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A JOINT INVESTIGATION OF EVAPOTRANSPIRATION DEPLETION OF TREATED AND NON-TREATED SALTCEDAR AT THE ELEPHANT BUTTE DELTA, NEW MEXICO

WRRI Technical Completion Report No. 328

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A Joint Investigation of Evapotranspiration Depletion of Treated and Non-Treated Saltcedar at the Elephant Butte Delta, New Mexico

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ABSTRACT

Saltcedar (*Tamarix sp.*) was introduced to the U.S. as an ornamental plant to control soil erosion. But now the control of saltcedar has become a major concern since studies in the past have shown that evapotranspiration (ET) of saltcedar has been reported to range between 3 ft-5 ft of water per year. To study the reduction of saltcedar ET by herbicide treatment, a large area of dense saltcedar was treated, and an adjacent area was left untreated in order to compare the effects of ET losses after herbicide treatment.

Evapotranspiration of saltcedar was measured using the eddy covariance method. A robust one-propeller eddy covariance (OPEC) system and a three-dimensional sonic eddy covariance (3D-SEC) system were used to measure the ET of saltcedar at both the non-treated and herbicide-treated sites. Latent heat flux was estimated as a residual from energy balance. Sensible and latent heat fluxes at both the sites were compared to each other and also with both systems of measurement (OPEC and 3D-SEC).

Evapotranspiration measurements from both sites indicated that the treated saltcedar stand during a comparison of 83 growing days was less than the non-treated site by about 57%. Total ET of 327 mm was measured at the non-treated site and 142 mm at the treated site. For the 149 days of data comparison, during the non-growing season, the treated site had higher ET than the non-treated site by 37%. Total ET of 161 mm at the non-treated site and 220 mm at the treated site was measured.

Evapotranspiration of the non-treated site was estimated during the growing season of 2005 using crop coefficient as a function of cumulative GDD (growing degree days) developed based on ET measurements at Bosque del Apache National Wildlife Refuge. The estimated ET for non-treated saltcedar was 1002 mm when compared to measured ET of 386 mm at the treated site, a difference of 61% for 189 days. This was close to the 57% difference (non-treated ET of 327 mm and treated ET of 142 mm) for 83 days determined by direct measurements during the growing season from April 23 through May 11, 2005.

Soil salinity data were also collected from the treated and non-treated sites. The data were collected from October 9, 2004 through July 21, 2005. Soils at the study site were slightly alkaline. The salinity at the treated site was lower than the non-treated site by an average of 33%.

TABLE OF CONTENTS

LIST OF APPENDICES

LIST OF TABLES

Table Page

LIST OF FIGURES

1. INTRODUCTION

This research addresses one of the major concerns of the United States Bureau of Reclamation (USBoR), New Mexico Interstate Stream Commission (NM ISC), and other water management agencies of whether managing saltcedar (*Tamarix* sp.) by either mechanical or herbicide treatment would result in a reduction in evapotranspiration (ET). Water management agencies have spent millions of dollars in an effort to control the saltcedar invasion of riparian regions in an effort to reduce ET, allow indigenous plants to grow back, and better manage the rivers.

Saltcedar is known as an exotic species in the United States. It was introduced as an ornamental plant from Asia and the Mediterranean. In the Southwest it has replaced indigenous plants such as cottonwood (*Populus* spp.) and willow (*Salix* spp.), which flourished along the riparian regions. The control of saltcedar in the United States is a major concern in riparian areas, but it is difficult and expensive to control. It is a very intrusive plant and a legendary consumer of large amounts of water. Several methods are used to control saltcedar, primarily mechanical, biological, competitive, and chemical. In this study, saltcedar was controlled by chemical treatment using Arsenal® (common name, *Imazapyr*) at the study site. It was applied aerially by a helicopter on September 20-21, 2003, at an applied rate of 2 qts/acre (3/4 lb. acid equivalent /acre) calibrated to deliver 15 gal/acre total solution using water as a carrier along with 1 qt/acre of non-ionic surfactant (See Figure 31 in Appendix N).

The ET of saltcedar has been studied in the past and reported in literature (Bawazir 2000; Devitt et al. 1998; Gay and Fritschen 1979; Blaney and Hanson 1965). The amounts of ET consumed by saltcedar from these studies have been reported to range from 1 to 1.5 m/yr (3 to 5 ft/yr). In an effort to study the reduction of saltcedar ET by herbicide treatment, the USBoR and the Sierra Soil and Water Conservation District (Sierra SWCD) undertook an initiative to control a large area of dense saltcedar that occupied the Elephant Butte Reservoir Delta (EBRD) at north Monticello located in the south central part of New Mexico. As part of this study, they left an adjacent area of dense saltcedar untreated in order to compare the effects of ET losses after treatment.

1.1. Objectives

This study focused on the ET measurement of the treated and non-treated saltcedar areas at Elephant Butte Reservoir Delta. The objectives of the study were as follows:

1. to measure ET of herbicide treated and non-treated saltcedar using the energy budget method by the eddy covariance technique
2. to determine if there were any reductions in ET due to herbicide treatment of saltcedar
3. to calculate the crop coefficient of non-treated saltcedar based on the standardized Penman-Monteith equation referenced to grass, and as a function of growing degree days (GDD).

4. to measure and compare salinity at herbicide treated and non-treated saltcedar sites

1.2. Scope and limitations

The scope of this study was to measure ET of saltcedar for at least a year in order to assess ET losses during the growing and non-growing seasons and to monitor how soil salinity varied during this period. The data collection of saltcedar ET was limited to those days when there were no long periods of rainfall and the area was not completely flooded. These limitations were due to some of the sensors used in the study to measure the components of the energy balance. For example, the sonic anemometer for measuring sensible heat and the krypton hygrometer (KH2O) for measuring latent heat do not function during rain, and the soil heat flux plates that measure energy lost or gained due to warming or cooling of soil do not function well under flooding conditions.

2. LITERATURE REVIEW

2.1. History of saltcedar

Saltcedar was introduced to the western United States in the early 1800s as an ornamental plant whose origin was in Asia and northern parts of Africa. It was introduced to the U.S. by nurserymen on the East Coast in the year 1823. However, by 1870, the plants had escaped cultivation (Robinson 1965). According to Thompson (1958), the earliest introduction of saltcedar to New Mexico was in 1910. Around 1926-1927 saltcedar was planted to control soil erosion on the river banks. After floods in 1929, saltcedar spread swiftly, occupying 5,500 acres in approximately seven years (Robinson 1965). Since then saltcedar has continued to spread along river banks, irrigation ditches, and canals. In New Mexico along the Rio Grande, saltcedar is commonly found growing in riparian regions of moist sandy, sandy loam, loamy and clayey soils of alkaline pH. It grows at various elevations ranging from 2,000 ft to as high as 7,000 ft.

2.2. Identifying saltcedar

Saltcedar is classified as a facultative phreatophyte, a plant that grows in the presence of an attainable source of groundwater, but it can also survive in the absence of a damp substrate. They are shrubs or small trees that can grow up to 20 ft (Barranco 2001). Saltcedar has long branches that are slender and form long wide thickets. The stems bear pink to white flowers (Figure 1). The leaves are narrow and as small as 1.5 cm long. The leaves often overlap and crowd the stems. The leaves are scaly, bluish-green, smooth, sessile and grow alternatively up to 1/6 inch long. The pods containing seeds are pinkish red to greenish yellow in color. The seeds have a tuft of fine silky hair that helps them in transport. A mature plant can produce as many as 600,000 seeds in one growing season. The roots can grow to a depth of 30 ft, but it is observed to have become established mostly in places where the water table is not deeper than 25 ft (Barranco 2001).

Figure 1: An example of white and pink flowers of saltcedar densely crowding the tip of branches at the non-treated study site

2. 3. Evapotranspiration (ET) of saltcedar

Evapotranspiration of saltcedar has been studied and reported in published literature (Bawazir 2000; Devitt et al. 1998; Gay and Fritschen 1979; Blaney and Hanson 1965). The ET of saltcedar varies from location to location reflecting factors such as where it was measured, its density, depth to groundwater, the technique used in measurement, and so on. A comparison of ET published in literature was best summarized by Bawazir (2000, Table 6.1, page 111). See Table 1 adopted from Bawazir (2000). The ET of saltcedar ranged from 1.33 to 1.45 m per year (January through December). The ET of saltcedar reported included those days when the plants were dormant. The ET of 1.2 m during the growing season (April 5 - November 21, 1999) was reported by Bawazir from measurements of ET of dense saltcedar at the Bosque del Apache National Wildlife Refuge, New Mexico. Bawazir's study site was located about 100 km (62 mi) north of this study site. His methodology used in measuring ET was the energy balance method using the eddy covariance technique. The same method was used to measure ET of saltcedar at this study site.

Table 1: Comparison of saltcedar ET published in literature

Author	**Location**	**Method**	**Date Measured**	**ET**	**Water table**
Blaney and Hanson (1965)	Carlsbad, New Mexico	lysimeter	Jan - Dec, 1940	1.45 m/yr	0.92 m
Gay and Fritschen (1979)	Bernado, New Mexico	BREB lysimeter	June 14-18, 1997 June 14-18, 1997	8.2 mm/day 7.9 mm/day	1.5 m ----*
Luo (1994)	Bernado, New Mexico	Blaney-Criddle (lysimeter data)	April – Oct,1962 - 1968	1.43 m/yr	2.23 m
Van Hylckama (1974)	Buckeye, Arizona	lysimeter	1961 - 1967	1.5 m/yr 1.0 m/yr	2.10 m 2.7 m
Sala et al. (1996)	Virgin River, Nevada	Heat Balance	July - Oct, 1993	10 mm/day	2 – 3 m[†]
Devitt et al. (1998)	Virgin River, Nevada	BREB	1996	1.45 m/yr	----*
Bawazir (2000)	Bosque, New Mexico	Eddy Covariance	Jan 1 - Dec 31, 1999	1.33 m/yr	1.8 -2.5 m[‡]

* data were not reported

[†] water table data were recorded from August to September, 1993

[‡] water table during growing season (April 5 – November 21)

(table adopted from Bawazir 2000)

2.4. Methods used in measuring ET

Several methods are used to measure or estimate ET including water budget, micrometeorological, physiological and semi-empirical methods. These methods have been thoroughly reviewed by many authors in textbooks such as Dingman (2002), Jensen and others (1990), Cuenca (1989) and others. A review of the most commonly used methods is presented here.

2.4.1. Water budget

This method is used to estimate ET as a residual from a mass balance that accounts for inflows and outflows of large confined areas of watersheds. This method is applied to large confined areas where errors due to inflow (positive into the system) and outflow (negative out of the system) are reduced (Jensen et al. 1990). The algebraic sum of all the inflows and outflows minus any changes in storage should equal zero (see Equation 1). Using this equation ET could be determined as a residual.

$$P \pm R - D - ET - \Delta S = 0 \tag{1}$$

Where:

ΔS = change in water storage in soil (mm)
P = precipitation and/or irrigation (mm)
R = runoff (mm); inflow (+) or outflow (-) from the region
D = percolation or deep drainage (mm)
ET = evapotranspiration (mm)

This method is commonly used to estimate evaporation (a component of ET) from large water bodies such as lakes or large water catchments. In theory this could be applied to any scale including small fields or individual plants. But accurate field measurements of individual terms in Equation 1 are difficult, which makes this method uncertain.

2.4.2. Energy budget

The energy budget method is a micrometeorological method where the microclimate at the earth's surface interacting with the atmosphere is measured. This method is sometimes referred to as the energy balance method, and it applies the principle of conservation of energy; thus, energy coming to the system (vegetation surface) of hypothetical surface at the earth-atmosphere interface must equal the energy leaving the surface during a given period of time. These energies are made up of four major vertical fluxes of net radiation (Rn), soil heat (G), sensible heat (H), and latent heat (LE). The summation of these four flux densities should be zero for a stipulated time of measurement (see Equation 2).

$$Rn + G + H + LE = 0 \tag{2}$$

Where:

Rn = net radiation (MJ/m^2)
G = soil heat flux (MJ/m^2)
H = sensible heat flux (MJ/m^2)
LE = latent heat flux (MJ/m^2)

Energy components such as heat storage within the canopy and that used in photosynthesis are considered minor on a daily basis and are thus ignored in most cases. The sign convention in this study is designated such that when these fluxes are directed to the surface (i.e., positive sign) they are added to the energy balance and those away from the surface (i.e., negative sign) are subtracted from the energy balance.

2.4.2.1. Bowen ratio

This method was first introduced by Bowen (1926). Measurements required for this method include ambient temperature and vapor pressure concentrations at two different heights above the canopy (Bawazir 2000; Gay 1993). From these measurements, the Bowen ratio (β) could be expressed in terms of sensible heat (H) and latent heat (LE). The Bowen ratio assumes that the turbulent exchange coefficient for heat transfer and the exchange coefficient for water vapor transport are the same. With the assessment of available net radiation (Q) and change in soil stored energy (G), Equation 2 (energy balance) could be written in terms of Bowen ratio (β) where ET could be determined (see Equation 3).

$$\mathrm{LE} = -\frac{(\mathrm{Q}+\mathrm{G})}{(1+\beta)} \tag{3}$$

Where:

$$\beta = \frac{\mathrm{H}}{\mathrm{LE}} = \gamma g \left[\frac{\Delta \mathrm{T}}{\Delta \mathrm{Z}} \Big/ \frac{\Delta \mathrm{e}}{\Delta \mathrm{Z}} \right] = \gamma g \left(\frac{\Delta \mathrm{T}}{\Delta \mathrm{e}} \right)$$

H = sensible heat flux (MJ/m²)

LE = latent heat flux (MJ/m²)

G = soil heat flux (MJ/m²)

γ = psychrometric constant (kPa/°C)

ΔT = difference in potential temperature (°C) at two vertically separated points or ΔZ (m)

Δe = vapor pressure (kPa) at the same displaced points the temperature is measured or ΔZ (m)

According to Gay (1993), the displacement height, ΔZ where temperature and vapor pressure are commonly measured, is 0.5 to 1 m for smooth canopies and 2 to 5 m for rough forest canopies. The temperature and humidity gradients above the canopy are usually small and thus require measurements with a high degree of precision in the energy balance. Bias related to temperature and humidity sensors could be reduced by exchanging the sensors at the two heights. The sensors at the bottom are exchanged with those at the top every 15 minutes.

2.4.2.2. Eddy covariance

The eddy covariance technique is currently the method of choice for measuring ET and is widely accepted by researchers in the field. This technique is used to determine turbulent (or eddy) fluxes of water vapor, momentum, sensible heat, or other admixtures such as carbon dioxide, from their covariances. As explained by Rosenberg and others (1983), “In the surface layer… all atmospheric entities exhibit short-period fluctuations about their mean value…” In practice the turbulent fluxes are determined by measuring the fluctuation of the vertical wind velocity, vapor pressure, temperature, horizontal wind velocity and other atmospheric entities from the mean, and then computing cross-correlation over a suitable averaging period. An averaging period of 30-minutes or longer is a common practice (Brutsaert 1982). From rapid measurements (greater than 5 Hz sample rate) of vertical wind velocity, temperature and water vapor density, sensible (H) and latent (LE) flux densities can be determined over a suitable averaging period (see Equations 4 and 5).

$$H = \rho \bullet cp \bullet cov[\ wT\ ] = \rho \bullet cp \bullet \left[\overline{w'T'} \right] \qquad (4)$$

$$LE = \lambda \bullet cov\left[wq \right] = \lambda \left[\overline{w'q'} \right] \qquad (5)$$

Where:

ρ = density of moist air in (g/m^3)
cp = heat capacity of air at constant pressure (J/g/°C)
cov = covariance between w and T or q
w = vertical air velocity in m/s and $w'$is the fluctuation from mean value
T = air temperature (°C) and T' is the fluctuation from mean value
q = density of water vapor (g/m^3) and q' is the fluctuation from mean value (The bar signifies average value of the instantaneous products during sampling period.)

The eddy covariance technique was chosen for this study, based on its sound theoretical foundation as explained by Rosenberg and others (1983) and Brutsaert (1982) and more recently by Lee and others (2002). The same technique was successfully used to measure ET of dense saltcedar by Bawazir and King (2003) for a whole year in the Middle Rio Grande at Bosque del Apache National Wildlife Refuge in New Mexico. They concluded from their study that ET measured by the eddy covariance methods compared well with those measured in the past (published in literature) using different methods.

Two major instrumentation systems are used to measure ET using the eddy covariance method. These systems include a three-dimensional sonic eddy covariance system known as 3D-SEC and a one-propeller eddy covariance system known as OPEC.

The 3D-SEC system uses a highly sensitive three-dimensional sonic anemometer to measure the turbulent fluctuations of horizontal and vertical wind velocity and a fine wire thermocouple (12.7 micron diameter, chromel-constantan thermocouple) that responds to fluctuations in air temperature. Sometimes a fine wire thermocouple is not used in the field due to its fragility. However, the sonic anemometer such as the model used in this study, CSAT3 (Campbell Scientific Inc., Logan Utah) is capable of measuring virtual temperature. Thus from these measurements sensible heat (H) can be determined. The 3D-SEC measurement of H is combined with measured net radiation (Rn) and G in Equation 2 to calculate LE as a residual. The sonic anemometer vertical wind velocity measurements can also be combined with a fast response KH2O krypton hygrometer (Campbell Scientific Inc., Logan Utah) that measures water vapor density. From these measurements a flux density (LE or ET) at the same sampling period can be determined and, in addition, a check of closure in the energy balance can be verified.

The one-propeller eddy covariance (OPEC) system is another method that was first adopted by Amiro and Wuschke (1987) to successfully measure seasonal energy and water balance in a boreal forest. However, it was noticed that the height of the instrument above the vegetation and atmospheric instability contributed errors to sensible heat measurements. These errors were mainly due to inadequate frequency response of the sensors to completely characterize the vertical wind velocity fluctuations close to the surface where small scale eddies (frequencies > 0.5 Hz) predominate (Hicks 1972; Horst 1973; Garratt 1975). The OPEC system consists of a single, vertically oriented, sensitive propeller associated with a fine-wire thermocouple (76 micron diameter). In this study a pair of OPEC systems was used to measure ET. The OPEC system was locally constructed as described in detail by Bawazir (2000).

Blanford and Gay (1992) examined experimental evidence that the fraction of sensible heat flux sensed by an OPEC system increased with placement height as predicted by the similarity theory (Businger et al. 1967) and that theoretical corrections could be applied for their limited frequency. Therefore, appropriate corrections must be made in the determination of sensible heat. Most recently, Bawazir and King (2003) used the OPEC system to measure long-term ET of dense saltcedar in the Middle Rio Grande in New Mexico. They concluded from their study that sensible heat measured by OPEC and 3D-SEC systems compared reasonably well especially on a daily basis.

2.4.3. Climatological methods

Many methods/models exist to estimate and/or predict ET from readily available climatic data that are normally measured by “weather stations.” Many of these methods use empirical or semi-empirical equations. Climatic data such as air temperature, solar radiation, and relative humidity are commonly used in hydrologic studies, in the design of irrigation systems, and in the management of irrigation. Several climatological methods have been thoroughly discussed by Jensen and others (1990). In general these methods/models estimate ET of a reference crop, mainly alfalfa and grass, which is then multiplied by a crop coefficient (Kc) to obtain ET of the crop in question. For example, ET of saltcedar could be determined by multiplying the crop coefficient of saltcedar (which was originally derived from measured ET of saltcedar divided by ET referenced to grass) by ET referenced to grass (ET = Kc x ETgrass).

Due to different methodologies and inconsistencies in the equations used for estimating reference ET, in 1999 the Irrigation Association requested the American Society of Civil Engineers (ASCE) Irrigation and Hydrology Committee to develop a new ET equation that could serve as a standard and that could be accepted in the diverse communities of engineering, science, and policy (Allen et al. 1998). This improved equation is known as the ASCE standardized equation and is described in detail by Allen and others (2005). The same method is used in this study to estimate ET referenced to grass.

2.4.3.1. ASCE Standardized Reference Evapotranspiration Equation

According to Jensen and others (1990), reference evapotranspiration is defined as "…the rate at which water, if readily available, would be removed from the soil and plant surfaces…" of a specific crop. This definition was slightly modified for the standardized reference ET (Allen et al. 2003) as "the ET rate from a uniform surface of dense, actively growing vegetation having specified height and surface resistance, not short of soil water, and representing an expanse of at least 100 m of the same or similar vegetation.” Two surfaces or references could be used in this equation: 1) a short crop such as clipped, cool-season grass (ET_{os}) and 2) a tall crop such as full-cover alfalfa (ET_{rs}).

The standardized reference ET equation assumed the reference (ET_{os}) for a short crop having an approximate height of 0.12 m and the daily Cn and Cd (see equation 6) values of 900 and 0.34 respectively; and reference (ET_{rs}) for a tall crop having an approximate height of 0.50 m and the daily Cn and Cd values of 1600 and 0.38 respectively (see Equation 6). The variables in Equation 6 are described in detail by Allen and others (1998) and/or Jensen and others (1990). In this study the calculation of ET referenced to grass followed the standardized method and the variables were calculated using equations from Allen and others (1998).

$$\mathrm{ETsz} = \frac{0.408 \cdot \Delta \cdot (Rn - G) \ + \gamma \dfrac{Cn}{T + 273} u_2 (es - ea)}{\Delta + \gamma \cdot (1 + Cd \cdot u_2)} \qquad (6)$$

Where:

ETsz = standardized reference crop evapotranspiration for short (ETos) or tall (ETrs) surfaces (mm d^{-1} for daily time steps or mm h^{-1} for hourly time steps)
Rn = calculated net radiation at the crop surface ($\text{MJ/m}^2\ \text{d}^{-1}$ for daily time steps or $\text{MJ/m}^2\ \text{h}^{-1}$ for hourly time steps)
G = soil heat flux density at the soil surface ($\text{MJ/m}^2\ \text{d}^{-1}$ for daily time steps or MJ/m^2 h-1 for hourly time steps)
T = mean daily or hourly air temperature at 1.5 to 2.5 m height (°C)
u_2 = mean daily or hourly wind speed at 2 m height (m/s)
es = saturation vapor pressure at 1.5 to 2.5 m height (kPa), calculated for daily time steps as the average of saturation vapor pressure at maximum and minimum air temperature
ea = mean actual vapor pressure at 1.5 to 2.5 m height (kPa)
Δ = slope of the saturation vapor pressure-temperature curve (kPa/°C)

γ = psychrometric constant (kPa/°C)

Cn = numerator constant that changes with reference type and calculation time step (K mm s^3 Mg^{-1} d^{-1} or K mm s^3 Mg^{-1} h^{-1})

Cd = denominator constant that changes with reference type and calculation time step (sm^{-1})

Unit for the 0.408 coefficient is m^2 mm/MJ

3. METHODOLOGY

3.1. Description of the study site

Two sites were selected for this study, located at North Monticello, Elephant Butte Reservoir on part of the alluvial fan formed at the mouth of the La Canada Alamosa arroyos and within the storage pool of the Reservoir itself. This area was formed and is influenced by Reservoir storage levels and by intermittent flows from the creek drainage to the west. This site has been inundated often since the completion of the Elephant Butte Dam in 1916. During periods of low water storage, dry land emerges at the study sites and vegetation quickly establishes itself. The vegetation occupying the study sites emerged during late 2001 and early 2002 with declining storage levels and experienced significant growth during 2002 (see Appendix N).

The soils at the non-treated and treated sites differed in texture by field observation. The non-treated site had finer texture material with about 50 cm of clay layer. This is due to settlement of alluvial fine texture material as the water in the lake declined. At the treated site, the soil was composed of sandy-loam with a mixture of gravel in certain spots. This was due to deposits of soil material from precipitation runoff from the mountains and subsequent flooding. The non-treated site was located at the end of the Monticello Arroyo, which descended into the Elephant Butte Reservoir, while the treated site was upstream in the same arroyo.

3.2. Location

The sites under consideration were located in south central New Mexico in the Lower Rio Grande Basin where a part of the Elephant Butte Reservoir extended into Sierra County. A handheld GPS (geographical position system from Magellan Corporation) that uses a NAD27 (North American Datum of 1927) coordinate system and a (North American Mesoscale) NAM Land-1.03 base map were used to find the geographic coordinates and elevations at the sites. The latitude and longitude of the sites were determined as follows: non-treated site latitude and longitude was N33° 18′ 57.18″ and W107° 10′ 23.32″ with a site elevation of 1334 m. The latitude and longitude of the treated site was N33° 18′ 16.08″ and W107° 12′39.18″ and an elevation of 1352 m. The area of study was approximately 550 acres at the non-treated site and 700 acres at the treated site (see Figure 2).

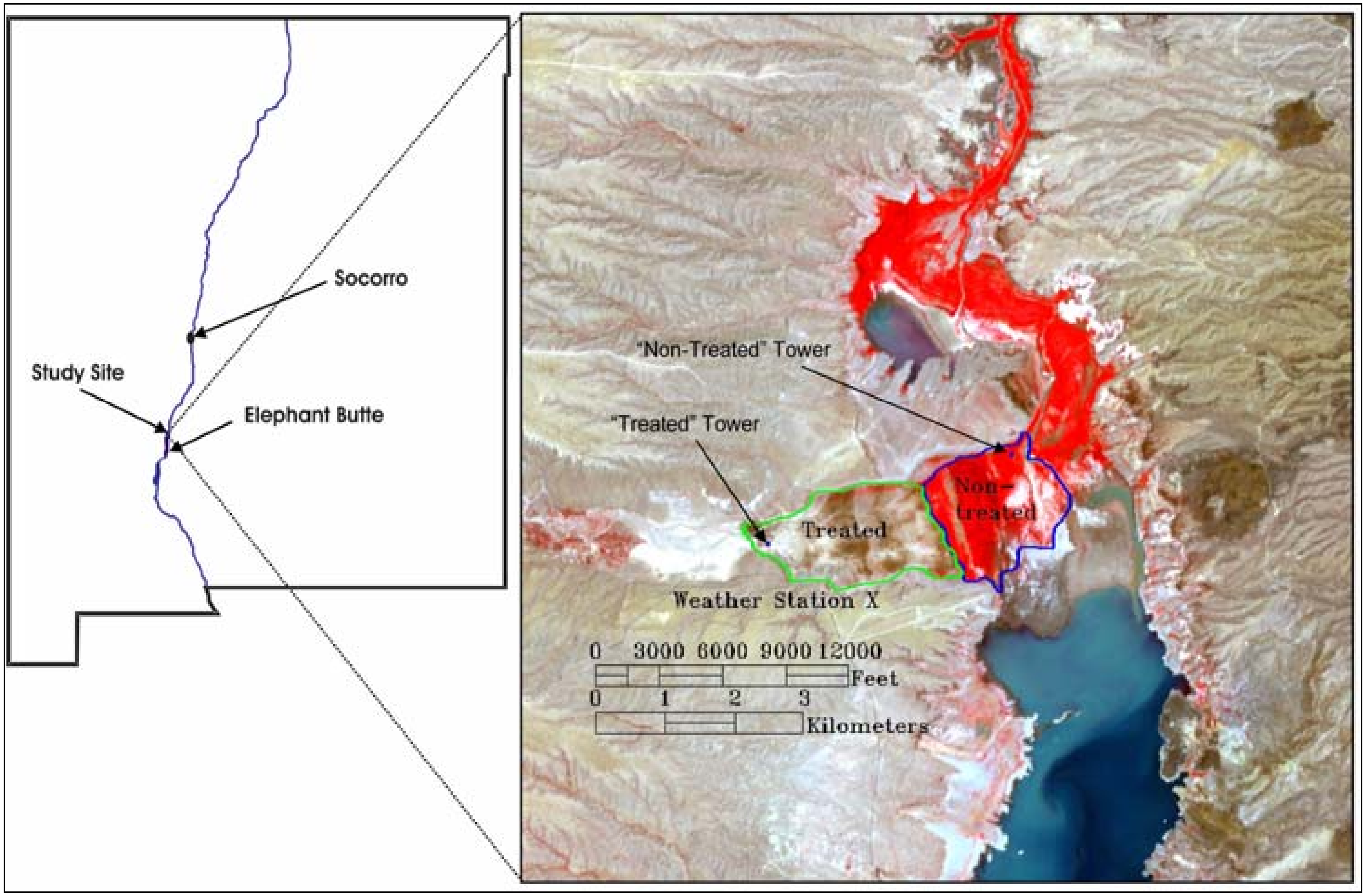

Figure 2: Satellite (NASA-ASTER) image of Elephant Butte Reservoir showing the study site.

3.3. Hydrogeology of the site

The Rio Grande brings water to the Elephant Butte Reservoir as a perennial river flowing from Colorado and entering into northern New Mexico by flowing through the center of the Carson National Forest. Passing through the center of the state, it flows through the city of Anthony before it enters the state of Texas. The primary source of water into the Elephant Butte Reservoir is the Rio Grande. However, close to the study site in Elephant Butte Reservoir is a tributary called Alamosa Creek. It is also referred to as the Monticello River. This ephemeral arroyo is dry most of the year. The Creek passes south of the Cibola National Forest and enters into the Monticello Canyon before it connects to the Elephant Butte Reservoir.

The groundwater table at the non-treated site was very shallow, averaging a depth of 4 ft from the ground surface, while the groundwater table at the treated site, due to its higher elevation when compared to the former, was deeper than 10 ft. The groundwater flow in this area is generally from the north to the south. According to Williams (1986), the Rio Grande passes the Black Mesa landform at San Marcial located to the north of the study site (N33° 41' 30" and W107° 01' 18") and enters the Cuchillo Plains by the Elephant Butte Reservoir (both are part of the Mexican Highlands).

The soil type at the treated site is classified as Doña Ana complex, hummocky (U.S. Soil Conservation Service 1984). Grass and scattered shrubs grow predominantly in this region. This type of soil is deep and well drained as it is formed from mixed alluvium. The surface layer of the soil at the site is reddish brown loamy fine sand approximately 12 inches thick. Underneath this lies the reddish brown very fine sandy loam up to 4 inches thick. The next 14 inches is subsoil that is reddish brown sandy clay loam. The substratum is weakly cemented pinkish sandy clay loam up to 60 inches deep. Permeability of the soil at the treated site is moderate.

The soil type at the non-treated site is classified as Doña Ana-Tres Hermanos association. It is made up of 50% Doña Ana very fine sandy loam and 30% Tres Hermanos gravelly fine sandy loam. The former is found in the broadway while the latter can be located on the drainageways. The subsoil is light brown sandy clay loam. The top surface of soil is made of light brown very fine sandy loam up to 3 inches deep. Subsoil is made of light brown sandy clay loam up to 15 inches with the next 11 inches as the pink sandy clay loam. The lower 60 inches is made up of light brown loamy soil. Permeability of the soil is slow moderate and available water capacity is high (U.S. Soil Conservation Service 1984).

3.4. Topography

The Rio Grande Rift was formed by tectonic movement around 20 million years ago and led the way for the river to flow along it (Williams 1986). The Elephant Butte Reservoir runs along the western side of the range of the Fra Cristobal Mountains. The mountain range is located at latitude of N 33° 20' 7.5" and longitude of W 107° 06' 24". The highest peak of the mountain range close to the site is 6,223 ft. On the eastern side of the mountain range is the Jornada del Muerto (rangeland) with the Red Lake close to the mountains. The San Mateo Mountains extend to the northwest part of the Elephant Butte Reservoir. Behind the San Mateo Mountains spreads the Cibola National Forest.

3.5. Climate

According to Williams (1986), the warmest month in New Mexico falls in July and the coldest month varies between December and January. Scurlock (1998) observed that most of the days from early July to late September in New Mexico are covered with moist, unstable air from the Gulf of Mexico, which provides about 50% of the annual precipitation. The study site, being in an arid region of the state, experiences an annual precipitation of less than 10 inches. Mountainous areas are drastically cooled often due to these weather conditions. Temperature variation is very broad in New Mexico when observed on a daily and annual basis.

Due to the occurrence of dry air in the area, the daytime relative humidity is less than or close to 30%. This causes large amounts of moisture to evaporate. Even in winter the dry air makes evaporation rates high. Temperatures recorded from 1951 to 1980 at Truth or Consequences, New Mexico, which is approximately 19 miles south of the study site, had recorded maximum temperatures that ranged from 98 to 106°F and minimum temperatures that ranged from 17 to -5°F; the average highest temperature was 101.9°F and average lowest temperature was 7.8°F during the period recorded (Williams 1986).

3.6. Vegetation at the sites

The vegetation at the non-treated site was dominated by dense saltcedar with a few scattered trees of black willows and other riparian vegetation. The saltcedar plants measured an average height of 4 m at an age of 3-4 years old. Enough fetch distance existed to measure the flux coming upon saltcedar plants (1,765 ft in the west, 840 ft in the south, 1,320 ft in the north, and 2,140 ft in the south-east direction). It was found that the adjacent mountain range contained sparse vegetation of bush muhly, black grama, and creosote bush. The potential plant community present in the surrounding areas included black gamma, bush muhly, cane bluestem, sand dropseed, threeawn, and other plants that occupied the exterior boundaries of the saltcedar stands.

The treated site had stands of dead saltcedar plants that had been treated with herbicides (see Figure 3). The age of saltcedar at this site was not known but the height of the dead saltcedar also averaged 4 m tall. The two sites were located close to each other with more or less similar environmental conditions. The non-treated site, however, was adjacent to the Rio Grande, which had small amounts of water flowing as seen in Figure 3.

Figure 3: Non-treated (left) and herbicide-treated (right) saltcedar

3.7. Instrumentation and data collection

Evapotranspiration of saltcedar at the sites was measured using the two systems of instrumentation as described earlier. Initially a 30 ft tower was installed at each of the two sites. As the water level was expected to rise at the lake by the beginning of May 2005, the tower at the non-treated site was extended by another 10 foot section. It was observed that saltcedar was growing taller and also that the water level had risen at the site up to 15 ft by the month of June 2005. The OPEC system was used to measure ET throughout the year while the 3D-SEC system was used for a short span from August 13 to October 15, 2004 at the treated site and from June 28 to October 15, 2004 at the non-treated site. On March 5, 2005, the 3D-SEC system was reinstalled at the non-treated site. The 3D-SEC system measured sensible heat that was used as a check for OPEC measured sensible heat.

The data collected by propellers, thermocouples, and net radiometer were sampled at 8 Hz (8 samples per second), while all the other parameters mentioned in Table 2 were measured at 1 Hz (one sample per second). The measured data were partially processed in the field using a CR23X datalogger. Datalogger-support software, Logger Net (version 2.1c) from Campbell Scientific, Inc was used to communicate with the datalogger. Raven 100 CDMA digital phones with an 8DB Yagi antenna to boost the reception of signal from the service provider to a digital cell phone were used to download data remotely. Data were either downloaded using the cellular phone or directly from the datalogger in the field and later processed at New Mexico State University.

After collection, the data were analyzed at the New Mexico State University Water Resources Engineering Laboratory. The 30-minute data were analyzed on a daily basis by plotting figures and also by comparing with other sensors to understand the traditional behavior of the sensor, making sure that there were no missing data. The daily flux data for the treated and non-treated sites for the year 2004 and 2005 are given in Appendices A through D.

3.8. Flux towers

The tower at the non-treated site was referred to as NLSC (North Lake Saltcedar) while the treated site was referred to as NLTSC (North Lake Treated Saltcedar). The metal chosen for the towers was galvanized steel to prevent corrosion. Three tubular sections of 1.0 inch diameter were spaced at 17 inches to form a triangular tower. Pipes were prevented from buckling by providing solid cross rods of 0.375 inches diameter at 16 inches spacing in a horizontal direction. The tower was assembled in 10 ft sections. An extended mast for holding the propellers and thermocouples was placed at the top of the tower section. The tower provided a sturdy mounting platform for the sensors. The sensors were placed at sufficient heights (Table 2) above the canopy and with consideration to fetch distance. The instrumentation at the tower consisted of the following sensors:

- A pair of one propeller eddy covariance (OPEC) systems, built locally as shown in Figure 4, having a pair of thermocouples and sensitive propellers following the setup described by Bawazir (2000).
- HMP45C-L Vaisala temperature and relative humidity probe having a R.M. Young 12-plater Gill radiation shield by Campbell Sci. Inc, Logan, Utah.
- Q7.1 net radiometer from Radiation and Energy Balance Systems, Inc., (REBS), Seattle, WA.
- A pair of HFT3 soil heat flux plates manufactured by REBS (Radiation Energy Balance Systems) Seattle, WA.
- CS 616-L water content reflectometer and TCAV-L averaging soil thermocouple probe to measure soil moisture from Campbell Scientific Inc, Logan, Utah.
- R.M. Young wind sentry to measure wind speed and direction from Campbell Scientific Inc, Logan, Utah.
- MSX20R-20 watt solar panel with CH100-12 V charger/regulator to provide power to the datalogger from Campbell Scientific Inc, Logan, Utah.

- CR23X measurements and control module datalogger with wiring panel to connect the sensors from Campbell Scientific Inc, Logan, Utah.
- Redwing 100 is an IS-95 CDMA-based modem manufactured by AirLink for use on Verizon cellular networks from Campbell Scientific Inc, Logan, Utah. The signal strength is increased with the usage of 800 MHz 8 dBd Yagi antenna.
- CSAT3 3-D sonic anemometer with rain protection on sonic probes from Campbell Scientific Inc, Logan, Utah.
- KH2O krypton hygrometer from Campbell Scientific Inc, Logan, Utah.
- Rain and weather proof enclosure from Campbell Scientific Inc, Logan, Utah.

Figure 4: Setup of propellers and fine wire thermocouples

Table 2: Sensors used at the non-treated and herbicide-treated site and their placement on the towers

Description		Non-treated site		Treated site
		Sensor height		Sensor height
Measurement	Sensor type	before flooding	after flooding	
Sensible heat	pair of propellers	41.10 ft*	41.10 ft*	30.80 ft*
Air temperature	pair of thermocouples	41.10 ft*	41.10 ft*	30.80 ft*
Relative humidity	humidity probe	22.60 ft*	33.10 ft*	15.80 ft*
Net radiation	Q7.1 net radiometer	26.50 ft*	26.50 ft*	21.40 ft*
Wind speed/direction	Cup anemometer and vane	27.60 ft*	27.60 ft*	17.00 ft*
Wind speed/sonic temperature	3D-Sonic anemometer	26.35 ft*	26.35 ft*	21.90 ft*
Atmospheric water vapor	krypton hygrometer	26.35 ft*	26.35 ft*	21.90 ft*
Soil moisture content	CS616-L water content reflectometer	-2.00 cm[†]	-2.00 cm[†]	-2.00 cm[†]
Soil heat flux/ temperature gradient	HFT3 soil heat flux plates	-8.00 cm[†]	-8.00 cm[†]	-8.00 cm[†]
Soil temperature	2-TCAV averaging soil thermocouple probe	-2 cm[‡] and -6 cm[‡]	-2 cm[‡] and -6 cm[‡]	-2 cm[‡] and -6 cm[‡]

* Measured from ground surface

† Depth into the ground with bare surface

‡ Depths of two thermocouple probes placed at 2 cm and 6 cm below the ground surface

3.9. Weather stations

Two weather stations close to the study site in Sierra County were used to obtain weather data. One weather station was called NLWS (north lake weather station) and the other was called SLWS (south lake weather station). The NLWS was located at an elevation of 1345 m with latitude and longitude of N 33° 17' 50" and W 107° 11' 38". The SLWS was located at an elevation of 1378 m with latitude and longitude of N 33° 08' 45.52" and W 107° 11' 3.44".

Both weather stations had a modem and cellular phone connected to a datalogger for remotely downloading the data to New Mexico State University. They were inspected on a regular basis for maintenance purposes. The daily weather data are shown as a comparison between the NLWS and SLWS in Appendices E through H. The sensors used and their heights at the NLWS and SLWS are shown in Tables 3 and 4. Data collected from these weather stations included solar radiation, ambient temperature, relative humidity, soil temperature, wind speed and direction.

Table 3: Sensors used at the north lake weather station (NLWS)

Measurement	Sensor Type	Instrument Model	Manufacturer	Placement
Solar radiation	Silicon pyronometer	LI200S pyronometer	LI_COR	2.50 m *
Air temperature/ Relative humidity	UUT51J1 Thermistor Fenwall	CS 500 probe	CSI	1.50 m *
Soil temperature	UUT51J1 Thermistor Fenwall	107 probe	CSI	-10.00 cm†
Wind speed/Direction	Cup anemometer and vane	014A (wind) and 024A (direction)	Met One	3.75 m *
Precipitation	Tipping bucket	TE 25 rain gage	Texas Electronics	100 cm ‡

* Measured from ground surface

† Depth into the ground with bare surface

‡ Measure to the top of the rain gage from the ground surface

Table 4: Sensors used at the south lake weather station (SLWS)

Measurement	Sensor Type	Instrument Model	Manufacturer	Placement
Solar radiation	Silicon pyronometer	LI200S pyronometer	LI_COR	3.35 m *
Air temperature/ Relative humidity	UUT51J1 Thermistor Fenwall	CS 500 probe	CSI	2.44 m *
Soil Temperature	UUT51J1 Thermistor Fenwall	107 probe	CSI	-10.00 cm†
Wind speed/Direction	Cup anemometer and vane	014A (wind) and 024A (direction)	Met One	3.89 m *
Precipitation	Tipping bucket	TE 25 rain gage	Texas Electronics	43 cm ‡

* Measured from ground surface

† Depth into the ground with bare surface

‡ Measure to the top of the rain gage from the ground surface

3.10. Salinity

Saltcedar plants exude salt from their leaves, but it is not understood very well as to whether the salt in soil is reduced or increased by presence of saltcedar. In an attempt to understand this, the electric conductivity, total dissolved solids, and temperature were measured. All these parameters were measured at both the non-treated and treated sites to compare the salinity values. In addition, the above said parameters were also measured for the water in the Rio Grande at the non-treated saltcedar site.

Four soil samples were collected randomly at both the treated and non-treated sites within a radius of 66 ft (20 m) from the flux tower. Samples were collected approximately 8 in (20 cm) below the soil surface and placed in zipped plastic bags for analysis. Small amounts of soil from all four locations were mixed as a homogenous sample and batched as “mix”, and this became the fifth sample for comparison. The samples were sent to the Soil and Water Testing Laboratory (SWAT) at New Mexico State University for further analysis.

3.11. Data collection at treated and non-treated sites

Flux data collection started at the non-treated saltcedar site on June 29, 2004 (DOY 181) and at the treated site on August 14, 2004 (DOY 227). The discrepancy in starting dates at treated and non-treated study sites was due to unavailability of instrumentation for the treated site. Flux data were collected using the one-propeller eddy covariance (OPEC) system and a three-dimensional sonic eddy covariance

(3D-SEC) system. Using the OPEC system, sensible heat (H) was collected at 8 Hz (8 samples per second). The 3D-SEC system was run periodically as a check for OPEC system. Using the 3D-SEC system, sensible heat (H) and latent heat (LE) fluxes were collected at 10 Hz (10 samples per second). Net radiation (Rn) was collected using a Q7.1 net radiometer (Radiation and Energy Balance Systems, Inc., Seattle, WA; REBS Inc.) and soil heat (G) flux using soil heat flux plates (REBS Inc.) was also collected. The rate of heat storage in soil was determined from measurements of soil moisture and soil temperature. Time series data were stored and partially processed on a 23X datalogger (CSI) to obtain 30-min fluxes.

Later the data were downloaded either by cellular telemetry system from New Mexico State University or manually in the field. Additional climatological data collected included wind speed and direction, ambient temperature, and relative humidity. The 30-min data were later analyzed and then totaled to daily fluxes to determine evapotranspiration (ET). In addition to flux towers, weather data were collected at the north lake weather station, which was located in the vicinity of the study area. The weather station data were collected on an hourly basis as part of New Mexico network of weather stations.

The sensors were maintained on a regular basis; net radiometer domes were cleaned by distilled wet cloth and changed as necessary; OPEC thermocouples and propellers were routinely checked for any damage and replaced as needed. Quality control of data and instrumentation upkeep allowed for a continuous collection of data. However, there were some days when the data were lost when either the sensors were being replaced, when there was rain, or when the site was inaccessible due to wet soil and rain. The missing days were ignored in the analyses of data.

3.12. Data quality control and calculations

The data at the non-treated site were recorded continuously during the year 2004 and with a few missing days in the year 2005. The missing data were from February 26 to March 5, 2005. It was during this time that the tower was raised from 30 to 40 ft as the water level was expected to rise. The rise of water was anticipated as higher levels of the spring snow runoff forecast from southern Colorado and northern New Mexico were expected to increase the storage in Elephant Butte Reservoir. During these missing days, the tower was being raised and stabilized by pouring a concrete foundation for the guy wire anchors. The two missing days of data in the month of June (16-18), 2005 were due to field maintenance wherein the sensors on the tower were raised as the water level at the site was increasing.

At the treated site measurements of flux data using the OPEC system were started on August 14, 2004 (DOY 227) and continued through year 2005 with an exception of a few days of missing data. The missing data were mainly due to those days when the sensors were maintained. A 3D-SEC system was installed in late August through September, 2004 as a check for OPEC sensible heat measurements and as a check for energy closure. All the data were collected in similar manner as at the non-treated site.

3.13. Description of Bosque del Apache saltcedar site

Saltcedar at Bosque del Apache National Wildlife Refuge (Bosque) was located on the Middle Rio Grande floodplain in New Mexico north of the treated and non-treated sites. This site was more than 10 years old and covered an area of about 200 acres. The site was located at the south end of the Bosque (33° 46' 26" N latitude and 106° 52' 50.03" W longitude at an elevation of 1370 m) and had a 40 ft flux tower. This site was chosen to calculate the crop coefficient that was used in predicting annual ET of non-treated saltcedar at the lake site. The weather station at the Bosque located at 33° 46' 0" N latitude and 106° 54' 0" W longitude at an elevation of 1375 m was used to process the weather data. Data from the Bosque flux tower and weather station were processed in the same way as the treated and non-treated sites and north lake weather station. The detailed description of the sites and weather station at the Bosque can be found from Bawazir (2000).

4. RESULTS AND DISCUSSION

4.1.1. Net radiation

Net radiation was measured using Q7.1 net radiometer (REBS Inc.) at both the treated and non-treated sites. The net radiometer was brand new and was calibrated by the manufacturer. However to check if the sensor was reading radiation correctly, it was compared to another net radiometer of the same model to ensure consistency. During data collection the net radiation data were plotted and compared to solar radiation sensors (global solar radiation) collected at NLWS near the site. The trends allowed a quick check of net radiometer performance. Also the net radiation data were plotted against the data from other net radiometers that were located in dense saltcedar at other study sites in the Rio Grande for validation.

4.1.2. OPEC sensible heat

A pair of OPEC systems was installed at the same height and with similar planar orientation to record two sets of sensible heat flux data. The presence of the pair of propellers helped to validate sensible heat flux data recorded by each system in the field. This type of arrangement served as a backup when one system was not functioning well. A 30-min comparison between the two sensible heat flux data for the non-treated site, as an example, is shown in Figure 5 for year 2004. A similar comparison for the treated site is shown in Figure 6 for the 2004.

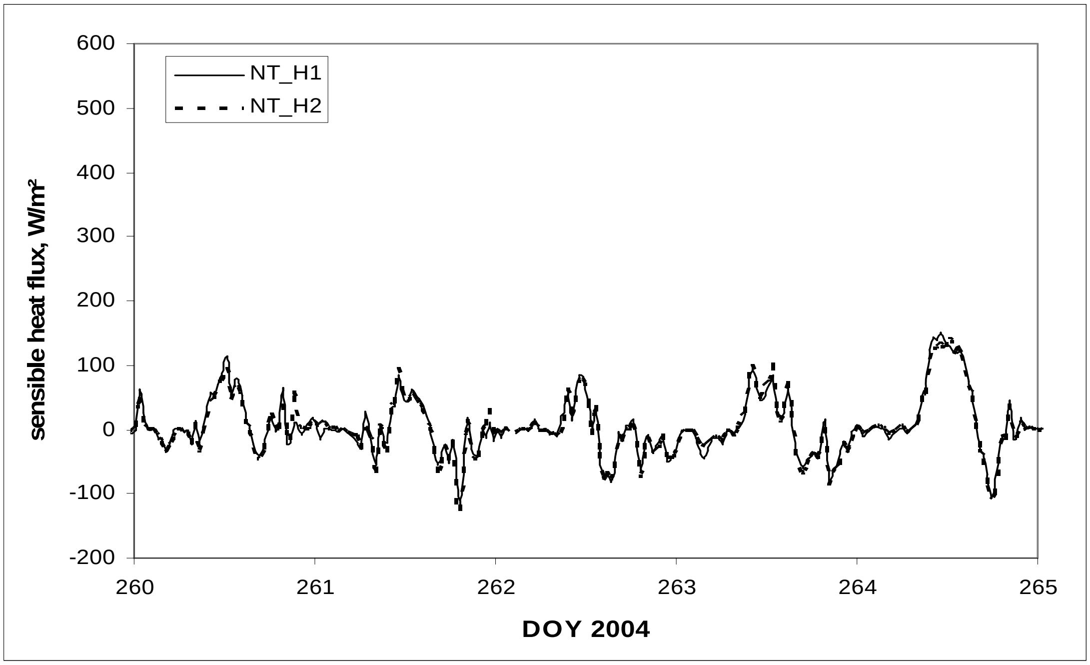

Figure 5: Comparison of 30-min mean sensible heat flux (H1 and H2) measured at the non-treated site in 2004

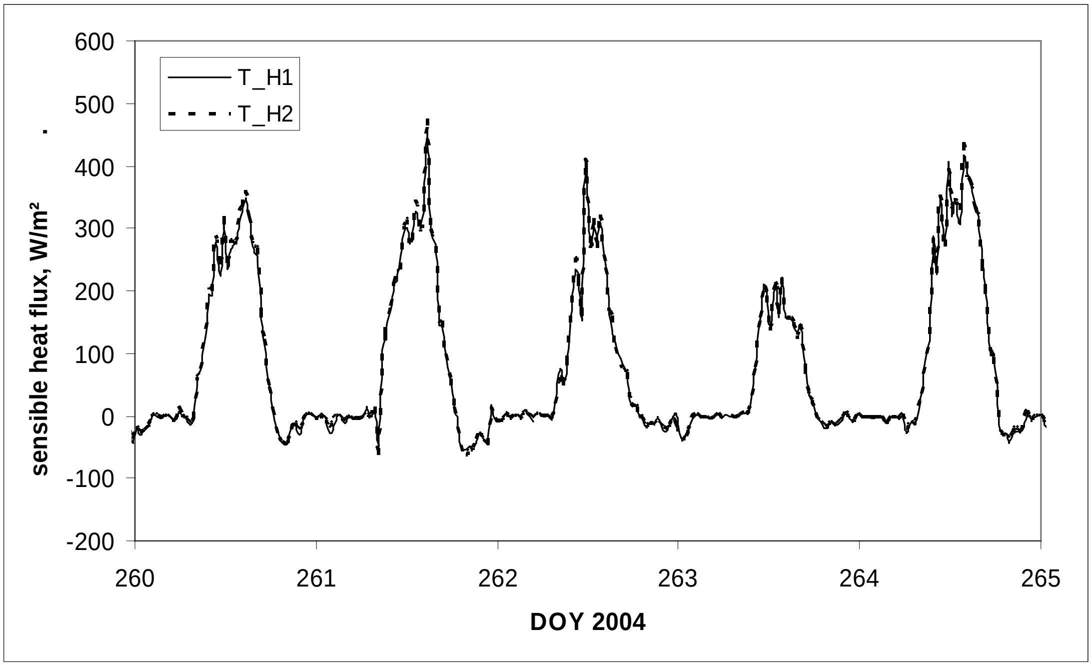

Figure 6: Comparison of 30-min mean sensible heat flux (H1 and H2) measured at the herbicide-treated site in 2004

The setups of the OPEC systems were the same at the treated and non-treated sites except that their heights above the canopy were different (see Table 2). The same trends of sensible heats (H1 and H2) were observed at both sites in 2004 and 2005; each year H1 and H2 followed each other closely. The results of statistical analyses (linear regression) for the year 2004 which compare treated and non-treated sites are shown in Table 5. Sensible heat (H1) was arbitrarily chosen as the independent axis. A close correlation between the values of H1 and H2 indicate the validity of measured sensible heat flux data measured in the field by the pairs of OPEC systems.

Table 5: Regression analyses of sensible heat flux at both the sites in 2004

Site (2004)	Regression	Sample (n)	SEE (W/m²)	adj.R²
Non-treated site	H2 = 0.98 H1 + 0.71	16500	10.12	0.98
Treated site	H2 = 0.98 H1 + 0.99	16417	11.03	0.99

4.1.3. Soil heat flux

The amount of heat flux going into the ground was measured using two soil heat flux plates (REBS Inc.). However, one soil heat flux plate did not function well at the non-treated site and data from only one plate were used instead at this site. The non-treated site was densely populated with saltcedar indicating that the soil heat flux values obtained there would be less than those measured at the treated site. At the treated site, two soil heat flux plates were placed at different locations within the canopy and outside, to reflect the variation of energy going into heating the ground based on dead canopy distribution.

Two chromel-constantan temperature thermocouples were placed at 2 and 6 cm below the ground and above the soil heat flux plates placed at 8 cm below the ground to monitor the temperature gradient above the plates. A volumetric soil moisture sensor Model CS616 (CSI) was inserted at 45° angle to monitor moisture in the top 20 cm of the soil profile. The rate of change in heat storage per unit surface area in the top 8 cm layer of the soil profile was determined using soil moisture values, mean temperature above the soil heat flux plate, and soil properties (as described by Campbell 2004). The soil heat flux at the surface was then determined by adding the change in stored heat per unit surface area in the top 8 cm layer to the soil heat flux measured at 8 cm by the soil heat flux plate to obtain the surface soil heat flux (G).

4.1.4. Latent heat flux

The latent heat flux was calculated as a residual from the energy budget equation (see Equation 2). The 30-min mean latent energy (LE in W/m^2) values were converted into cumulative daily LE values and the units converted to MJ/m^2. These data were then converted into equivalent depth of water in mm. From MJ/m^2, equivalent depth of water was obtained by dividing with latent heat of vaporization for water, which is about 2.45 MJ/kg at 20^oC. Daily flux behaviors of individual components of the energy budget and the resultant LE values as a residual plotted against day of the year (2005 as an example) are shown in Figures 7 and 8 for both non-treated and treated sites. The acronyms in the Figures 7 and 8 are as follows:

NT_Rn = Net radiation measured at non-treated site
T_Rn = Net radiation measured at treated site
NT_G = Soil heat flux measured at non-teated site
T_G = Soil heat flux measured at treated site
NT_LE = Latent heat flux at non-treated site calculated as a residual from energy balance (see equation 2)
T_LE = Latent heat flux at treated site calculated as a residual from energy balance (see equation 2)
NT_H = Sensible heat flux measured by OPEC system at non-treated site
T_H = Sensible heat flux measured by OPEC system at treated site
NLWS-Rs = Global solar radiation measured at North Lake Weather Station
NLWS-Ra = Extraterrestial radiation calculated using methodology described by Allen and others, 1998 and data collected at North Lake Weather Station
NLWS-Rso= Clear solar sky solar radiation using methodology described by Allen and others, 1998

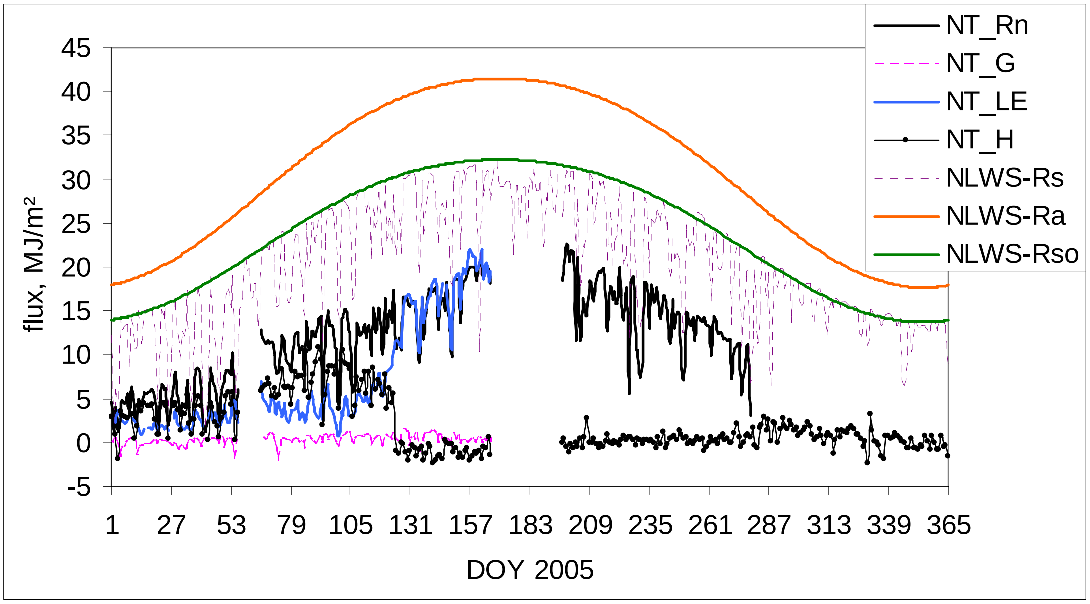

Figure 7: Daily flux behavior of individual components of energy budget measured at the non-treated site in the year 2005

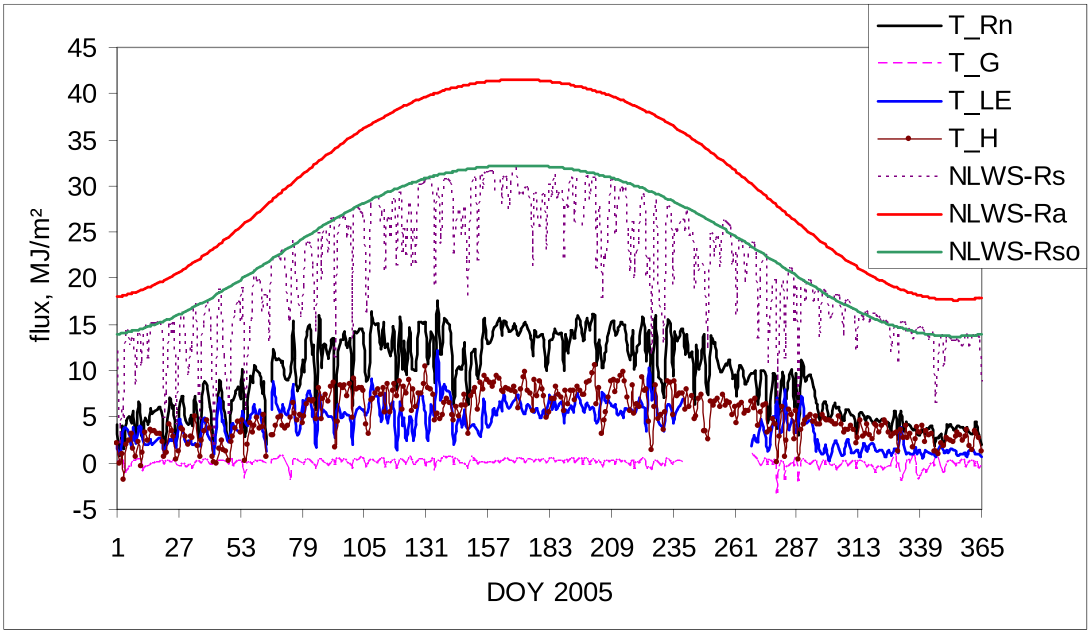

Figure 8: Daily flux behavior of individual components of energy budget measured at the treated site in the year 2005

4.1.5. 3D-SEC sensible heat

Periodic measurements of sensible heat (3D_H) were measured using a three-dimensional sonic anemometer (Model CSAT3 by CSI) as a check for OPEC measured sensible heat (H). The eddy covariance sensible heat measured by CSAT3 was corrected as follows: coordinate rotation of the 3D sonic wind speed vectors following Tanner and Thurtell (1969), sonic temperature correction to actual temperature following Munger and Loescher (2004). All data collected during rainy periods and during cleaning of the 3D-SEC sensors were rejected.

Orientation corrections helped in the removal of tilt errors and/or cross contamination among components of eddy flux. Data contamination can be shown by plotting momentum flux, COV(vw), as a function of wind direction. As an example, data contamination before and after correction at the non-treated site for the year 2005 is shown in Figures 9 and 10. Most contaminated data were either in the direction of prevailing wind through the tower or behind the CSAT3 sensor. An example of similar corrections is shown in Figures 11 and 12 for treated site in the year 2004.

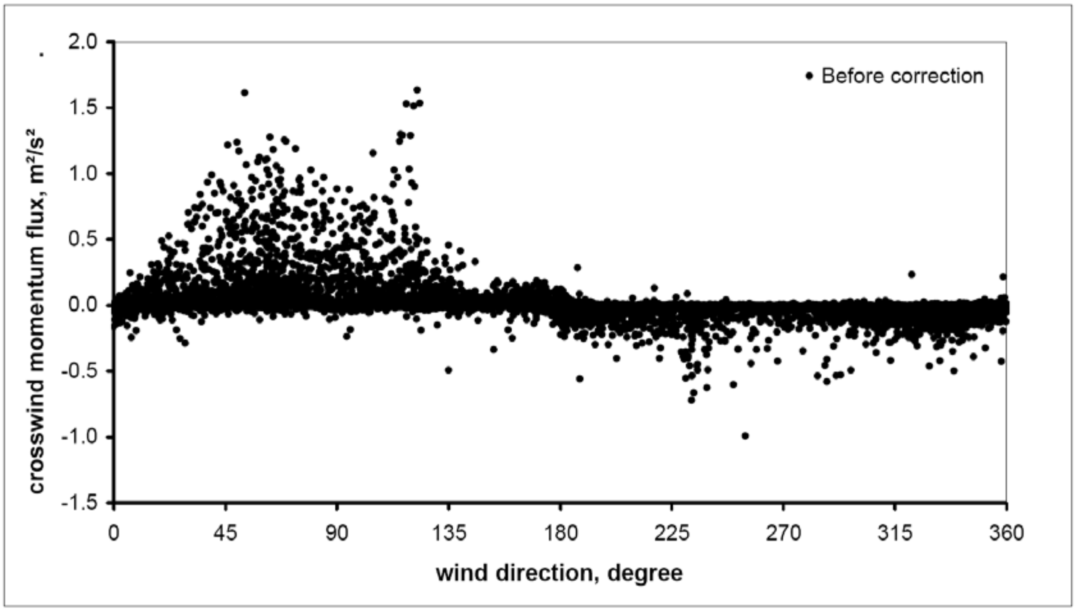

Figure 9: Cross-wind momentum flux [COV(vw)] in planar fit coordinates as a function of wind direction before correction for orientation (Year 2005, non-treated site)

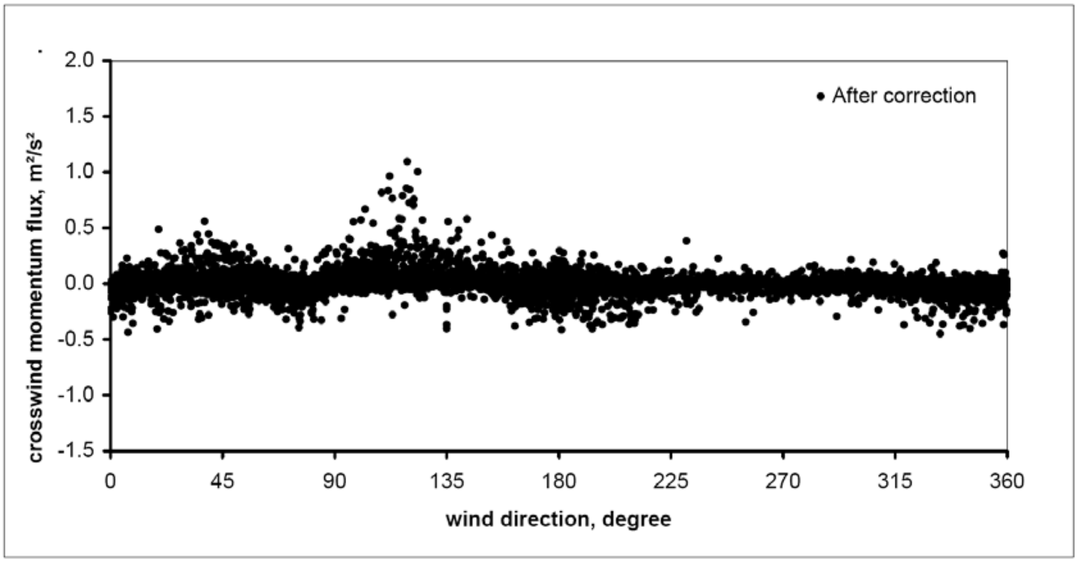

Figure 10: Cross-wind momentum flux [COV(vw)] in planar fit coordinates as a function of wind direction after correction for orientation (Year 2005, non-treated site)

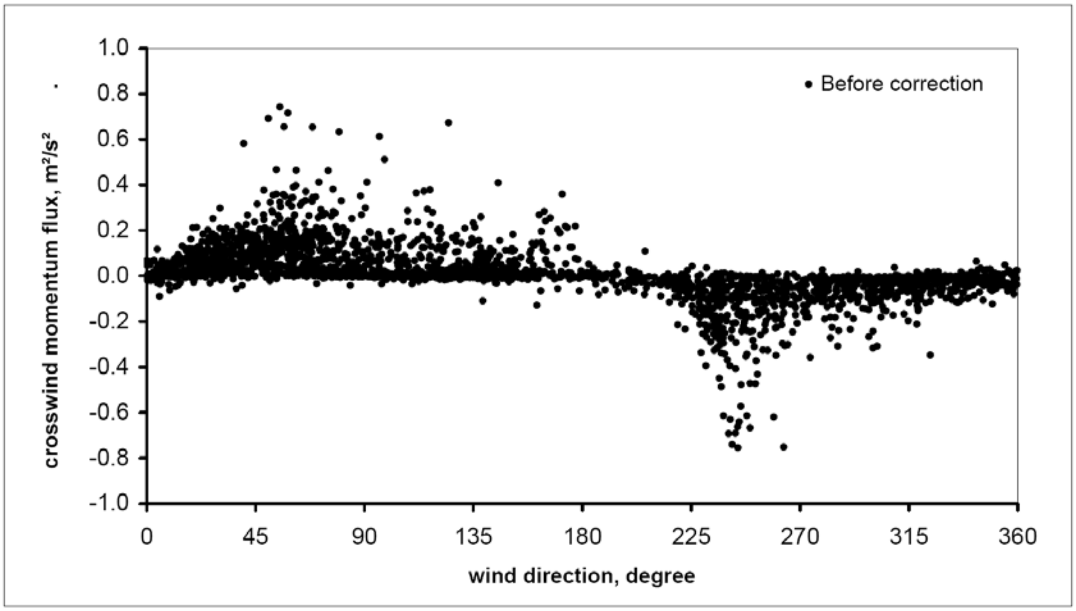

Figure 11: Cross-wind momentum flux [COV(vw)] in planar fit coordinates as a function of wind direction before correction for orientation (Year 2004, treated site)

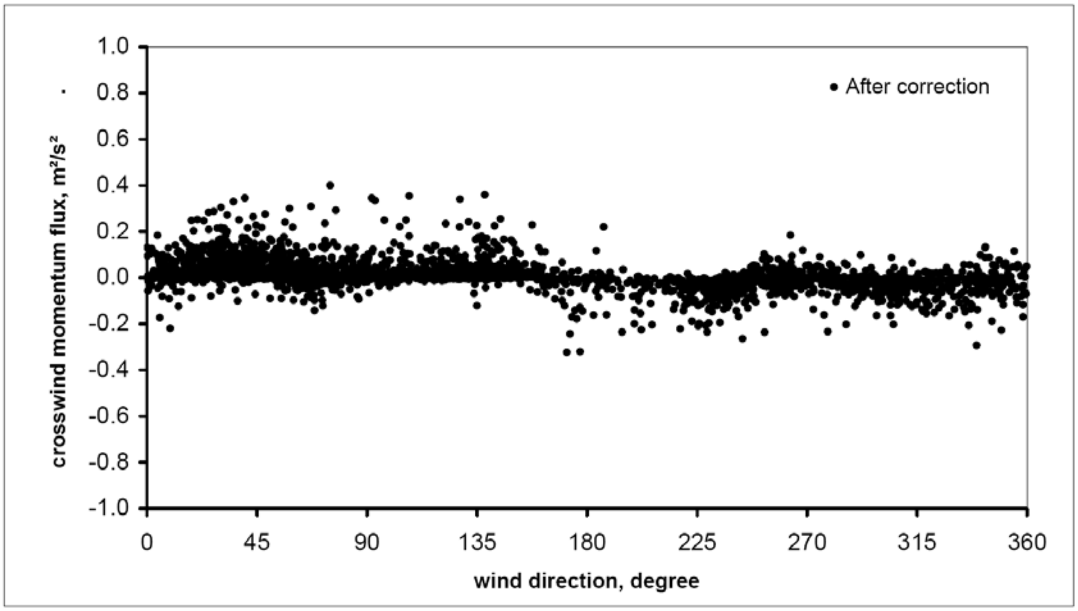

Figure 12: Cross-wind momentum flux [COV(vw)] in planar fit coordinates as a function of wind direction after correction for orientation (Year 2004, treated site)

4.1.6. Latent heat flux using krypton hygrometer

A krypton hygrometer (Model KH2O by CSI) was used to measure water vapor density at both the treated and non-treated sites. The eddy covariance latent heat flux (3D_LE) was derived using measurements of vapor density by KH2O and corrected wind speed measured by CSAT3. The krypton hygrometer was calibrated by the manufacturer over a wide range of vapor densities in a controlled environment. The 3D_LE was corrected for oxygen density fluctuation as specified by the manufacturer (CSI), for absorption of oxygen by van Dijk and others (2003), for density effects due to heat and water vapor transfer (Webb et al. 1980), and for sensor separation to reduce flow distortion (Horst 1973).

4.1.7. Verification of sensible heat flux

Eddy covariance derived sensible heat fluxes measured by the OPEC system and 3D-SEC system were compared to verify long-term sensible heat measurements from OPEC system and to make sure that the OPEC sensors were not drifting. The 30-min corrected flux data using the 3D-SEC system were compared with flux measurements of OPEC for the same duration and plotted for five days chosen randomly as a sample-plot (DOY 245 to 250 in the month of September 2004). It can be observed from Figures 13 and 14 that sensible heat measured by the two systems followed the same trends and behaved similarly during unstable daytime conditions and during stable nighttime conditions. Similar trends were observed in 2005 for both sites.

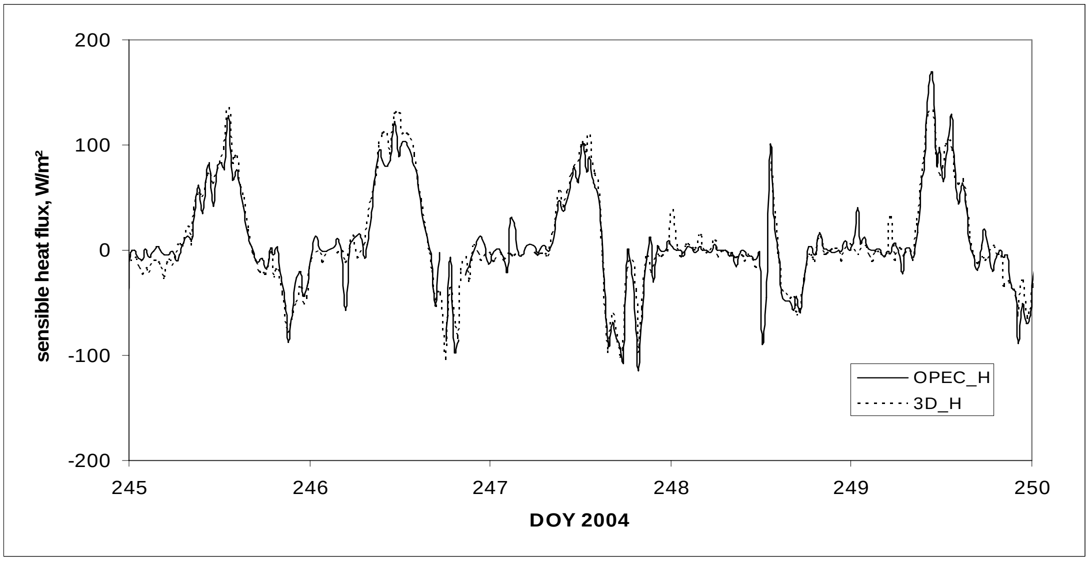

Figure 13: Comparison of 30-minute mean sensible heat flux measured using OPEC and 3D-SEC at the non-treated site in the year 2004

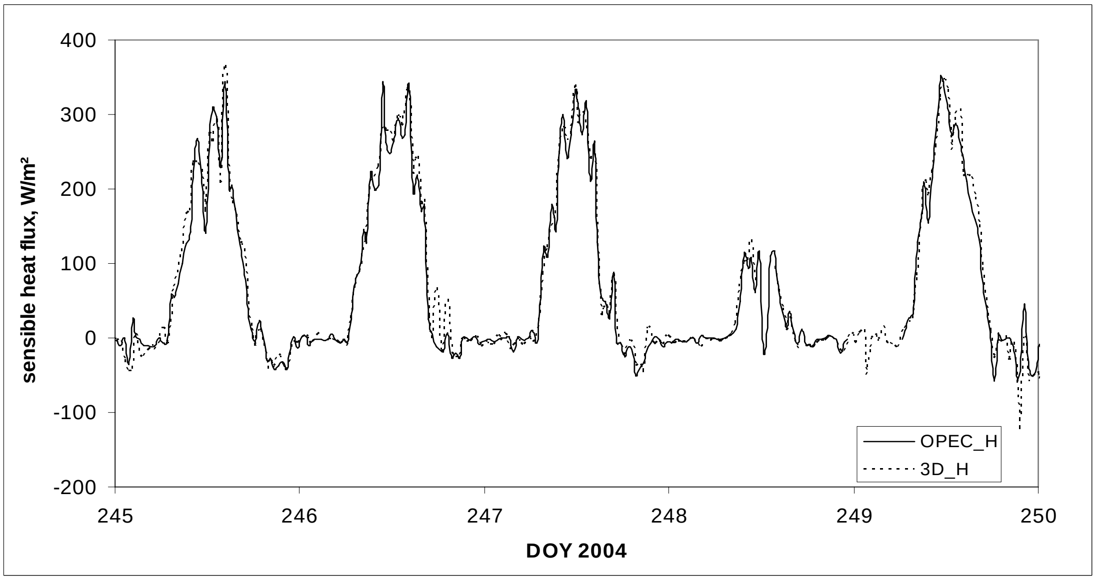

Figure 14: Comparison of 30-minute mean sensible heat flux measured using OPEC and 3D-SEC at the treated site in the year 2004

4.1.8. Verification of latent heat flux

Thirty-minute latent heat flux calculated as a residual from energy balance using the OPEC system was compared to measured latent heat flux using the KH2O. A sample plot of comparison is shown in Figures 15 and 16 for the non-treated and treated sites during the same period in 2004. Latent heat flux measured by KH2O was often lower than latent heat calculated as a residual at both sites. The difference ranged from -83% to 68% with an average of 22% for 172 days of data comparison at the non-treated site during 2004 and 2005 measurements. Of this range, a difference of 0 to 30% was observed 97 days out of 172 days (56% of the time) and 31% to 50% was observed 50 days out of 172 days (29% of the time) of measurements. The difference at the treated site ranged from -80% to 88% with an average of 29% for 42 days of data comparison. Of this range, a difference of less than 0% was observed for 12 days, 0 to 30% was observed for 5 days, 31% to 50% for 7 days, and above 50% for 18 days out of 42 days respectively. See data in Appendix A. A similar lower trend was observed by Bawazir (2000) in measurements of latent heat using KH2O at the Bosque del Apache National Wildlife Refuge dense saltcedar site in 1999 when compared to latent heat calculated as a residual. Residual latent heat energy assumes energy budget closure of 1, that is, all the available energy (Rn-G) is partitioned into sensible and latent heat (H + LE); energy budget closure = 1. The mean energy budget closure [(3D_H + 3D_LE) / (Rn – G)] using a 3D-SEC system measurements of 0.85 and 0.90 was observed at non-treated and treated sites respectively.

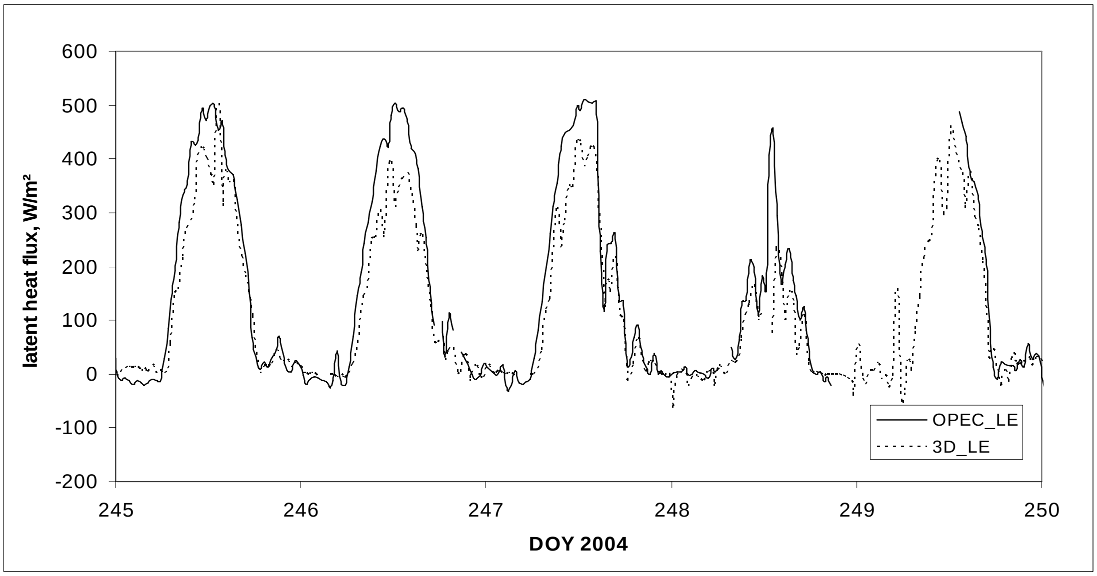

Figure 15: Comparison of 30-minute mean latent heat flux measured using OPEC and 3D-SEC at non-treated site in the year 2004

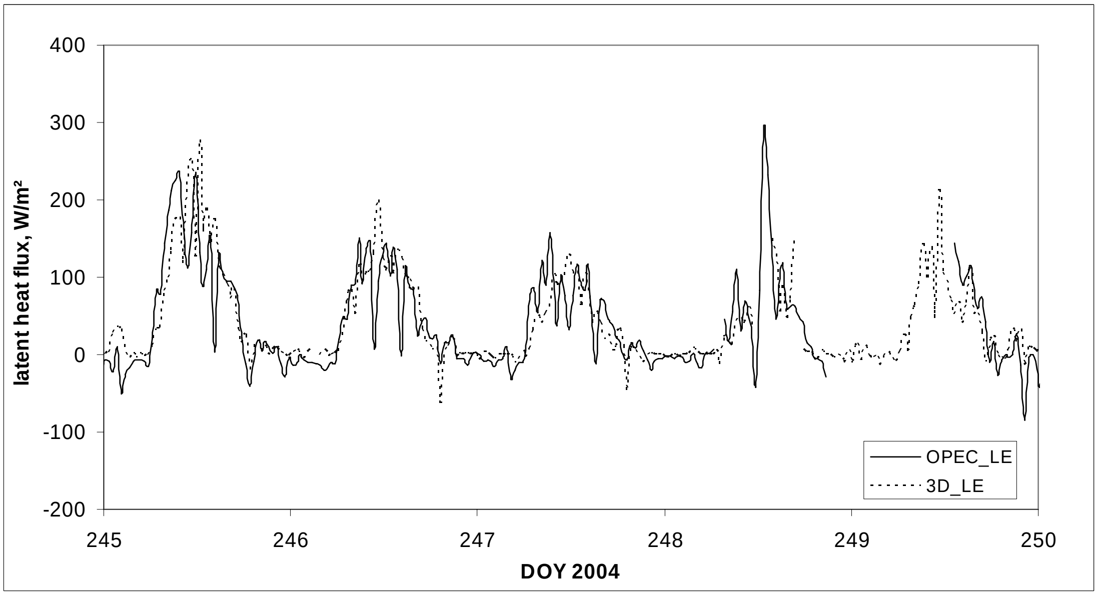

Figure 16: Comparison of 30-minute mean latent heat flux measured using OPEC and 3D-SEC at treated site in the year 2004

4.2. Weather data

Relative humidity, air temperature, wind speed, and direction were measured at both the non-treated and treated sites. Relative humidity and air temperature were used in the correction of 3D-SEC measurements and for checking measured virtual temperature by the CSAT3. Wind speed and direction were used similarly to check the horizontal measurements of wind speed by 3D-SEC and also to check and observe the direction of prevailing wind at both sites.

Thirty minute mean wind direction was measured using a wind sentry model 03001-L (CSI). The prevailing wind directions were referenced to true north. The wind direction at the non-treated site (Figure 17) was observed as mostly coming from the southeast to the southwest direction during summers and coming from the northern direction during winters. In the northern direction fetch distance was adequate, being more than 1,000 ft for the sensor to measure the prevailing wind above saltcedar. Only 7% of the wind was observed at the non-treated site coming from the northeast-east direction where the fetch was limited to about 1,000 ft.

At the treated site the wind was predominantly from the southwest-west direction (see Figure 18). At this site the fetch distance extended up to 840 ft in the southern direction. Only 14% of the time the wind blew from south-southwest direction and 86% of the time the wind blew over the treated site where the fetch distance was more than 1,300 ft (see Figure 2 and Figure 18). Winds from the north blew over saltcedar for a fetch of 1,320 ft. This indicated that the prevailing winds blew over adequate fetch distances in all directions that were measured and analyzed to observe the behavior of wind at both the study sites successfully. Tables 6 and 7 indicate the analysis of monthly wind direction and frequency for the non-treated and treated sites in the year 2004 and 2005 as an example.

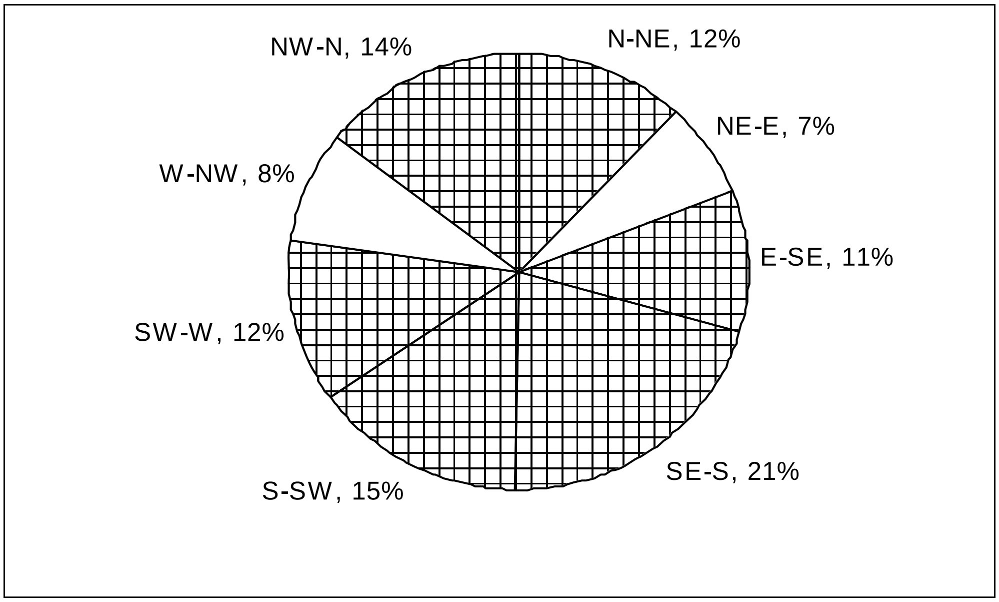

Figure 17: Wind directional analysis at the non-treated site in the year 2004

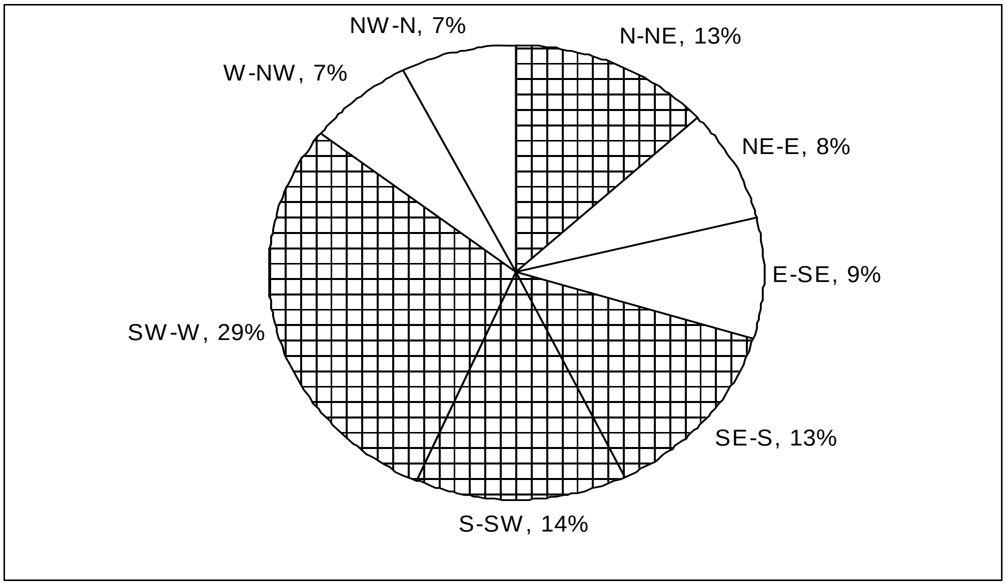

Figure 18: Wind directional analysis at the treated site in the year 2004

Table 6: Monthly wind direction analysis at the non-treated site for the year 2004-2005

				September 2004			October 2004			November 2004			December 2004		
	Wind Direction		**deg**	**freqn**	**%**	**cumm %**	**freqn**	**%**	**cumm %**	**freqn**	**%**	**cumm %**	**freqn**	**%**	**cumm %**
1	N-NE	0 - 45	45	178	12%	12%	165	11%	11%	220	15%	15%	207	14%	14%
2	NE-E	46 - 90	90	120	8%	21%	99	7%	18%	95	7%	22%	103	7%	21%
3	E-SE	91 - 135	135	147	10%	31%	137	9%	27%	128	9%	31%	120	8%	29%
4	SE-S	136 - 180	180	302	21%	52%	369	25%	52%	189	13%	44%	170	11%	40%
5	S-SW	181 - 225	225	245	17%	69%	211	14%	66%	169	12%	56%	138	9%	50%
6	SW-W	226 - 270	270	197	14%	83%	181	12%	78%	182	13%	68%	184	12%	62%
7	W-NW	271 - 315	315	89	6%	89%	125	8%	86%	151	10%	79%	214	14%	76%
8	NW-N	316 - 360	360	162	11%	100%	201	14%	100%	306	21%	100%	352	24%	100%
				January 2005			**February 2005**			**March 2005**			**April 2005**		
	Wind Direction		**deg**	**freqn**	**%**	**cumm %**	**freqn**	**%**	**cumm %**	**freqn**	**%**	**cumm %**	**freqn**	**%**	**cumm %**
1	N-NE	0 - 45	45	146	10%	10%	141	12%	12%	165	13%	13%	120	8%	8%
2	NE-E	46 - 90	90	58	4%	14%	36	3%	15%	57	5%	18%	78	5%	14%
3	E-SE	91 - 135	135	84	6%	20%	67	6%	20%	67	5%	23%	111	8%	21%
4	SE-S	136 - 180	180	245	17%	37%	228	19%	39%	191	15%	38%	295	20%	42%
5	S-SW	181 - 225	225	163	11%	48%	99	8%	47%	182	14%	53%	240	17%	59%
6	SW-W	226 - 270	270	177	12%	60%	148	12%	59%	285	23%	75%	261	18%	77%
7	W-NW	271 - 315	315	234	16%	76%	108	9%	68%	156	12%	88%	149	10%	87%
8	NW-N	316 - 360	360	81	5%	100%	146	10%	100%	99	7%	100%	50	3%	100%
				May 2005			**June 2005**			**July 2005**			**August 2005**		
	Wind Direction		**deg**	**freqn**	**%**	**cumm %**	**freqn**	**%**	**cumm %**	**freqn**	**%**	**cumm %**	**freqn**	**%**	**cumm %**
1	N-NE	0 - 45	45	125	8%	8%	40	4%	4%	95	8%	8%	166	11%	11%
2	NE-E	46 - 90	90	83	6%	14%	34	3%	7%	65	5%	13%	67	5%	16%
3	E-SE	91 - 135	135	151	10%	24%	116	11%	17%	121	10%	22%	170	11%	27%
4	SE-S	136 - 180	180	406	27%	51%	335	31%	48%	328	26%	48%	409	27%	55%
5	S-SW	181 - 225	225	236	16%	67%	202	19%	67%	222	18%	66%	249	17%	71%
6	SW-W	226 - 270	270	192	13%	80%	213	20%	87%	123	10%	76%	123	8%	80%
7	W-NW	271 - 315	315	96	6%	87%	67	6%	93%	84	7%	83%	84	6%	85%
8	NW-N	316 - 360	360	199	13%	100%	79	7%	100%	220	17%	100%	220	15%	100%

Table 7: Monthly wind direction analysis at the treated site for the year 2004-2005

				September 2004			**October 2004**			**November 2004**			**December 2004**		
	Wind Direction		**deg**	**freqn**	**%**	**cumm %**	**freqn**	**%**	**cumm %**	**freqn**	**%**	**cumm %**	**freqn**	**%**	**cumm %**
1	N-NE	0 - 45	45	130	14%	14%	153	10%	10%	234	16%	16%	190	12%	12%
2	NE-E	46 - 90	90	85	9%	23%	111	7%	18%	112	8%	24%	123	8%	20%
3	E-SE	91 - 135	135	83	9%	32%	148	10%	28%	103	7%	31%	132	9%	29%
4	SE-S	136 - 180	180	131	14%	46%	266	18%	46%	144	10%	41%	157	10%	39%
5	S-SW	181 - 225	225	130	14%	60%	258	17%	63%	182	13%	54%	191	12%	52%
6	SW-W	226 - 270	270	232	25%	85%	375	25%	88%	413	29%	83%	527	34%	86%
7	W-NW	271 - 315	315	59	6%	91%	99	7%	95%	112	8%	90%	110	7%	93%
8	NW-N	316 - 360	360	80	9%	100%	78	5%	100%	140	10%	100%	106	7%	100%
				January 2005			**February 2005**			**March 2005**			**April 2005**		
	Wind Direction		**deg**	**freqn**	**%**	**cumm %**	**freqn**	**%**	**cumm %**	**freqn**	**%**	**cumm %**	**freqn**	**%**	**cumm %**
1	N-NE	0 - 45	45	122	8%	8%	218	16%	16%	144	11%	11%	81	6%	6%
2	NE-E	46 - 90	90	137	9%	17%	93	7%	22%	63	5%	15%	78	5%	11%
3	E-SE	91 - 135	135	122	8%	26%	99	7%	29%	74	6%	21%	107	7%	19%
4	SE-S	136 - 180	180	167	11%	37%	182	13%	43%	117	9%	30%	214	15%	33%
5	S-SW	181 - 225	225	215	14%	51%	198	14%	57%	227	17%	47%	202	14%	48%
6	SW-W	226 - 270	270	514	35%	86%	335	24%	81%	448	33%	80%	566	39%	87%
7	W-NW	271 - 315	315	130	9%	95%	121	9%	90%	171	13%	93%	137	10%	97%
8	NW-N	316 - 360	360	81	5%	100%	146	10%	100%	99	7%	100%	50	3%	100%
				May 2005			**June 2005**			**July 2005**			**August 2005**		
	Wind Direction		**deg**	**freqn**	**%**	**cumm %**	**freqn**	**%**	**cumm %**	**freqn**	**%**	**cumm %**	**freqn**	**%**	**cumm %**
1	N-NE	0 - 45	45	157	11%	11%	120	8%	8%	169	11%	11%	210	14%	14%
2	NE-E	46 - 90	90	126	8%	19%	110	8%	16%	148	10%	21%	133	9%	23%
3	E-SE	91 - 135	135	179	12%	31%	160	11%	27%	196	13%	34%	198	13%	36%
4	SE-S	136 - 180	180	225	15%	46%	185	13%	40%	192	13%	47%	205	14%	50%
5	S-SW	181 - 225	225	200	13%	60%	234	16%	56%	199	13%	61%	197	13%	63%
6	SW-W	226 - 270	270	392	26%	86%	476	33%	89%	354	24%	85%	329	22%	85%
7	W-NW	271 - 315	315	125	8%	94%	107	7%	97%	119	8%	93%	95	6%	92%
8	NW-N	316 - 360	360	84	6%	100%	48	3%	100%	111	7%	100%	121	8%	100%

4.3. Salinity measurements

Results from the Soil Water and Air Testing (SWAT) laboratory analysis indicated that there was higher soil salinity in the non-treated saltcedar site than the treated saltcedar site. The soils in this area, at both sites, were slightly alkaline (pH of 7.3 to 7.4). The salinity levels (EC) in the non-treated site decreased as the leaves senesced but later increased in late December 2004 through early February 2005. However, the salinity was noticed to increase in early March 2005 (Figure 19). This coincided with the budbreak of leaves in the non-treated site.

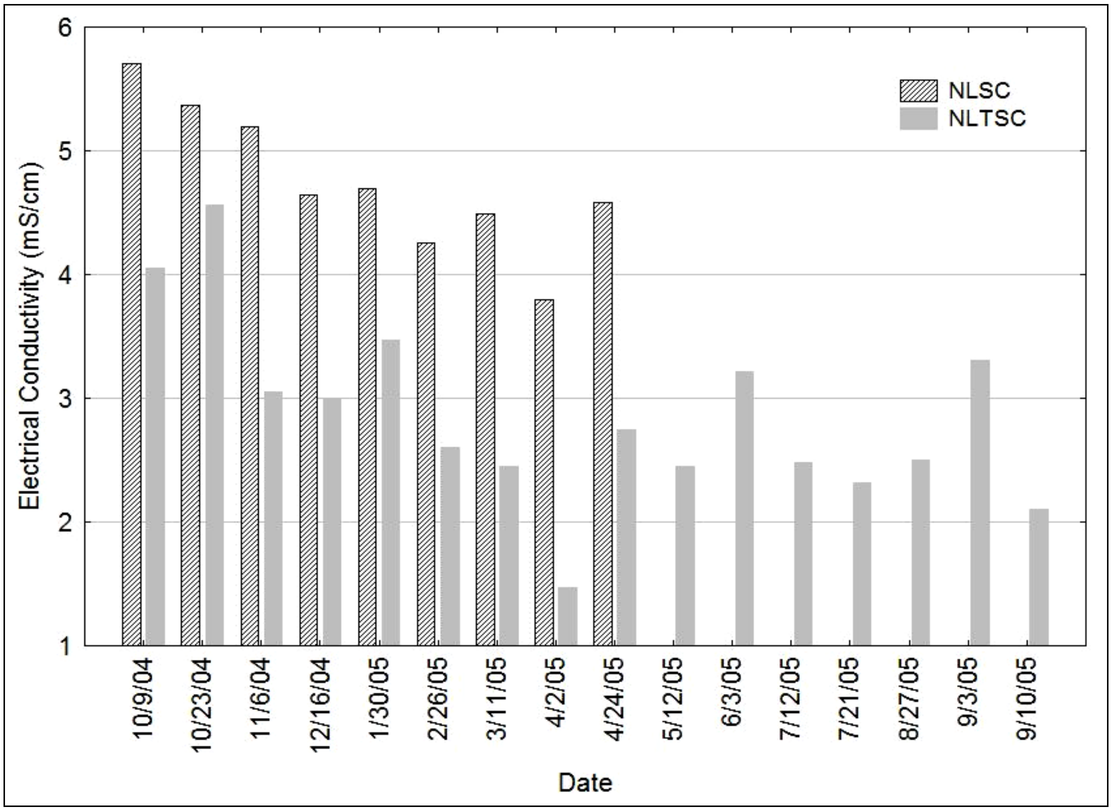

Figure 19: Comparison of salinity between the non-treated and treated sites (NLSC refers to non-treated site and NLTSC refers to the treated site)

The SWAT laboratory results of soil EC (< 6mS/cm) of both treated and non-treated sites indicated that they would be able to sustain plants that are moderately sensitive to salinity, such as cottonwood and other native riparian vegetation. Laboratory tests of soil samples at both sites show that the soils do not have sodium related problems (SAR <13). The collected data indicated that the salinity in the treated site generally followed a declining trend (see Figure 19).

4.4. Reference ET

The ASCE Standardized Reference ET equation was used to calculate ET_{os} (mm) referenced to grass using the data measured at north lake weather station (NLWS). Daily ET_{os} values at the NLWS ranged from 0.61 mm to 7.53 mm in the year 2004. In the year 2005 the values of ET_{os} varied from 0.60 mm to 9.14 mm.

The ratio of measured ET to ET_{os} is known as the crop coefficient (Kc). It was observed in 2004 that the mean crop coefficient value at the non-treated site was 0.94 and in the year 2005 for the few days that data were collected the mean value of 0.60 was observed.

The solar radiation data from the NLWS were analyzed and plotted with respect to time as shown in Figure 20 for the year 2004 and in Figure 21 for the year 2005. Extraterrestrial radiation (Ra) is the amount of solar radiation (short-wave) that would reach a horizontal surface without being obstructed by clouds or atmosphere. Rs is defined as solar radiation reaching the earth surface in a given period of time whereas Rso or clear sky solar radiation (Allen et al. 1998) is the amount reaching the earth in the same time interval but during cloudless conditions.

These three solar radiations plotted with respect to time in Figure 20 provide an understanding of the solar radiation behavior at the site. A very good envelope was formed that indicated that solar radiation was measured very well at the weather station. These solar radiation data were useful to predict the behavior of net radiation measured at both the treated and non-treated sites.

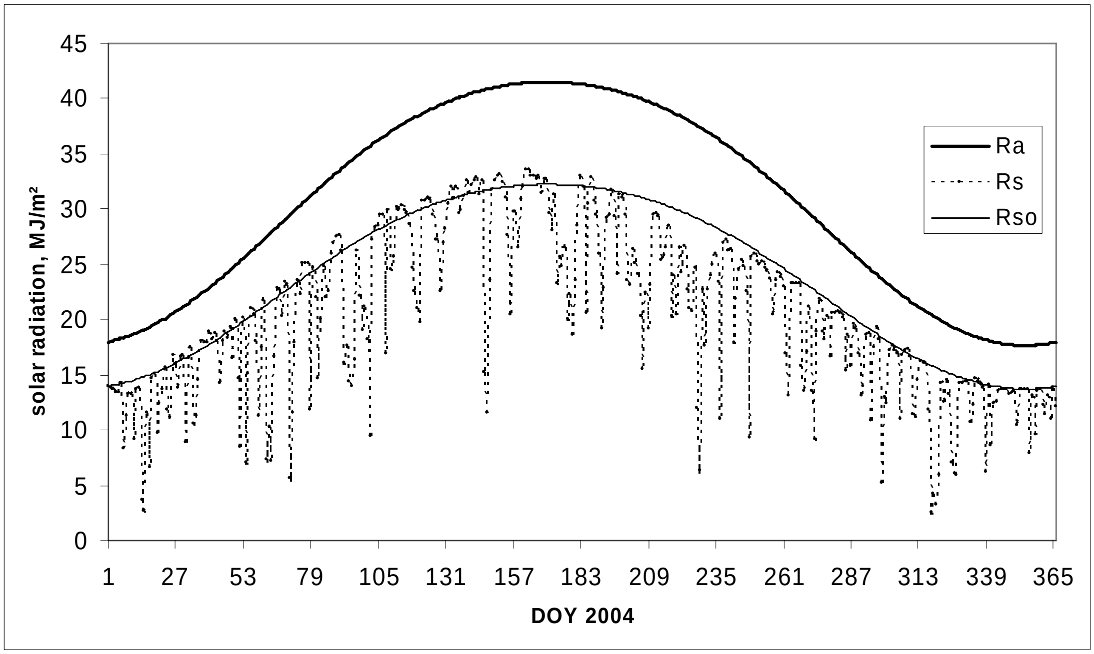

Figure 20: Comparison of solar radiation measured at north lake weather station (NLWS) in the year 2004

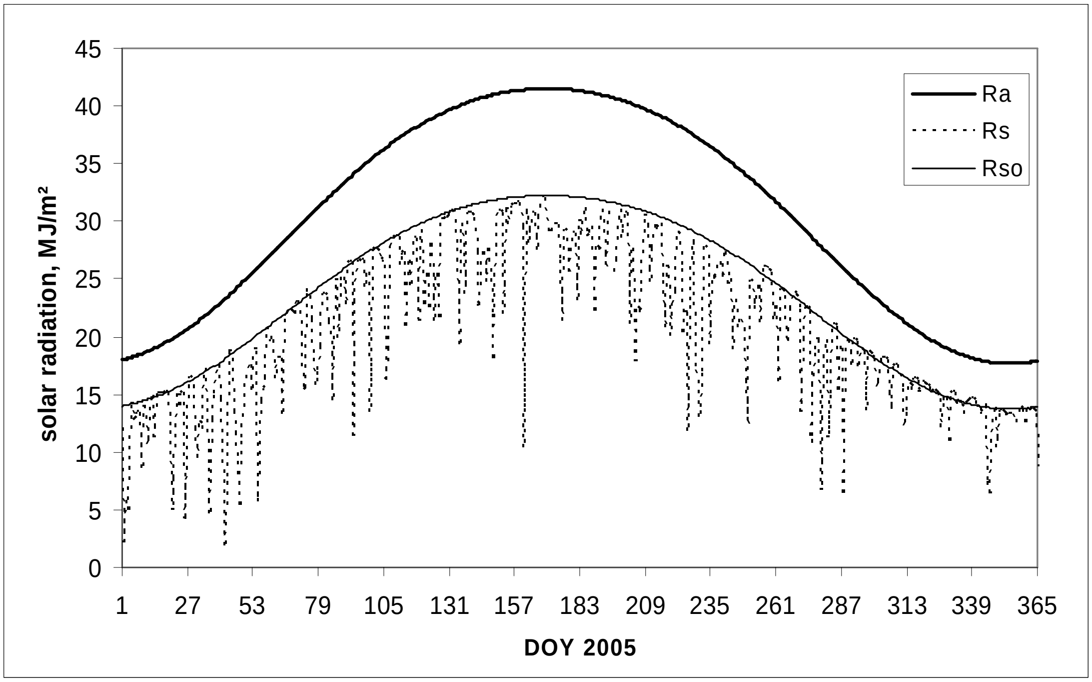

Figure 21: Comparison of solar radiation measured at north lake weather station in the year 2005

4.5. Comparison of flux data between the non-treated and treated sites

The fluxes of net radiation, soil heat, sensible, and latent heat measured at the two sites were compared to each other to observe the variations. Salinity measurements at both sites were also compared.

4.5.1 Comparison of net radiation

Net radiation data are one of the most important and largest components of the energy budget. Thirty-minute mean values of net radiation data were compared between the non-treated and herbicide-treated sites. A sample of this comparison is shown in Figure 22. It was observed that the net radiation at the non-treated site was higher than at the treated site. This was because the saltcedar plants at the non-treated site absorbing more radiation than at the treated site, where most of the radiation was reflected by the soil, that is, the higher albedo.

It was also observed that during the growing season the net radiation flux measured at the non-treated site was higher than the treated site, but during the non-growing season, the net radiation flux values measured at both the sites were almost the same. This is due to the fact that during winter the saltcedar plants at the non-treated site were dormant. This continued until April 22, 2005 when the budbreak occurred at the non-treated site.

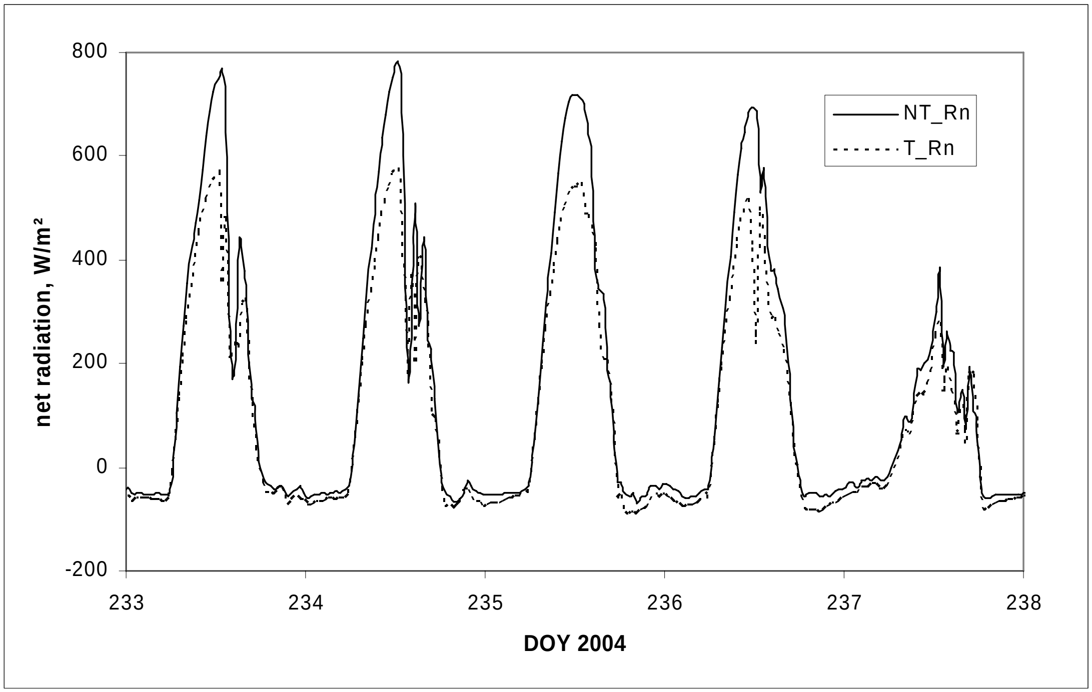

Figure 22: Comparison of 30-min mean net radiation flux measured at the non-treated and treated sites for the growing season in the year 2004

4.5.2. Comparison of soil heat flux

During the growing season it was observed that soil heat flux measured at the non-treated site was very small when compared to net radiation values. However, soil heat flux values increased during the non-growing season when compared to the growing season as the plants were dormant. It was also observed at the treated site that soil heat flux was higher when compared to the non-treated site by approximately 40% on average. This was expected since there was no plant cover at the treated site.

4.5.3. Comparison of sensible heat flux

The sensible heat flux measured at the treated and non-treated sites was compared at both sites. During the growing season smaller values of 30-min mean sensible heat flux data were measured at the non-treated site when compared to the treated site. This was expected as the energy was partitioned into mostly latent energy flux as the plants were active and transpiring. During the non-growing season (from November 4, 2004 to April 22, 2005), when plants were dormant at the non-treated site, both sites measured closer values of sensible heat flux data. Figure 23 shows the comparison of 30-min mean sensible heat values measured at the treated and non-treated sites for the growing season in the year 2005.

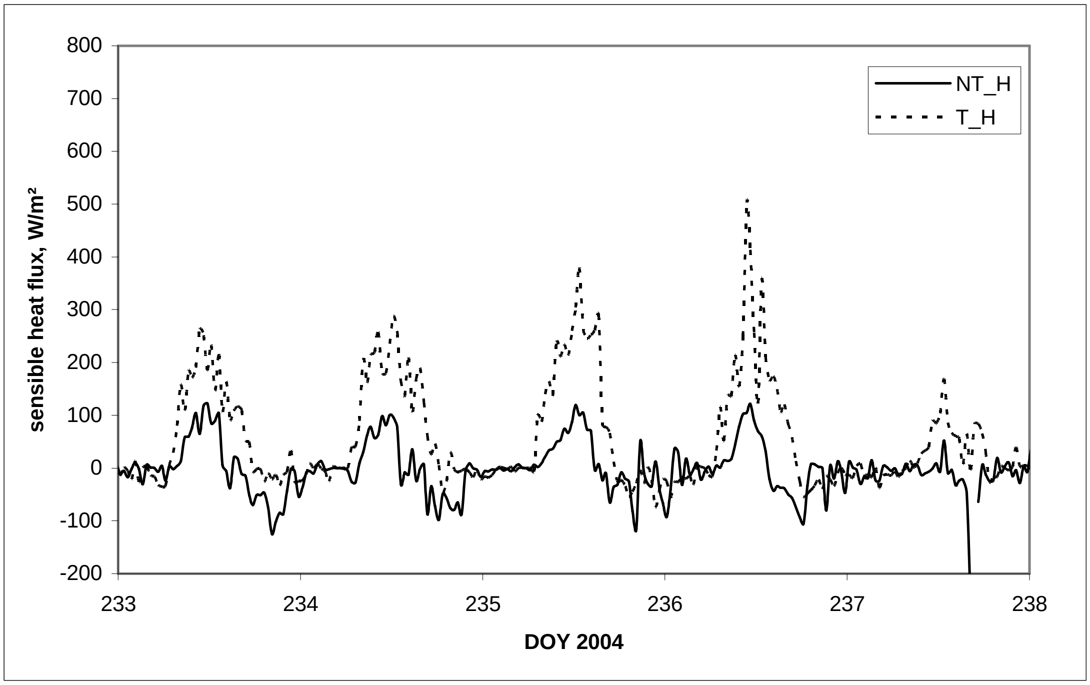

Figure 23: 30-min mean sensible heat flux data measured at the non-treated and treated sites for the growing season in the year 2005

4.5.4. Comparison of latent heat flux (ET)

The latent heat flux was calculated as a residual and is considered in this report as the ET of non-treated and treated saltcedar. Figure 24 shows the comparison of latent heat flux for a few days as a sample in the year 2004, during the growing period. It was observed that LE at the treated site was less than that at the non-treated site.

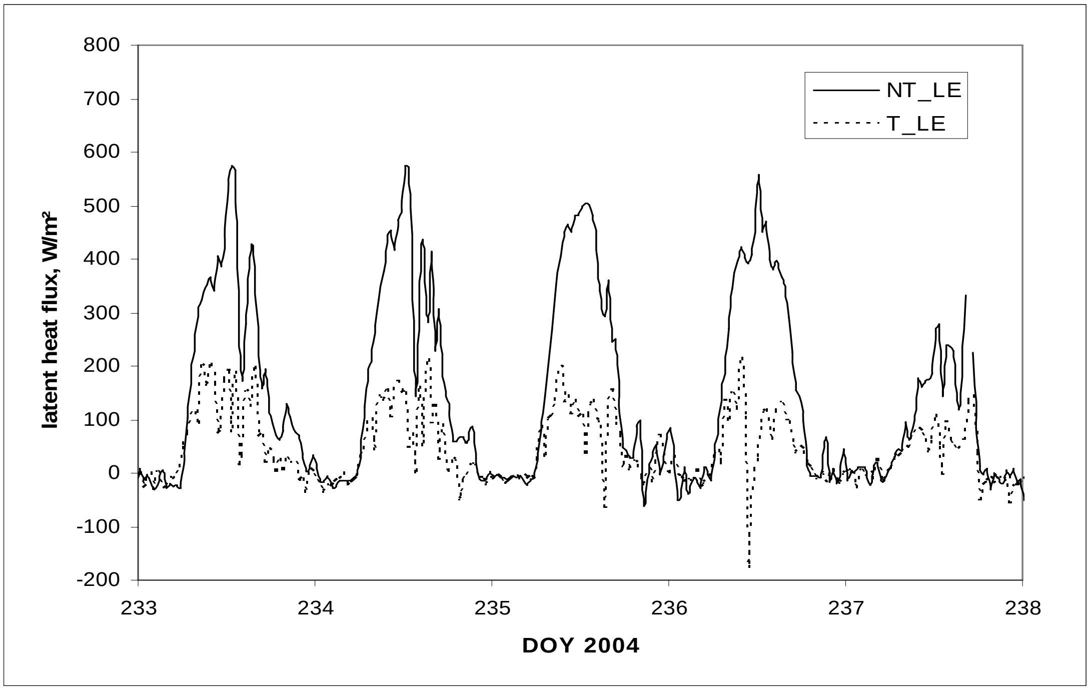

Figure 24: 30-min mean latent heat flux data measured at the non-treated and treated sites for the growing season in the year 2004

The daily values of latent energy flux at both the sites were compared during the growing and non-growing seasons. The days when data were missing at both sites were discarded from the comparison. Even if data were missing at one site, that particular day was discarded for comparison to eliminate any sort of "mis-comparison." The comparisons are shown in Table 8. For the 149 days of good data available for comparison during the non-growing season, it was observed that the treated site had more evapotranspiration than the non-treated site by a total of 59 mm for those days mentioned (ET at the treated site was higher than the non-treated site). During the growing season, the comparison of 83 days of good data indicated that the non-treated site had higher values of ET than the treated site by a cumulative of 185 mm for those days mentioned (ET at the non-treated site was higher). This means that a significant amount of water loss could be accounted for up to 57% during the growing season, if the saltcedar site is cleared using an herbicide–treatment.

Table 8: Comparison of ET rates measured at the treated and non-treated sites for the period of study during growing and non-growing seasons

	Dates	**ET (mm)**		**# of days**	**Diff, mm**	**% diff**
		Non-trd*	Trd†			
NGS‡	November 4, 2004 - April 22, 2005	161	220	149	-59	-37%
GS	August 14, 2004 - November 3, 2004 and April 23, 2005 - May 11, 2005	327	142	83	185	57%

*Non-treated site (NLSC)
†Treated site (NLTSC)
‡NGS: Non-growing season, GS: Growing season

The ET during the non-growing season was observed to be higher at the treated site. This might be due to several factors such as rainfall during the non-growing season, soil type, and the amount of organic matter at the site. The non-treated site soil had a layer of clay toward the surface and the organic matter during the non-growing season was higher due to the dead leaves from the trees when compared to the treated site. This might have reduced direct evaporation from soil at the non-treated site during the non-growing season as clay would reduce moisture loss and organic matter would act as mulch. The graphical representation of the difference in ET measured at both the sites is shown in Figure 25 for the days data were collected in the years 2004 and 2005.

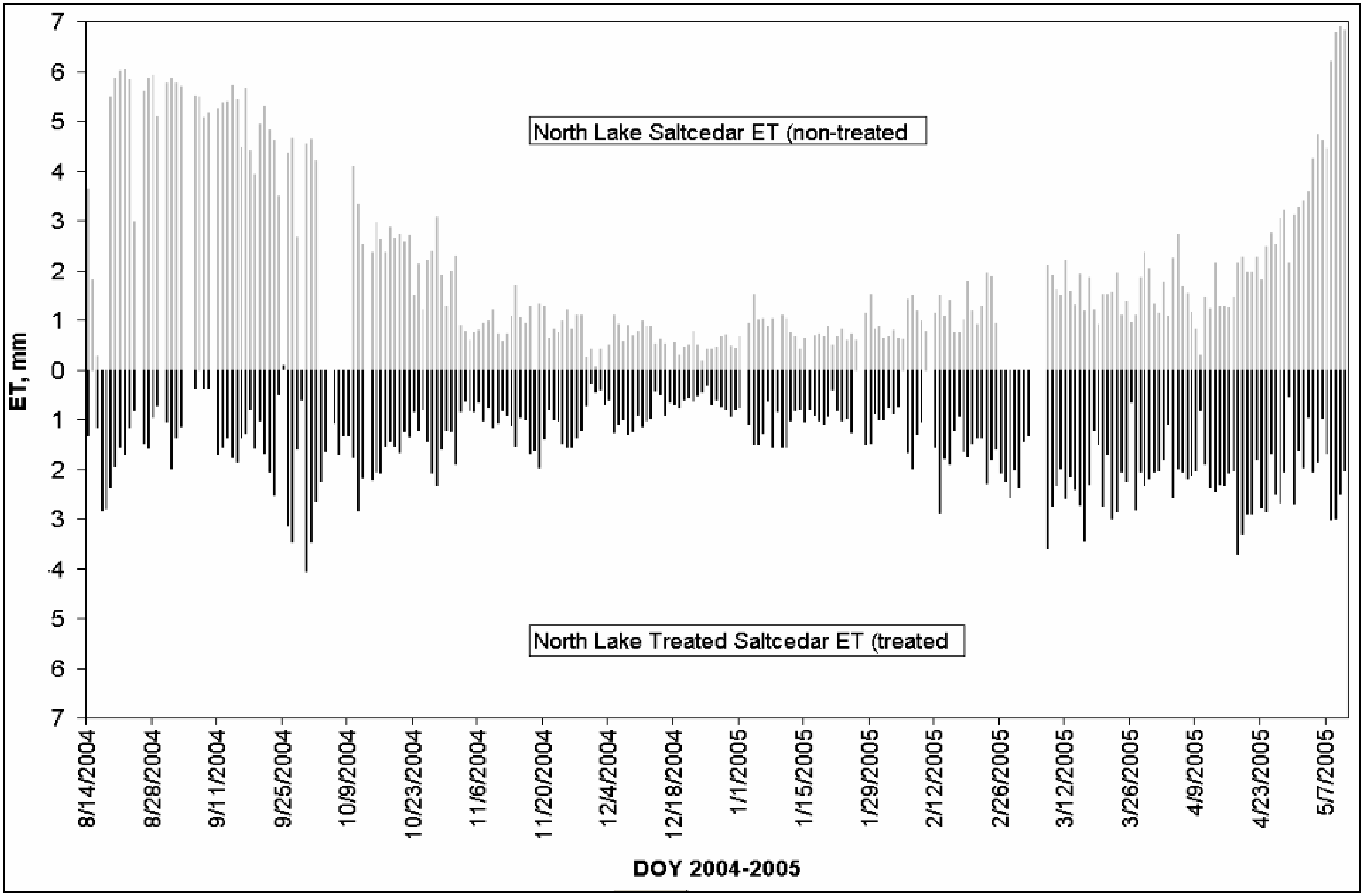

Figure 25: Comparison of ET rates between treated and non-treated sites in the year 2004 and 2005

4.6. Crop coefficient

Saltcedar ET at the non-treated site could not be measured for a full year due to flooding that occurred after May 11, 2005. Instead, the saltcedar ET measured at the Bosque during the same period was used to estimate annual ET of non-treated saltcedar at the Elephant Butte Reservoir study site.

The daily flux data at the Bosque were analyzed and compared to that of the non-treated site. The comparison is shown in Figure 26. The higher ET rates after day 131 (May 11, 2005) at the non-treated site were due to an increase in the water levels in the Reservoir that contributed to higher groundwater levels and soil moisture, creating conditions for higher ET.

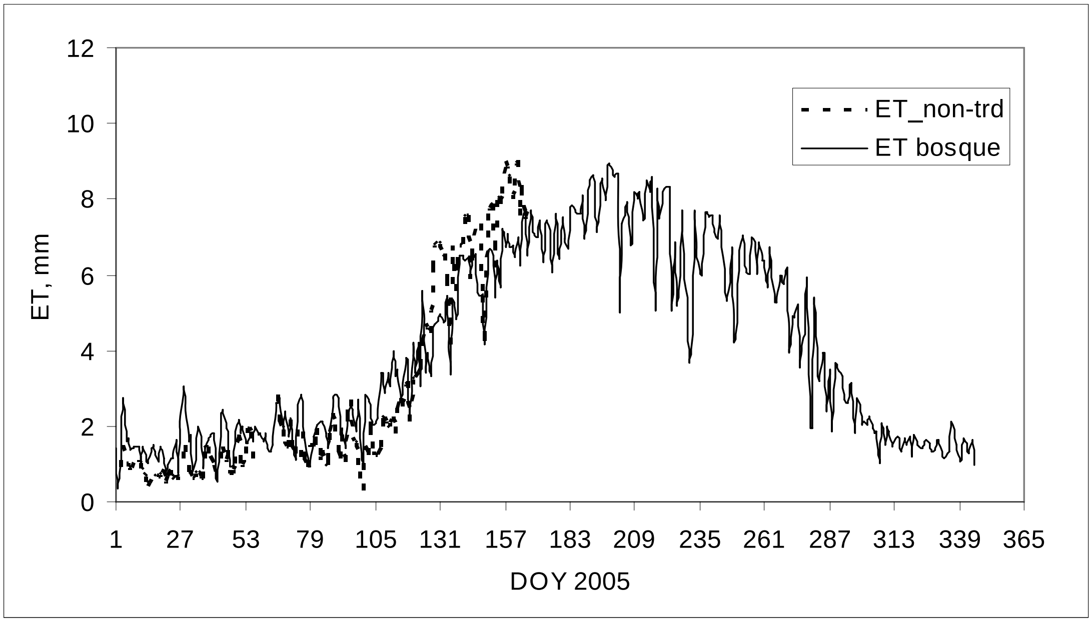

Figure 26: Comparison of saltcedar ET measured at the Bosque and the non-treated site for the year 2005

The crop coefficient (Kc) of saltcedar at Bosque was calculated as a ratio of the ET measured and reference ET_{os} calculated using the ASCE Standardized Reference Evapotranspiration Equation (Allen et al. 2003) referenced to short crop (see Equation 6). The growing degree days (GDD) were calculated using the base temperature of saltcedar as 15.5°C (Bawazir 2000). GDD was calculated as shown:

$$\mathrm{GDD} = \left[\frac{\mathrm{Daily\ Tmax} + \mathrm{Daily\ Tmin}}{2}\right] - \mathrm{Base\ Temp.} \tag{7}$$

Where:

Daily Tmax = Daily maximum temperature in °C
Daily Tmin = Daily minimum temperature in °C
Base Temp.= Base temperature taken as 15.5°C for saltcedar

In the calculation of GDD, the maximum and minimum temperatures are replaced with base temperature to avoid negative values. Taking the cumulative GDD as abscissa and Kc as ordinate the crop coefficient curve was plotted as shown in Figure 27 and fitted with a fourth degree polynomial function ($R^2 = 0.78$). The Kc function obtained was:

$Kc = -2.2182 \times 10^{-12}(\text{cumulative GDD})^4 + 6.6592 \times 10^{-9}(\text{cumulative GDD})^3 - 6.7285 \times 10^{-6}(\text{cumulative GDD})^2 + 3.0672 \times 10^{-3}(\text{cumulative GDD}) + 0.3648$, where cumulative GDD is the cumulative growing degree days in degrees centigrade.

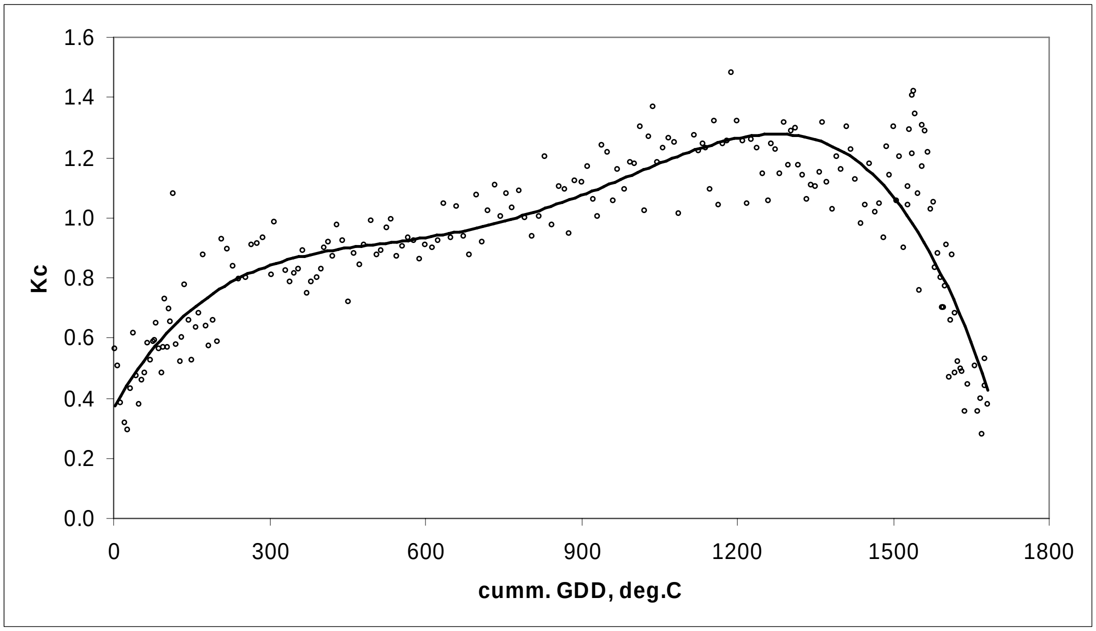

Figure 27: Crop coefficient as a function of cumulative GDD for saltcedar at the Bosque in 2005

A saltcedar crop coefficient as a function of cumulative growing degree days developed could be used to calculate the crop coefficient of saltcedar at other regions of different climate. Using this Kc function, and the reference ET (ET_{os}) calculated at the north lake weather station using Equation 6, the ET of non-treated saltcedar at the lake was estimated. Cumulative GDD for Bosque was estimated as 1,681.42 and at the non-treated site as 1,930.97 degrees Celsius, respectively. Due to difference in cumulative GDD at both sites, a multiplication factor of 0.871 (1,681.42/1,930.97) was used to adjust the cumulative GDD to estimate Kc of non-treated saltcedar. Appendices I and J give the daily flux data and weather data measured at Bosque. The crop coefficient, reference ET and GDD of saltcedar at the Bosque is given in Appendix K and for the lake in Appendix L. The ET "estimated" by using this function was plotted with the ET "measured" at the same site with respect to cumulative GDD (during growing season) as shown in Figure 28. From this comparison, it was found that the prediction of saltcedar ET at the non-treated site using the Kc function developed from Bosque was lower by 10% when compared with the measured ET value of non-treated saltcedar.

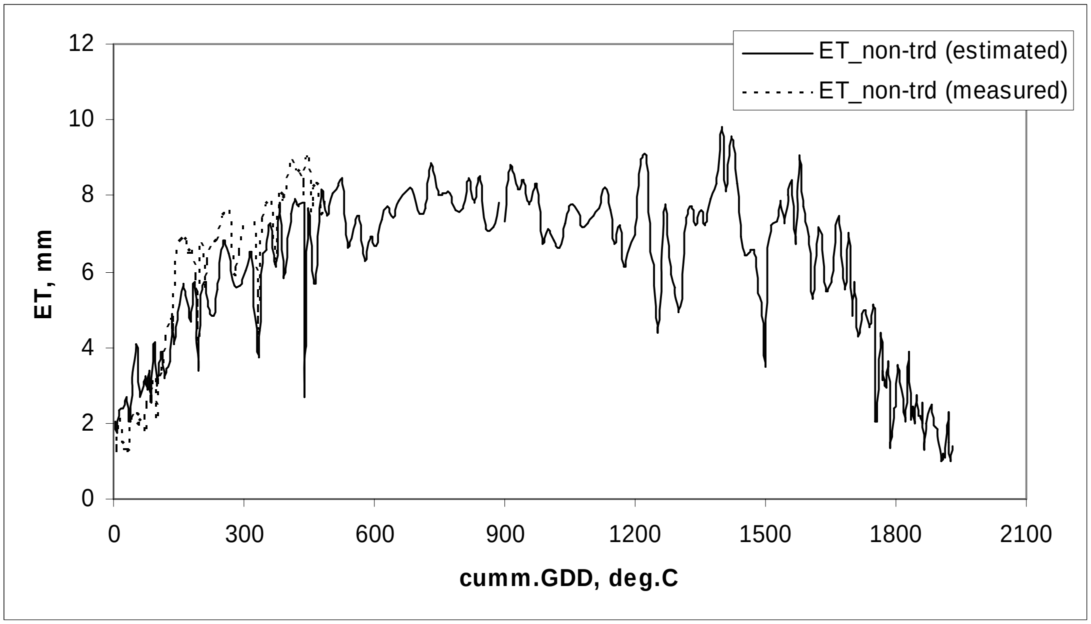

Figure 28: Comparison of measured and estimated saltcedar ET with respect to cumulative GDD at the non-treated site in 2005

The estimated ET based on cumulative GDD during the growing season at the non-treated site, when compared with ET measured at the treated site in 2005 for 189 days of data comparison, was 61%. This reflected the 1002 mm of ET as estimated at the non-treated site and 386 mm measured at the treated site. This percentage difference was close to the 57% ET difference (185 mm) based on a comparison of 83 days of measured ET as shown in Table 8. It should be noted that the 57% did not include ET difference during peak summer months where the difference in ET would be expected to be higher. The growing season for 2005 was based on saltcedar growth at the Bosque site from April 11 through November 14, 2005.

4.7. Comparison of salinity

The field data for salinity were collected from October 9, 2004 through July 21, 2005 for analysis. From the field measurements it was noticed that the EC/TDS at the treated site was lower than the non-treated site. The average percentage difference was about 33% during the period data were collected. The EC/TDS in the non-treated site was noticed to decline from when the leaves were active in September 2004 to after the leaves had senesced in 2004. But then in late December to early February it was noticed to increase again. This was attributed to the leaves that fell probably containing salt. However, the fallen leaves were not sampled for salinity content. Salinity sampling of the fallen and decomposed leaves is anticipated during the winter of 2005.

A slight increase of salinity was observed in the Rio Grande and at the treated site. On January 2 and 3, 2005 the site received total precipitation of about 18 mm. The runoff from precipitation flushed the salt from the soil into the river. This was observed by a slight decline in salinity at both sites and an increase in the river. The salinity in the non-treated site was noticed to increase after early March 2005. This coincided with the leaves' emerging. The cause of this increase is not yet known.

Data collection from both sites (treated and non-treated) was anticipated during the growing season of 2005. Unfortunately, the non-treated site was flooded in early May. The flooding was due to spring snow runoff from the north. Data from the treated site continued to be collected.

The salinity in the treated site continued to stay lower than the non-treated site. Values of EC measured by the extraction method and reported by the SWAT laboratory (see Appendix M) were less than 6 mS/cm. This means that soils of both treated and untreated sites would be able to sustain plants that are moderately sensitive to salinity, such as cottonwood and other native riparian vegetation. The sodium adsorption ratio or the sodium hazards for both untreated and treated sites were less than 13 indicating that the soils in this area are not susceptible to sodium related problems.

5. CONCLUSION

Saltcedar is known to consume a large amount of water. One of the methods for its control has been treating sites with herbicides. This study compared two adjacent sites of saltcedar to determine evapotranspiration (ET) between herbicide-treated saltcedar and non-treated saltcedar sites. These were compared using two different eddy covariance techniques. Sensible heat measured at all the sites using both the OPEC and 3D-SEC systems compared very well. From the energy balance, ET (latent heat) was determined as a residual.

Measurements of ET from both sites indicated that the treated saltcedar stand during a comparison of 83 growing days was less than the non-treated site by about 57% (treated site ET = 142 mm and non-treated site = 327 mm; difference of 185 mm). During 149 days of the non-growing season (dormant season), on average the daily ET was about 0.40 mm higher at the treated site when compared to the non-treated site. This amount accumulated to about 59 mm total during the non-growing season of data comparison (treated site ET = 220 mm and non-treated site ET = 161 mm). The results presented were for data collected from August 14, 2004 through May 11, 2005 (the non-treated site was flooded on May 11, 2005). The percent difference could be larger during the full growing period at the peak of the season. The peak of the season in New Mexico is usually in late June or early July. Also, it was noticed that the ET of the treated stand was not equal to zero due to evaporation from the soil.

Finally, the data collected using the OPEC system was compared with the 3D-SEC system at both the sites. The comparison of sensible heat flux and latent heat flux measured at both the sites using OPEC system and 3D-SEC system came out close to each other. The crop coefficient as a function of cumulative GDD was calculated for saltcedar at the Bosque and then used to estimate the ET of non-treated saltcedar at the Elephant Butte Reservoir during the growing season of 2005 (April 11 through November 14, 2005). The estimated ET for non-treated saltcedar was 1002 mm when compared to measured ET of 386 mm at the treated site, a difference of 61% for 189 days. This was close to the 57% difference (non-treated ET of 327 mm and treated ET of 142 mm) for 83 days determined by direct measurements during the growing season from April 23 through May 11, 2005.

5.1. Future work and recommendations

A full year of comparison was not possible due to flooding at the non-treated saltcedar site. It is recommended that a full year of ET be measured. This would reflect those days in the season when saltcedar growth is at its peak. A longer period of measurement would allow a better understanding of variation of salinity in treated and non-treated sites.

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