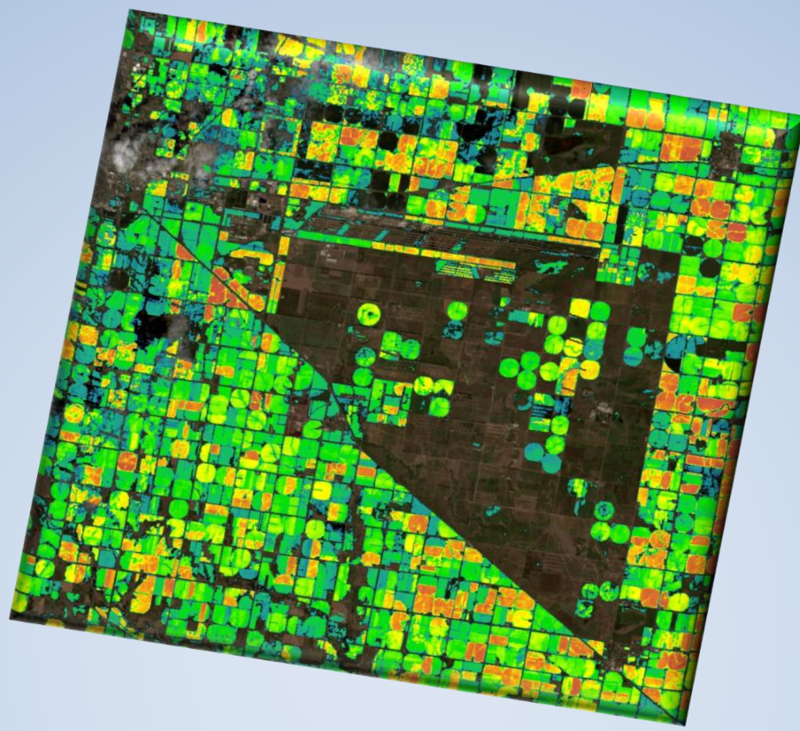
LAND USE CLASSIFICATION: A SURFACE ENERGY BALANCE AND VEGETATION INDEX APPLICATION TO MAP AND MONITOR IRRIGATION IN NEBRASKA



PROJECT REPORT

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SUMMARY

There is an urgency to model and predict with high precision water allocation to the agricultural sector which consumes the largest share of available fresh water in Nebraska. This study introduces a remote sensing based systematic method that integrates surface energy balance modeling and vegetation indices to classify irrigated and non-irrigated lands at fine spatial resolution. The new NDVI-Evaporation fraction-Green Index (*NEG)* irrigation classification scheme integrates two new indices that highly contrast the spectral signature of irrigated and non-irrigated fields. The fusion of two indices enhances the classification efficiency by adding another filtering layer which re-characterizes misclassified areas. The scheme was implemented on three years with different wetness scenarios during the growing season (dry, normal and wet) over the South Central Nebraska. The results revealed that NEG classification accounted for more than 97% variation in NASS county irrigation data. The mean absolute percentage error between NEG and NASS irrigated acreages during the three wetness scenarios was 8.27%. The results demonstrated that NEG irrigation classification scheme is an effective and consistent approach to estimate irrigated acreages during dry, normal and wet years. With ancillary techniques to gap-fill missing data due to clouds and stripping in Landsat data, NEG irrigation classification scheme is designed and skilled to map, quantify and monitor irrigated lands, with complete spatial coverage, from field- to regional-scale.

INTRODUCTION

Nebraska is fortunate to have aquifers below it, supplying water to over 8.3 million acres of irrigated cropland and pasture (NASS, 2014). The state economy is predominately driven by agriculture, which consumes 71% of the state's total water use (CALMIT, 2007). In recent years, however, states overlaying the High Plains aquifer have filed lawsuits related to over consumption of surface water and groundwater. The Kansas vs. Nebraska suit, Pumpkin Creek conflict, Platte River Cooperative Agreement, South Platte River Compact and the Republican River Compact are some of the examples of water conflicts involving increasing water shortage (NDNR, 2007; Aiken, 2008). The severity of water shortage is exacerbated by increasing frequency of droughts, warming climate, decreasing snowpacks which feed many rivers, and increasing demand from municipalities as urban population grows. In light of these concerns, there is urgency for informed policy and decision making for sustainable management of the limited water resource. The realization of this goal is tasked to the scientific and engineering community to develop precision models that predict accurate and reliable statistics on consumptive water use from field to regional scale. Such statistics are regarded as the starting point for efficient water resource management (Singh, 2009).

Annual reports from the National Agricultural Statistics Service (NASS) provide county aggregated estimates of several agricultural statistics, including irrigated acreages for all counties across the United States. However, high precision modeling requires high spatio-temporal resolution input data to estimate consumptive water use in fine detail. In situ at-field scale survey of irrigation status in large irrigation districts, counties and regions is a greatly time- and labor-intensive, and expensive campaign. Therefore, an efficient and accurate method for determining irrigation status of croplands in a spatially explicit manner is much needed to support water resources-related modeling, governance and decision making.

RATIONALE AND OBJECTIVE

Most of the previous methods were largely developed using satellite images with coarser spatial resolution (>250 m) with the purpose of mapping irrigation status over broad geographic areas. The irrigation information produced at regional scales often created difficulties in linking the dataset to the water resource management in the local areas. However, very few studies have been conducted to map the irrigated land areas at finer spatial resolution. In this study, we develop a remote sensing-based classification scheme that integrates vegetation indices and surface energy balance modeling to classify irrigated and non-irrigated croplands at high spatial resolution. We exploit the Normalized Difference Vegetation Index (NDVI) index which has been widely investigated to discriminate irrigated from non-irrigated fields, and the Green Index (GI) (Gitelson et al., 2003) which was described as the most sensitive index to vegetation development (Gitelson et al., 2005). The Surface Energy Balance System (SEBS) algorithm (Su, 2002) is used to partition surface energy balance components from which evaporation fraction is derived and synthesized with the NDVI and GI to generate a highly spectral contrasting scheme of irrigated and non-irrigation land use signature. The classification scheme and thresholds are developed to be consistent and accurate during dry, normal and wet growing seasons.

LITERATURE REVIEW

Several attempts have been made to map irrigation status of croplands at different scales and geographic areas (Ozdogan et al., 2010). Alexandris et al. (2008) applied and compared four types of methods for classifying irrigated and non-irrigated land, including traditional classification of spectral bands, Normalized Difference Vegetation Index (NDVI), Normalized Difference Water Index (NDWI), and Principal Component Analysis (PCA) along with supervised, unsupervised classification and simple thresholding in a Mediterranean basin. The PCA, NDWI and NDVI methods showed better accuracy overall, but the applicability of methods is subject to the arid or semiarid regions where high spectral contrast between irrigated and non-irrigated areas exists.

Annual peak MODIS-derived NDVI has been used in combination with the U.S. Department of Agriculture (USDA) County-level NASS data to map the extent of irrigated land in the conterminous U.S. (Pervez and Brown, 2010; Brown and Pervez, 2014). This method provided a fast and cost-effective means of mapping irrigation status over large geographic areas; however, it relies on a few key assumptions that may be difficult to meet on a yearly basis, including 1) the use of satellite images from at least two years with contrasting precipitation conditions, and (2) irrigated crops exhibiting higher peak NDVI values than non-irrigated crops, irrespective of change in cropping patterns at coarse spatial resolution. In a similar fashion, irrigated areas in Afghanistan over the past decade was evaluated along with more refined consideration for non-irrigated area masks (e.g., pasture land, forests, and high slope areas) (Pervez et al., 2014). Wardlow and Egbert (2008) used time-series MODIS-derived NDVI data collected over the growing season along with a decision tree classification technique to classify the crop types and irrigation status in U.S. State of Kansas. The distinction of its irrigation status was reported to be affected by the higher-than-normal precipitation status.

STUDY AREA AND DATASETS

Study area

The domain of this study is twelve counties (Fillmore, Thayer, Clay, Nuckolls, Adams, Webster, Kearney, Franklin, Phelps, Harlan, Gosper and Furnas) located in the South Central Nebraska (Figure 1). These counties are among the most extensively irrigated corn and soybean producing regions of Nebraska. Climate across the counties varies from sub-humid in the east to semi-arid in the west. Based on the 30-year (1961-1990) annual average, precipitation across the counties varies from 22 inches to 30 inches from west to east (http://www.wrcc.dri.edu/pcpn/ne.gif). The elevation across the counties also has a strong east to west gradient, increasing from about 450m to 800m.

Datasets

The hourly weather data from two automated weather data network stations at Grand Island and Holdrege NE were downloaded from the High Plains Regional Climate Center (HPRCC) website (http://www.hprcc.unl.edu/). The Grand Island station elevation is 506.5 m above Mean Sea Level (MSL) and located at latitude 40.88° N and longitude 98.50° W. The Holdrege station elevation is 706.5 m above MSL and located at latitude 40.50° N and longitude 99.35° W. The two station locations are shown in Figure 1. The instrumentation specifications for the measurement of air temperature, soil temperature, relative humidity, wind speed, wind direction, precipitation and solar radiation are also presented on the HPRCC website (http://www.hprcc.unl.edu/awdn/instruments/manual.pdf).

Digital Elevation Dataset (DEM) at 15-meter resolution was downloaded from the Nebraska Department of Natural Resources website (http://www.dnr.ne.gov/elevation-data). The DEM data used in this study were sampled to 30-m resolution. The Cropland Data Layer (CLD) datasets available at

30-meter resolution were retrieved from http://nassgeodata.gmu.edu/CropScape/. CLD was used as the land cover and crop classification data for the study. County-level NASS data was obtained directly from the USDA Farm Service Agency and was used for verification with county statistics of irrigated acres.

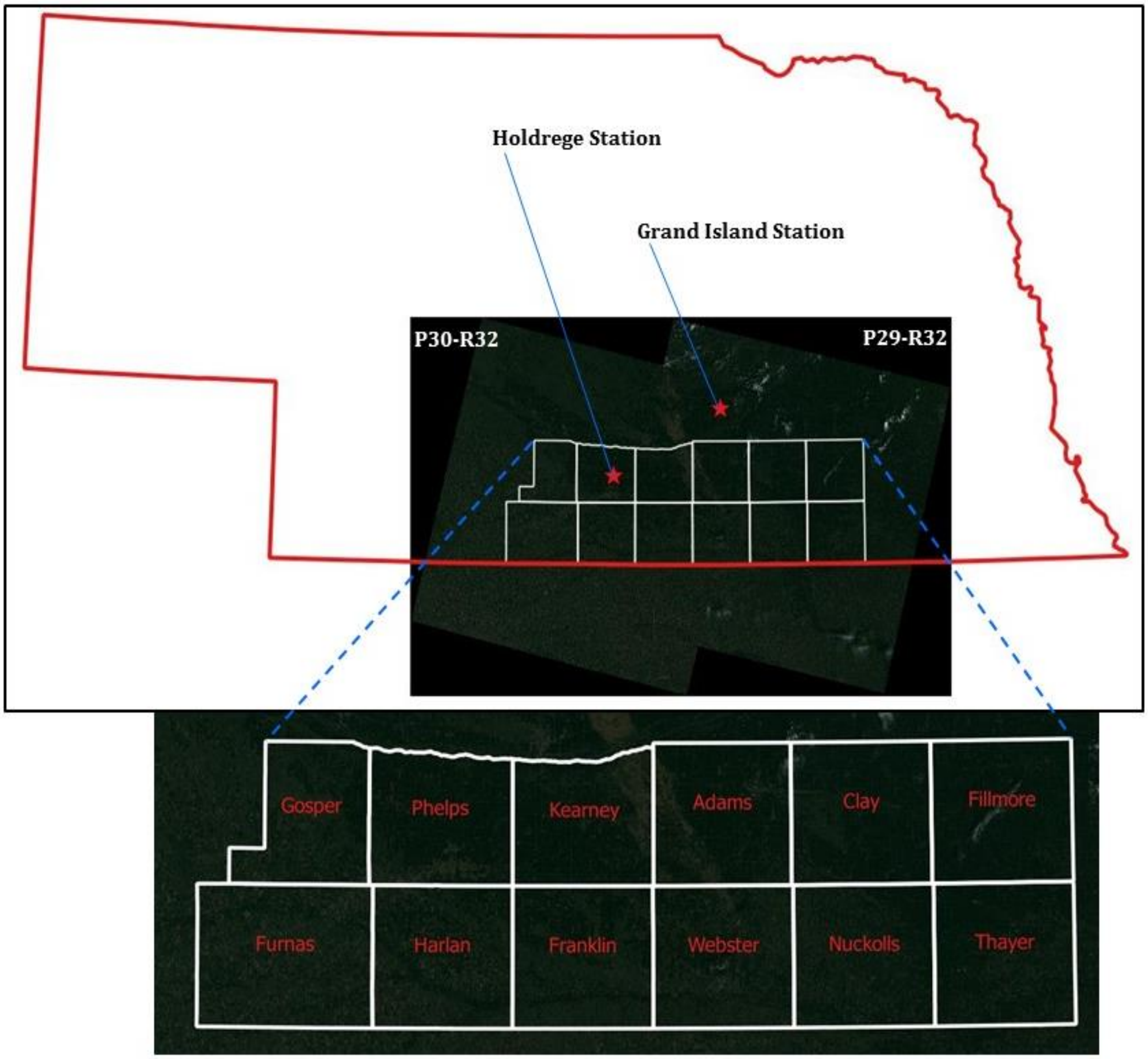


Figure 1: Map of Nebraska showing location of study counties, weather stations, and the two Landsat scenes (mosaicked) used in this study. The Landsat images show the true color band combination of the scenes at the time of overpass.

Groundtruth data were collected across the study region by Riverside Technology, Inc., in 2014, as part of a large intensive data collection campaign for Cooperative Hydrology Study (COHYST) (http://cohyst.dnr.ne.gov/). A Riverside team strategically traversed the region surveying and recording land cover and irrigation information. Surveyed points were located based on identified data needs, and for accuracy assessment of irrigation classification.

The Landsat data for this study were downloaded from United States Geological Survey Global Visualization Viewer website (http://glovis.usgs.gov). The twelve counties considered were all located in two Landsat scenes, Path 29-Row 32 and Path 30-Row 32, and the scene acquisition dates, scene and satellite identifications are presented in Table 1.

Usually, irrigation season in Nebraska starts in mid-June and lasts through the end of August or early September. Therefore, for effective classification of irrigated areas, images acquired between mid-July and mid-August were the first priority for the classification scheme. In case of cloud contamination and gap strips particularly in Landsat 7, supplementary images were downloaded outside the optimal window to gap-fill and de-strip the missing data. In total, 20 images from Landsat 5 Thematic mapper (TM), Landsat 7 Enhanced Thematic Mapper Plus (ETM+) and Landsat 8, over a period of three growing seasons (2009, 2012 and 2014) were downloaded and processed for this study.

Normal, dry, and wet growing seasons

The conception of this study is to develop and validate an irrigation classification scheme that is applicable and reliable in most wetness scenarios (dry, normal and wet growing seasons). Recent dry, wet and normal growing seasons were determined and selected using the National Oceanic and Atmospheric

Administration (NOAA) – National Climatic Data Center (NCDC) climate monitoring portal (http://www.ncdc.noaa.gov/cag/). Using the portal tool, the time series of Nebraska South Central average precipitation of June, July and August from 1980 to 2014 was plotted with the long term average of 1990 – 2000 (Figure 2). The most recent wettest growing season in the Figure (2) was 2014, the driest was 2012, and normal was 2009. The summer precipitation of 2009 was 28.2 mm above the long average of 253.2 mm. In the "State of the Climate in 2009", Arndt et al. (2010) described the summer (Jun – Aug) precipitation of Conterminous United States as overall near normal, ranking the 54th wettest out the 115 years before.

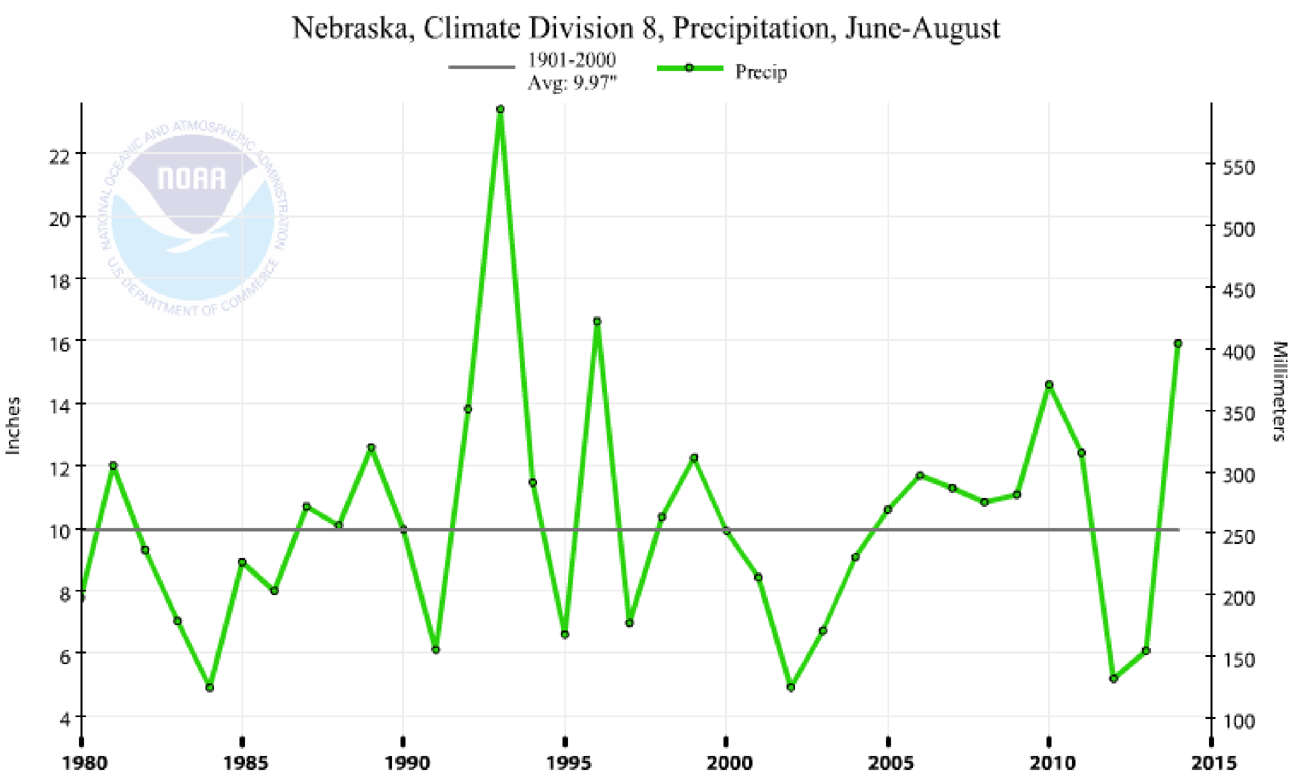


Figure 2: South Central (NE, Climate Division 8) precipitation average during the months of June, July, and August from 1980 to 2014. Source: http://www.ncdc.noaa.gov/cag/time-series/us

Table 1: Landsat scene name, acquisition spacecraft and date, path and row of image used in this study.

SCENE ID	SPACECRAFT ID	DATE	PATH	ROW
LC80300322014203LGN00	Landsat 8	07/22/14	30	32
LC80300322014251LGN00	Landsat 8	09/08/14	30	32
LE70300322012206EDC00	Landsat 7	07/24/12	30	32
LE70300322012222EDC00	Landsat 7	08/09/12	30	32
LT50300322009189PAC02	Landsat 5	07/08/09	30	32
LT50300322009205PAC01	Landsat 5	07/24/09	30	32
LC80290322014164LGN00	Landsat 8	06/13/14	29	32
LC80290322014180LGN00	Landsat 8	06/29/14	29	32
LC80290322014196LGN00	Landsat 8	07/15/14	29	32
LC80290322014212LGN00	Landsat 8	07/31/14	29	32
LC80290322014260LGN00	Landsat 8	09/17/14	29	32
LE70290322012183EDC03	Landsat 7	07/01/12	29	32
LE70290322012199EDC00	Landsat 7	07/17/12	29	32
LE70290322012215EDC00	Landsat 7	08/02/12	29	32
LT50290322009198PAC02	Landsat 5	07/17/09	29	32
LT50290322009214PAC01	Landsat 5	08/02/09	29	32

METHODOLOGY

Normal Difference Vegetation Index and Green Index

NDVI and GI indices were computed from the reflectance of green (ρ_{green}), red (ρ_{red}) and near infrared (ρ_{nir}) spectral bands as shown below:

$$NDVI = \frac{\rho_{nir} - \rho_{red}}{\rho_{nir} + \rho_{red}} \tag{1}$$

$$GI = \frac{\rho_{green}}{\rho_{nir}} \tag{2}$$

Where ρ_{green}, ρ_{red} and ρ_{nir} are reflectance from band 2, band 3 and band 4, respectively, for Landsat 5 and 7, and band 3, band 4 and band 5, respectively, for Landsat 8 . NDVI has been widely used as an important vegetation and irrigation monitoring tool (Pervez et al., 2014; Pervez and Brown, 2010; Wardlow and Egbert, 2008; Goward et al., 1991; DeFries et al., 1998; Mutiibwa and Irmak, 2012). GI, on the other hand, is a less exploited index, yet studies (Ozdogan and Gutman, 2008; Gitelson et al., 2008) have found the index more sensitive to soil moisture stress than NDVI, Enhanced Vegetation Index (EVI) (Huete et al., 1999), and Wide Dynamic Range Vegetation Index (WDRVI) (Gitelson, 2004). According to Ozdogan and Gutman (2008), the high sensitivity of GI is based on the evidence that, in the green spectrum (centered around 510 nm), the specific absorption coefficient of chlorophylls is very low, while green leaves absorb more than 80% (e.g., Gitelson and Merzlyak, 1994). In contrast, the depth of light penetration into leaves in the blue and red spectral ranges is four to six times lower (e.g., Merzlyak and Gitelson, 1995). Therefore, in the green spectrum, absorption of light is high enough to provide high sensitivity of GI to chlorophyll content but much lower than in the blue and red to avoid saturation (Gitelson et al., 2003).

Surface Energy Balance System (SEBS)

SEBS is a physical model that uses the principle of conservation of energy (eqn. 3) to partition net available energy from the sun (i.e. net radiation (Rn)) into the major surface energy components; that is, soil heat (G), sensible heat (H) and latent heat (λE) flux.

$$Rn = \lambda E + H + G \tag{3}$$

Net radiation (Wm^{-2}) was determined as the radiation balance of net shortwave and net long wave radiation (Su et al.,1999; Su, 2001; Samani et al., 2007). Soil heat flux (Wm^{-2}) was estimated as a fraction of net radiation by an empirical function derived by Choudhury et al. (1987), and the constants calibrated by Monteith (1973) and Kustas and Daughtry (1989). Sensible heat flux (Wm^{-2}) was estimated by using the similarity theory and solving a system of non-linear equations using the Broyden method (Press et al., 1997). The non-linear equations are the similarity relationships for the profiles of friction velocity, Monin Obukhuv length, aerodynamic resistance and mean temperature (i.e. the difference between surface temperature and air temperature). The procedure to derive sensible heat flux is systematically described in Su (2002) and requires only wind speed, temperature at the reference height and surface temperature as inputs.

SEBS estimates latent heat flux (evapotranspiration) by interpolating the *relative evaporation* between the dry-limit and wet-limit (Su, 2002). Under the dry-limit, latent heat flux becomes zero due to the limitation of soil moisture, and sensible heat flux is at maxima. Under the wet-limit, latent heat flux is at potential rate limited only by the available energy under the given surface and atmospheric conditions, and sensible heat flux at minima. The SEBS evaporative fraction (ETrF) used to generate the irrigation classification index in this study, was estimated using equation 4. SEBS estimates ETrF in the range of 0 to 1 (Su, 2002).

$$ETRF = \frac{\lambda E}{Rn - G} \tag{4}$$

The SEBS model inputs are surface emissivity, albedo, Surface temperature and NDVI. These inputs are pre-processed separately from spectral reflectance and radiance of Landsat optical and thermal bands. The remaining inputs include weather station variables, air temperature, air pressure, relative humidity, wind speed, wind speed and measurement height, and Julian day and time of Landsat scene overpass. From the vegetation indices (*NDVI and GI*) and ETrF, two irrigation indices, eqn.5 and eqn.6, were developed as described in the next sub-section, to detect irrigated areas.

$$EGI = \frac{EFRF}{GI} \tag{5}$$

$$NGI = NDVI * GI \tag{6}$$

Irrigation indices development

Using groundtruth data from 2014 growing season, irrigated pixels of an index were extracted using polygons of irrigated fields. Similarly non-irrigated pixels were extracted using polygons of non-irrigated fields. Prior, non-agricultural areas in the index were removed by masking using the 2014 land cover classification CDL data. Distribution functions were then fit on the irrigated pixels, non-irrigated pixels and all pixels combined as shown in Figures 3. This scheme was applied on several indices, including, among others, ETrF, GI, NDVI, maximum NDVI and GI, cumulative NDVI and GI, max daily λE and cumulative daily λE. The ideal index had to generate a distribution that separated irrigated from non-irrigated pixels. Two indices, EGI (eqn. 5) and NGI (eqn.6), were found to generate the widest distribution contrast between irrigated and non-irrigated fields and were thus selected for the irrigation classification scheme for the study.

Thresholds development

Figure 3A shows the empirical distribution of NGI for both irrigated and non-irrigated pixels combined. From Figures 3B and 2C, it's apparent that the distribution of NGI segregates irrigated pixels to the right and non-irrigated pixels to the left. Similarly, Figure 3D shows the empirical distribution of EGI for both irrigated and non-irrigated pixels combined, however, from Figures 3E and 2F, it's evident that this distribution segregates irrigated pixels to the left and non-irrigated pixels to the right. Although both indices had good spectral contrast between irrigated and non-irrigated pixels, there was still some overlap in the middle. For NGI, most of the irrigated pixels had index values which were greater than 4 (Figure 3B), which overlaps with some non-irrigated pixels in Figure 3C. For EGI, most irrigated pixels had index values of less than 0.23 (Figure 3E), which also overlapped some non-irrigated pixels (Figure 4F). Therefore, to enhance the isolation of irrigated pixels and thus increase the classification efficiency, the two indices were fused to take advantage of both distribution properties. The fusion of the two indices was systematically formulated by first applying a *lax* threshold of value 3 on NGI to exclude non-irrigated pixels (NGI < 3), then removed the remaining non-irrigated pixels in NGI conditioned on a *tight* EGI threshold (EGI > 0.22). The two thresholds were selected by training with several values until the optimal combination of the two thresholds classified all the irrigated fields in the groundtruth data. The fusion of NGI and EGI classification scheme is defined as NDVI-Evaporation fraction-Green Index irrigation classification scheme, denoted as *NEG* hereafter.

Figures 4 show the distribution of NGI pixels for irrigated (Figure 4A) and non-irrigated (Figure 4B) areas after the thresholds had been applied to all fields (Figure 3A). The distributions of irrigated and non-irrigation pixels in Figures 4 were used as a reference whenever NEG irrigation classification scheme was extended to other Landsat scenes. That is, for every Landsat scene, the scheme was applied to classify irrigated areas, the output distribution of irrigated and non-irrigated pixels had to nearly match the shape structure in Figure 4. Groundtruth pixels used for the development of the indices and thresholds were extracted from Landsat 8 scene of Path 29-Row 32 on July 31, 2014. Before extending NEG to other growing seasons, the scheme was validated on groundtruth pixels extracted from Landsat 8 scene of Path 30-Row 32 on July 22, 2014.

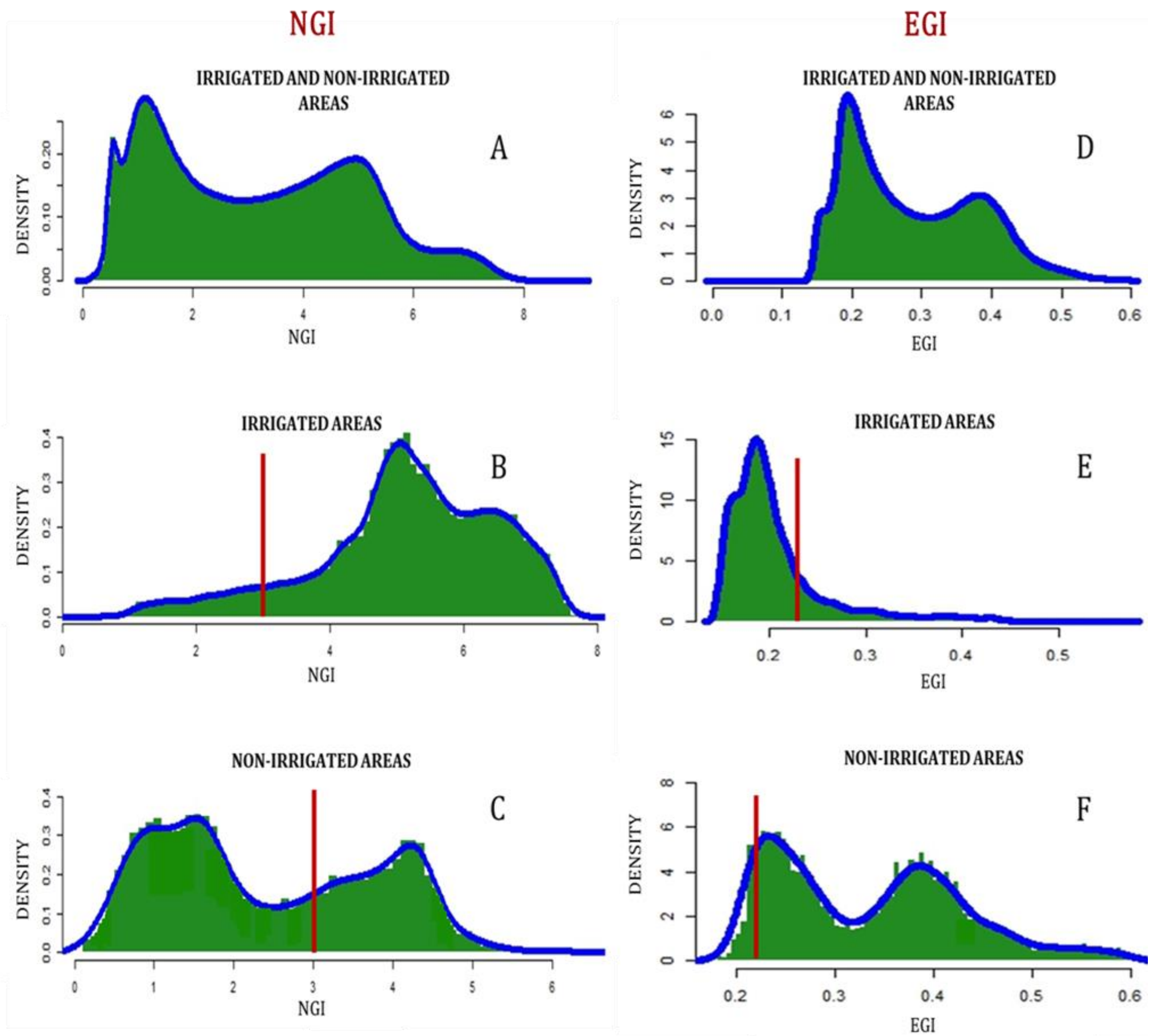


Figure 3: Empirical distributions of NGI and EGI indices for all fields combined (Irrigated and non-irrigated areas), irrigated, and non-irrigated areas.

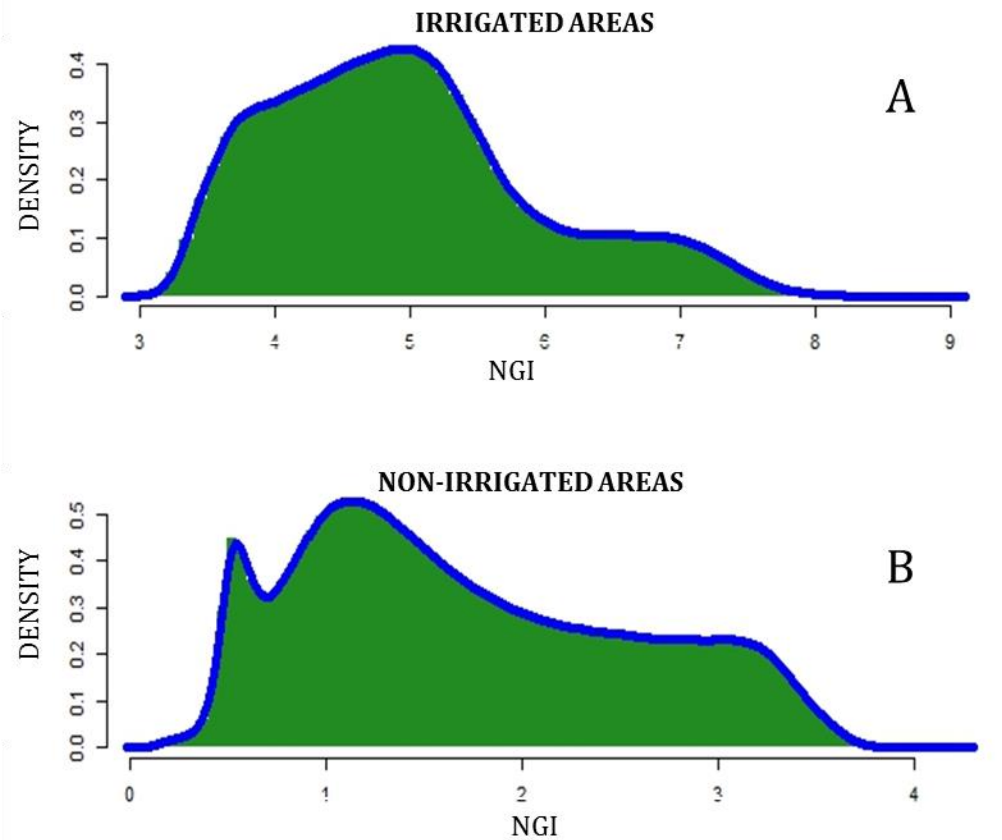


Figure 4: Empirical distributions of NEG index for irrigated and non-irrigated areas after the classification scheme has been applied.

Performance Assessment

The performance of NEG irrigation classification scheme was evaluated using the coefficient of determination (R^2) as a measure of goodness of fit (i.e., the measure of total variance in NASS county data accounted for by NEG county estimated irrigation acreage), Root Mean Square Difference (RMSD) as a measure of the absolute difference between NASS and NEG, and Mean Absolute Percent Error (MAPE) as a measure of NEG accuracy in percentage terms (eqn.7). Where *N* is the number of counties.

$$MAPE = \frac{1}{N}\sum\left(\frac{|NASS - NEG|}{NASS}\right) * 100 \quad (7)$$

RESULTS

NEG Irrigation classification scheme and NASS

NASS data are approximates of agricultural statistics; therefore NASS county irrigated acreages were used as a reference, not measures of exact precision, for the performance of NEG irrigation classification scheme. The results in Table 2 show that NEG estimated county irrigated acreages with percentage error ranging from -0.2% to 27.8%. Nuckolls was the only county that for all three years had percentage errors above 20%. Overall NEG classified irrigated areas during the three years with MAPE of 8.27% (Table 3). The regression R^2 shows that NEG estimates correlated and explained variation in NASS county irrigation by 0.97 (Figure 5). The scheme overall underestimated by only 2% (slope: Table 3 and Figure 5).

In 2014, NEG estimated irrigated area within ±7% for six counties out of ten. The 2014 NASS Irrigated acreage for Phelps and Gosper counties was not available. Therefore, for comparison between NEG and NASS, the two counties were excluded. The total irrigated acreages from the remaining ten counties was estimated at 1,361,450 acres by NEG and 1,317,500 by NASS. The RMSD across the ten counties was 10,148.6 acres. In 2014, MAPE shows that NEG estimated county irrigated acreages within 7% of NASS estimates. In 2012, NEG estimated irrigated area of seven counties out of twelve within ±7% as well. A total of 1,744,100 acres and 1,810,032 acres were classified as irrigated in the twelve counties by NASS and NEG, respectively. That is, NEG estimation of irrigated area in 2012 was within 8.5% of NASS. The summer of 2012 experienced an extraordinary drought in terms of intensity and extent across the United States.

Table 2: NASS and NEG estimated irrigated area (acres) and percentage difference for each county. [*] denotes missing NASS data for Phelps and Gosper in 2014.

COUNTY	NASS	NEG	% Error	NASS	NEG	% Error	NASS	NEG	% Error
YEAR		2014			2012			2009	
Adams	222400	206452.8	-7.2	225700	199703.3	-11.5	217500	192214.7	-11.6
Clay	214000	219221.8	2.4	211900	223073.7	5.3	201200	183123.4	-9.0
Fillmore	232400	246762.3	6.2	226300	240420.2	6.2	217200	236786.8	9.0
Franklin	93500	94689.35	1.3	101600	110192.9	8.5	97700	101078.3	3.5
Harlan	49000	52035.87	6.2	92700	92546.36	-0.2	87400	85451.97	-2.2
Kearney	192200	191280.2	-0.5	215700	228001.1	5.7	211600	214129.4	1.2
Nuckolls	61100	74725.22	22.3	67300	86034.42	27.8	61900	74269.53	20.0
Thayer	162300	180392.9	11.1	153600	180392.9	17.4	142600	178798.5	25.4
Webster	51200	52499.34	2.5	62300	69067.2	9.8	61700	66957.87	8.5
Furnas	39400	43389.83	10.1	54100	51665.36	-4.5	48300	50553.61	4.7
Phelps	*	232239.9	-	246200	245411.2	-0.3	237100	253480.4	6.9
Gosper	*	79196.6	-	86700	83523.59	-3.7	87200	80568.41	-7.6

During that growing season, the U.S. Department of Agriculture declared 1692 counties, about 63% of the conterminous U.S., as disaster areas (Mutiibwa et al., 2015). Nevertheless, Nebraska ranked top for the most irrigated land (8,298,573 acres) harvested in 2012 (NASS, 2014). That is, 44% of cropland harvested across the state in 2012 was irrigated. In 2009, NEG also estimated irrigated acreages of seven counties out of twelve within ±7%. The total irrigated acres in the twelve counties was 1,671,400 acres and 1,717,413 acres according to NEG and NASS respectively. The trends in Table 3 show that the statistics (R^2, MAPE and RMSE) improve from 2009 to 2014. This could be associated with improvement in sensor instrumentation as new Landsat satellites are put in orbit, coupled with increased spectral and spatial resolution in the new systems.

To determine the trend in irrigated area during the three-year wetness scenarios, the two counties with missing NASS data were disregarded. Results from both NASS and NEG reveal that 2012, which was a dry year, was the most irrigated (NASS-1,317,500 acres and NEG-1,361,450 acres), followed by 2009 which was a normal year (NASS-1,744,100 acres and NEG-1,810,032 acres), and 2014 which was a wet year (NASS-1,347,100 acres and NEG-1,383,364 acres). Intuitively, more farmers irrigated their crops during dry season than during normal or wet season.

Table 3: Coefficient of determination (R^2), Slope, MAPE and RMSE between NASS and NEG county estimated irrigated area for 2014, 2012, 2009 and All YEARS combined.

STATS	2014	2012	2009	ALL YEARS
R^2	0.98	0.97	0.95	0.97
SLOPE	1.02	1.03	1.02	1.02
MAPE (%)	6.98	8.49	9.13	8.27
RMSE (acres)	10148.6	14013.4	16278.1	13896.9

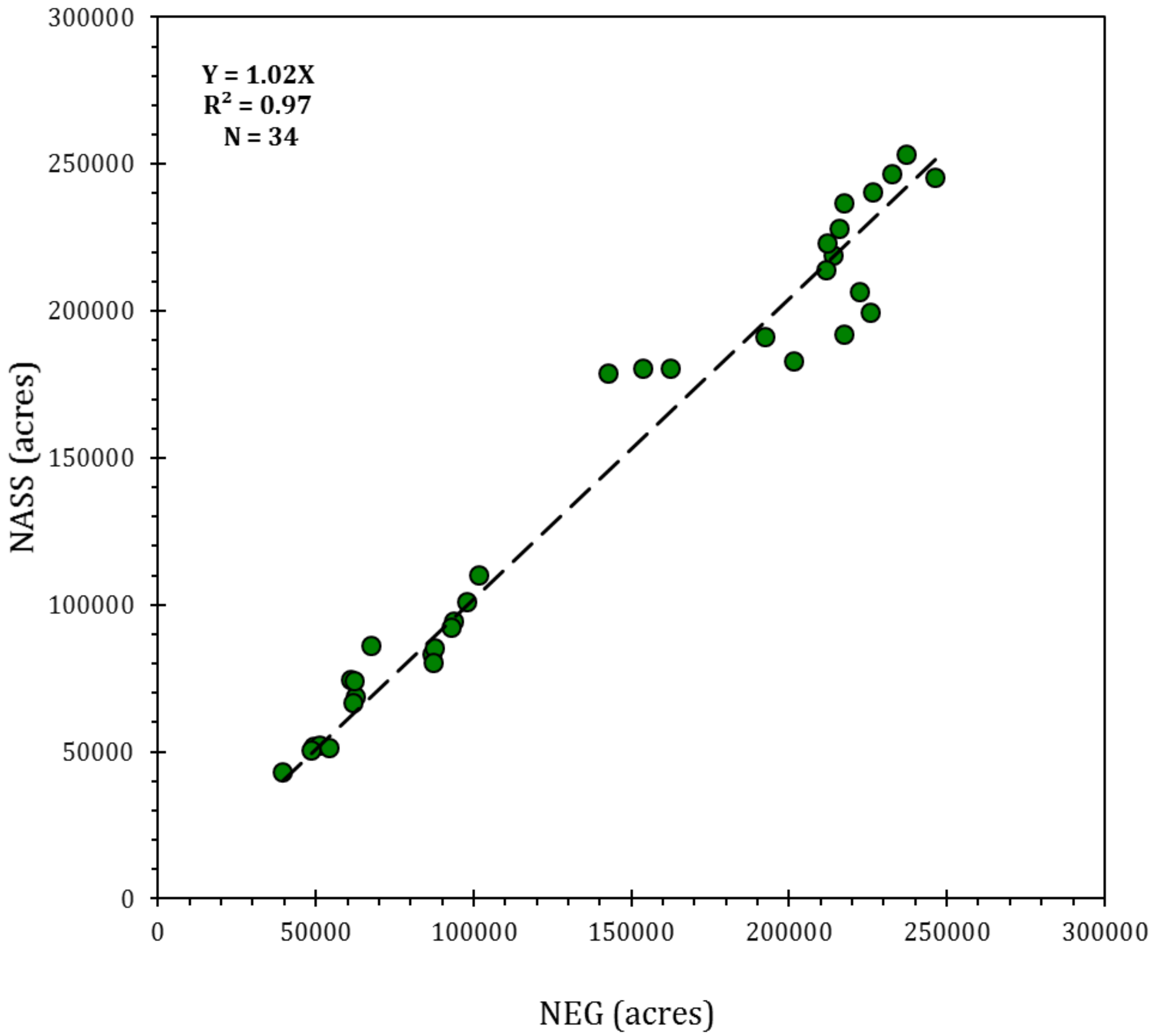


Figure 5: Regression between NASS and NEG county estimated irrigated area for All YEARS combined. N is the number of points, 10 from 2014, 12 from 2012 and 12 from 2009.

Spatial distribution of Irrigated fields

There are subtle differences in the spatial distribution of irrigated fields in South Central Nebraska during the growing seasons of 2014, 2012 and 2009 (Figure 6). However, based on NEG results (Table 2), 2014 irrigated area was 147,000 acres less than 2012, and 54,381 acres less than 2009. With the available NASS data, it is not possible to make a similar assessment, because of the missing irrigation data for Phelps and Gosper in 2014. Such gaps in critical data demonstrate the superiority of remote sensing methods such as NEG over survey methods to map, quantify and monitor irrigated areas at county, regional and state level. In Figure 6, the upper counties starting with Phelps to Fillmore combined with Thayer, appear the most densely irrigated in the study region. In 2014, Fillmore was the most irrigated county, although from the three-year average, Phelps was the most irrigated. During the three years, Furnas was the least irrigated in the study region.

The consistent overestimation of irrigated acreages by NEG relative to NASS in Nuckolls and Thayer was examined, revealing that NASS data may be underestimating. NASS irrigated acreages for the study counties were estimated mainly based on corn and soybean crops. However, the 2005 land use map of the study counties (Figure 7) reveals that small grains (e.g., oats, millet, rye and barley), sorghum, and alfalfa also dominate much of Nuckolls, with the exception of the North East. This crop spatial distribution across Nuckolls is most likely still prevailing with little variation, and many of these fields may be irrigated. In fact, by extracting crop specific irrigated acreages from CDL using 2014 NEG irrigation results (Figure 6), more than 5% of the 34000 acres of sorghum, alfalfa and winter wheat were irrigated. Similarly, Thayer has a signification distribution of these crops in addition to small grain, especially in the South East. Therefore, NEG estimates for Nuckolls and Thayer, in all likelihood, may be better estimates of county irrigated acreages, even for other counties. Besides, NEG irrigation classification scheme is less prone to producing incomplete data, in contrast, for instance, to the missing NASS data for Gosper and Phelps in 2014. In general, satellite-based remote sensing methods are susceptible to clouds nuisance and gap stripping particularly in Landsat 7.

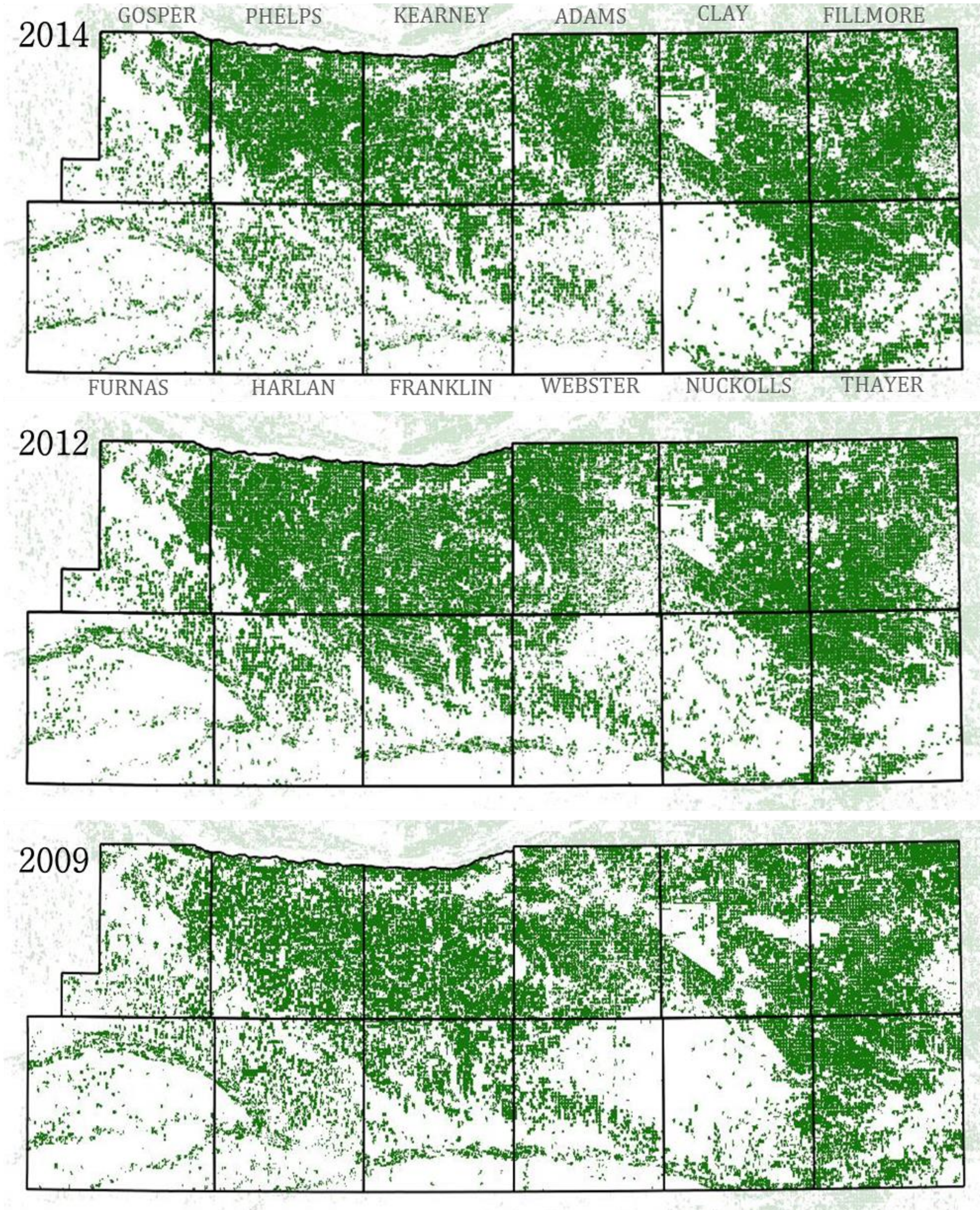
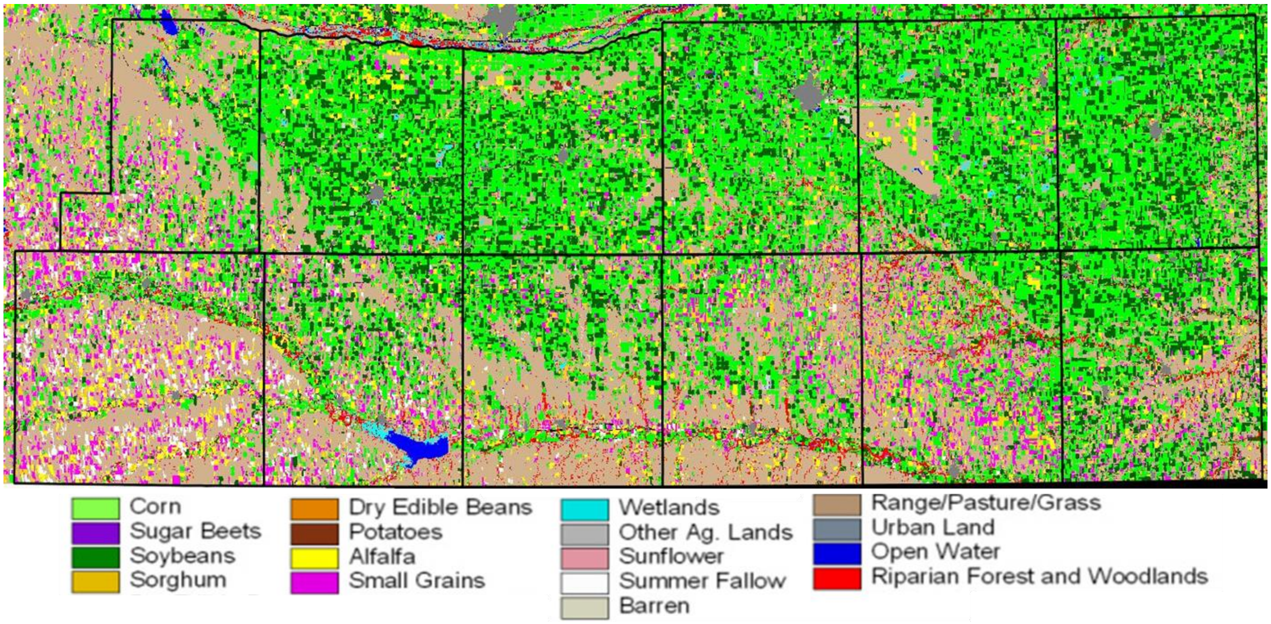


Figure 6: Spatial distribution of irrigated fields in the twelve study counties during the growing season of 2014, 2012 and 2014.



Landcover Legend

Figure 7: 2005 Land use map of the study counties (CALMIT, 2007).

Therefore, ancillary techniques for NEG irrigation classification scheme to fill missing data due to clouds and stripping are developed and presented below. With these ancillary techniques, NEG irrigation classification scheme generates a complete dataset of spatial distribution of irrigated areas in a region of interest. Thus, the scheme is capable of complete mapping, quantification, and monitoring of irrigated fields at the county, regional and state level.

Seasonal profile of NGI and EGI

The progression of NGI and EGI during the growing season shows that, during the initial stage of crop growth, the index values of irrigated and non-irrigated corn and soybean are closely similar (Figure 8A and B). In the study region, evapotranspiration during this growth stage is primarily soil evaporation (Allen et al., 1998), driven by soil moisture from the previous winter snow melt and spring rainfall. As crop development stage sets in and progresses, NGI and EGI of irrigated and non-irrigated crops start to diverge owing to soil moisture availability. Figure 8A shows that during the mid-season stage of crop growth, NGI was acutely sensitive to soil moisture availability for both corn and soybean. The peak NGI value for irrigated corn was about 7, while non-irrigated corn only got to a maximum of about 4. From Figure (8A) and the available data of NGI values starting from 1.6 and 1.2 for irrigated and non-irrigated corn, respectively, the NGI sensitivity coefficient between irrigated and non-irrigated corn was about 2. For soybean, the NGI sensitivity coefficient between irrigated and non-irrigated areas was even higher at 2.7.

In Figure 8B, EGI decreased during the crop development stage, and after the mid-season stage appears to increase during crop senescence in the late stage. EGI sensitivity coefficient between irrigated and non-irrigated was less than NGI at about 1.0 for both crops. Likewise, EGI had a higher contrast between irrigated and non-irrigated soybean than corn during the mid-season stage. Both indices generated the maximum contrast between irrigated and non-irrigated conditions during the mid-season of crop growth. Therefore, for optimal classification, NEG irrigation classification scheme should in principle be implemented on satellite imagery acquired during the mid-season of crop growth stage which normally lasts between mid-July and mid-August.

Many studies (Zhu et al., 2014; Pervez and Brown, 2010; Ozdogan et al., 2006) have used a single index to classify irrigated areas with good success. However, these methods are likely to be more susceptible to misclassification due to index saturation and variation in crop development as a result of crop management practices such as planting dates. A single index based method is also more likely to misclassify irrigated/non-irrigated areas due to the index being more sensitive to one crop than another. The fusion of two indices as presented here increases the classification efficiency by adding another filtering layer which re-characterizes misclassified areas. For instance, if non-irrigated corn in Figure 8A was a single pixel (each data point in the Figure is an average of nine sampled contiguous pixels forming a square), the NGI threshold of 3 would have misclassified it as irrigated, however the EGI filter with a threshold of 0.22 would have correctly characterized it as non-irrigated.

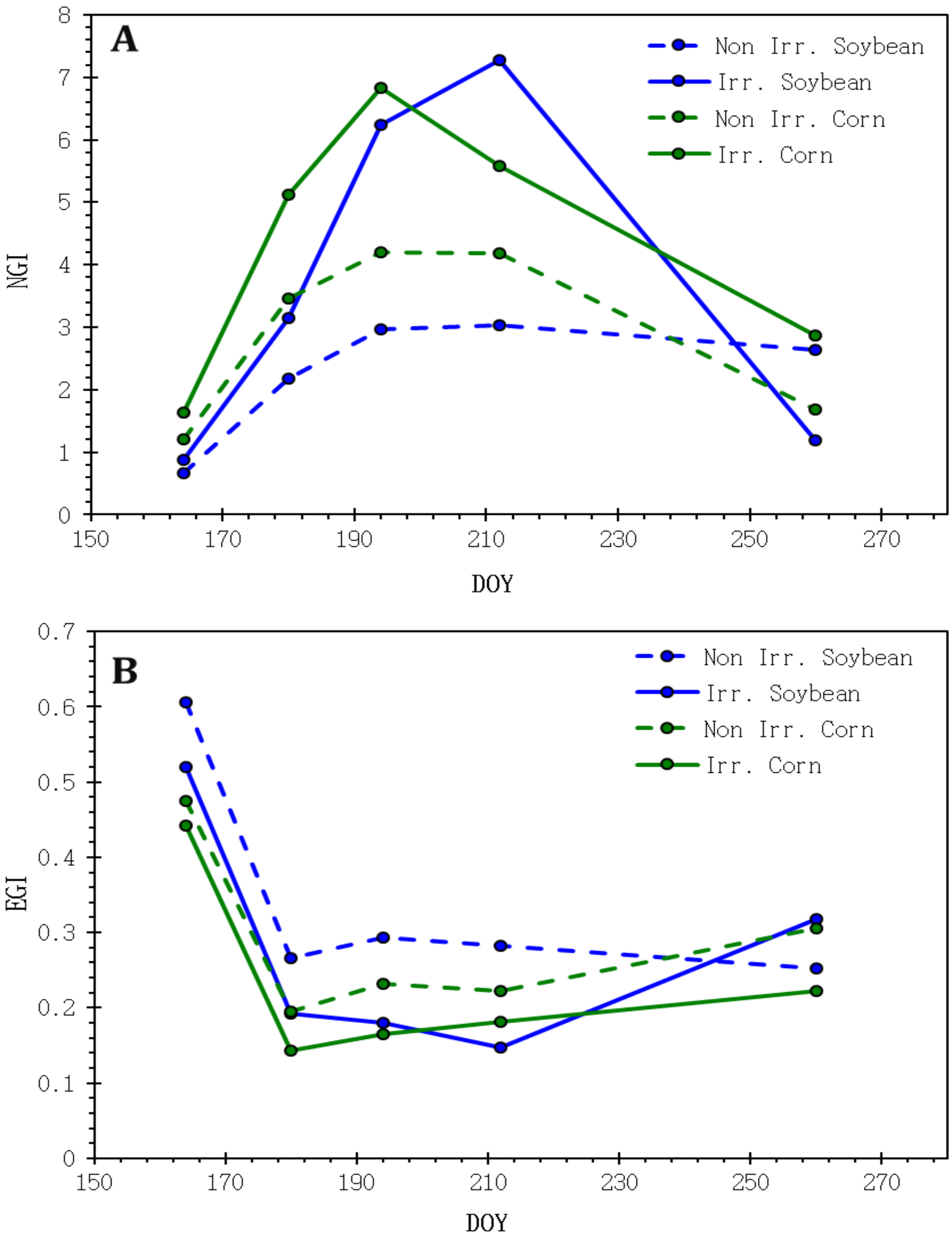


Figure 8: Seasonal profile of NGI (A) and EGI (B) for irrigated and non-irrigated soybean and corn during the 2014 growing season. Each data point in the figures is an average of nine contiguous pixels forming a square. DOY denotes Day of Year.

Clouds and Stripping

Clouds are the most intermittent and natural menace of airborne and spaceborne remote sensing. Over the years, research has strived to develop methods to gap-fill cloud contamination in remote sensed data. Many of these reconstruct methods are based on time series interpolation, for instance, volumetric spline interpolation (Neteler, 2010), asymmetric Gaussian function fitting (Jönsson and Eklundh, 2004) and Iterative Interpolation for Data Reconstruction (IDR) (Julien and Sobrino, 2010), while others (Menenti et al., 1993; Roerink et al., 2000; Verhoef et al., 1996) have used harmonic analysis which is a frequency domain Fourier transformation method.

Because this study is a binary (irrigated or non-irrigated) classification scheme, the devised gap-filling method is a non-arithmetic procedure that takes advantage of images acquired in the immediate timeframe to fill cloud contaminated areas in the affected *base* image. In this method, the cloud affected area is isolated from the base scene, and replaced (by mosaicking) with a NEG processed scene from an image with a clear sky over the area. In Figure 9A, a cloud contaminated area in a July 31, 2014 base scene was gap-filled (Figure 9B) with a NEG processed scene from a July 15, 2014 image which had a clear sky over the area. This method is effective, because during the optimal classification window (mid-July to mid-August) NGI and EGI are at the highest phase of spectral contrast between irrigated and non-irrigated conditions. About 2-3 Landsat scenes over an area are usually available during this timeframe. In case a cloud free image over the affected area is not available, the optimal window is better extended to mid-September than before mid-July.

A scan Line Corrector (SLC) failed in 2003 causing gap-strips of missing data in Landsat 7 ETM+ bands. NEG classification results from Landsat 7 scenes were affected by these strips as shown in the base scene of July 17, 2012 (Figure 10A). Fortunately, the stripping in the different scenes in a time series over an area are offset, and significantly in most cases. Therefore, strips in a base scene can be gap-filled with information extracted from another an immediate scene in time. For this reason, the strips in the base scene of July 17, 2012 (Figure 10A) were gap-filled with results from NEG irrigation classification scheme on an Aug 02, 2012 scene (Figure 10B). Similarly, in case a cloud free image is not available, the optimal window is better extended to mid-September than before mid-July.

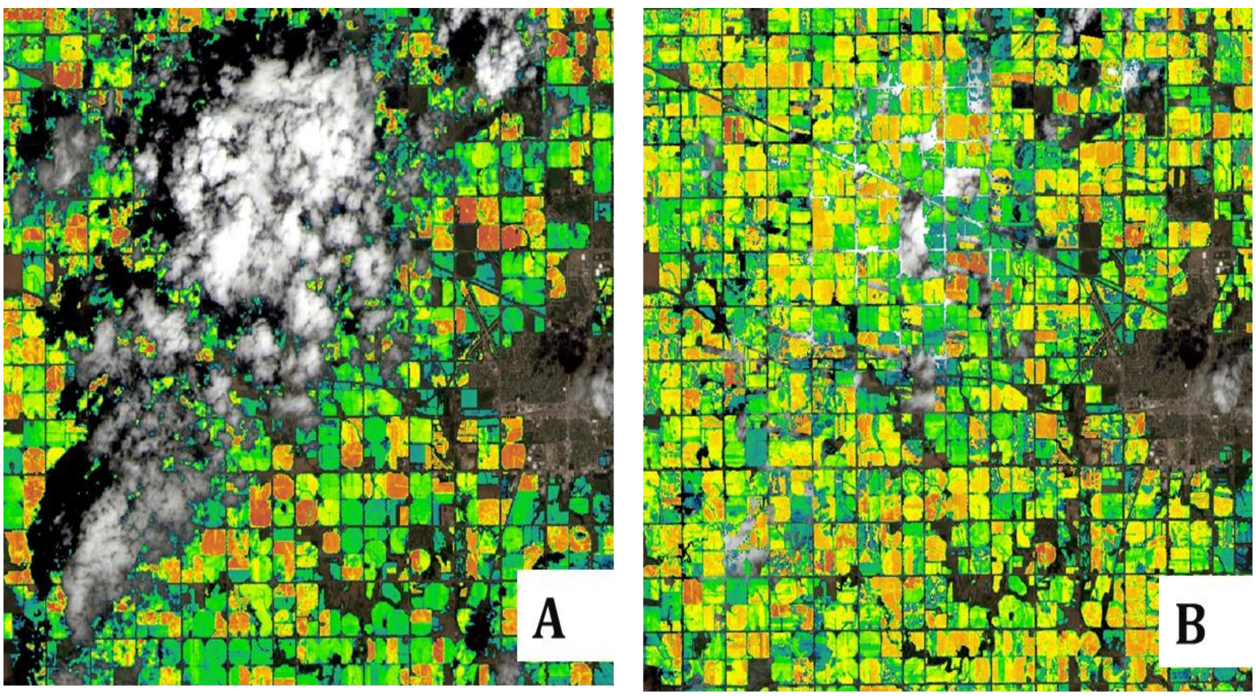


Figure 9: Image pair showing gap-filling results. Original results showing cloud contamination in the base scene of July 31, 2014 (A), and (B) original scene gap-filled using results July 15, 2014. The image backgrounds show the true color band combination of the scene.

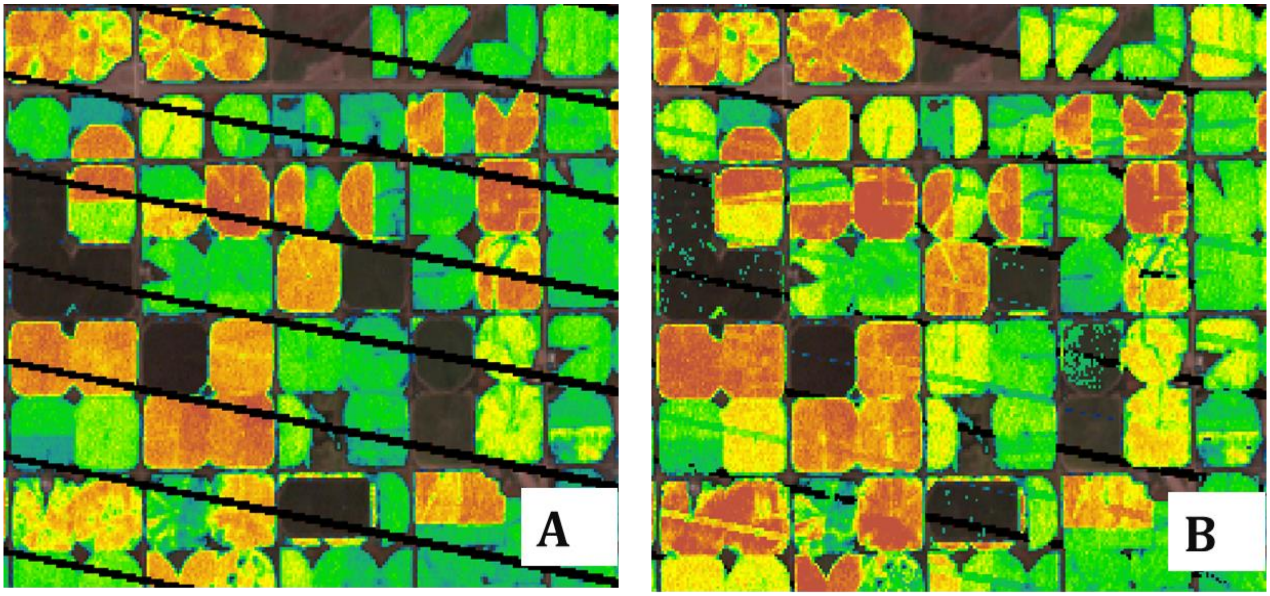


Figure 10: Image pair showing de-stripping results. Original results showing gap-strips in the base scene of July 17, 2012 (A), and (B) original scene de-stripped using results Aug 02, 2012 scene. The image backgrounds show the true color band combination of the scene.

CONCLUSION

This study introduces a new irrigation classification procedure derived from surface energy balance modeling and vegetation indices. The new NEG irrigation classification scheme is a systematic integration of two new indices, NGI and EGI, that highly contrast the spectral signature of irrigated and non-irrigated conditions. The fusion of two indices enhanced the classification efficiency by adding another filtering layer which re-characterizes misclassified areas. The scheme was implemented in three wetness scenarios (dry, normal and wet growing seasons), and over twelve counties of South Central Nebraska. The results revealed that NEG classification explained 97% variation in NASS county irrigation data. The overall mean absolute percentage error between NEG and NASS irrigated acreages during the three wetness scenarios was 8.27%. These results demonstrate that NEG irrigation classification scheme is an effective and consistent approach to estimate irrigated acreages during dry, normal and wet growing seasons. With ancillary techniques to gap-fill missing data due to clouds and stripping in Landsat data, NEG irrigation classification scheme is skilled to map, quantify and monitor irrigated lands from field- to regional-scale. For optimal results, the scheme should in principle be implemented on satellite imagery acquired during the mid-season of crop growth stage.

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APPENDIX

Supplementary crop specific irrigation data

This appendix is a supplementary to the *irrigation classification method development* project. Presented here are pilot results on the utilization of NEG irrigation classification and mapping results to determine crop specific irrigation acreages in a county. Tables (A4, A5 and A6) present the total acreages (irrigated and non-irrigated) for a specific crop, the irrigated acreages for that crop, and the percentage of that crop that is irrigated in each of the twelve counties and three-year wetness scenarios considered in this study. Fourteen crops were selected as the most commonly grown in the region and they include corn, soybean, sorghum, potatoes, sugar beet, dry bean, alfalfa, sweet- and pop-corn, winter wheat, millet, rye, oats, barley, and 'other small grain'.

The *total* acreages for each crop in a county and specific year were obtained from the annual Cropland Data Layer (CLD) dataset. The *irrigated* acreages for each crop in a county were then extracted from the respective crop total acreages using the irrigated spatial data (Figure 6) generated by NEG irrigation classification scheme. The irrigated percentage of each crop was computed as;

$$\%\,AGE = \frac{IRRIGATED}{TOTAL} * 100$$

The results show that corn, soy bean, sorghum, and alfalfa are the most irrigated crops in the twelve counties. The total irrigated area of these four crops accounted for between 90 – 99% of overall irrigated area in these counties. Alfalfa results should be used with caution, because the cuttings during the growing season may cause irrigation misclassification, especially if the Landsat overpass happens within a few days after the cutting.

Recommendation

The statistics in Tables (A4, A5, & A6) demonstrate the importance and advanced utilization of NEG irrigation classification results. The mapping of irrigated acreages at fine spatial resolution enables estimation of *crop specific irrigated acreages*, a key variable in accurately predicting seasonal water requirements for a county or region. This is critical and empowering information for water resources managers allocating and distributing water to irrigation districts, counties and regions. Therefore, it is recommended that after the project phase of implementing NEG irrigation classification scheme to determine and map county irrigated areas across the state, the next phase would be to break down the county data to crop specific irrigated acreages.

Table A4: 2014 total acreages (TOTAL), irrigated acreages (IRRIGATED), and percentage of the crop that is irrigated (% AGE) for the 14 crops in each of the twelve counties considered in this study. TOTAL IRRIGATED* is the total irrigated area in the county including other crops on top of the 14 crop listed in the table.

FILLMORE COUNTY **2014**

CROP	TOTAL (ACRES)	IRRIGATED (ACRES)	% AGE
CORN	185837.51	137058.84	73.75
SOYBEAN	115610.00	101681.66	87.95
SORGHUM	933.17	560.21	60.03
POTATOE	0.22	0.00	0.00
SUGAR BEET	0.00	0.00	NA
DRY BEAN	0.00	0.00	NA
ALFALFA	3864.10	645.39	16.70
SWEET & POP CORN	12.01	8.45	70.37
WINTER WHEAT	1941.95	76.95	3.96
MILLET	2.45	0.67	27.27
RYE	2.89	1.11	38.46
OATS	59.38	9.79	16.48
BARLEY	0.00	0.00	NA
OTHER SMALL GRAIN	0.00	0.00	NA
*TOTAL IRRIGATED**		*246762.3*	

CLAY COUNTY **2014**

CROP	TOTAL (ACRES)	IRRIGATED (ACRES)	% AGE
CORN	177265.99	132062.97	74.50
SOYBEAN	87556.05	81102.38	92.63
SORGHUM	327.36	172.58	52.72
POTATOES	0.22	0.00	0.00
SUGAR BEET	0.00	0.00	NA
DRY BEAN	0.00	0.00	NA
ALFALFA	5857.65	2090.06	35.68
SWEET & POP CORN	111.42	26.24	23.55
WINTER WHEAT	3755.80	142.78	3.80
MILLET	32.02	3.34	10.42
RYE	1.56	0.00	0.00
OATS	109.86	15.35	13.97
BARLEY	0.00	0.00	NA
OTHER SMALL GRAIN	0.00	0.00	NA
*TOTAL IRRIGATED**		*219221.8*	

ADAMS COUNTY **2014**

CROP	TOTAL (ACRES)	IRRIGATED (ACRES)	% AGE
CORN	177878.24	140757.93	79.13
SOYBEAN	90974.70	56631.65	62.25
SORGHUM	637.16	244.86	38.43
POTATOE	1.11	0.44	40.00
SUGAR BEET	0.00	0.00	NA
DRY BEAN	0.00	0.00	NA
ALFALFA	3205.15	1310.35	40.88
SWEET & POP CORN	866.67	545.76	62.97
WINTER WHEAT	4356.93	219.50	5.04
MILLET	3.56	0.44	12.50
RYE	59.16	11.56	19.55
OATS	97.63	10.90	11.16
BARLEY	0.00	0.00	NA
OTHER SMALL GRAIN	0.00	0.00	NA
*TOTAL IRRIGATED**		*206452.8*	

KEARNEY COUNTY **2014**

CROP	TOTAL (ACRES)	IRRIGATED (ACRES)	% AGE
CORN	158159.63	135268.79	85.53
SOYBEAN	94054.19	51741.41	55.01
SORGHUM	548.87	317.58	57.86
POTATOE	777.49	749.47	96.40
SUGAR BEET	0.00	0.00	NA
DRY BEAN	0.00	0.00	NA
ALFALFA	3785.82	2455.68	64.87
SWEET & POP CORN	121.87	97.63	80.11
WINTER WHEAT	7421.30	385.19	5.19
MILLET	3.56	1.11	31.25
RYE	28.91	7.12	24.62
OATS	48.48	11.56	23.85
BARLEY	0.00	0.00	NA
OTHER SMALL GRAIN	0.00	0.00	NA
*TOTAL IRRIGATED**		*191280.2*	

PHELPS COUNTY **2014**

CROP	TOTAL (ACRES)	IRRIGATED (ACRES)	% AGE
CORN	162422.71	132992.80	81.88
SOYBEAN	100235.20	90453.85	90.24
SORGHUM	1249.63	711.00	56.90
POTATOES	195.04	195.04	100.00
SUGAR BEET	0.00	0.00	NA
DRY BEAN	0.00	0.00	NA
ALFALFA	3777.37	2872.22	76.04
SWEET & POP CORN	0.00	0.00	NA
WINTER WHEAT	3770.03	1117.98	29.65
MILLET	0.00	0.00	NA
RYE	2.22	0.89	40.00
OATS	199.49	18.46	9.25
BARLEY	0.00	0.00	NA
OTHER SMALL GRAIN	0.00	0.00	NA
*TOTAL IRRIGATED**		*232239.9*	

GOSPER COUNTY **2014**

CROP	TOTAL (ACRES)	IRRIGATED (ACRES)	% AGE
CORN	76615.79	41183.68	53.75
SOYBEAN	32335.05	25836.68	79.90
SORGHUM	3418.20	664.96	19.45
POTATOE	0.00	0.00	NA
SUGAR BEET	0.00	0.00	NA
DRY BEAN	0.00	0.00	NA
ALFALFA	1527.41	1066.83	69.85
SWEET & POP CORN	0.00	0.00	NA
WINTER WHEAT	16950.69	232.85	1.37
MILLET	0.00	0.00	NA
RYE	0.00	0.00	NA
OATS	597.13	34.03	5.70
BARLEY	1.11	0.00	0.00
OTHER SMALL GRAIN	0.00	0.00	NA
*TOTAL IRRIGATED**		*79196.6*	

THAYER COUNTY **2014**

CROP	TOTAL (ACRES)	IRRIGATED (ACRES)	% AGE
CORN	145279.21	104971.76	72.26
SOYBEAN	88666.69	73049.25	82.39
SORGHUM	1736.46	744.80	42.89
POTATOE	2.67	0.00	0.00
SUGAR BEET	0.00	0.00	NA
DRY BEAN	0.00	0.00	NA
ALFALFA	4506.16	881.57	19.56
SWEET & POP CORN	8.67	2.67	30.77
WINTER WHEAT	14987.83	271.54	1.81
MILLET	4.67	0.22	4.76
RYE	38.03	1.11	2.92
OATS	105.41	10.67	10.13
BARLEY	0.00	0.00	NA
OTHER SMALL GRAIN	0.00	0.00	NA
*TOTAL IRRIGATED**		*180392.9*	

NUCKOLLS COUNTY **2014**

CROP	TOTAL (ACRES)	IRRIGATED (ACRES)	% AGE
CORN	114515.15	43699.63	38.16
SOYBEAN	63618.62	31259.33	49.14
SORGHUM	2929.38	288.22	9.84
POTATOE	0.22	0.00	0.00
SUGAR BEET	0.00	0.00	NA
DRY BEAN	0.00	0.00	NA
ALFALFA	5426.87	886.02	16.33
SWEET & POP CORN	8.67	2.89	33.33
WINTER WHEAT	25413.02	112.09	0.44
MILLET	2.22	0.00	0.00
RYE	1.78	0.00	0.00
OATS	273.99	6.23	2.27
BARLEY	0.00	0.00	NA
OTHER SMALL GRAIN	0.00	0.00	NA
*TOTAL IRRIGATED**		*74725.22*	

WEBSTER COUNTY **2014**

CROP	TOTAL (ACRES)	IRRIGATED (ACRES)	% AGE
CORN	79844.74	22921.76	28.71
SOYBEAN	55714.71	23001.60	41.28
SORGHUM	2961.85	698.10	23.57
POTATOE	0.67	0.00	0.00
SUGAR BEET	0.00	0.00	NA
DRY BEAN	0.00	0.00	NA
ALFALFA	6746.56	2441.45	36.19
SWEET & POP CORN	185.25	41.81	22.57
WINTER WHEAT	26051.74	1317.47	5.06
MILLET	0.22	0.22	100.00
RYE	413.65	141.67	34.25
OATS	414.32	69.16	16.69
BARLEY	0.00	0.00	NA
OTHER SMALL GRAIN	0.00	0.00	NA
*TOTAL IRRIGATED**		*52499.34*	

FRANKLIN COUNTY			2014
CROP	**TOTAL (ACRES)**	**IRRIGATED (ACRES)**	**% AGE**
CORN	81790.03	62341.85	76.22
SOYBEAN	58645.43	29175.71	49.75
SORGHUM	2648.94	911.15	34.40
POTATOE	8.90	3.11	35.00
SUGAR BEET	0.00	0.00	NA
DRY BEAN	0.00	0.00	NA
ALFALFA	4467.24	1670.41	37.39
SWEET & POP CORN	4.23	3.56	84.21
WINTER WHEAT	14476.33	417.66	2.89
MILLET	4.00	0.44	11.11
RYE	6.00	0.44	7.41
OATS	375.18	17.12	4.56
BARLEY	0.00	0.00	NA
OTHER SMALL GRAIN	0.00	0.00	NA
*TOTAL IRRIGATED**		*94689.35*	

HARLAN COUNTY			2014
CROP	**TOTAL (ACRES)**	**IRRIGATED (ACRES)**	**% AGE**
CORN	63974.92	32050.46	50.10
SOYBEAN	63974.92	16567.75	57.63
SORGHUM	7504.04	944.06	12.58
POTATOE	0.22	0.00	0.00
SUGAR BEET	0.00	0.00	NA
DRY BEAN	0.00	0.00	NA
ALFALFA	2040.91	1064.49	52.16
SWEET & POP CORN	0.00	0.00	NA
WINTER WHEAT	27595.35	941.55	3.41
MILLET	0.00	0.00	NA
RYE	0.00	0.00	NA
OATS	1282.77	86.51	6.74
BARLEY	0.00	0.00	NA
OTHER SMALL GRAIN	0.00	0.00	NA
*TOTAL IRRIGATED**		*52035.87*	

FURNAS COUNTY **2014**

CROP	TOTAL (ACRES)	IRRIGATED (ACRES)	% AGE
CORN	82068.02	16415.16	20.00
SOYBEAN	28798.98	14807.92	51.42
SORGHUM	14416.28	2515.28	17.45
POTATOE	0.67	0.67	100.00
SUGAR BEET	0.00	0.00	NA
DRY BEAN	0.22	0.22	100.00
ALFALFA	9588.09	6444.10	67.21
SWEET & POP CORN	0.22	0.22	100.00
WINTER WHEAT	64681.44	1934.83	2.99
MILLET	0.44	0.00	0.00
RYE	6.45	3.56	55.17
OATS	1474.70	93.18	6.32
BARLEY	2.67	0.44	16.67
OTHER SMALL GRAIN	0.00	0.00	NA
*TOTAL IRRIGATED**		*43389.83*	

Table A5: 2012 total acreages (TOTAL), irrigated acreages (IRRIGATED), and percentage of the crop that is irrigated (% AGE) for the 14 crops in each of the twelve counties considered in this study. *TOTAL IRRIGATED** is the total irrigated area in the county including other crops on top of the 14 crop listed in the table.

FILLMORE COUNTY **2012**

CROP	TOTAL (ACRES)	IRRIGATED (ACRES)	% AGE
CORN	202504.43	147790.04	72.98
SOYBEAN	103110.76	88776.77	86.10
SORGHUM	604.25	249.30	41.26
POTATOE	0.00	0.00	NA
SUGAR BEET	0.00	0.00	NA
DRY BEAN	0.00	0.00	NA
ALFALFA	2415.87	544.87	22.55
SWEET & POP CORN	2.89	2.00	69.23
WINTER WHEAT	1937.28	61.16	3.16
MILLET	0.00	0.00	NA
RYE	0.22	0.00	0.00
OATS	50.26	34.92	69.47
BARLEY	0.00	0.00	NA
OTHER SMALL GRAIN	0.00	0.00	NA
*TOTAL IRRIGATED**		*240420.2*	

CLAY COUNTY **2012**

CROP	TOTAL (ACRES)	IRRIGATED (ACRES)	% AGE
CORN	185354.47	138048.05	74.48
SOYBEAN	83135.51	77792.04	93.57
SORGHUM	801.95	551.76	68.80
POTATOE	0.67	0.22	33.33
SUGAR BEET	0.00	0.00	NA
DRY BEAN	0.00	0.00	NA
ALFALFA	5196.47	1991.32	38.32
SWEET & POP CORN	78.06	39.36	50.43
WINTER WHEAT	2218.83	172.80	7.79
MILLET	2.89	0.44	15.38
RYE	0.22	0.00	0.00
OATS	3.78	0.00	0.00
BARLEY	0.00	0.00	NA
OTHER SMALL GRAIN	0.00	0.00	NA
*TOTAL IRRIGATED**		*223073.7*	

ADAMS COUNTY **2012**

CROP	TOTAL (ACRES)	IRRIGATED (ACRES)	% AGE
CORN	188475.34	124868.95	66.25
SOYBEAN	83368.14	69994.44	83.96
SORGHUM	154.79	37.14	23.99
POTATOE	154.56	143.22	92.66
SUGAR BEET	0.00	0.00	NA
DRY BEAN	0.00	0.00	NA
ALFALFA	2913.59	995.88	34.18
SWEET & POP CORN	824.86	640.50	77.65
WINTER WHEAT	2752.80	63.16	2.29
MILLET	1.56	0.22	14.29
RYE	2.45	0.44	18.18
OATS	6.23	0.00	0.00
BARLEY	0.00	0.00	NA
OTHER SMALL GRAIN	0.00	0.00	NA
*TOTAL IRRIGATED**		*199703.3*	

KEARNEY COUNTY **2012**

CROP	TOTAL (ACRES)	IRRIGATED (ACRES)	% AGE
CORN	166077.76	138647.18	83.48
SOYBEAN	91351.88	85430.40	93.52
SORGHUM	78.28	30.69	39.20
POTATOE	831.76	709.88	85.35
SUGAR BEET	0.00	0.00	NA
DRY BEAN	0.22	0.00	0.00
ALFALFA	2786.38	1548.31	55.57
SWEET & POP CORN	79.62	53.37	67.04
WINTER WHEAT	5029.90	368.73	7.33
MILLET	0.44	0.22	50.00
RYE	45.15	25.35	56.16
OATS	18.46	0.00	0.00
BARLEY	0.00	0.00	NA
OTHER SMALL GRAIN	0.00	0.00	NA
*TOTAL IRRIGATED**		*228001.1*	

PHELPS COUNTY **2012**

CROP	TOTAL (ACRES)	IRRIGATED (ACRES)	% AGE
CORN	179355.60	154884.43	86.36
SOYBEAN	89488.43	85601.87	95.66
SORGHUM	197.49	104.75	53.04
POTATOE	496.83	324.03	65.22
SUGAR BEET	0.00	0.00	NA
DRY BEAN	0.22	0.00	0.00
ALFALFA	3512.94	2015.56	57.38
SWEET & POP CORN	0.22	0.22	100.00
WINTER WHEAT	2177.46	569.77	26.17
MILLET	8.01	4.00	50.00
RYE	0.00	0.00	NA
OATS	5.12	0.22	4.35
BARLEY	0.00	0.00	NA
OTHER SMALL GRAIN	0.00	0.00	NA
*TOTAL IRRIGATED**		*245411.2*	

GOSPER COUNTY **2012**

CROP	TOTAL (ACRES)	IRRIGATED (ACRES)	% AGE
CORN	88438.06	56179.52	63.52
SOYBEAN	32565.23	26121.35	80.21
SORGHUM	731.46	159.90	21.86
POTATOE	3.11	3.11	100.00
SUGAR BEET	0.00	0.00	NA
DRY BEAN	0.00	0.00	NA
ALFALFA	1682.41	764.59	45.45
SWEET & POP CORN	1.78	1.78	100.00
WINTER WHEAT	10408.51	122.98	1.18
MILLET	0.89	0.67	75.00
RYE	1.78	0.00	0.00
OATS	259.76	2.22	0.86
BARLEY	0.00	0.00	NA
OTHER SMALL GRAIN	0.00	0.00	NA
*TOTAL IRRIGATED**		*83523.59*	

THAYER COUNTY **2012**

CROP	TOTAL (ACRES)	IRRIGATED (ACRES)	% AGE
CORN	148208.81	94233.00	63.58
SOYBEAN	85065.90	57984.70	68.16
SORGHUM	1206.27	473.70	39.27
POTATOE	0.67	0.00	0.00
SUGAR BEET	0.00	0.00	NA
DRY BEAN	0.00	0.00	NA
ALFALFA	2759.92	466.81	16.91
SWEET & POP CORN	20.02	14.46	72.22
WINTER WHEAT	15310.75	300.01	1.96
MILLET	1.11	0.44	40.00
RYE	1.56	1.56	100.00
OATS	21.57	0.22	1.03
BARLEY	0.00	0.00	NA
OTHER SMALL GRAIN	0.00	0.00	NA
*TOTAL IRRIGATED**		*180392.9*	

NUCKOLLS COUNTY **2012**

CROP	TOTAL (ACRES)	IRRIGATED (ACRES)	% AGE
CORN	119388.71	50234.69	42.08
SOYBEAN	59634.64	35043.81	58.76
SORGHUM	3547.86	845.32	23.83
POTATOE	2.00	0.00	0.00
SUGAR BEET	0.00	0.00	NA
DRY BEAN	0.00	0.00	NA
ALFALFA	3727.11	321.14	8.62
SWEET & POP CORN	0.22	0.00	0.00
WINTER WHEAT	26228.76	375.40	1.43
MILLET	13.12	0.00	0.00
RYE	0.00	0.00	NA
OATS	6.00	0.00	0.00
BARLEY	0.00	0.00	NA
OTHER SMALL GRAIN	0.00	0.00	NA
*TOTAL IRRIGATED**		*86034.42*	

WEBSTER COUNTY **2012**

CROP	TOTAL (ACRES)	IRRIGATED (ACRES)	% AGE
CORN	89740.63	38048.81	42.40
SOYBEAN	52254.48	30465.38	58.30
SORGHUM	1612.80	353.83	21.94
POTATOE	3.11	0.67	21.43
SUGAR BEET	0.00	0.00	NA
DRY BEAN	0.00	0.00	NA
ALFALFA	5237.17	747.25	14.27
SWEET & POP CORN	0.67	0.00	0.00
WINTER WHEAT	21268.92	320.47	1.51
MILLET	6.00	1.33	22.22
RYE	15.12	0.44	2.94
OATS	26.24	1.78	6.78
BARLEY	0.00	0.00	NA
OTHER SMALL GRAIN	0.00	0.00	NA
*TOTAL IRRIGATED**		*69067.2*	

FRANKLIN COUNTY **2012**

CROP	TOTAL (ACRES)	IRRIGATED (ACRES)	% AGE
CORN	91615.19	61623.74	67.26
SOYBEAN	55978.25	45996.96	82.17
SORGHUM	627.37	157.23	25.06
POTATOE	5.34	3.78	70.83
SUGAR BEET	0.00	0.00	NA
DRY BEAN	0.00	0.00	NA
ALFALFA	4163.45	1212.27	29.12
SWEET & POP CORN	4.00	3.78	94.44
WINTER WHEAT	9601.22	419.21	4.37
MILLET	10.90	5.56	51.02
RYE	5.34	1.56	29.17
OATS	25.13	0.00	0.00
BARLEY	0.00	0.00	NA
OTHER SMALL GRAIN	0.00	0.00	NA
*TOTAL IRRIGATED**		*110192.9*	

HARLAN COUNTY **2012**

CROP	TOTAL (ACRES)	IRRIGATED (ACRES)	% AGE
CORN	85931.68	46416.62	54.02
SOYBEAN	45235.71	27457.27	60.70
SORGHUM	7504.04	1421.55	18.94
POTATOE	0.22	0.00	0.00
SUGAR BEET	0.00	0.00	NA
DRY BEAN	0.00	0.00	NA
ALFALFA	3958.18	2505.72	63.30
SWEET & POP CORN	0.00	0.00	NA
WINTER WHEAT	33457.03	1276.10	3.81
MILLET	0.00	0.00	NA
RYE	0.00	0.00	NA
OATS	1282.77	116.98	9.12
BARLEY	0.00	0.00	NA
OTHER SMALL GRAIN	0.00	0.00	NA
*TOTAL IRRIGATED**		*92546.36*	

FURNAS COUNTY **2012**

CROP	TOTAL (ACRES)	IRRIGATED (ACRES)	% AGE
CORN	82068.02	16415.16	20.00
SOYBEAN	28798.98	14807.92	51.42
SORGHUM	14416.28	2515.28	17.45
POTATOE	0.67	0.67	100.00
SUGAR BEET	0.00	0.00	NA
DRY BEAN	0.22	0.22	100.00
ALFALFA	9588.09	6444.10	67.21
SWEET & POP CORN	0.22	0.22	100.00
WINTER WHEAT	64681.44	1934.83	2.99
MILLET	0.44	0.00	0.00
RYE	6.45	3.56	55.17
OATS	1474.70	93.18	6.32
BARLEY	2.67	0.44	16.67
OTHER SMALL GRAIN	0.00	0.00	NA
*TOTAL IRRIGATED**		*51665.36*	

Table A6: 2009 total acreages (TOTAL), irrigated acreages (IRRIGATED), and percentage of the crop that is irrigated (% AGE) for the 14 crops in each of the twelve counties considered in this study. *TOTAL IRRIGATED** is the total irrigated area in the county including other crops on top of the 14 crop listed in the table.

FILLMORE COUNTY **2009**

CROP	TOTAL (ACRES)	IRRIGATED (ACRES)	% AGE
CORN	175711.00	141220.95	80.37
SOYBEAN	109544.86	87656.57	80.02
SORGHUM	1528.07	439.23	28.74
POTATOE	0.00	0.00	NA
SUGAR BEET	0.00	0.00	NA
DRY BEAN	0.00	0.00	NA
ALFALFA	2099.85	406.54	19.36
SWEET & POP CORN	9.12	0.22	2.44
WINTER WHEAT	2403.64	56.93	2.37
MILLET	2.00	0.22	11.11
RYE	0.00	0.00	NA
OATS	142.11	3.56	2.50
BARLEY	0.00	0.00	NA
OTHER SMALL GRAIN	0.00	0.00	NA
*TOTAL IRRIGATED**		*236786.8*	

CLAY COUNTY **2009**

CROP	TOTAL (ACRES)	IRRIGATED (ACRES)	% AGE
CORN	165669.00	115729.21	69.86
SOYBEAN	84272.39	62701.91	74.40
SORGHUM	339.37	62.27	18.35
POTATOE	12.01	2.67	22.22
SUGAR BEET	0.00	0.00	NA
DRY BEAN	0.00	0.00	NA
ALFALFA	4183.02	1042.14	24.91
SWEET & POP CORN	26.46	10.23	38.66
WINTER WHEAT	5197.80	52.93	1.02
MILLET	0.00	0.00	NA
RYE	3.34	0.00	0.00
OATS	39.81	3.56	8.94
BARLEY	0.00	0.00	NA
OTHER SMALL GRAIN	4.45	0.00	0.00
*TOTAL IRRIGATED**		*183123.4*	

ADAMS COUNTY **2009**

CROP	TOTAL (ACRES)	IRRIGATED (ACRES)	% AGE
CORN	172656.19	118356.35	68.55
SOYBEAN	80550.62	66942.30	83.11
SORGHUM	361.61	61.60	17.04
POTATOE	134.33	133.44	99.34
SUGAR BEET	0.00	0.00	NA
DRY BEAN	0.00	0.00	NA
ALFALFA	2274.43	471.92	20.75
SWEET & POP CORN	233.96	100.97	43.16
WINTER WHEAT	4947.83	81.84	1.65
MILLET	5.78	0.67	11.54
RYE	1.78	0.00	0.00
OATS	43.37	1.11	2.56
BARLEY	0.89	0.00	0.00
OTHER SMALL GRAIN	0.00	0.00	NA
*TOTAL IRRIGATED**		*192214.7*	

KEARNEY COUNTY **2009**

CROP	TOTAL (ACRES)	IRRIGATED (ACRES)	% AGE
CORN	160507.45	146043.58	90.99
SOYBEAN	82048.00	53641.33	65.38
SORGHUM	251.75	103.19	40.99
POTATOE	592.46	583.12	98.42
SUGAR BEET	0.00	0.00	NA
DRY BEAN	0.00	0.00	NA
ALFALFA	1972.86	1132.66	57.41
SWEET & POP CORN	10.45	10.45	100.00
WINTER WHEAT	6209.70	224.40	3.61
MILLET	16.01	9.79	61.11
RYE	2.22	0.89	40.00
OATS	116.98	16.23	13.88
BARLEY	0.00	0.00	NA
OTHER SMALL GRAIN	0.00	0.00	NA
*TOTAL IRRIGATED**		*214129.4*	

PHELPS COUNTY **2009**

CROP	TOTAL (ACRES)	IRRIGATED (ACRES)	% AGE
CORN	171503.52	161162.84	93.97
SOYBEAN	83392.16	30569.90	36.66
SORGHUM	440.79	144.33	32.74
POTATOE	0.00	0.00	NA
SUGAR BEET	0.00	0.00	NA
DRY BEAN	0.00	0.00	NA
ALFALFA	3721.10	1834.09	49.29
SWEET & POP CORN	0.44	0.00	0.00
WINTER WHEAT	2557.09	61.16	2.39
MILLET	2.67	2.45	91.67
RYE	0.44	0.00	0.00
OATS	20.68	7.34	35.48
BARLEY	0.00	0.00	NA
OTHER SMALL GRAIN	0.00	0.00	NA
*TOTAL IRRIGATED**		*253480.4*	

GOSPER COUNTY **2009**

CROP	TOTAL (ACRES)	IRRIGATED (ACRES)	% AGE
CORN	77202.69	59835.46	77.50
SOYBEAN	29055.17	4346.03	14.96
SORGHUM	1555.87	113.20	7.28
POTATOE	0.00	0.00	NA
SUGAR BEET	0.00	0.00	NA
DRY BEAN	0.00	0.00	NA
ALFALFA	1270.76	779.27	61.32
SWEET & POP CORN	0.00	0.00	NA
WINTER WHEAT	10707.85	74.50	0.70
MILLET	0.00	0.00	NA
RYE	0.00	0.00	NA
OATS	187.70	2.00	1.07
BARLEY	0.00	0.00	NA
OTHER SMALL GRAIN	0.00	0.00	NA
*TOTAL IRRIGATED**		*80568.41*	

THAYER COUNTY **2009**

CROP	TOTAL (ACRES)	IRRIGATED (ACRES)	% AGE
CORN	125088.23	100183.38	80.09
SOYBEAN	82767.00	67777.17	81.89
SORGHUM	3170.90	1621.26	51.13
POTATOE	0.89	0.89	100.00
SUGAR BEET	0.00	0.00	NA
DRY BEAN	0.00	0.00	NA
ALFALFA	2947.62	704.32	23.89
SWEET & POP CORN	1.78	0.00	0.00
WINTER WHEAT	15951.69	387.63	2.43
MILLET	27.13	0.89	3.28
RYE	1.78	1.33	75.00
OATS	47.81	2.67	5.58
BARLEY	0.00	0.00	NA
OTHER SMALL GRAIN	0.44	0.00	0.00
*TOTAL IRRIGATED**		*178798.5*	

NUCKOLLS COUNTY **2009**

CROP	TOTAL (ACRES)	IRRIGATED (ACRES)	% AGE
CORN	95239.33	40948.16	43.00
SOYBEAN	55770.76	30626.17	54.91
SORGHUM	3554.53	351.16	9.88
POTATOE	8.45	0.00	0.00
SUGAR BEET	0.00	0.00	NA
DRY BEAN	0.00	0.00	NA
ALFALFA	4112.52	580.67	14.12
SWEET & POP CORN	3.78	0.00	0.00
WINTER WHEAT	31252.65	206.83	0.66
MILLET	0.00	0.00	NA
RYE	4.89	0.00	0.00
OATS	32.02	1.11	3.47
BARLEY	0.00	0.00	NA
OTHER SMALL GRAIN	7.12	0.00	0.00
*TOTAL IRRIGATED**		*74269.53*	

WEBSTER COUNTY **2009**

CROP	TOTAL (ACRES)	IRRIGATED (ACRES)	% AGE
CORN	71624.37	35618.26	49.73
SOYBEAN	48459.32	27099.44	55.92
SORGHUM	1833.64	171.24	9.34
POTATOE	0.00	0.00	NA
SUGAR BEET	0.00	0.00	NA
DRY BEAN	0.00	0.00	NA
ALFALFA	4831.52	1311.46	27.14
SWEET & POP CORN	48.48	38.70	79.82
WINTER WHEAT	22105.79	84.07	0.38
MILLET	10.23	0.44	4.35
RYE	1.33	0.00	0.00
OATS	79.17	2.22	2.81
BARLEY	0.89	0.00	0.00
OTHER SMALL GRAIN	5.12	0.00	0.00
*TOTAL IRRIGATED**		*66957.87*	

FRANKLIN COUNTY **2009**

CROP	TOTAL (ACRES)	IRRIGATED (ACRES)	% AGE
CORN	77980.63	68477.05	87.81
SOYBEAN	53145.17	26541.00	49.94
SORGHUM	1923.49	381.41	19.83
POTATOE	3.56	2.67	75.00
SUGAR BEET	0.00	0.00	NA
DRY BEAN	0.00	0.00	NA
ALFALFA	3081.05	1093.51	35.49
SWEET & POP CORN	58.93	58.93	100.00
WINTER WHEAT	12443.64	180.14	1.45
MILLET	74.28	18.68	25.15
RYE	3.56	0.00	0.00
OATS	123.65	3.78	3.06
BARLEY	0.00	0.00	NA
OTHER SMALL GRAIN	27.35	0.00	0.00
*TOTAL IRRIGATED**		*101078.3*	

HARLAN COUNTY **2009**

CROP	TOTAL (ACRES)	IRRIGATED (ACRES)	% AGE
CORN	82829.05	64423.02	77.78
SOYBEAN	40190.02	6892.01	17.15
SORGHUM	2881.79	223.51	7.76
POTATOE	0.00	0.00	NA
SUGAR BEET	0.00	0.00	NA
DRY BEAN	0.00	0.00	NA
ALFALFA	2944.50	721.67	24.51
SWEET & POP CORN	0.00	0.00	NA
WINTER WHEAT	23897.62	207.05	0.87
MILLET	8.01	0.89	11.11
RYE	0.00	0.00	NA
OATS	487.04	5.56	1.14
BARLEY	0.00	0.00	NA
OTHER SMALL GRAIN	0.00	0.00	NA
*TOTAL IRRIGATED**		*85451.97*	

FURNAS COUNTY **2009**

CROP	TOTAL (ACRES)	IRRIGATED (ACRES)	% AGE
CORN	80797.48	35059.16	43.39
SOYBEAN	20159.62	3363.05	16.68
SORGHUM	11127.51	748.58	6.73
POTATOE	0.00	0.00	NA
SUGAR BEET	0.00	0.00	NA
DRY BEAN	0.00	0.00	NA
ALFALFA	9647.47	4067.82	42.16
SWEET & POP CORN	0.00	0.00	NA
WINTER WHEAT	50270.50	228.40	0.45
MILLET	0.00	0.00	NA
RYE	0.89	0.89	100.00
OATS	167.91	0.00	0.00
BARLEY	0.00	0.00	NA
OTHER SMALL GRAIN	0.44	0.00	0.00
*TOTAL IRRIGATED**		*50553.61*	