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NEBRASKA WATER AND ENERGY FLUX MEASUREMENT, MODELING, AND RESEARCH NETWORK (NEBFLUX)

Suat Irmak

ABSTRACT. *Surface energy and water vapor fluxes play a critical role in understanding the response of agro-ecosystems to changes in environmental and atmospheric parameters. These fluxes play a crucial role in exploring the dynamics of water and energy use efficiencies of these systems. Quantification of the fluxes is also necessary for assessing the impact of land use and management changes on water balances. Accomplishing these goals requires measurement of water vapor and energy exchanges between various vegetation surfaces and microclimates for long-enough periods to understand the behavior and dynamics involved with the flux transfer so that robust models can be developed to predict these processes under different scenarios. Networks of flux towers such as AMERIFLUX, FLUXNET, FLUXNET-CANADA, EUROFLUX, ASIAFLUX, and CAR-BOEUROPE have been collecting data on exchange processes between biosphere and atmosphere for multiple years across the globe to better understand the functioning of terrestrial ecosystems and their role in regional and/or continental and global carbon, water, and energy cycles, providing a unique service to the scientific community. Nonetheless, there is an imperative need for these kinds of networks to increase in number and intensity due to the great diversity among ecosystems and agro-ecosystems in species composition, physiological properties, physical structure, microclimatic and climatic conditions, and management practices. The Nebraska Water and Energy Flux Measurement, Modeling, and Research Network (NEBFLUX) is a comprehensive network that is designed to measure surface energy and water vapor fluxes, microclimatic variables, plant physiological parameters, soil water content, surface characteristics, and their interactions for various vegetation surfaces. The NEBFLUX is a network of micrometeorological tower sites that uses mainly Bowen ratio energy balance systems (BREBS) to measure surface water vapor and energy fluxes between terrestrial agro-ecosystems and microclimate. At present, ten BREBSs and one eddy covariance system are operating on a long-term and continuous basis for vegetation surfaces ranging from tilled and untilled irrigated and rainfed croplands, irrigated and rainfed grasslands, alfalfa, to Phragmites (*Phragmites australis*)-dominated cottonwood (Populus deltoides var. occidentalis) and willow stand (Willow salix) plant communities. The NEBFLUX project will provide good-quality flux and other extensive supportive data on plant physiology [leaf area index, stomatal resistance, within-canopy radiation parameters, productivity (yield and/or biomass), and plant height], soil characteristics, soil water content, and surface characteristics to the micrometeorology, water resources and agricultural engineering, and science community on broad spectrum of agro-ecosystems. The fundamental premise of the NEBFLUX project is to measure continuous and long-term (at least ten complete annual cycles for each surface) exchange of water vapor and energy fluxes. In addition to the scientific and research objectives, information dissemination to educate the general public and youth is another important objective and output of the network. This article describes the specific goals and objectives, basic principles, and operational characteristics of the NEBFLUX.*

Keywords. *Bowen ratio, Energy balance, Energy and water flux, Evapotranspiration, Flux network, Microclimate.*

Availability of freshwater resources for agro-ecosystems has been an important issue for the sustainability of agricultural production in the U.S. and around the world. Concerns include increased competition for water resources due to a combination of recent drought cycles as a result of global climate change, over-pumping of ground and surface water resources due to poor irrigation management strategies, degradation of surface and groundwater quality, an increasing trend in industrial and environmental development, and expansion of irrigated lands. In the U.S., the quantity of freshwater withdrawn for irrigation in 2000 was estimated as 55.4 billion m^3, which represented 39.7% of the nation's total freshwater use (USGS, 2000) for all off-stream categories, including public supply, domestic, livestock, aquaculture, industrial, mining, and thermo-electric power generation. Of the 1.31 billion $m^3\ d^{-1}$ freshwater used daily in the U.S., 0.52 billion $m^3\ d^{-1}$ was used for irrigation (Hutson et al., 2004). Thus, withdrawal of freshwater resources for irrigation plays a critical role in water balances.

Water use efficiency has become an important issue with the increase in irrigated lands, increasing prices of inputs for agro-ecosystem production, and because irrigation water available for use is becoming increasingly less than the full requirement for maximum production. These problems recently have become widespread, especially in many parts of the Midwestern U.S., including Nebraska. Several

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consecutive years of drought coupled with steadily increasing total water use has endangered the long-term viability of Nebraska's water resources and caused significant declines in water table depths in some parts of the state, with some locations experiencing greater than 18 m decline (CSD, 2008). Based on the irrigation survey conducted by the USDA-NASS in 2007 (NASS, 2007), Nebraska was ranked as first in the nation in the area irrigated with center-pivot systems and first in the total irrigated lands and irrigated farms. In Nebraska, total irrigated areas have more than doubled in the last four decades, increasing from about 1.6 million ha in 1970 to over 3.6 million ha in 2008, with over 105,000 active irrigation wells. Total irrigated land in Nebraska alone represents about 14% of the total irrigated lands (21.2 million ha) in the U.S. Currently, of the 3.6 million ha of irrigated land, approximately 75% is irrigated with center pivots and 25% with surface irrigation. Withdrawal of freshwater resources for irrigation represents the largest water pumping demand in Nebraska. The withdrawal of both surface and groundwater for irrigation has increased 15%, from 40 million m^3 d^{-1} in 1995 to 46.6 million m^3 d^{-1} in 2000 (USGS, 2000). Total withdrawal of freshwater has increased by 1.2% from 1995 to 2000 nationwide, whereas the increase in Nebraska was above the national average. Nebraska uses about 46.8 million m^3 d^{-1} of freshwater, and irrigation comprises 72% of this use (Hutson et al., 2004).

In Nebraska, declining groundwater tables, reduced well outputs, and restricted surface and groundwater pumping have become common over the past few years. Litigations between interstate "downstream" and "upstream" users have placed certain restrictions on the amount of water available to agro-ecosystems in several major watersheds. Recently, some watersheds have been declared as fully or over-appropriated [fully appropriated watersheds are considered those where supply and demand are equal; over-appropriated watersheds are considered those where use (evapotranspiration) exceeds available water] under the provisions of state law LB962 (NDNR, 2004), which requires Natural Resources Districts (NRDs) associated with these watersheds to develop integrated management plans, rules, and regulations that prevent drilling new irrigation wells and restricting or closely regulating irrigation activities on existing irrigated areas.

These extensive water withdrawal conditions coupled with rising fuel and other input costs require good planning and management of water resources at field, watershed, statewide, and regional scales through reliable estimates of surface energy fluxes, including latent heat (*LE*) (or actual evapotranspiration, ET_a) in irrigated and rainfed agro-ecosystems. Accurate determination of ET_a can be a viable tool in better utilization of water resources through well-designed water resources management programs. Reliable estimation of ET_a is also vital to develop criteria for in-season water management; water allocations; long-term estimates of water supply, demand, and use; design and management of water management infrastructures; and assessing the impact of land use and management changes on water balances. Despite these extensive water resources, irrigation, and agro-ecosystem production activities in Nebraska, a network infrastructure for ET_a measurement to provide short and long-term improved ET_a data for water resources policy-makers, planners, regulators, and users on a continuous basis does not exist. This article describes preliminary work that has been underway to establish a surface energy and water vapor flux measurement network; outlines the objectives and goals, instrumentation information, methodology used; and presents sample data of measured surface energy fluxes for one of the NEBFLUX sites.

Nebraska Water and Energy Flux Measurement, Modeling, and Research Network (NEBFLUX)

Nebraska has approximately 19.6 million ha of land that comprises approximately 12 million ha of grassland (rangeland), 1.9 million ha of irrigated maize, 1.5 million ha of rainfed maize, 0.8 million ha of irrigated soybean, about 1 million ha of rainfed soybean, and other vegetation surfaces (fig. 1). The distribution of these various vegetation surfaces in the state is presented in figure 2. Most of the irrigated maize and soybean are located in the central, south-central, and eastern parts of the state, whereas most of the grasslands are located in the sand hills of the north and north-central parts. Historically, irrigated maize has been the dominant vegetation type that has been grown in the state, and the emphasis has been given to this vegetation in determining the ET_a rates for water resources management. This was mainly due to the significant economic advantages and incentives of maize as compared with other agronomical plants. However, in the last two decades or so, other vegetation surfaces such as grasslands, soybean, and other small grains have become significant elements of the state's agricultural practices and economy. Furthermore, in addition to maize, other agronomical plants and rangelands significantly impact the state's water balance dynamics. Thus, measurement and modeling of surface energy fluxes, including ET_a, for various surfaces that have an impact on the water and energy balances is vital for better planning and management of water resources. This requires measurement of water vapor and energy exchanges between the vegetation surfaces and microclimates for long-enough periods to understand the behavior and dynamics involved with the flux transfer so that robust models can be developed to predict these processes under different scenarios. Collection of good-quality and long-term flux data is also necessary for the development, assessment, and improvement of mechanistic and biophysical models of agro-ecosystem physiology that can be util–

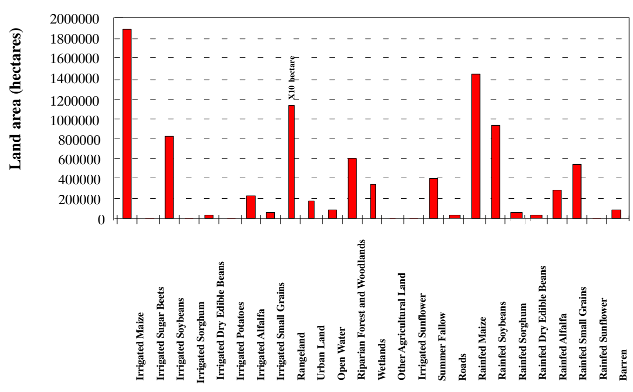

Figure 1. Land area by vegetation type in Nebraska as of 2005 (CALMIT, 2005).

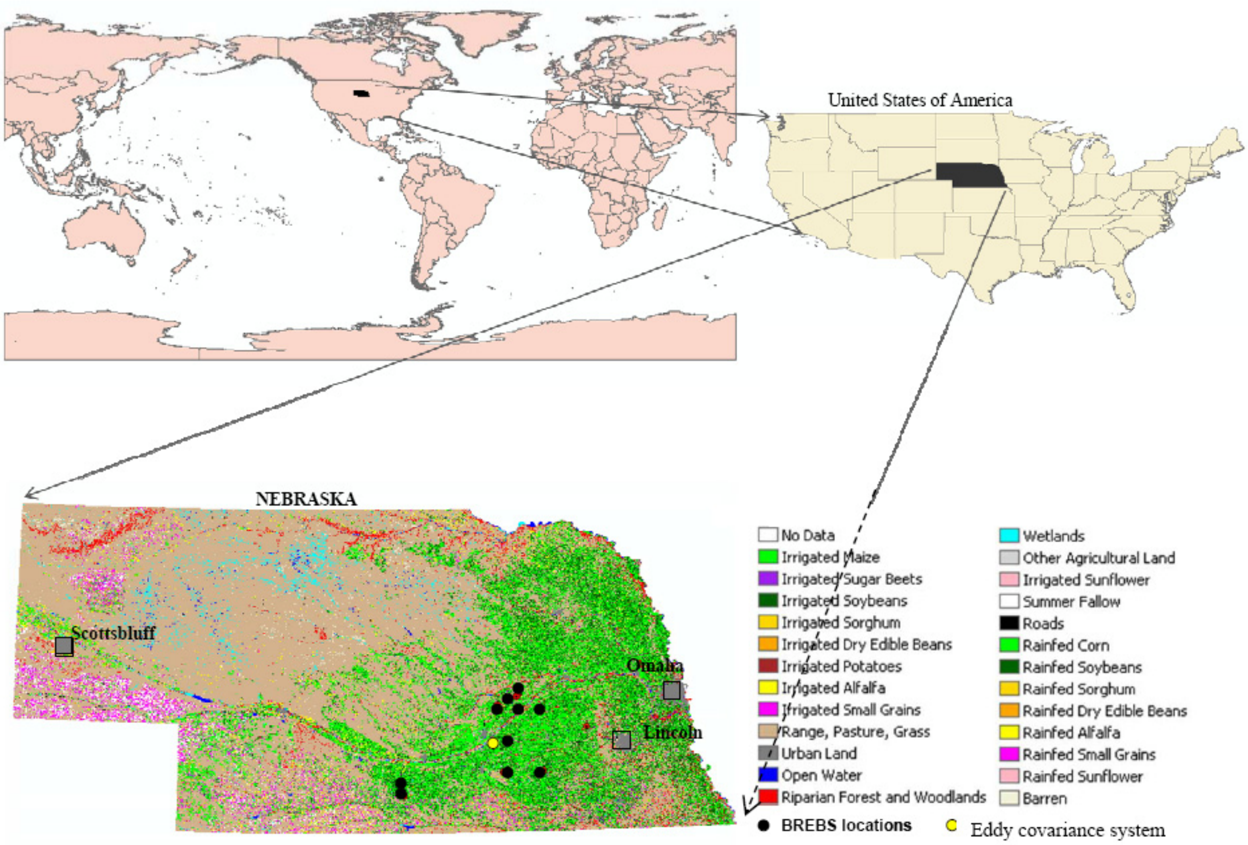

Figure 2. Land use map of Nebraska as of 2005 and the locations of the NEBFLUX Bowen ratio energy balance systems and eddy covariance system.

ized to estimate the response of vegetation to future and potential environmental/climate change.

A number of coordinated research programs and networks for measuring and modeling water vapor, surface energy, and carbon fluxes, such as AMERIFLUX (http://public.ornl.gov/ameriflux/), FLUXNET (http://daac.ornl.gov/FLUXNET/) (Baldocchi et al., 2001), FLUXNET-CANADA (www.fluxnet-canada.ca/) (Margolis et al., 2006), EUROFLUX (Aubinet et al., 2000), ASIAFLUX (www.asiaflux.net/), and CAR-BOEUROPE (www.carboeurope.org/), have been developed to better understand the functioning of terrestrial ecosystems and their role in regional and/or continental and global carbon, water, and energy cycles. However, there is a need for these kinds of networks to increase in number and intensity due to the great diversity among ecosystems and agro-ecosystems in species composition, physiological properties, physical structure, microclimatic and climatic conditions, and also due to the great diversity of management practices.

The Nebraska Water and Energy Flux Measurement, Modeling, and Research Network (NEBFLUX), initially, is a statewide network that is designed to measure surface energy fluxes, microclimatic variables, plant physiological parameters, soil water content, surface characteristics, and their interactions for various vegetation surfaces. The NEBFLUX is a network of micrometeorological tower sites that use mainly the Bowen ratio energy balance systems (BREBS) to measure surface water and energy fluxes between terrestrial agro-ecosystems and microclimate. At present, ten BREBSs and one eddy covariance system (ECS) are operating on a long-term and continuous basis. The NEBFLUX project, sponsored by the Central Platte Natural Resources District, Nebraska Environmental Trust, University of Nebraska-Lincoln (UNL) Rural Initiative, and UNL Extension, will provide good-quality flux and other extensive supportive (plant physiology, soil characteristics, soil water content, and surface characteristics) data to the micrometeorology, water resources and agricultural engineering, and science community on a broad spectrum of agro-ecosystems and climatic environments. The fundamental premise of the NEBFLUX project is to make continuous and long-term (at least ten complete annual cycles for each vegetation surface) exchange of water vapor and energy fluxes between agro-ecosystems and the microclimatic environment. It is also sought to investigate, and provide information about, the role of the agro-ecosystems in water resources balances, plant water use efficiency, and radiation use efficiency in the watershed. The important and relevant question of how various agro-ecosystem management practices can alter an ecosystem's water and energy balances on a field and watershed scale is a further output of the project. Understanding the relationship between the surface characteristics and plant physiological parameters and surrounding microclimate in terms of water and energy transport is another vital output of the project.

Currently available surface energy flux measurement methods such as eddy covariance system (Swinbank, 1951; Tanner, 1960; Kizer and Elliot, 1991; Anthoni et al., 1999; Wilson et al., 2001; Sun et al., 2008), Bowen ratio energy balance system (Tanner, 1960; Denmead and McIlory, 1970; Fuchs, 1973; Lang, 1973; Blad and Rosenberg, 1974; Massman, 1992; Malek and Bingham, 1993; Zhang et al., 2008; Irmak et al., 2008a, 2008b; Irmak and Mutiibwa, 2009a, 2009b), and surface renewal (Paw et al., 1995; Snyder et al., 1996; Spano et al., 2000; Zapata and Martinez-Cob, 2001; Castellvi et al., 2006) provide imperative and essential flux data on a point scale. In many cases, these fluxes need to be up-scaled for field, irrigation or natural conservation district or watershed levels to evaluate the spatial and temporal distribution of the fluxes. One of the approaches to establish the integration of the spatial distribution of water vapor and energy transport between the surface and microclimate can be done by combining BREBS flux measurements with biophysical models and/or remote sensing satellite methodologies. Remote sensing of the biophysical properties of the surface coupled with field-measured flux information enables the use of BREBS data to scale water vapor and energy flux information from the individual grid or field to larger spatial and temporal scales. In another significant component of the NEBFLUX project, two remote sensing/satellite methods, i.e., Surface Energy Balance Algorithm for Land (SEBAL) and Mapping Evapotranspiration with Internalized Calibration (METRIC) (Bastiaanssen et al., 1998; Bastiaanssen et al., 2002; Allen et al., 2007a; Allen et al., 2007b; Singh et al., 2008), are being used to scale fluxes from field scale to larger scales to study the spatial distribution of fluxes for various vegetation surfaces.

NEBFLUX has several operational and structural components, including the project's main office, which currently houses the principal investigator, three post-doctoral research scientists, five graduate students (four PhD and one MS), and a full-time research technician. In the same office, the research procedures, records, and data archive are maintained, serving as a central repository for network data and information. The main office also serves as the planning center for public educational programs to inform public, state, and federal agencies regarding the progress and findings of the NEBFLUX. Information dissemination to inform and educate the general public is another important objective and output of the project. A comprehensive web page for the NEBFLUX is being developed. It is intended that the current and archived flux, soil, soil water content, plant physiology, and other supporting data will be posted on the web page. Background information on vegetation types, instrumentation details and locations, data collection procedures, maintenance, and operational characteristics of the NEBFLUX are provided in the following sections.

Materials, Methods, and Procedures

NEBFLUX Site Descriptions

The agro-ecosystems that were selected for the placement of the NEBFLUX sites were, initially, based on the pressing needs for the ET_a information that is required for water resources assessments. With the current configuration, the NEBFLUX is able to deduce certain information on energy and water vapor fluxes on a field scale from the towers that are placed across a spectrum of vegetation functional regions, vegetation surfaces, management practices, microclimates, and soil conditions. The vegetation surfaces include both tilled and untilled rainfed and irrigated croplands, irrigated and rainfed grasslands, and riparian vegetation comprised of Phragmites (*Phragmites australis*)-dominated cottonwood (*Populus deltoides* var. *occidentalis*) and willow stand (*Willow salix*) plant community. The locations of ten BREBSs and one eddy covariance system (ECS) are presented in figure 2. The flux towers are installed on state, federal, or privately owned lands. Detailed location information on BREBS (BREBS-1 through BREBS-10) and ECS data, including observation years, latitude, longitude, elevation, and vegetation type, are given in table 1. The systems are installed on large fields, and the fetch distance is adequate for each BREBS site (table 1). Thus, the BREBS measurement heights were considered to be within the boundary layer over each vegetation surface.

The elevation of the fields where the flux towers are installed ranges from 409 to 702 m (table 1). The sites differ in terms of soil characteristics, ranging from fine-textured to very coarse-textured soils, with significant variations in water holding capacity, organic matter content, field capacity, permanent wilting point, saturated hydraulic conductivity, and other soil properties (table 2). The soil characteristics data presented in table 2 were determined from a combination of direct field measurements and those obtained from the USDA-NRCS Web Soil Survey site (http://websoilsurvey.nrcs.usda.gov). Photographs from various BREBSs that reflect the changes that the vegetation surfaces exhibit throughout the calendar year are presented in figures 3a and 3b. The following sections provide brief descriptions of the field management practices and vegetation characteristics for each NEBFLUX site.

BREBS-1 and ECS-1

BREBS-1 and ECS-1 (fig. 3a) have been running side by side (within 10 m) since October 2004 at Clay Center, Nebraska. The study area is in a transition zone between sub-humid and semi-arid zones, with strong winds. The weather in this area is influenced by extremely cold dry continental air masses passing through Canada and the Rocky Mountains during the winter periods, and warm and humid turbulent air moving from the Gulf of Mexico during the summer periods. The depth to groundwater at the site is approximately 60 m. This research field (14 ha) was planted to irrigated continuous maize in 2004, 2005, and 2006; irrigated soybean in 2007 and 2008; and irrigated winter wheat in 2009 and 2010 (figs. 3a and 3b). The field was maintained as ridge-till with a row spacing of 76 cm for maize and soybean and 19 cm for winter wheat with an east-west row direction for all vegetation surfaces. The average planting population is 73,000 plants ha^{-1} for maize, 385,000 plants ha^{-1} for soybean, and about 2,500,000 plants ha^{-1} for winter wheat. BREBS-1 and ECS-1 have been measuring energy and water vapor fluxes for variety of surfaces ranging from maize, soybean, and wheat in summer and spring to residue-covered soil after harvest in fall, snow and/or ice-covered surface in dormant (winter) months, to nearly bare soil in spring before planting.

In addition to the flux measurements, other soil and plant parameters such as soil water content up to 1.8 m with 0.30 m increments is measured in several locations in the field. Plant height (*h*), leaf area index (*LAI*), and leaf stomatal resistance (using a dynamic diffusion porometer) are measured on selected periods. In 2006 and 2007, extensive field campaigns were conducted to measure leaf stomatal resistance, photosynthetic photon flux density, *LAI*, *h*, leaf

Table 1. Data/year, location, vegetation characteristics, and fetch distance of the NEBFLUX Bowen ratio energy balance system (BREBS) sites.

BREBS/ ECS	Observation Years	Latitude	Longitude	Elev. (m)	Fetch[a] (m)	Vegetation Surface
BREBS-1	2004-2006	40°34′ N	98°08′ W	552.0	NS = 520; EW = 280	Subsurface drip-irrigated maize (*Zea mays* L.)
BREBS-1	2007-2008	40°34′ N	98°08′ W	552.0	NS = 520; EW = 280	Subsurface drip-irrigated soybean [*Glycine max* (L.) Merr.]
BREBS-1	2009-continue	40°34′ N	98°08′ W	552.0	NS = 520; EW = 280	Subsurface drip-irrigated winter wheat (*Triticum aestivum L.*)
ECS-1	2004-2006	40°34′ N	98°08′ W	552.0	NS = 520; EW = 280	Subsurface drip-irrigated maize
ECS-1	2007-2008	40°34′ N	98°08′ W	552.0	NS = 520; EW = 280	Subsurface drip-irrigated soybean
ECS-1	2009-continue	40°34′ N	98°08′ W	552.0	NS = 520; EW = 280	Subsurface drip-irrigated winter wheat
BREBS-2	2007-continue	41°17′ N	97°56′ W	577.3	NS = 780; EW = 800	Center-pivot-irrigated grassland, mixture of tall fescue (*Festuca arundinacea*), Kentucky bluegrass (*Poa pratensis*), smooth bromegrass (*Bromus inermis*), and creeping foxtail (*Alopecurus arundinacea*)
BREBS-3	2008-continue	41°16′ N	97°56′ W	549.0	NS = 1200; EW = 640	Rainfed grassland, mixture of native Buffalograss (*Bouteloua dactyloides* Nutt.) and tall fescue
BREBS-4	2008-continue	41°08′ N	98°10′ W	409.3	NS = 1400; EW = 430	Rainfed winter wheat
BREBS-5	2008-continue	40°58′ N	97.65° W	573.6	NS = 300; EW = 800	Center-pivot-irrigated no-till soybean-maize rotation
BREBS-6	2008-continue	40°34′ N	97.39°W	576.0	NS = 500; EW = 800	Center-pivot-irrigated disk-tilled soybean-maize rotation
BREBS-7	2009-continue	41°7.9′ N	97°55′ W	510.5	NS = 120; EW = 200	*Phragmites australis*-dominated cottonwood (*Populus deltoides* var. occidentalis) and willow stand (Willow salix) plant community
BREBS-8	2009-continue	41°11′ N	98°1.1′ W	546.2	NS = 430; EW = 800	Center-pivot-irrigated alfalfa (*Medicago sativa*)
BREBS-9	2010-continue	40°21′ N	99°19′ W	694	NS = 460; EW = 800	Center-pivot-irrigated no-till soybean-maize rotation
BREBS-10	2010-continue	40° 22′ N	99° 19′ W	707	NS = 460; EW = 800	Center-pivot-irrigated disk-tilled soybean-maize rotation

[a] NS = north-south; EW = east-west.

temperature, and within-canopy radiation (light) distribution parameters throughout the growing seasons for maize and soybean. In addition, diurnal readings (from 8:00 a.m. to 6:00 p.m. Central Standard Time) of the same variables were taken several times during the each growing season to study the diurnal variation in stomatal resistance in relation to aforementioned environmental factors (Irmak et al., 2008b; Irmak and Mutiibwa, 2008, Irmak and Mutiibwa, 2009a, 2009b). Similar measurements have been taken at the BREBS-7 site since May 2009. *LAI*, *h*, dry matter production, and other physiological parameters are measured at some BREBS sites. Yield data from each vegetation surface and grain quality (fiber, oil, starch, and protein content) for some surfaces are determined every year. In addition to the water and energy flux measurements, BREBS-1 was equipped with infrared thermometers that are installed at the soil surface, canopy surface, and additional canopy temperature sensors at 1.8, 3.6, and 5.4 m above the soil surface to measure surface temperature profiles every 15 min throughout the year since 21 July 2007.

BREBS-2 AND BREBS-3

The BREBS-2 and BREBS-3 towers are installed on irrigated and rainfed grasslands, respectively (fig. 3a), with approximately 400 m distance from each other near Central City, Nebraska, approximately 10 km north of the Platte River. Both fields have similar topography and soil structures. Both fields are maintained as pasture and have controlled grazing. Both sites are in a transition area from sub-humid to semiarid zones. The irrigated grassland is approximately 64.7 ha in size and contains a mixture of cool-season grasses, i.e., tall fescue (*Festuca arundinacea*), Kentucky bluegrass (*Poa pratensis*), smooth bromegrass (*Bromus inermis*), and creeping foxtail (*Alopecurus arundinacea*). The irrigated grassland was established in 1970. The rainfed grassland is approximately 70 ha in size and contains primarily buffalograss (*Bouteloua dactyloides* Nutt.) (~90%) and tall fescue. This grassland was established in 1980 and still maintains its natural establishment conditions. It is basically native grassland. Significant spring rains and irrigation in the summer keep the grasslands in well-watered conditions at the BREBS-2 site. The BREBS-3 site experiences plant water stress, especially during July and August. Both fields are fertilized as needed. Both grasslands are grazed throughout most of the growing season, and the grass height varies between approximately 5 and 13 cm throughout the season. In addition to the flux measurements, grass height, leaf area index, and dry matter production were measured every 10 days in 2007 and 2008 at both sites. The soil water content is measured every 0.30 m up to 1.8 m on an hourly basis throughout the year. All agronomical and

Table 2. Basic soil characteristics for different soil layers at the NEBFLUX research sites.

Soil Layer (cm)	Particle Size Distribution % Sand	% Silt	% Clay	Bulk Density (g cm^{-3})	Saturated Hydraulic Cond. (μm s^{-1})	Organic Matter Content (%)	Field Capacity (%)	Permanent Wilting Point (%)	Saturation (cm^3 cm^{-3})	Soil Classification and Soil Taxonomy	Slope (%)
BREBS-1	16.2	53.7	30.1	1.3	1.4		34.6	14.0	0.51	Silt loam; Crete fine, smectitic, mesic Pachic Argiustolls	1.0
0-25.4	25	52	23	1.2-1.4	4.2-14.1	2.0-4.0					
25.4-33	19	48	33	1.25-1.45	1.4-4.2	1.0-3.0					
33-71	5	46	49	1.2-1.3	0.07-0.4	0.5-2.0					
71-81	17	48	35	1.25-1.45	0.4-1.4	0.5-1.0					
81-203	18	57	25	1.3-1.45	4.2-14.1	0.5-1.0					
BREBS-2	93.1	4.7	2.2	1.83	39.7		7.2	1.9	0.31	Sand; Fonner sandy, mixed, mesic Cumulic Haplustolls	1.0
0-23	80	16	4	1.6-1.8	42.0-141.0	0.5-1.0					
23-46	80	16	4	1.6-1.8	42.0-141.0	0.0-0.5					
46-203	97	2	1	1.70-1.95	141.0-705.0	0.0-0.5					
BREBS-3	93.7	1.5	4.8	1.72	24.8		10.9	3.9	0.35	Loamy fine sand; Ipage mixed, mesic Oxyaquic Ustipsamments	1.0
0-23	87	7	6	1.4-1.5	42.0-141.0	0.5-2.0					
23-152	95	1	4	1.5-1.6	42.0-141.0	0.0-0.5					
BREBS-4	30.1	53.7	16.2	1.42	4.06		23.4	10.3	0.46	Silt loam; Leshara fine-silty, mixed, superactive mesic Fluvaquentic Endoaquolls	1.0
0-30	11	68	21	1.3-1.5	4.2-14.1	1.0-3.0					
30-117	12	69	19	1.3-1.5	4.2-14.1	0.5-1.0					
117-152	92	4	4	1.7-1.9	42.0-141.0	0.0-0.5					
BREBS-5	15.1	47.7	37.2	1.27	0.94		32.3	21.2	0.52	Silt loam; Crete fine, smectitic, mesic Pachic Argiustolls	2.0
0-18	25	52	23	1.2-1.4	4.2-14.1	2.0-4.0					
18-30	19	48	33	1.25-1.45	1.4-4.2	1.0-3.0					
30-84	5	46	49	1.2-1.3	0.4-1.4	0.5-2					
84-152	20	48	32	1.3-1.45	1.4-14.1	0.5-1.0					
BREBS-6	15.1	47.7	37.2	1.27	0.9		32.3	21.2	0.52	Silt loam; Crete fine, smectitic, mesic Pachic Argiustolls	0.0
0-18	25	52	23	1.2-1.4	4.2-14.1	2.0-4.0					
18-30	19	48	33	1.25-1.45	1.4-4.2	1.0-3.0					
30-84	5	46	49	1.2-1.3	0.42-1.41	0.5-2					
84-152	20	48	32	1.3-1.45	1.41-14.1	0.5-1.0					
BREBS-7	87.5	10.3	2.2	1.82	32.4		6.4	1.6	0.31	Loamy sand; Gothenburg mixed, mesic Typic Psammaquents	2.0
0-8	79	16	5	1.5-1.6	42.0-141.0	0.5-1.0					
8-152	88	10	2	1.55-1.7	141.0-705	0.0-0.5					
BREBS-8	82.6	12.3	5.1	1.69	18.7		12	5.1	0.36	Sandy loam over sand; O'Neill coarse loamy over sandy or sandy-skeletal, mixed, superactive, mesic Typic Haplustolls	1.0
0-58	69	24	7	1.6-1.8	14.1-42.3	1.0-3.0					
58-76	68	20	12	1.6-1.8	42.3-141.0	0.5-1.0					
76-152	97	2	1	1.5-1.7	141.0-705	0.0-0.5					
BREBS-9	8.8	65.6	25.6	1.31	2.3		30.5	16.2	0.51	Silt loam; Holdrege fine-silty, mixed, superactive, mesic Typic Argiustolls	0.0
0-41	9	67	24	1.4-1.6	4.2-14.1	2.0-4.0					
41-76	7	62	31	1.2-1.4	1.4-4.2	0.5-2					
76-100	9	66	25	1.3-1.5	4.2-14.1	0.0-0.5					
100-152	9	67	24	1.4-1.6	4.2-14.1	0.0-0.5					
BREBS-10	8.8	65.9	25.3	1.31	2.4		30.4	16	0.5	Silt loam; Holdrege fine-silty, mixed, superactive, mesic Typic Argiustolls	2.0
0-36	9	67	24	1.4-1.6	4.2-14.1	2.0-4.0					
36-66	7	62	31	1.2-1.4	1.41-4.2	0.5-2					
66-86	9	66	25	1.3-1.5	4.2-14.1	0.0-0.5					
86-152	9	67	24	1.4-1.6	4.2-14.1	0.0-0.5					

management practices and information are recorded every year.

BREBS-4

The BREBS-4 tower (fig. 3a) is installed on a rainfed winter wheat field of approximately 65 ha. The site has a uniform slope with a very shallow groundwater depth (≈2.0 m), although the depth to groundwater fluctuates with season. The management practices are somewhat different from those practiced at the BREBS-1 winter wheat site. The planting depth was 4.0 cm with a row spacing of 19.0 cm and a planting population of approximately 2,000,000 plants ha^{-1}. At this site, in an average year, winter wheat usually experiences significant plant water stress, and the ground-water usually does not contribute to the available water content in the plant root zone (approximately 90 cm) due to sandy soil conditions. The soil water content generally increases steadily throughout the spring with a spike in early June. Soil water content usually trends downward in the top 60 cm soil profile starting in early to mid-June. In addition to the flux measurements, vegetation samples for plant height, leaf area index, and dry matter production are collected from randomly selected locations in four quadrants within a 120 m radius of the BREBS-4 tower. The winter wheat samples

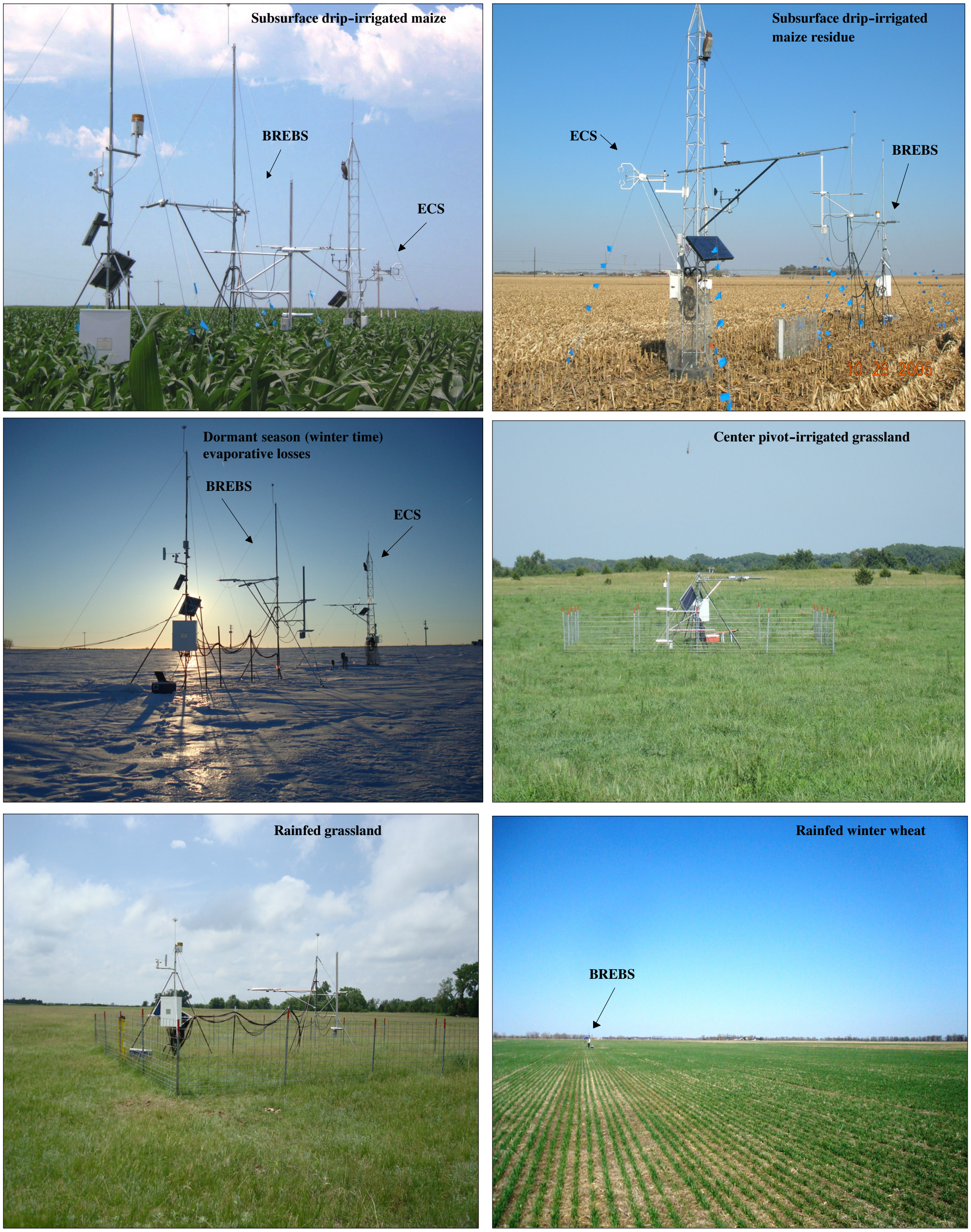

Figure 3a. Some of the NEBFLUX vegetation surfaces where the Bowen ratio energy balance systems (BREBS) are installed.

consisted of all above-ground vegetation within a 1.0 m length of one row. For all samples, green leaf material was separated from all other material, and leaf area index was calculated using only the area of the green leaf material. The soil water content is measured on an hourly basis every 0.30 m up to 1.8 m on an hourly basis. All agronomical and management practices data and information are recorded every year.

BREBS-5 and BREBS-6

BREBS-5 is installed on a center-pivot irrigated no-till soybean-maize rotation field, while BREBS-6 is installed on an adjacent field on a center-pivot irrigated disk-tilled soybean-maize rotation field (fig. 3b). Both fields have a history of either no-till or disk-till soil management practice for at least seven years. The main objective of running BREBS-5 and BREBS-6 side by side is to measure, investigate, and understand the impact of tillage practices on soil properties, energy and water balance, microclimate,

Figure 3b. Some of the NEBFLUX vegetation surfaces where the Bowen ratio energy balance systems (BREBS) are installed.

plant physiological parameters, yield, and their interactions. The same instrument deployment is replicated in a drier part of the state (BREBS-9 and BREBS-10). At each site, the paired no-till and disk-tilled fields have the same soil properties, slope, and terrain characteristics; the same planting date, depth, and row direction; the same soybean cultivar and corn hybrid; similar fertility, irrigation (similar irrigation system capacity, nozzle size, etc.), insecticide, pesticide, and herbicide management practices; and the same field size. Thus, the only difference between the fields is the tillage practice. In addition to the energy fluxes [net radiation (R_n), E_{Ta}, soil heat flux (G), sensible heat flux (H)], plant physiological measurements such as plant height and leaf area index are measured in each pair of fields on a weekly basis from 30 locations in each field for each physiological parameter. In addition, the surface runoff, infiltration rate, and deep percolation are measured in each field to account for all water balance parameters to study the potential differences and their causes between the two fields.

In addition to all other NEBFLUX BREBS sites, remote sensing methodology is being applied comprehensively to quantify ET_a and other surface energy fluxes from tilled and untilled fields at the BREBS-5, 6, 9, and 10 sites using a land surface energy balance model (METRIC). The key remotely sensed data collected from these projects involves an airborne platform with 0.90 or 2.1 m spatial resolution that consists of 62 hyperspectral bands (62@10 nm) between 400 and 1000 nm and a thermal band. Airborne images were acquired twice a month for each site during the growing season under clear sky conditions. The AISA imager and thermal infrared camera at CHAMP (CALMIT Hyper-spectral Aerial Monitoring Program at the University of Nebraska-Lincoln; CALMIT, 2005) is being used to acquire images on scheduled mission dates. Furthermore, the LANDSAT TM/ETM scenes are acquired for at least seven or eight dates for each year during the growing season. The repeat coverage interval for LANDSAT data is 16 days. Calibrated METRIC parameters obtained with the airborne images are being utilized to run the model with the LANDSAT data to upscale the flux measurements. The ability of the METRIC model (using both airborne and satellite remote sensing data) to predict daily and seasonal ET_a is compared with the measured data from BREBS. One of the ultimate goals of the remote sensing methodology in this project is to develop a technique to separate ET_a for tilled and untilled fields (A. Irmak, 2010, personal communication).

BREBS-7

BREBS-7 (fig. 3b) measures the evaporative losses and surface energy balance variables on a Phragmites-dominated cottonwood and willow stand plant community on an island in the Platte River channel, approximately 7 km east of Central City, Nebraska. *Phragmites australis*, also known as common reed, is one of the invasive species that has been a concern to Midwestern states, including Nebraska. It is a perennial, wetland grass that can grow to 4.5 m or more in height. Where conditions are suitable, it can spread at 5.0 m or more per year by horizontal stolons (rhizomes), which expands roots at regular intervals. It can grow in wet grounds, in standing water, or even as a floating mat. An invasive variety of Phragmites is becoming widespread in the Platte River valley, Nebraska, and is becoming a concern for the ecological health of wetlands and natural habitat, especially in the river banks. Managers and ecologists have been concerned with this invasive species for potentially altering the river hydrology, reducing plant biodiversity, changing wildlife communities ranging from benthic invertebrates to migrating birds and fish communities, affecting nutrient cycling, and altering biogeochemical properties in invaded systems. Water management and policy-makers are also concerned that Phragmites, cottonwood, and willow stands utilize considerable amounts of water from the hydrologic system. The main objective of BREBS-7 is to measure total evaporative losses from these three plant species. The transpiration rates of individual species will be determined from Jarvis (1976) and Penman-Monteith (Monteith, 1965)-type parameterization of stomatal resistance vs. transpiration and ET_a relationships (Irmak and Mutiibwa, 2009b. For this purpose, the micrometeorological parameters, above- and within-canopy radiation transfer parameters, and plant physiological variables such as leaf area index for sunlit and shaded leaves, light interception above and within the canopy (at various layers in the canopy), stomatal resistance of sunlit and shaded leaves, plant height, and photosynthetic photon flux density are measured for all three plant species several times a week (including diurnal measurements once a week) through an extensive field campaign to scale up leaf level stomatal resistance to canopy resistance (using a similar approach presented by Irmak et al., 2008b; Irmak and Mutiibwa, 2008; and Irmak and Mutiibwa, 2009a, 2009b) for transpiration and ET_a modeling for each plant species individually. These measurements and information will also be utilized to better understand the relationships and dynamics involved between evaporative losses from each species and plant physiological and microclimatic parameters. Similar remote sensing/satellite methodology used at BREBS-5, 6, 9, and 10 is being applied at the BREBS-7 site.

BREBS-8, BREBS-9, and BREBS-10

BREBS-8 is set up on a center-pivot irrigated two-year-old alfalfa stand (fig. 3b). The field is about 65 ha in size with a relatively uniform slope and soil properties. The alfalfa stand in the experimental region is usually cut five times during the season starting in early June, and the cutting can continue until late September. In Nebraska conditions, alfalfa typically begins in early to mid-April. At the BREBS-8 site, the alfalfa growth parameters (*LAI* and *h*), cutting dates and height, yield production in each cutting, soil water content, and every 0.30 m up to 1.8 m are monitored. BREBS-9 and BREBS-10 have similar characteristics as BREBS-5 and BREBS-6, as described earlier, to determine the tillage impact on water and energy fluxes and plant physiological parameters in two different climatic regions.

Instrumentation for Bowen Ratio Energy Balance Systems

The surface energy balance components, including ET_a, H, G, R_n, and microclimatic variables, at each site are measured using a deluxe version of a Bowen ratio energy balance system (BREBS) (Radiation and Energy Balance Systems, REBS, Inc., Bellevue, Wash.). At all NEBFLUX sites, identical BREBSs are used so that the data are intercomparable between the sites. A summary of the specifications of the sensors and instruments used to measure fluxes, microclimatic variables, soil moisture, and plant physiological parameters for various vegetation surfaces at all the NEBFLUX sites is presented in table 3. The height or the depth for the instrumentation is listed in table 4. The following sections briefly describe the main instrumentation used for the BREBSs, which apply to each NEBFLUX site.

Incoming and Outgoing Shortwave and Longwave Radiation and Net Radiation

Net radiation is measured using a REBS Q*7.1 net radiometer that is installed approximately 4.5 m above the soil surface. The height of the net radiometer changed with the vegetation height (table 3). At each site, the net radiometer is extended away from the tripod (horizontally to the vegetation canopy) so that only the R_n at the vegetation surface is measured. Thus, the reflection of heat and radiation from any other instruments that are installed on the tripod is eliminated. The REBS Q*7.1 is sensitive to wavelengths from 0.25 to 60 μm. The Q*7.1 is designed and calibrated to account for the windshield temperature effect on R_n by measuring and incorporating the temperature inside the upper and lower radiation domes (shield) into the calculations continuously to minimize the error caused by windshield temperatures. Thus, the R_n measured with a Q*7.1 net radiometer may not agree exactly with the R_n

Table 3. Summary of specifications of the sensors and instruments used to measure microclimatic variables, soil moisture, and plant physiological parameters for various vegetation surfaces using the Bowen ratio energy balance systems (BREBS) at the NEBFLUX sites.

Variable/Unit	Instrument	Specified Accuracy or Resolution
Air temperature (°C)	TH04015 chromel-constantan thermocouple[a]	±0.0055°C
Relative humidity (%)	TH04016 chromel-constantan thermocouple[a]	±0.033%
Wind speed (m s^{-1}) and direction (degrees)	034B cup anemometer[b]	0.12 m s^{-1} for WS < 10.1 m s^{-1}; ±1.1% for WS > 10.1 m s^{-1}; 0.5° resolution for wind direction
Soil heat flux (W m^{-2})	REBS HFT-3.1 soil heat flux plate[a]	0.906 W m^{-2}
Soil temperature (°C)	REBS STP-1 soil thermocouple probes[a]	±0.02°C
Barometric pressure (kPa)	276 barometric pressure sensor[c]	±0.25%
Surface soil moisture (% vol)	REBS SMP1R soil moisture probes[a]	±2.0%
Profile soil moisture (% vol)	CS616 soil water content reflectometer[d]	±2.0%
Rainfall (mm)	TR-525 rainfall sensor[e]	1.0% or 0.1 mm
Net radiation (W m^{-2})	REBS Q*7.1 net radiometer[a]	±0.10%
Incoming and outgoing shortwave and longwave radiation (W m^{-2})	THRDS7.1 double-sided total hemispherical radiometer[a]	±0.10%
Surface albedo	Calculated from the ratio of outgoing shortwave to incoming shortwave radiation	--
Leaf area index	LAI-2000 plant canopy analyzer[f]	2.0% to 8.0%
Leaf stomatal resistance (s m^{-1} or m s^{-1})	AP4 steady-state porometer[g]	1.0% to 10%/0.5 μmol s^{-1} m^{-2}
Photosynthetic photon flux density (μmol s^{-1} m^{-2})	AP4 steady-state porometer[g]	0.5 μmol s^{-1} m^{-2}
Leaf temperature (°C)	AP4 steady-state porometer[g]	±0.2°C
Surface temperature (°C)	IRTS-precision infrared thermocouple[h]	±0.2°C from 15° to 35°C; ±0.3°C from 5° to 45°C
Vegetation height (m)	Laser scale/portable ruler	--

[a] Radiation and Energy Balance Systems, Inc., Bellevue, Washington.
[b] Met-One Instruments, Grants Pass, Oregon.
[c] Setra Systems, Inc., Boxborough, Massachusetts.
[d] Campbell Scientific, Inc., Logan Utah.
[e] Texas Electronics, Inc., Dallas, Texas.
[f] Li-Cor Biosciences Corp., Lincoln, Nebraska.
[g] Delta-T Devices, Ltd., Cambridge, U.K.
[h] Apogee Instruments, Logan, Utah.

calculated using other radiometers if the other radiometers are not used with proper or similar windshield temperature correction algorithms.

Incoming and outgoing shortwave and longwave radiation envelopes are measured simultaneously using a REBS model THRDS7.1 double-sided total hemispherical radiometer. The incoming shortwave radiation consists of direct beam and diffuse radiation and is defined as the wavelengths from 0.25 to 4 μm. Incoming longwave radiation consists mainly of longwave atmospheric radiation and is defined as the wavelengths from 4 to 100 μm. The THRDS7.1 is sensitive to wavelengths from 0.25 to 60 μm. At each site, the THRDS7.1 extends away from the tripod so that only the incoming and outgoing radiation at the vegetation surface is measured. The surface albedo is calculated as the ratio of outgoing shortwave to incoming shortwave solar radiation. The outer transducer surfaces (sensor surface) and the surrounding surfaces of both the Q*7.1 and the THRDS7.1 are flat black, and the frame is black to reduce internal reflections within the radiometers, thus providing more uniform performance over reflective surfaces. The black paint used in both radiometers has superior absorption properties compared to that used in the previous versions of radiometers. The sensor surfaces are protected from excessive convective cooling by hemispherical polyethylene windshields. The polyethylene windshield is used in the sensor because it is transparent to both longwave and shortwave energy. Two chromel-constantan (type E) differential thermocouple junctions are installed to measure temperature differences between the core and upper and lower windshields. A desiccant tube is contained in the support arm of all radiometers, and a fan blows air continuously though the radiometers at a constant velocity to keep the air space inside radiometer shields dry and to reduce or eliminate condensation inside the radiation domes (C. Fritschen, 2010, personal communication).

Air Temperature and Relative Humidity Gradients

The chromel-constantan thermocouple for the air temperature (T_a) and relative humidity (*RH*) probes (model THP04015 for T_a, and THP04016 for *RH*), with a resolution of 0.0055°C for T_a and 0.033% for *RH*, are used to measure T_a and *RH* gradients. Each of the T_a and *RH* sensors are located at the center of a coaxial anodized aluminum radiation shield and continuously aspirated by a brushless 12 VDC fan at approximately 2.6 m s^{-1} constant air velocity. In addition to T_a and *RH*, humidity cavity temperature is measured in each housing unit. The temperature sensors for determining *RH* cavity temperatures are platinum resistance temperature detectors. The T_a and *RH* sensors are made of fine-wire thermocouples. Each *RH* sensor is contained in a housing protected by an appropriate filter to prevent contamination. Temperature sensor sensitivities are crucial in the BREBS method because the method requires that the gradients of both T_a and RH be measured with great accuracy. With the BREBS method, the resolution of temperature gradients must be in the order of a few thousandths of a degree. Vapor pressure gradients require similar resolution. Even small biases between T_a sensors in the upper and lower exchanger arms can result in incorrectly determined gradients, causing significant errors in Bowen ratio and measured ET_a. Consequently, it is necessary to frequently exchange T_a and RH sensor locations to remove these potential biases in the sensors. It is especially critical to exchange the T_a and RH sensors when computing the LE and H flux densities when the flux densities and/or gradients are small. Fritschen and Simpson (1982) and Fritschen et al. (1985) reported that when the evaporative flux densities over alfalfa and salt cedar trees ranged from 800 to 900 W m^{-2}, the accompanying temperature gradients were about 2°C and 0.2°C m^{-1}, respectively, and the vapor pressure gradients were about 0.4 and 0.05 kPa m^{-1}, respectively. Over 30 m Douglas fir with an evaporative flux of 250 to 350 W m^{-2}, the temperature gradient was about 0.03°C m^{-2} while the vapor pressure gradients were about 0.002 kPa m^{-1}. These observations illustrate that increased data recording resolution is required for Bowen ratio analyses over aerodynamically rough surfaces. Temperature gradient measurements to one part in one hundred require a resolution of 0.02°C over alfalfa and 0.0003°C over rough Douglas fir. These results show not only that an adequate resolution is needed, but also that it is essential for the success of the Bowen ratio method to frequently interchange T_a and RH sensor positions when the gradients are small, even if the sensor offsets or biases are small. At all NEBFLUX sites, the deluxe version of the BREBS uses an automatic exchange mechanism that physically exchanges the T_a and RH sensors at two heights above the canopy. T_a and RH sensors are exchanged during the last 2 min of each 15 min interval. The upper exchanger tube that houses the T_a and RH probes is driven down in the first and third 15 min periods of each hour, and the bottom tube is driven up in the second and fourth 15 min periods of each hour.

The housing units (aspirated radiation shield, ARS) for the T_a and RH measurements are faced north in each system so that direct sunlight does not reach inside the aluminum housing units and impact the T_a and RH measurements. The ARS is constructed with two highly polished concentric aluminum tubes (exchanger tubes) that house the T_a and RH sensors. The low-emissivity surfaces of these tubes and the fact that they are thermally isolated from each other minimizes both longwave and shortwave radiation loading effects on the sensors. The forced downdraft ventilation of the ARS housing maintains an adequate ventilation velocity no matter which way the wind is blowing. Thus, the forced ventilation keeps the conditions measured by the T_a and RH sensors very close to the ambient conditions. The T_a sensors inside each ARS unit are housed in a 19 mm diameter stainless steel tube. The RH sensor is housed in a stainless steel hydrophobic filter to exclude debris and condensation. The exposed end of the outer tube of the ARS is cut at an angle to act as a shade and to minimize the accumulation of water on its inside base during rain storms or irrigation (which would affect the humidity measurements) (C. Fritschen, 2010, personal communication). With this design, it is extremely difficult for rain or irrigation water to enter the ARS. This is also important when the BREBS is installed under an irrigation system that periodically wets the system in addition to precipitation. BREBS-2, 5, 6, and 8 are installed on fields that are irrigated with a center-pivot system, and all the BREBS components are fit to clear the truss rods of the pivot system. Figure 4 shows a typical setup of a BREBS (i.e., BREBS-6) that is installed under the center-pivot system. To illustrate that rain or irrigation water does not enter the ARS unit, a photograph was taken on 25 August 2008 when the center-pivot system was running and passing over the BREBS-6. Figure 4c clearly shows that the design of the exchanger tubes prevents irrigation and rain water from entering the exchanger housing. Water does not wet the T_a and RH sensors and therefore does not impact the measurements.

Precipitation, Wind Speed and Direction, Soil Heat Flux, and Datalogging

Precipitation is recorded using a model TR-525 rain sensor that has 0.1 mm resolution and 1.0% accuracy at rainfall intensity of 10 mm h^{-1} or less with a 0.75 ms response time. The rain gauges at all NEBFLUX sites are installed above the canopy, and the height varies with the vegetation height. The gauges are installed high enough so that the rainfall interception by the other instruments, towers, solar panel, and control box is prevented. At the BREBS-1 site, in addition to a rain gauge, an AC-powered snow gauge is also installed to measure winter precipitation more accurately. Wind speed and direction at 3 m height (for most vegetation surfaces) (table 4) are monitored using a model 034B cup anemometer that has a wind speed range of 0 to 44.7 m s^{-1} with a starting threshold of 0.28 m s^{-1}. The accuracy of the wind direction sensor is ±4° with a 0.5° resolution. Each BREBS is equipped with a barometric pressure sensor. At each site, the soil heat flux density is measured using three REBS HFT-3.1 heat flux plates and three soil thermocouples. Each plate is placed at a depth of 0.06 m below the soil surface under the net radiometer. The REBS STP-1 soil thermocouple probes are installed in close proximity to each plate at a depth of approximately 0.06 m below the soil surface. Measured G values are adjusted to soil temperatures and surface soil water content as measured using three REBS SMP1R soil moisture probes. One soil moisture probe is installed in close proximity to each soil heat flux plate. All variables are sampled every 60 s and averaged and recorded every hour for energy balance calculations using a model CR10X datalogger and AM416 relay multiplexer (Campbell Scientific, Inc., Logan, Utah). All system components are powered by a solar panel and a 12 V, 140 A marine battery.

Additional Measurements

In addition to aforementioned measurements, the profile soil water content at each BREBS site is measured every 0.30 m up to 1.8 m on an hourly basis throughout the year using CS616 water content reflectometers (WCR) (table 3). The WCR is a frequency-domain-type sensor that has two 0.30 m rods to send and receive frequency signals along the 0.30 m soil profile. In the WCR approach, nanosecond rise times produce waveform reflections characteristic of an open-ended transmission line. The return of the reflection

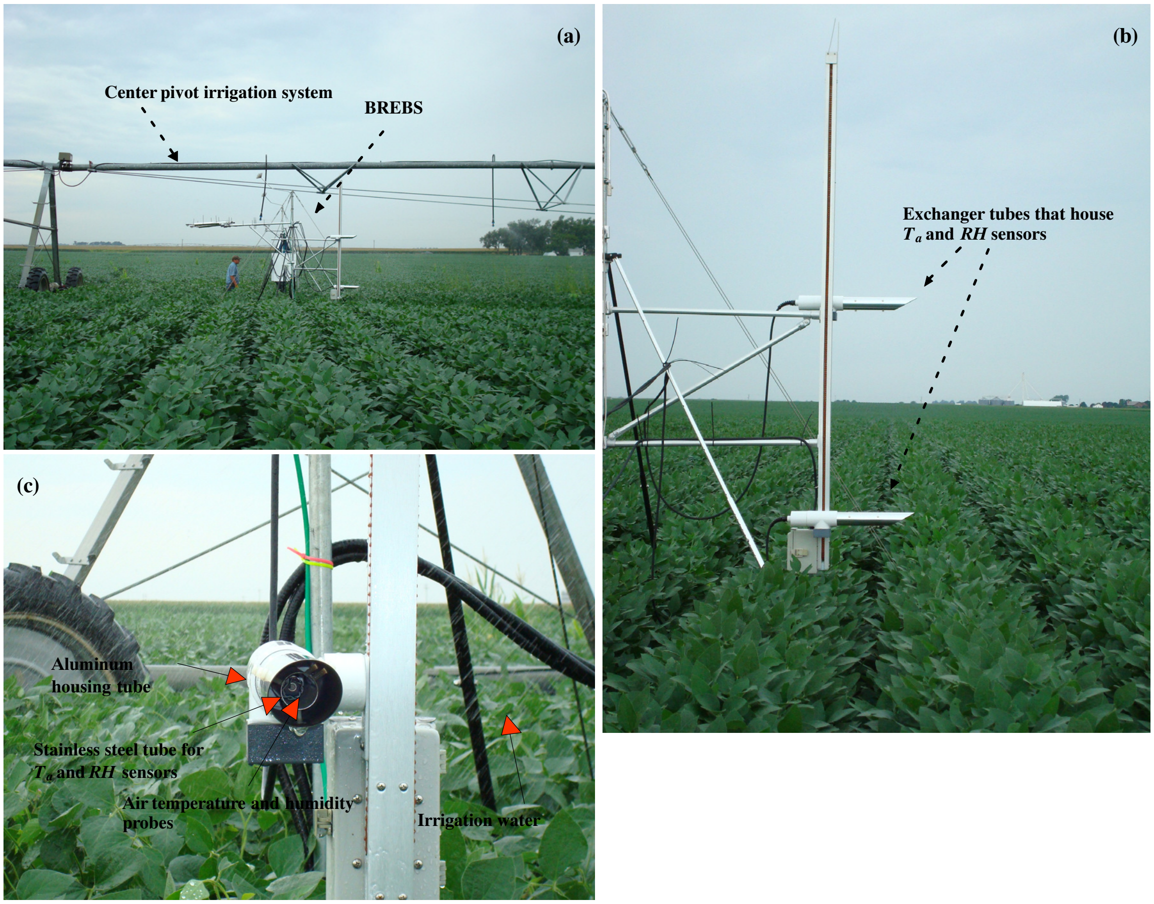

Figure 4. Seasonal, annual and inter-annual distribution of Bowen ratio energy balance system (BREBS)-measured hourly surface fluxes (net radiation, latent heat flux, soil heat flux, and sensible heat flux) for maize vegetation surface at the BREBS-1 of the NEBFLUX site at Clay Center, Nebraska. Data for the growing and non-growing (dormant) seasons from 2004 through 2007 are included.

Table 4. Summary of instrumentation height/depth of the Bowen ratio energy balance systems at various vegetation surfaces at the NEBFLUX sites.

Variable	Sensor/Instrumentation Height or Depth	Sampling and Averaging Intervals
Air temperature (°C)	2.0 m; height is adjusted for taller canopies (i.e., maize and Phragmites, cottonwood, willow)	60 s and 1.0 h
Relative humidity (%)	2.0 m; height is adjusted for taller canopies (i.e., maize and Phragmites, cottonwood, willow canopy)	60 s and 1.0 h
Wind speed (m s^{-1}) and direction (degrees)	3.0 m	60 s and 1.0 h
Soil heat flux (W m^{-2})	0.06 m below the soil surface	60 s and 1.0 h
Soil temperature (°C)	0.04 to 0.06 m below the soil surface	60 s and 1.0 h
Barometric pressure (kPa)	1.5 m	60 s and 1.0 h
Surface soil moisture (% vol)	0.04 m	60 s and 1.0 h
Profile soil moisture (% vol)	Every 0.30 m up to 1.80 m in each site	60 s and 1.0 h
Rainfall (mm)	3.5 m	60 s and 1.0 h
Net radiation (W m^{-2})	3.0 m; height is adjusted for taller canopies (i.e., 4.5 m for maize and Phragmites, cottonwood, willow canopy)	60 s and 1.0 h
Incoming and outgoing shortwave and longwave radiation (W m^{-2})	3.0 m; height is adjusted for taller canopies (i.e., maize and Phragmites, cottonwood, willow canopy)	60 s and 1.0 h
Leaf area index	Above and beneath the canopy	Every week
Leaf stomatal resistance (s m^{-1})	Sunlit and shaded leaves, above and within the canopy	Selected days
Photosynthetic photon flux density (μmol s^{-1} m^{-2})	Sunlit and shaded leaves, above and within the canopy	Selected days
Leaf temperature (°C)	Sunlit and shaded leaves, above and within the canopy	Selected days
Surface temperature (°C)	At the soil surface, at the canopy surface, and at 1.8 m, 3.6 m, and 5.4 m above the surface	60 s and 15 min
Vegetation height (m)	From the soil surface to the tip of the tallest leaf	Every week

from the ends of the rods triggers a logic state change, which then initiates propagation of a new wave front. Because water has high dielectric permittivity (larger than the solid phase of soils), the resulting oscillation frequency is dependent upon the average soil water content of the bulk soil surrounding the rods. The probe responds quickly to the bulk electrical permittivity of the material (Irmak and Irmak, 2005).

The WCRs at each site are installed vertically to integrate the volumetric soil water content along the 0.30 m soil profile. While vertical installation of soil moisture sensors has the advantage of easy installation and removal, and integrating soil water content over a certain distance, the major disadvantage of vertical installation, especially in the topsoil, is the impact of preferred paths for water infiltration in the case of shrinking-swelling that can be experienced with soils that have high clay content. Sensors can be installed at a 45° angle to minimize the impacts of shrinking-swelling, cracking, worm channels, and rooting patterns on the measured soil water content. Horizontally placed sensors may better integrate (average) the spatial variability of soil moisture horizontally, but the difficulty in horizontal installation is the need to dig a soil profile for the probe placement, which can be challenging. Most soils where the NEBFLUX systems are installed have either silt-loam or loamy-sand textures, and shrinking-swelling has not been an issue to impact the soil water content measured by vertically installed CS616 WCRs.

Instrumentation for Eddy Covariance System

The instrumentation type and height/depth for the open-path Eddy Covariance System-1 (ECS-1) are presented in table 5. The sensible heat, sonic temperature, and turbulent fluctuations of horizontal and vertical wind are measured using a CSAT3 three-dimensional ultrasonic anemometer. From the covariance from the vertical winds and scalars, sensible heat is directly measured. The CSAT3 measures wind speed and the speed of sound on three nonorthogonal axes. The sonic anemometer also provides upper and lower transducers that are separated by a vertical distance of 0.10 m and are oriented 60° from horizontal. From the turbulent wind fluctuations, momentum flux and friction velocity are calculated. The sensible heat is also calculated from the temperature gradients that are measured with a fine-wire thermocouple that has a 60 μV/°C output. It is a type-E thermocouple that is 0.0000127 m in diameter. The fine-wire thermocouple is installed to the side of the CSAT3 sonic anemometer in the midway between the upper and lower arms of the sonic sensors. The latent heat flux is measured directly using a highly sensitive KH20 krypton hygrometer that determines the rapid fluctuations in atmospheric water vapor. It has a 100 Hz frequency response. Other instrumentation to measure soil heat flux, incoming shortwave and net radiation, air temperature and humidity, soil water content, precipitation, and soil temperature are presented in table 5. With the ECS-1, all variables are sampled with a 10 Hz frequency and averaged and recorded on an hourly basis using a CR5000 datalogger (Campbell Scientific, Inc., Logan, Utah).

System Maintenance

All BREBSs and the ECS are closely supervised and general maintenance is provided on a weekly basis. Some of the basic maintenance includes cleaning the thermocouples and housing units (upper and lower exchanger tubes), servicing radiometers by cleaning domes, checking/ replacing the desiccant tubes, and making sure that the

Table 5. Summary of instrumentation height/depth of the Eddy Covariance System-1 (ECS-1) at the Clay Center, Nebraska, NEBFLUX site. Negative height indicates depth below the soil surface.

Variable/Unit	Instrument	Specified Accuracy or Resolution	Height (m)
Turbulent fluctuations of horizontal and vertical wind (m s^{-1}), sonic temperature (°C), and sensible heat (W m^{-2})	CSAT3 3D ultrasonic anemometer[a]	Resolution: 0.5 to 1.0 mm s^{-1}; accuracy: 2 to 4 cm s^{-1}	≈4.0
Fluctuations of atmospheric water vapor (W m^{-2})	KH20 krypton hygrometer[a]	--	≈4.0
Wind speed (m s^{-1}) and direction (degrees)	034B cup anemometer[b]	0.12 m s^{-1} for WS < 10.1 m s^{-1}; ±1.1% for WS > 10.1 m s^{-1}; 0.5° resolution for wind direction	3.0
Incoming shortwave radiation (W m^{-2})	Li-Cor LI-200X silicon pyranometer[c]	Absolute error in natural daylight: ±5% maximum; ±3% typical; Sensitivity: 0.2 kW m^{-2} mV^{-1}	4.5
Net radiation (W m^{-2})	REBS Q*7.1 net radiometer[d]	±0.10%	4.5
Soil heat flux (W m^{-2})	REBS HFT-3.1 soil heat flux plate[d]	0.906 W m^{-2}	-0.06
Air temperature and relative humidity (°C, %)	HMP45C-L probe[a]	±2% over 10% to 90% RH; ±3% over 90% to 100% RH	2.5
Rainfall/snowfall (mm)	385-L 30 cm AC-heated rain/snow gauge[a]	±0.5% at 12.7 mm h^{-1} or less	3.0
Soil temperature (°C)	REBS STP-1 soil thermocouple probes[d]	±0.02°C	-0.04 to -0.06
Surface soil moisture (% vol)	Horizontally installed CS616 soil water content reflectometers[a]	±2.0%	-0.04
Sensible heat (W m^{-2})	FW05 chromel-constantan fine-wire thermocouple[a]	--	≈4.0

[a] Campbell Scientific, Inc., Logan Utah.
[b] Met-One Instruments, Grants Pass, Oregon.
[c] Li-Cor Biosciences Corp., Lincoln, Nebraska.
[d] Radiation and Energy Balance Systems, Inc., Bellevue, Washington.

radiometers are properly leveled. The radiation domes are replaced every 3 to 4 months or earlier when needed. Some system components (radiometers, thermocouples, hygrometers, wind sensor, etc.) are sent to the manufactures for performance checking and/or re-calibration at least every other year or earlier when necessary. For some croplands, the upper and lower exchanger arms are adjusted as needed as the plant height increases during the season. The lower exchanger tube is always kept at least 0.90 to 1.0 m above the canopy throughout the growing season. The distance between the lower and upper exchanger tubes is kept at a constant distance of 0.90 m throughout the season. The thermocouples and the interior of the exchanger tubes are cleaned on a monthly basis. Each BREBS is equipped with a BIRD-X-PELLER system (Bird-X, Inc., Chicago, Ill.) to keep birds away from the BREBS. The BIRD-X system works on a sonic repeller principle and uses distress calls on a predetermined intervals and predator howls to create a "danger zone" that frightens infesting birds away from the system components. It is programmable for species-specific repelling in a given area. The maintenance of the ECS-1 includes replacing the fine-wire thermocouple (the thermocouple usually lasts about a week to ten days), cleaning the KH20 krypton hygrometer upper and lower surfaces, and cleaning the radiation shields of the temperature and humidity probe. All systems are visited on a weekly basis for data downloading and maintenance all year long. Winter maintenance is especially important due to ice formation on the radiometers, exchanger tubes, and other instruments and sensors. Each site is also visited on a weekly basis during the winter to conduct maintenance and remove ice from the systems. Thus, through a vigorous field campaign, the data loss from all systems is minimized.

Sample Data and Analyses for BREBS-1

This section provides a sample dataset of the surface energy and water vapor fluxes for one of the BREBSs of the NEBFLUX sites, without a detailed discussion or interpretation of the data. The sample data represent only some of the parameters that are measured at each BREBS site. The BREBS-1 site was selected to present sample data as this system has been running for the longest period of time among all the NEBFLUX systems. Daily average values of Bowen ratios as measured with BREBS-1 for various vegetation surfaces from 13 October 2004 through 28 August 2009 are presented in figure 5. The planting and harvest dates for each vegetation surface are marked in the figure. The non-growing (dormant) and growing seasons are separated with vertical dashed lines. The measured Bowen ratio showed inter-annual variations throughout the period with changing vegetation and surface characteristics. From 2004 to 2009, the field surface in which BREBS-1 is installed changed from irrigated maize, irrigated soybean, and irrigated winter wheat to residue-covered soil and a snow/ice-covered surface in dormant periods. The ratio was usually higher in dormant (winter) periods than in spring and summer. On average, the ratio was usually closer to zero during the middle of the growing season and had larger positive values during the dormant seasons. The ratio is usually lower in the growing season due to smaller magnitude of sensible heat flux and larger magnitude of ET_a. The ratio is usually at its lowest value during the peak ET_a month (usually July-August). Before and after the growing season, the magnitude of H exceeds the magnitude of ET_a, resulting in larger Bowen ratios. During the six-year period of measurements, the ratio ranged from -9.7 to 9.9.

The BREBS-1-measured hourly surface energy fluxes [R_n, ET_a (LE), H, and G] for maize, soybean, and winter wheat surfaces are presented in figures 6, 7, and 8, respectively. The field was planted to maize on 4 May 2004 and harvested on 8 October 2004. BREBS-1 was installed on 12 October 2004. The field was planted to maize again on 22 April 2005 and harvested on 17 October 2005. Year 2006 was the last year for maize research, with planting and harvest days of 12 May and 5 October, respectively. The emergence dates for maize in 2004, 2005, and 2006 were 14 May, 12 May, and 20 May, respectively. Soybean was planted on 21 May 2007 and 19 May 2008. The harvest dates were 24 October 2007 and 1 October 2008. The emergence for soybean was five days after planting in both years. Winter wheat was planted on 3 October 2008, emerged on 18 October, and was harvested on 9 July 2009.

For all three vegetation surfaces, ET_a was low early in the season, gradually increased with plant growth and development, and peaked at mid-season at full canopy. It gradually decreased again towards the end of the growing

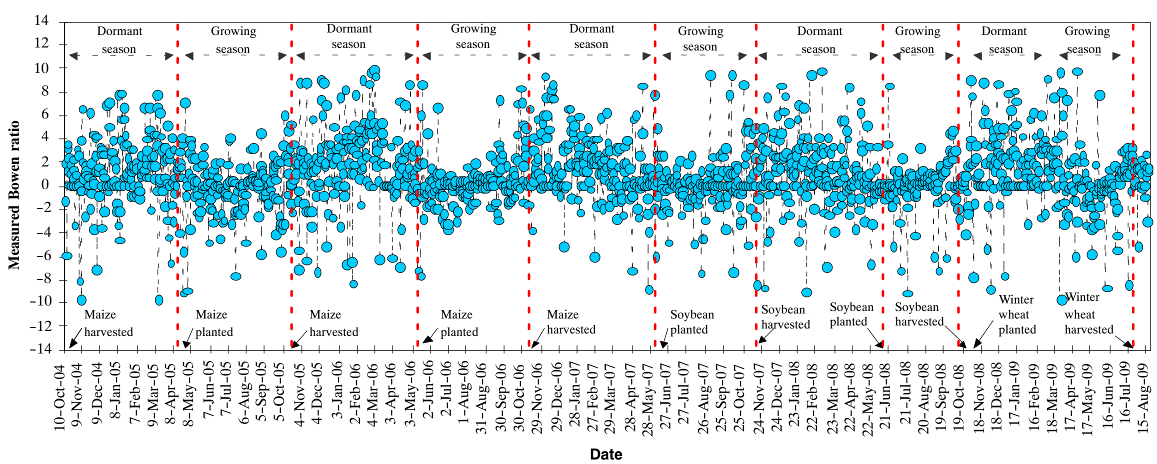

Figure 5. Seasonal, annual, and inter-annual distribution of daily average measured Bowen ratio for maize, soybean, winter wheat, and their residues from October 2004 through August 2009 at the BREBS-1 site of the NEBFLUX at Clay Center, Nebraska.

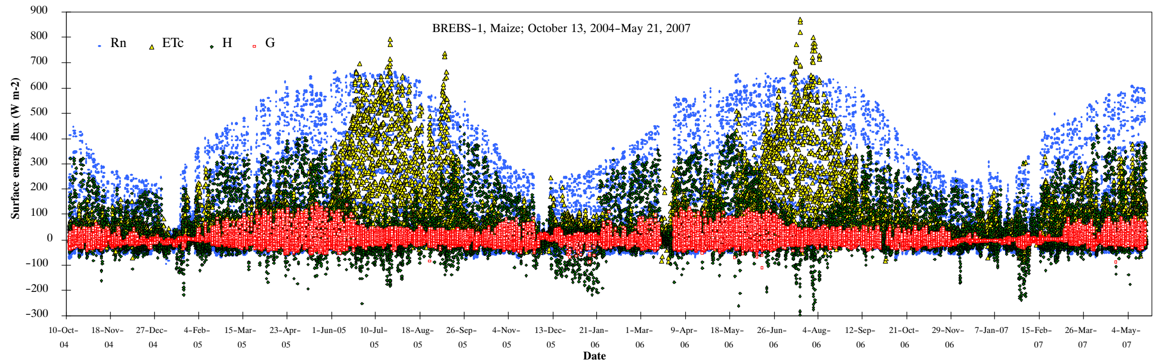

Figure 6. Seasonal, annual, and inter-annual distribution of Bowen ratio energy balance system (BREBS)-measured hourly surface fluxes (net radiation, latent heat flux, soil heat flux, and sensible heat flux) for maize vegetation surface at the BREBS-1 site of the NEBFLUX at Clay Center, Nebraska. Data for the growing and non-growing (dormant) seasons from 2004 through 2007 are included.

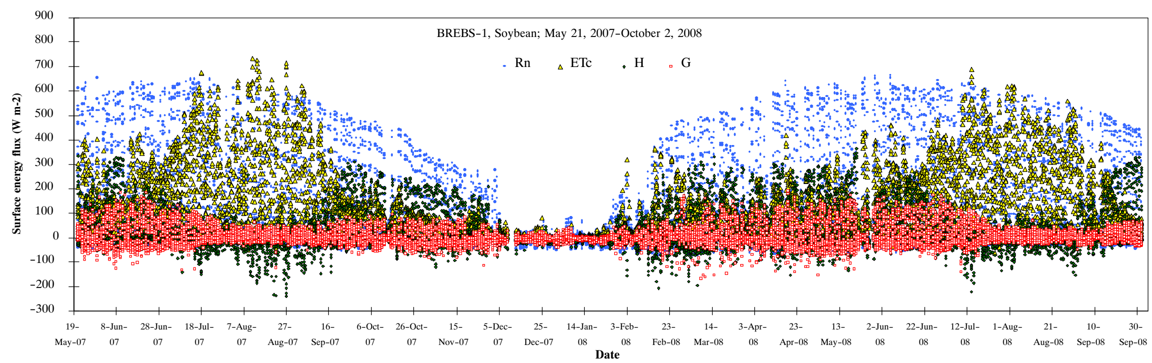

Figure 7. Seasonal, annual, and inter-annual distribution of Bowen ratio energy balance system (BREBS)-measured hourly surface fluxes (net radiation, latent heat flux, soil heat flux, and sensible heat flux) for soybean vegetation surface at the BREBS-1 site of the NEBFLUX at Clay Center, Nebraska. Data for the growing and non-growing (dormant) seasons from 2007 through 2008 are included.

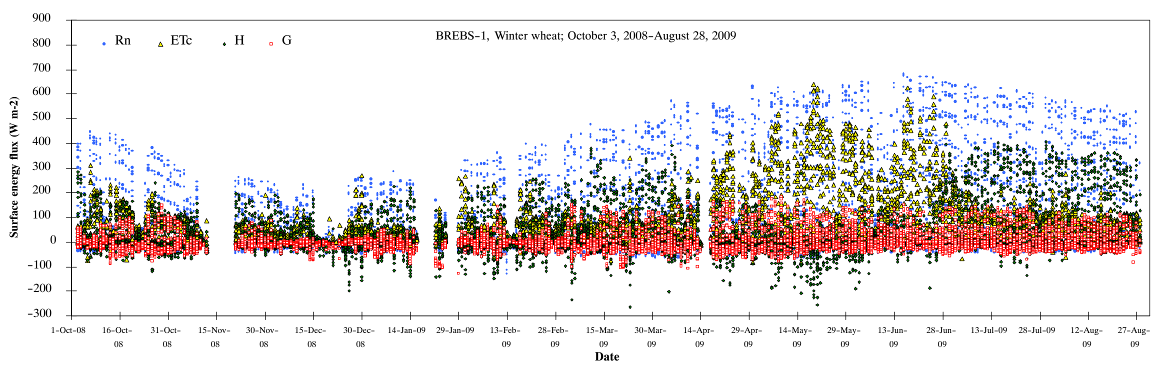

Figure 8. Seasonal, annual, and inter-annual distribution of Bowen ratio energy balance system (BREBS)-measured hourly surface fluxes (net radiation, latent heat flux, soil heat flux, and sensible heat flux) for winter wheat vegetation surface at the BREBS-1 site of the NEBFLUX at Clay Center, Nebraska. Data for the growing and non-growing (dormant) seasons from 2008 through 2009 are included.

season with leaf aging, physiological maturity, and senescence. As expected, G was the smallest and R_n was the largest component of the energy fluxes for all three vegetation surfaces. For maize and soybean, R_n and ET_a were highest during July, and H was lowest during the peak ET_a periods. Winter wheat was dormant from late October-early November 2008 and greened up again in mid-March 2009. For all surfaces ET_a and H showed opposite trends. H had its minimum values during the growing season, especially during full canopy closure periods. During the maize research period (2004-2006), R_n ranged from -97 to 664 W m^{-2} and R_s ranged from -7 to 986 W m^{-2}. The range for ET_a and H for the same period was between -88 and 871 W m^{-2}, -296 and 452 W m^{-2}, and -113 and 143 W m^{-2}, respectively. Maximum hourly ET_a for maize occurred on 19 July 2006 at 3:00 p.m. as 1.28 mm h^{-1} (fig. 6). Daily total ET_a on that day was measured as 10.1 mm d^{-1}. Hourly (at 3:00 p.m.) microclimatic variables measured on 19 July were as follows: R_s = 861 W m^{-2}, R_n = 614 W m^{-2}, T_a = 37°C, RH = 30.4%, wind speed at 3 m (u_3) = 3.13 m s^{-1}, G = 39.3 W m^{-2}, and H = -296 W m^{-2}. Another high ET_a for maize canopy was measured on 23 July 2005 at 1:00 p.m. as 1.16 mm h^{-1}. Daily total ET_a on the same day was measured as 9.7 mm d^{-1}. There was no rainfall event during or a few days before 19 July 2005 or 23 July 2006, so the high diurnal and daily total ET_a was mainly a result of the microclimatic conditions and plant transpiration rather than the soil surface conditions on both days. Peak ET_a values measured for soybean and winter wheat were lower than those for maize. The peak ET_a for soybean occurred on 11 August 2007 at 2:00 p.m. as 1.08 mm h^{-1} (fig. 7), and the daily total ET_a on that day was measured as 7.7 mm d^{-1}. In 2008, the maximum soybean ET_a occurred on 14 July 2008 at 3:00 p.m. as 1.1 mm h^{-1}, with a total ET_a of 8.72 mm d^{-1}. The maximum ET_a for winter wheat in 2009 occurred on 19 May 2009 at 3:00 p.m. as 0.94 mm h^{-1} (fig. 8). The daily total ET_a on that day was measured as 8.22 mm d^{-1}. While the peak hourly ET_a was higher for soybean, the measured daily maximum ET_a (8.22 mm d^{-1}) was about 6% higher for winter wheat than for peak ET_a of soybean. G fluctuated in a narrower range for the maize surface than for soybean and winter wheat due to the great influence of maize residue on moderating heat flow from and towards the soil. Including the growing and non-growing seasons, from 2004 to 2009 hourly G fluctuated between 143 and -113 W m^{-2} for the maize surface, between 192 and -167 W m^{-2} for the soybean surface, and between 182 and -127 W m^{-2} for the winter wheat. Fluctuation in G for the soybean surface was larger than for wheat. As shown in figures 6, 7, and 8, in some cases ET_a exceeded available energy (R_n - G) primarily due to advective conditions. When the ratio $(R_n - G)/ET_a$ exceeds 1.0, this indicates advection, which is an indication of additional energy moving into the research field from a drier environment, which causes ET_a to exceed the available energy measured with the BREBS. Thus, during these conditions, additional heat was extracted from the soil and environment for evaporation.

The 2005 maize growing season was selected to further supplement the general discussion. The magnitude and trends of BREBS-measured ET_a, precipitation, and irrigation amounts are discussed in detail for the BREBS-1 site, which is under subsurface drip irrigation and located at the South Central Agricultural Laboratory near Clay Center, Nebraska. Maize was planted on 22 April, emerged on 12 May, and was harvested on 17 October 2005. The seasonal fluctuations in daily ET_a and daily total precipitation and irrigation events are presented in figure 9a, and the cumulative values of the same variables are presented in figure 9b. Daily ET_a showed a typical bell-shaped distribution, gradually increasing from early season toward mid-season and decreasing again toward the end of the season, as a function of climatic conditions, physiological maturity, and leaf senescence. ET_a ranged from 1.0 to 2.0 mm d^{-1} early in the season before emergence to approximately 10 mm d^{-1} in late July (23 July). There were twelve irrigation applications throughout the growing season, and a total of 224 mm of irrigation water was applied to the experimental field (fig. 9b). Irrigations occurred from late June to late August, with the first irrigation starting on 30 June and the last irrigation application starting on 22 August. The cumulative rainfall from planting (22 April) until day before harvest (16 October) was 321 mm. The largest daily total rainfall event occurred on 5 September as 37 mm d^{-1}. The BREBS-measured seasonal total ET_a for the subsurface drip-irrigated maize canopy was 667 mm from planting until harvest. When the period from plant emergence (12 May) to physiological maturity (20 September) was considered, the seasonal total ET_a for subsurface drip-irrigated maize was 610 mm. The sum of the irrigation and precipitation from emergence until physiological maturity was 507 mm. The difference between ET_a and the sum of precipitation and irrigation in the same period (610 mm - 507 mm = 103 mm) was compensated by available soil water.

The seasonal average daily surface albedo for all surfaces as calculated from the ratio of outgoing to incoming shortwave radiation fluctuated between 0.14 and 0.27 during the growing seasons from 2004 to 2009 (fig. 10). From 2004 to 2009, including dormant and growing seasons, the albedo varied from 0.10 to 1.0. The seasonal daily average albedo values for maize, soybean, and winter wheat were similar during the growing seasons. In figure 10, when the dashed lines that separate the growing and dormant seasons for each vegetation surface are considered, the dormant season average albedo values after maize harvest (three dormant seasons) were 0.26, 0.24, and 0.37, respectively. The growing season average albedo value for the two maize growing seasons was 0.19. The seasonal average albedo values for the first and second (2007 and 2008) soybean growing seasons were 0.18 and 0.19, respectively. The dormant season albedo values after soybean harvest in 2007 and 2008 were 0.37 and 0.31, respectively. The growing season winter wheat albedo was 0.17. Albedo was high, ranging from 0.35 to 1.0, during the winter due to high reflection of the snow/ice-covered surface. The albedo exhibited large fluctuations in the dormant season as a function of variations in the influence of energy and aerodynamic terms on the surface and also due to color and age of the snow/frozen soil surface. The albedo values presented in figure 10 for various vegetation and ground surface conditions are in agreement with those reported by Monteith (1959), Gates and Hanks (1967), Brutsaert (1982), and Monteith and Unsworth (1990).

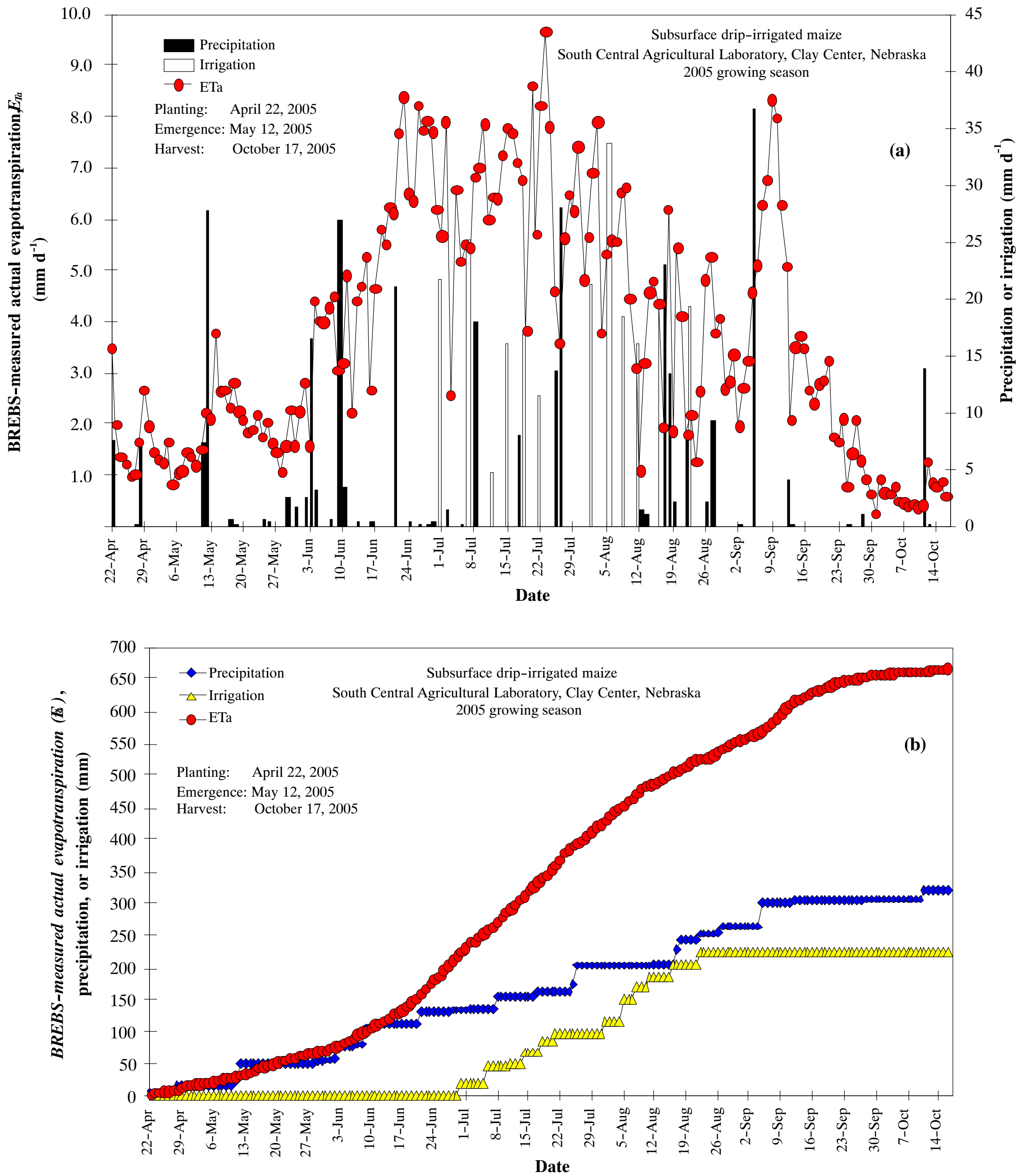

Figure 9. Bowen ratio energy balance system (BREBS)-measured actual evapotranspiration (ET_a), precipitation, and irrigation for (a) subsurface drip-irrigated maize and (b) cumulative totals of the same variables.

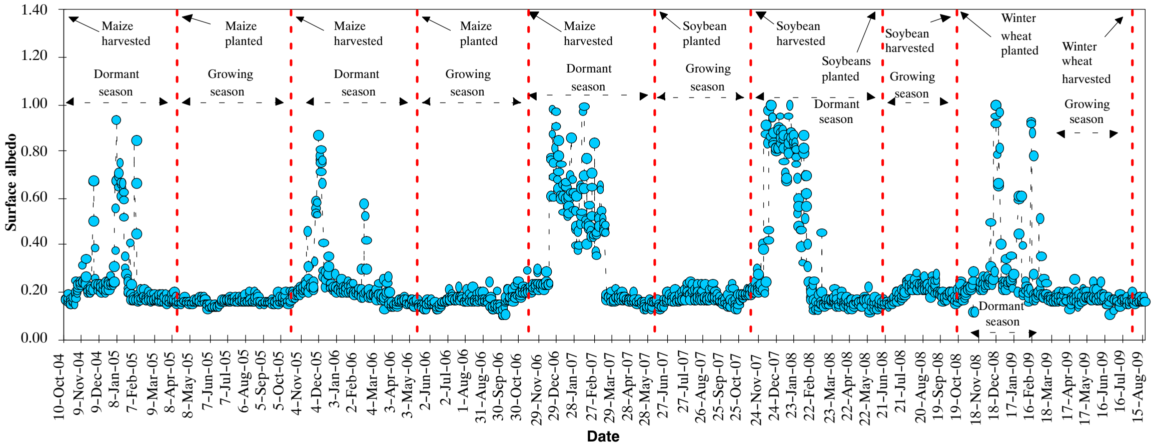

Figure 10. Seasonal, annual, and inter-annual distribution of surface albedo for maize, soybean, winter wheat, and their residues from October 2004 through August 2009 at the BREBS-1 site of the NEBFLUX at Clay Center, Nebraska. Data for the growing and non-growing (dormant) seasons are included.

Conclusion

The Nebraska Water and Energy Flux Measurement, Modeling, and Research Network (NEBFLUX) is established to measure surface energy fluxes, including actual evapotranspiration, for various vegetation surfaces. The NEBFLUX is a network of micrometeorological tower sites that use mainly the Bowen ratio energy balance systems (BREBS) to measure surface water and energy fluxes between terrestrial agro-ecosystems and microclimate. It is designed to continuously measure surface energy fluxes, microclimatic variables, plant physiological parameters, soil water content, surface characteristics, and their interactions for various vegetation surfaces. At present, ten BREBSs and one eddy covariance system (ECS) are operating on a long-term and continuous basis. The network sites range from tilled and untilled irrigated and rainfed cropping systems, irrigated and rainfed grasslands, irrigated alfalfa, to invasive species. The network objective is to make at least 10 years of complete cycle (annual) measurement for each surface to better understand the interactions between surface and water and energy fluxes. The network will also provide data to the water resources, agricultural engineering, and scientific community as well as policy and decision-makers to make better-informed decisions on water resources planning, management, and infrastructure design purposes. Information dissemination to inform and educate the general public is another important objective and output of the project.

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