurately derived using the BREB.

Much can be learned about the local energy balance through partitioning of energy into its various components. Due to the complexity and maintenance needs of these instruments, long-term energy balance measurements are uncommon. These measurements are usually confined to special field projects and highly maintained networks such as the Oklahoma Mesonet and Atmospheric Boundary Layer Experiment.

Instrumentation

Gradients in air temperature and vapor pressure must be measured to satisfy (2.6). Additionally, ground heat flux (G) and net radiation (Q*) values are necessary to complete equations (2.1) and (2.2). Table 1 summarizes instruments that were mounted on a portable, adjustable tripod to make the required measurements:

Table 1

Instrumentation used for BREB northern Illinois study

Instrument	Manufacturer	Measurement	Accuracy
Net Radiometer	Campbell Scientific	Net Radiation (W/m^2)	Not specified
AT/RH (2)	Met One Instruments	T (°C), RH (%)	± 0.1° C, ± 2%
Ground heat flux	Campbell Scientific	Ground heat flux (W/m^2)	± 5%

Net Radiometer

Net radiometers, also known as net pyrradiometers, measure total global radiation: shortwave and longwave. The surface consists of a black plate where a thermopile sits with one set of junctions in contact with the upper face and the other with the lower face. A thermopile consists of at least two thermocouples connected in series so that alternate junctions are at the measuring temperature and reference temperature. In this way the thermoelectric voltage is amplified. Once the measuring surface is aligned parallel to a flat surface, the thermopile output is directly related to the temperature difference across the plate. This temperature difference is proportional to the difference between incoming and outgoing radiation fluxes at all wavelengths (Oke, 1987).

The sensor is actually measuring the difference in the energy balance of the two surfaces. This balance can be affected by radiative and convective exchanges. To reduce the effect of wind on the plate, the surface is shielded with a dome of silicon or polyethylene. These materials are nearly completely transparent to radiation with wavelengths from 0.3 to 100 microns. The domes also protect the sensor from handling and weather-related damage.

Sensors must be mounted level to accurately sense fluxes. The Q-7.1 has a bubble level near the sensor head that is accurate to ± 1 degree. The sensor must be installed facing due south so no mounting equipment casts a shadow on the sensor. There should be no obstructions between the lower-facing sensor and the ground. Anything located in the downward-looking footprint will alter the outgoing longwave and reflected shortwave readings. Finally, the instrument should be located in a place free from shade and reflections for the entire measurement period. If the above requirements are met, accurate readings are possible.

For the purpose of BREB measurements, the Q-7.1 net radiometer manufactured by Radiation and Energy Balance Systems and sold through Campbell Scientific is relatively inexpensive and accurate. It contains a 60-junction thermopile with a small resistance of four ohms and linear calibration. There is a built-in level and ball joint for ease in leveling. The frame and surfaces are black to reduce internal reflections. Spectral response is 0.25 to 60 microns, with a time constant of 30 seconds and an uncorrected wind effect of up to 6% reduction at 7 ms^{-1}. This economical sensor is widely used for short-term studies.

AT/RH Probe

AT/RH probes are designed to measure the air temperature and relative humidity. More specifically, in relation to the measurement of latent and sensible heat fluxes through the use of BREB, two AT/RH sensors are placed at a vertical distance apart from one another. The relative humidity sensor measures relative humidity through a change in capacitance of a polymer thin film capacitor. The polymer layer absorbs water molecules through a thin metal electrode and the capacitance change caused by the absorption of water molecules is proportional to relative humidity (Met One Instruments, 2004).

The temperature and relative humidity sensors are both located at the far end of the probe. The remainder of the probe contains the electronics that are necessary to provide readable output. The sensors themselves are protected by a membrane filter. Since AT/RH probes measure air temperature, the same exposure errors experienced by air temperature sensors occur in AT/RH probes. AT/RH probes should be placed in a radiation shield without forced aspiration when in use outside. The radiation shield limits the amount of error caused by shortwave and longwave radiation (Brock and Richardson, 2001).

The 083-D AT/RH sensor is available from Met One Instruments, Inc., and is the particular sensor is used for BREB measurements in this study. The relative humidity sensor is located in a small probe with options for a temperature sensor to also be mounted inside the probe (required for all meteorologically-related measurements). The probe body itself is made of corrosion-resistant aluminum and is water tight. The relative humidity sensor in the probe produces relative humidity readings from 0-100% with accuracies of ± 2-3%. The temperature sensor records temperatures in the range of -20° C to 60° C. Response time is typically less than 15 seconds. The instrument is 190.5 mm in length and 19 mm in diameter, meaning it is small and easily portable. Due to the lower price and moderate accuracy, the AT/RH probe is ideal for use in field measurement.

Ground heat flux sensor

Ground heat flux plate sensors are designed to measure the heat flux at the surface. Soil heat flux often consumes 5-15% of the energy from net radiation (University of Nebraska-Lincoln, 2004), so it is important to consider and measure this quantity, especially in a BREB assessment study. Most heat flux plates use a thermopile to measure gradients in temperature across the plate. The thermopile is enclosed in a plastic filling material. Each individual thermocouple in the thermopile generates an output voltage that is proportional to the temperature difference across the plate. When many of the individual thermocouples are used, such as the setup in a typical thermopile, the net output will provide a more accurate value. Soil heat flux is measured in Watts per square meter (W/m^2).

The installation of ground heat flux plates must follow a strict set of guidelines if proper and accurate measurements are desired. First, the ground heat flux plates must be inserted into an area that is representative of the majority of the desired study area (Campbell Scientific, Inc., 2004). It is important for the soil heat flux plates to be located from 1-8 cm below the surface to minimize the effects of the disruption of root growth, natural flow of water, and to eliminate the possibility of exposure to direct sunlight through cracks in the soil surface (University of Nebraska-Lincoln, 1999).

The soil heat flux plates should be placed approximately 1.0 m apart to ensure accurate sampling. It is also important to keep the soil as undisturbed as possible when placing the ground heat flux plates in the soil. This provides more accurate and representative measurements of the soil heat flux around the study location. The plate must also be in full contact with the soil (Campbell Scientific, Inc., 2004).

Campbell Scientific, Inc. manufactures the Model HFT3 soil heat flux plate. The operating temperature range is -40° C to 55° C and the plate has a thickness of 3.91 mm and a diameter of 38.2 mm. It is able to measure heat flux over a range of ± 100 W/m^2 at an accuracy of better than ± 5% of the reading.

These instruments were connected to a Campbell Scientific CR-10 data logger programmed to take a reading every five seconds and store an average value every five minutes. The CR-10 was housed in an environmental-fiberglass case along with a 12V battery to power the array. A solar panel manufactured by Solarex was mounted on the tripod to charge the battery. The tripod was fully collapsible and extendible to a height of 2.7 m. To measure the temperature and vapor pressure gradients required by (2.6), the two AT/RH sensors were placed at a vertical distance of 1.0 m apart. When the top of the corn canopy reached the height of the lower AT/RH sensor, the entire tripod was raised to keep the lower sensor above the top of the canopy. Ground heat flux sensors were consistently buried approximately 4.0 cm below the surface. The array was placed as to maximize sampling fetch. Adequate fetch requires 20 times the height of vegetation to capture steady state conditions. Typically setup occurred with at least 500 m of upwind vegetation. Figure 3 shows the array after full setup.

Figure 3. Bowen ratio energy balance equipment in field setup.

Several errors may have been introduced either inadvertently or by the nature of the BREB system.

- The BREB system assumes “forced closure” of the energy balance. In truth, there is about 10% heat storage within the canopy. This value was not accounted for.
- Additional assumptions are that the canopy and soil are homogeneous; this is rarely true.
- Soil heat flux is difficult to accurately measure unless thermal conductivity of the soil is known. Soil thermal conductivity was not measured.

- While AT/RH probes were calibrated within 0.1° C and ±2% for temperature and relative humidity, respectively, any bias within these sensors introduced errors.
- AT/RH sensors were consistently located at a fixed level above the canopy regardless of canopy height. For ideal measurements the lower sensor should continuously be adjusted to be at 1.25 times the height of vegetation, with a 1.0 m separation between sensors. When the vegetation becomes tall (> 2 m), ideal separation between sensors is 2.0 m to capture larger transporting eddies (Cook, 2004). Tripod configuration did now allow for adjustment of sensor height. However, the entire array was raised to keep the lower AT/RH sensor above the corn canopy in late summer.

These errors are acknowledged and may have impacted results. However, these errors should be uniform regardless of the vegetation type measured. Uniform error should allow for fair comparison of results among the three vegetation types studied.

Data were downloaded in the field to a laptop computer. Data from all measurements were subjected to quality control (Ohmura, 1982) to ensure accurate readings. For example, data spikes and questionable data were removed and replaced by linear interpolation. Data were then entered into a FORTRAN program (Appendix A) to compute sensible and latent heat fluxes, Bowen ratio, and ET (mm/m^2) for the observation period, 8:30 A.M. to 4:30 P.M., local daylight time.

Several additional field instruments were used to obtain supplemental data. To measure the Normalized Difference Vegetation Index (NDVI), a multi-spectral radiometer (MSR) was connected to a MSR data logger. Four separate measurements were averaged to attain an NDVI reading. To measure leaf area index (LAI), a linear

PAR ceptometer (Decagon Devices) was used. Again, four measurements were averaged to obtain a LAI value. To obtain soil moisture readings, a soil sample cylinder was used. The moist sample was weighed, dried at 100ºC for 72 hours, then weighed again. The difference in weight, (wet-dry), divided by the dry weight, gave a percentage of soil moisture.

CHAPTER 4

DATA ANALYSIS

Kansas Data

The long-term continuous nature of this dataset allows for a detailed examination of how soil moisture, available energy, and plant health drive ET and affect surface energy fluxes. All data analysis were based on average daily data. Data were first analyzed on a monthly time-scale for ET, then on a daily time-scale for Bowen ratio, and finally annual comparisons within each field were conducted. Again, the Whitewater site represented an ungrazed prairie that was measured using a Bowen ratio energy balance technique, while the Smileyberg site represented a grazed prairie which was measured using the Eddy correlation technique. The Whitewater site was cut for harvest once annually in late July.

The methods used for this study do not allow for direct comparison between field sites due to the fact that different instruments and different flux measurement techniques (Bowen ratio energy balance for Whitewater and Eddy correlation for Smileyberg) were used. The eddy correlation method is known to underestimate surface energy fluxes by 10-20%. The inherent variance allowed in the adjustment of the values using this technique could artificially skew results. However, relevant conclusions can be made about the effects of available energy, soil moisture, and plant health on ET for each field.

Effects on Evapotranspiration

Whitewater: ungrazed prairie

Graphs of ET, soil moisture, available energy, and NDVI for Whitewater are presented in Figure 4 (a-d). All data were available for the period of 2000-2003 except August 2003. NDVI measurements were taken manually periodically through each growing season; hence the scattered data present in Figure 4d. General trends show a rapid increase in ET during the spring to a peak in June of 3.5-4.5 mm/day. Then ET drops sharply in July, followed by a more gradual decrease for the rest of the year. Volumetric soil moisture shows high values of 25-45% during the spring, followed by a decrease through the summer to a low of 5-20% during late summer, then a recharge toward higher values during late fall and winter. Available energy is very consistent from year to year following the solar cycle. Highest values occur during summer with a peak of 160 W/m^2 per day in July. NDVI values show a high degree of variability both inter-annually and intra-annually. This variability is closely related to the variability seen in soil moisture, both of which impact ET.

To determine the effects of these variables on ET, intra-annual ET differences were analyzed. July showed large ET variability, with a high of nearly 4.0 mm/day in 2000 and a low of only 2.0 mm/day in 2002. Examination of available energy showed nearly identical energy values for both years, so this did not influence ET differences. However, soil moisture was much greater in 2000 than 2002 (17% versus 7%), and NDVI values were slightly higher in 2000 (0.48 to 0.42). This suggests that higher soil moisture in 2000 promoted healthier vegetation, which led to higher ET.

Another example of significant ET differences was in September, where 2003 reached ET values of 2.3 mm/day, while 2000 ET values only reached 1.1 mm/day. Available energy was slightly higher in 2003, and soil moisture values were much higher in 2003 (33% versus 6%). NDVI data were not available for comparison. Further analysis of these graphs shows the same general trends: intra-annual ET variability can be explained by variation in soil moisture and NDVI, while available energy differences are small enough to have little influence. Higher ET values are found when higher soil moisture and better plant health are present.

Smileyberg: grazed prairie

Graphs of ET, soil moisture, available energy, and NDVI for Smileyberg are presented in Figure 5 (a-d). Overall trends at Smileyberg were similar to Whitewater. ET increased through the spring to a peak in mid-summer, then declined in the fall; this trend matches the available energy curve. Also, soil moisture was highest in the spring, then declined to a yearly minimum in late summer, before recharging in the fall. As was seen in the Whitewater graphs, distinct ET differences are present from year to year which can be explained by soil moisture, NDVI, and available energy data.

June ET values ranged from a maximum of 5.0 mm/day in 2002 to a minimum of 3.8 mm/day in 2001. Results from Whitewater would suggest that higher 2002 ET values result from higher soil moisture and higher NDVI. Soil moisture actually showed the opposite trend with 2002 drier, although only by 4% (26% in 2001 to 22% in 2002). NDVI was slightly higher in 2002 at 0.62, versus 0.59 in 2001. Also, available energy was greater in 2002 by 16 W/m^2. So with slightly less soil moisture, but slightly higher NDVI and available energy, ET was greater in June 2002.

One month later significant ET differences arose again. Maximum July ET was 5.5 mm/day in 2000, while a minimum occurred in 2002 at 3.6 mm/day. As expected, soil moisture was higher in 2000 (22% versus 13%), NDVI was higher in 2000 (0.70 versus 0.58), and available energy was higher in 2000 (181 versus 171 W/m^2). One final comparison was made for September when 2002 ET was 2.7 mm/day and 2000 ET was only 1.3 mm/day. Once again, soil moisture was higher in 2002 (16% to 9%), NDVI was higher in 2002 (0.55 to 0.40), and available energy was nearly the same for both years. Smileyberg results support the analysis results from Whitewater data: variation in ET can be explained by soil moisture and NDVI, and to a lesser extent, available energy.

Effects on Bowen Ratio

An analysis was conducted on the Kansas data to determine effects of soil moisture and NDVI on Bowen ratio. Since the Bowen ratio is defined as sensible heat flux divided by latent heat flux, lower Bowen ratio values mean more available energy is partitioned into ET from the surface - soil and vegetation. Conversely, higher Bowen ratio values correspond with more energy directed toward heating the surface.

Figure 6a (Smileyberg 2000) presents soil moisture, NDVI, and Bowen ratio by day of year. Soil moisture data had a predetermined maximum of 0.46, and minimum of 0.03. NDVI data were collected at about two-week intervals during the growing season and several samples were taken on each measurement day. The range of NDVI shows the heterogeneity of the surface. Soil moisture and NDVI correspond to the left y-axis, while Bowen ratio corresponds to the right y-axis. Some Bowen ratio values were greater than the maximum value of the scale, especially early and late in the year, but the scale was truncated at 5.0 to show better detail during the growing season. These Bowen ratio values are derived from an average of midday values, 12 P.M. to 3 P.M. local daylight time. Figure 6b represents Whitewater 2001, and is analogous to Figure 6a, except maximum soil moisture was set at 0.38, and minimum at 0.02. Graphs for each year, for each field were generated and analyzed; however, presentation of these two graphs represents all years well.

Smileyberg 2000 (Figure 6a) showed high soil moisture, near 0.40, for the first 100 days of the year. Soil moisture gradually declined through the summer, although large spikes resulted from rainfall. There was a significant dry period in early fall, followed by wetter conditions later in the fall. NDVI data showed a green-up of the prairie around day 125 (early May), with a large range of values until mid-summer. Maximum NDVI values near 0.70 occurred in mid to late summer, then decreased through the fall. Bowen ratio values were high through winter and early spring, generally greater than 2.0, and then decreased below 1.0 once the prairie green-up

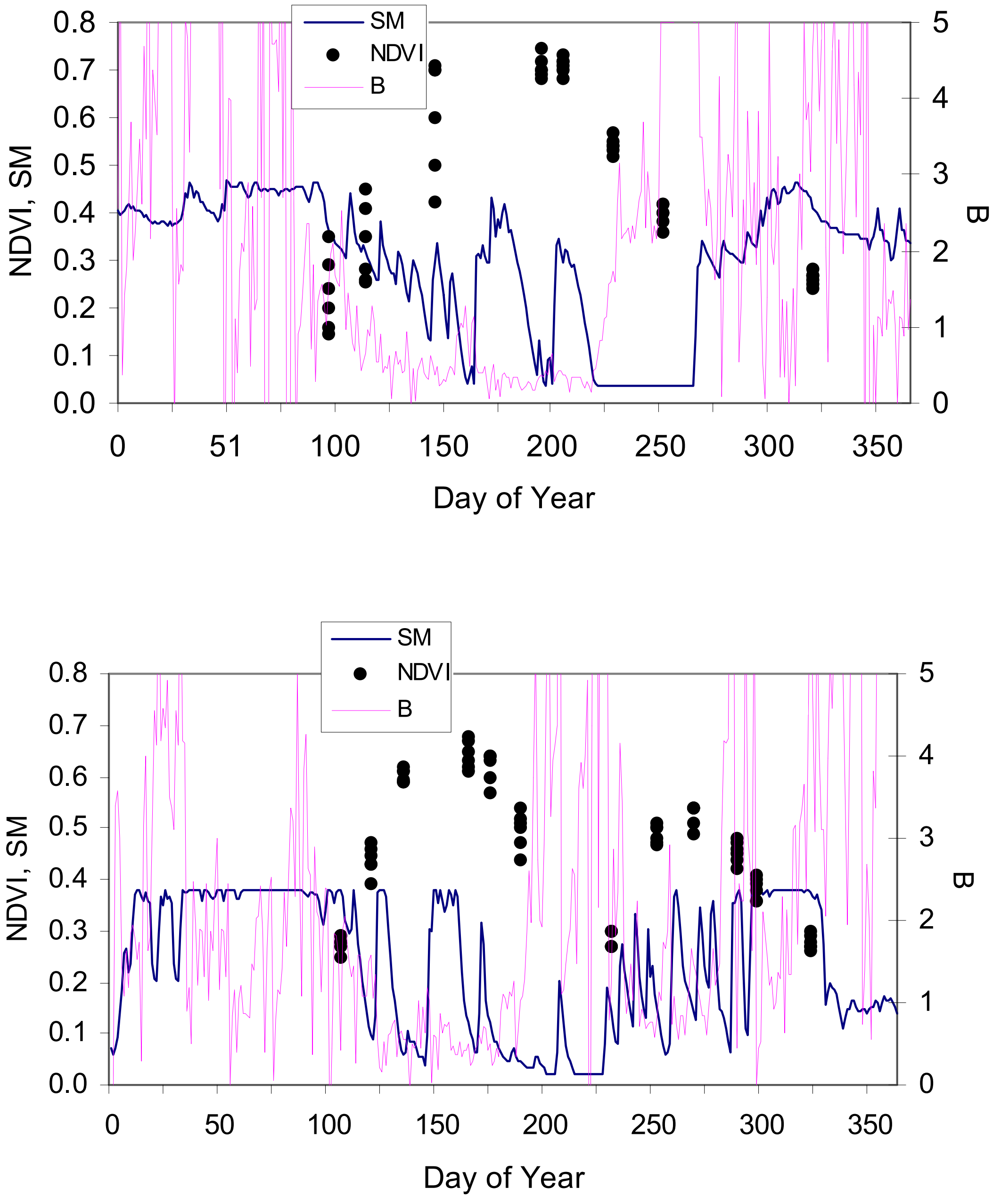

Figure 6. Soil moisture (SM), NDVI, and Bowen ratio (B), for (a) Smileyberg 2000 and (b) Whitewater 2001.

occurred. Lowest Bowen ratio values occurred from days 125-225, when NDVI values were highest. During this time local spikes in Bowen ratio occurred when soil moisture was low, and dips in Bowen ratio occurred when soil moisture was high. When significant drying occurred from days 220-260, Bowen ratio rapidly increased. Bowen ratio remained high through the fall, with spikes and dips corresponding to low and high soil moisture values, respectively.

Whitewater 2001 results (Figure 6b) were similar to Smileyberg 2000. Highest Bowen ratio values occurred in fall through early spring when NDVI values were low and soil moisture was high. Lowest Bowen ratio values occurred from days 125-175 when high NDVI (>0.50) was coupled with adequate soil moisture. NDVI dropped to 0.30 near day 225 as a result of the prairie being cut. NDVI then jumped to 0.50 from days 250-275. The NDVI drop resulted in a spike in Bowen ratio to values greater than 2.0, then as NDVI increased, Bowen ratio dropped to 1.0-2.0. As in Smileyberg, jumps in soil moisture correspond to dips in Bowen ratio, and dips in soil moisture result in spikes in Bowen ratio. One difference noted in the Whitewater graph is more consistent NDVI values, likely the result of this prairie being non-grazed.

Figures 6a and 6b clearly illustrate the dependence of Bowen ratio on soil moisture and NDVI. When NDVI is high more energy is partitioned toward ET (low Bowen ratio). However, if there is little water available as shown by low soil moisture, more energy is available to heat the surface (high Bowen ratio). Distinct seasonal variations occurred. High soil moisture from late fall through early spring does not result in low Bowen ratio values because healthy vegetation is not present. Only when high

NDVI values are coupled with adequate soil moisture do lowest Bowen ratio values occur.

ET is driven by atmospheric effects such as solar energy, humidity gradients, wind speed, and available moisture (Robinson and Henderson-Sellers, 1999). Through analysis of real data this portion of the study is able to support this knowledge base. ET over healthy vegetated prairie generally mimics the available energy curve over the course of a typical year. A reduction in soil moisture tends to decrease ET, especially during summer when available energy is high. This finding is supported by other research (Song et al., 2005). Soil moisture has a much smaller effect on ET during spring and fall, when available energy is low. A good example of the available energy/soil moisture effect is Smileyberg in 2000-2002 (Figure 5). Both 2000 and 2001 saw highest ET values in July due to high available energy and sufficient soil moisture. However, in 2002 ET was lower in July than either June or August. Results showed that soil moisture reached a yearly minimum in July, while available energy was less in July than June, and only slightly higher than August. Clearly, ET is driven by these two variables. Since NDVI values indicate crop health, they match well with ET values. NDVI is strongly related to soil moisture. While available energy is generally consistent from year to year at a given location, soil moisture has much greater variability due to seasonal precipitation. This variation can have a significant effect on plant health and ET, especially during the June through August period, when available energy is highest.

Annual Comparisons

A final analysis of the Kansas data examined annual ET, Bowen ratio, and soil moisture (Figure 7). Annual total ET for each field showed large variation, ranging from 625 mm to 725 mm at Whitewater, and 748 mm to 825 mm at Smileyberg. These ET values are very similar to average annual precipitation. These similarities indicate that advection of Gulf of Mexico moisture, both at the surface and aloft through the low level jet, contribute to regional rainfall.

While strict comparison between fields is not wise due to measurement technique and grazing differences, general trends can be analyzed. The large ET gap between fields can be attributed to a large disparity in soil moisture. Figure 7 shows a 3-7% excess in soil moisture at Smileyberg. With more available soil moisture at Smileyberg greater ET was produced on an annual basis. These higher soil moisture values were likely the result of soil quality differences between the sites. Previous results of the Kansas data set suggest that higher ET values correspond with a lower Bowen ratio. However, examination of Figure 7 shows that higher Bowen ratio values were found at Smileyberg than Whitewater. One possible explanation of this trend is that grazing reduced above-ground biomass to a point where substantial amounts of bare soil were present. Evaporation would occur quickly from this bare soil, contributing to ET, but once the soil dried, higher Bowen ratio values would result.

While solar energy drives ET, this portion of the study supports the view that vegetation also has a strong influence on ET. Clearly, soil moisture and plant health

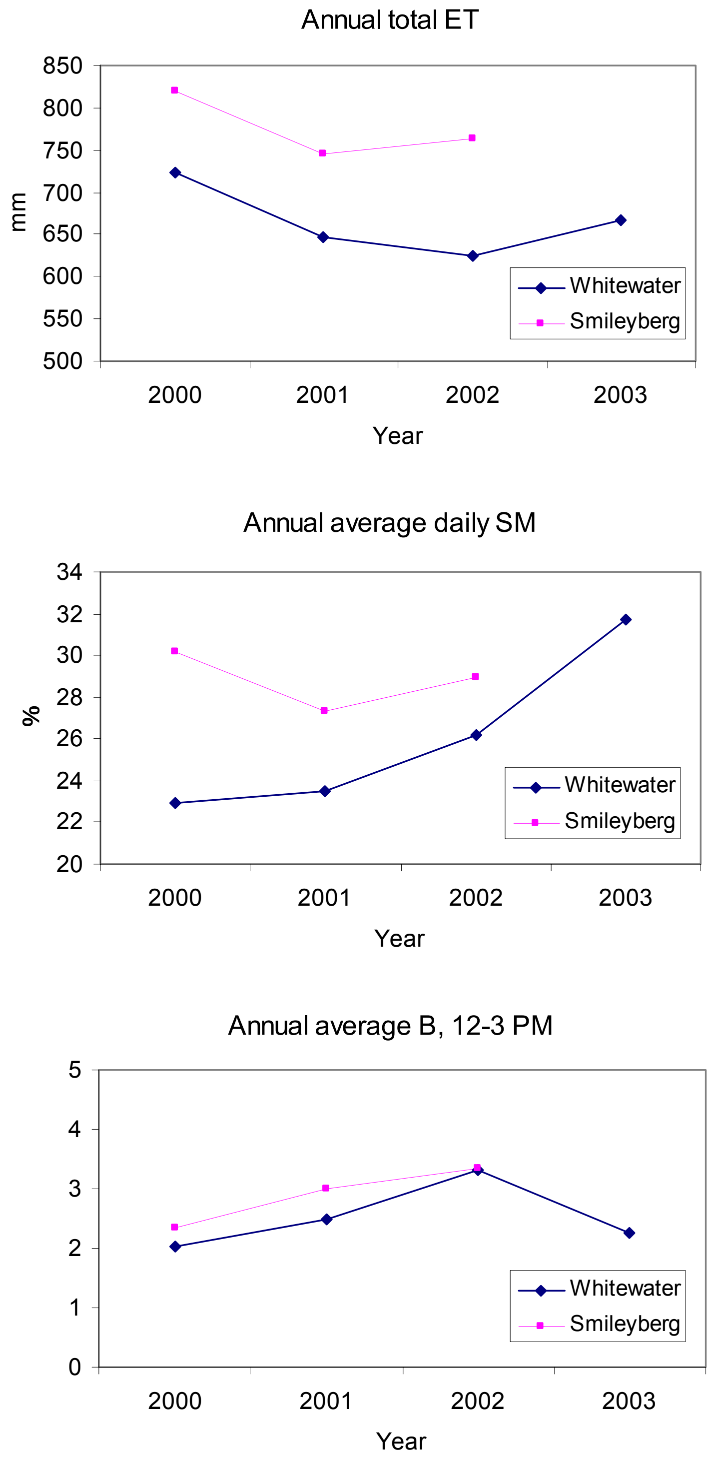

Figure 7. Annual ET (a), soil moisture (b), and Bowen ratio (c) for Whitewater and Smileyberg.

play an important role in ET, and extremes could significantly raise or lower ET values in any given year. Land cover and soil moisture effects on ET are strong. Highest ET occurs when substantial soil moisture and robust plant health are present. Of course solar energy drives the ET process, but does not vary significantly from year to year at any particular location.

One possible link for qualitative comparison between the Kansas and Illinois datasets is the Bowen ratio relationship for the ungrazed Whitewater Kansas prairie and the Illinois prairie. Measurement technique differences should not significantly affect Bowen ratio values. Data from mid June, mid July, and mid August, 2003, were compared between the sites. Both sites exhibited midday Bowen ratio values between 0.26 and 0.44 over the comparison periods. This homogeneity indicates that over a given surface, the partitioning of latent and sensible heat is approximately equal, regardless of distance or climate division. The same physical processes that drive and affect ET in Kansas do the same in Illinois. With a solid understanding of what drives ET for a given surface, attention now turns to ET differences over several different vegetative surfaces in northern Illinois.

Northern Illinois Data

Field data were collected from northern Illinois during the summer of 2003 and consisted of Bowen ratio energy balance data from several fields: corn, soybean, winter wheat, and prairie. Because only one growing season worth of data was collected, weather anomalies during this season could have influenced results. For this reason, an extensive study of weather effects on corn and soybean yields in northern Illinois was conducted. The growing season of 2003 was compared to a 54- year record of weather and yield relationships to determine how representative 2003 was.

Standardized regression parameter estimates were used to quantify the effects of growing season temperature (May through August growing degree days) and rainfall (May through August precipitation) on yield. These parameter estimates remove the mean and units of regression, allowing for a fair comparison among variables. It is assumed that high yields result from healthy plants, and healthy plants produce more ET than unhealthy plants. Relevant results for soybeans showed that high yields were most dependant on abundant August precipitation, followed by high June and July precipitation. For corn, better yields are expected when July precipitation is high, August temperatures are cool, and August rainfall is high.

These results match well with weather conditions and yield reports in 2003. Adequate July rainfall and few negative factors allowed for high corn yield. Hence, ET rates are expected to be representative of a “good” year. On the other hand, very dry conditions experienced in August led to lower soybean yields. So, ET rates for soybeans, especially later in the growing season, are likely an underestimate of what would be obtained in more favorable years.

The field measurement part of the study took place between spring and late summer. In the northern cornbelt this period is characterized by warm temperatures and highly variable rainfall. To assess how summer 2003 conditions varied from the 30-year average (1971-2000), data were downloaded from the Midwestern Regional Climate Center (mcc.sws.uiuc.edu) for three stations in northern Illinois: Geneseo, Moline, and

Morrison. Precipitation and modified growing degree days (base = 50º F, ceiling = 86º F) were analyzed for May 1 through August 31. Data were averaged for the three stations. Climate results are presented in Tables 2 and 3.

Table 2

Summer 2003 rainfall in a climatological perspective

Station	2003 Precipitation*	30-year Average	Difference
Moline	14.96”	17.32”	-2.36”
Geneseo	15.17”	16.63”	-1.46”
Morrison	14.8”	17.27”	-2.47”
Average	14.98”	17.07”	-2.10”

* May 1 - Aug. 31

Table 3

Summer 2003 temperature in a climatological perspective

Station	2003 Degree Days**	30-year Average	Difference
Moline	2415	2456	-41
Geneseo	2408	2496	-88
Morrison	2131	2320	-189
Average	2318	2424	-106

May 1 - Aug. 31

** Modified Growing degree day (base = 50, ceiling = 86)

Precipitation for May through August was 14.98”; over 2” below average. Much of the dryness occurred in August, with many stations receiving approximately 1” of rain (4” is average). Temperatures were slightly cooler than average with 2318 modified growing degree days, compared to an average of 2414. These weather conditions allowed for above-average corn yields of near 180 bushels/acre (Minneart, 2003), below average soybean yields of 30 to 40 bushels per acre (DeKlerk, 2003), and near average winter wheat yields (Diedrich, 2003). The dryness of mid to late summer may have had an impact on ET.

One important post-processing procedure was completed to allow for an unbiased comparison among the four fields. Since measurements were taken on different days for different fields, net radiation values showed variation from day to day as a result of cloud cover. Because net radiation drives ET, this would have a significant impact on ET results. So, measurement days were grouped by week, and one “standardized net radiation day” was picked from that week and applied to all measurements from that week. This process was repeated for every week of the study. Sensible and latent heat fluxes and ET were based on the new, standardized net radiation values. Now, a fair comparison among fields was possible.

Corn Field Data

Data from the corn field were acquired on six dates from 9 June to 2 September, 2003. A journal of daily weather and crop conditions is presented in Appendix B. Figure 8 shows results for selected data: evapotranspiration (ET), available energy (AE), NDVI, soil moisture (SM), and mean Bowen ratio (B). Available energy is net radiation minus ground heat flux, a true measure of energy available for sensible and latent heat fluxes.

On 6/9 the crop was five weeks mature. Plants were 25-30 cm tall with 8-10 leaves present. The NDVI value of 0.24 indicated the canopy was not yet closed. Soil moisture was at the average value for this field (23%). The Bowen ratio for the day was 0.32, indicating latent heat release was an important part of the energy budget for the day. Computed water loss from the field was 3.37 mm/m^2.

By 6/27 the crop was in week seven and growing rapidly. With a growth of 75 cm in 18 days the plants were now 1.0 m tall, with 12 to 14 leaves per plant. Vegetation was healthy and the canopy was nearly closed with an NDVI of 0.80. Soil moisture was at the highest value for this field, 31.8%, with 1.3 inches of rain two days ago. Available energy was at the highest value for this field at 478 W/m^2. Bowen ratio was lowest of the study for corn at 0.13, indicating more energy was going into latent heat release than on any other day. ET was at the highest value for this site, at 4.94 mm/m^2.

On 7/13 (week nine) the crop was measured at 2.0 m tall; a growth of 1.0 m in 16 days and 1.75 m in 34 days. Plants were beginning to tassel. The NDVI value of 0.89 was highest for this field, showing the canopy was closed with healthy vegetation. Due to 4” of rain in the past week, soil moisture was very high at 28.9%. Available energy averaged 440 W/m^2. This day had the second lowest Bowen ratio (0.27) and second highest ET (4.05 mm/m^2).

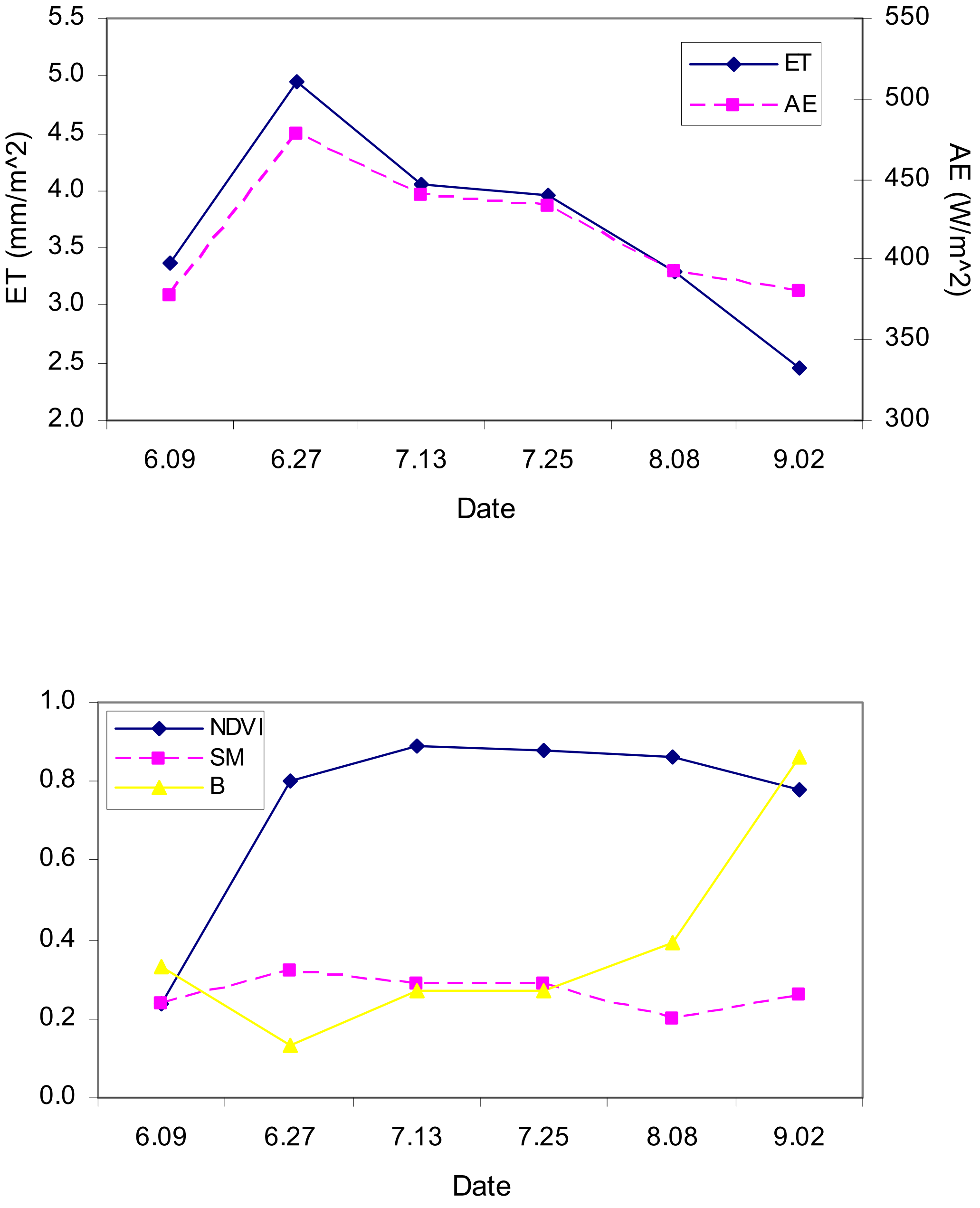

Figure 8. 2003 Corn field results: (a) ET and available energy (AE), and (b) NDVI, SM, and B. X-axis represents month and day, for example, 6.09 is June 9.

By 7/25 (week 11) corn had begun grainfill. Plants were at their maximum height of 2.5 m. NDVI remained high at 0.88. Soil moisture also remained high at 28.7%. Available energy of 433 W/m^2 was starting to decline at one month past summer solstice. Both Bowen ratio and ET were nearly the same as the previous measurement, 0.27 and 3.95 mm/m^2, respectively.

On 8/8 (week 13) grainfill was nearly complete. Plants remained 2.5 m tall, and NDVI was nearly unchanged at 0.86. A leaf area index (LAI) measurement was taken on this date; its value was 4.05, indicating that a 1 meter by 1 meter square would be occupied by 4.05 layers of leaves. Soil moisture was low, at 20%, as recent conditions were dry. Available energy fell to 393 W/m^2. As would be expected due to lower available energy, ET fell to 3.29 mm/m^2. Bowen ratio had risen from the previous measurement to 0.42, indicating more energy was being directed toward sensible heating than previously.

The final measurement for this field was conducted on 9/2. By this time (week 16) corn was mature and bottom leaves were yellowing. The NDVI value had fallen to 0.78, and LAI had fallen sharply to 2.8. Soil moisture was at 26% due to 0.5” of rain on the previous day. Nearly full sunshine produced an available energy value of 380 W/m^2. The Bowen ratio more than doubled from the previous measurement to 0.89, showing that latent heat was playing a much less important role in the energy budget than previously. As expected, ET dropped sharply to 2.45 mm/m^2, less than half of the value nine weeks ago.

Soybean Field Data

Data from the soybean field were collected on six dates beginning 17 June and ending 3 September. A daily journal for this field is presented in Appendix B. Figure 9 shows results for the soybean field.

On 6/17 plants were at the end of their fourth week of growth. Plant height varied from 4-6 cm with 6-8 leaves present. A low NDVI value of 0.37 indicated a large portion of bare soil was still present. Soil moisture was at the highest value for this field: 20%. Available energy was low, at 362 W/m^2, as a large portion of solar energy went directly into ground heat. This measurement had the highest Bowen ratio (0.61) and lowest ET (2.63 mm/m^2) for this site.

By 6/30 (week six) the crop had grown to near 25 cm in height and the canopy was not yet closed with an NDVI reading of 0.76. Soil moisture was 17.7%; this field remained at 17% soil moisture for the rest of the growing season. Available energy was still low, at 368 W/m^2, as a large portion of energy was still going into ground heat. The Bowen ratio decreased from the previous measurement to 0.44 while ET increased from 2.63 to 3.06 mm/m^2.

On 7/15 plants were near 65 cm tall: a growth of 35 cm in two weeks. The NDVI measurement on this date was significant because it was the highest of soybean field readings at 0.90. The canopy was closed with very healthy vegetation. Available energy increased from the previous measurement to 471 W/m^2, as the canopy was now

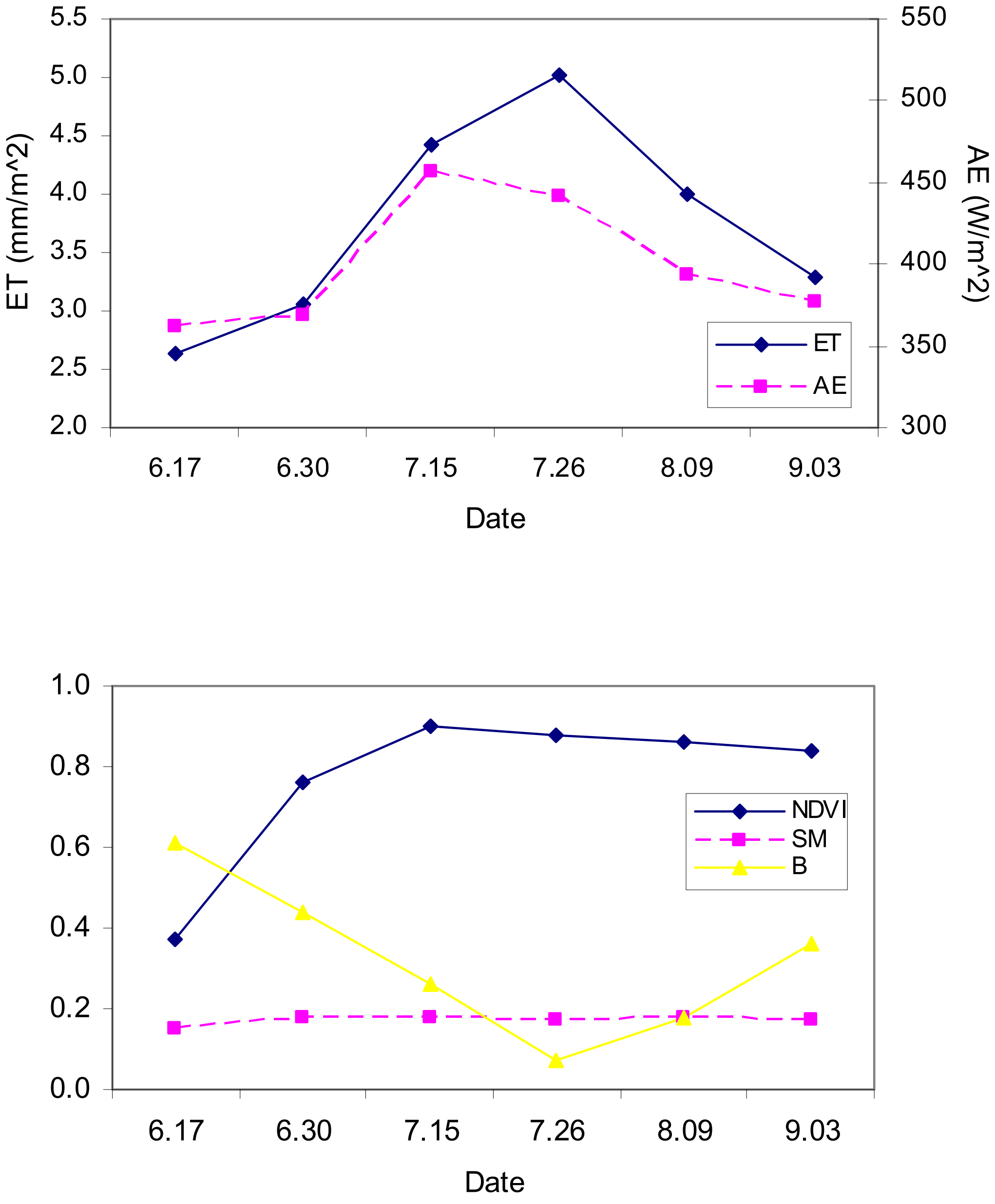

Figure 9. 2003 Soybean field results: (a) ET and available energy (AE), and (b) NDVI, SM, and B.

closed and less energy was going toward ground heat. Bowen ratio decreased sharply again to 0.26. ET on this date was second highest for the field at 4.57 mm/m^2.

On 7/26 plants had continued rapid growth to 90 cm, growing 25 cm in 11 days. NDVI remained high at 0.88. Available energy decreased slightly to 442 W/m^2. An extremely low Bowen ratio of 0.07 showed that latent heat release was proportionately greater than sensible heat compared with any other day. Consequently, ET attained a maximum value for this field at 5.01 mm/m2. This peak ET value is of interest because it occurred after peak available energy. Soybeans were planted later, and matured slower than corn, hence, more vigorous health was present later in the season than any other field.

On 8/9 (week 12) plants were 1.0 m tall with 2 cm long bean pods. The NDVI reading of 0.86 was still high. Available energy dropped to 393 W/m^2. A LAI measurement was taken on this day. A value of 5.65 m^2/m^2 was obtained; 1.65 m^2/m^2 higher than corn measured on the previous day. Bowen ratio remained low (0.18) while ET dropped from the previous measurement to 4.00 mm/m^2.

The final soybean field measurement was taken on 9/3 (week 15). At this time plants were nearly 1.5 m tall with many pods. Leaves were beginning to yellow slightly but NDVI remained high at 0.84. Available energy continued to drop, now down to 377 W/m^2. A LAI measurement of 4.4 was obtained. Mean Bowen ratio increased to 0.41 while ET decreased to 3.29 mm/m^2.

Winter Wheat Field Data

Winter wheat field data were collected on four dates occurring near the peak and end of its growing season: 27 May, 12 June, 24 June, and 10 July. Data were collected as soon as the author arrived to begin working on field data collection. A daily journal for this field is in Appendix B. Figure 10 shows results for this field. Due to limitations of field setup at this site, ET calculations are based on only six hours of data: 10 A.M. to 4 P.M.

On 5/27 the canopy was closed with healthy, green vegetation that was uniformly 0.75 m tall. The highest NDVI measurement of the entire field study was attained: 0.92. Low soil moisture (17%) and high available energy (489 W/m^2) data were attained. A moderately low Bowen ratio of 0.36 was calculated on this day, and the resultant latent heat values produced an ET reading of 3.21 mm/m^2.

On 6/12 the field still showed healthy green vegetation with an NDVI reading of 0.86. The crop had attained maximum height by this time of 0.9 m. Soil moisture rose slightly from the previous measurement to 20%. Although the day was the most overcast of the entire study, substitution of net radiation data (for standardized available energy calculations) produced high available energy of 497 W/m^2. Measurement conditions may have impacted sensible and latent heat fluxes, as the Bowen ratio increased to 0.48. Therefore, a lower ET value of 3.01 mm/m^2 was attained.

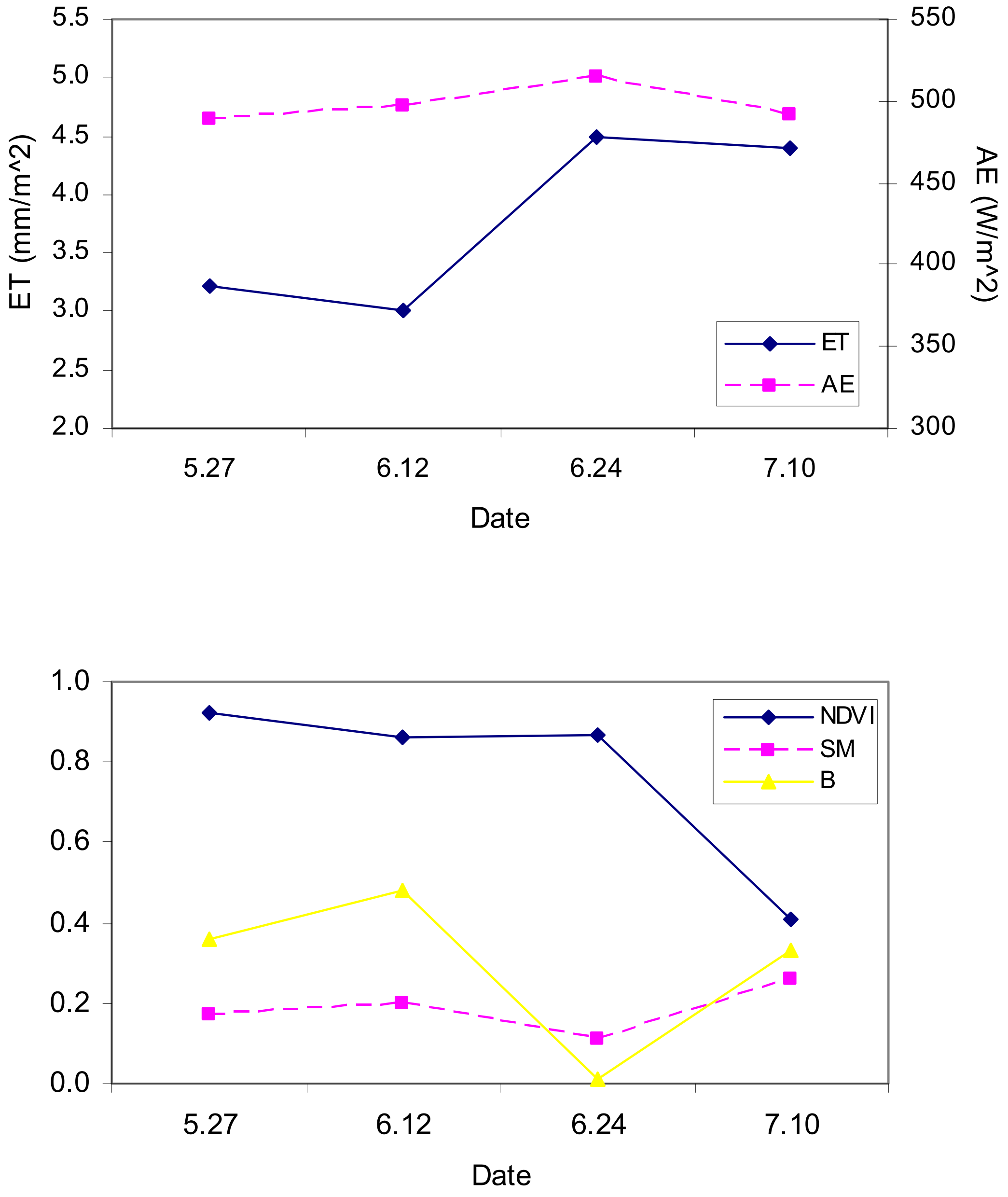

Figure 10. 2003 Winter wheat field results: (a) ET and available energy (AE), and (b) NDVI, SM, and B.

By 6/24 the crop showed some beginning signs of yellowing but NDVI was still high at 0.87. Only 11% soil moisture was present. Available energy was highest of all measurement days at 515 W/m^2. A strong south to southwest breeze of 20-25 mph was present on this day which may have acted through horizontal advections to help produce an extremely low Bowen ratio reading of 0.03. The highest ET for this field was measured on this day at 4.49 W/m^2.

On the final measurement day, 7/10, the crop was golden, as individual plants had gone dormant. Harvest was scheduled in a few days. NDVI dropped sharply to 0.41. Due to heavy overnight rain, soil moisture of 26% was the highest of all readings for this field. Available energy was high, at 491 W/m^2. Bowen ratio rose substantially from the previous measurement to 0.33. Interestingly, ET was the second highest reading for this field, at 4.39 mm/m^2. It is expected that this higher reading can be attributed to the evaporation part of the ET term, because of overnight rainfall and the fact that plants were dormant.

Prairie Field Data

Prairie field data was obtained on three dates during the growing season: 16 June, 19 July, and 15 August. Fewer readings were taken than for crop fields because of the fact that prairie grass does not experience rapid change in mid-summer. A daily journal for this field is in Appendix B. Figure 11 shows results for this field.

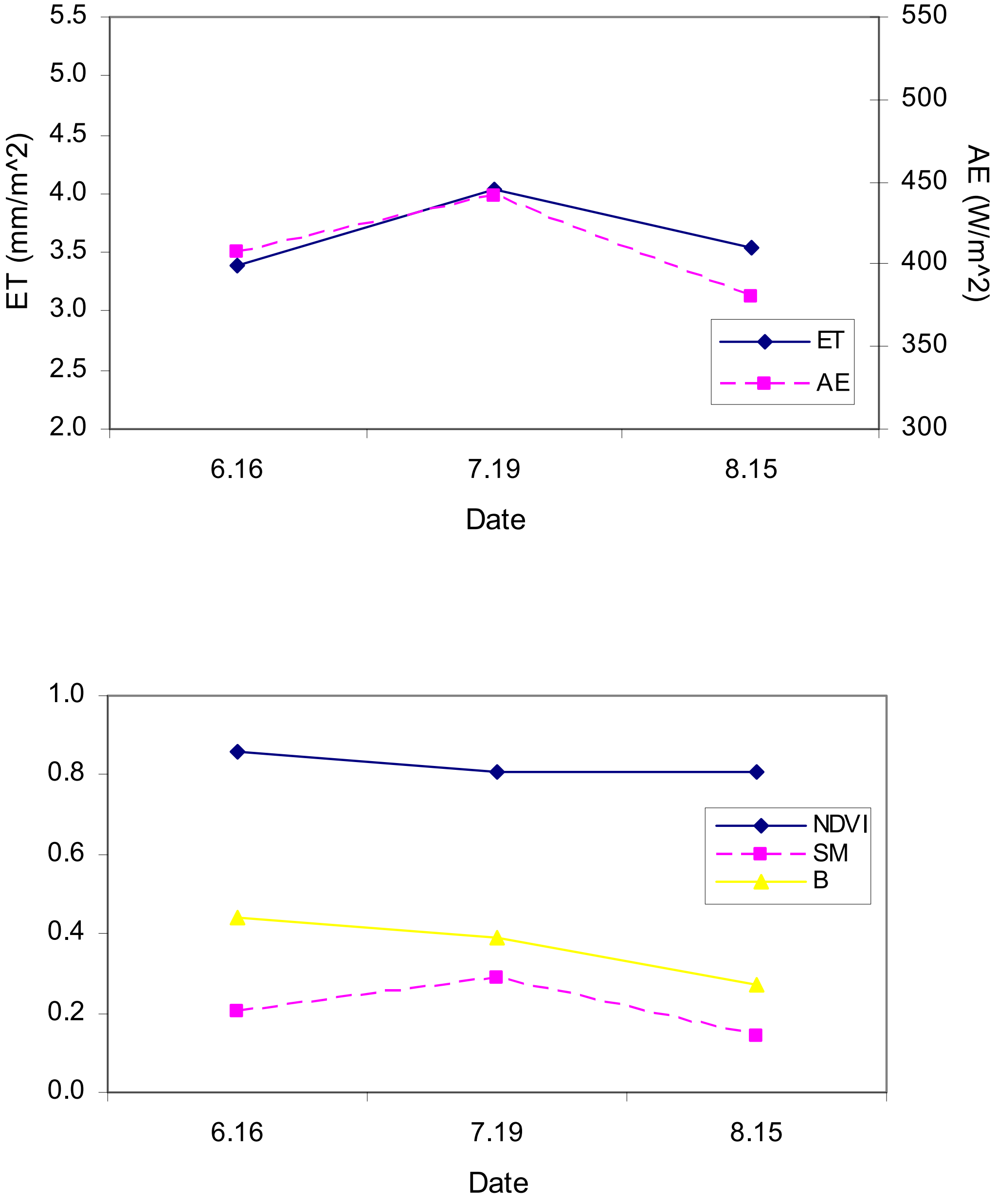

Figure 11. 2003 Prairie field results: (a) ET and available energy (AE), and (b) NDVI, SM, and B.

On 6/16 plants were 25-35 cm tall. NDVI was high compared to other fields at this time: 0.86. Soil moisture was highest of all field measurements at 31.8%. Available energy was 407 W/m^2. A moderately high mean Bowen ratio of 0.44 was attained. ET on this date was 3.39 mm/m^2.

By 7/19 some growth had reached over 1.0 m while some new growth was about 10 cm tall. NDVI had lowered slightly to 0.81. Soil moisture remained high at 28.9%. Again a high available energy value was obtained (441 W/m^2). The mean Bowen ratio decreased to 0.39 while ET increased to 3.77 mm/m^2. Even with slightly lower soil moisture, Bowen ratio decreased from the previous measurement and ET increased slightly. These changes are likely the result of more available energy and new plant growth.

The final measurement was taken on 8/15. Plants ranged from 20 cm to 1.5 m in height. NDVI was unchanged at 0.81. Soil was very dry with a value of 14%; lowest for this field. Available energy declined to 380 W/m^2. A LAI measurement of 2.8 was taken on this date. This value was nearly half of corn or soybean LAI measured at the same time. Mean Bowen ratio decreased again, to 0.27. ET also decreased to 3.55 mm/m^2.

CHAPTER 5

DISCUSSION

Important distinctions are seen when examining ET for corn and soybean fields during the measurement period. The highest corn ET values were attained in late June and early July. Highest soybean ET values were attained from mid-July through early August. These differences are large. In late June corn transpired at 4.94 mm/m^2 while soybeans were at 3.06 mm/m^2, a 1.88 mm/m^2 per day larger value for corn. However, one month later in late July, the scenario was reversed. Now corn transpired at 3.95 mm/m^2, while soybeans were at 5.01 mm/m^2, a 1.06 mm/m^2 per day larger value for soybeans. These differences cannot be explained by a nine-day difference in planting alone; clearly the crops mature at different rates and expel maximum amounts of moisture at different times in their growth stages. Results show that maximum ET occurred when crops were near the end of the vegetative stage just prior to the reproductive stage.

The northern Illinois prairie showed much less variability and lower peak ET than agricultural fields. When corn ET peaked at nearly 5.0 mm/m^2, prairie ET was at less than 3.5 mm/m^2. One month later when soybean ET peaked at 5.01 mm/m^2, prairie produced maximum ET at 4.04 mm/m^2. Figure 12 shows ET for each measurement day of the northern Illinois field study. Clearly, crop cover shows

greater peak ET than prairie. From an energy budget perspective, the fields were standardized with respect to available energy, so this cannot explain differences. Physical differences between modern vegetation and natural prairie cover are distinct. Leaf area index of crop fields nearly doubles prairie resulting in more photosynthetically active area. Slightly higher NDVI values were found for crops. Crops have been bred to thrive during a shortened growing season, hence most of their ET occurs during a three-month period, while prairie begins growth, and ET, earlier in the spring and lasts later into the fall.

Figure 13 shows a conceptual illustration of how cropland may be altering the growing season evapotranspirative scheme, especially since the mid-1900s when intense row cropping of corn and soybeans essentially entirely replaced prairie and pasture land. The key finding is that from mid-June to mid-August, when corn and soybeans peak in growth, they dominate prairie in ET. A compressed growing season for these crop fields requires that they use more moisture than prairie during this part of the growing season. The addition of moisture during a two-to-three month period may have implications on weather conditions as well as human health and comfort. While deviation in ET among the ecosystems varies from summer to summer, current results and previous findings suggest that a detectable addition of water vapor is a result of ET from current vegetation.

Calculations were made relating the observed ET differences to dew point temperatures. Crop ET peaked at near 5.0 mm/m^2, while prairie peaked near 4.0 mm/m^2. Given a standard mixing depth of 1000 m, an additional 1 gram per kilogram of moisture would be present over crop fields. This result matches well with earlier findings of Bonan (1997). With a pressure of 1000 millibars, temperature of 30° C (86° F) and 70% relative humidity, a daily average dew point over prairie is 24.0° C (75.3°F). Advection of this airmass over a crop field with higher ET (1 g/kg of additional moisture) would produce a dew point temperature of 24.9° C (76.8° F). On a drier day with 40% relative humidity, a prairie dew point of 15.4° C (59.8° F) is produced, while a crop dew point of 16.7° C (62.2° F) is produced. There is a distinct difference between dew points over natural land cover and current agricultural land cover.

Initially, these small differences alone do not appear sufficient to explain the existence of increased dew point levels, or the more frequent occurrence of extreme dew points. However, this seemingly small addition of moisture, applied over a large geographic area, combined with other processes, could speculatively explain a substantial amount of dew point increases. Processes that could enhance moisture levels include: wetter soils resulting from irrigation, moisture pooling near frontal boundaries, suppressed mixing depths (strong subsidence), and transport of moisture from low level jets. One or more of these factors acting on a slight increase in ET during mid-summer could explain a substantial portion of the observed dew point increases.

Possible impacts of increased dew point levels are numerous. Changnon et al. (2003) found that recent Chicago heat waves are more dangerous due to higher atmospheric water vapor levels. They speculated that changes in agricultural practices may be part of the cause. Results support this hypothesis. The addition of low-level water vapor also assists in destabilizing the atmosphere and initiating deep convection. Research has shown that warm season Mesoscale Convective Systems (MCSs) initiate and propagate through areas with greatest low-level moisture availability, in the absence of organized forcing (Bentley and Mote, 1998). Previous research has speculated that the primary source for this low-level moisture during weak-flow regimes in the Midwest is due to ET from crops and other vegetation, not moisture from the Gulf of Mexico (Chang and Wetzel, 1991; Johns, 1993; Bentley and Mote, 1998). Current research suggests that increased ET from crops during a mid-June to late-August period may increase frequency and/or intensity of MCSs. In addition, human health and discomfort may be adversely affected by heat waves augmented by higher water vapor levels. Weather sensitive industries such as agribusiness and utilities could also be affected.

It is important to note that prairie ET is likely higher than agricultural ET both before crops emerge in spring and early summer, and when crops are dormant in late summer and early fall. When averaged from June through September, cropland averaged ET of 3.72 mm/m^2, while during June through August natural ET averaged 3.60 mm/m^2. Clearly, overall differences in ET through the entire growing season are small.

CHAPTER 6

SUMMARY AND CONCLUSIONS

The partitioning of sensible and latent heat fluxes and moisture fluxes over various surfaces is an active research area in atmospheric science. A better understanding of how these fluxes vary over a heterogeneous landscape will eventually allow for more accurate prediction of future atmospheric conditions. These improvements will result in mitigation of human suffering and economic loss that currently result from the rare, but increasing occurrence of extreme low-level atmospheric water vapor levels.

An examination of the effects of surface characteristics on these fluxes was accomplished by: (1) examining a long-term continuous data set of energy flux data from two Kansas prairies, and (2) conducting a field study in northern Illinois over four common vegetative surfaces. The Kansas data set was analyzed by looking at seasonal and yearly variation of surface properties for several variables including soil moisture, NDVI, Bowen ratio, and ET. Continuous measurements for several years made these data valuable. The field study portion of the project provided ET data over heterogeneous surfaces. Data were collected and analyzed from corn, soybean, winter wheat, and prairie fields. Due to the nature of the field study, continuous measurements were not possible. A detailed analysis of ET over these surfaces was conducted to quantify water loss among past and present dominant ecosystems in the Midwest.

Results of the Kansas dataset showed that surface conditions of soil moisture and plant health (measured through NDVI) have a strong influence on sensible and latent heat fluxes, and resulting ET. Maximum ET is produced when soil moisture is abundant and vegetation is healthy. When these conditions are present Bowen ratio is low: much more available energy is being directed into latent heat release than sensible heating. These conditions are only possible when solar energy, which drives the surface energy budget, is high, generally from late spring through early fall. Results on an annual scale showed higher ET was attained where soil moisture was higher, and grazing affected fluxes.

Prairie was the dominant ecosystem in the Midwest until the mid 1800s; now 80 to 100 percent of land surface in the cornbelt is occupied by corn and soybeans during the growing season. For this reason, research on this land cover is vital. Very few studies have produced actual field measurements of summertime ET in the Midwest; none directly attempted to relate increasing dew point levels to crop ET.

Distinct differences were noted between ET for cropland and prairie. As previous results from the Kansas data showed, highest ET was attained when soil moisture and plant health were high. However, agricultural fields have a compressed growing season when compared to prairie; hence plants grow much faster and use water much quicker. As a result, maximum ET values were found to be 1 mm/m^2 per day higher for corn and soybean fields than prairie. Through calculations this difference was shown to produce an increased dew point temperature on the order of 2° F during a typical summer day. This increase, applied over a large geographic area, and combined with other meteorological factors, could explain a substantial amount of the observed increase in summertime dew point temperatures over the 20th century. Land surfaces affect ET. Anthropogenic land use change has altered ET.

The results obtained from this study further improve our understanding of seasonal and annual differences in ET among several key ecosystems in the central U.S. In particular, results help quantify water loss among corn, soybean, winter wheat, and prairie. Significant differences are present between agricultural fields and prairie fields. Much remains to be learned with respect to surface energy fluxes and ET which can only be accomplished through continuous measurement of fluxes over various land surfaces. Integration of this knowledge into computer modeling can benefit society by reducing losses during extreme heat events that are now augmented by higher dew point levels.

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APPENDIX A

FORTRAN PROGRAM

```
c using bowen ratio method to estimate Latent and sensible heat fluxes
c variable names in the program:
c iday--day of year; it--time of the day (at every 5 min interval);
c t1 rh1--temperature (C) and RH(%) at upper level of tripod;
c t2 rh2--temperature (C) and RH(%) at lower level of tripod;
c g1 and g2-- ground heat flux at two locations near surface w/m^2;
c rn--net radiation w/m^2
c observation period is total water loss
c heat capacity for air (ca) 1206J/m^3/K
c latent heat of condensation (l) 2450J/g or 2.45x10^6J/kg
c gas constant for water vapor (rv) 461.5J/kg/K
c sum of LE divided by L and integrate at 300s interval (5 min)
c to get total water loss from surface during observation period.
c 1kg/m^2/(water density 1000kg/m^3)=0.001m/m^2=1mm/m^2
c 1kg/m^2 water loss is equivalent to 1mm/m^2 water loss in depth
c ---------------------------------------------------------------------
      program bowen
      real l,le,h
      parameter(ca=1206,l=2.45e6,rv=461.5)
      open(1,file='4_ww411.txt')
      open(2,file='4_ww411b')
      read(1,*)
      sum=0
      do i=1,400
      read(1,*,end=90)id,iday,it,t1,rh1,t2,rh2,g1,g2,rn
      e1=611.2*exp(17.67*t1/(t1+243.5))
      e1=e1*rh1*0.01
      e2=611.2*exp(17.67*t2/(t2+243.5))
      e2=e2*rh2*0.01
      tav=(t1+t2)*0.5+273.5
      b=ca*(t1-t2)/(l/(rv*tav)*(e1-e2))
      le=(rn-(g1+g2)*.5)/(1+b)
      h=b*le
      sum=sum+le
      write(*,'(i5,5f8.2 )')it,b,le,h,rn,(g1+g2)*.5
      write(2,'(i5,5f8.2 )')it,b,le,h,rn,(g1+g2)*.5
      end do
   90 write(2,*)'total water loss from surface
     & during observation period is',sum/l*300 ! kg/m2 or mm/m2
      stop
      end
```

APPENDIX B

FIELD JOURNAL OF CROP AND WEATHER CONDITIONS

5/27/03
Winter Wheat (40 acres located 2 miles northeast of DeKalb, IL, 100lbs/acre)
Mostly sunny, fair weather cumulus, light and variable breeze, temps in 70s. Crop 2.5 feet tall. Soil dry.

06/09/03
Corn (127 acres located approx. 4 miles east of Colona, IL. 30K seeds/acre)
AM 100% sun, SW wind 5-12 mph, AM temp~60, PM temp~80, PM cu<20%.
Corn healthy, 25-30 cm tall.
Soil moist, ~.2” rain yesterday.

6/12/03
Winter Wheat (30 acres locate 2 miles northeast of DeKalb, IL. seeded 200 lbs. per acre)
AM cloudy, PM partly sunny. Light ENE wind. PM temps in 70s. Crop at 95 cm tall with seeds present.

06/16/03
Prairie (21 acres, surrounded by 100s of acres of deciduous forest – Illiniwek Forest Preserve, Hampton, IL., Oak, Maple, Sumack, Elm, Apple, poison ivy, Virginia creeper, grass, weeds)
100% sun, light wind, AM temp~60s, PM temp~80s.
Vegetation ~25-35 cm tall.

06/17/03
Soybean (140 acres, located approx. 6 miles east of Port Byron, Il. 200K seeds/acre)
100% sun, AM temp~60s, PM temp~upper 80s, wind E-NE at 2-5mph.
Soybeans 4-6 cm tall.

6/24/03
Winter Wheat
Hazy, warm and humid. 40% cirrus coverage in PM. South wind 8-12 mph. Crop was mature and beginning to yellow.

06/27/03
Corn
100 % sun, AM temp~60s, SW wind 5-10 mph.
Corn healthy, growing 75 cm in 18 days…1 m tall.
Soil moist, 1.3” rain two days ago.

06/30/03
Soybean
AM CI<20%. Light winds.
Soybeans 22-27 cm tall.

07/10/03
Winter Wheat
AM 100% low clouds, PM fair wx cumulus, 30-70%. WNW wind 10-20 mph. Soil moist from rain last night. Wheat golden at 95 cm, harvest in a few days.

07/13/03
Corn
100 % sun, S wind 10-20 mph.
Corn 2 m tall (grew 1 m in last 16 days, 1.7 m in 34 days)
Soil moist, 4” rain in last week.

07/15/03
Soybean
Mostly clear, few CI/CU, <20%. Wind light & var.
Soybeans healthy, 60-70 cm tall.

07/19/03
Prairie
100 % sun, wind light & var.
Grass/weeds 10 cm-1.5 m tall.

07/25/03
Corn
100% sun, wind SSW 10-20 mph, temp~80s, Td~60s.
Corn 2.5 m tall, tasseling, small ears present.
Tripod set on wood crates so AT/RH2 > 2.5 m.

07/26/03
Soybean
AM CI~50%, PM 100% sun, wind SSW 10-25 mph.
Soybeans 90 cm tall.

08/08/03
Corn
CU~30-70%, NE wind 7-12mph.
Ear is full-size, corn 2.5 m tall.

08/09/03
Soybean
CU~10-20%, T~80s, NW wind 5-10mph.
Soybean~1 m tall, bean~2 cm long.

08/15/03
Prairie
AM 100% sun, PM CU~20-50%, temp~90s, Td~70s, W wind 3-7 mph.
Soil is very dry, vegetation 20 cm-1.5 m.

09/02/03
Corn
PM CU~10-30%, light wind, T~70s, Td~60.
Corn 2.5 m tall, bottom leaves yellowing, ear is mature.
Moist soil ~.5” rain yesterday.

09/03/03
Soybean
100% sun, calm wind, T~80, Td~50s, NW wind 10-15 mph.
Soybean 1.1-1.2 m tall, many bean pods, leaves beginning to yellow.
Moist soil ~ .3” rain 2 days ago.

09/20/03
Corn
100% sun, wind S < 5 mph, 3” rain in last 7 days, but top 1” of soil dry.
Corn continuing to brown.

09/21/03
Soybean
Went to set up and found plants completely defoliated. Brown pods and stems present.

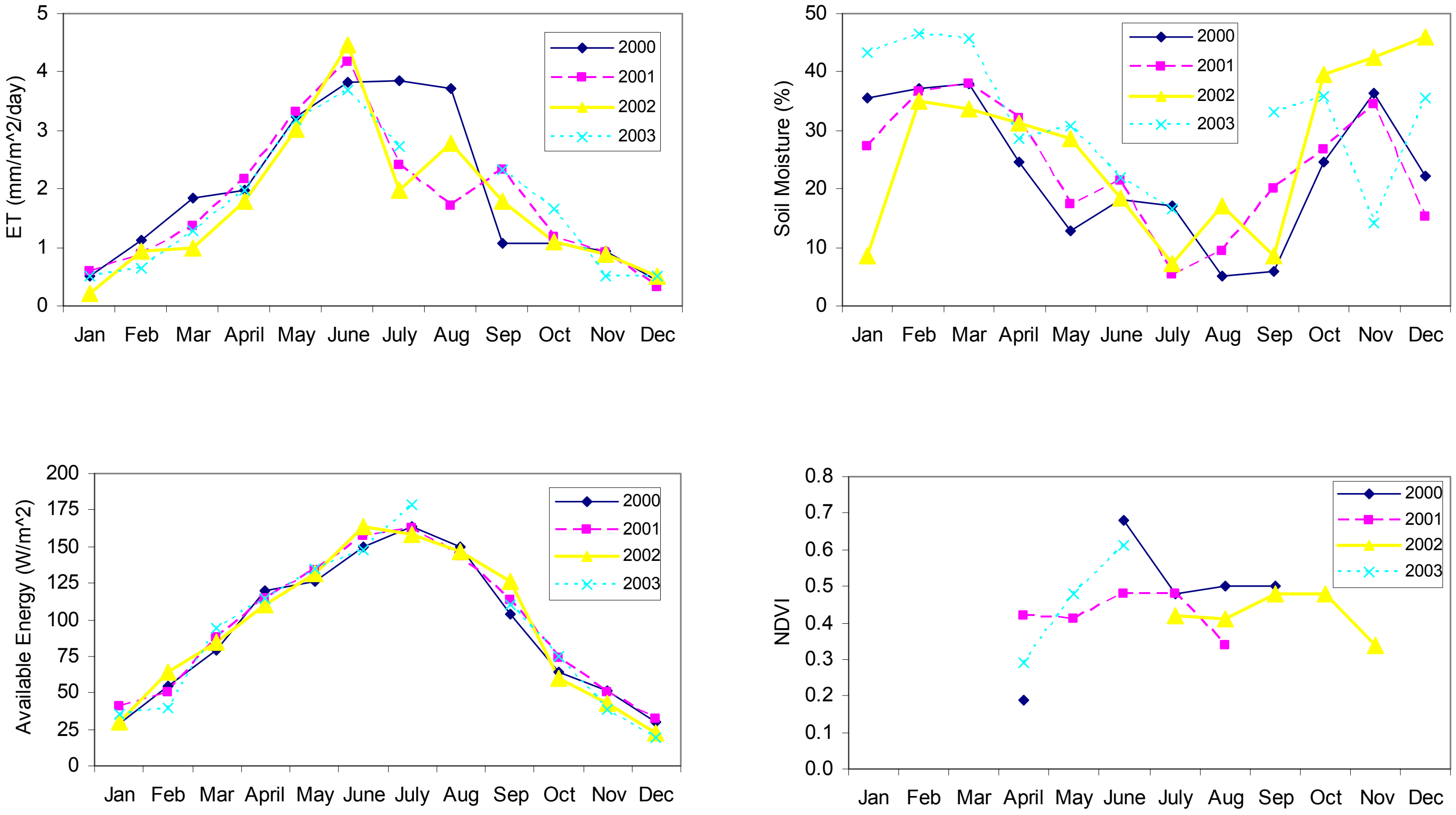

Figure 4. Seasonal and intra-annual variation in Whitewater surface characteristics of (a) ET, (b) soil moisture, (c) available energy, and (d) NDVI.

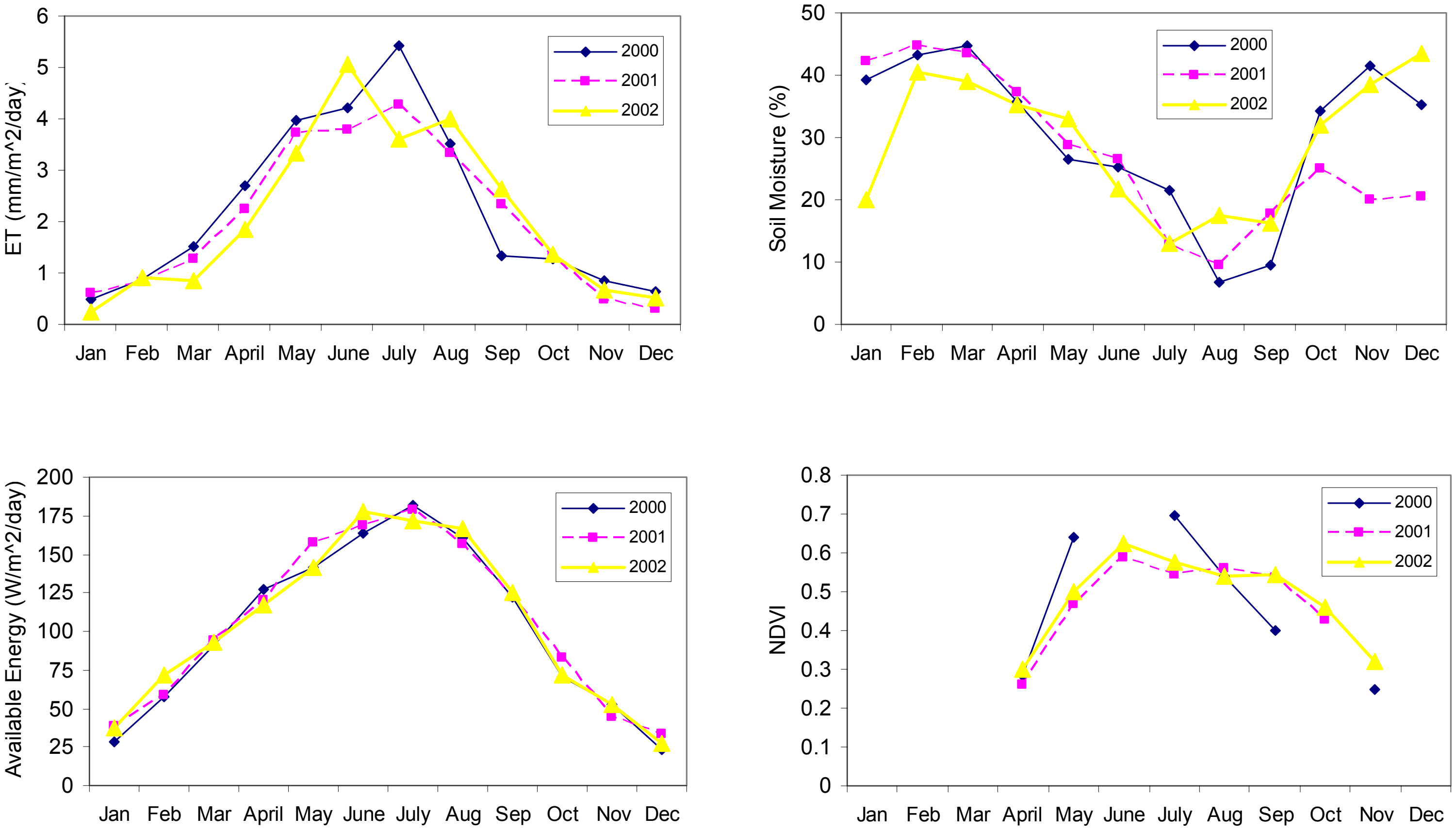

Figure 5. Seasonal and intra-annual variation in Smileyberg surface characteristics of (a) ET, (b) soil moisture, (c) available energy, and (d) NDVI.

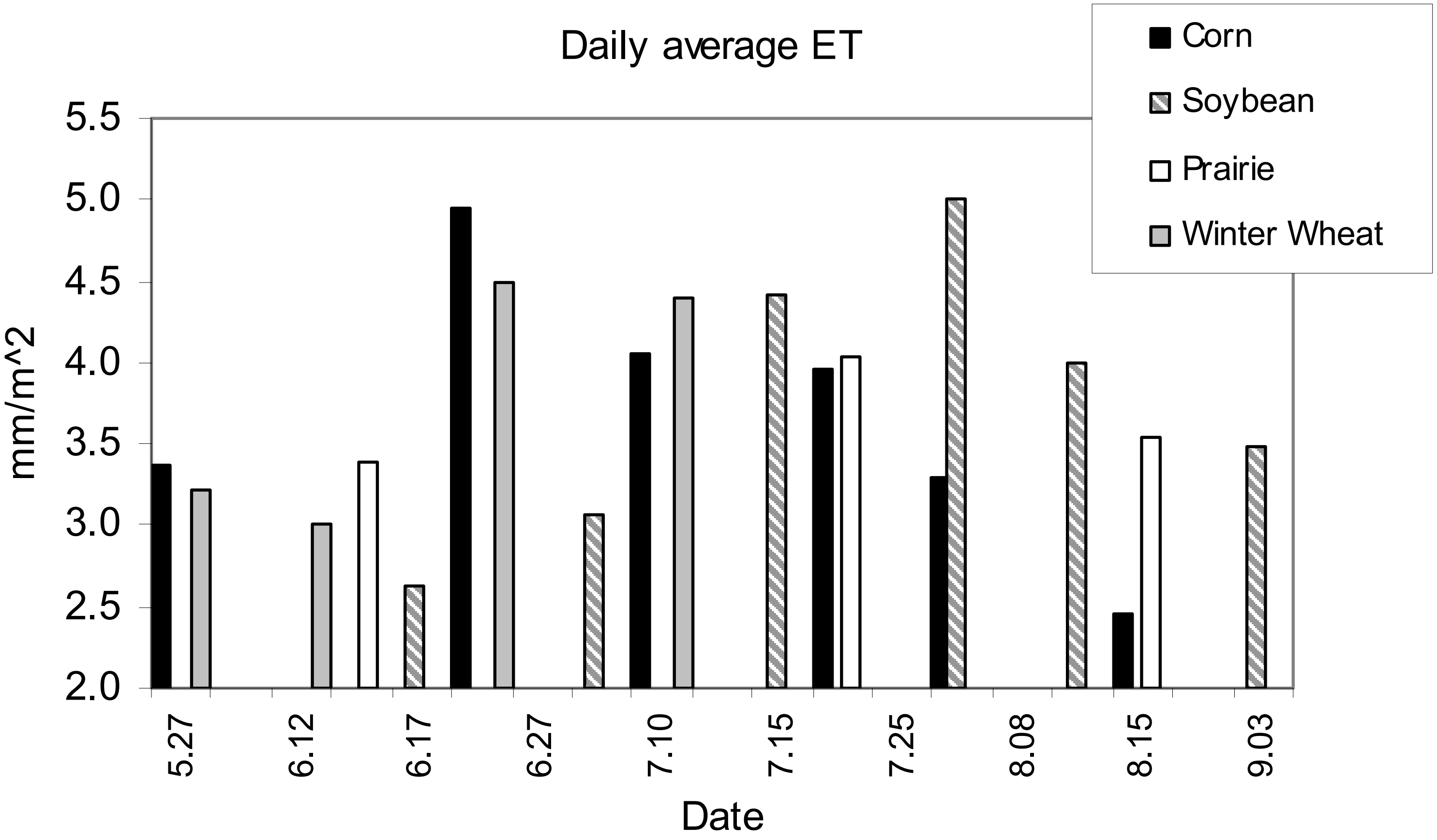

Figure 12. Composite daily average ET for Northern Illinois Fields, 2003.

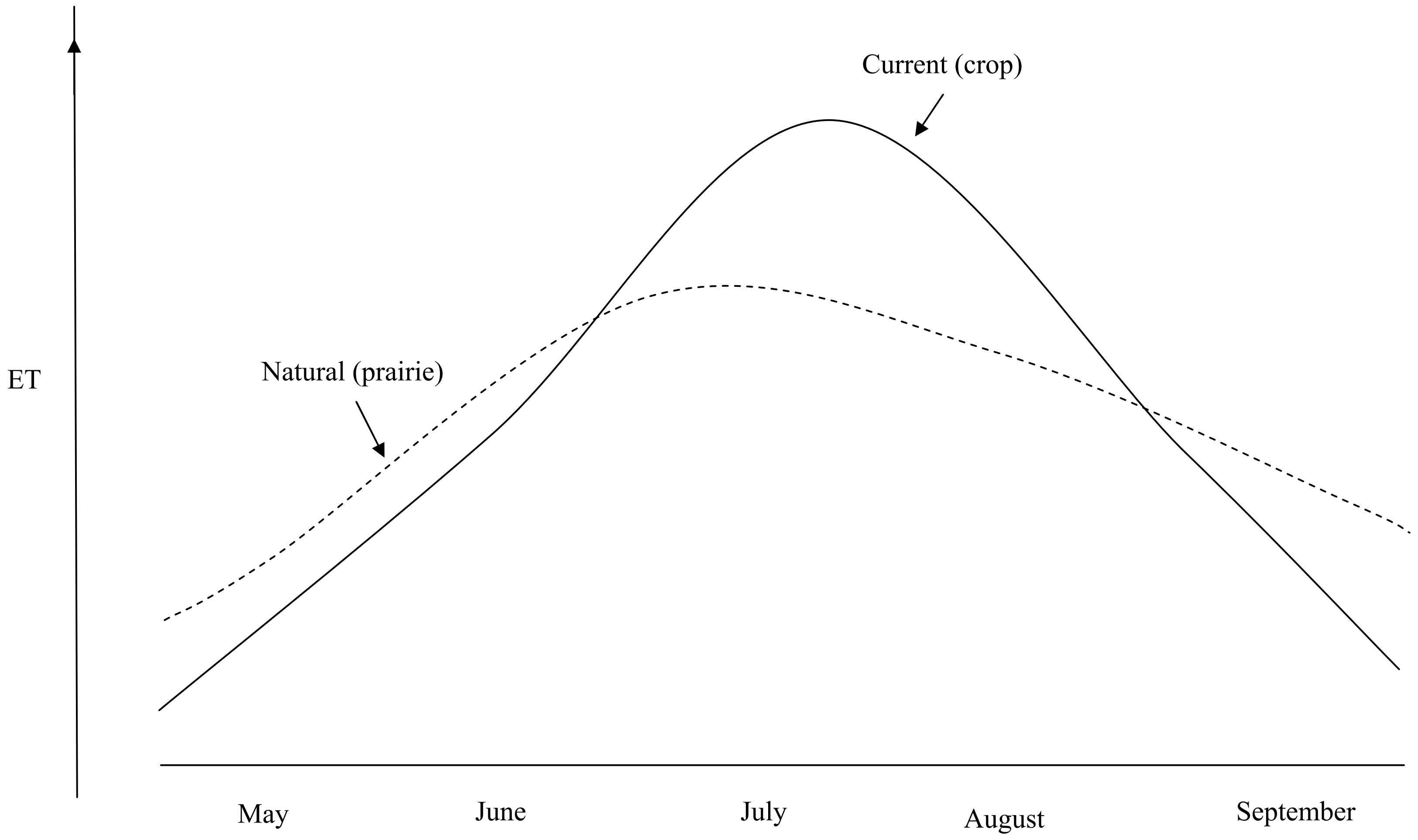

Figure 13. Conceptual illustration of ET under natural and current vegetation.