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# IRRIGATED AND RAINFED CROPS *Zea mays* L. (MAIZE) AND *Glycine max* (SOYBEAN) ACTING AS A SOURCE OR SINK FOR ATMOSPHERIC WARMING AT MEAD, NEBRASKA

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**Irrigated and Rainfed Crops *Zea mays* L. (MAIZE) and *Glycine max* (SOYBEAN) acting as a source or sink for atmospheric warming at Mead, Nebraska.**

Jane A. Okalebo<sup>1\*\*</sup>, Kenneth G. Hubbard<sup>1</sup>, and Andrew E. Suyker<sup>1</sup>

**ABSTRACT**

Land Use and Land Cover Change (LULCC) influence the climate at a global and local scale. Using long term microclimate data (2002-2009, 2011-2012) from the Carbon Sequestration Project (CSP), Mead, NE, this study examines how crop selection and water management can mitigate heat in the atmosphere. Mitigation of global warming is dependent on the management of crop lands, and the amount and timing of rainfall during the growing season. Rainfed crops were found to heat the passing air. The irrigated maize crop was able to mitigate 20 to 62% of the sensible heat (H) compared to the rainfed maize counterpart, the lower value for wet years and the larger value for dry years. Soybeans under irrigation, on the other hand, extracted a maximum of 37% of cumulated H in comparison to rainfed soybean. The irrigated maize field can reduce the warming by as much as 76% compared to the rainfed soybean crop. In addition to increasing yields, irrigation of maize greatly reduces the heating of air, thus moderating regional climate in east central Nebraska.

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**Keywords:** Rainfed, Irrigated, soybean, maize, mitigation of warming, microclimate

Article type: Primary research article.

## 1.0 Introduction

There exists worldwide evidence at the local to the global scale of significant climatic impacts attributed to land use and land cover change (LULCC) (e.g. Adegoke et al., 2007; Douglas et al., 2009; Pielke et al., 2011; Mahmood et al., 2010; Dirmeyer et al., 2010; Deng et al., 2014; Verheggen et al., 2014). The most significant land cover changes (LCC) occur as a result of agricultural expansion, desertification, urbanization, deforestation and afforestation (Mahmood et al., 2014). The impact of LULCC on the natural ecology and its processes vary at different scales. It is vital to estimate the effects of LULCC in order to prepare and mitigate the effects of LULCC on global warming since natural resources such as air, water and soil are significantly impacted with some regions being more vulnerable than others (Loveland and Mahmood, 2014). Long term research is therefore key to informing mitigation efforts to prevent devastating effects such as global warming, extinction of plant and animal species, disruptions of water and nutrient cycling among others.

Crop and livestock production have increased significantly with more land under natural vegetation being converted to crop lands for food production (Adegoke et al., 2007). Additionally, irrigation has converted tracts of land in otherwise unproductive areas such as semi-arid and desert areas into productive bread baskets (Adegoke et al., 2007; Lo and Famiglietti, 2013). Access to inputs such as fertilizers, water, improved seeds and pesticides has made agricultural production both intensive and profitable. Farmers have invested in irrigation systems to reduce crop failure risks due to insufficient and unreliable precipitation. Due to intensive irrigation, evapotranspiration has been shown to exceed rainfall. For example, in the Central Valley of California, in a year, precipitation is below evapotranspiration by about 60% (Faunt, 2009 *as cited in* Lo and Famiglietti, 2013).

In the Great Plains, LULCC from native grasslands to intensively managed irrigated croplands has had a dramatic influence on ecological processes, near-surface meteorology, surface fluxes and natural resources (Adegoke et al., 2003; Mahmood and Hubbard, 2002; Mahmood et al., 2006; Adegoke et al., 2007; Sohl et al., 2012; Mahmood et al., 2013; Mutiibwa et al., 2014). Nebraska for example has a total of 3.5 million hectares of irrigated land which is more than any other state. The application of irrigation is by sprinkler (72.96%), micro- (0.01%) and surface (27.03%) irrigation (Maupin et al., 2014). On average about 1 out of every 14 ha are irrigated in the state. This dramatic change in LULCC in the Great Plains has been prompted by the presence of underlying water in the Ogallala Aquifer which provides immense volumes of water for both drinking and irrigation purposes (Sohl et al., 2012). By applying extra water to crops during the growing season, irrigation has been noted to influence the local climate through enhanced land surface cooling and precipitation in several sites that have been studied (e.g. Mahmood et al., 2006; Mahmood et al., 2014). Huber et al., (2014) conducted simulations using the Advanced Research Weather Research and Forecasting (WRF) model and compared the rainfed and irrigated portions of the Great Plains region. The July precipitation in the region downstream of irrigated lands increased by about 50% (Huber et al., 2014). Additionally, Lo and Famiglietti, (2013) have also reported that the southwestern hydrological cycle in the United States has been strengthened by the irrigation conducted in the Central Valley of California. They indicated that the

Colorado River streamflow over the summer increased by about 30% due to the 15% increase in summer precipitation caused by intensive irrigation on 5.2 million hectares of agricultural land in the Central Valley.

A substantial increase in available soil water above that of a rainfed scenario, increases both transpiration and soil evaporation. Applying water to increase soil water availability will decrease temperature of the microenvironment due to the greater latent energy (LE) and associated cooling effects at the irrigated site. Since available incident radiation is partitioned to heating the ground, heating the plant tissues in the crop canopy, vaporizing water at the surface and soil profile (latent heat, LE), and heating air above the surface (sensible heat, H), a soil with a large water holding capacity will maintain or increase LE above the rainfed value. This will result in a cooling of the canopy and a decrease of H into the air and possibly even a reversal in H so that it is toward the surface. When soil water is limiting, LE decreases and more energy is available for sensible heating thereby increasing near-surface temperature (Seneviratne et al., 2010; Lo and Famiglietti, 2013).

The extent to which irrigation influences the partitioning of net radiation has been examined using simulation models and applying major LULCC such as deforestation and irrigation. Some models have been applied to quantify the impacts of surface cooling due to irrigation. For example, Adegoke et al., (2007) utilized the Regional Atmospheric Modeling System (RAMS) to determine that irrigation reduced temperature at the 2m level by 1.2°C, increased Latent Energy (LE) by 36% and reduced sensible heat by 15%; in Nebraska. Kueppers et al., (2008) utilized 3 regional climate models to measure changes in the 2-m level, mean August temperatures (-1.4 to -3.1°C) in the western United States. Mahmood et al., (2006) have also examined pre- and post- 1945, 1950, 1955 periods and compared non-irrigated (Halsey) and irrigated (Alliance) locations in Nebraska for near surface cooling using the average maximum growing season temperature. The data indicated that there was more cooling of the air in the later part of the 20<sup>th</sup> Century of 1.65°C compared to 0.64°C during the earlier part (post-1945). Ge, (2010) demonstrated the impact of intensive wheat production on surface temperature utilizing long-term satellite data (2002-2008). When compared to surrounding grasslands, maximum temperatures in the wheat fields were on average, 2.3°C lower during the growing season but after harvest, temperatures were 1.61°C higher (Ge, 2010).

There exists a general consensus that surface cooling occurs, however, it is important to be able to quantify the impact of irrigation at the field-level for specific crops and their water management practices e.g. soybeans and corn in rainfed and irrigated regimes in order to ensure that modelled results compare favorably with ground measurements.

The main objective of this study is to quantify the effect of irrigation on microclimate energy partitioning in adjacent rainfed and irrigated sites in Mead for both Maize and Soybean in the east central part of Nebraska.

## **2. Materials and Methods**

### **2.1 Site Description and Data**

The microclimate and yield data from the long term Carbon Sequestration Project (CSP) at Mead, Nebraska were used in evaluating the sensitivity of crops under rainfed and

irrigated regimes. The study sites are located at the University of Nebraska Agricultural Research and Development Center. Data from three sites (1, 2 and 3) were used in our analysis. Since 2001, site 1 has been cropped under continuous maize while site 2 and 3 are cropped alternately under a maize and soybean rotation. At sites 1 and 2, irrigation provided supplemental water while site 3 was rainfed. Site 1 will be referred to as Irrigated Continuous Maize (ICM); site 2 will be referred to as Irrigated Maize-Soybean Rotation (IMS) while Site 3 is Rainfed Maize-Soybean Rotation (RMS). The details of management practices for each site are given in Table 1.

Irrigation was conducted in site 1 and 2, using center pivot irrigation, to achieve sufficient available soil water for the crops. It is important to note here that the amount of litter under continuous maize was higher than that in the other sites. IMS and RMS are similar with respect to crop rotation and their soil chemical and physical properties (Table 2), but not water management.

Additionally, the amount of surface biomass and its composition were comparable in both sites 2 and 3. No-till (conservation tillage) was employed for all sites. The soils in the sites are generally deep silty clay loams (Suyker and Verma, 2009). However, it is important to note that in the autumn of 2005, the presence of a “heavy litter layer” (Suyker and Verma, 2009) necessitated the use of a conservation-plow that distributed litter below the surface (0.2-0.25 m depth) while maintaining 1/3 of the litter on the soil surface. Detailed descriptions of the sites and recommended best management practices may be found in publications by Verma et al., (2005), Suyker and Verma (2009) among others. In 2010, the IMS was converted into irrigated continuous maize. During that year, heavy hail caused severe damage and crop losses. Thereafter, in 2011 and 2012; site 2 was under continuous irrigated maize management. There was a comparatively representative range of dry and wet years for this study 2002-2009, 2011- 2012). Because of hail damage, 2010 was excluded from the study.

## **2.2 Phenology, Leaf Area Index, and Plant height measurements**

Each site had Intensive Management Zones (IMZs) that were 20 m by 20 m in dimension and wherein detailed measurements of crop growth, “canopy and soil gas exchange” (Verma et al., 2005) were taken. Maize growth and developmental stages were observed in the IMZs weekly. During the vegetative development of the plant, the number of fully formed leaves (with leaf collar) were counted and recorded. Visual observations of silking (R1) stage were recorded at the start of the reproductive period when at least 50% of the plants being sampled showed emerging silks from the tip of the ear shoot. Records of the blister (R2), milk (R3), dough (R4), dent (R5), and physiological maturity (R6) reproductive stages were also observed by examining the kernels. In the case of soybean, a visual count of nodes (beginning with the unifoliate node) on the main stem of the plant, was used for vegetative staging. For example, V3 was the 3<sup>rd</sup> node stage with three nodes and fully developed leaves on the main stem. Thereafter, records of observed flowering marked the first reproductive stage (R1), opening of flowers on either of the two most uppermost nodes, also known as full bloom (R2), beginning pod (R3), full pod (R4), beginning seed (R5), full seed (R6), beginning maturity (R7) and full physiological maturity (R8).

<b>Year</b>	<b>Management</b>	<b>Crop</b>	<b>Precipitation and/or Irrigation (mm)</b>	<b>Grain Yield (Mg/ha)</b>
2002	ICM <sup>1</sup>	maize	716	13.0
	IMS <sup>2</sup>	soybean	630	3.9
	RMS <sup>3</sup>	soybean	426	3.3
2003	ICM	maize	729	12.1
	IMS	maize	729	14.0
	RMS	maize	393	7.7
2004	ICM	maize	617	12.2
	IMS	soybean	588	3.7
	RMS	soybean	441	3.4
2005	ICM	maize	670	12.0
	IMS	maize	659	13.2
	RMS	maize	390	9.1
2006	ICM	maize	705	10.5
	IMS	soybean	576	4.4
	RMS	soybean	501	4.3
2007	ICM	maize	847	12.8
	IMS	maize	899	13.2
	RMS	maize	726	10.2
2008	ICM	maize	734	12.0
	IMS	soybean	884	4.2
	RMS	soybean	802	4.0
2009	ICM	maize	548	13.3
	IMS	maize	578	14.2
	RMS	maize	517	12.0
2011	ICM	maize	700	12.0
	IMS	maize	642	13.4
	RMS	maize	521	10.4
2012	ICM	maize	597	13.1
	IMS	maize	630	13.9
	RMS	soybean	297	2.0

Table 1: Year, management, total water added to site through precipitation and/or irrigation (mm) and yield of maize (Mg/ha) grown in CSP Mead NE Experimental sites between 2002-2009, 2011-2012 growing season. <sup>1</sup> Irrigated Continuous maize, <sup>2</sup> Irrigated Maize-Soybean Rotation, <sup>3</sup> Rainfed Maize-Soybean Rotation

SITE	DEPTH	$\theta_s$	FC	WP	Bulk Density	Ks
	cm	$\text{kg m}^{-3}$	$\text{kg m}^{-3}$	$\text{kg m}^{-3}$	$\text{kg m}^{-3}$	(mm/hr)
ICM <sup>1</sup>	10	0.53	0.37	0.19	1.26	11.64
	25	0.49	0.42	0.22	1.34	1.51
	50	0.46	0.41	0.21	1.42	0.66
	100	0.46	0.43	0.26	1.42	0.163
IMS <sup>2</sup>	10	0.44	0.40	0.25	1.48	0.32
	25	0.44	0.42	0.25	1.48	0.05
	50	0.47	0.43	0.26	1.40	0.49
	100	0.48	0.44	0.26	1.38	0.40
RMS <sup>3</sup>	10	0.46	0.40	0.23	1.42	1.85
	25	0.47	0.42	0.22	1.42	1.49
	50	0.48	0.41	0.23	1.37	2.29
	100	0.48	0.41	0.24	1.37	4.88

Table 2: The soil physical properties measured for soils in sites 1, 2 and 3, Mead, Nebraska, including, soil depth (Depth), Saturated Volumetric Water content ( $\theta_s$ ), field capacity (FC), wilting point (WP), bulk density (Bulk Density) and Saturated Hydraulic conductivity (Ks). <sup>1</sup> ICM-Irrigated Continuous maize, <sup>2</sup> IMS-irrigated Maize-Soybean Rotation, <sup>3</sup> RMS-Rainfed Maize-Soybean Rotation.

Leaf Area Index (LAI) measurements were made by destructive sampling in the IMZs on a frequency of approximately two weeks (Suyker and Verma, 2009). Samples were taken from 1 m linear row sections from six different locations within each of the sites and LAI was calculated as the ratio of the total green leaf area to the underlying ground area (Suyker and Verma, 2009). Average plant height measurements were also made and recorded. Comparisons in LAI development and crop height were related to phenological development and were utilized to explain and relate the differences between irrigated and rainfed development of maize.

### 2.3 Temperature and outgoing longwave radiation measurements

Aspirated Vaisala HMP 50Y temperature sensors were utilized to measure temperatures at 10 cm, 1 m, and 6 m above the soil surface. Incoming and outgoing longwave radiation and shortwave radiation were measured using a Kipp and Zonen CNR 1 Net Radiometer (Suyker and Verma, 2009).

### 2.4 Flux Measurements:

Sensible heat flux (H) and latent heat flux (LE) measurements were made for each of the sites. An omnidirectional 3D sonic anemometer (Model R3: Gill Instruments Ltd., Lymington, UK) and an open-path infrared CO<sub>2</sub>/H<sub>2</sub>O gas analyzing system (Model LI7500. LI-COR Inc., Lincoln, NE) were used for measurements (e.g. Suyker et al., 2009). Detailed descriptions on measurements, calculations, and filling of missing data are not discussed here but can be found in Suyker et al., (2003).

## 2.5 Data Analysis

Descriptive statistical analysis was conducted using Microsoft® Excel for most weather variables. Additionally, linear regressions to establish correlations between two biophysical variables and corresponding phenological development were conducted. Using weather station data as a reference, differences between the reference station maximum temperature and that of proxy canopy temperatures of all sites were also analyzed. In addition, we looked for the point that the sensible heat in the rainfed field began to depart from the sensible heat in the irrigated fields. We found this point occurring at the first irrigation. We will term this point in time as the phenological divergence point (PDP). We used PDP to separate the earlier season, when the two microclimates were nearly identical, from the later season when stress in the rainfed and extra LE in the irrigated fields began to change the partitioning of evapotranspiration and sensible heat. Thus the phenology development should be nearly identical in all fields until PDP. Sensible and latent heat flux was cumulated over the growing season and compared for the 33 site-years.

## 3. Results and Discussion

### 3.1 Weather Data and Irrigation

During the long-term study, planting was conducted between the end of April and mid-May depending on soil temperature, moisture and field workability. The average maize plant population were 82,500 and 61,300 plants/ha for irrigated and rainfed regimes. In the case of soybean, a planting population of 370,644 plants/ha, was the general standard irrespective of water management. On average, the hottest and driest years were 2003, 2005 and 2012 (Table 1, Fig 1, 2 and 3).

A comparison between actual rainfall amounts and potential evapotranspiration indicate that evaporative demand in 2003 and 2012 was high (Fig. 2) with limited water availability. The Growing Season (GS) precipitation recorded during these three years was 393, 390 and 297 mm. During these years an average of 11 irrigations were applied over the growing season. During the wet years; 2007 and 2008 that recorded 726 and 802 mm of precipitation during the GS, 7 irrigation events took place for maize. Despite the fact that 2008 was wet, 7 irrigation events were reported and these took place due to the distribution of rainfall. Most of the heavy rainfalls fell before July 23<sup>rd</sup> (DOY 205). An average year like 2006 recorded 8 and 4 irrigation events for maize and soybeans respectively. The year 2011 in which maize was planted in all sites, only 4 irrigation events were scheduled over the GS. The amount and distribution of rainfall during 2011 was favorable for the crops.



Year	Management	Crop	Precipitation and/or Irrigation (mm)	Grain Yield (Mg/ha)
2002	ICM <sup>1</sup>	maize	716	13.0
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	RMS	maize	517	12.0
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	IMS	maize	642	13.4
	RMS	maize	521	10.4
2012	ICM	maize	597	13.1
	IMS	maize	630	13.9
	RMS	soybean	297	2.0

Table 3: Year, management, total water added to site through precipitation and/or irrigation (mm) and yield of maize (Mg/ha) grown in CSP Mead NE Experimental sites between 2002-2009, 2011-2012 growing season. <sup>1</sup> Irrigated Continuous maize, <sup>2</sup> Irrigated Maize-Soybean Rotation, <sup>3</sup> Rainfed Maize-Soybean Rotation

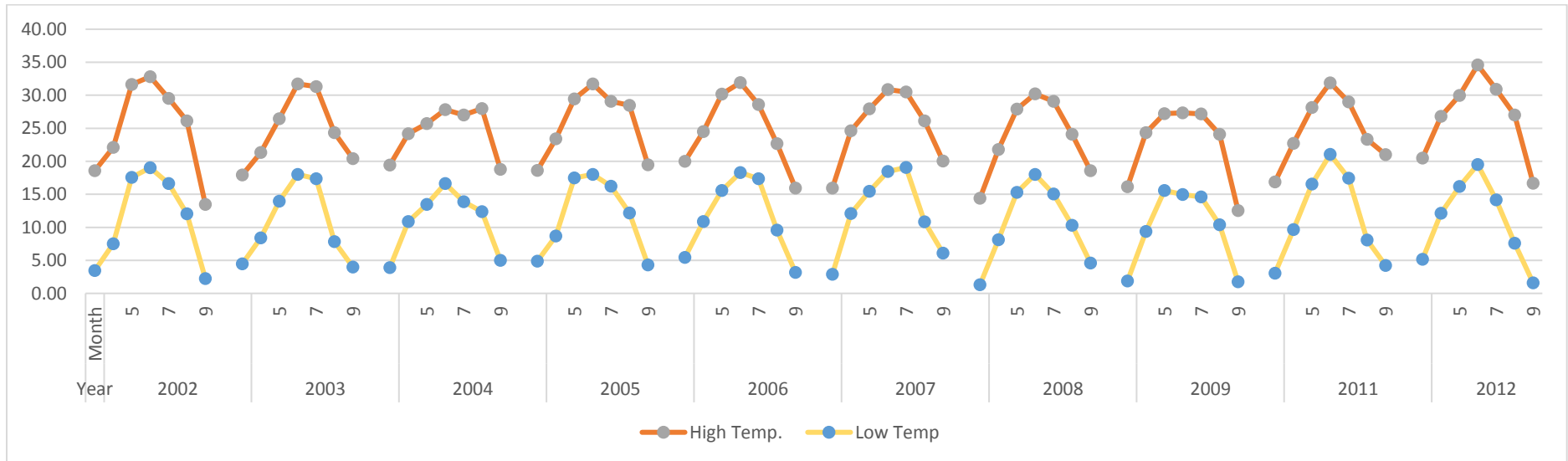


Figure 1: Monthly maximum and minimum temperatures (2-m level) recorded at the nearest Automated Data Network (AWDN) MeadTurf Station for the growing season (April-October) 2002-2009, 2011 and 2012.

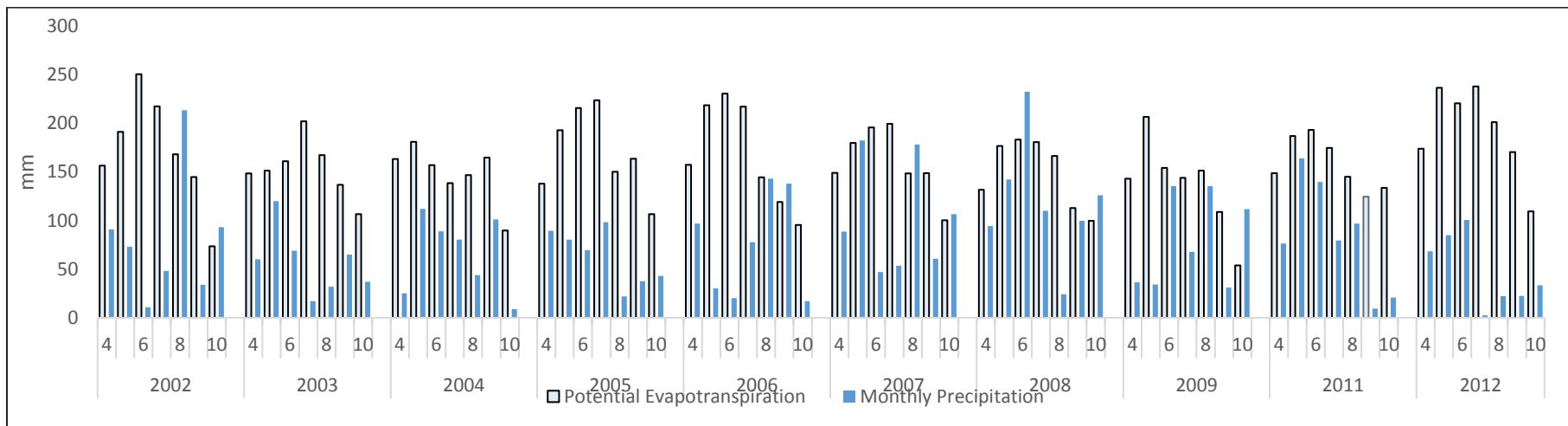


Figure 2: Monthly cumulated potential evapotranspiration and precipitation recorded at the nearest Automated Data Network (AWDN) MeadTurf Station for the growing season (April-October) 2002-2009, 2011 and 2012.

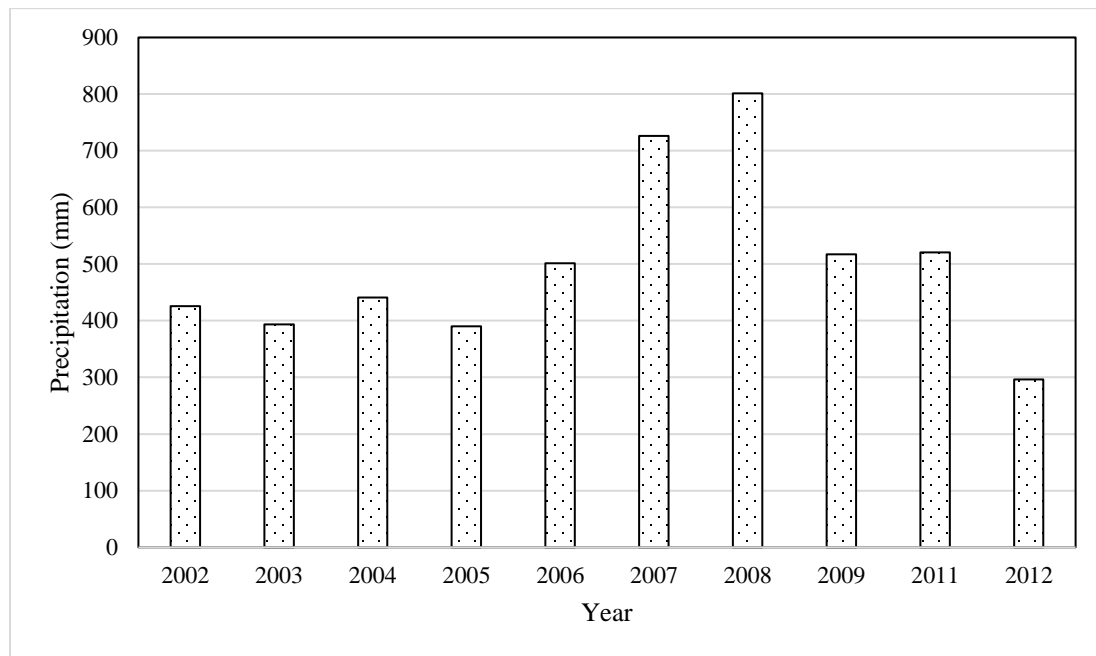


Figure 3: Total cumulative Precipitation during the growing season (April-October) 2002-2009, 2011 and 2012 at the CSP Mead, NE experimental station.

### 3.2 Crop Yields

As expected, both ICM and IMS (irrigated maize and soybean) produced a higher yield than RMS (rainfed maize and soybean) during all years (Table 1). It is worth noting that the effect of rotational management on soil texture and nutrient availability resulted in higher yield production in IMS as compared to RMS. The highest maize production

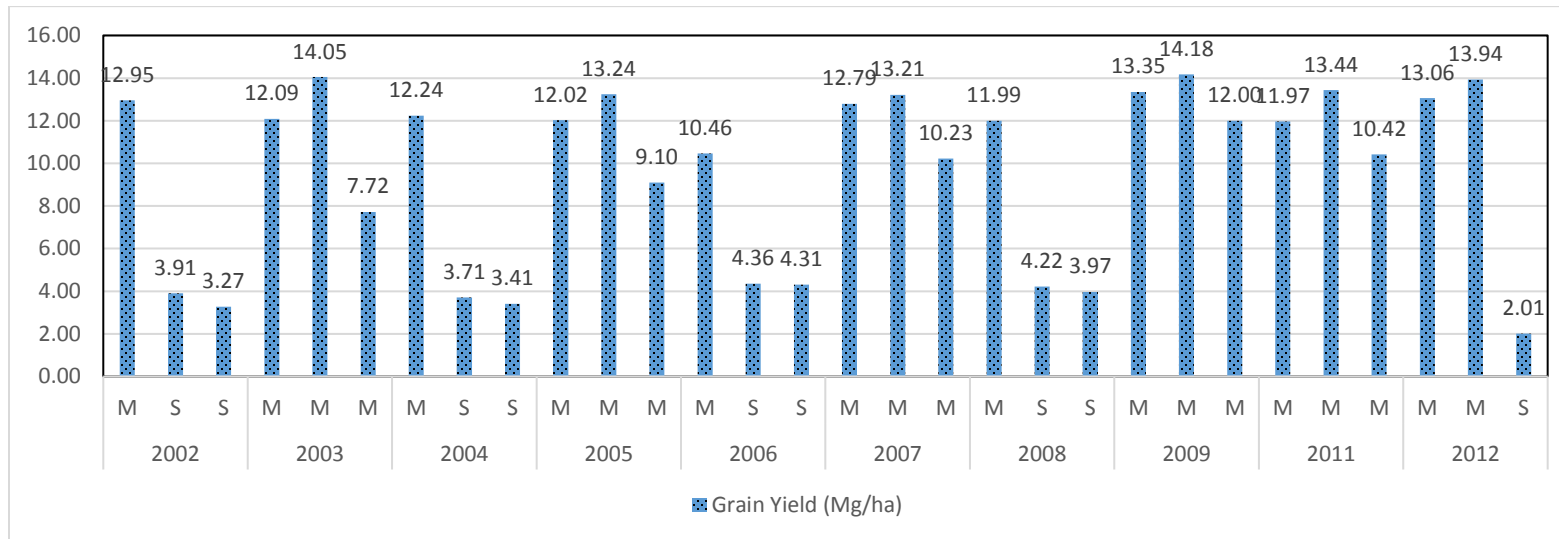


Figure 4: Seed yield (Mg/ha) for maize (M) and soybean (S) growing during the growing seasons (April-October) of 2002-2009, 2011 and 2012 at the CSP Mead, NE experimental sites.

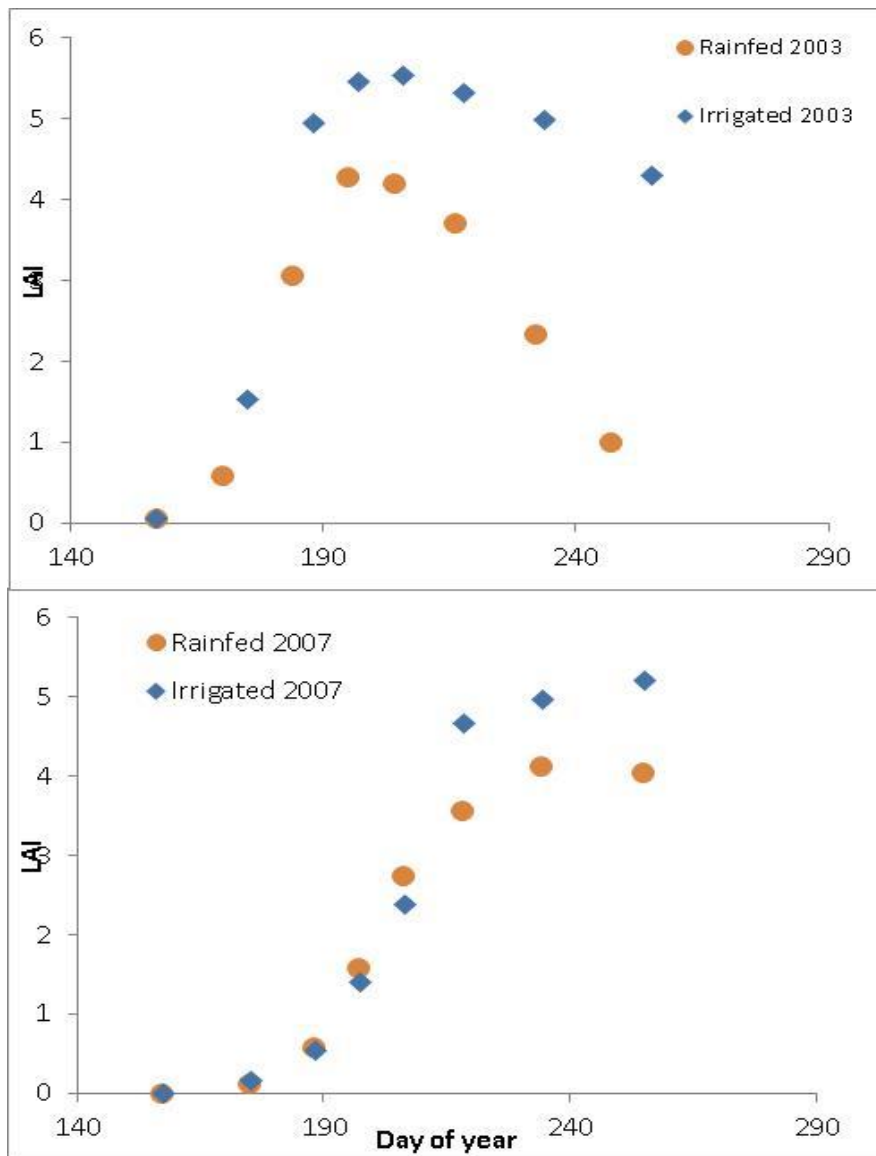


Figure 5: The Leaf Area Index (LAI) for maize growing in IMS (irrigated maize-soybean rotation) and RMS (rainfed maize-soybean rotation) during 2003 and 2007 growing seasons.

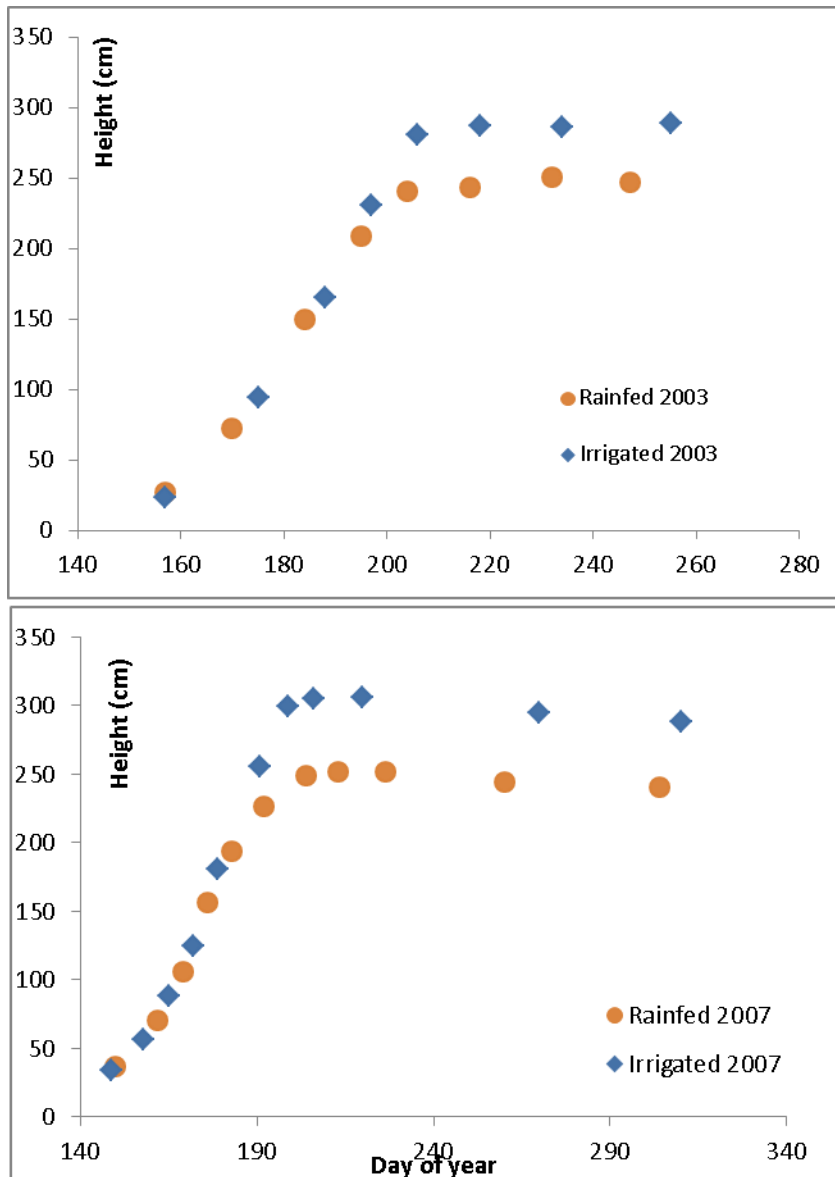


Figure 6: The height for maize growing in IMS (irrigated maize-soybean rotation) and RMS (rainfed maize-soybean rotation) during 2003 and 2007 growing seasons.

under irrigation management was  $14.18 \text{ Mgha}^{-1}$  which occurred in 2009 following a relatively high soybean yield in the previous year ( $4.22 \text{ Mgha}^{-1}$ ).

As expected, rainfed crop did not do as well as irrigated crop since the growth rate and final yields were affected by availability of water in the soil profile to dissolve and supply nutrients such as nitrates, phosphates and potassium to the plants. Nevertheless, the highest maize yields under RMS occurred in 2009 ( $12.00 \text{ Mgha}^{-1}$ ) when the rainfall amounts and distribution were favorable (Fig 2). The worst maize yields reported over the study duration was during the 2003 drought year,  $7.72 \text{ Mgha}^{-1}$  (Fig. 4). Year 2012 was also a drought year, however maize production was under irrigation and a good harvest was reported (ICM –  $13.06$  and IMS –  $13.94 \text{ Mgha}^{-1}$ ). Soybean yields were adversely affected and a small harvest of  $2.01 \text{ Mgha}^{-1}$  was attained in 2012. The highest soybean production occurred in 2006 when rainfall was ample (501 mm) and well distributed. In 2002 and 2004, the maximum or peak LAI for soybean was 5.7 and 4.4 respectively (Suyker and Verma, 2008).

On average, using two contrasting years (2003 and 2007); the maximum LAI for irrigated maize ranged between 5 and  $6 \text{ m}^2\text{m}^{-2}$  while that of rainfed maize was slightly above  $4 \text{ m}^2\text{m}^{-2}$  (Fig.5) Maize height for irrigated site-years was slightly above 300 cm while that of RMS was about 50 cm shorter (Fig. 6). Suyker and Verma (2008) found a strong linear relationship between daily ET/ETo and LAI between an LAI of 3 and 4. Usually the cumulative evapotranspiration for maize was higher than that of soybeans. For example, between 2001 and 2005, cumulative ET for the entire growing season (planting to harvest) was 430-474 mm for soybean; while that of corn was 544-578 mm.

### 3.3 Temperature

Temperature measured at 10 cm above the surface, ( $T_{10}$ ) in both ICM and IMS were lower than in RMS during all the years (Fig 7) reflecting the effect of additional evaporative cooling in the irrigated fields. Irrigation was responsible for higher evapotranspiration at the irrigated sites, resulting in evaporative cooling during vegetative development as reflected in the 10 cm temperature,  $T_{10}$ . The explanation for this temperature difference was that solar radiation was partitioned to both latent heat and sensible heat for the irrigated field while the rainfed field had more energy directed into sensible heat, thereby increasing canopy temperatures. As the cropping season progressed to a fuller canopy cover, more energy went into latent heat, and evaporative cooling resulted in the downward flux of sensible heat. Several studies (e.g. Bonan, 2001, Mahmood and Hubbard, 2002) have also documented both dew point temperature increments and maximum temperature decrements during the summer in the vicinity of irrigation. The differences between  $T_{10}$  in irrigated and rainfed sites will tend to disappear when rainfall is adequate and well distributed during the growing season. However, in the situation where climatic conditions are drier and hotter, the timing of sensible heat departures measured in the different sites is prominent. In Fig. 8 all sites (e.g. year 2003 and 2012) have sensible heat moving upward after emergence because the canopy is quite sparse and therefore the soil/canopy generally stays warmer than the air. The summation of the sensible heat exchange continues upward for both sites through

time until the evapotranspiration has depleted the soil to the point that irrigation is needed to replenish water lost from the profile. As the canopy becomes larger and draws more

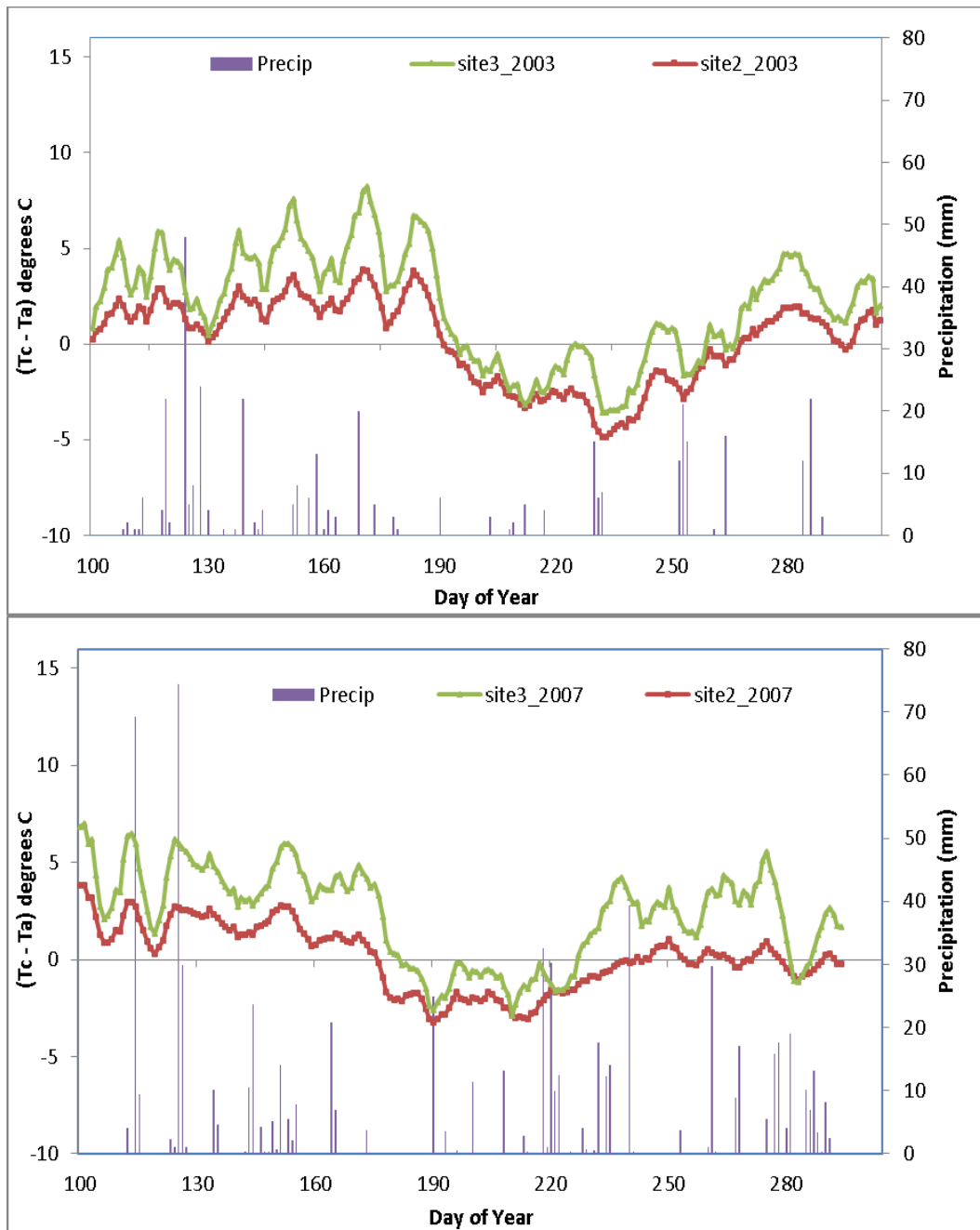


Figure 7: Moving 7-day average maximum Ta-Tc at Mead Turf Farm Station for sites 2 and 3 during the growing season (April-October) during the years a) 2003 (dry) and b) 2007 (wet).



water from the soil, the evapotranspiration causes the temperature of the irrigated canopy to fall below the air temperature. This is the point when sensible heat changes sign and is directed downward toward the canopy. In the past, when sensible heat was directed to the canopy it was coined sensible heat advection but as can be seen here, it can also be viewed as a consequence of surface cooling due to evapotranspiration. While still using 2003 as an example, departures in the amount of sensible heat between IMS and RMS began around LAI of  $4.2 \text{ m}^2\text{m}^{-2}$  for the irrigated crop and  $3.0 \text{ m}^2\text{m}^{-2}$  for the rainfed crop (Fig.5). Sensible heat measurements remained generally upward for the rainfed crop and generally downward for the irrigated crop (at about day 190) which corresponds to the timing when the irrigated crop had attained larger LAI and height than that of RMS. It is important here to note that during the early part of the long-term study (2001 – 2004 GS); maize residues were not incorporated into the soil or removed from the soil surface. A higher albedo from site 1 (continuous irrigated maize (ICM)) increased the sensible heat in atmosphere compared to site 2 (IMS). The maize residue also served to conserve and prevent water losses into the atmosphere thereby reducing partitioning of energy to LE. After 2005, a large proportion of residue from ICM was incorporation deeper in the soil (Suyker and Verma, 2009). Therefore, in the more recent years (e.g. 2012 (Fig 8b)) ICM and IMS were in closer agreement as compared to 2003 (Fig 8a).

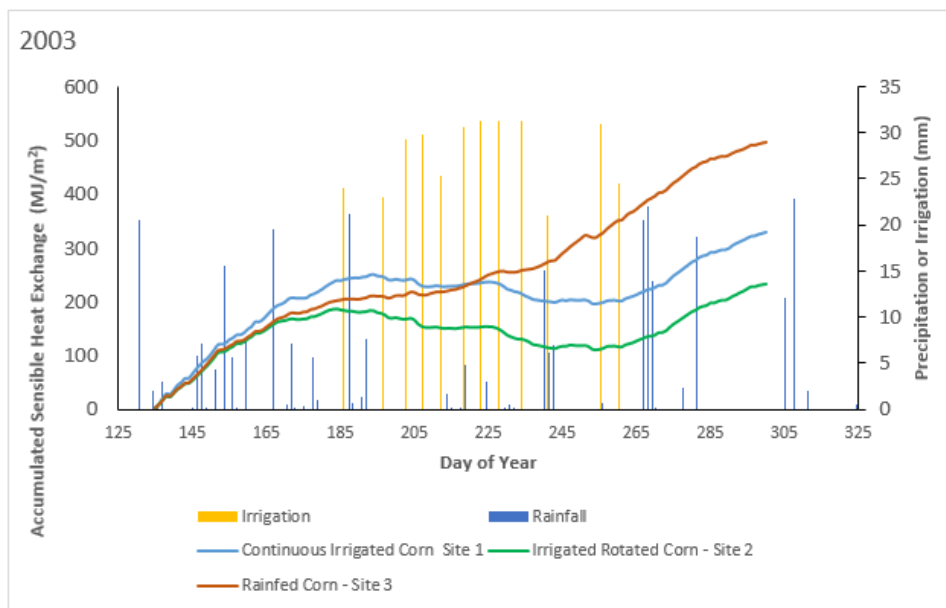


Figure 8a: Cumulative sensible heat (H), precipitation and irrigation measured for maize: Irrigated Continuous Maize (ICM), Irrigated Maize-Soybean Rotation (IMS) and Rainfed Maize-Soybean Rotation (RMS) during the growing season (GS) (April – October, 2003) at the CSP Mead, NE experimental stations.

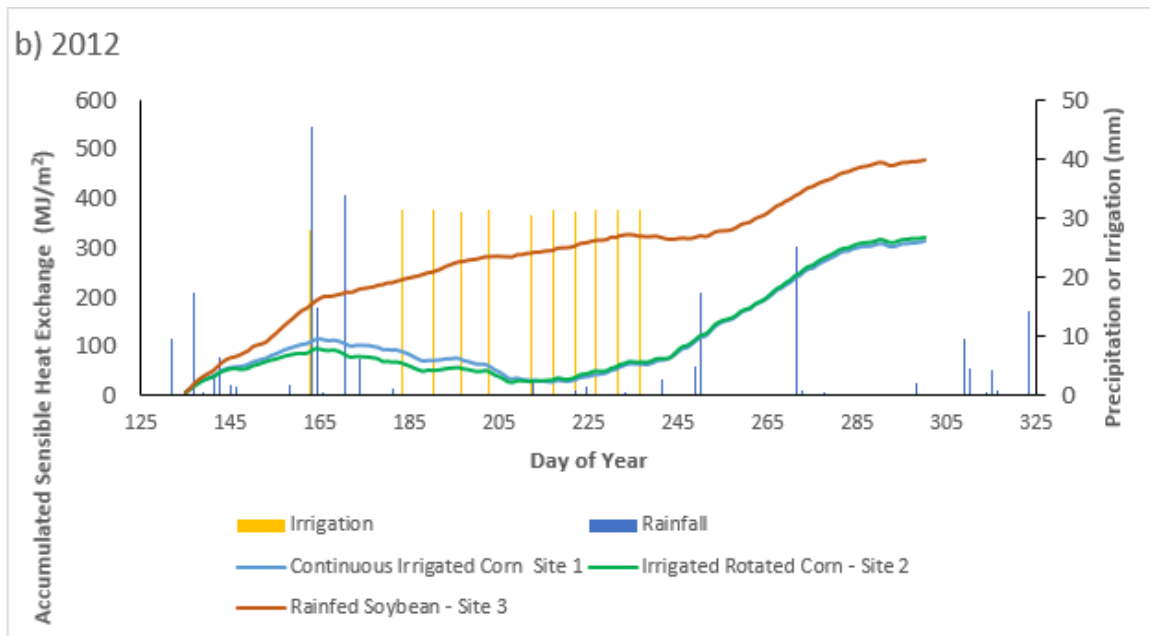


Figure 8b: Cumulative sensible heat (H), precipitation and irrigation measured for maize: Irrigated Continuous Maize (ICM1), Irrigated Continuous Maize (ICM2) and Rainfed Maize-Soybean Rotation (RMS) during the growing season (GS) (April – October, 2012) at the CSP Mead, NE experimental stations.

An annual volumetric soil water time series showed that soil water for most years was high at the beginning of the season because precipitation in the form of rainfall in the spring and snowfalls in the winter season recharged the soil water profile (data not shown here). When crop growth commenced, the soil water declined due to evaporation and transpiration from the crops. Recharging occurred with effective precipitation events and irrigation applications (ICM and IMS). Stresses to the crop due to water depletion began approximately at the point when half of the available soil water (approximately  $0.24 \text{ cm}^3 \text{ cm}^{-3}$ ) was depleted from the soil profile by evapotranspiration. During a dry year, such as 2003, soil water decreased below the stress line in RMS over a continuous period that was broken once during the crops reproductive stages. Water stresses in RMS were not as severe during the 2007 season for example, because stresses were short-lived.

### 3.4 Irrigated and Rainfed Maize

The microclimates in irrigated and rainfed maize were comparable up to the phenological divergence point (PDP). After PDP, a cooling effect was found in the irrigated compared to the rainfed canopy. The effects of the deficits of soil water at the rainfed sites became increasingly pronounced on many measures such as H, LE, LAI, and crop height. For example, between 2001 and 2005, Suyker and Verma (2009) recorded an average of 548 and 482 mm of ET for irrigated and rainfed maize respectively. Lower accumulated H over the season resulted from irrigation events that supplemented rainfall as compared to the rainfed site-years. Additional available water increased transpiration from the crop as well as soil evaporation. The rainfed crop lost heat into the air (increased H) as compared to the irrigated crop that extracted heat from the air for evapotranspiration thereby

increasing LE. For these reasons, the proxy canopy temperatures of the rainfed crop were higher than that of the irrigated crop.

### 3.5 Irrigated and Rainfed Soybean

Both irrigated and rainfed soybeans were planted in 2002, 2004, 2006 and 2008. The difference in yield between the two water managements was 0.64, 0.30, 0.05 and 0.26 Mgha<sup>-1</sup>. The differences between ET measurements over the irrigated and rainfed soybean fields were normally low. For example, Suyker and Verma, (2009) recorded an average of GS ET of 452 and 431 for irrigated and rainfed soybean between 2001 and 2005. It was also interesting to note that the cumulated H for irrigated and rainfed soybean were nearly the same in the years when the yield differences were very small. Additionally, the LE values were similar for both management types. The explanation for these similarities lies in the architecture of the plant (e.g. leaf angle distribution) and the physiological behavior of plants (e.g. closure of its stomates) in managing and avoiding the effects of water stresses (Barfield and Norman, 1983). For instance, a combination of a planophile leaf distribution and albedo of approximately 0.21, increases the  $R_n$  reflective capabilities of soybeans in comparison to that of corn, an erectophile whose albedo ranges from 0.2 to 0.23 (Doughty et al., 2011). Soybeans respond to water deficits by allocating more resources (photosynthates) to the roots in the lower soil profile, thereby avoiding drought conditions and associated yield reductions (Licht et al., 2013). Soybeans can also continue to photosynthesize at lower water potentials than those of corn thereby withstanding drought (Boyer, 1970). Yield reductions of soybean occur significantly during “early formation and pod filling”, (Sionit and Kramer, 1977) and in 2002, water stress occurred about that critical time while in 2004 and 2006, the rainfall distribution allowed rainfed soybean to produce about the same yield as irrigated soybean. In 2002, water stresses limited transpiration resulting in the ratio, of LE to incident radiation ( $R_n$ ), to decrease logarithmically as stomatal resistance ( $r_s$ ) increased (Baldocchi et al., 1985). The partitioning of net radiation to increase H, decreases the cumulative LE in the soybean canopy over the growing season. The similarities in 2004, 2006 and 2008 may have been fostered by the practice of rotating soybean with maize since these rotations have been studied and reported to favor an increase in root activity (Copeland et al., 1993), thereby increasing rooting depth and water uptake by plants.

### 3.6 Role of Irrigation in mitigating global warming

During the growing season rainfed crops generally release more sensible heat to the air than irrigated crops because of the decreased amount of transpiration and limited available soil water. Irrigated continuous maize crop (ICM), at Mead, mitigated from 20 to 62 % (Table 3) of this sensible heating that otherwise would have gone into the air because irrigation caused more available energy to be partitioned into evaporation and less into sensible heat and even with drew heat from the air under advective conditions. Thus, irrigated maize acted to mitigate warming over the irrigated areas. Irrigating soybeans, on the other hand did not consistently mitigate atmospheric warming. For instance, in 2006 and 2008, the difference between cumulative H in IMS and RMS over

the GS, was insignificant (Fig. 9) and so was the yield difference. These results may be explained by the edaphic conditions (e.g. available soil water, soil water holding capacity) and active rooting depth of the crop (Moore and Heilman, 2011). In 2002 and 2004, irrigation of soybeans (IMS) mitigated 37 and 9 % of H released into the atmosphere by a neighboring rainfed soybean field (RMS). The higher level of mitigation (in 2002) may be attributed to a larger biomass and yield difference between the irrigated and rainfed soybean crop. Upon comparing the irrigated maize and rainfed soybean LULLC, the impact of irrigation in mitigating atmospheric warming is amplified during 2002 and 2012, which were both hot and dry years. Approximately 56 and 76% of the cumulative sensible heat released to the air from the rainfed soybean fields was accounted for in the irrigated fields because of partitioning more  $R_n$  into LE for 2002 and 2012 respectively (Table 3).

Year	Management	crop	Number of full Irrigations	% Mitigation
2002	ICM	maize	8	56
	IMS	soybean	6	37
	RMS	soybean		
2003	ICM	maize	11	25
	IMS	maize	13	63
	RMS	maize		
2004	ICM	maize	8	22
	IMS	soybean	6	9
	RMS	soybean		
2005	ICM	maize	10	30
	IMS	maize	9	36
	RMS	maize		
2006	ICM	maize	8	45
	IMS	soybean	4	0
	RMS	soybean		
2007	ICM	maize	8	62
	IMS	maize	7	32
	RMS	maize		
2008	ICM	maize	7	37
	IMS	soybean	7	-1
	RMS	soybean		
2009	ICM	maize	6	20
	IMS	maize	6	4
	RMS	maize		
2011	ICM	maize	4	33
	IMS	maize	4	28
	RMS	maize		
2012	ICM	maize	10	76
	IMS	maize	11	69
	RMS	soybean		

Table 3: Year, management, crop, number of full irrigations and % Mitigation of sensible heat energy as a result of irrigation of crops grown in CSP Mead NE Experimental sites between 2002-2009, 2011-2012 growing seasons. <sup>1</sup> Irrigated Continuous maize, <sup>2</sup> Irrigated Maize-Soybean Rotation, <sup>3</sup> Rainfed Maize-Soybean Rotation.

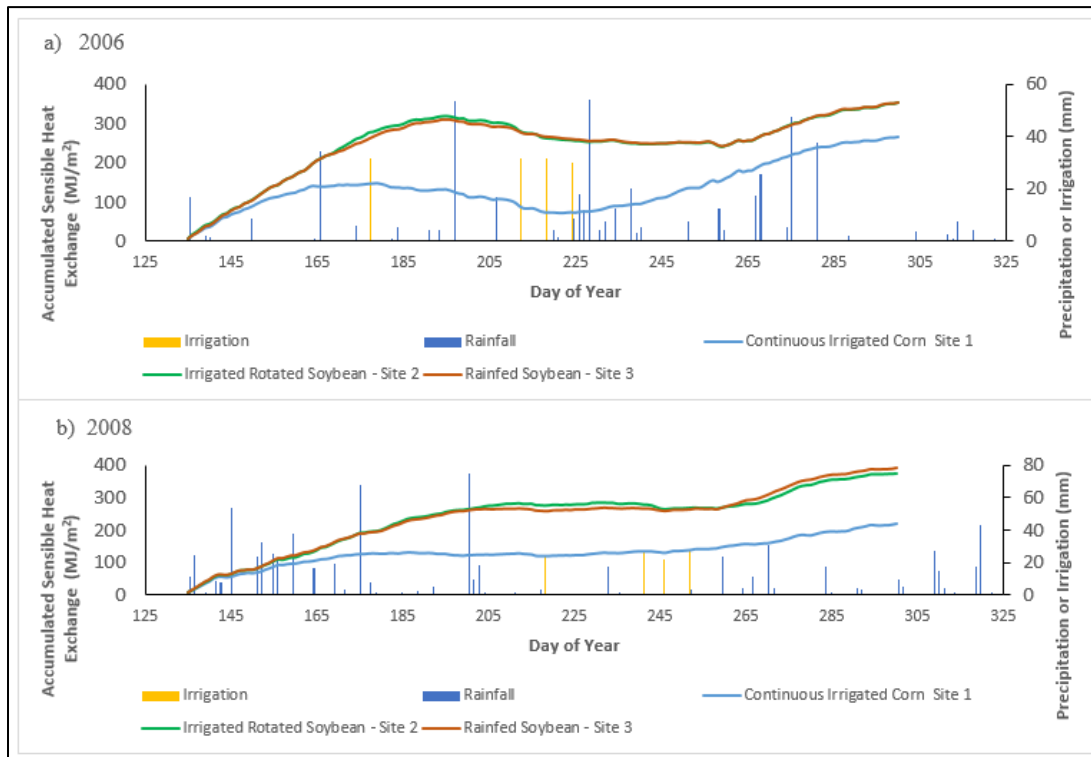


Figure 9: Cumulative sensible heat ( $H$ ), precipitation and irrigation measured for Irrigated Continuous Maize (ICM), Irrigated Maize-Soybean Rotation (IMS) and Rainfed Maize-Soybean Rotation (RMS) during the growing season (GS) (April – October, a) 2006 and b) 2008; at the CSP Mead, NE experimental stations.

#### 4.0 Conclusions

The frequency and severity of drought is expected to increase in Nebraska with increasing temperatures necessitating food producers to rely on irrigation much more (Wilhite et al., 2014). In 2003 and 2012, for instance, Nebraska experienced drought during the growing season (April – October). During those years, water extraction from the Ogallala aquifer for the purposes of irrigation, increased (Hornbeck and Keskin, 2014). Intensive agriculture coupled with increased irrigation has been observed to result in surface cooling and the redistribution of some energy from  $H$  to  $LE$ . Irrigation influences convective cloud formation and precipitation development at a regional-scale as several studies have documented (e.g. Adegoke et al, 2007; Mahmood et al., 2014).

In realizing our objective, we came to understand the large contrast in the microclimates of rainfed and irrigated maize and soybean managed ecosystems and we quantified the impact irrigation has on mitigating atmospheric warming.

The long-term *in situ* field observations of adjacent fields provided by the CSP, Mead, NE, was an excellent resource for comparing the direct effects of irrigation and crop type on both  $H$  and  $LE$  heat fluxes and temperatures. It is clear that the microclimate of rainfed and irrigated crops begins to depart substantially with the first irrigation. Further,

rainfed crops generally release heat to the air above the canopy. Irrigated crops however, because the canopy is cooled by evapotranspiration, generally remove heat from the air. In dry years the amount of heat that is mitigated by irrigated crops is larger than in wet years. The microclimate of irrigated and rainfed crops is not so different in wet years. These results also demonstrate that irrigated maize mitigates atmospheric warming more than soybean, most likely because of their physiological differences (e.g. rooting depth; albedo, surface roughness). Maize transpires more and is not as tolerant of low water potentials as is soybean. In support of this fact, maize was reported to have a lower canopy surface conductance ( $G_{smax}$ ) of  $29 \text{ mms}^{-1}$  compared to soybean whose  $G_{smax}$  ranged from  $36\text{-}41 \text{ mms}^{-1}$  with a corresponding LAI of 4.4 and 5.7 between the GS of 2001 and 2005 (Suyker and Verma, 2008).  $G_{smax}$  is the reciprocal of the resistance in the Penman-Monteith equation and reflects on the “biosphere’s control” of ET. Therefore, a soybean canopy has a higher control of ET as compared to maize which is positively attributed to the content of nitrogen in the leaves (Suyker and Verma, 2008). Soybeans which have a higher albedo than corn and better tolerance to low water potentials; have been shown here to preferentially increase H into the atmosphere. Such differences, in the type of crops and their tolerance and/or avoidance mechanisms to drought, are vital in the construction of realistic simulation models that mimic LULCC. More work needs to be done to increase understanding of the influence that vegetation type and irrigation have on other physical processes such as transpiration, cloud formation and precipitation at the local to global scale. The combined impact of irrigation and the promotion of crop cultivars with significantly higher albedos (Doughty et al., 2011) and crops with deeper active rooting systems (Moore and Heilman, 2011); may potentially offset atmospheric warming in temperate regions (latitudes  $>30^\circ$ ).

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