# 9.2 SPATIAL AND TEMPORAL VARIATION OF WATER, ENERGY AND CARBON FLUXES FROM TOWER AND AIRCRAFT MEASUREMENTS

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## INTRODUCTION

There are important implications for surface energy balance and carbon dioxide ($CO_2$) uptake associated with major land use conversions. In the case of the Upper Midwest region native prairie grasslands have been replaced with row configured corn (*Zea mays* L.) and soybeans (*Glycine max* (L.) Merr.). Mass and energy flux exchange processes between a surface and the boundary layer of the atmosphere for a native prairie are altered when a prairie is transformed from a continuously covered grass surface to a corn-soybean production system in which the soil surface annually transitions from bare to sparse to full canopy cover to residue and bare soil again.

Exposed soil surface during the non-growing portion of a year as well as during the emerging crop phase represents an important source and/or sink of energy (Ham et al., 1991) that responds to changing surface conditions. Surface heterogeneity induced by early row crop development (exposed soil with changing crop canopy) contributes to the challenge of quantifying and understanding energy balance exchange processes from bare soil and emerging crops. Byre et. al., (2000) report significant altered hydrologic budgets for Wisconsin prairies converted to a corn-soybean agro-ecosystem.

Estimating the surface energy balance components and understanding the complex processes of energy and mass exchange from land surfaces and the boundary layer of the atmosphere is critical to many applications in meteorology and hydrology. Measurement of mass, energy and $CO_2$ fluxes across a watershed of production corn and soybean fields in cental Iowa was the focus of this study. Assuming advection is negligible, the fluxes are related by:

$$Q^* + G + H + LE + S = 0 \quad \ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots \quad (1)$$

where Q* is net radiation, G is soil-heat flux, H is sensible-heat flux, LE is latent-heat flux (L is the latent-heat of vaporization of water and E is the evapotranspiration rate) and S is an accumulated storage term for the surface of interest. Normally the storage terms for non-forested surfaces (canopy heat storage in biomass and water content and energy for photosynthesis) are assumed negligible relative to the other terms.

Significant spatial variation in $CO_2$ fluxes has also been observed. Soegaard et al. (2003) observed differences among crops and fields within their study in western Denmark and used a weighted field value of $CO_2$ to determine the regional estimate of $CO_2$ uptake.

Variation of energy balance and $CO_2$ fluxes for large production agricultural areas has not been well documented. In central Iowa, Hatfield and Prueger (2001) have found large variations in water use across a production cornfield that ranged between 300 to 600 mm during a growing season. With such significant variations, it then becomes relevant to ask how single tower measurements in different ecosystems including agricultural crops, can be used to estimate regional carbon uptake and water use. To address this question, an intensive field study-using tower based mass and energy flux measurements as well as aircraft-based flux measurements over multiple fields across a typical production corn and soybean watershed in central Iowa was conducted in the summer if 2002. The objective in this study was to quantify spatial and temporal variations in water (LE) and $CO_2$ fluxes over intensive corn and soybean fields at a watershed scale and evaluate whether patch scale flux tower measurements can be representative of fluxes over the landscape as measured by an aircraft-based system.

## MATERIALS AND METHODS

### Site Description

This study provided the opportunity to place multiple eddy covariance (EC) towers across the Walnut Creek Watershed (WCW) in central Iowa to measure and evaluate the spatial and temporal variation among fluxes across corn and soybean production fields that are typical for the Upper Midwest region. The towers were in operation during an intensive measurement period (June 15 - July 12, 2002) of a remote sensing campaign that included aircraft-based measurements of surface energy fluxes and $CO_2$. This provided an excellent opportunity to not only measure and evaluate differences of turbulent fluxes between corn and soybeans but also the spatial and temporal variability of turbulent flux exchange of $CO_2$ and $H_2O$ across the WCW landscape from half-hourly to daily time scales.

The WCW is a 5100 ha watershed of approximately equally planted areas of privately owned production corn and soybean fields that range in size from 80-160 ha. The topography of the WCW is characterized by flat to gently rolling terrain with elevations ranging from 265 – 363 m.

***Instrumentation-eddy covariance-ancillary***

Turbulent fluxes of H, LE and $CO_2$ were measured using eddy covariance (EC) in 12 fields, 6 in corn and 6 in soybeans. Each EC system was comprised of a three-dimensional sonic anemometer (CSAT3 Campbell Scientific Inc. (CSI) Logan, UT) and a fast response water vapor ($H_2O$) and $CO_2$ density open path infrared gas analyzer (IRGA) (LI7500 LICOR Inc., Lincoln, NE) or only water vapor with CSI KH20 krypton hygrometer. At all sites, EC instrument height was maintained on the towers at approximately 2 h (where h = canopy height in m) above the surface. The sampling frequency for the EC systems was 20 Hz with the data stored on PCMCIA cards.

Ancillary instrumentation on each tower included either a 4-component net radiometer ($Q^*$) (CNR-1 Kipp & Zonen Inc., Saskatoon, Sask.) or Radiation and Energy Balance System (REBS) model Q*7, soil heat flux plates (G) (REBS HFT-3), Cu-Co Type T soil thermocouples, two high precision infrared radiometric temperature sensors (IRT 15º FOV) (Apogee Instruments Inc., Logan, UT) and an air temperature/ relative humidity ($T_a$, RH) sensor (Vaisala HMP-35, Campbell Scientific [1]Inc. Logan UT). The sampling frequency for the ancillary measurements was 0.1 Hz (10 s) with measured values stored as 10 min averages.

***Eddy Covariance Intercomparison***

In order to better address the question of variability of the turbulent fluxes from similar corn and soybean surfaces, the degree of instrument variability over a common surface needed to be evaluated. Prior to and after the study, two intercomparison measurement campaigns were conducted with the EC systems. The first took place in early June over an alfalfa field and the second in late August over a grass surface. During both intercomparisons, all 12 EC systems were aligned in a straight line in the respective fields at the same height (1.85 m) above the alfalfa and grass fields and spaced 2 m apart from each other. The upwind fetch of the prevailing wind direction during intercomparison was over 200 m. The sampling frequency was 20 Hz and the turbulent fluxes of H, LE and $CO_2$ were output as 30-minute averages.

***Aircraft Eddy Covariance Measurements***

The National Research Council of Canada Twin Otter atmospheric research aircraft flew transects over the WCW study area designed to intersect several of the tower EC stations and to be used as a means of estimating large-scale fluxes representative of the region. Fluxes of sensible heat, water vapor, momentum and carbon dioxide were measured at an altitude of approximately 40 m on repeated passes ranging in length from 5.7 to 12.2 km. A flight mission was approximately 2 hours in duration and covered transects during the period between 1000-1200 CST.

**RESULTS AND DISCUSSION**

***Surface Energy Balance Closure***

The surface energy balance closure is an issue that continues to plague turbulent flux measurements made by eddy covariance technique (Wilson et al., 2002). It has been suggested as a routine tool for quality assurance of the eddy flux measurements (Brotzge and Crawford, 2003). However, it also becomes an issue when comparing to land surface models that by design require energy conservation.

The closure ratio was computed as a ratio of the sum of the turbulent fluxes of H and LE to the available energy ($Q^*$-G). Energy closure values computed from the 30-min average surface energy components and summed into daily flux totals for the corn and soybean sites are presented in Fig. 1. Overall closure ratio for the corn and soybean sites averaged 0.85 and is considered satisfactory for energy balance measurements. The main findings from the intercomparison portion of the study were the minimum threshold differences required to determine true variability of the turbulent flux measurements among similar surfaces as 9 and 11 W $m^{-2}$ for H and LE respectively and 0.1 mg $m^{-2}$ $s^{-1}$ for $CO_2$. The closure and intercomparison results provide a defensible basis to evaluate local spatial and temporal variation of mass and energy exchange for this study.

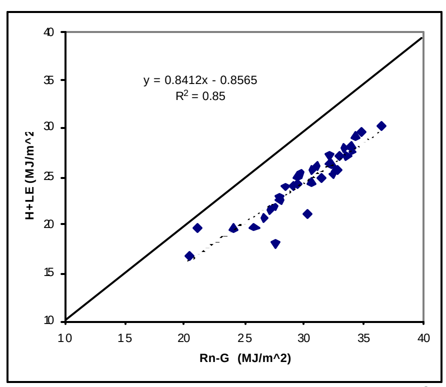


Figure 1. Comparison of daytime ($Q^*$>50 W $m^{-2}$) closure values for both corn and soybeans.

[1] *Mention of trade names or commercial products in this article is solely for the purpose of providing specific information and does not imply recommendation of endorsement by the U.S. Department of Agriculture

***Daily fluxes***

Daily total fluxes of mass and energy were computed from the daytime 30 min averages and averaged for all corn and soybean sites respectively. These were plotted with the maximum and minimum daily flux totals from the corn and soybean sites and are shown in Fig. $2_{a\text{-}e}$. Net radiation values (a) were slightly larger (~ 2%) over the corn than for the soybeans while the max/min totals were larger for the soybeans. This was expected as the soybean fields had considerably less vegetation cover which affected the partitioning of the incoming solar radiation. It was observed that as time progressed toward day of year (DOY) 190 the max/min values for corn were steadily increasing relative to the beginning of the period. This was attributed to one corn site (#25) that significantly differed in vegetative cover from all other corn sites. Canopy height and development was poor and resulted in more soil exposure that contributed to increasing variation in $Q^*$ for this site. Mean and max/min soil heat flux totals (b) were greater in the soybeans than in the corn but could be observed to begin converging toward the end the intensive period as soybean vegetation cover increased covering more of the soil. In both cases for corn and soybeans, daily totals of G can be observed to decrease as the season progresses. Sensible heat flux totals (c) were greater for the soybeans, which also showed the significantly more variation, which is expected for a surface with more soil surface exposed. Similar to the plot for G, H for both corn and soybeans can clearly be seen to converge rapidly after about DOY 182 in response to increasing soybean cover. The relative magnitude of H between corn and soybeans is small suggesting a substantial portion of the available energy is going into evaporation and is supported by the figure for LE (d). In this plot mean LE can be observed to be substantially greater for the corn for most of the period but gradually converging with the soybeans as the soybean canopy matures. The max/min totals suggest considerable spatial variation across all sites in the WCW. Carbon mean and max/min (e) total uptake show the greatest differences in magnitude and spatial variability between crops. This is of course expected given the significant difference in plant physiology between corn and soybean. What is interesting is the difference in the max/min totals with corn showing large variation while soybeans were very low. We suspect that part of the explanation for this may be related to the atypical vegetation condition site 25 mentioned earlier was contributing to the enhanced minimum daily totals. The variation in energy balance and $CO_2$ uptake between corn and soybeans across the WCW is summarized as a fractional difference in the energy balance between corn and soybeans in Fig. xx. Carbon dioxide differences are clearly the largest and persist throughout the study. Energy balance components normalized by the available energy show the distribution of the fractional differences to be distinct and relatively stable throughout the most dynamic portion of vegetation development until approximately DOY 182 when the energy balance components begin to rapidly converge in response to a fully vegetated surface. The transition phase from a bare soil to full corn and soybean cover is distinct from the native prairie grass surface that once dominated the Upper Midwest region.

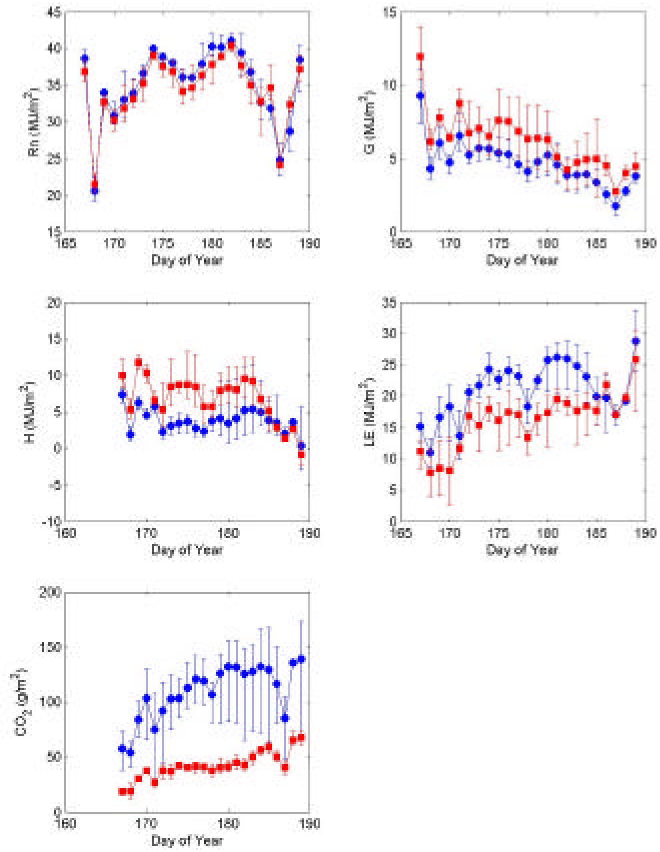


Figure 2. Daytime mean and max/min values for corn (circles) and soybean (square) for a) Rn, b) G, c)H, d)LE, e)CO2

***Biomass Feedback***

An obvious conclusion of the fractional difference results is that the energy partitioning and $CO_2$ uptake is strongly influenced by the vegetation cover of the surface. A common parameterization of vegetation biomass development is the Leaf Area Index (LAI). In this study the LAI for ~100 x 100 m area surrounding the tower sites in the corn and soybean fields were computed using remotely sensed vegetation index data from aircraft and satellite imagery with calibrated equations derived from ground-based samples of LAI. These LAI estimates were compared to h mean water use (LE) and $CO_2$ uptake values for corn and soybeans for the four remote sensing scenes collected on June 16 (DOY 167), June 23 (DOY 174), July 1 (DOY 182) and July 8 (DOY 189). Collected imagery separated approximately a week apart provides nearly a full dynamic range in LAI for the two crops. Figure $3_{a-d}$ show the relationship of LE and $CO_2$ with LAI. A strong correlation for corn LE and $CO_2$ with LAI was observed with an $R^2$ of 0.88 and 0.82 for LE and $CO_2$ respectively. This is consistent with a vegetated surface that as increases in biomass accumulation occur, increases in water use and $CO_2$ uptake result. In the soybean case, (c & d) the correlation was also significant with an $R^2$ of 0.84 and 0.89 for LE and $CO_2$ respectively. Clearly both crops show a strong relationship between biomass/LAI accumulation and water use and net carbon exchange suggesting indirect remote sensing vegetation index methods being proposed may provide operational surrogates to more complicated land surface models.

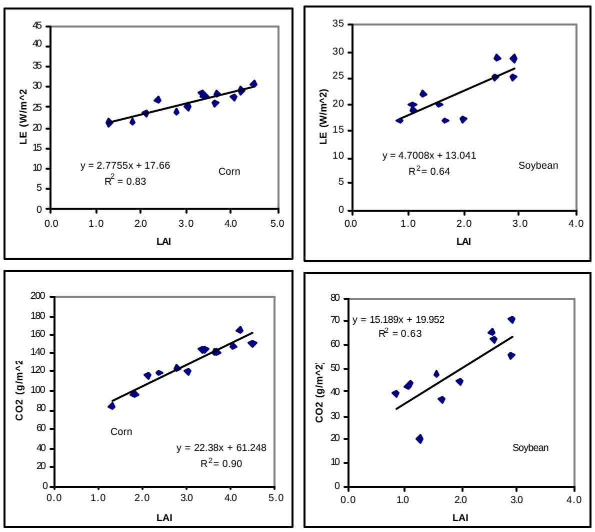


Figure 3. Relationship of Leaf Area Index (LAI) with $CO_2$ and LE fluxes for corn and soybeans.

### *Comparison with Aircraft Data*

In order to evaluate how representative the tower measurement network was in providing a more regional-scale estimate of the fluxes, the average fluxes from the network were compared to the average fluxes measured by the aircraft-based system for all transects flown on each day. The tower measurements were averaged over the sampling period of the aircraft missions (usually approximately a 2 hour window) Comparison of the three energy balance components, H, LE and Rn are illustrated in Figure 4. These results indicate very close agreement in H, slightly more scatter in Rn, and the most scatter in LE. The root mean square difference (RMSD) of the fluxes was 10, 25 and 45 W $m^{-2}$ for H, $Q^*$, and LE respectively. A closer examination of the scatter in LE is performed by computing the residual flux (Rn-G-H-LE) for the tower network and by using the tower network average G for the aircraft observations (see Fig 4). The resulting residual values indicate that at times the residual is larger for the aircraft than the tower and vice versa. When differences between tower and aircraft residuals are plotted against differences in aircraft and tower LE, the correlation is significant ($R^2$ = 0.77). For cases having significantly larger aircraft versus tower residuals (data points in the upper left hand corner in Fig. 4), the earlier case (DOY 169) occurred during times of relatively high winds, (>10 m $s^{-1}$) but there was no unique meteorological condition associated with the other periods. The largest tower residual value (data point in the lower right hand corner of Fig 4), the wind direction was almost due north, and hence coming behind the EC instrumentation, which were oriented to the south. These effects appear to be largely manifested in LE relative to H, suggesting that when closure appears most problematic for either measurement system, it tends to manifest itself considerably more in LE, than in H.

The $CO_2$ flux, the temporal plot of the tower average along with the average from soybean and corn sites for all the days are plotted along with the aircraft transect average. Although there is a marked difference between net carbon exchange between the soybean and corn, the averaging of the two crops results in good agreement with the aircraft average, yielding an RMSD of 0.15 mg $m^{-2}$ $s^{-1}$ close to the uncertainty in the $CO_2$ measurement of 0.1 mg $m^{-2}$ $s^{-1}$. A notable exception is DOY 171 where the average $CO_2$ flux for the corn sites significantly departs from the overall trend. Winds were light that day at around 1 m $s^{-1}$, and coming from the northeast; however, these conditions did not result in significant differences in LE between the tower network and aircraft.

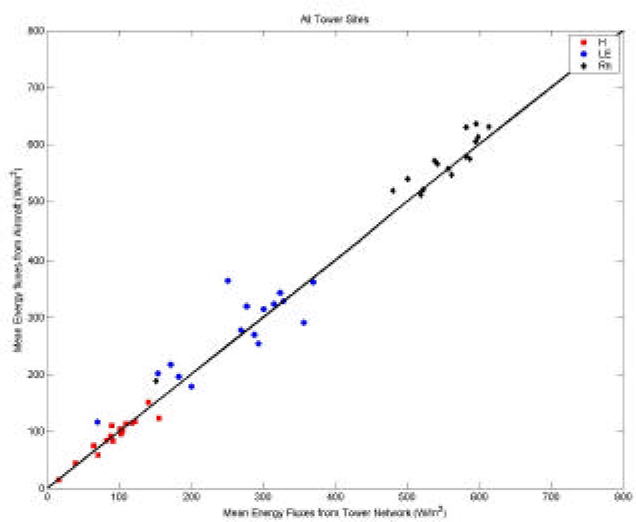


Figure 4. Relationship between mean tower fluxes and mean aircraft fluxes for both corn and soybeans.

### SUMMARY

Results shown thus far demonstrate substantial spatial and temporal variation of the surface energy balance components and $CO_2$ uptake for an emerging corn and soybean landscape. The period of emergence and canopy development represents a unique and critical phase of Midwest landscape development. Results also show a general convergence of the variation as canopies mature over time in response to increasing LAI. Comparisons with aircraft based measurements of the flux components were favorable and suggest that the potential for estimating $CO_2$ and LE using remotely sensed estimates of LAI is viable for Midwest cropping systems. Further analysis will include comparisons between point averaged fluxes from a pair of corn and soybean towers and compared to the aircraft measurements to determine whether point averaged fluxes can represent area averaged fluxes.

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