Alfalfa Water Use and Crop Coefficients Across the Watershed: From Theory to Practice

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ABSTRACT

In this study, remote sensing technology and crop production functions were used to compare the theoretical crop coefficient (K_c) and the theoretically optimal or potential crop evapotranspiration (ET) with actual ET for 751 alfalfa fields in Lower Rio Grande Valley, New Mexico. Results of the remote sensing showed that while potential alfalfa water use for the year 2008 was 1451 mm, actual water use at the field-level ranged from 386 mm to 1241 mm with an average ET of 901 mm for the growing season. Average ET was also calculated using the average yield and published crop production functions. The average ET estimated from average yield using two different crop production functions was between 975-979 mm. Reasons for field-level ET and crop coefficient variability include current irrigation methods and technology, lack of knowledge of irrigation scheduling, limited water supply, interference of harvesting schedule with the irrigation, cultural practices, and economic factors. The results of the study have implications on water rights adjudication and economic return from alfalfa production. The results also reflect the potential for improvement in agricultural productivity and economic return by changing irrigation techniques and agronomic practices.

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Introduction

The Lower Rio Grande Valley (LRG) is a major agricultural area in southern New Mexico, with approximately 32,000 hectares in irrigated crop production. The region's mean annual precipitation is about 200 mm and irrigated agriculture relies on Rio Grande surface water and supplemental groundwater. The annual surface water allotment ranges from 10,000 m³/ha in a full allotment year to as low as 1,000 m³/ha in a drought year. Pecan, alfalfa, and cotton are the main crops grown in the area, with corn silage, chile peppers, and other vegetable crops also produced.

Currently about one-third of the cultivated land in the region is used for alfalfa production. The demand for alfalfa is driven by the state's dairy industry, which ranks 9th in total U.S. milk production. The LRG's limited water supply, increasing demand for water, and periodic severe and prolonged drought has prompted interest in better management of water, particularly for alfalfa given the crop's prominent position within the regional agricultural economy. Because water is the key limiting factor in LRG crop production, understanding actual alfalfa water use is essential for proper management of the basin's irrigation water, planning for the future, and long-term hydrologic sustainability. Knowledge of the magnitude and diversity of actual field-scale ET is critical for formulating water resource policy and programs, and assessing the economic returns from agricultural water use.

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Theoretically, alfalfa has 1400-1500 mm of potential annual evapotranspiration (ET) in an eight to nine month growing season in the LRG (Skaggs et al. 2011). However, at the field-scale, actual LRG alfalfa water consumption and obtained yields are considerably lower than potential. Highly variable alfalfa ET and yield are due to several factors including limited availability of water, agronomic constraints, and lack of irrigation scheduling knowledge, infrastructure limitations, and economic considerations.

Theoretically, alfalfa ET can be calculated using the crop coefficient (K_c) multiplied by reference evapotranspiration (ET_r) as proposed by Wijk and de Vries (1954) and Jensen (1968) :

$$ET = K_c \times ET_r \qquad (1)$$

ET_r is calculated using various equations such as Hargreaves and Samani (1982, 1985), Penman-Monteith (Allen 1986), Allen et al. (1998) and others. A dual crop coefficient also has been recommended to account for specific wetting events of the crop coefficient (Jensen and Heermann 1970). This approach consists of splitting K_c into two separate coefficients, one for transpiration which is known as the basal crop coefficient (K_{cb}) and the other for soil evaporation (K_e). Both of these approaches assume that no limitations are placed on plant growth or crop evapotranspiration. However, under deficit irrigation practices common in dry climates such as New Mexico's LRG, actual crop ET is often lower than ET estimated using traditional approaches (Samani et al. 2005; Skaggs and Samani 2005; Skaggs et al. 2011). This study was undertaken to assess the spatial and temporal variability of field scale K_c and ET for alfalfa using remote sensing technology on the field-scale in the Lower Rio Grande Valley, New Mexico, USA.

Methodology

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Theoretical ET Calculations

Theoretically, alfalfa ET can be calculated by multiplying the crop coefficient (K_c) by reference

evapotranspiration (ET_r) as shown in equation 1. Everson et al (1978) describe the growing

season for alfalfa as the last -4°C day in the spring until the first -4°C day in the fall. USDA

technical report #21 (1967) defines the growing season for alfalfa as 10°C mean ambient

temperature in the spring to first -2.2^{o}C frost in the fall. Everson et al (1978) and USDA (1967)

criteria were used to identify the beginning and end of the alfalfa growing season in the LRG

during 2008. To identify crop coefficients throughout the growing season, a relationship between

crop coefficients and growing degree days (GDD) was developed for each cutting or harvest

cycle using crop coefficient values for alfalfa reported by Wright (1981). The duration of each

cutting cycle was determined using the criteria developed by Smeal et al. (1995), who found an

average GDD of 1144 based on degrees Fahrenheit for each cutting cycle of alfalfa in

Farmington, New Mexico. Using climate data measured at the Leyendecker weather station

(Latitude 32°12$^'$03.27$^"$N, Longitude 106^o 44$^'$ 33.53$^"$W, figure 1). The reference

evapotranspiration (ET_r) was calculated using standardized reference evapotranspiration equation

for alfalfa (Allen et al 2005). The reference evapotranspiration equation is developed for alfalfa

crop at standard height of 0.5 m. However, the actual alfalfa ET was calculated using equation

(1) with crop coefficients adjusted for stage of growth and cutting process. Total alfalfa water

use for the growing season in the study region and study year (2008) was calculated as 1451 mm

based on Everson et al (1978) and 1454 mm based on USDA (1967).

Figure 1 here

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Remote Sensing Model

The Regional ET Estimation Model (REEM) (Samani et al. 2009; Samani et al. 2007a; Samani et al. 2006) was used to calculate daily ET for 751 alfalfa fields in New Mexico's LRG. The 751 alfalfa fields were identified in a crop survey conducted by the New Mexico Office of State Engineer in 2008.   REEM is based on the surface energy balance similar to that presented by Bastiaanssen et al. (1995) and Allen, Tasumi (2003), and Trezza (2002) with the latent heat flux (LE) determined as a residual of the surface energy equation:

$$LE = R_n - G - H \tag{2}$$

where, LE is the latent heat flux, R_n is the net radiation flux at the surface, G is the soil heat flux and H is the sensible heat flux .

Daily net radiation over the crop canopy was calculated using methodology developed by Samani et al. (2007b) as:

$$R_n = R_{ni}\left(\frac{R_s}{R_{si}}\right)\left(\frac{T_a}{T_i}\right)^4 \tag{3}$$

where, R_n is the daily net radiation in MJ/m^2/day, R_{ni} is instantaneous clear sky net radiation (W/m^2), R_s is daily short wave solar radiation (MJ/m^2/day), R_{si} is the instantaneous short wave solar radiation (W/m^2), T_a is average daily temperature in Kelvins (K), and T_i is the instantaneous air temperature (K).

Instantaneous net radiation (R_{ni}) was calculated after Campbell (1977):

$$R_{ni} = (1-\alpha)R_{si} + RL\downarrow - RL\uparrow \tag{4}$$

where, R_{ni} is instantaneous net radiation (W/m²), R_{si} is instantaneous incoming short wave radiation (W/m²), $RL\downarrow$ is instantaneous effective incoming long wave radiation (W/m²), $RL\uparrow$ is instantaneous outgoing long wave radiation (W/m²), α is surface albedo (dimensionless).

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Effective incoming long wave radiation (RL↓) was calculated using Stefan-Bolzmann Law

(Unsworth and Monteith, 1975) as :

$$RL \downarrow = \varepsilon_{eff} \times \sigma \times T_i^4 \tag{5}$$

where, ε_{eff} is effective atmospheric emissivity, σ is Stefan-Boltzman constant (5.67 x10^{-8}

W/m²/K⁴), T_i is instantaneous near surface air temperature (K). Effective atmospheric emissivity

((ε_{eff}) is calculated using the product of atmospheric emissivity and surface emissivity (ε_axε_o).

Atmospheric emissivity (ε_a) is calculated using an equation by Bastiaanssen (1995) as:

$$\varepsilon_a = 0.85 \times \left(-\ln \tau_{sw}\right)^{0.09} \tag{6}$$

where, τ_{sw} is the atmospheric transmissivity calculated from elevation (Allen et al. 1998).

Surface emissivity (ε_o) is calculated after Tasumi (2003) where, ε_o =0.95 + 0.01 LAI when LAI

< 3 and ε_o = 0.98 when LAI ≥ 3, LAI is leaf area index. The LAI is the ratio of total upper leaf

surface area of vegetation divided by the surface area of the land on which the vegetation grows

(m²/m²).

The instantaneous outgoing long wave radiation (RL↑) was calculated using Stefan-Bolzmann

Law:

$$RL \uparrow = \varepsilon_o \times \sigma \times T_s^4 \tag{7}$$

Where, T_s is surface temperature (in K).

Satellite data from Landsat-5 (2008) and Landsat-7 (2008) were used to calculate

Normalized Difference Vegetation Index (NDVI, equation 8), albedo, and surface temperature

for the study site. The LANDSAT sensor makes multispectral observations in seven wavelength

regions as shown in Table 1. The dates when useable satellite images were available are shown

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in Table 2. The remote sensing software package ENVI®, by Research Systems Inc., Boulder,

Colorado and its many tools were used for data processing.

Table 1 goes here

Table 2 goes here

NDVI was calculated using the following equation:

$$\text{NDVI} = \frac{\rho_{\text{nir}} - \rho_{\text{red}}}{\rho_{\text{nir}} + \rho_{\text{red}}} \tag{8}$$

where, ρ is surface reflectance for Landsat-5 Thematic Mapper (TM) and Landsat-7 Enhanced

Thematic Mapper Plus (ETM+), the near-infrared (nir) band is band 4 and the red band is band 3.

Albedo (α) was calculated using the methodology described by Liang et al. (2002):

$$\alpha = 0.356\rho_1 + 0.13\rho_3 + 0.373\rho_4 + 0.085\rho_5 + 0.072\rho_7 - 0.0018 \tag{9}$$

where, ρ_i is the reflectance in band i.

The thermal radiation observed by satellite is converted to T_s using a methodology

proposed by Barsi et al. (2005):

$$L_{\text{TOA}} = \tau\varepsilon_o L_T + L_u + \tau(1 - \varepsilon_o)L_d \tag{10}$$

where, L_{TOA} is the space-reaching or top of atmosphere (TOA) radiance measured by the satellite

instrument, τ is the atmospheric transmissivity, L_T is the target radiance with a blackbody surface

emissivity of 1, L_u is the upwelling or atmospheric path radiance, and L_d is the downwelling or

sky radiance. Radiances are in units of W/(m^2 sr μm) and the transmissivity and emissivity are

unitless. The web-based calculator (http://atmcorr.gsfc.nasa.gov/) was used to determine the

atmospheric correction parameters necessary to complete the process. The calculator provides

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the necessary parameters for equation 10 with the exception of surface emissivity, ε_o. The L_T was

determined by rearranging equation 10 as follows:

$$L_T = \left[L_{TOA} - L_u - \tau(1 - \varepsilon_o)L_d \right] / \tau\varepsilon_o \tag{11}$$

L_T is then converted to radiometric temperature at the surface (T_s) using the Planck

equation:

$$T_s = K_2 / \ln\left(1 + K_1 / L_T\right) \tag{12}$$

where, K_1 equals to 666.09 and 607.76 for Landsat-7 and Landsat-5, respectively and K_2 equals

1282.71 and 1260.56 for Landsat-7 and Landsat-5, respectively (Barsi et al. 2005).

Using ground heat flux data ranging from 35 W/m² to 150 W/m² and NDVI ranging from

0.20 to 0.85, Samani et al. (2006) developed the following equation to estimate instantaneous

soil heat flux (G_i) at the time of satellite overpass:

$$\frac{G_i}{R_{ni}} = 0.26e^{(-1.97NDVI)} \tag{13}$$

The instantaneous sensible heat flux (H_i) was calculated by combining the bulk

aerodynamic equation with Monin-Obukhov similarity theory. The bulk aerodynamic equation is

defined as:

$$H_i = \rho_a C_p \frac{T_o - T_a}{r_{ah}} = \rho_a C_p \frac{dT}{r_{ah}} \tag{14}$$

where, ρ_a is the air density (kg/m³), C_p is specific heat of air (1004 J/kg/K), T_o is the

aerodynamic surface temperature in Kelvins (K), T_a is the air temperature (K), r_{ah} is the

aerodynamic surface resistance, and dT is the air temperature gradient calculated using a linear

function described by Bastiaanssen (1995):

$$dT = aT_s + b \tag{15}$$

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where, a and b are calibration constants that are empirically determined by using reference extreme points on the ground. Calibration of equation 15 requires a minimum of two points on the ground where dT values can be calculated from sensible heat (H_i) fluxes using equation 14. In this study, two sensible heat values were used. One sensible heat value was measured using a one-propeller eddy covariance (OPEC) system in a mature, well-watered pecan orchard which extended more than 5 km in the predominant wind direction as shown in figure 1 (Latitude $32^o13^{'}31.57^{''}N$, Longitude $106^o 45^{'} 23.57^{''}W$). The other sensible heat value was estimated for a dry fallow field with no vegetation by setting instantaneous latent heat (LE_i) equal to zero and estimating instantaneous R_{ni} and ground flux G_i from equations 4 and 13. The H_i value for the dry field was then calculated as a residual of the energy balance as:

$$H_i = R_{ni} - G_i \qquad (16)$$

The aerodynamic resistance (r_{ah}) in equation 14 was calculated using wind speed extrapolated from blending height of 200 m and an iterative stability correction based on Monin-Obukhov similarity theory (Bastiaanssen 1995; Allen et al. 2007).

Once the values of "a" and "b" in equation 15 were estimated, the sensible heat flux at the time of satellite overpass was calculated for each pixel using equations 14 and 15. During the calculation of sensible heat flux, each pixel's r_{ah} value was calculated iteratively as described earlier. The other components of the energy, R_{ni} and G_i, for the time of satellite overpass were calculated using equations 4 and 13.

The evaporative fraction (E_f) for each pixel is defined as the ratio of the latent heat flux to the available energy and is calculated using the values of H_i, G_i, and R_{ni}:

$$E_f = \frac{R_{ni} - G_i - H_i}{R_{ni} - G_i} \qquad (17)$$

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Once the evaporative fraction is calculated and assuming the evaporative fraction is constant

over the 24-hour period, daily ET can be calculated by multiplying E_f by daily available energy

as:

$$ET = E_f(R_n - G) \tag{18}$$

Assuming negligible daily G (Allen 1998), daily ET can be calculated by multiplying E_f by daily

net radiation (R_n).

Field ET Measurement

Three OPEC towers were operating in 2008 in the LRG as shown in figure 1. Two of the

flux towers were installed in mature pecan orchards and the third was installed in an alfalfa field

located at Latitude 32°04′.20″N and Longitude 106°40′9.9″W (Kirksey 2009). The alfalfa flux

tower was located in a 16 ha alfalfa field surrounded by other alfalfa fields. The height of the

OPEC tower was 5 meters. Three components of net radiation, sensible heat, and soil heat fluxes

were measured at a frequency of 15,000 samples every thirty minutes.

Net radiation was measured using a Q7.1 net radiometer (Radiation and Energy Balance

Systems, Inc., Seattle, Washington), and sensible heat was measured using a pair of OPEC

systems to ensure consistency in data collection. The OPEC systems consisted of a gill propeller

anemometer model 27106 (R. M. Young Company, Traverse City, Michigan) and a 76-micron

diameter type E fine-wire thermocouple (Campbell Scientific Inc., Logan, Utah). Sensible heat

measured with the OPEC systems was verified with measurements using a three-dimensional

sonic eddy covariance system (Campbell Scientific Inc., Logan, Utah). The soil heat flux was

measured using two soil heat flux plates (Radiation and Energy Balance Systems, Inc., Seattle,

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Washington) buried at a depth of 1 cm below the surface, and assumed that energy storage within the one cm of soil was negligible (Kirksey, 2009). Latent heat flux was determined as a residual in the energy budget assuming the energy budget closed. Evapotranspiration, in equivalent depth of water, was then determined by dividing the latent heat flux by latent heat of vaporization of water (~2.45 MJ/kg).

Comparison of Predicted and Measured ET

Daily water use was calculated for various fields using remote sensing techniques for clear days when satellite data were available. A total of 11 scenes were available for 2008 as shown in table 2. Using the calculated daily ET values, crop coefficients were calculated by dividing daily ET values by standardized grass-referenced evapotranspiration (ET_{sz}) (Allen et al. 2005). The daily ET_{sz} was calculated using weather data from an automated weather station located in a near-by agricultural area as shown in figure 1. For days when useable satellite images were not available, K_c was interpolated using Piecewise Cubic Hermite Interpolation Polynomial (PCHIP) techniques (Fritsch and Carlson 1980; Kahaner et al 1988). The interpolated K_c values were then used to estimate daily ET by multiplying the daily K_c values by daily ET_{sz}.

Kirksey (2009) reported monthly ET measurements for 2008 using OPEC technology. Figure 2 compares the results of monthly alfalfa ET measurement reported by Kirksey (2009) with monthly ET values determined from remote sensing and theoretical calculations as described above for a single LRG alfalfa field during 2008. The results of the comparison are summarized in table 3. The ratio of annual ET predicted from remote sensing versus measured annual ET was 0.88 and the ratio of theoretically calculated annual ET over measured annual ET was 1.17. The standard errors of the estimate (SEE) for monthly ET were 34.5 mm/month and

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42 mm/month for the remotely sensed ET and theoretically calculated ET, respectively. The SEE was calculated as:

$$\text{SEE} = \sqrt{\frac{\sum (y - y')^2}{n - 1}} \tag{19}$$

where, y is measured ET values and y′ is predicted monthly ET values for the 10-month growing season.

Figure 2 goes here

Table 3 goes here

Results and Discussion

Estimating ET from remote sensing for a single alfalfa field is subject to some error due to the periodic cutting of alfalfa during the growing season because periodic satellite images may or may not coincide with a particular field's average growth condition. However, the error in the overall ET histogram reduces as the number of fields are increased due to the random nature of alfalfa harvesting throughout the LRG. The error for both individual fields and ET histogram will also reduce if the number of satellite observations are increased. The number of satellite observation was increased in this study by combining images from Lansat-5 and Landsat-7. Despite the potential error in a single field, results of the comparisons in figure 2 and table 3 show that ET predicted from remote sensing is reasonably close to annual ET measured with the flux tower. Figure 3 shows growing season ET as a function of field size for 751 alfalfa fields in 2008. There is larger variability in annual ET for smaller fields. This is likely due to greater management diversity on smaller fields relative to large commercially-managed fields. Figure 4 shows the histogram of annual alfalfa ET for the same 751 fields. Annual ET for all fields

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ranged from 386 mm to 1217 mm with an average of 901 mm (figure 4). The figure 4 histogram shows that only a small number of fields are within the range of the theoretically optimal or potential ET. Figure 5 shows the histogram of annual K_c for 751 alfalfa fields. The histogram shows a maximum annual and average Kc value of 0.80 and 0.59, respectively. These results indicate there is signification variation in K_c values between the alfalfa fields and that none of them are at the highest level, even though a small number of fields have K_c and ET close to the theoretical potential.

Figure 3 goes here

Figure 4 goes here

Figure 5 goes here

Average ET calculated using remote sensing techniques was compared with ET predicted from average yield as reported by New Mexico Agricultural Statistics (2001-2009). New Mexico Agricultural Statistics reports an average yield of 7.3 tons/acre (16.4 metric tons/ha) for 2001-2009. Smeal et al. (1995) provides a yield function for estimating alfalfa yield from seasonal ET. Using the Smeal et al. (1995) yield function, the ET corresponding to the 16.4 metric tons/ha , after adjusting for 20 percent moisture content, is equal to 974.8 mm. Guitjens (1982) reported a yield function of one ton/acre for every six inches of ET. Using this criterion the average alfalfa ET in the LRG watershed was estimates as 979 mm. Results are summarized in table 4, where data in the table show that the average regional ET calculated from remote sensing is almost equal to average ET calculated from yield functions recommended by Smeal et al. (1995) and Guitjens (1982).

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Table 4 goes here

There are several reasons for the large variability in seasonal ET and yield of alfalfa in the LRG. The central reason has to do with the random nature of farming and alfalfa production Farmers' abilities, objectives, resources, and resource constraints vary; thus, not all farmers can or seek to do a "perfect" job of growing a crop and achieve the potential ET and thus yield. Some grow their crops under optimal or near optimal conditions while other farmers produce under very different, sub-optimal conditions. These differences will manifest in a range or distribution of ET and yield outcomes, with a majority of farmers achieving approximately average ET, crop yield, crop quality, and economic outcomes. The histogram of alfalfa ET shown here for 751 fields is therefore normally distributed due to variable farmer abilities, objectives, resources, and constraints.

Farm-level alfalfa production skills include farmer's understanding of crop water requirements and irrigation scheduling. Some farmers have little to no understanding of these factors and base their timing and amounts of irrigation on established habits, convenience, or folk knowledge while others apply rigorous analysis and tools to determine when and how much water to apply. The distribution of alfalfa ET is in part derived from the distribution of farmer awareness of soil-water-plant relationships and application of that knowledge in the alfalfa production process. Unfortunately, even the best knowledge and planning may not overcome the constraints imposed by a surface water delivery system which extends over hundreds of miles, is subject to delays, inadequate infrastructure, and an increasingly fragmented service area due to rural residential subdividing.

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The nature of the alfalfa crop is also a key factor in the less than potential ET levels identified in this research. Alfalfa grown in the LRG is typically harvested six or seven times per growing season. LRG farmers cut the alfalfa two to three weeks after the preceding irrigation depending on soil type. Quite often, irrigation is delayed to allow the soil to dry up before cutting. The alfalfa then has to be dried, baled, and removed from the field. The majority of alfalfa producers are small land owners and part-time farmers who do not own alfalfa harvesting equipment. They depend on other farmers or on custom harvesters, and as a result, the process of cutting, baling, and removing hay can require another one to two weeks depending on machinery and labor availability. After each hay cutting is removed from the field, the crop will again be irrigated. Machinery breakdowns, weather delays due to brief but intense summer rainfall events, and other demands on part-time farmers' labor also result in extended periods between irrigations. It is not uncommon for intervals between irrigation events to be as long as five weeks, while the ideal irrigation interval for alfalfa is between two and three weeks (Allen et al. 1998). Routine hay harvesting and unexpected delays result in extended time periods between irrigations which reduce both ET and yield. Although harvesting delays could be avoided and intervals between irrigations reduced if LRG farmers were to use underground drip irrigation instead of flood irrigation, drip irrigation is cost prohibitive (particularly on small fields) and problematic due to large and variable sediment loads in the surface water. Timing of surface water deliveries presents another obstacle to widespread drip irrigation technology adoption, while impermanence syndrome (Lopez, Adelaja, and Andrews 1988) further hinders LRG farmers' investments in advanced irrigation technology (Skaggs and Samani 2005).

Water is a limited resource in the LRG and when farmers face a limited water supply, they will deficit irrigate, apply the limited water supply to more land area, and thus maximize net

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returns to water (English 1990). Water spreading over larger land areas or several discontinuous fields is also a portfolio management strategy which helps farmers reduce the risk of catastrophic loss due to extreme events (e.g., hail, insect infestations, or plant diseases). Traditionally, when water is the limiting factor, deficit irrigation practices result in higher economic returns by increasing water use efficiency (defined as crop yield divided by the water used to produce the yield (Howell 2001; FAO 2000). However, LRG farmers tend to deficit irrigate their crops by intuition rather than by knowledge of soil-water-plant relationships and irrigation events are not timed in accordance with crop water needs at different stages of growth.

The role of the local dairy industry in the LRG alfalfa market is also a factor which influences alfalfa irrigation management, ET, and yield. Alfalfa production in the LRG is strongly influenced by the demand for "dairy quality" hay. Dairy producers want premium quality hay that is cut early, bright green, leafy, immature, in the bud stage, with high digestibility (Orloff and Putnam 2007). Alfalfa hay fields successfully harvested to meet dairy quality requirements will not be the highest yielding fields given the tradeoff between hay quality and yield; however, revenues from dairy quality hay sales are likely to be higher than hay sold for other uses (Orloff and Putnam 2007). The yield sacrifice of producing dairy quality hay also results in reducing ET.

Conclusion

These results show that the ET of virtually all alfalfa fields in the LRG is lower than potential ET. As shown in figure 4, none of the 751 alfalfa fields were at potential ET, and only two fields were close to the theoretically estimated potential ET. The theoretical equation for calculating crop ET (equation 1) is for crops growing under pristine conditions where there are no limiting

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factors such as nutrient and water deficiency, salinity, disease or pests problem. The remote

sensing measures alfalfa ET which is the result of the combined effect of various growth factors

including water limitation, pests, disease, nutrient deficiency, population density, soil properties,

management practices, tillage, etc., which affect both yield (biomass) and ET. Further research

would be needed to identify the specific factor or factors which cause the yield and ET reduction

in each case. In addition to agronomic factors, the marginal economic return normally

diminishes as production approaches peak yield prompting producers to manage crops below the

optimum growth. In alfalfa there is an additional factor which influences yield and that is the

harvesting and baling schedule which overrides the irrigation schedule. These basin-wide results

are consistent with English's (1990) analytical framework for understanding deficit irrigation

practices and for estimating the economically optimal levels of water use which occur using

deficit irrigation strategies.

In the LRG there are many factors which influence irrigation and ET at the field-level. A

variety of constraints and farmer objectives influence ET and yields in the LRG (as well as in

other irrigated basins). The assumption that farmers can and will use their resources

(specifically, irrigation water) to achieve maximum potential (or theoretically optimal) yields is

not consistent with economic behavior, although it may be appealing from an engineering and

agronomic perspectives. Under-irrigation is economically rational when irrigation water is

limited in supply and not free.

Under-irrigation in the LRG is also a function of resource limitations and constraints

related to the nature of the crop being irrigated; however, dealing with these limitations and

constraints presents hydrologic as well as economic dilemmas. For example, because of frequent

drought-induced water shortages in the LRG and growing demands to transfer water out of

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agriculture to other uses, it is often speculated that the implementation of modern drip and sprinkler irrigation systems would result in water savings by ending "wasteful" surface irrigation practices. The results of this study show that the majority of alfalfa is produced under water deficit conditions. Thus, widespread adoption of modern "water saving" irrigation technologies would most likely result in additional consumptive use by crops. This would further stress the LRG's limited water resources, reduce groundwater recharge, and impair downstream flows, even though it could increase individual farmers' incomes if their alfalfa yields and quality increased.

In order for alfalfa fields to achieve the theoretically potential level of 1400-1500 mm/year of ET, harvesting would have to be instantaneous under flood and sprinkler irrigation conditions. Drip irrigation would allow for closer to instantaneous harvesting if it were otherwise economically or physically feasible. However, surface water availability throughout the LRG is not and will never be instantaneous. To our knowledge, there is no timing delay in the yield functions used to estimate theoretically optimal or potential consumptive use for alfalfa or for other crops produced with similar cultural practices.

Basin adjudications are frequently founded on the notion that water rights should be established for the potential ET of full crop water demand. For example, the LRG is currently undergoing adjudication, and claims for farm delivery requirements (FDRs) are being made on the basis of theoretical annual potential ET (Skaggs et al. 2011). The results reported here for alfalfa are significant with respect to the LRG adjudication process. If basin-wide water rights are adjudicated based on the K_c of optimally managed fields, this would most likely result in over-allocation of water resources with serious consequences for groundwater depletion and

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downstream water delivery obligations. A more realistic approach would be to determine the historical consumptive use based on average K_c and average reference ET_{sz}.

New irrigation system design has usually been predicated on meeting full crop water demands. Recommendations, public policy, and investments for improving existing irrigation systems and practices are also founded on the notion that individual farmers should and do want to achieve potential ET and yields and that society will be better off with irrigation systems that meet full crop water demands. However, the results presented here indicate that engineering and agronomic criteria for optimal irrigation are likely to be inconsistent with farm level economic decisions, irrigation practices, and irrigation outcomes.

Use of equation 1 in irrigation system design or rehabilitation, in recommendations for improved irrigation practices or technology, or in water rights adjudications will result in overestimation of alfalfa water use. Equation 1 is not consistent with real world economic decisions and basin-level hydrologic sustainability.

As noted above, there are several reasons why actual field-level ETs are lower than the theoretically optimal or potential ET. Crop production is subject to nature, farm-level resources (including supplemental ground water, soil type, labor, time, money, knowledge, etc.) vary, water delivery systems have constraints, and farmers have diverse objectives. The histogram of alfalfa ET is therefore normally distributed. In 2008, the average ET for 751 alfalfa fields was 901 mm, while potential ET was 1451 mm.

The average alfalfa ET found in this study is 901 mm which implies an average yield of 6.72 tons/acre, while the potential yield with 1451 mm of ET would be 10.82 tons/acre. New Mexico Agricultural Statistics reported an average alfalfa yield of 7.3 tons/acre for the study region for the years 2001-2009. Although there is agronomic potential to increase the region's

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average alfalfa yield to 11-12 tons/acre, this theoretical yield goal is not consistent with real-world alfalfa production. Most LRG alfalfa producers are unlikely to ever make major investments in modern irrigation technology or significantly change their irrigation management and cultural practices. Their farm-level economic decisions clearly involve mental models at odds with engineering or agronomic "best practices" and reflect the diversity of outcomes inherent in any complex system. Incorporating this reality into current water resource policy, public and private investments, programs, and adjudications is strongly recommended.

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Figure 1. ET distribution in the Lower Rio Grande (LRG) for July 2, 2008 and location of eddy covariance flux towers and weather stations.

Figure 2. Comparison of daily measured and predicted alfalfa ET for year 2008

Figure 3. Annual average ET of 751 alfalfa fields versus the area of the fields in the Lower Rio Grande (LRG)

Figure 4. Histogram of annual ET of 751 alfalfa fields in the Lower Rio Grande (LRG) for year 2008

Figure 5. Histogram of annual Kc distribution of alfalfa fields in the Lower Rio Grande (LRG) for year 2008

Figure 2

ET 2008 Alfalfa

Legend:
- REEM ET, mm/month
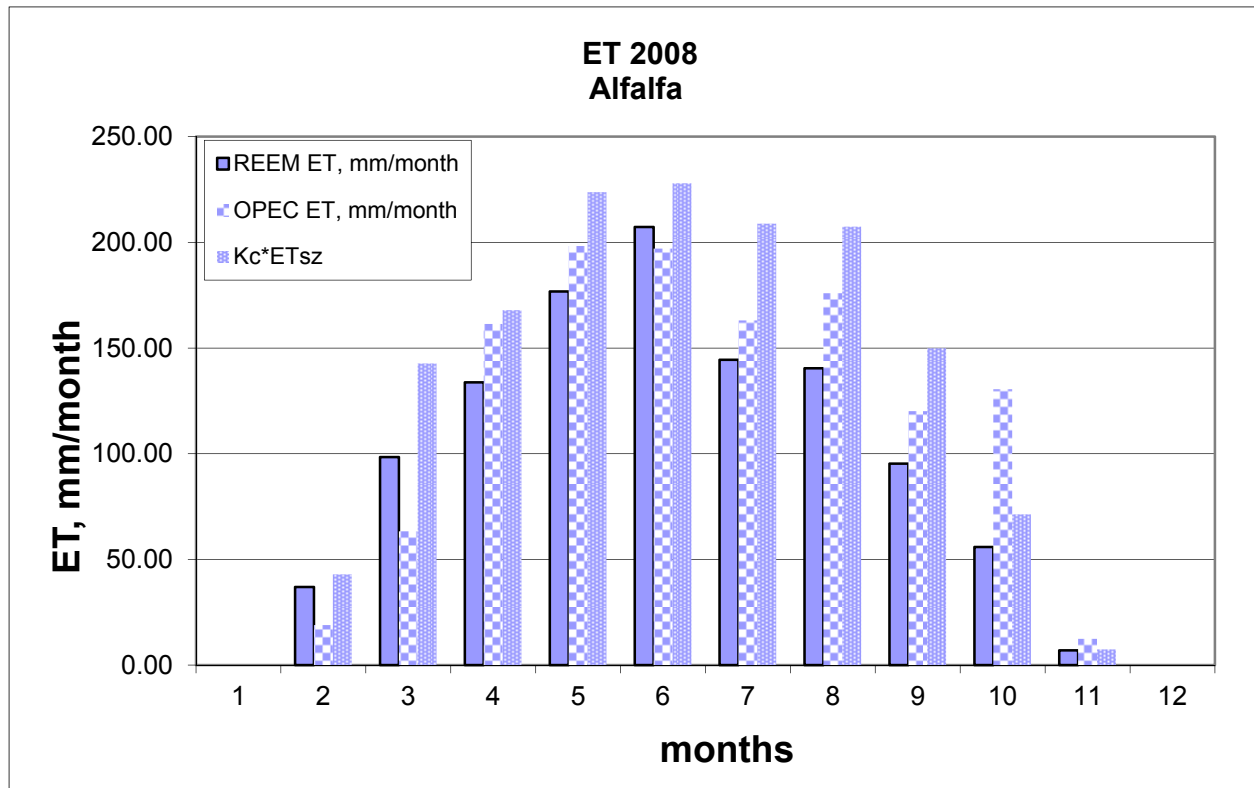- OPEC ET, mm/month
- Kc*ETsz

Figure 2. Comparison of daily measured and predicted alfalfa ET for year 2008

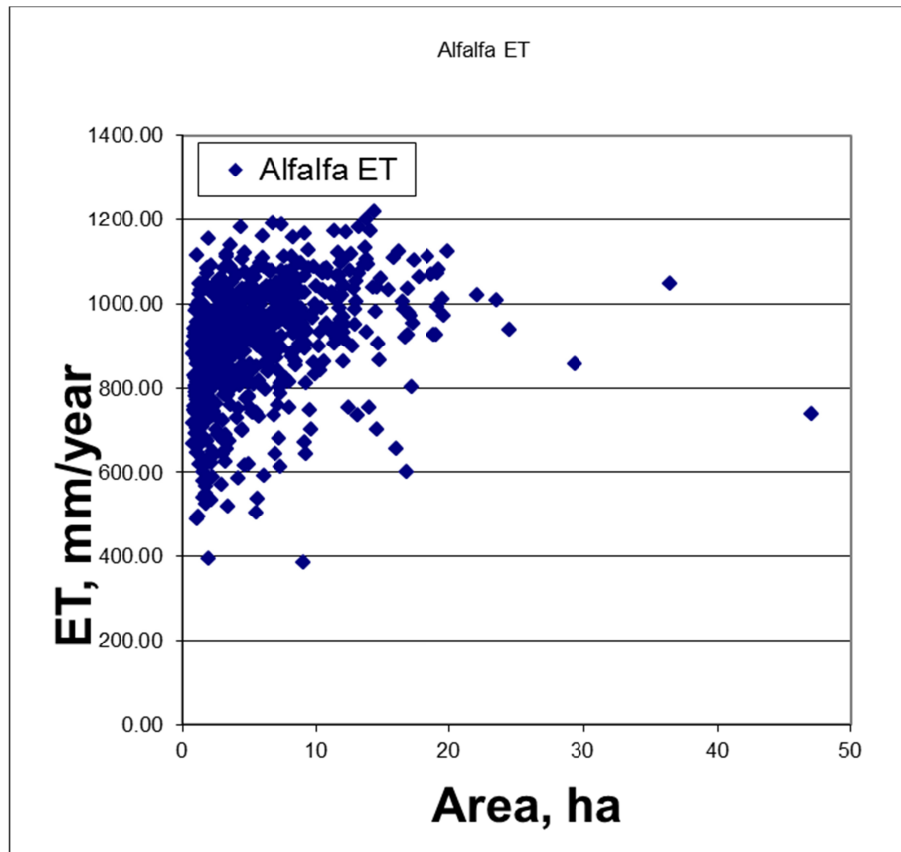Accepted Manuscript
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Figure 3

Figure 3. Annual average ET of 751 alfalfa fields versus the area of the fields in the Lower Rio Grande (LRG)
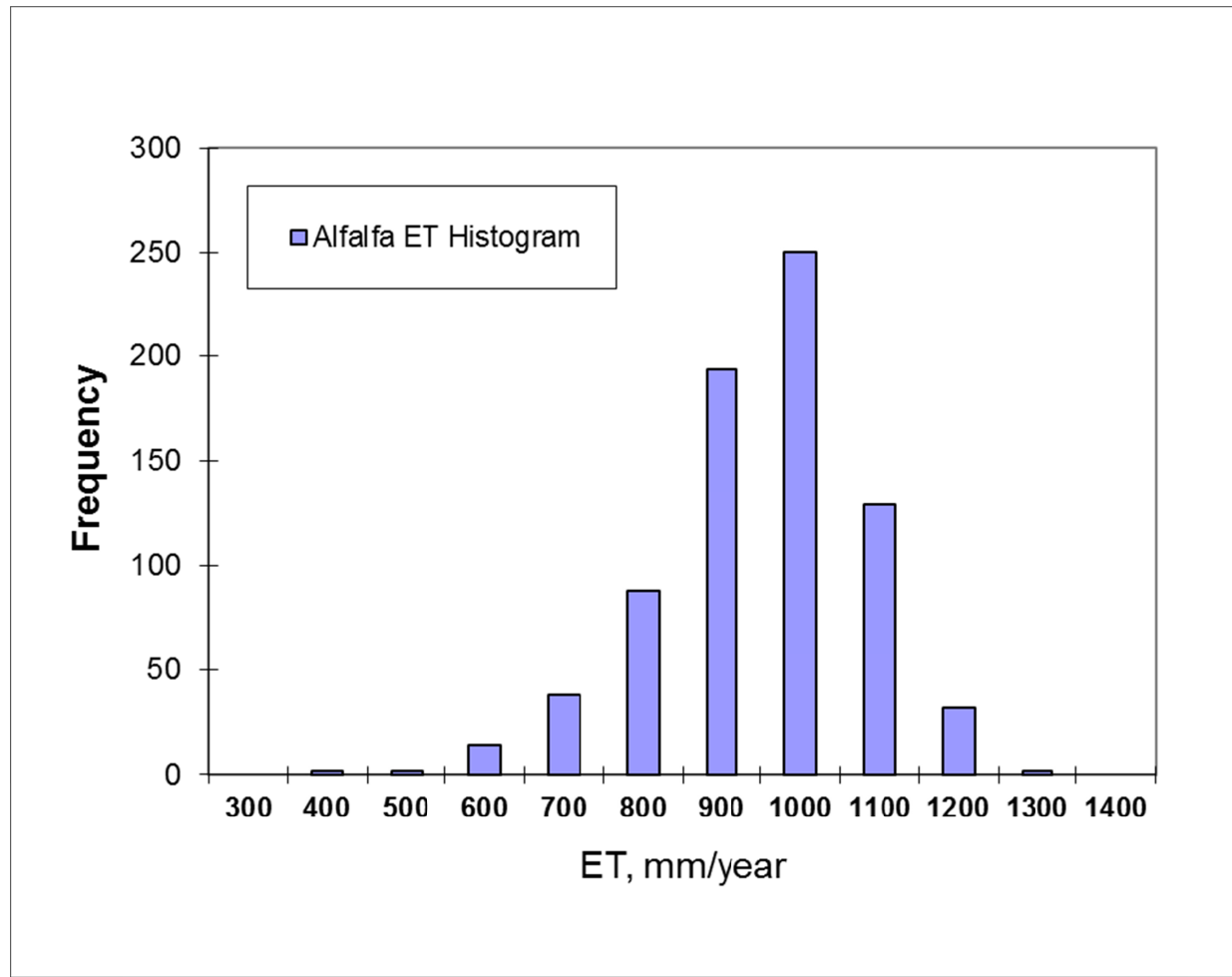
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Figure 4

Figure 4. Histogram of annual ET of 751 alfalfa fields in the Lower Rio Grande (LRG) for year 2008
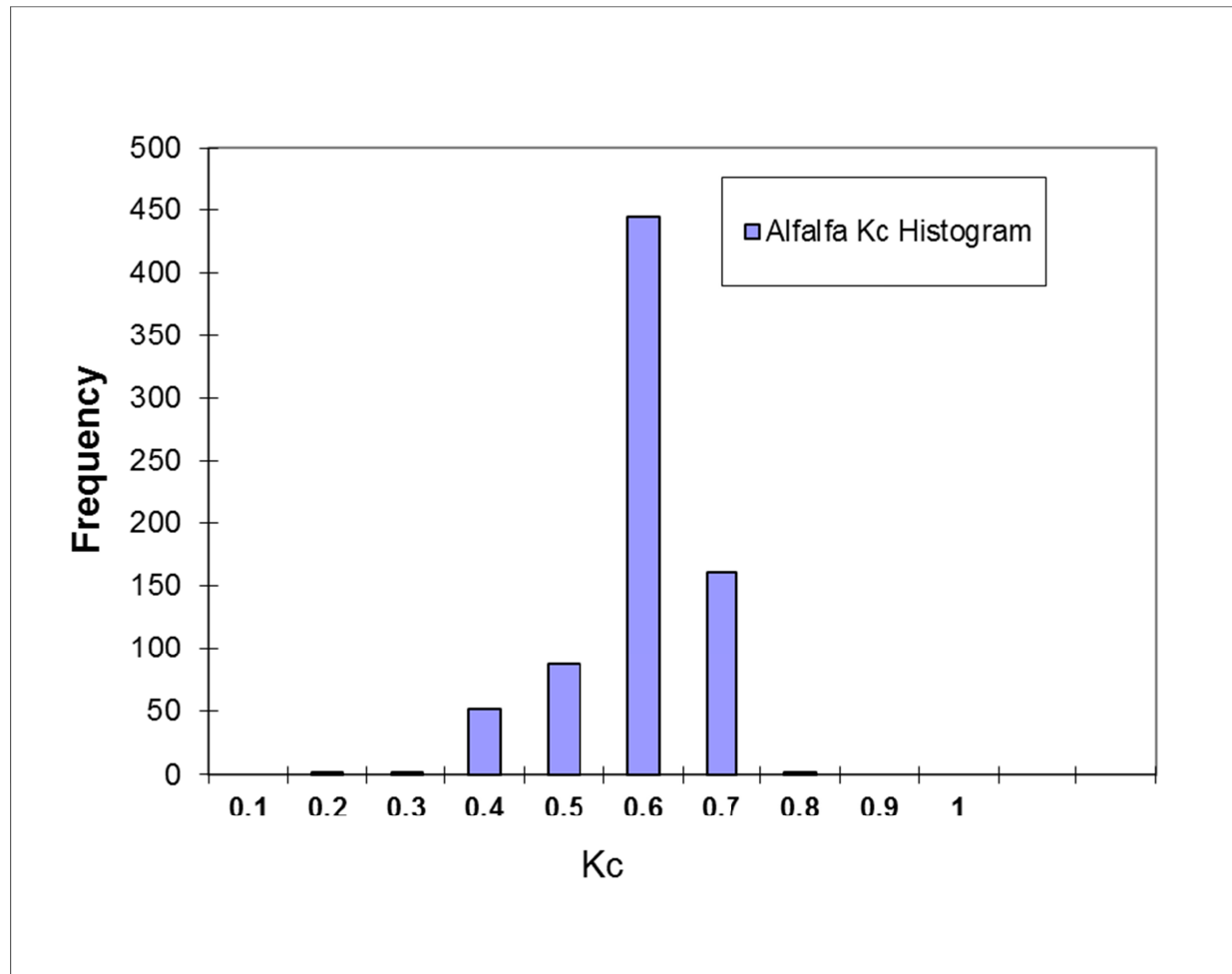
Figure 5

Figure 5. Histogram of annual K_c distribution of alfalfa fields in the Lower Rio Grande (LRG) for year 2008

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Table 1

Table 1. Landsat multispectral bands

Band No.	Wavelength Interval (μm)	Spectral Response	Resolution (m)
1	0.45 - 0.52	Blue-Green	30
2	0.52 - 0.60	Green	30
3	0.63 - 0.69	Red	30
4	0.76 - 0.90	Near IR	30
5	1.55 - 1.75	Mid-IR	30
6	10.40 - 12.50	Thermal IR	60, 120*
7	2.08 - 2.35	Mid-IR	30

*Landsat 5 is 120 m, while Landsat 7 is 60 m

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Table 2

Table 2. Dates of satellite image used in the model

Image date	Satellite
03/04-2008	Landsat 5
04/05-2008	Landsat 5
05/07-2008	Landsat 5
06/08-2008	Landsat 5
07/02-2008	Landsat 7
08/03-2008	Landsat 7
09/04-2008	Landsat 7
09/28-2008	Landsat 5
10/30-2008	Landsat 5
11/15-2008	Landsat 5
12/01-2008	Landsat 5

Table 3

Table 3. Comparison of measured and predicted alfalfa ET for a single field, 2008

Method	Annual ET, mm	Ratio (estimated/measured)	SEE, mm/month
Remote sensing	1096	0.88	34.5
Theoretical	1451	1.17	42
Measured, flux tower	1241.7		

Table4

Table 4. Comparison of growing season alfalfa ET (Feb-Nov.) for the year 2008

Reference	Growing season ET (Feb.-Nov.) (mm)
ET range, remote sensing (this study)	386-1217
Kirksey (2009), single field flux tower	1242
Average ET remote sensing (this study)	901
Average ET estimated from yield function by Smeal et al. (1995), this study	974.8
Average ET estimated from yield function by Guitjens (1982), this study	979

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