

PROGRESS REPORT:

Project Title: Remote Sensing-Based Energy Balance for Mapping Riparian Evapotranspiration
Along North Platte River Basin, Nebraska

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INTRODUCTION

Previous studies across the High Plains and the Arid West have produced widely varying impacts of riparian evapotranspiration (ET) on surface and ground water. Many producers as well as various state agencies have advocated removing all trees along the river basins as a method of riparian control for water reclamation. Although eradication of trees might be effective method for water reclamation in the short-term, it has not been yet proven whether such water savings are possible on a stream level. Mean water use of riparian trees has been reported in relatively few studies, and most of the previous studies have been of short duration. Currently, there is uncertainty in the water use of riparian systems due to the narrow and sparse vegetation commonly associated with them. Our primary goal is spatiotemporal estimation of ET using satellite-and aerial derived spectral radiances in conjunction with a land surface energy balance model and flux measurements to evaluate water use and water distribution within and between riparian systems along North Platte River Basin (NPRB) in Nebraska (NE). Specific objectives of the proposal are:

1. Quantify daily and seasonal distributions of ET over riparian systems in the NPRB. The major outcome of this work would be quantitative surface energy balance flux components for riparian systems.
2. Comparison of water use among riparian species by utilizing ETmaps with riparian species distribution map. The riparian species map will be integrated into METRICtm ET maps to quantify amount of ET flux from each riparian species.

MATERIALS AND METHODS

Study Area

The study area was Landsat path 33, row 31, which included parts of western Nebraska, eastern Wyoming, and north-eastern Colorado (fig. 1). An essential component in estimating riparian ET is the determination of the area for various vegetation types or classes within the riparian zone. We built on existing maps, methodologies and classification procedures developed at CALMIT.

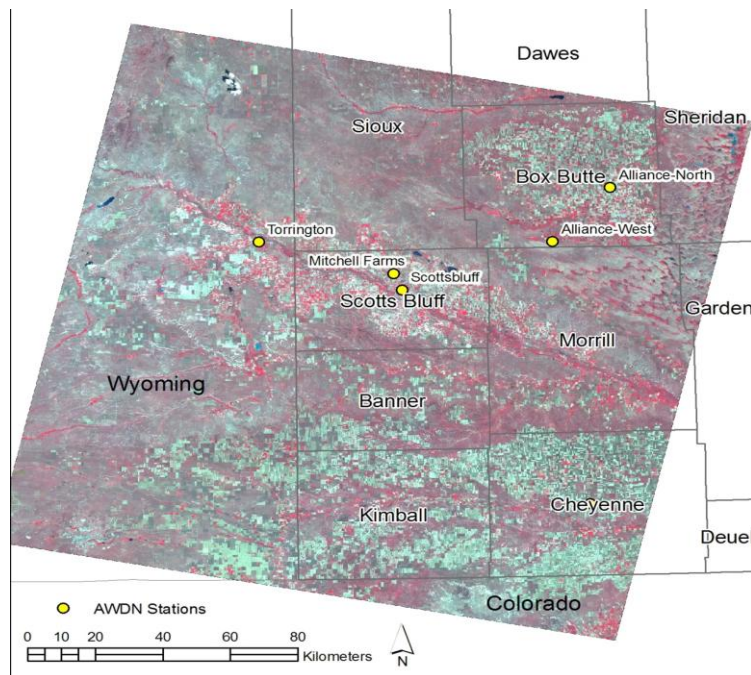


Figure 1. Geographic footprint of Landsat path 33, row 31. Images cover parts of the Nebraska Panhandle, Wyoming, and Colorado.

Land Surface Energy Balance Model

The landsat images for 2005 for Path32 Row 31 were processed using the algorithms in METRIC (Mapping evapotranspiration at high resolution with internalized calibration) model which requires parameterization of the energy balance and estimate surface energy fluxes based on spectral satellite measurements (Allen et al., 2007). The model is originated from SEBAL model and a “hybrid” energy balance model that uses thermal bands from Landsat imagery to compute ET. In particular, it combines remotely-sensed energy balance (satellite) data and ground-based ETr (reference ET) data to determine ET. METRICtm computes LE as a residual of the energy balance as:

$$LE = R_n - G - H \quad (1)$$

where R_n is the net radiation, G is the soil heat flux, H is the sensible heat flux, and LE is the latent heat flux. The units for all the fluxes are in $W m^{-2}$. METRICtm calculates net radiation (R_n) as the difference between incoming radiation at all wavelengths and reflected short-wavelength ($\sim 0.3 - 3 \mu m$) and both reflected and emitted long-wavelength ($3\sim 60 - \mu m$) radiation (Allen et al., 2007a).

The LE time integration was split into two steps. The first step was to convert the instantaneous value of LE into daily values of actual ET (ET_{24}) values by holding the reference ET fraction constant (Allen et al., 2007b). An instantaneous value of ET (ET_{inst}) in equivalent evaporation depth is the ratio of LE to the latent heat of vaporization. The reference ET fraction (ET_rF) usually range from 0 to 1.05 and is defined as the ratio of instantaneous ET (ET_{inst}) for each pixel to the alfalfa-reference ET calculated using the standardized ASCE Penman-Monteith equation for alfalfa (ET_r) following the procedures given in ASCE-EWRI (2005):

$$ET_rF = \frac{ET_{inst}}{ET_r} \quad (2)$$

The procedures outlined in ASCE-EWRI (2005) were used to calculate parameters in the hourly ET_r equation. The daily ET at each pixel was estimated by considering ET_rF and 24-hour ET_r as:

$$ET_{24} = ET_rF \times ET_{r-24} \quad (3)$$

where ET_{24} is the daily values of actual ET ($mm day^{-1}$), ET_{r-24} is 24 hour ET_r for the day of image and calculated by summing hourly ET_r values over the day of image.

Meteorological Data

High quality hourly weather data consisting of air temperature, relative humidity, wind speed, incoming solar radiation, and precipitation are required for the operation of the METRIC model. Hourly weather data were acquired from the High Plains Regional Climate Center’s (HPRCC) Automated Weather Data Network (AWDN). Weather data were acquired for 2005 from the Scottsbluff (latitude: 41.22 N; longitude: 103.02 W; elevation=1208 m) AWDN station to calibrate METRIC model. The weather data was quality controlled following the recommendations of Allen (1996) and ASCE-EWRI (2005) for all the weather stations in and out of Landsat path. Table 2 shows the list of AWDN stations used in this analysis. Hourly and daily observed solar radiation (R_s) values were compared with that of calculated clear sky solar radiation (R_{s0}). R_{s0} is the theoretical estimate of incoming solar radiation to the ground surface on a clear sky day with low atmospheric aerosol content (e.g. no haze, dust, smoke from fires, etc.) and is calculated based on atmospheric pressure, sun angle, and precipitable water in the atmosphere (i.e. fig.2). Corrections are only applied when the data exhibits systematic errors (Fig. 3). Individual values are not corrected for. Reasons for errors in the solar radiation values can be due to misalignment or miscalibration of the sensor. Reference ET (ET_r) values were calculated using the ASCE-EWRI (2005) standardized Penman-Monteith equation for alfalfa reference. These calculations were carried out using Ref-ET software (University of Idaho and Allen, 2003). Ref-ET requires weather data to be in columnar format ordered consistently.

Table 1. HPRCC AWDN station coordinates and elevation on path 33, row 31.

Station	Latitude	Longitude	Elevation (m)
Alliance-North, NE	42.18	102.92	1213
Alliance-West, NE	42.02	103.13	1213
Arapahoe Prairie, NE	41.48	101.85	1097
Arthur, NE	41.65	101.52	1097
Gordon, NE	42.73	102.17	1109
Gudmundsen, NE	42.07	101.43	1049
Mitchell Farms, NE	41.93	103.70	1098
Scottsbluff, NE	41.88	103.67	1208
Sidney, NE	41.22	103.02	1317
Sterling, CO	40.47	103.02	1200
Torrington, WY	42.03	104.18	1216

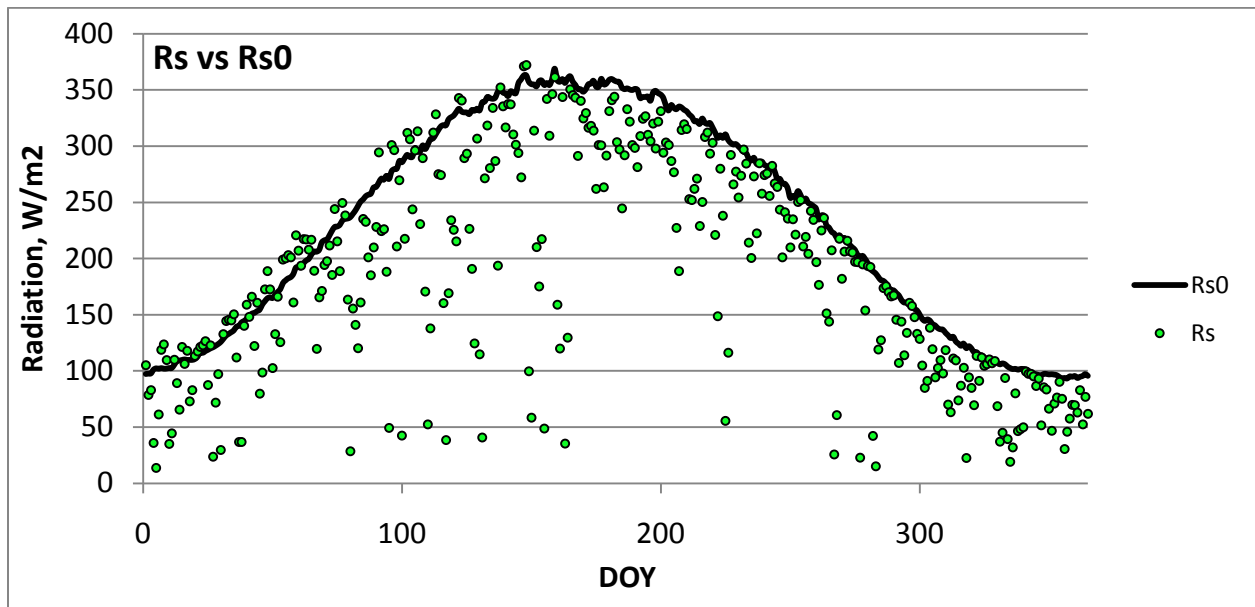


Figure 2. Scottsbluff 2005 observed solar radiation (W/m^2) and calculated clear sky solar radiation (W/m^2).

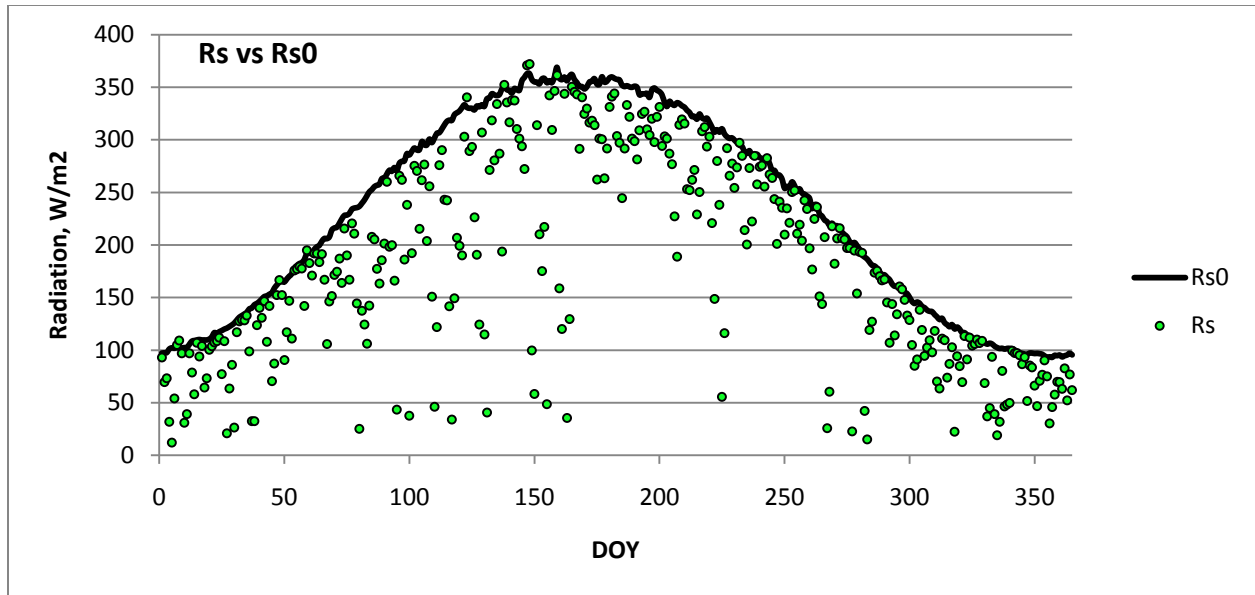


Figure 3. Scottsbluff 2005 corrected observed solar radiation (W/m^2) and calculated clear sky solar radiation (W/m^2). For DOY 1-123 (03 May) a 6% decrease in Rs values were applied.

Satellite Data

A total of nine Landsat images from year 2005 were ordered for the Nebraska Panhandle region (Table 2). Landsat images were ordered for path 33, row 31 as NLAPS systematic terrain-corrected (Level 1T), 30 meter spatial resolution, with nearest neighbor resampling method. The thermal band was resampled by USGS to 30 meters. UTM zone 13, NAD 1983 was the projection and datum used. For Landsat 7 imagery, the high gain on the thermal band was used. The Landsat 7 thermal band is acquired in both low and high gain. The low gain provides an expanded dynamic range generating less saturation at high values, but lower radiometric resolution (sensitivity). The thermal high gain band has higher radiometric resolution but provides a less dynamic range.

Table 2. Landsat imagery of Nebraska Panhandle acquired for 2005.

Date	Satellite	Path	Row
13 April 2005	Landsat 5	33	31
15 May 2005	Landsat 5	33	31
31 May 2005	Landsat 5	33	31
02 July 2005	Landsat 5	33	31
10 July 2005	Landsat 7	33	31
19 August 2005	Landsat 5	33	31
20 September 2005	Landsat 5	33	31
14 October 2005	Landsat 7	33	31
23 November 2005	Landsat 5	33	31

Preprocessing of Landsat Images

1. Gap-filling of Landsat 7 ETM+

On 31 May 2003, image data from the ETM+ sensor onboard the Landsat 7 satellite began exhibiting “striping” artifacts (USGS, 2008). It was determined that the problem was a result of the failure of the Scan Line Corrector (SLC) which compensates for the forward motion of the satellite. The post-SLC failure images of Landsat 7 are termed as SLC-off images. Due to the SLC failure, about 22% of the scene area is missing in SLC-off images. Processing of SLC-off images requires replacing the missing data. Various approaches are used for filling the missing data. Some of these approaches use data from the previously acquired images to replace the missing pixels. However, this approach is not very useful for agricultural applications due to temporal dynamics. Because Landsat 7 was still able to acquire imagery, the USGS developed new image products to fix the striping problem by combining two separate dates or by interpolation to fill in the data gaps.

We carried out our own correction to the scan line correction for Landsat7 datasets by using convolution filtering (nearest neighborhood method) with a 5X5 pixels majority function (Singh et al., 2008). In our application, we have used the approach of gap filling utilizing same time images with spectral information from the neighboring pixels. For this, the convolution filtering algorithm with majority function has been used to replace the missing data. The majority function is preferred due to our overall objective of estimating ET from the agricultural fields. This technique works perfectly for the inner missing lines. However, the missing pixels at the edges of the image scene are not well represented due to large gaps. Hence, it is advisable to subset the images leaving the outer edges.

2. Thermal shift in Landsat 5 Imagery

Inspection of Landsat 5 L1T NLAPS images, ordered through the AmericaView Project, indicates a systematic vertical downward shift of 30 to 90 m in the resampled band 6 (thermal band). Band 6 was resampled during the L1T process from the original 120 m to 30 m. The shift problem seems to occur for both cubic convolution and nearest neighbor resampling schemes. This shift has been evident in Landsat 5 images for p33r31 and p32r31 from 1997, 2002, and 2005. A shift of band 6 was not obvious in Landsat 7 images that were ordered. Discussions with our collaborators at UI have concluded that manually shifting the thermal band north 60 meters (2 pixels) will rectify the problem.

3. Preparation of Digital Elevation Model

A digital elevation model (DEM), a map of the surface topography, is required input in METRIC for the image area. A DEM is required for the calculation of DEM-corrected surface temperature, determination of hot and cold pixel elevations, and the calculation of air density for use in sensible heat estimation in METRIC. A DEM (USGS, 1999) of the study area was obtained from the EROS Data Center Seamless Data Distribution System. The DEM data has a spatial resolution of 1 arc second (30 meters) and was reprojected to UTM 13, GRS 1980 NAD 83 using cubic convolution. The data distribution system has a limit on the areal extent of data to be downloaded. Generally, more than one DEM image is required to cover a study area. Because of this, the DEM files were mosaicked, or stitched, together in order to provide a single, seamless dataset that encompassed the entire study area.

4. Preparation of Land Use Map

MERIC does not require a land cover map but it does improve the parameterization and estimation of the surface roughness parameter. For this purpose the Nebraska Land Use Map of 2005 and the Nebraska GAP land cover map were used. By combining the classification strengths of both maps surface roughness estimation can be improved. The focus of the land cover classes differs between the two maps. The classification classes of the Nebraska Land Use Map describe in detail agricultural crop types. While the classification classes of the Nebraska GAP map describes in more detail forested/woodland, prairie/rangeland, and riparian areas. Due to the different land cover systems having the same values for different classes, the Nebraska GAP and Nebraska Land Use values were changed. A value of 100 was added to the GAP data and a value of 120 was added to the Nebraska Land Use data. Pixels of non-agricultural classes were removed from the Nebraska Land Use Map and replaced with the geographically

corresponding pixels from the Nebraska GAP map. A value of 100 was used in order to account for class values (1-99) from National Land Cover Dataset (NLCD) data.

METRIC does not require a land cover map but is recommend in order to improve the parameterization and estimation of the surface roughness parameter (Allen et al., 2007). The land use maps are a composite of (1) the 1991-1993 Nebraska Gap Analysis Program (GAP), (2) the 2005 Nebraska Cooperative Hydrology Study (COHYST), and (3) the 2001 National Land Cover Dataset (NLCD). The land use map was reprojected into NAD 83 GRS 1980 UTM 13 using nearest neighbor resampling.

For areas outside of Nebraska, the 2001 NLCD map was used. For areas within the Nebraska state boundary, the Nebraska GAP map was used for non-agricultural classes and a COHYST map was used for agricultural classes. The COHYST data extends across the Nebraska border by 2 miles.

Due to the different land use systems having the same values for different classes, NE GAP and NE COHYST values were changed. For the GAP data, a value of 100 was added to each class. For the COHYST data, a value of 120 was added to each class. Values for non-agricultural classes in the COHYST data were then reclassified to zero.

5. Cloud Masking

Cloud and cloud shadow masking was carried out manually using Erdas Imagine. Cloud and cloud shadows were identified in Landsat imagery from visual detection by combining different band combinations in the color display. Polygons were ‘drawn’ around cloud and cloud shadows using the Imagine AOI tool. Automatic cloud cover algorithms were not implemented due to difficulty of identifying cloud shadows and thin clouds using these methods as well as the greater ability of the user to distinguish and provide context for cloud and cloud shadow areas. This is especially true for thin, wispy clouds, including airplane contrails. Once cloud areas were defined, the cloud areas were filled-in (masked) using the Imagine ‘Fill’ function with a value of -9 in the ETrF images. A value of -9 distinguishes the cloud masked areas from actual values of ETrF when the cloud-filling method is applied.

6. Cloud Filling of Landsat with Linear Interpolation

A model was employed to fill in cloud covered areas for ETrF imagery. The model accommodates up to eight ETrF images and their corresponding dates. The first image needs to be cloud-free or already filled in. The next image is the image to be filled while the six subsequent images are used for the interpolation. The model is coded for which if the first subsequent image has cloud cover over the same area as the image to be filled, then the model looks to the next image for a value and so on until an ETrF value is found. A value for the masked out pixels needs to be identified as well as the day of year for each image used in the model (e.g., -9). The model output is a filled-in ETrF image as well as a corresponding image indicating from which ETrF image date the cloud filled pixel came from.

For our study, images from 15 May, 31 May, 10 July, and 19 August which had significant cloud cover were used. Table 3 provides the images employed in the linear interpolation model and the number of days between each previous image. While the maximum days between images is 40 days, for the 15 May and 31 May images, the interpolation is actually between the 13 April and the 02 July images which resulted in the number of days between the images to be 80 days. The same is true for the 10 July and 19 August images, where the interpolation is between 02 July and 20 September, which is also 80 days.

Table 3. Image dates used in cloud filling model and the number of days between each previous image.

Date	13 Apr	15 May	31 May	02 Jul	10 Jul	19 Aug	20 Sep	14 Oct	23 Nov
# of Days	-	32	16	32	8	40	32	24	40

7. Use of MODIS Satellite Data for Cloud Filling Landsat Images

The NDVI/ETrF Ratio for ET estimation approach is based on the linear interpolation method, but uses Moderate Resolution Imaging Spectroradiometer (MODIS) derived NDVI to provide information on vegetation development for the Landsat scene to be filled. The rationale for using MODIS data for cloud-filling is that the availability of cloud free MODIS data is greater than that of Landsat data, and that

NDVI can provide information of the development vegetation during the missing period. MODIS data were acquired from the NASA Warehouse Inventory Search Tool (WIST, <https://wist.echo.nasa.gov/api/>). The data set selected was the MODIS/Terra Surface Reflectance Daily L2G Global 250m SIN Grid V005. The tile location used was horizontal 10, vertical 04. Images were selected to be within at least five days of Landsat cloud covered imagery (Table 4).

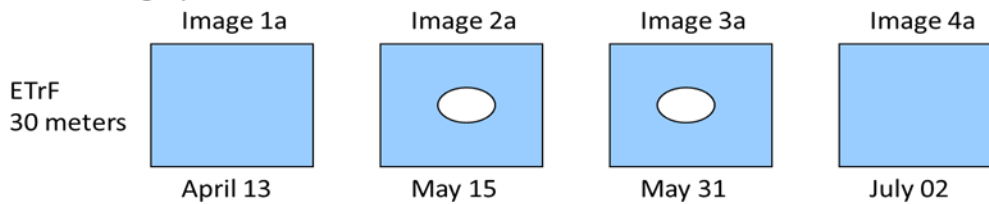
MODIS i has 36 spectral bands spanning from 0.405 to 14.385 μm and spatial resolutions at 250 m (bands 1-2), 500 m (bands 3-7), and 1000 m (bands 8-36). The orbit of the satellites is timed so that Terra passes north to south across the equator at 10:30 am local time and Aqua passes south to north across the equator at 1:30 pm local time. The swath of the MODIS sensor is 2,330 km and allows global coverage every one to two days. However, due to cloud cover, actual usable data is every four days or so.

The normalized difference vegetation index (NDVI) is described as the ratio of spectral bands (NIR - Red) and (NIR + Red), where NIR is the spectral reflectance in the near-infrared band (0.76 – 0.90 μm), and Red is the spectral reflectance in the red band (0.63-0.69 μm). Daily MODIS NDVI data are available at 250 meter spatial resolution and provide information on the development of vegetation during the missing time period and missing spatial extent caused by cloud cover in Landsat. The data are MODIS bands 1 (620-670 nm) and 2 (841-876 nm). These data were converted into surface reflectance by multiplying the data by 0.0001. NDVI was then calculated:

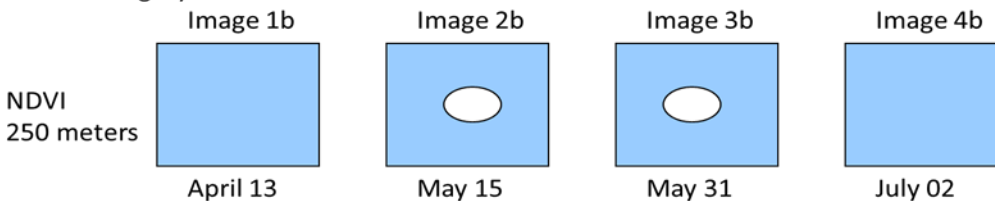
$$\text{NDVI} = (\text{near infrared} - \text{red}) / (\text{near infrared} + \text{red})$$

On Figure 4, Landsat images 1a (April 13), 2a (May 15), 3a (May 31), and 4a (July 02), images 2a and 3a have cloud cover over the same geographic area. MODIS cloud free images were acquired corresponding to the Landsat image dates; 1b (16 April), 2b (18 May), 3b (28 May), and 4b (06 July). MODIS data for April 13 were acquired. However review of the data revealed a diagonal boundary from north to south across the image with data values of the west portion of the image having lower brightness values than that of the eastern portion. This is possibly due to data from different acquisition times being stitched together. Because of this, a cloud free MODIS image from 16 April was used.

Landsat Imagery



MODIS Imagery



* Acquire MODIS image within 5 days of Landsat image.

Figure 4. Schematic representation of Landsat cloud filling procedure with MODIS data.

Table 4. The list of MODIS images in order to fill clouds for corresponding Landsat images

Landsat Date	13 April 2005	15 May 2005	31 May 2005	02 July 2005
MODIS Date	16 April 2005	18 May 2005	28 May 2005	06 July 2005

ETrF/NDVI ratio is generated by dividing the MODIS NDVI images 1b and 4b by the cloud free Landsat ETrF images 1a and 4a. Next, an ETrF/NDVI ratio image is generated for images 2 and 3 by using linear interpolation between dates 1 and 4 to the dates of image 2 and 3. These images are then multiplied by the NDVI values from images 2b and 3b which leaves ETrF values. These images are then used to fill in the cloud masked areas in images 2a and 3a.

8. Adjusted Background Evaporation Methodology

The Adjusted Background Evaporation cloud-filling approach is based on linear interpolation of ETrF images but in addition, incorporates data derived from a daily soil evaporation model in order to generate cloud-fill data. This method is designed to look in both directions in time to determine the closest image that has a valid ETrF values. Once that value is found, the ETrF data for the image to be cloud-filled is determined by linear interpolation, weighted by temporal distance between the images.

NDVI and ETrF values were taken from the hot (bare soil) and cold (full cover) pixel locations. The FAO-56 Ke evaporation model was run on a daily basis using daily precipitation and daily ET acquired and generated from the Scottsbluff AWDN weather station data to estimate daily evaporation from wet soil. The Ke estimated for each image date is assigned as the background ETrF for bare soil in that image. ETrF for full cover is generally 1.05, however it is a function of crop type and crop stage. Early and late season crops generally are not at full cover and thus have a lower ETrF value assigned for the cold pixel.

Table 5. The NDVI and ETrF values for bare soil and full cover of image dates used in adjusted background evaporation cloud-filling approach.

Date	NDVI-Bare soil	NDVI-Full cover	ETrF-Bare soil	ETrF-Full cover
4/13/2005	0.13	0.73	0.56	0.9
5/15/2005	0.14	0.78	0.16	1.05
5/31/2005	0.16	0.83	0.80	1.05
7/2/2005	0.12	0.84	0.02	1.05
7/10/2005	0.19	0.84	0.00	1.05
8/19/2005	0.15	0.82	0.13	1.05
9/20/2005	0.23	0.84	0.05	1.05

Four images were selected to be cloud-filled due to abundant cloud cover: 15 May, 31 May, 10 July, and 19 August. Cloud-free images on either side of the images to be cloud-filled were used for the interpolation. NDVI and ETrF values were collected from Hot/Cold pixel selection locations (Table 5). Coefficients for each date were calculated.

$$ET_r F_2 = \frac{\Delta t_2 (ET_r F_1 + a_2 - a_1 + [b_2 - b_1] NDVI_1) + \Delta t_1 (ET_r F_3 + a_2 - a_3 + [b_2 - b_3] NDVI_3)}{\Delta t_1 + \Delta t_2}$$

Where:

b1=(ETrF full cover – EtrF bare soil) / (NDVI full cover – NDVI bare soil)

a1=ETrF full cover – b1 * (NDVI full cover)

b2=(ETrF full cover – EtrF bare soil) / (NDVI full cover – NDVI bare soil)

a2=ETrF full cover – b2 * (NDVI full cover)

b3=(ETrF full cover – EtrF bare soil) / (NDVI full cover – NDVI bare soil)

$$a_3 = \text{ETrF full cover} - b_3 * (\text{NDVI full cover})$$

Δt_1 is the time difference between image 1 and image 2 and Δt_2 is the time difference between image 2 and image 3 (both are positive). NDVI1 and NDVI 3 are the NDVI values of the two source images.

$$\text{ETrF}_1 = a_1 + b_1(\text{NDVI})$$

$$\text{ETrF}_3 = a_3 + b_3(\text{NDVI})$$

Figure 5 shows original Landsat image on August 19, 2005 with cloud-masked and the ETrF for the image after cloud- is filled by linear interpolation using adjusted background evaporation methodology.

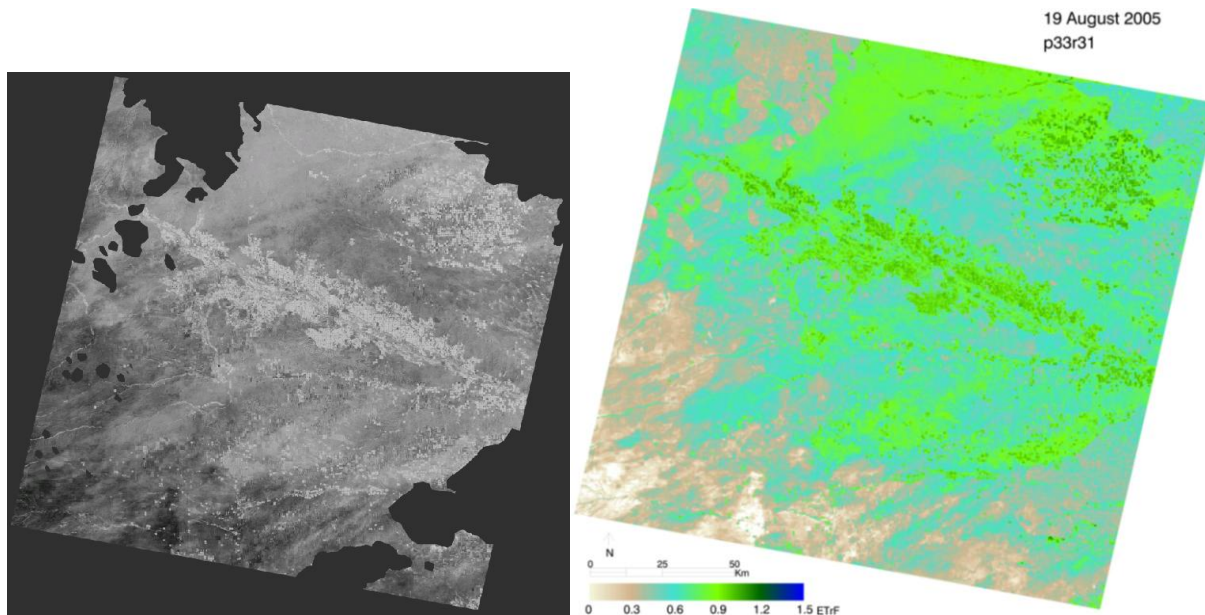


Figure 5. Masked out cloud areas on Landsat image (left) and cloud filled Landsat image showing spatial distribution of evaporative fraction (ETrF) after adjusting background evaporation.

RESULTS

We utilized both satellite and air-borne remote sensing data with an energy balance model to provide a better understanding and quantification of evapotranspiration for selected invasive species. We utilized METRIC to quantify spatial distribution and seasonal variation of actual ET over riparian zone in North Platte River during growing season for 2005. Next, we integrated ET maps with invasive species map to estimate the mean and the range of water use for each riparian species. The invasive species map developed using hyperspectral aerial imagery (AISA) in 2005 at 1.5 meter resolution at North Platte River Basin was used.

Figure 6 through 9 shows the histogram of seasonal actual ET for individual and combination of various riparian species. The y axis on each figure (histogram) shows number of AISA pixels (1.5 m) for each riparian species while x axis shows corresponding actual ET values in inches. We observed that there is no single ET value for invasive species. Results showed that salt cedar water use was lowest compared to other invasive species. Russian olive also has substantial water use during growing season. For most species seasonal actual ET ranged from 20 to 35 inches.

Statistics provided in table 1 indicates the water use during the growing season for individual invasive species. Comparison is difficult due to non-uniform distribution of species and difference in age. Water use varied considerable even in the same species due to plant density, plant distribution and plant height of individual species. ET roughly ranged from 12in to as high as 43 in for all the invasive species for May 1st to September 31st. Average actual seasonal ET ranged from 27 inches to 30 inches for all the invasive species. Overall, the remote sensing based energy balance approach based on landsat image in conjunction with high resolution hyperspectral image was useful to obtain distribution of ET estimates from riparian systems.

Table 6. Comparison of seasonal water use in inches from May 1st to September 30th in 2005.

Species	Minimum ET	Maximum ET	Average ET
Russian Olive	12	42	29
Salt Cedar	14	40	27
Thistle	12	42	30
Thistle+Salt Cedar+Reed Canary Grass	15	41	28
Thistle+Reed Canary Grass	16	43	30

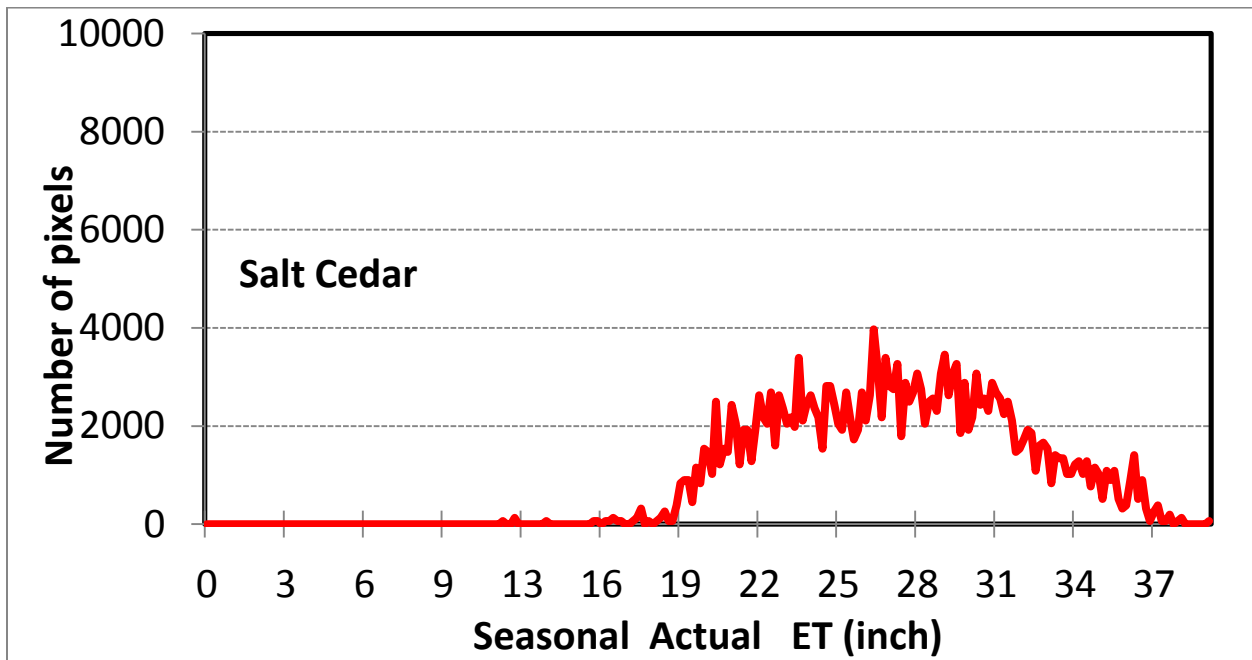


Figure 6. The histogram of seasonal actual ET (inch) for Salt Cedar.

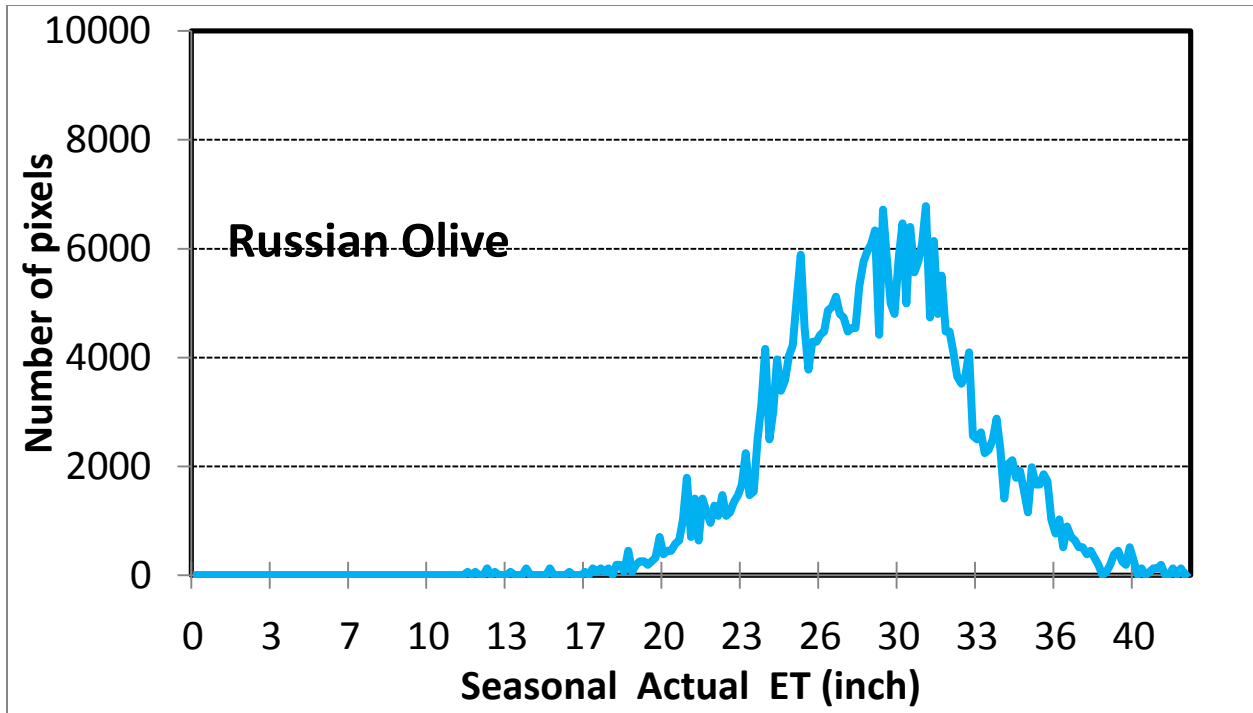


Figure 7. The histogram of seasonal actual ET (inch) for Russian Olive..

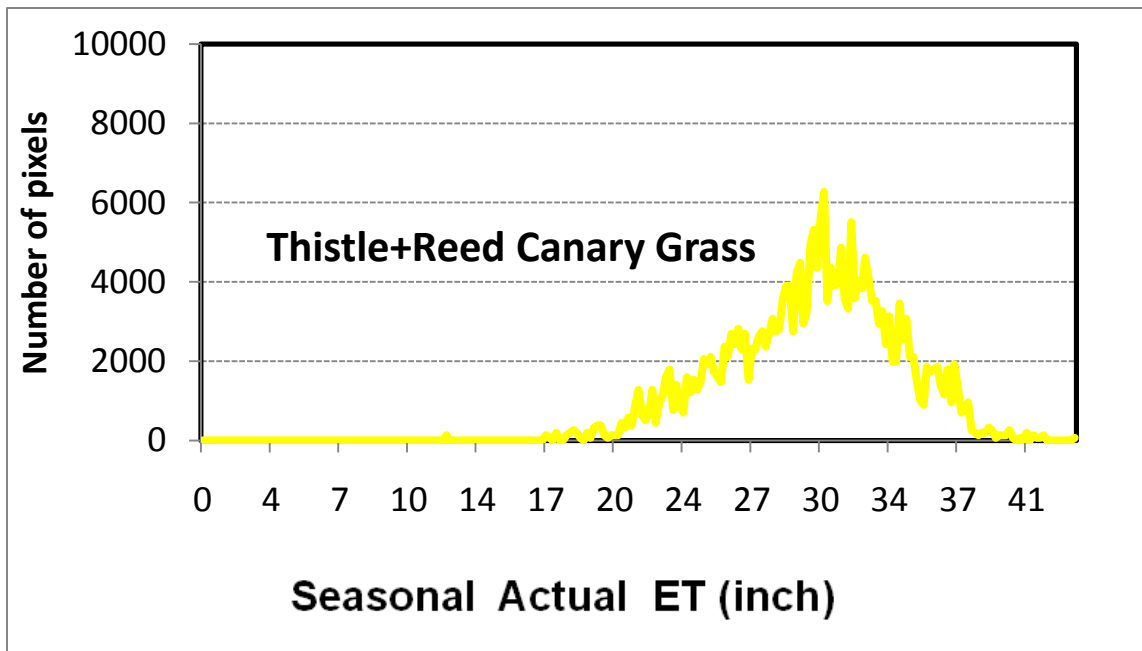


Figure 8. The histogram of seasonal actual ET (inch) for combination of riparian species (Thistle + Reed canary grass).

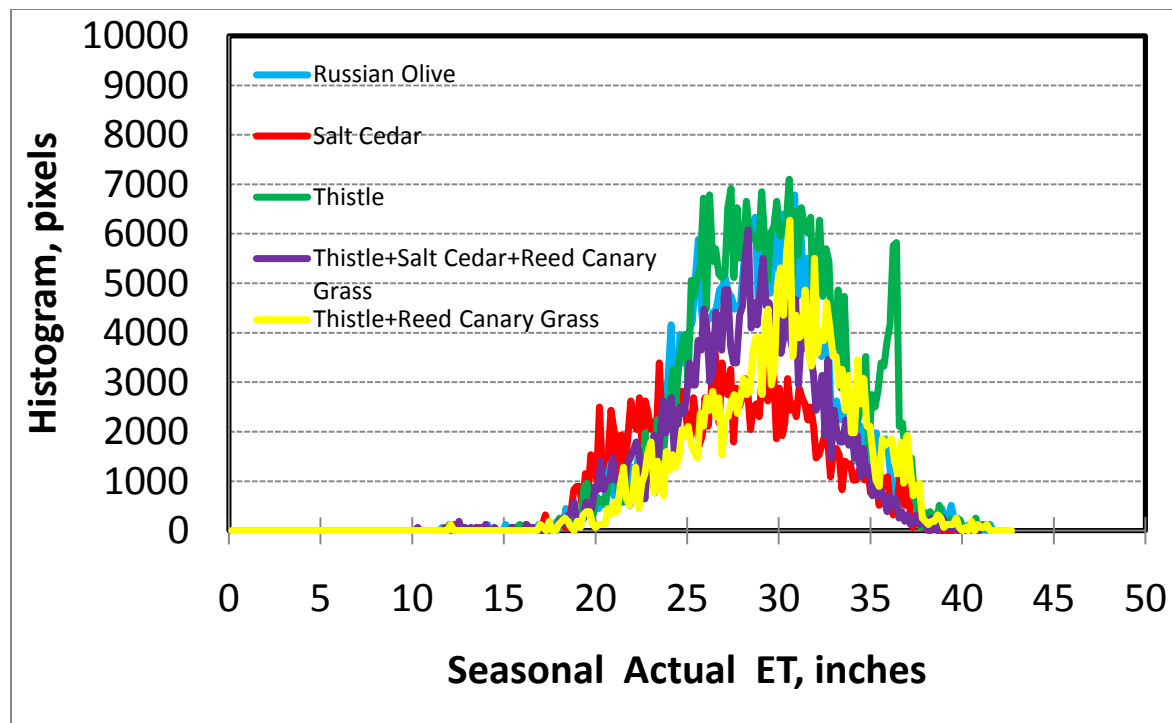


Figure 9. The comparison of water use (seasonal actual ET, inch) for individual and combination of various riparian species.

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