DISSERTATION

MODELING A VARIABLE SURFACE RESISTANCE (r_s) FOR ALFALFA AND ASSESSING THE ASCE r_s PERFORMANCE IN THE REFERENCE EVAPOTRANSPIRATION EQUATION

Submitted by
Abhinaya Subedi
Department of Civil and Environmental Engineering

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Doctoral Committee:

Advisor: José Chávez
Co-Advisor: Allan Andales

Jorge Ramirez
Jay Ham

ABSTRACT

MODELING A VARIABLE SURFACE RESISTANCE (r_s) FOR ALFALFA AND ASSESSING THE ASCE r_s PERFORMANCE IN THE REFERENCE EVAPOTRANSPIRATION EQUATION

Accurate quantification of crop water requirement is necessary for proper irrigation water management. The knowledge of actual crop evapotranspiration (ET_c) is important and is necessary for estimating irrigation water requirements. The most common procedure of obtaining actual crop evapotranspiration (ET_c) is by first calculating the reference crop evapotranspiration (ET_r) and then multiplying it with the appropriate crop coefficients (K_c). If the surface resistance (r_s) of a particular crop can be modeled, then ET_c can be directly calculated without using K_c. The overall objectives of this dissertation were to model surface resistance for alfalfa reference crop and to find an effective value of the surface resistance of alfalfa in the ASCE Standardized Reference ET equation. It has been found that using a single K_c curve for different climatic conditions can lead to significant error in estimating ET_c. Hence it is important to find appropriate K_c for different crops for local climatic condition. Lysimeters are generally used to determine the values of K_c, as lysimetry is considered a reliable method of quantifying the ET losses from a control volume. This study found that using lysimeter ET data to obtain K_c can be problematic especially when the field is heterogeneous. In order to develop K_c for various crops, it is recommended to use some years of reliable data with uniform healthy and unstressed crop surface conditions both inside and outside the lysimeter.

This study was focused on to develop a model for surface resistance (r_s) of alfalfa in order to calculate alfalfa ET_c in a one-step approach without the need for K_c values. Surface resistance was estimated by inverting the aerodynamic equation using ET measured from lysimeter and sensible heat flux (H) measured from large aperture scintillometer (LAS). This observed r_s showed a very good correlation with leaf area index (LAI) and crop height (h_c). The alfalfa r_s was then modeled as a function of LAI and h_c (which is referred to as $r_{s\,(LAI)}$ and $r_{s\,(hc)}$ respectively). Then these modeled r_s s were incorporated into the Penman Monteith (PM) equation to estimate alfalfa hourly ET, which performed very well when compared with the measured hourly lysimeter ET. The conventional alfalfa r_s, developed by Allen et al. (1989) was found to underestimate r_s significantly especially when the crop height was short (less than 25 cm). It was found that $ET_{\_conventional\_rs}$ was not applicable to estimate alfalfa ET when the crop height was less than 25 cm. The modeled $r_{s\,(LAI)}$ and $r_{s\,(hc)}$ are constant throughout the day, but in reality, r_s changes throughout the day. Hence hourly variable r_s was also developed based on aerodynamic resistance (r_a), canopy temperature (T_c) and vapor pressure deficit (VPD). It was found that PM equation incorporating the hourly variable r_s improved the alfalfa ET estimation when compared with the conventional r_s approach.

ASCE-EWRI Standardized Reference ET for tall reference crop was found to underestimate measured ET by about 10 per cent. The equation assumes the value of r_s for alfalfa as 30 s/m. When the value of r_s was changed from 30 s/m to 10 s/m, the performance of the equation improved, resulting in no bias and root mean square error (RMSE) reduction from 0.08 mm/h (15.3%) to 0.06 mm/h (11.4%) in 2009 and from 0.09 mm/h (14.1%) to 0.06 mm/h (10.1%) in 2010.

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CHAPTER 1

Introduction

Water is the basis of life. Water plays a pivotal role in agricultural, industrial, municipal and energy sectors. The total available water on Earth can be divided into freshwater, which is less than 3 per cent of the total water on Earth; and saline water (water on sea or ocean), which is approximately 97 per cent of the Earth water. The saline water has little significance to human welfare as it cannot be used without proper treatment for agricultural and municipal sectors. Agriculture is the largest consumer of the freshwater resource, as globally roughly 70% of freshwater is used for crop production, whereas in developing countries, more than 90% of freshwater is used (WWDR, 2015).

The hydrologic cycle is a continuous transport of water molecules in the Earth, which starts with evaporation from the oceans and other water bodies as well as transpiration from the plants, condensation, precipitation, infiltration and runoff. For a vegetated surface, evaporation from the land and transpiration from the plant surfaces are hard to distinguish, hence a common term evapotranspiration (ET) is often used to represent both evaporation and transpiration. ET is also termed as consumptive use of plants, since the water lost in ET process is the water actually consumed by the crop. Hence the knowledge of ET is important in both hydrologic science/engineering as well as irrigation science/engineering.

There are different ET measurement or estimation methods available. Some of the common ET measurement methods are lysimetry, eddy covariance, scintillometry, Bowen Ratio Energy

Balance System, aerodynamic profile tower and soil moisture methods. Weighing lysimeter has a load cell, which is very sensitive to the mass inside the lysimeter box. When ET takes place, there is a difference of load cell readings before and after certain duration. By using the calibration equation of the load cell, the difference in load cell readings can be converted to ET values (in mm/h or mm/d). Weighing lysimeter is considered as one of the most precise ET measurement techniques; however, certain conditions need to be fulfilled to obtain the precise ET values (Marek et al., 1988). It is important to find out under what conditions lysimeter ET can be misleading as lysimeters are often used to develop crop coefficients (K_c). Reliable K_c values are necessary to optimize the irrigation water. Scintillometer measures sensible heat flux and ET is indirectly measured using surface energy balance equation by measuring net radiation and soil heat flux. The soil moisture methods such as neutron probe use the soil water balance method to estimate ET. By knowing the change in soil water storage using soil moisture sensors, and the measurement of precipitation, runoff and infiltration, ET can be indirectly calculated. The soil moisture method can be used to measure ET in a longer time period (may be weekly, monthly or seasonal basis) whereas the other methods can be used for shorter time periods as well (hourly or daily).

The most common ET estimation methods are FAO 56 Reference ET equation and corresponding crop coefficients; and ASCE Standardized Reference ET equation and corresponding K_c. Both of these reference ET equations are based on Penman-Monteith (PM) equation. The PM equation follows a single layer or a big leaf approach, which considers whole crop as one big leaf and the incoming/outgoing flux originates from one single layer of the canopy (Allen, 2005; Alves et al., 1998). In recent days, remote sensing method is also getting popular to estimate crop ET from larger area. It is possible to find the spatial and temporal variation of ET using the remote sensing techniques. However, to estimate ET in small field scale, the remote sensing method is still not very common.

The use of the reference ET equation and K_c is considered as a two-step ET estimation method. The FAO 56 Reference ET equation uses grass as a reference crop whereas the ASCE Standardized Reference ET equation uses either grass or alfalfa as reference crop. It is recommended to use the corresponding K_c values to use for the particular reference ET equations as the reference ET values will be different by using different reference ET equations. It has also been recommended to develop K_c values under local conditions to incorporate local climatic, environmental, and crop management factors (Evett et al., 2000). However, the usual practice is to use the K_c values recommended in FAO 56 as the K_c values have not been developed for all crops for all places. On the other hand, there has been report of ET underestimation by the PM equations for the arid and semiarid climatic conditions (Rana et al., 1994; Steduto et al., 1996; Pereira et al., 1999; Todorovic, 1999; Ventura et al., 1999; Sellers, 1965; Lecina et al., 2002; Lascano and van Bavel, 2007; Subedi et al., 2016). Hence the cumulative error in calculating reference ET and selecting K_c value could be significant. The issue of underestimation of ASCE Standardized equation for the arid and semiarid conditions could be solved by finding an effective value of surface resistance in the PM equation. There is also an alternative by using one-step ET estimation technique instead of the two-step. The one-step ET estimation technique, however, requires finding the value of surface resistance (r_s) of a crop. The modeling of r_s using the weather variables and important biophysical variables like leaf area index (LAI) or canopy temperature (T_c) could be an option.

The overall objectives of this dissertation were to model surface resistance for alfalfa reference crop and to find an effective value of the surface resistance of alfalfa in the ASCE Standardized Reference ET equation. The specific objectives were as follows:

- To explore different ET estimation methods to date and find a gap in the existing methods (Chapter 2)
- To compare lysimeter measured ET with ET measured using micrometeorological methods; to find under what conditions these measured ET can be very different (Chapter 3)
- To model surface resistance for alfalfa reference crop and investigate if the modeled r_s performed better compared to the conventional approach (Chapter 4)
- To find an effective value of r_s for alfalfa and recommend the value of C_d in the ASCE Standardized Reference ET equation for the tall reference crop (Chapter 5)

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CHAPTER 2

Crop evapotranspiration (ET) estimation models: A review and discussion of the applicability and limitations of ET methods

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Overview

This is a review paper on existing methodologies to calculate crop evapotranspiration (ET_c). We have attempted to present all the important ET estimation procedures to date starting from the simple empirical Blaney Criddle method to the complex Shuttleworth model. The common approach to calculate ET_c is to estimate a reference crop ET rate (ET_{ref}) using weather variables from nearby weather station, and multiplying it by an appropriate crop coefficient (K_c). Recently, there have been attempts to calculate actual crop ET (ET_a) directly without using K_c. The latter method is still in the developmental phase. This study reviews the existing literature on ET estimation and identifies research needs in the current methods and technology. The extension of the Shuttleworth model for hourly time step and the validity of Irmak and Mutibwaa model at field level for various crops would be a good milestone for one step ET estimation. Also the development of a new variable canopy surface resistance ($r_{s)}$ model which can be applicable for different crops at different climatic conditions would be a good contribution in this field.

List of Abbreviations Used:

Δ : slope of saturation vapor pressure with air temperature, kPa/°C

γ : psychrometric constant, kPa/°C

φ : latitude of site, radians

ET : evapotranspiration rate, mm/h or mm/d or inches/d

PET: potential ET rate, mm/h or mm/d or inches/d

ET_0 : reference evapotranspiration rate from a grass surface, mm/h or mm/d or inches/d

ET_{sz}: : reference evapotranspiration rate from a standardized surface, mm/h or mm/d

ET_c : crop evapotranspiration, mm/h or mm/d

u : monthly consumptive use (ET), inches/mon. or mm/mon.

U: seasonal consumptive use (ET), inches/season or mm/season

K_c : crop coefficient developed by FAO 56 method

k : empirical crop coefficient for monthly period

K : empirical crop coefficient for irrigation season or growing period

T_a : mean monthly/daily/hourly air temperature, °C

T_F: mean monthly/daily/hourly air temperature, °F

t : difference between actual canopy temperature and canopy temperature in wet conditions, °C

u_2: wind speed at 2m height, m/s

r_s : canopy surface resistance, s/m

r_a : aerodynamic resistance, s/m

r_l : daily average stomatal resistance: s/m

r_i : climatological resistance, s/m

r^* : climatic resistance, s/m

RH : relative humidity, %

R_n : net radiation, MJ/m^2/d or MJ/m^2/h

R_s : incoming solar radiation, MJ/m^2/d or MJ/m^2/h

Ra : extraterrestrial radiation, MJ/m^2/d or MJ/m^2/h

e_a : actual vapor pressure, kPa

e_s : saturation vapor pressure, kPa

D : vapor pressure deficit, kPa

p : monthly percentage of daytime hours of the year, %

f : monthly consumptive use (ET) factor

F: sum of monthly consumptive use (ET) factors for the period

i : heat index

I : sum of the 12 monthly heat index i

S : measured sunshine hours times 100 divided by the number of possible sunshine hours

K_{RS} : calibration coefficient

TD : mean maximum minus mean minimum temperature, °C

K : dimensionless constant developed empirically from data analysis

C : dimensionless coefficient related to climatic parameters

G : soil heat flux, MJ/m^2/d or MJ/m^2/h

f(u) = wind speed function

J : Julian day of the year

λ : latent heat of evaporation, MJ/kg

ρ : air density, kg/m^3

C_p : specific heat capacity of air at constant pressure, J/kg/K

D : zero plane displacement height, m

hc : crop height, m

z_m : height of wind measurements, m

z_h : height of humidity measurements, m

z_{om} : roughness lenth governing momentum transfer, m

z_{oh} : roughness length governing heat transfer

k : von – Korman’s constant (0.41)

U_z : wind speed at height z, m

LAI : leaf area index, m^2/m^2

C_n : numerator constant that changes with reference type and calculation time step, K mm s^3 M/g/d or K mm s^{3}M/g/h

C_d : denominator constant that changes with reference type and calculation time step, s/m

W_{aero} : empirical weighted factor

INTRODUCTION

Water is the basis of life. In the modern world, the demand of water is increasing because of the growing population as well as the increased urbanization and industrialization. As a result, water for agriculture is becoming limited. For this reason, accurate estimation of crop water requirement is very important. The problem of over irrigation or under irrigation will be minimized if we are able to accurately estimate crop water requirement or crop ET. The schematic diagram of ET process is shown in Figure 2.1. Heat storage and metabolic heat production are usually negligible, and are excluded from the surface energy balance. Various methods have been developed so far to estimate the crop ET. John Dalton (1766-1844) was the pioneer in developing an equation for evaporation from large water bodies, such as lakes and reservoirs. In his equation, the evaporation rate was calculated as the product of the vapor pressure deficit and a factor “K” which is dependent on the wind speed. Since then, various ET methods have been developed, which are described in this article.

This paper reviews various ET estimation models that have been developed to date. Among these models, the Penman Monteith (PM) equation is found to be more consistent over a wider range of climatic conditions (Allen et al., 2005). The most challenging part in the PM equation is to calculate the canopy surface resistance. FAO 56 PM equation and ASCE – EWRI (Environmental and Water Resources Institute of American Society of Civil Engineers) 2005 Standardized PM equation are based on the fixed canopy surface resistance approach. These two methods calculate the reference crop ET, which along with the crop coefficient (K_c) is used to calculate the actual crop ET (or ET_a). Recently, some researchers have pointed out flaws in this technique of estimating ET_a, so there have been attempts to calculate ET_a directly using variable surface resistance values, without requiring crop coefficient. Katerji and Perrier (1983), Todorovic (1999); and Shuttleworth (2006) are notable researchers in variable surface resistance approach, which are described later in the manuscript. The subsequent sections describe different ET estimation techniques in the chronological order.

EVOLUTION OF DIFFERENT METHODS

1. Blaney-Criddle method

The Blaney-Criddle method was first developed in 1942. It is an empirical equation and very simple to use. They developed a simple mathematical model as given by equation (2.1) (Blaney and Criddle, 1962).

$$u = kf \tag{2.1}$$

$$U = \sum kf = KF \tag{2.2}$$

where,

f = $T_F \times p / 100$ = monthly consumptive use factor,

T_F = mean monthly temperature, in degrees Fahrenheit,

p = monthly percentage of daytime hours of the year,

u = Monthly consumptive use, in inches,

k = empirical consumptive use crop coefficient for monthly period

U = seasonal consumptive use (or evapotranspiration), in inches,

F = sum of the monthly consumptive use factors for the period (sum of the products of mean monthly temperature and monthly percentage of daytime hours of the year),

K = empirical consumptive use crop coefficient for irrigation season or growing period.

In metric units,

$$u = kp(\frac{45.7T_a + 813}{100}) \tag{2.3}$$

where, u = monthly consumptive use, in millimeters

and T_a = mean monthly temperature, in degrees Centigrade.

Although the method was originally developed to compute ET on a monthly basis, it can be modified to estimate daily values of ET with mean daily temperature (ASCE, 1990). As temperature methods tend to underestimate ET in arid regions while overestimating ET in humid regions, local calibration of the empirical coefficients is required to produce reliable estimates of ET (ASCE, 1990). The advantage of this method is the simplicity and disadvantage is that it underestimates ET grossly compared to the measured ET values (Sammis et al., 2011).

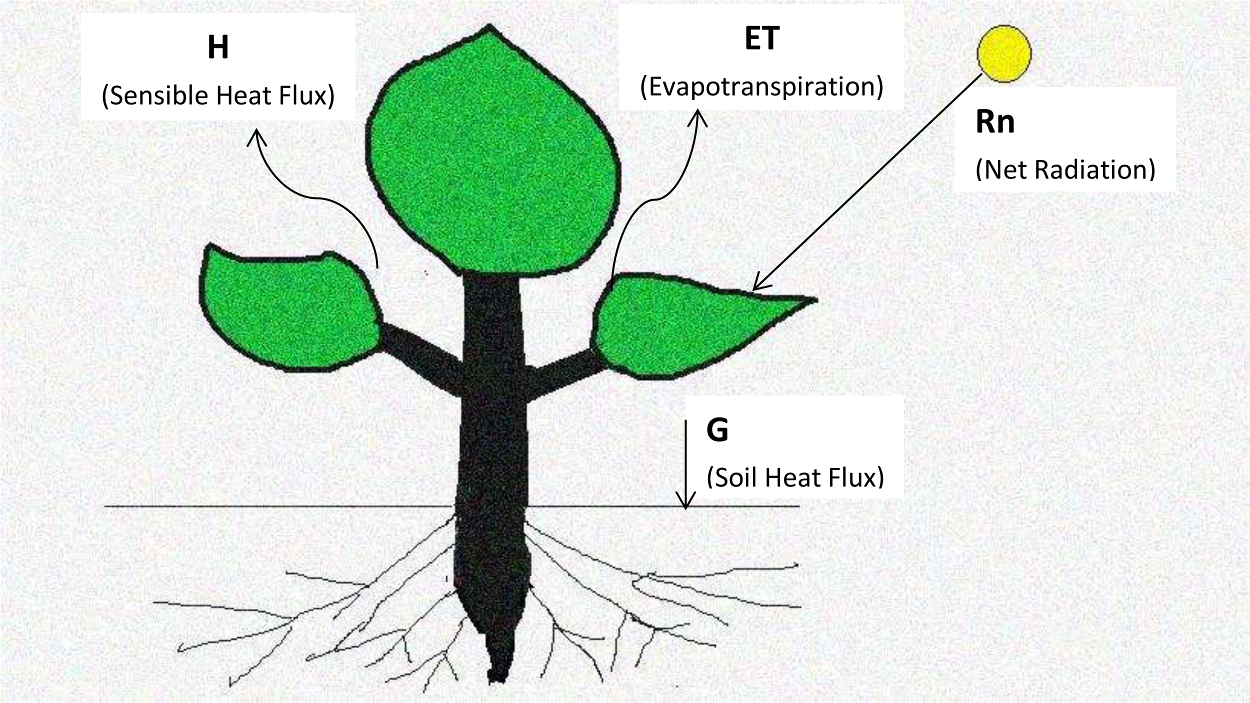

Figure 2.1. Schematic diagram of ET process from a crop canopy (Major components of the surface energy balance, excluding the heat storage and metabolic heat production terms)

2. Thornthwaite method

In 1948, Thornthwaite and Penman both developed potential evapotranspiration equation independently. Potential ET here refers to the maximum ET that can occur from a given crop surface. Penman's equation was more mechanistic while Thornthwaite's equation was more empirical. It was easy to use the Thornthwaite (1948) equation than Penman equation as it used less climatic data. His equation is as follows:

$$PET = 16(10T_a/I)^a \tag{2.4}$$

where,

PET = potential evapotranspiration rate, in mm per month.

T_a = mean monthly temperature, in degrees Celsius,

I = summation of the 12 monthly heat index i, where i = $(T_a / 5)^{1.514}$

ɑ = an empirical coefficient, which is calculated using the following equation:

$$a = 0.675 * 10^{-6} I^3 - 77.1 * 10^{-6} I^2 + 0.01792 I + 0.49239 \tag{2.5}$$

This method is not based on strong mathematical and physical principles, as it is purely empirical. However, as it is easy to use and gives acceptable result, many parts of the world still use it to estimate irrigation water requirement.

Kumar et al., 1987 compared the Thornthwaite and Penman method in India to calculate potential ET. They found that Penman's method seems more realistic picture of the mean annual potential evapotranspiration distribution over India. They also reported that Penman's potential evapotranspiration estimates are higher than Thornthwaite's during the winter and pre-monsoon months and lower during the monsoon months, at most of the Indian stations. Pereira and De

Camargo (1989) concluded that Thornthwaite method is not appropriate for estimating ET in advective condition, however, it can be used for irrigation scheduling purposes when fetch requirement is met. Bautista et al., 2009 concluded that Thornthwaite method worked perfect during the rainy months in both of their research sites, however, for drier months, the use of Thornthwaite method was not recommended without the adjustment in coefficient “16”.

3. Hargreaves Equation

Hargreaves (1975) developed an equation for estimating ET which doesn’t require wind speed data. His equation is as follows:

$$ET_0 = 0.0075\, R_s\, T_F \tag{2.6}$$

where,

ET_0 = potential ET for a grass reference surface in the same units as with R_s,

R_s = global solar radiation at the surface in equivalent water evaporation, usually mm of evaporation

T_F = mean temperature in degrees Fahrenheit.

For degrees Celsius, the equation is modified as:

$$ET_0 = 0.0135\, R_s\, (T_a + 17.8) \tag{2.7}$$

Hargreaves (1977) developed the equation for R_s as below, where R_s and R_a needs to be in the same unit:

$$R_s = 0.075 R_a S^{0.50} \tag{2.8}$$

Hargreaves (1977) developed the equation for S to be applicable for Central America as:

$$S = 12.5(100 - RH)^{0.50} \tag{2.9}$$

where, RH = mean monthly relative humidity, %.

Hargreaves and Samani (1982) developed an equation to determine R_s, from extraterrestrial radiation (R_a), and the measurement temperature range:

$$R_s = K_{RS} R_a TD^{0.50} \tag{2.10}$$

where, R_s and R_a are in the same units, K_{RS} is a calibration coefficient and TD is mean maximum minus mean minimum temperature in degree Celsius.

Hargreaves et al., 1985 obtained the following equation for ET_0.

$$ET_0 = 0.0022 R_a (T_a + 17.8) TD^{0.50} \tag{2.11}$$

For months of peak demand, Hargreaves and Samani (1985) recommended that the coefficient be increased to 0.0023. Allen et al., 1999 in their FAO 56 paper recommended using equation (2.11) when solar radiation data, relative humidity data and /or wind speed data are missing.

Hargreaves equation is also empirical and very easy to use. Bautista et al. (2009) compared the Hargreaves equation (equation 2.11) with FAO 56 PM equation, the latter equation considering the standard method. They found that Hargreaves method compared well with PM equation with coefficient index of 0.82. However, the coefficient index improved to 0.91 after adjusting the coefficient “0.0022” in equation (2.11) from 0.0021 to 0.0024 (based on seasons) for tropical subhumid climate site and from 0.0022 to 0.0026 for semiarid climate site. Ravazzani et al., 2012 also compared Hargreaves - Samani (HS) equation to FAO 56 equation for daily time steps in alpine river basins and found that HS equation didn’t perform well, as it showed overestimation at lower elevation sites and underestimation at higher elevation sites. However, after using a correction factor, they found that the HS equation was in very good agreement to the FAO 56 PM equation.

4. Christiansen method

Christiansen (1968) developed a simple method to estimate pan evaporation and crop evapotranspiration. According to Christiansen, the reasons for using pan evaporation data were: they were more consistent, already considerable work had been done to relate pan evaporation data with consumptive use and the pan evaporation data were readily available. The mathematical model that he developed was as follows:

$$E = K\,R_a\,C \tag{2.12}$$

where E is used in a general sense to apply to evaporation or evapotranspiration, K is a dimensionless constant developed empirically from data analysis, and C is a dimensionless coefficient related to climatic parameters, and R_a is the extraterrestrial radiation, expressed as equivalent depth of evaporation in the same units as E. The coefficient C is expressed as the product of any number of subcoefficients that are functions of specific climatic parameters that are found to have a significant effect on the evaporation or evapotranspiration (Christiansen, 1968). Mathematically,

$$C = C_T C_W C_H C_S C_E \tag{2.13}$$

where, C_T, C_W, C_H, C_S and C_E represent the coefficients for temperature, wind, humidity, sunshine percentage and elevation respectively. The value of K was adjusted so that all coefficients were equal to unity for standard and approximate mean values of the parameter they represent (Christiansen, 1968). Christiansen (1968) described in detail about how to calculate the different parameters in equation (2.13) using his Tables in the article.

This method is purely empirical as it is not based on any physical equation. This method can somehow accurately estimate ET on monthly basis, but this method cannot be used to calculate ET on daily basis or shorter time steps. Wai et al., 2004 evaluated the performance of the Christiansen method and Penman method with respect to the measured pan evaporation in Malaysia. They found that Penman method compared better than the Christiansen method for estimating potential evapotranspiration.

5. Penman related equations

5.1 Original Penman equation

Penman (1948) developed a mechanistic approach to calculate ET. He used combination approach by combining the surface energy balance equation and aerodynamic equation. Several ET estimation models, for example, FAO 56 PM equation, ASCE – EWRI Standardized PM equation, CIMIS Penman method have been based on Penman equation. The original Penman equation is as follows:

$$ET = \frac{(\mathit{\Delta}(R_n - G) + k_w(e_s - e_a)f(u)\gamma)}{\lambda(\Delta + \gamma)} \tag{2.14}$$

where,

$f(u)$ = wind speed function = $a_w + b_w\, u_2$ (u_2 is the wind speed in m/s) (2.15)

k_w = unit coefficient (6.43 for ET in mm/d and 0.268 in mm/h)

Penman (1948) recommended the value of a_w and b_w as 1.0 and 0.537 respectively for clipped grass. Doorenbos and Pruitt (1977) in FAO 24 paper recommended a constant of 6.61 in place of 6.43. They also recommended the values of a_w and b_w as 1 and 0.864 for clipped grass. Wright and Jensen (1972) recommended the use of 0.75 and 0.993 for a_w and b_w for full cover alfalfa (Allen et al., 1989). Wright (personal communication, 1987) as cited by Allen at al., 1989 derived an improved form of the Wright (1982) variable wind function by using the normal probability density function equation to approximate the change in a_w and b_w coefficients for an alfalfa reference with time of season at Kimberly, Idaho. The equations for a_w and b_w are:

$$a_w = 0.4 + 1.4\exp[-\left(\frac{[J-173]}{58}\right)^2] \tag{2.16}$$

$$b_w = \{0.007 + 0.004\exp\left[-\left(\frac{[J-243]}{80}\right)^2\right]\}(86.4) \tag{2.17}$$

Equations (2.14) and (2.15), with a_w and b_w calculated with equations (2.16) and (2.17) were termed 1982 Kimberly Penman equation by Allen et al. (1989).

Sun and Song (2008) evaluated the performance of original Penman equation with measured ET using eddy covariance for a marshland in Northeast China. They found that the Penman model overpredicted the mean measured ET for the growing season by 35 %. Yoder et al., 2005 compared ET estimations from eight different equations with measured lysimeter ET. Yoder et al., 2005 found that FAO 56 PM equation performed best followed by the original Penman equation.

5.2 CIMIS Penman Method

CIMIS Penman calculates grass reference ET (ET_0) using the Penman combination equation, as modified by Pruitt and Doorenboss, with a wind function that was developed at the University of California, Davis (Temesgen et al., 2005). CIMIS Penman method uses $a_w = 0.29$ and $b_w = 0.53$ for $R_n > 0$ and $a_w = 1.14$ and $b_w = 0.40$ for $R_n \leq 0$. These coefficients are applied hourly using equation (2.14) where ET_0 is in mm/h, R_n is in MJ/m^2/h and k_w = 0.268 (ASCE-EWRI, 2005). Temesgen et al., 2005 showed that the CIMIS Penman method correlated well with FAO 56 PM equation for daily time step and with ASCE Standardized equation for both daily and hourly time steps for 37 different studied sites in the state of California, USA. The limitation of this method is that this method may not be applicable in different climatic conditions as the coefficients were mainly developed for the climatic condition of California.

5.3 Penman Monteith equation

Monteith (1965) introduced some crop resistance terms in the original Penman equation and the equation later became the well – known "Penman-Monteith" ET equation. This equation is the physically based and has demonstrated the robustness as it does not require local calibrations, provided there are complete input data (Temesgen et al., 2005; Allen et al., 1999). This equation does not have any wind function; rather it has aerodynamic and surface resistance terms. The wind function in the Penman equation is calculated empirically whereas the aerodynamic and surface resistance terms are calculated using physically based and semi – empirical equations respectively. Aerodynamic resistance (r_a) is the resistance to molecular and turbulent diffusion of water vapor between leaf surfaces and the air above the canopy at a reference height (Robins, 1974). Surface resistance (r_s) is the resistance to the diffusion of water vapor within the evaporating surface (Monteith et al., 1965). The popular reference ET equations like FAO 56 PM equation and ASCE Standardized Reference PM ET equation are also based on Penman Monteith equation. The equation (2.18) is the Penman-Monteith equation:

$$\lambda E = \frac{\left(\Delta(R_n - G) + \rho C_p(e_s - e_a)/r_a\right)}{\Delta + \gamma(1 + r_s/r_a)} \tag{2.18}$$

In the PM equation, all other parameters except r_s is relatively straightforward to calculate. Some sort of procedures has been developed to calculate r_s for the grass and alfalfa surface. For this reason, to calculate the actual crop ET, the trend is to first calculate the reference crop ET considering the grass or alfalfa as the reference crop surface and then multiplying the reference ET by the appropriate crop coefficients. Direct use of the PM equation (equation 2.18) to calculate actual crop ET is very rare in practice, although some researchers have tried this recently, which will be discussed in subsequent paragraphs.

6. Priestley Taylor method

Priestley and Taylor (1972) developed a semi-empirical equation to calculate potential evaporation, which is applicable for partial equilibrium condition. Their equation is as follows:

$$\lambda E = \alpha \frac{\Delta(R_n - G)}{\Delta + \gamma} \tag{2.19}$$

where α is a variable that can range from 1.15 to 1.50 depending on the surfaces, climate and season. For water surfaces under condition of minimal advection, Priestley and Taylor (1972) approximated the value of α as 1.26. The value of α will be different for different crops and open water bodies. Researchers are still working on finding appropriate value of α for different surfaces. Hobbins et al., 2001 found the value of α as 1.3177 for vegetation while using a calibration subset of 92 basins. This method is more suitable to find the ET rate on a large scale which is more applicable on hydrology. The disadvantage of this method is that it is not applicable in advective condition. This method is simpler to use than the PM equation as it has less parameters.

7. Fixed Surface Resistance Approach

Allen et al. (1998) developed guidelines for computing crop water requirements or crop ET, in the FAO 56 paper. They recommended using Penman - Monteith equation to calculate reference grass ET based on surface canopy resistance and aerodynamic resistance. They also tabulated the crop coefficient (K_c) values for the initial, mid and end stages for various crops based on previous researchers' findings. The FAO 56 equation was mainly developed to calculate daily crop ET, however, the authors claimed that it can also be used to calculate hourly crop ET if the hourly weather data are available. FAO 56 method assumes a fixed surface resistance of 70 s/m for whole day or for whole 24 hours. The fixed surface resistance value for 24 hours has been used for the daily or hourly FAO 56 equation.

In many parts of the world including the US, grass cannot sustain for the entire year, hence alfalfa is used as another reference crop. Alfalfa can tolerate harsh weather condition compared to the grass surface cover. Keeping this in mind, in 1999, the Irrigation Association (IA) requested the Evapotranspiration in Irrigation and Hydrology Committee of American Society of Civil Engineers (ASCE) – Environmental and Water Resources Institute (EWRI) to establish and define a benchmark reference evapotranspiration equation. Then the committee in 2005 came up with a reference evapotranspiration equation which is applicable for both tall (alfalfa) and short (grass) reference crops. As a part of the standardization, the ASCE Penman – Monteith (ASCE – PM) equation and associated equations for calculating aerodynamic and bulk surface resistance have been combined and condensed into a single equation that is applicable to both surfaces (ASCE – EWRI, 2005). For the ASCE standardized PM equation, there is one fixed surface resistance for daytime and another fixed surface resistance for nighttime for each reference crop, hence this method is improved version of FAO 56 PM equation.

7.1 FAO 56 Penman Monteith equation

FAO 56 equation was based on the Penman Monteith equation. The FAO 56 method defines the reference crop as a hypothetical crop with an assumed height of 0.12 m having a surface resistance of 70 s/m and an albedo of 0.23, closely resembling the evaporation of an extensive surface of green grass of uniform height, actively growing and adequately watered. Equation (2.18) can be approximated to equation (2.20) after using the aerodynamic and surface resistance equations, which is the FAO 56 equation.

$$ET_0 = \frac{0.408\Delta(R_n - G) + \left(\frac{\gamma 900}{T_a + 273}\right) u_2 (e_s - e_a)}{(\Delta + \gamma(1 + 0.34 u_2)} \tag{2.20}$$

where,

ET_0 = grass reference ET (mm/d),

R_n = net radiation at the crop surface (MJ/m^2/d),

G = soil heat flux density (MJ/m^2/d),

The equations used for aerodynamic and surface resistances while deriving FAO 56 equation are as follows:

$$r_a = \frac{\ln\left(\frac{z_m - d}{z_{om}}\right) \ln\left(\frac{z_h - d}{z_{oh}}\right)}{k^2 U_z} \tag{2.21}$$

where r_a is the aerodynamic resistance (s/m) for neutral atmospheric conditions, z_m is height of wind measurements (m), z_h is height of humidity measurements (m), d is zero plane displacement height (m) = $0.67h_c$, h_c is the crop height (m), $z_{om} = 0.123\ h_c$ is the roughness length governing transfer of momentum (m), $z_{oh} = 0.1\ z_{om}$ is the roughness length governing transfer of heat and water vapor (m) (Allen et al., 1999), k is von-Karman's constant (taken as 0.41), and u_z is wind speed at height z (m/s).

$$r_s = \frac{r_l}{0.5LAI} \tag{2.22}$$

where r_s is the canopy resistance (s m^{-1}), r_l is the daily average stomatal resistance (which is assumed as 100 s m^{-1} for clipped grass and full cover alfalfa), and LAI is leaf area index.

Lopez et al., 2006 found that FAO 56 PM equation performed best under semiarid climatic conditions of Albacete, Spain, as it agreed better with the measured lysimeter ET compared to the other versions of Penman equations and Hargreaves equation

7.2 ASCE-EWRI Standardized Penman Monteith Evapotranspiration equation

The ASCE Standardized Reference Evapotranspiration Equation is based on the Penman-Monteith equation, with some simplification and standardization on the aerodynamic and surface resistances. This equation is applicable for both tall (alfalfa) and short (grass) reference surfaces. A grass reference crop is defined as an extensive, uniform surface of dense, actively growing, cool-season grass with a height of 0.12 m, and not short of soil water; whereas a full cover alfalfa reference crop is defined as an extensive, uniform surface of dense, actively growing alfalfa with a height of 0.50 m, and not short of soil water (ASCE-EWRI, 2005). The equation is as follows:

$$ETsz = \frac{0.408\,\Delta\,(R_n - G) + \gamma\,C_n\,u_2\,\frac{e_s - e_a}{T_a + 273}}{\Delta + \gamma(1 + C_d\,U_2)} \tag{2.23}$$

where,

ET_{sz} = standardized reference crop evapotranspiration for short crop (grass) (ET_{os}) or tall crop (alfalfa) (ET_{rs}) surfaces (mm/d for daily time steps or mm/h for hourly time steps)

R_n = calculated net radiation at the crop surface (MJ/m^2/d for daily time steps or MJ/m^2/h for hourly time steps)

G = soil heat flux density at the soil surface (MJ/m^2/d for daily time steps or MJ/m^2/h for hourly time steps)

The values for C_n for the short and tall references are 900 and 1600 respectively for the daily time steps whereas 37 and 66 for hourly time steps. Similarly the values for C_d for short and tall references are 0.34 and 0.38 for daily time steps whereas 0.24 and 0.96 for short-daytime and short-nighttime respectively and 0.25 and 1.7 for long-daytime and long-nighttime respectively. C_n is a function of the time step and aerodynamic resistance whereas C_d is a function of the time step, surface resistance and aerodynamic resistance (ASCE – EWRI, 2005).

Irmak et al., 2005 found good correlation between ASCE Standardized ET_o and FAO 56 ET_o calculated on hourly time steps, but FAO 56 estimated 5 % to 8 % lower ET compared to the ASCE Standardized ET_o. They explained it due to the higher surface resistance values during daytime periods in the FAO 56 equation. The authors also compared the daily ET_o given by ASCE Standardized daily equation with the sum of the hourly ET_o calculated using the ASCE Standardized hourly equation. They observed that the daily ET_o values were generally higher than the sum of the hourly ET_o and they recommended to use the hourly ET_o values especially in advective condition.

7.3 Valiantzas Model

Valiantzas (2006) developed a set of equations to determine ET rate which was based on simplifications made to the Penman (1963) equation. His purpose was to enable ET computation with limited meteorological data. Valiantzas (2013 a) then improved these equations and claimed that his model performed equivalent in accuracy to the Penman (1963) equation. His simplified equation to calculate reference ET (grass surface) is as follows:

$$ET_o \approx 0.0393 R_s \sqrt{T_a + 9.5} - 0.19 {R_s}^{0.6} \varphi^{0.15} + 0.048(T_a + 20)(1 - \frac{RH}{100}) {u_2}^{0.7} \quad (2.24)$$

where ET_o is the grass reference ET (mm/d), R_s is the measured or estimated incoming solar radiation (MJ/m^2/d), T_a is the mean daily air temperature (°C), φ is the latitude of the site (radians), RH is the relative humidity (%) and u_2 is the mean wind speed at 2 m height (m/s). He also developed an equation to calculate reference ET when the wind speed data is not available. The equation is as follows:

$$ET_o \approx 0.0393 R_s \sqrt{T_a + 9.5} - 0.19 {R_s}^{0.6} \varphi^{0.15} + 0.078(T_a + 20)(1 - \frac{RH}{100}) \quad (2.25)$$

Valiantzas (2013 b) also developed a set of equations to calculate reference ET for arid and humid regions. His equation to calculate reference ET with two different aerodynamic term weighted factors is as follows:

$$ET_o \approx 0.0393 R_s \sqrt{T_a + 9.5} - 2.4 \left(\frac{R_S}{R_a}\right)^2 - 0.024(T_a + 20)\left(1 - \frac{RH}{100}\right) \quad (2.26)$$

$$+ W_{aero} 0.066(T_a + 20)\,)(1 - \frac{RH}{100}) u^{0.6}$$

where, R_a is the extraterrestrial radiation (MJ/m^2/d) and W_{aero} is an empirical weighted factor. The value of W_{aero} is as follows:

$W_{aero} = 0.78$ when $RH > 65$ %

$W_{aero} = 1.067$ when $RH \leq 65$ %.

Again, when the wind speed data is not available, he developed the following equation:

$$ET_o \approx 0.0393R_s\sqrt{T_a + 9.5} - 2.4\left(\frac{R_S}{R_a}\right)^2 + C_u(T_a + 20)\left(1 - \frac{RH}{100}\right) \qquad (2.27)$$

$C_u = 0.054$ when $RH > 65$ % and 0.083 when $RH \leq 65$ %.

Valiantzas model might be a good substitute when some weather data are missing. However, when there is good data available, the use of the mechanistic Penman Monteith equation seems more justifiable than the empirical methods.

8. Variable Surface Resistance Approach

All of the above mentioned equations in section 7 calculate ET for a reference crop surface, which is either grass or alfalfa. In order to calculate the actual crop ET, the current practice is to multiply the reference crop ET with a crop coefficient (K_c). The crop coefficients have been developed for different crop stages for various crops. However, Katerji and Rana (2006) have pointed out that the difference of ± 40% could be observed between the K_c values reported by Allen et al. (1999) and the experimentally obtained K_c values from different researchers. Based on previous researchers' findings (Rana et al., 1994; Steduto et al., 1996; Ventura et al., 1999; Lecina et al., 2003; Pereira, 2005; de Medeiros et al., 2006), they indicated that there is up to 18% of underestimation and 13.4% of overestimation in ET_o in semi-arid regions and humid regions respectively due to the use of fixed r_s. Hence the cumulative error from reference ET calculation and the use of K_c seems very significant and is of concern for irrigation water management. In order to address this problem, some researchers have started to use variable surface resistance instead of fixed surface resistance to calculate actual crop ET directly without using crop coefficient approach. This approach is also called one step ET estimation approach as there is no need of using the crop coefficients. The variable surface resistance approaches that have been developed so far are discussed below:

8.1 Jarvis Model

Jarvis (1976) developed a multiplicative model to calculate stomatal resistance from weather parameters including air temperature, vapor pressure deficit, leaf water potential and ambient carbon dioxide (CO_2) concentration. However, Penman-Monteith equation needs bulk surface resistance and hence the knowledge of stomatal resistance only may not be enough to calculate ET. The upscaling of the stomatal resistance to the canopy level is required to calculate the bulk surface resistance. Alves and Pereira (1999) objected the methodology adopted by Jarvis, as they questioned the validity of the multiplicative model and also they expressed doubt in the assumption of weather parameters acting independently.

8.2 Katerji and Perrier (KP) Model

Katerji and Perrier (1983) found that a linear relationship can be established between the two ratios r_s / r_a and r^* / r_a, where r^* is a climatic resistance. They developed the following empirical relation:

$$\frac{r_s}{r_a} = a\frac{r^*}{r_a} + b \tag{2.28}$$

where a and b are empirical calibration coefficients requiring experimental determination. The resistance, r^*, is defined as:

$$r^* = \frac{\Delta + \gamma}{\Delta\gamma} \frac{\rho c_p D}{R_n - G} \tag{2.29}$$

where the units of R_n and G are W/m2.

Katerji and Rana (2006) reported that the coefficients a and b have already been developed for alfalfa, rice, grass, lettuce, sweet sorghum, sunflower, grain sorghum, soybean, clementine orchard and sloping grassland. The coefficients have also been adapted for water stress conditions (Rana et al., 1997; Rana et al., 2001). Rana et al. (1997) claimed that the coefficients “a” and “b” have multi-local validity (i.e. they do not change with the site but only with the crop species).

The downside of this method is that there is no physical meaning of these coefficients. Also the coefficients need to be tested for different species. Alves and Pereira (1999) indicated that equation (2.28) is only valid for periods where the Bowen ratio varies between -0.3 and 0.3.

8.3 Todorovic Model

Todorovic (1999) came up with a mechanistic approach to calculate surface resistance using the weather parameters. His methodology in summary is as follows:

$$t = \frac{\gamma}{\Delta} \frac{D}{(\Delta + \gamma)} \tag{2.30}$$

At first, t which is the difference between actual canopy temperature and canopy temperature (°C) in wet conditions is calculated using equation (2.30). Then, using quadratic equation (2.31), X, which is the ratio of surface resistance (r_s) to climatological resistance (r_i), is calculated.

$$X = \frac{a + \sqrt{b^2 - 4ac}}{2a} \tag{2.31}$$

where,

$$a = \frac{\Delta + \gamma \Delta}{\Delta + \gamma} \gamma D \tag{2.32}$$

$$b = -\gamma Y t \tag{2.33}$$

$$c = -(\Delta + \gamma) t \tag{2.34}$$

The climatological resistance (r_i) can be calculated using:

$$r_i = \frac{\rho c_p D}{\gamma (R_n - G)} \tag{2.35}$$

In equation (2.33), Y is the ratio of climatological resistance (r_i) to aerodynamic resistance (r_a). The unit of all the resistances, which is the reciprocal of conductance, is in s/m. The units of R_n and G in equation (2.35) are W/m^2.

Then, after finding X, r_s will be calculated by multiplying X and r_i. The calculated r_s will be inserted in the Penman Monteith equation (2.18) to calculate the actual crop ET. The actual crop ET can be defined as the rate of ET that occurs in the field condition.

Lecina et al., 2003 evaluated the KP and Todorovic model based on measured ET from lysimeter and eddy covariance. Based on their finding, they recommended to use the Todorovic model to calculate the hourly ET under the semiarid and windy topographic condition. They didn’t find any improvement in ET estimates using the KP model. On the other hand, Shi et al. (2008) found that the KP model agreed better with the measured eddy covariance ET values for half – hourly and daily ET by summing the half – hourly ET values. They reported that the Todorovic model overestimated ET by about 30 % in their experimental site in China.

8.4 Li et al. model

Lie t al., 2009 found some error in Todorovic model in the derivation of "t". Li et al., 2009 derived "t" as"

$$t = \frac{\gamma D C}{\Delta(\Delta + \gamma)} \tag{2.36}$$

Li et al. proved that Todorovic missed the term C while deriving "t". The missing parameter C was as in equation (2.37):

$$C = \frac{\left(\frac{\Delta}{\gamma}\right) \cdot \left(\frac{1}{r_i}\right) + \frac{1}{r_a}}{\left(1 + \frac{\gamma}{\Delta}\right)\left(\frac{1}{r_s}\right) + \left(\frac{\gamma}{\Delta}\right)\left(\frac{1}{r_a}\right)} \tag{2.37}$$

In their article, Li et al., 2009 replaced C with (1 + D / D_0), where D_0 is a parameter which accounts for the response of t to vapor pressure deficit. They used D_0 as 1.5 kPa for their research, which they claimed is applicable for the winter wheat crop in North China Plain. They also mentioned that the value of D_0 can vary with crops and climatic conditions.

Li et al., 2009 showed that Todorovic model severely underestimated the canopy temperature and sensible heat flux and severely overestimated the latent heat flux. On the other hand, their model gave acceptable results for latent heat flux at both half – hourly and hourly time scales. The limitation of this method is that there is no physical meaning of D_o and the value of D_o is needed to compute "t" and ultimately "r_s".

8.5 Shuttleworth model

Shuttleworth (2006) introduced the concept of the crop independent blending height (50 m) to use as a reference height instead of 2 m reference height to enable one step ET calculation for different crops. Shuttleworth and Wallace (2009) used the existing PM equation and then calculated r_s as a function of weather variables and K_c values documented in FAO - 56. They worked on daily time step instead of hourly; hence their model is not applicable for hourly ET estimation. They concluded that the use of fixed crop coefficients (K_c) to calculate actual crop ET can be problematic. The authors mentioned that the recommended K_c values are said to be appropriate for wind speeds of 2 m/s and “humid” conditions with 45 % relative humidity. Whenever the weather conditions change, the reported values of K_c cannot provide reasonable estimates of ET. The authors also mentioned that the FAO – 56 equation and Priestley Taylor equation with $\alpha = 1.26$ give identical ET values in “humid” conditions. They showed from their equation (2.11) that the ambient weather changes the value of the K_c via the values of the climatological resistance and wind speed. They developed the relationship between r_s and K_c where r_s was a function of K_c, r_s^1 and r_s^2, where r_s^1 and r_s^2 could be calculated using their equations (2.14 and 2.15) or performing interpolation from their Table 2.1 (See Appendix at the end of this chapter). The authors concluded that use of their approach will yield estimates of ET as good as those given by FAO – 56 in humid conditions whereas it improves ET estimation in arid climates and with taller crops.

8.6 Irmak and Mutibwaa model

Irmak et al. (2008) were able to upscale stomatal resistance (leaf scale) to the whole canopy surface resistance for maize using photosynthetic photon flux density (PPFD), leaf area index

(LAI) for sunlit and shaded leaves, solar zenith angle, direct and diffuse solar radiation. They measured the stomatal resistance using porometer. They developed their model for corn and then successfully validated it for soybean with recalibration of some parameters (Irmak and Mutiibwa, 2008; Irmak et al., 2008; Mutiibwa and Irmak, 2010; Mutiibwa and Irmak, 2012; Irmak et al., 2013). Irmak and Mutiibwa (2009) showed that estimation of crop ET using one step approach was superior compared to the two step approach, i.e. using the reference crop ET multiplied by the crop coefficients. The one step approach ET was within 2 per cent of the measured ET using the Bowen Ratio instrument whereas for the two step ET calculation, there was no distinct pattern of over or under estimation. On the other hand, the two step ET method underestimated actual ET (measured) especially when there was high evaporative demand, this suggests that the use of fixed surface resistance while calculating the reference ET is illogical (Irmak and Mutibwaa, 2009).

Irmak and Mutibwaa (2009) were able to modify the Jarvis model, which they referred to as Modified-Jarvis-model (NMJ) and showed that their model is an improvement of the older version, as NMJ model improved the stomatal resistance estimation by 10 % in RMSD (root mean square deviation) when compared to the measured stomatal resistance using dynamic diffusion porometer. Irmak and Mutiibwa (2010) developed a set of empirical equations for nonstressed maize crop to calculate r_s from weather variables. They used the measured ET from Bowen Ratio instrument, then inverted the PM equation to back calculate r_s. Then they used linear regression technique to find the relationship of r_s with sets of weather variables. Irmak et al. (2013) also developed similar set of empirical equations for soybean crop to calculate r_s from weather variables.

Table 2.1 has summarized all the methods that have been discussed in the text and the main equations associated with those equations whereas Table 2.2 has summarized the advantages, limitations and application timestep of all the models that have been discussed.

Table 2.1: Summary of Different ET Estimation Methods

	Methods	Equations
1.	Blaney-Criddle Method (1942)	$u = kf$
2.	Thornthwaite Method (1948)	$PET = 16(10T_a/I)^a$
3.	Hargreaves Equation (1975) (for deg. F) For deg. C	$ET_0 = 0.0075\, R_s\, T_F$ $ET_0 = 0.0135\, R_s\, (T_a + 17.8)$
4.	Christiansen Method (1968)	$E = K\, R_a\, C$
5.	Penman Related Equations	
5.1	Original Penman Equation (1948)	$ET = \frac{(\Delta(R_n - G) + k_w(e_s - e_a)f(u)\gamma)}{\lambda(\Delta + \gamma)}$ $f(u) = a_w + b_w u_2$
5.2	CIMIS Penman Method	$a_w = 0.29$, $b_w = 0.53$ for $R_n > 0$ $a_w = 1.14$, $b_w = 0.40$ for $R_n \leq 0$
5.3	Penman Monteith Equation (1965)	$\lambda E = \frac{0.408\Delta(R_n - G) + \left(\frac{\gamma 900}{T_a + 273}\right) u_2(e_s - e_a)}{(\Delta + \gamma(1 + 0.34u_2)}$
6.	Priestley Taylor Method (1972)	$\lambda E = \alpha\, \Delta(Rn - G)/(\Delta + \gamma)$ where $\alpha = 1.26$ for water surfaces with minimum advection
7.	Fixed Surface Resistance Approach	
7.1	FAO 56 PM Equation (1998)	$ET_0 = \frac{0.408\Delta(R_n - G) + \left(\frac{\gamma 900}{T_a + 273}\right) u_2(e_s - e_a)}{(\Delta + \gamma(1 + 0.34u_2)}$
7.2	ASCE-EWRI Standardized PM Equation (2005)	$ET_{sz} = \frac{0.408\Delta(R_n - G) + \gamma C_n u_2 \frac{(e_s - e_a)}{T_a + 273}}{(\Delta + \gamma(1 + C_d u_2)}$
7.3	Valiantzas Model (2006, 2013)	$ET_o \approx 0.0393 R_s \sqrt{T_a + 9.5} - 0.19 {R_s}^{0.6} \varphi^{0.15} + 0.048(T_a + 20)(1 - \frac{RH}{100}) u^{0.7}$
8.	Variable Surface	

	Resistance Approach	
8.1	Jarvis Model (1976)	
8.2	Katerji-Perrier Model (1983)	$$\frac{r_s}{r_a} = a\frac{r^*}{r_a} + b$$ $$r^* = \frac{\Delta + \gamma}{\Delta\gamma}\frac{\rho c_p D}{R_n - G}$$
8.3	Todorovic Model (1999)	$$t = \frac{\gamma}{\Delta}\frac{D}{(\Delta + \gamma)}$$
8.4	Li et al. Model (2009)	$$t = \frac{\gamma DC}{\Delta(\Delta + \gamma)}$$ $$C = \frac{\left(\frac{\Delta}{\gamma}\right).\left(\frac{1}{r_i}\right) + \frac{1}{r_a}}{\left(1 + \frac{\gamma}{\Delta}\right)\left(\frac{1}{r_s}\right) + \left(\frac{\gamma}{\Delta}\right)\left(\frac{1}{r_a}\right)}$$

Table 2.2: Advantages, Limitations and Application Timestep of Different ET Estimation Models

	Methods	Variables Used	Advantages	Limitations	Application Timestep
1.	Blaney-Criddle Method (1942)	T_a, T_F, p, k, K	Simplicity	ET underestimation in general	Monthly
2.	Thornthwaite Method (1948)	T_a	Simplicity	ET underestimation in advective condition	Monthly
3.	Hargreaves Equation (1975)	R_s, T_F. T_a, R_a	Simplicity	Problems of over and under estimation of ET	Weekly
4.	Christiansen Method (1968)	K, R_a, C	More or less accurate to predict ET for monthly timestep	Not accurate to calculate ET for daily or shorter timesteps.	Monthly
5.	Penman Related Equations				
5.1	Original Penman Equation (1948)	Δ, R_n, G, e_s, ea, γ, f(u), λ	Physical equation based on the combination of surface energy balance equation and aerodynamic equation	Wind speed function is difficult to obtain. The equation was mainly developed for evaporation from free water surfaces.	Daily, hourly
5.2	CIMIS Penman Method	Δ, R_n, G, es, e_a, γ, f(u), λ	a_w and b_w coefficients used in f(u) are easy to obtain. Also applicable for hourly timesteps.	The coefficients used in this equation were developed for Californian condition, hence may not be applicable elsewhere.	Hourly
5.3	Penman Monteith	Δ, R_n, G, e_s, e_a, γ, ρ, c_p, r_a,	Physical equation with the inclusion of	It is difficult to directly implement this	Daily, hourly

	equation (1965)	r_s	r_s.	equation to calculate actual crop ET, as r_s is difficult to obtain.	
6.	Priestley-Taylor Method (1972)	$\alpha, \Delta, \gamma, R_n, G$	Relatively simple	ET underestimation mainly in advective condition.	Daily
7.	Fixed Surface Resistance Approach				
7.1	FAO 56 PM Equation (1998)	$\Delta, R_n, G, e_s, e_a, \gamma, Ta, u_2$	Considered very accurate to calculate grass reference ET on daily basis.	May not be applicable to apply for hourly timestep.	Daily
7.2	ASCE-EWRI Standardized PM Equation (2005)	$\Delta, R_n, G, e_s, e_a, \gamma, Ta, u_2$	It can calculate both grass and alfalfa reference crop ET on both hourly and daily timesteps.	Kc needs to be developed also for alfalfa reference surfaces. The use of fixed r_s for entire day may induce some errors in estimating reference ET.	Daily, hourly
7.3	Valiantzas Model (2006, 2013)	T, R_s, φ, RH, u_2	Relatively simple, can be used when some parameters like wind speed is missing.	It is semi-empirical, so may not be accurate enough as PM equation.	Daily
8.	Variable Surface Resistance Approach				
8.1	Jarvis Model (1976)		New concept to calculate stomatal resistance	It is not easy to obtain canopy resistance (r_c) from stomatal resistance.	
8.2	Katerji-Perrier Model (1983)	$\Delta, R_n, G, e_s, e_a, \gamma, T_a, u_2, a, b, r_a$	Relatively simple to calculate actual crop ET in one step process.	This is empirical method. The coefficients "a" and "b" needs to be tested for different species and also for different climatic conditions.	Daily, hourly
8.3	Todorovic Model (1999)	$\Delta, R_n, G, e_s, e_a, \gamma, T_a, u_2, r_a$	Mechanistic equation to calculate r_s	Some flaws in the procedure as shown by Li et al. (2009).	Hourly
8.4	Li et al. Model (2009)	$\Delta, R_n, G, e_s, e_a, \gamma, T_a, u_2, r_a$	Relatively simple to implement.	Only applicable for winter wheat crop in North China Plain.	Hourly
8.5	Shuttleworth Model (2006, 2009)	$\Delta, R_n, G, e_s, e_a, \gamma, Ta, u_2, r_a, K_c$	Provides one step ET for daily timestep based by calculating r_s based on K_c.	Complicated to use, r_s is a function of FAO 56 Kc values, in other words, r_s depends on the accuracy of K_c.	Daily
8.6	Irmak and Mutibwaa	PPFD, LAI	Already implemented	Complicated to use.	Hourly

	Models (2008, 2009, 2010, 2013)		their models successfully for corn and soybean.	Needs many variables to calculate r_c including PPFD (photosynthetic photon flux density).	

DISCUSSION

Accurate estimation of crop ET is important and significant contributions from various researchers have been made until now. The full version Penman Monteith equation is considered a robust method to calculate crop ET. However, it also has some limitations. The equation uses aerodynamic and surface resistance terms, where aerodynamic resistance is relatively straight forward to calculate. However, the calculation of surface resistance is not easy. The use of fixed surface resistance approach is a simplification of the true diurnal dynamics of this resistance, even for a reference crop under standard conditions. Hence, the modelling of the surface resistance would help in estimating crop ET with more accuracy.

Some authors (Lascano and van Bavel, 2007; Lascano, Van Bavel, & Evett, 2010; Paw, U, 1987, 1988, 1992; Tracy et al., 1984) point out that the exclusion of surface temperature while deriving the PM equation can induce some errors especially when the surface temperature and air temperature are significantly different. The other problem is with the linearity assumption of saturation vapor pressure and temperature curve. Lascano and Van Bavel (2007) and Lascano et al. (2010) calculated the surface temperature and ET simultaneously by iteration technique using fixed surface resistance (which they referred as RCM ET) and concluded that RCM yielded ET rates very close to the measured lysimeter ET while the PM equation underestimated RCM as much as 25 %. Paw U (1988, 1991) developed the fourth order, third order and second order equation to solve the energy budget equation for latent heat flux analytically and claimed that these methods are superior compared to the PM method, as the error associated with the linearity assumption is corrected by using higher degree polynomials.

Some researchers (Dodds et al., 1997) point out that the use of PM equation in advective condition would underestimate ET as the equation is incapable of incorporating the horizontal flow of sensible heat flux.

Shuttleworth and Wallace (1985) developed a two layer ET model, which could incorporate evaporation from the ground surfaces as well as the transpiration from the plant canopy. Their model is thus different from the Penman and Penman related equations which are basically a big leaf one layer ET model. Their model is more useful to calculate the ET rate from sparse canopy.

Regarding the one step ET estimation, KP model lacks physical meaning and it can only be applied when Bowen ratio is in between -0.3 and 0.3 (Alves and Pereira (2000) as cited by Lecina et al. (2003)). Also the coefficients used in the equation may vary among locations (Lecina et al. (2003)). The Todorovic model (1999) is a mechanistic model to calculate surface resistance, however, Li et al. (2009) showed a missing term in his equation. Li et al. in their 2009 article didn’t try to use the improved Todorovic model, but instead used the simpler empirical relation to get the missing term, which was only applicable for winter wheat crop. The Shuttleworth model (2009) is an improved model of the existing method of two step ET estimation; however, the surface resistance used in his model is a function of FAO56 crop coefficient, which may not be transferable accurately to different environmental, crop and soil conditions. In addition to that, Shuttleworth model is only applicable for daily time step, so it cannot work for hourly time step. Irmak and Mutibwaa tried to upscale the surface resistance from the measured stomatal resistance; however, the method needs several field level data including the photosynthetic photon flux density, which is not easy to obtain.

FUTURE WORK

By reviewing the findings to date from various researchers, it is evident that still there is room to improve the estimation of reference as well as actual crop ET. The calculation of actual crop ET with the one step approach, which does not use crop coefficients, seems challenging. However, if it can be done, then the error by using the fixed surface resistance as well as from crop coefficient could be minimized. There has been some progress so far in calculating the surface resistance directly, especially works from Katerji and Perrier, Todorovic, Li et al, Shuttleworth, and Irmak and Mutibwaa. The extension of Shuttleworth model for hourly time step to calculate r_s could be an advancement for better ET estimation using one step approach. Also the validation of Irmak and Mutibwaa model at field level for various crops could be another milestone. Another alternative would be to develop a new r_s model which is robust enough to apply for different crops at different climatic conditions.

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CHAPTER 3

Intercomparison of alfalfa evapotranspiration rates measured by weighing lysimeter and micrometeorological instruments

Overview

Monolithic weighing lysimeters are considered as one of the most accurate methods to measure crop water evapotranspiration (ET) rates. The advantage of a lysimeter compared to other ET measurement methods is that it can measure ET precisely using the soil water balance method. Lysimeters being considered as a reliable and accurate method, have been used globally to determine the crop coefficients (K_c) of various crops. This study explores the possible scenarios when lysimeter conditions may not be ideal to determine the K_c's. Large precision monolithic weighing lysimeters were found to be non-representative of the entire field when the lysimeter surface condition was different than the field surface condition. Based on the data analysis from 2009 to 2013 from the experimental alfalfa lysimeter field of Colorado State University (CSU) Arkansas Valley Research Center (AVRC) near Rocky Ford, Colorado, it was found that in most of the occasions, crop biomass and soil moisture content was greater inside the lysimeter box compared to the rest of the field. This condition caused larger alfalfa evapotranspiration (ET) rates at the lysimeter box compared to the micrometeorological based ET measurement methods (viz. large aperture scintillometer (LAS), eddy covariance (EC) and surface aerodynamic tower (SAT)), which measured ET from a larger footprint than the lysimeter. LAS, EC and SAT measurements of ET agreed reasonably well among each other. In addition, when the air was drier, there was more discrepancy (up to 40 % mean biased error in 2012) between lysimeter ET and the micrometeorological methods. On the other hand, when the weather was more humid as in years 2009 and 2010, the agreement of lysimeter ET with micrometeorological methods was good. The performance in 2009 was best among all the studied years, which is attributed to the good rainfall and the larger alfalfa field compared to the other years. When the field is heterogeneous especially in arid regions, the use of lysimeter ET in developing crop coefficients could cause serious errors as shown in this study. Good field management practices is essential to obtain high quality lysimeter data.

INTRODUCTION

Large monolith weighing lysimeter is considered a reliable method for measuring the evapotranspiration (ET) fluxes. The quantification of ET is important in both hydrology and irrigation fields. In hydrology, ET is a component of the water cycle with its accuracy related with accurate prediction of runoff and floods. In irrigation, ET is considered as a consumptive use of crops, which needs to be replenished by applying irrigation. A weighing lysimeter uses a load cell which is very sensitive to the mass present inside the lysimeter box. In daytime, when ET occurs, the lysimeter mass keeps decreasing, which is sensed by the load cell. The change in mass before and after certain duration is used to quantify the ET in that particular duration using a calibration coefficient of the load cell. In usual settings, the lysimeter is situated in the center of a field and both the field and lysimeter have same crops with similar biomass and moisture condition. However, many reports have shown that the crop growth inside and outside the lysimeter can be different. A lysimeter gives a point measurement of ET, hence, if the lysimeter microenvironment is different from the rest of the field, then ET fluxes measured by the lysimeter may not represent the entire field ET. In such a condition, it may be necessary to adjust the lysimeter ET in order to represent the entire field.

Evett et al. (2012) found that the lysimeter ET fluxes were up to 18 % larger than the overall field ET. They emphasized correction of the lysimeter ET based on the network of neutron probe access tubes, which is used to measure soil moisture content in the surrounding field.

Lysimeters are often used to develop a crop coefficient (K_c) curve for different crops. One of the main objectives of the Rocky Ford lysimeter project is to develop alfalfa based crop coefficients for major Southeastern Colorado crops like alfalfa, corn, sorghum, winter wheat, etc. The crop coefficient is the ratio of actual crop ET to the reference crop ET (which can be either grass based reference ET or alfalfa based reference ET). To develop the K_c, actual crop ET is generally measured by lysimeter whereas reference ET is generally calculated using the ASCE Standardized reference ET equation (Allen et al., 2005). The K_c of alfalfa using the alfalfa based reference ET equation (K_{cr}) should not be significantly larger than 1 or in some cases may be slightly smaller or larger than 1, as it is the ratio of measured alfalfa ET to calculated alfalfa ET. In other words, it is not expected to have a huge difference between the measured and calculated reference ET at reference condition. However, AlWahaibi (2011) in his PhD dissertation showed that in Rocky Ford lysimeter project in some cases, K_{cr} for alfalfa went up to 1.3, which is a big concern. The higher K_c most probably means that the lysimeter perhaps is capturing additional evaporative energy that is not accounted for by the theoretical reference ET equation. If the developed K_c values for major crops are significantly higher, then there will be overestimation of irrigation water requirements. This could lead to waste of precious irrigation water in agriculture, which could have been used for other useful purposes. Overirrigation leads to waste of water, waste of money, water logging on the field, water quality problems, and also reductions in yields. Hence there is a huge monetary loss as well as some environmental concerns associated with overirrigation. In order to mitigate this, it would be appropriate to find the reasons behind this high K_c values and possible solutions to address the problem before starting to find K_c for other field crops. The specific objectives of this study were to evaluate lysimeter ET rates for alfalfa based on other micrometeorological measurements (LAS, EC, SAT) for homogeneous and heterogeneous crop surface conditions around the weighing lysimeter at the CSU-Arkansas Valley Research Center, Rocky Ford, CO.

MATERIALS AND METHODS

Study Area

The study was conducted at the Colorado State University (CSU) Arkansas Valley Research Center (AVRC) near Rocky Ford, Colorado.

The geographic coordinates of the site is 38° 2' N and 103° 41' W and the elevation is 1,274 m above mean sea level. There are two large precision weighing lysimeters, one is called the crop lysimeter (CL) and the other is called the reference lysimeter (RL). The dimension of the crop lysimeter field is 160 m by 250 m (4 ha or 10 acre area) and the alfalfa was grown on the field from 2008 to 2012. Alfalfa was grown in CL until 2012 followed by corn in 2013 and 2014. A large monolithic weighing lysimeter (3 m × 3 m × 2.4 m) was located in the middle of the CL field. As part of the instrumentation in the field, there was a net radiometer (Q 7.1 net radiometer, REBS, CSI, Logan, Utah, USA), two infra-red thermometers (IRT Apogee model SI-111, CSI, Logan, Utah, USA) to measure crop radiometric surface temperature, soil heat flux plates (REBS model HFT3, CSI, Logan, Utah, USA) buried in the ground at the lysimeter locations, with depths of 10 cm, along with soil temperature and soil water content sensors, for the estimation of soil heat flux at the ground surface. The field was irrigated with furrow irrigation system using siphons and a head ditch. The reference lysimeter field is triangular in shape, where a weighing lysimeter (1.5 m × 1.5 × 2.4 m) is located in the middle of the field. This field was vegetated with alfalfa from 2011 and is planned to be kept with alfalfa until 2015. Similar instrumentation is provided in the RL field as in CL field. Figure 3.1 shows the layout of the lysimeter fields. Point 1 is the reference lysimeter location whereas point 2 is the crop lysimeter location.

The average annual maximum temperature is 21.1° C (70° F). The average annual minimum temperature is 2.4° C (36.3° F). The long-term average annual precipitation at the site is 301 mm (11.85 inches) with approximately two-thirds of the annual total occurring from May through September. The total average annual snowfall is 589 mm (23.2 inches). The average date of the last spring frost (0° C or 32° F) occurs at about May 1, and the average date of the first fall frost occurs October 5. Thus, the average length of the growing season for warm-season crops like corn is 158 days (http://www.wrcc.dri.edu/cgi-bin/cliMAIN.pl?corock) as cited by Berrada et al. (2011).

Figure 3.1: Lysimeter fields layout, point 1 showing the reference lysimeter box with triangular field and point 2 showing the crop lysimeter box with rectangular field.

Description of crop lysimeter

The crop lysimeter is a large precision weighing lysimeter. Berrada et al. (2011) has given a complete description regarding this lysimeter. The lysimeter consists of an inner soil monolith tank with dimensions of 3 m × 3 m × 2.4 m and an outer containment tank. It consists of a load cell which is connected to a Campbell Scientific CR7 data logger that records the mass of the inner tank and soil. Load cell readings are recorded in millivolts per volt (mV/V) and converted to equivalent load values using the field calibration. The calibration equation of the load cell was $y = 685.4 x – 142.9$ (y is mass in kilograms and x is the load cell output in mV/V), with standard deviation of the weight measurements less than 0.02 %. A change of 1 mV/V in the load cell output is equivalent to a water depth change of 76.1 mm on the lysimeter, which is simply obtained by dividing 685.4 by 9, where 9 m^2 is the evaporative area of the lysimeter. Andales (personal communication) corrected the effective evaporative surface area of the lysimeter by including the half thickness of the rubber seal, which separates the monolith interior wall from the external retainer wall of lysimeter. By doing so, the lysimeter effective surface area increases to 9.18 m^2 from previous 9 m^2 and so the calibration coefficient changes from 76.1 to 74.6 mm / (mV/V). Hence, changes in load cell output are multiplied by 74.6 to obtain the amount of water lost by ET or amount of water gained through precipitation or irrigation.

Description of reference lysimeter

The reference lysimeter is also a precision weighing lysimeter; however, it is smaller compared to the crop lysimeter. This lysimeter also has a similar instrumentation as in the crop lysimeter. Load cell (11.36 kg capacity; Interface, Inc. model SM-25) readings are recorded in millivolts per volt (mV/V) and then converted to equivalent mass values using the field calibration similar to the one for the crop lysimeter. The load cell is connected to the lysimeter monolith through a system of levers with a total mechanical advantage of 100. Thus, the load cell can effectively detect a maximum change in mass of 1136 kg. The calibration of the load cell was $y = 353.71x - 63.44$ (y is mass in kg and x is the load cell output in mV/V). A change of 1 mV/V in the load cell output is equivalent to a water depth change of 157.2 mm on the lysimeter, which is obtained by dividing 353.71 by 2.25, where 2.25 m^2 is the evaporative area of the lysimeter. Andales (personal communication) corrected the effective evaporative surface area of the reference lysimeter by including the half thickness of the rubber seal. By doing so, the lysimeter surface area increases to 2.341 m^2 from 2.25 m^2, which changes the calibration coefficient from 157.2 to 151.09 mm/(mV/V). Therefore, changes in load cell output are multiplied by 151.09 to obtain the amount of water lost by ET or amount of water gained through precipitation or irrigation for the reference lysimeter.

Description of Large Aperture Scintillometer (LAS)

Kipp and Zonen large aperture scintillometers (LAS) were deployed in the lysimeter fields from 2009 to 2013. LAS was installed in the CL field from 2009 to 2011 whereas in the RL field in 2012 and 2013. LAS does not directly measure ET; however, it measures sensible heat flux (H) using measured net radiation (R_n), soil heat flux (G) and atmospheric stability (mainly stable or unstable condition) (Samain et al., 2012). Soil moisture sensors were also installed along with the soil heat flux plates, which are required in the calculation of G. In order to obtain H from LAS, first Bowen ratio (β) is guessed, which outputs temperature structure parameter, temperature scale and Monin Obukhov length simultaneously. Friction velocity can be calculated after finding the Monin Obukhov length. Then H can be calculated using the friction velocity and temperature scale, however, this H is not the final H. The energy balance equation is then solved with this H and measured R_n along with G and again new β is obtained. Again this new β is used and new H will be obtained and so on. Several iterations are required in this process to stabilize all the parameters to get the final H, viz. Bowen ratio, temperature structure parameter, temperature scale, friction velocity, Monin Obuknov length and finally H. Rambikur (2012) has provided the detailed description of this procedure. After obtaining the final H, then LE can be obtained using the energy balance equation ($LE = R_n – G – H$), as heat storage and metabolic heat production terms are considered negligible.

Description of Eddy Covariance (EC)

Campbell Scientific CSAT3 Three Dimensional Sonic Anemometer and KH2O Krypton Hygrometer were used as components of eddy covariance (EC) instrument. The EC was installed in 2011 on crop lysimeter field whereas in 2012 and 2013 on reference lysimeter field. EC measures both H and LE flux, so it is considered as a direct ET measurement method. H and LE were obtained using EdiRe software (Available at: http://www.geos.ed.ac.uk/abs/research/micromet/EdiRe/). EC method has been found to underestimate especially the LE flux (Foken, 2008), which needs to be adjusted using energy balance closure methods.

Description of Surface Aerodynamic Tower (SAT)

Surface aerodynamic towers were also installed in both CL and RL fields. Six arms having almost one meter distance vertically were used in each tower, each arm having 3 way cup anemometer to measure wind speed as well as air temperature and relative humidity sensors. Arya (2001) has explained in detail the procedure to calculate the H and LE fluxes using this method. Also, net radiation was measured in each tower and soil moisture sensors along with the soil heat flux plates to calculate G. Only the second and the fourth arms from the tower were used to calculate the latent heat flux for this study.

Soil moisture, surface temperature and crop height measurement

Soil moisture was measured by using neutron probe method. Two access tubes were installed inside the monolith and four were installed immediately outside the lysimeter. A CPN 503 DR neutron probe was used to measure the soil water content (% by volume) at 0.1, 0.3, 0.5, 0.7, 0.9, 1.1, 1.3, 1.5, 1.7 and 1.9 m depths in the soil profile (Berrada, 2011). The calibration of the neutron probe was performed according to the method suggested by Evett et al. (2003) as cited by Berrada (2011).

Crop height measurement was done every week in both weighing lysimeters. In CL, four harvests of alfalfa was possible from 2008 to 2011, while in 2012, only 2 harvests were possible as the field was getting transitioned from alfalfa to corn. A linear interpolation was then performed to get the daily crop height from the measured weekly crop height.

In 2012 and 2013, crop height measurements and canopy surface temperatures (T_s) were taken for the whole lysimeter fields. Both the fields were divided into a network of grids as shown in Figure 3.2. The crop height readings were taken manually in each grid and also on the lysimeter surfaces. The measurements of T_s were taken using an infrared thermometer (IRT) temperature sensor also in each grid and on the lysimeter surfaces.

Figure 3.2: Lysimeter Field grids

Comparison of T_s

The reading of T_s in each grid was taken manually by using a temperature sensor. In both lysimeters, infrared (IRT) thermometers were installed, which recorded crop surface temperature automatically. When the crop is stressed, its T_s is supposed to be higher compared to the unstressed crop at the same time. It would be ideal to take temperature measurement in all the grids at the same time in order to evaluate the crop stress condition. Nevertheless it was not possible to record the reading at same time manually. Peters and Evett (2004) developed an equation to extrapolate the T_s to different daytime using pre-dawn canopy temperature, canopy temperature from the reference location at the same time interval that we are interested, one time measured canopy temperature at the remote location and measured reference temperature from the time that the remote temperature measurement was taken. The equation is as follows:

$$T_{rmt} = T_e + \frac{(T_{rmt,t} - T_e)(T_{ref} - T_e)}{T_{ref,t} - T_e} \tag{3.1}$$

where,

T_e = pre-dawn canopy temperature throughout the whole field (°C),

T_{rmt} = calculated canopy temperature at the remote location (°C),

T_{ref} = canopy temperature from the reference location at the same time interval as T_{rmt} (°C),

$T_{rmt,t}$ = one-time-of-day canopy temperature measurement at the remote location at any daylight time t (°C),

$T_{ref,t}$ = measured reference temperature from the time that the remote temperature measurement was taken (t).

Data Selection

EC data was not available in 2009 and 2010. EC was installed in 2011 on CL field. LAS was deployed in CL field from 2009 to 2011 and on RL field in 2012 and 2013. Due to this, LE comparison among all measurement methods was performed using CL field data from 2009 to

2011 and RL field data in 2012 and 2013. The data was selected when the alfalfa was at least 30 cm tall.

Evaluation Criteria

Several performance indicators were used to evaluate the performance of the lysimeter ET rates with respect to the micrometeorological methods. Hourly data was used for the evaluation process. The performance indicators that have been used are as follows:

Slope and y-intercept: The slope and y-intercept of the best-fit regression line can indicate how well simulated data matched measured data (Moriasi, 2007). A slope of 1 and y-intercept of zero indicate that the model perfectly reproduces the magnitudes and measured data (Wilmott, 1982). The slope and y-intercept are commonly examined under the assumption that measured and simulated values are linearly related, which implies that all of the error variance is contained in simulated values and that measured data are error free (Wilmott, 1982).

Co-efficient of determination (R^2): This is a measure of the proportion of variance in measured data that is explained by a model. It allows one to determine the certainty of making a prediction from a model. It ranges between 0 and 1, with a value of 1 being the optimal. Mathematically, R^2 is obtained by using equation (3.2).

$$R^2 = \frac{(\sum_{i=1}^{n}(O_i - \overline{O})^2(M_i - \overline{M}))^2}{\sum_{i=1}^{n}\left(O_i - \overline{O}\right)^2 \sum_{i=1}^{n}\left(M_i - \overline{M}\right)^2} \tag{3.2}$$

where, O is the observed or measured and M is the predicted or derived value. The bars above the variables indicate mean value.

Mean Bias Error (MBE): This indicator is usually used to calculate the mean model bias or mean over or under prediction. MBE is obtained by averaging the difference between predicted and measured values. Positive values indicate model over-estimation bias, and negative values indicate model under-estimation bias (Willmott, 1982), and zero indicate that there is no bias.

$$MBE = \frac{1}{n}\sum_{i=1}^{n}(M_i - O_i) \tag{3.3}$$

Root Mean Squared Error (RMSE): This is a commonly used error index statistic. A smaller RMSE value indicates a smaller error spread and variance and therefore a better model performance. It measures the magnitude of the spread of errors. It is calculated by squaring the differences between predicted and measured values, then averaging them and finally taking the square root of the average.

$$RMSE = \sqrt{\frac{1}{n}\sum_{i=1}^{n}(M_i - O_i)^2} \tag{3.4}$$

Index of agreement: Index of agreement is how close the model value agrees with the measured value. It can be obtained by using equation (3.5). The index of agreement of 1 indicates a perfect agreement between the measured and predicted values, and zero indicates no agreement at all (Wilmott, 1982).

$$d = 1 - \frac{\sum_{i=1}^{n}(y_i - x_i)^2}{\sum_{i=1}^{n}(y_i' - x_i')^2} \tag{3.5}$$

where, d is the index of agreement, y_i and x_i are the calculated and the measured values respectively; $y_i' = y_i - x'$ and $x_i' = x_i - x'$ and N is the total number of observations.

Nash-Sutcliffe Coefficient of Efficiency (NSCE): This is usually used to assess the predictive ability of a model. To determine NSCE, the sum of absolute squared differences between the predicted and observed values, normalized by the variance of the observed values is subtracted from 1. NSE values range between -∞ and 1. The closer the model efficiency is to 1, the more accurate the model is, with values above zero indicating an acceptable performance level, while values less than zero indicate unacceptable performance (Nash and Sutcliffe, 1970; Moriasi et. al., 2007). NSE is obtained by using equation (3.6).

$$NSE = \frac{\sum_{i=1}^{n}(O_i - \overline{O})^2 - \sum_{i=1}^{n}(M_i - O_i)^2}{\sum_{i=1}^{n}\left(O_i - \overline{O}\right)^2} \tag{3.6}$$

where, M is the model estimation value, O is the measured or observed value and n is the number of observations.

RESULTS AND DISCUSSION

Comparison of the latent heat fluxes

In 2009 and 2010, large aperture scintillometer (LAS) and surface aerodynamic tower (SAT) were installed in the CL field. Figures 3.3 and 3.4 show the comparison of the latent heat flux (LE) from these instruments with the precision weighing lysimeter. LAS and lysimeter agreed very well in 2009 as the slope of the regression line was close to one. SAT and lysimeter data also agreed well though there was some noise. It is expected that there is more noise in the SAT data compared to the LAS and lysimeter data because the procedure is affected by the accuracy of the air temperature and relative humidity sensors. Figure 3.5 shows the comparison of LE from SAT and LAS. The agreement in general is good with some scattered points.

Likewise, Figures 3.6 and 3.7 show the comparison of LAS and SAT with lysimeter. In 2010, both LAS and SAT measure less LE flux compared to the lysimeter. The slope of the regression line was 0.85 when LAS was compared with lysimeter whereas it was 0.88 when SAT was compared with lysimeter. However, there was a good agreement when LAS and SAT were compared (Figure 3.8), the slope being 1.02. The comparison in 2010 was better than in the following years.

In 2011, eddy covariance (EC) was also deployed in the CL field. EC method is considered a reliable method of measuring fluxes, but it underestimates the surface scalar fluxes and thus fails to close the energy balance (Mahrt, 1998; Aubinet et al., 1999; Oncley et al., 2007; Wilson et al., 2002). Previous researchers have provided two options to correct the fluxes from EC, first option is assuming H was correctly measured and LE being the residual of the energy balance and the second option was to adjust both H and LE maintaining the same Bowen Ratio. In this research, first option was chosen to adjust the EC fluxes, that is, the discrepancy (summation of measured net radiation, soil heat flux, sensible heat flux and latent heat flux) was added to the measured LE flux for the adjustment. Figures 3.9 through 3.11 show the comparison of LE fluxes from LAS, EC and SAT respectively with the lysimeter. In 2011, LAS was covering larger area than just CL field, so the measured flux was affected by other surrounding fields.. So it is expected that 2011 LAS data has some noise. Comparison of EC with lysimeter was better, though there is serious underestimation of LE from EC compared to the lysimeter. The slope of the regression line was 0.72 when EC was compared with lysimeter whereas, it was 0.74 when SAT was compared with lysimeter. Figures 3.12 and 3.13 show the comparsion of the LE fluxes when LAS and SAT were compared with EC. In general, LAS and EC agreed well, although there were some significant number of scattered points because of the set up issues with LAS. SAT and EC also agreed very well except for some scattered points.

In 2012, RL field was used for the comparison. LAS, EC and SAT all were installed on the field and LE fluxes from these instruments were compared with lysimeter data (Figures 3.14 through 3.16). It is evident that all of these instruments had similar slopes (0.72 to 0.74) when compared to the lysimeter. This means lysimeter ET was 26 to 28 % more in 2012 compared to the other instruments. Figures 3.17 and 3.18 show the comparison of LAS and SAT with EC flux. The agreement in both cases was good although there was some scattered point when SAT was compared (Figure 3.18).

In 2013, RL field was used for the comparison. All of those instruments were installed and then LE fluxes were compared with lysimeter data (Figures 3.19 through 3.21). Also in 2013, all of these instruments yielded similar slopes (0.77 to 0.79) when compared to the lysimeter. Figures 3.22 and 3.23 show the comparison of LAS and SAT with EC flux. The agreement was very good in both cases, even SAT performing very well in 2013.

2009

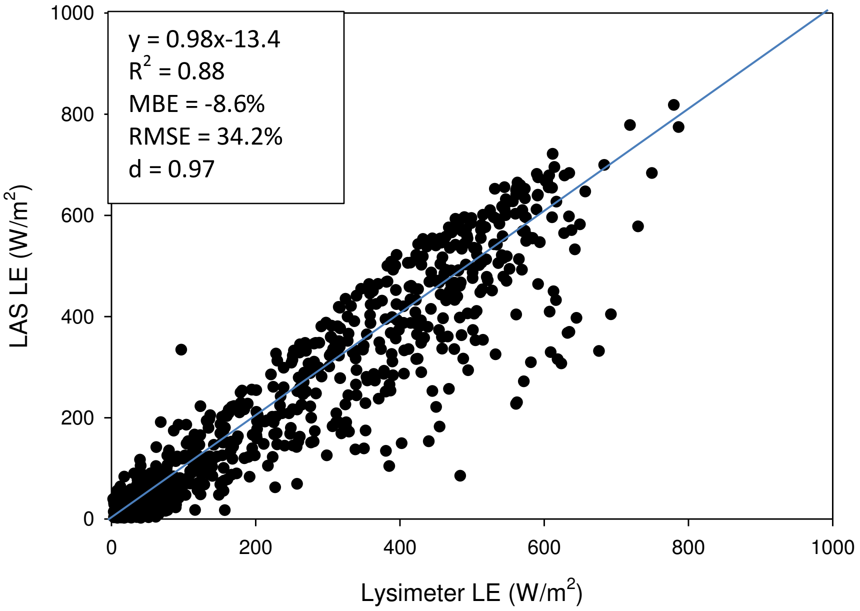

Figure 3.3: Comparison of latent heat fluxes from LAS and lysimeter in 2009

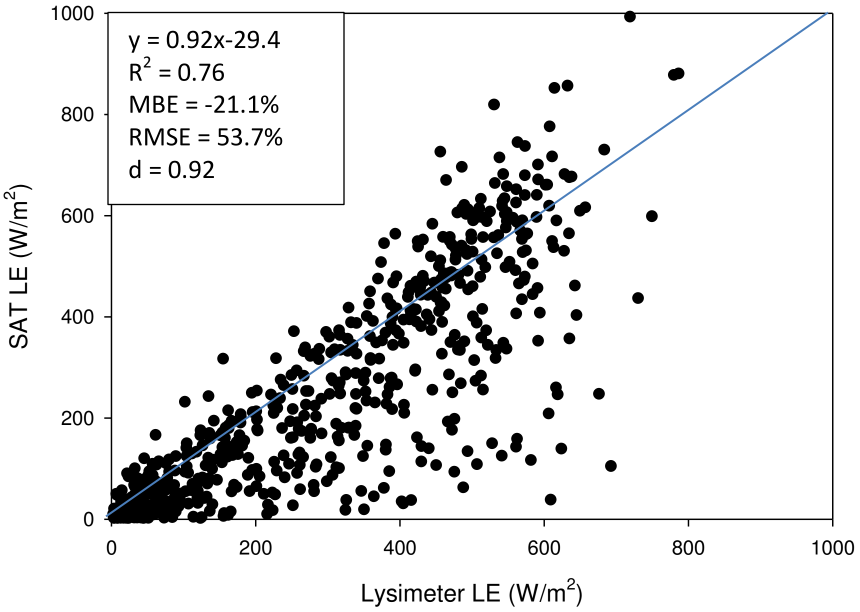

Figure 3.4: Comparison of latent heat fluxes from SAT and lysimeter in 2009

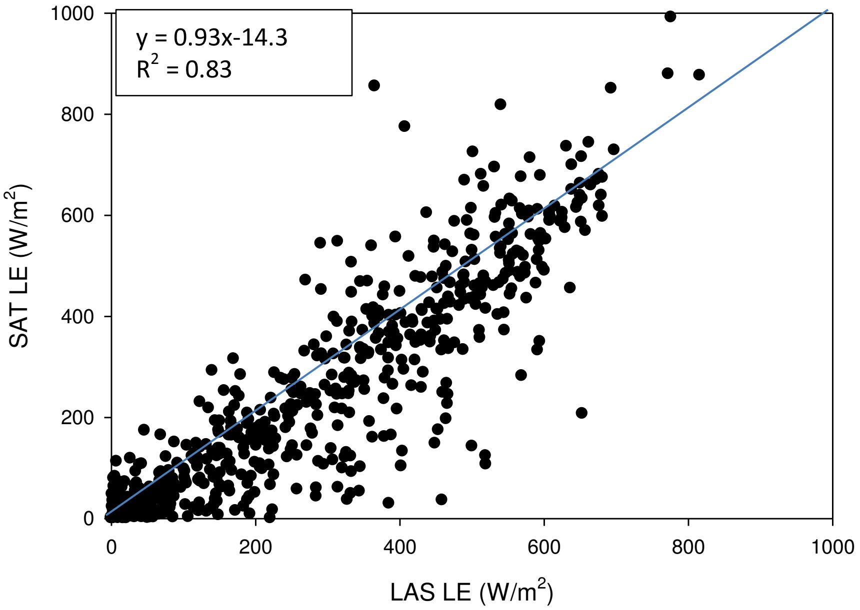

Figure 3.5: Comparison of latent heat fluxes from SAT and LAS in 2009

2010

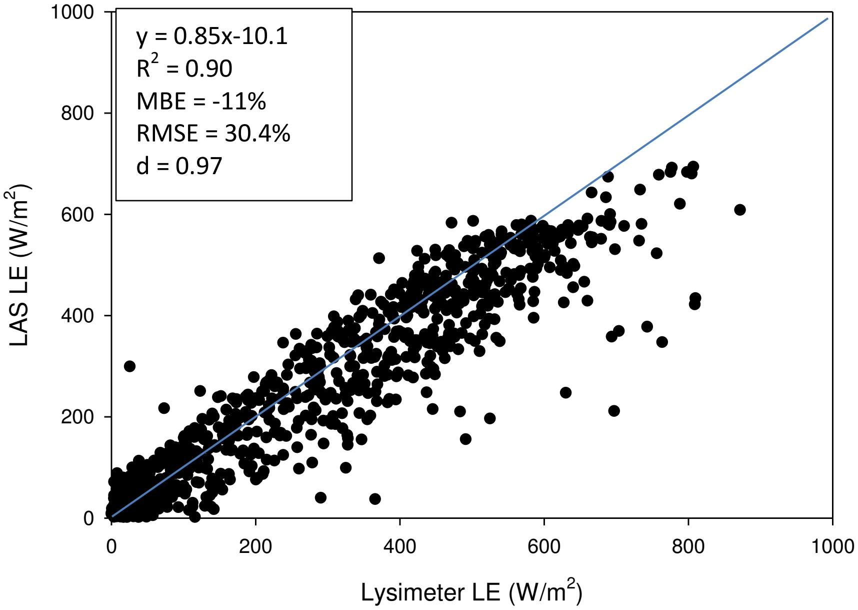

Figure 3.6: Comparison of latent heat fluxes from LAS and lysimeter in 2010

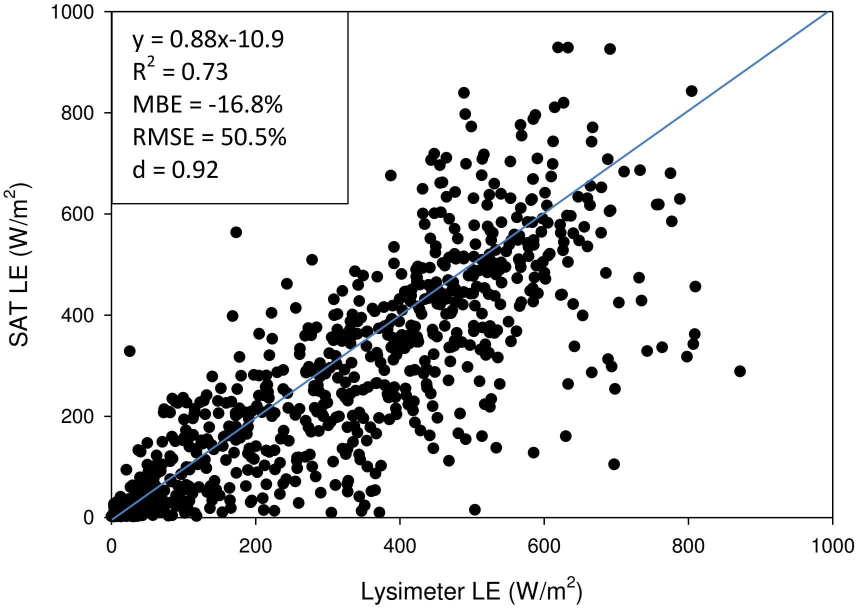

Figure 3.7: Comparison of latent heat fluxes from SAT and lysimeter in 2010

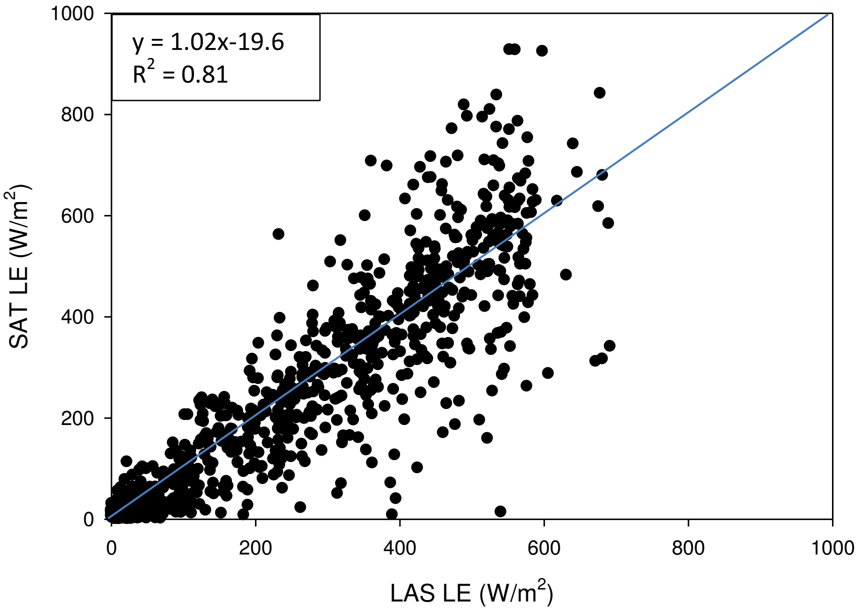

Figure 3.8: Comparison of latent heat fluxes from SAT and LAS in 2010

2011

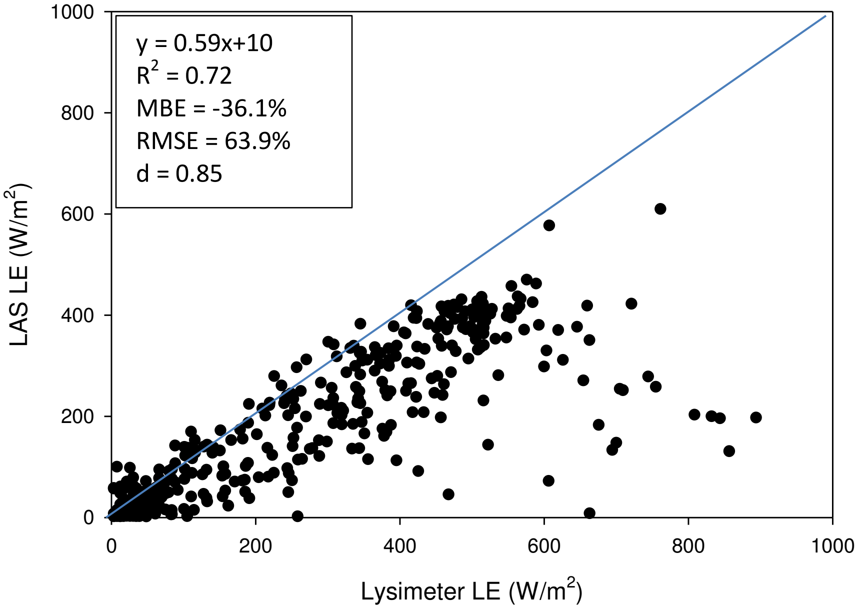

Figure 3.9: Comparison of latent heat fluxes from LAS and lysimeter in 2011

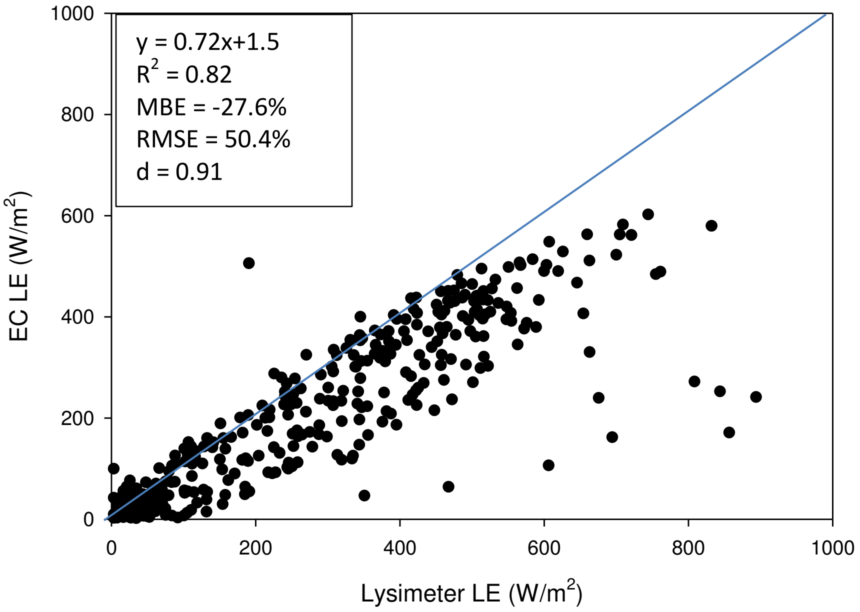

Figure 3.10: Comparison of latent heat fluxes from EC and lysimeter in 2011

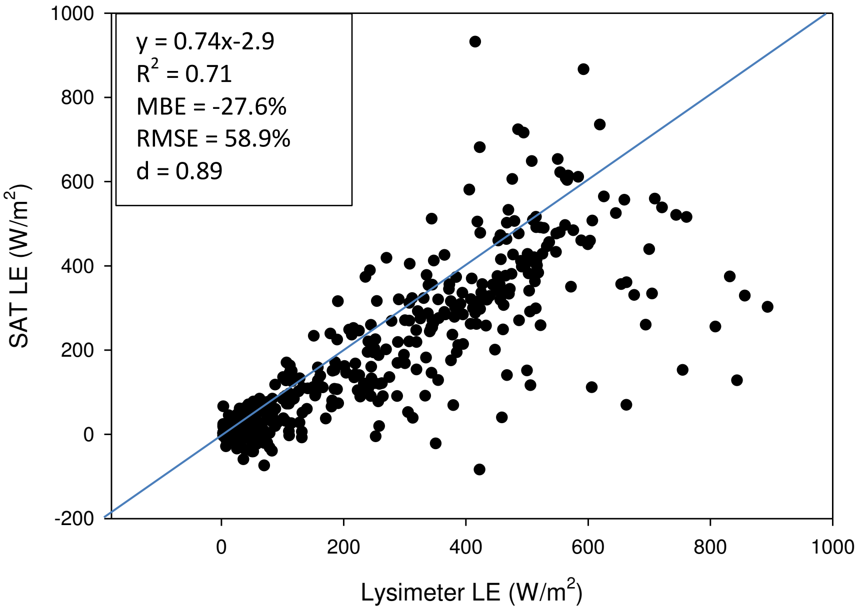

Figure 3.11: Comparison of latent heat fluxes from SAT and lysimeter in 2011

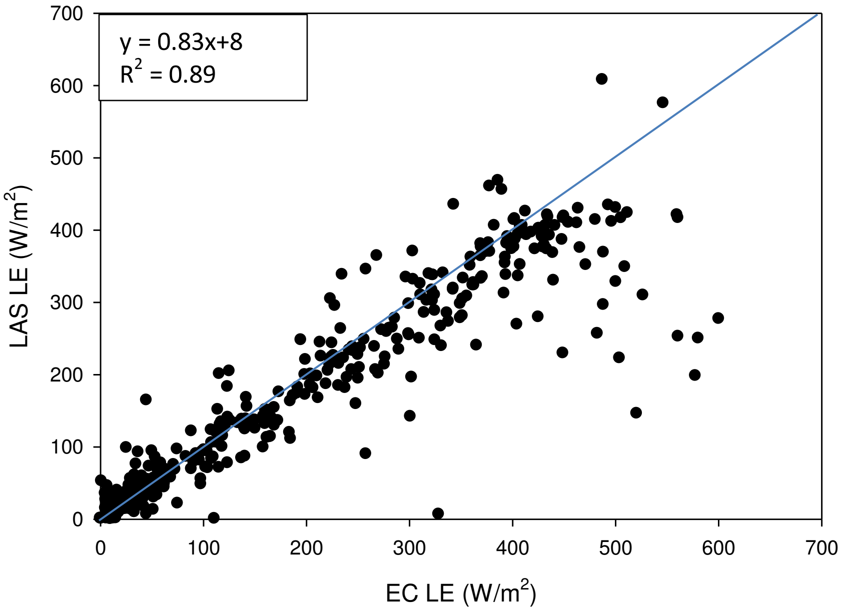

Figure 3.12: Comparison of latent heat fluxes from LAS and EC in 2011

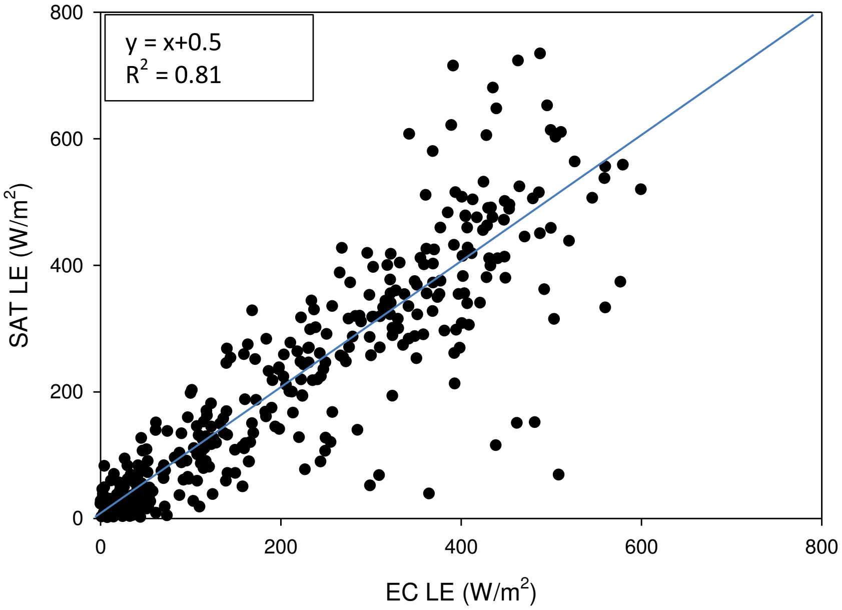

Figure 3.13: Comparison of latent heat fluxes from SAT and EC in 2011

2012

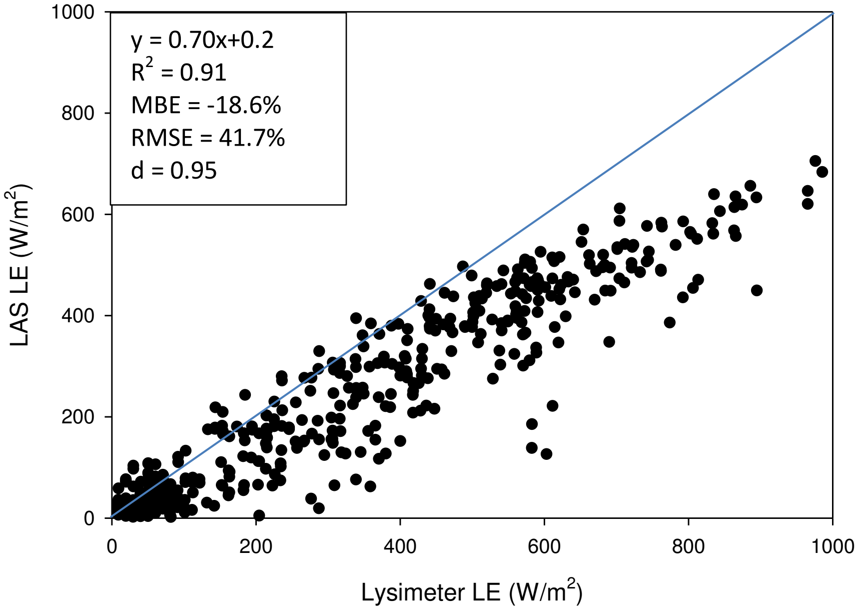

Figure 3.14: Comparison of latent heat fluxes from LAS and lysimeter in 2012

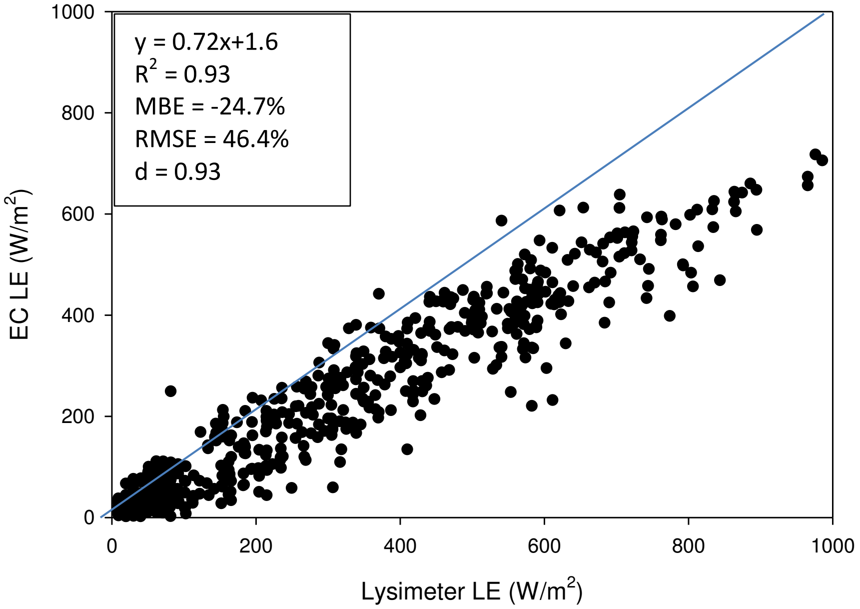

Figure 3.15: Comparison of latent heat fluxes from LAS and lysimeter in 2012

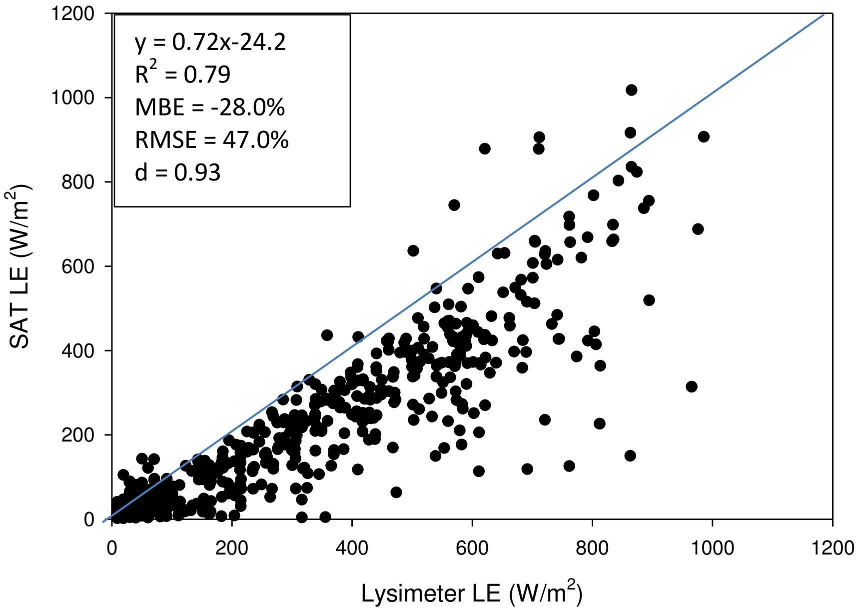

Figure 3.16: Comparison of latent heat fluxes from SAT and lysimeter in 2012

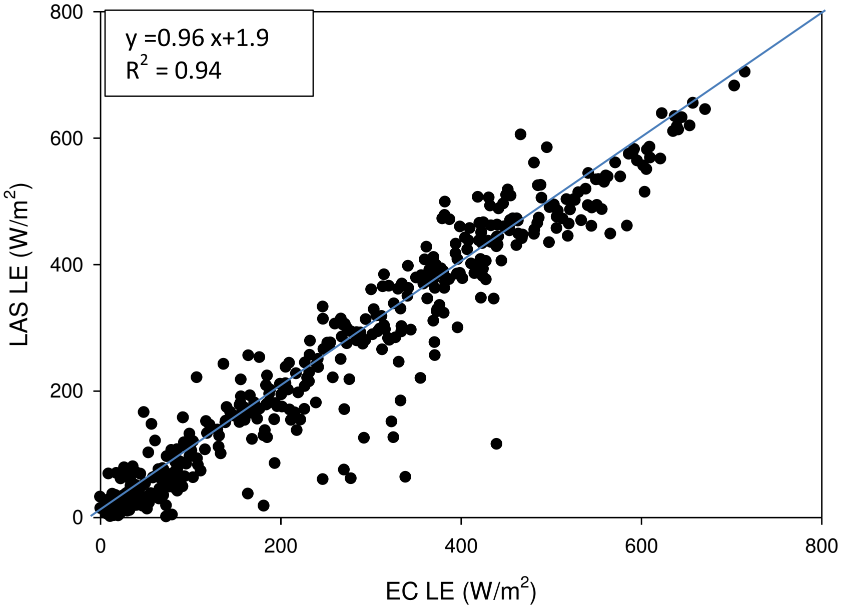

Figure 3.17: Comparison of latent heat fluxes from LAS and EC in 2012

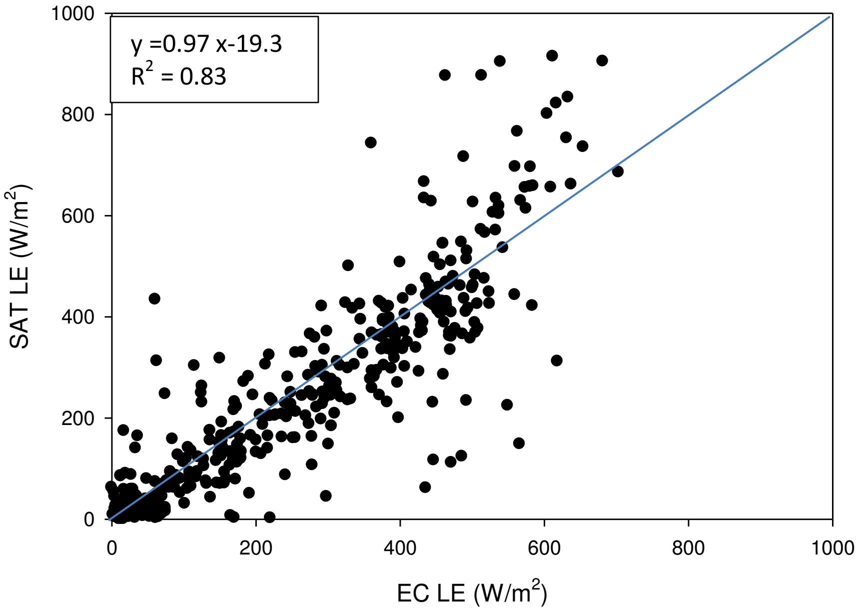

Figure 3.18: Comparison of latent heat fluxes from SAT and EC in 2012

2013

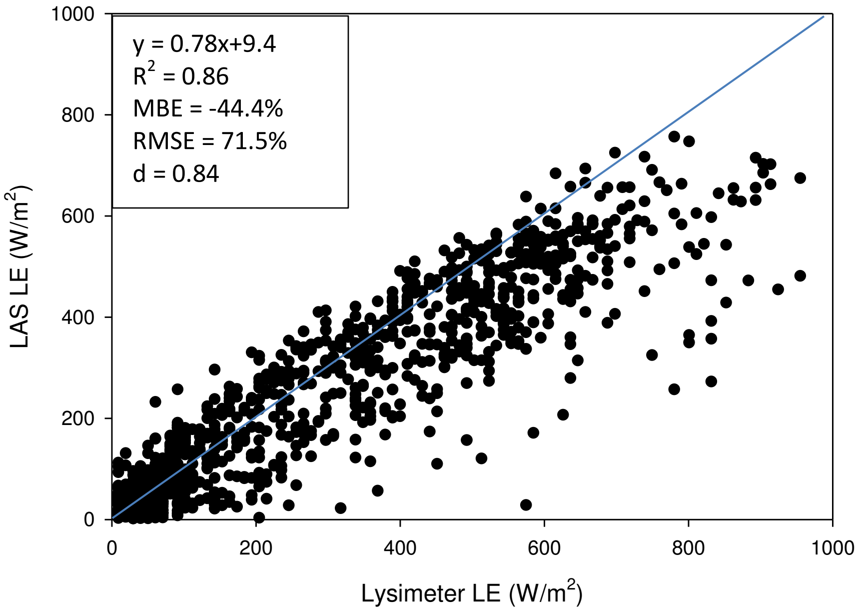

Figure 3.19: Comparison of latent heat fluxes from LAS and lysimeter in 2013

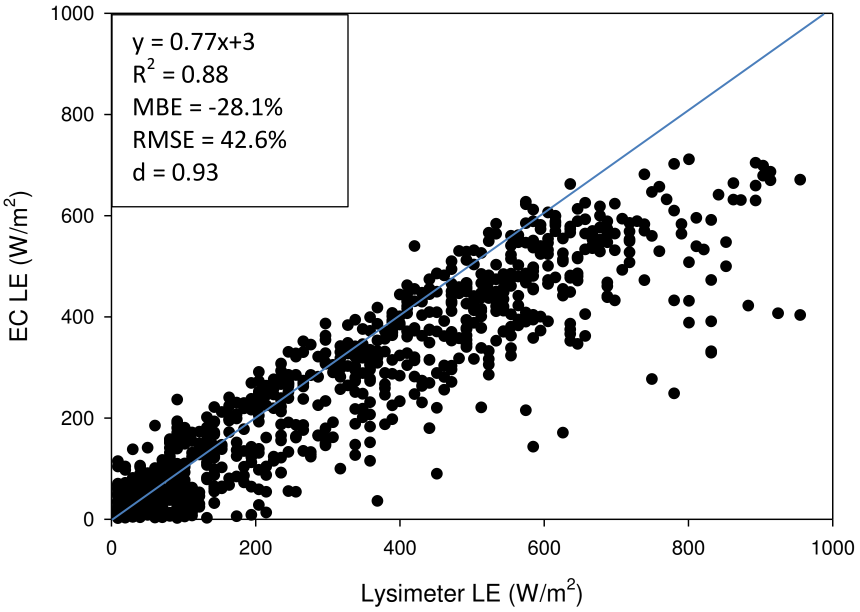

Figure 3.20: Comparison of latent heat fluxes from EC and lysimeter in 2013

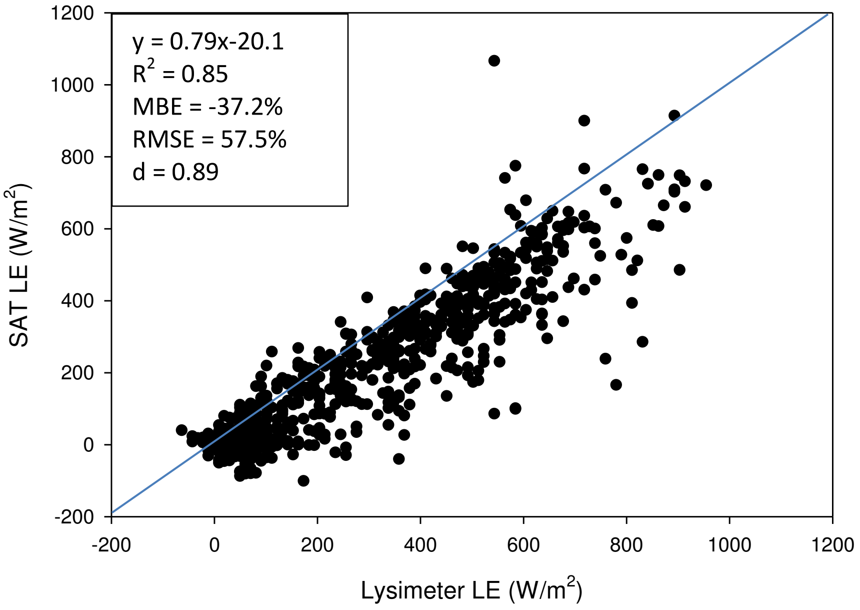

Figure 3.21: Comparison of latent heat fluxes from SAT and lysimeter in 2013

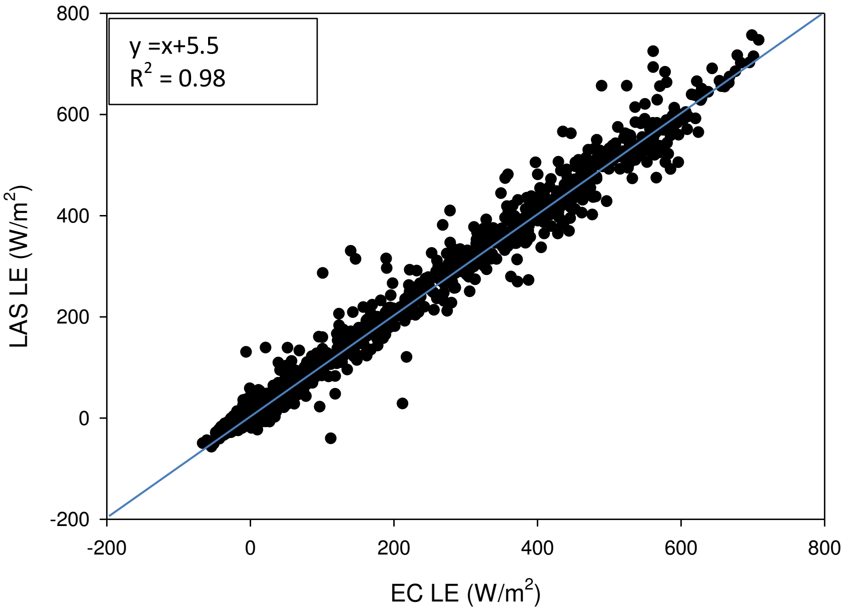

Figure 3.22: Comparison of latent heat fluxes from LAS and EC in 2013

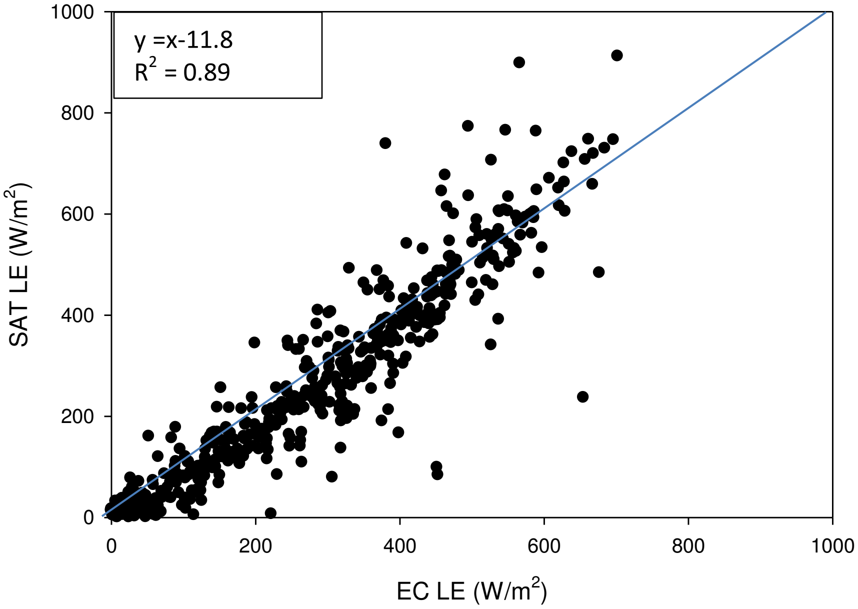

Figure 3.23: Comparison of latent heat fluxes from SAT and EC in 2013

Data Investigation

It is evident from Figures 3.3 through 3.23 that there were some outlier points in the plots. Since LAS, EC and SAT data agreed very well and LAS data was available for all of these years, only LAS data was analyzed in more detail in all years except 2011. In 2011, however, EC data was used as LAS data had some setup problems.

The investigation was first started for the 2009 data. Most of the outlier points were from 8/22 and 8/23. It was later found that the field was harvested on 8/21 whereas the lysimeter was harvested on 8/24. This resulted in the LE flux from LAS to be smaller as the field was already harvested. On the other hand, lysimeter LE was larger due to the oasis and clothesline effects. Hence data from 8/21 to 8/23 were excluded. Also there were some outlier points, where the wind speed was greater than 4 m/s. When wind speed was higher, it was observed that the difference of LAS and lysimeter flux was higher. Generally, when the wind speed is high and there is surface inhomogeneity in field (higher soil moisture content inside lysimeter compared to the field), lysimeter ET was found to be higher. This higher wind speed brings the advected heat from other sources and since the inside lysimeter has more moisture content, the difference between lysimeter ET and LAS becomes higher. All of those outlier points were filtered and then Figure 3.24 was obtained for the comparison of LAS and lysimeter LE flux. The agreement was very good as the slope was close to one, meaning most of the points follow one to one line.

In 2010, the same issue was observed. Most of the outliers were identified from the days when the field was harvested but not the lysimeter. Likewise, there were some outlier points with high wind speed (larger than 4 m/s). All of those outliers were filtered and then Figure 3.25 was obtained comparing LAS and lysimeter LE fluxes. In this case, LAS slightly underestimated lysimeter (slope being 0.89). Same procedure was followed in other years and Figures 3.26 through 3.28 were obtained for years 2011, 2012 and 2013 respectively.

The regression equation obtained from Figures 3.24 through 3.28 can be used to adjust the lysimeter LE in order to make it representative of the field ET.

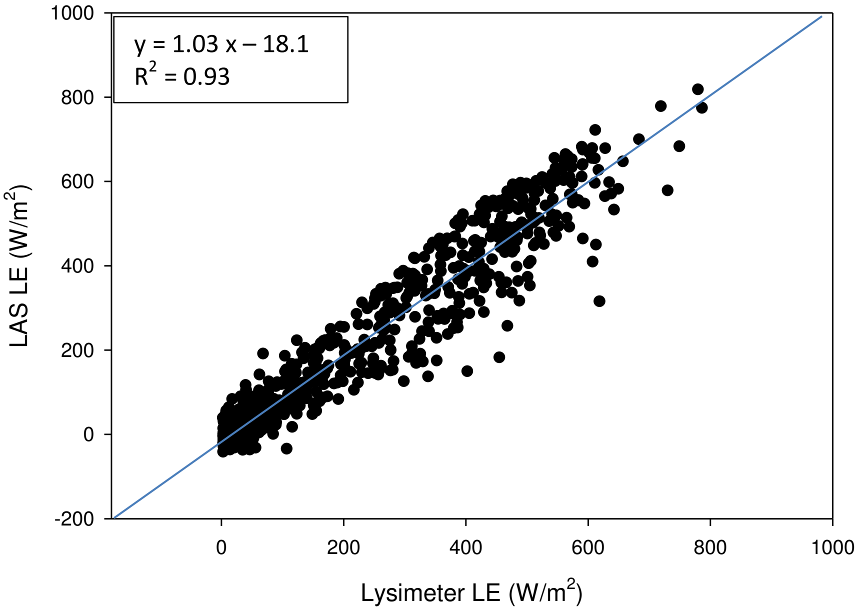

Figure 3.24: Comparison of latent heat fluxes from LAS and lysimeter in 2009 after filtering some outliers

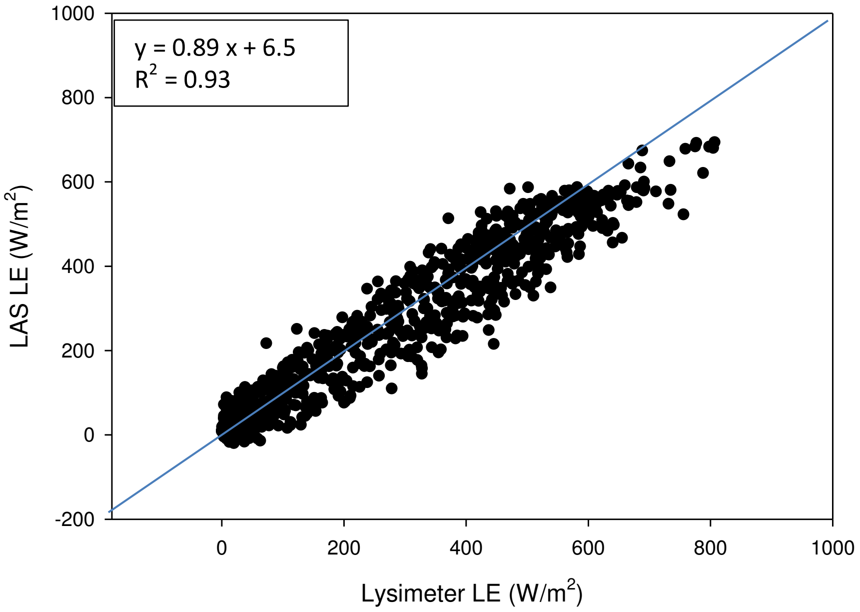

Figure 3.25: Comparison of latent heat fluxes from LAS and lysimeter in 2010 after filtering some outliers

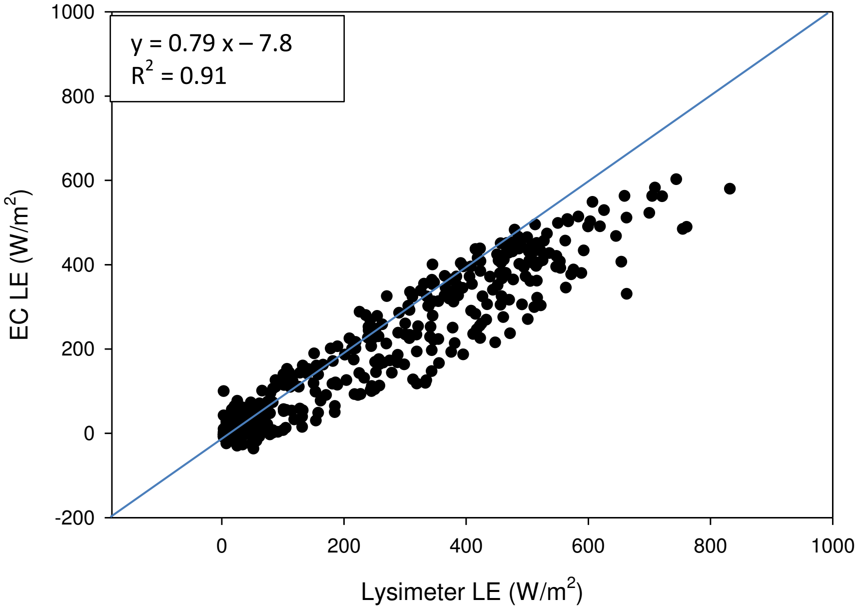

Figure 3.26: Comparison of latent heat fluxes from EC and lysimeter in 2011 after filtering some outliers

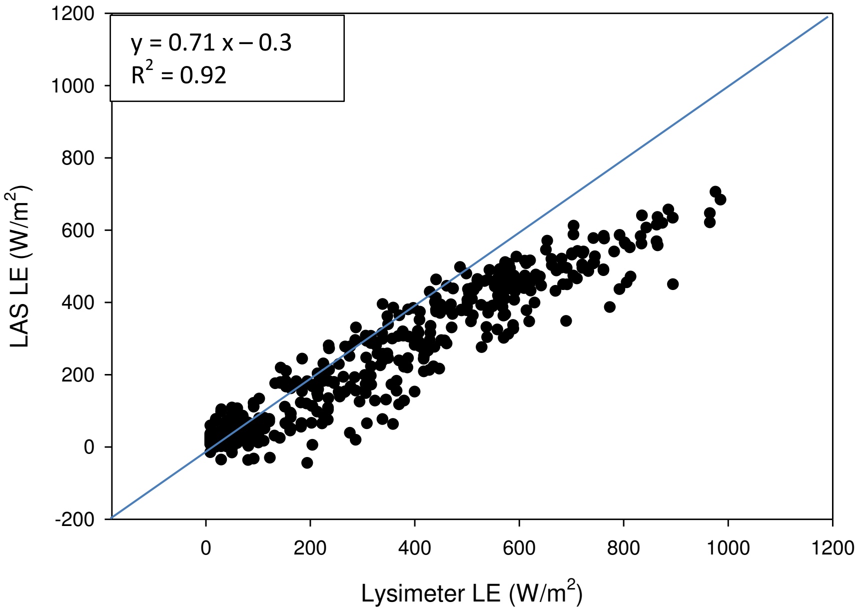

Figure 3.27: Comparison of latent heat fluxes from LAS and lysimeter in 2012 after filtering some outliers

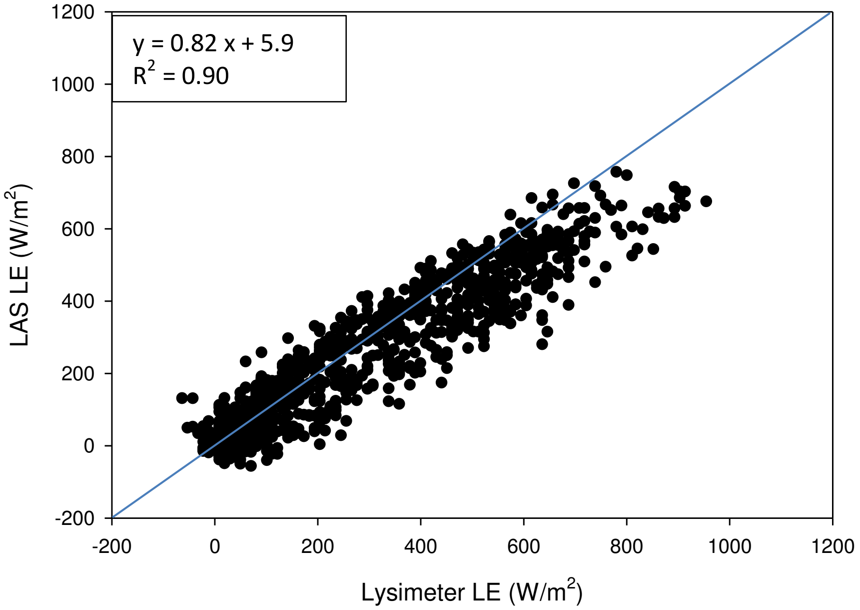

Figure 3.28: Comparison of latent heat fluxes from LAS and lysimeter in 2013 after filtering some outliers

Crop height, canopy surface temperature (T_s) and Irrigation Frequency analysis

Crop height readings were analyzed for CL field in 2012 and for RL field in 2012 and 2013. The difference in crop height of each grid with the lysimeter crop was calculated and the average difference on each measurement day on both lysimeters were calculated. Table 3.1 shows the average difference of crop height within the field when compared with the reference lysimeter crop height in 2012. The second column shows the crop height inside the lysimeter whereas the third column shows the average difference in crop height. It is apparent that in all of the cases, mean bias error (MBE) was negative, or in other words, crop height inside the lysimeter was larger than the average crop height of the field. In most of the cases, when the crop height increased, it was found that the difference in crop height also increased. Likewise, Table 3.2 shows the difference of crop height within the crop lysimeter field for 2012. Also in this case, crop height inside the lysimeter was always greater than the average crop height of the field. Similarly Table 3.3 shows the difference of crop height within the reference lysimeter field for 2013. Same result was found as in the previous two cases.

Table 3.4 shows the difference of surface temperature (T_s) within both lysimeter fields in 2012. All of the measured T_s data were adjusted to the time when the T_s at the lysimeter surface was recorded using equation (3.1). When the crop is stressed, then its surface temperature reading is higher compared to the unstressed crop at a given time. It can be inferred from Table 3.4 that the lysimeter fields were stressed in 2012 most of the time as the average difference in T_s was consistently higher than 2 degree Celsius except for couple of occasions. Table 3.5 shows the difference of T_s within both fields in 2013. Also in 2013, the average difference of T_s was positive in all occasions, however, the magnitude of the difference was lower compared to 2012. This means that the field was less heterogeneous in 2013 compared to 2012.

Table 3.6 shows the irrigation frequency inside the lysimeter and outside field. It can be observed that in all of the years in both lysimeters, the lysimeter monolith was irrigated more frequently compared to the outside field. Note that lysimeter irrigations were applied in order to maintain similar soil water content profiles inside and outside the lysimeter. However, limitations in irrigation water supply via the irrigation canal prevented concurrent irrigation of the entire surrounding field all at once. This meant the lysimeter monolith received more irrigation water compared to the rest of the field. This also agreed with the data from Tables 3.1 to 3.3 because more crop height can be related with more irrigation water.

In 2009 and in 2010, lysimeter ET agreed better with the other micrometeorological methods. The lysimeter field was larger in 2009 as the adjacent field, east of CL field was also planted with alfalfa. The lysimeter field area was 5.7 hectare in 2009 whereas it was only 4 hectare in other subsequent years. The predominant wind in the studied area is from Southwest direction, so increasing the alfalfa field in the predominant wind direction enabled the lysimeter to capture the flux footprint most of the times. Hence the larger available fetch may be one reason behind the good agreement of lysimeter ET with other ET measurement methods in 2009. Normalized Difference Vegetation Index (NDVI) was computed for two days in 2009 when the airborne multispectral remote sensing system was used. The two images were acquired on July 6 (DOY 187) and August 7 (DOY 219) over the crop lysimeter field. Figure 3.29 shows the image acquired on August 7, 2009. The image from CL field looks very red, which suggests there is healthy crop growing with high ET rates. Sixteen points were selected (Figure 3.30) systematically (matrix of 4 by 4) and the NDVI of each points were calculated. Tables 3.7 and 3.8 show the NDVI values of each point on DOY 187 and DOY 219 respectively. It is evident from the Tables that NDVIs were very high for all the points. Higher NDVI is associated with higher crop biomass and higher soil moisture content. The mean NDVIs of DOY 187 and 219 were 0.924 and 0.940 respectively. The coefficient of variation of NDVIs for those two days was 0.007 and 0.012 respectively. These results suggest that the field was very homogeneous on both of those days.

However, in 2011, 2012 and 2013, lysimeter ET was significantly higher compared to the other methods. This could be due to the fact that the crop height inside the lysimeter was greater than the rest of the field and also the soil moisture inside the lysimeter was higher compared to the field. All of the other methods viz. eddy covariance, large aperture scintillometer and surface aerodynamic tower cover a larger portion of the field, having larger footprint, hence ET measured by these instruments better represent field ET. On the other hand, ET measured by the lysimeter, when the monolith surface condition inside is different than the field surface condition, the lysimeter ET cannot represent the whole field.

Precipitation analysis revealed that 2009 and 2010 were wetter years whereas 2011, 2012 and 2013 were drier years. The total annual growing season precipitation in a calendar year for 2009, 2010, 2011, 2012 and 2013 were 247.6 mm, 294.6 mm, 144.8 mm, 97.8 mm and 107.4 mm respectively. Year 2012 was the driest year and also Colorado suffered with huge wildfires. It can be observed that when the weather was more humid as in years 2009 and 2010, lysimeter agreed better with other methods. On the other hand, lysimeter agreed less with other methods when the weather was drier. When the weather is very dry and the monolith is irrigated more, the lysimeter gets more energy from the surrounding because of the oasis effect. When the lysimeter gets more energy, certainly there will be more ET measured by the lysimeter in order to satisfy the energy balance. Again when the lysimeter has more biomass than the field, then the evaporative area inside the lysimeter is higher compared to the field because of the clothesline effect. The higher evaporative area inside the lysimeter is also responsible behind this overestimation from lysimeter. This can be clearly observed in 2012. In 2009, even though the monolith was irrigated more frequently compared to the field, more precipitation might have offset the effect. This could be the reason why the lysimeter compared well with LAS in 2009 and in 2010 compared to the other years.

Possible reasons for the difference in ET

The following list summarizes the possible reasons of discrepancies between the lysimeter measured ET and micrometeorological measured ET:

- More biomass inside the lysimeter box compared to the outside field.
- Lysimeter getting more moisture (more irrigation) compared to the outside field.
- The other reason could be the footprint of the instruments. Lysimeter is a point measurement whereas the other micrometeorological methods sense larger area and are also more affected by the condition even outside of the field.
- The accuracy of the instruments used also plays some role. For example, when LAS is used, in order to get ET, net radiation (Rn) and soil heat flux (G) also need to be known. Hence the measurement accuracy in H, R_n and G also will impact in the determination of LE or ET.

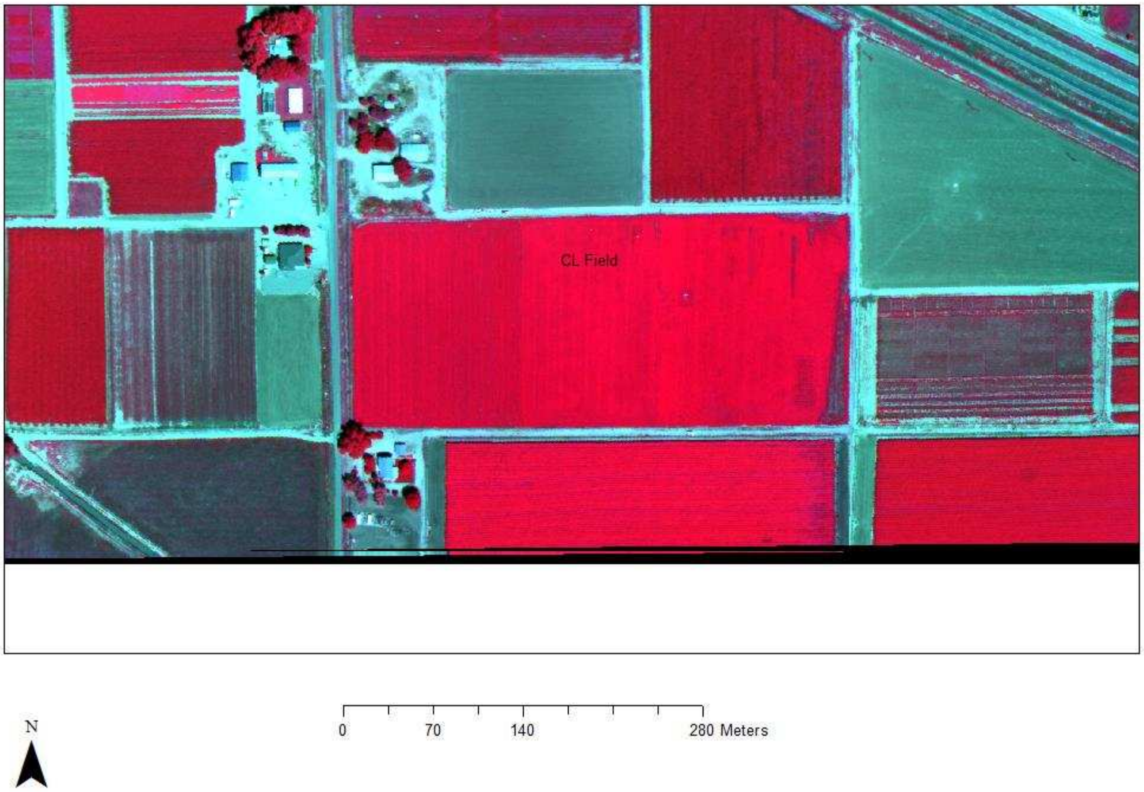

Figure 3.29: Aerial image taken on 8/7/2009 (Day of Year 219) showing CL alfalfa field

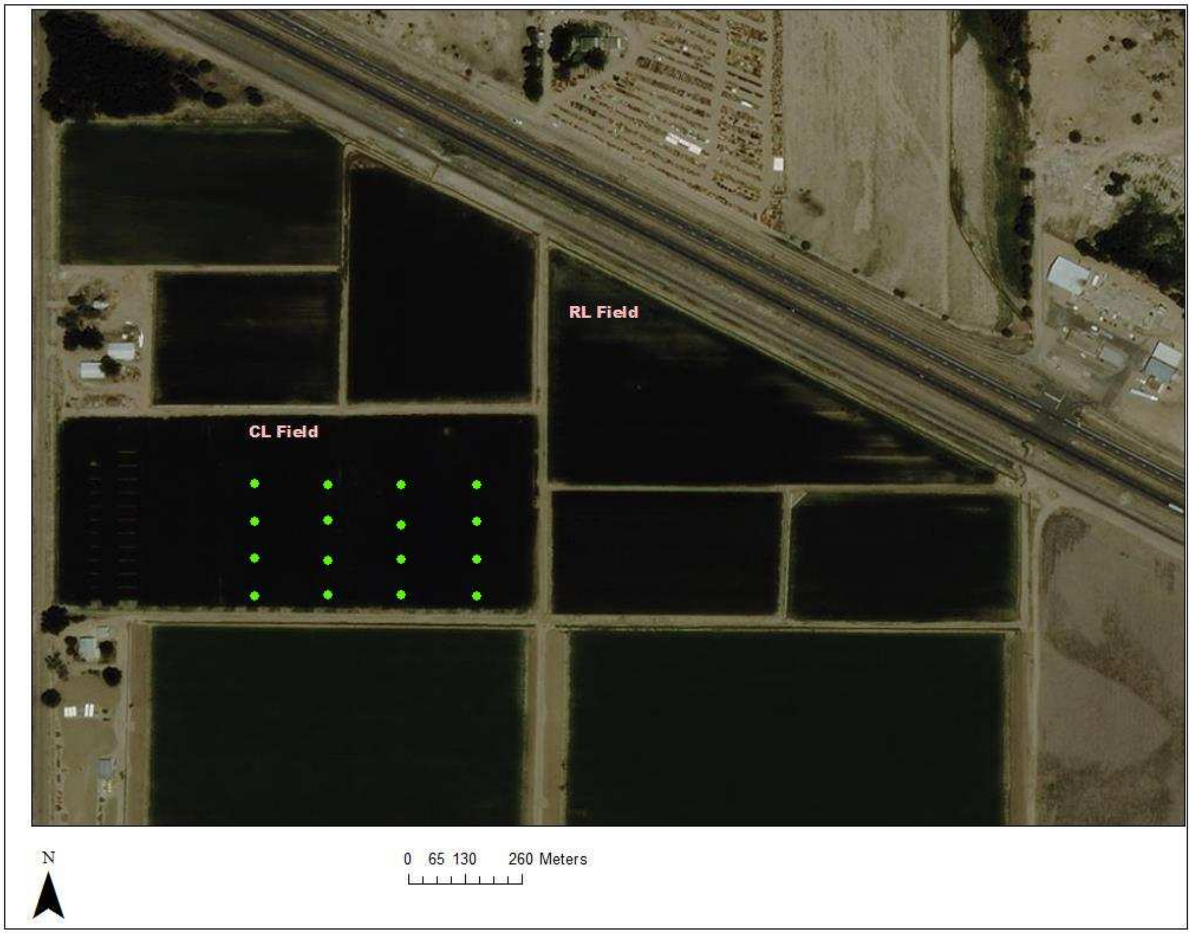

Figure 3.30: Position of sixteen points that were used to record NDVI values on 7/6/2009 and 8/7/2009

Table 3.1: Data showing crop height inside lysimeter and average difference of height inside lysimeter and outside field in 2012 for reference lysimeter field

2012 RL	Crop height inside the lysimeter (centimeters)	MBE (centimeters)
7/11/2012	20.32	-6.67
7/18/2012	40.64	-9.62
7/25/2012	60.96	-10.80
8/2/2012	68.58	-9.47
8/13/2012	15.24	-3.39
8/24/2012	40.64	-14.78
8/31/2012	55.88	-22.63
9/8/2012	60.96	-21.09

Table 3.2: Data showing crop height inside lysimeter and average difference of height inside lysimeter and outside field in 2012 for crop lysimeter field

2012 CL	Crop height inside the lysimeter (centimeters)	MBE (centimeters)
7/11/2012	20.32	-3.39
7/18/2012	40.64	-4.62
7/25/2012	63.5	-9.67
7/31/2012	63.5	-1.15

Table 3.3: Data showing crop height inside lysimeter and average difference of height inside lysimeter and outside field in 2013 for reference lysimeter field

2013 RL	Crop height inside the lysimeter (centimeters)	MBE (centimeters)
8/9/2013	50.8	-11.35
8/14/2013	58.4	-6.60
8/22/2013	71.1	-8.04
9/5/2013	20.3	-9.02
9/20/2013	43.2	-14.56
9/27/2013	50.8	-15.24
10/5/2013	63.5	-19.98

Table 3.4: Data showing canopy surface temperature (T_s) and average difference of T_s inside lysimeter and outside field in 2012 for both lysimeter fields

	CL		RL	
	T_s	MBE (°C)	T_s	MBE (°C)
7/11/2012	30.5	3.3	34.1	3.1
7/18/2012	27.4	2.4	27.9	0.6
7/25/2012	23.6	3.3		
8/13/2012			30.7	3.7
8/24/2012			27.0	2.6
8/31/2012			26.0	0.9
9/8/2012			21.3	2.8

Table 3.5: Data showing canopy surface temperature (T_s) and average difference of T_s inside lysimeter and outside field in 2013 for both lysimeter fields

	CL		RL	
	T_s	MBE (°C)	T_s	MBE (°C)
7/9/2013			26.5	0.3
8/9/2013			22.8	0.8
8/14/2013			24.4	0.2
8/22/2013			23.6	0.8
8/23/2013	30.2	1.0		
8/30/2013	30.7	0.4		
9/6/2013	30.3	0.4		
9/20/2013	22.4	0.3	16.6	1.4
9/27/2013	25.3	1.1		
10/5/2013	19.1	0.2	11.6	0.2

Table 3.6: Data showing the irrigation frequency in both lysimeters (monolith and outside) in different years

	Irrigation Frequency			
Year	CL		RL	
	Monolith	Field	Monolith	Field
2009	13	6		
2010	11	7		
2011	12	6	12	8
2012	8	4	9	7
2013	11	8	8	5

Table 3.7: Data showing the NDVI of different points in CL Field on July 6, 2009

0.918	0.907	0.932	0.916
0.930	0.930	0.933	0.926
0.924	0.936	0.926	0.927
0.928	0.931	0.933	0.892

Table 3.8: Data showing the NDVI of different points in CL Field on August 7, 2009

0.931	0.933	0.936	0.937
0.939	0.940	0.948	0.941
0.941	0.952	0.942	0.938
0.946	0.950	0.935	0.933

CONCLUSION

When there are differences in crop biomass and soil moisture inside and outside the lysimeter, then it was found that the lysimeter ET cannot be representative of the field ET. When the weather is very dry, the discrepancy in ET between lysimeter and other micrometeorological methods tends to be higher as it was observed in 2012. On the other hand, the agreement was better when the precipitation was higher as shown in years 2009 and 2010. The agreement was best when the field size was larger and the precipitation was also higher as shown in year 2009. It was found that when the field was not uniform, in other words, when the lysimeter inside had more soil moisture and crop biomass compared to the rest of the field, lysimeter ET was higher than ET measured from other micrometeorological methods. It was also found that the agreement among LAS, EC and SAT was very good for all years. In 2009, the lysimeter ET agreed very well with the ET obtained from micrometeorological methods. The good agreement in 2009 can be concluded because of the surface homogeneity in the lysimeter field. In conclusion, surface heterogeneity of the field played a big role in the discrepancy of the lysimeter with other micrometeorological methods. In all the years, the slope of the regression line between lysimeter and micrometeorological instruments was different, which perhaps is a function of surface heterogeneity (difference in soil moisture and crop biomass) and aridity. When the field is heterogeneous, then care must be taken before using the lysimeter ET as a reference.

RECOMMENDATIONS

It is recommended to have same irrigation frequency and same crop biomass inside and outside the lysimeter to make lysimeter ET representative of the whole field. The change in irrigation system from surface to sprinkler or drip would be helpful to irrigate evenly and have uniform soil moisture content inside and outside the lysimeter. It is also recommended to have a larger alfalfa field in order to lessen the impact of advection from drier regions. It is recommended only to use the good year data from lysimeter such as 2009 and 2010 (when the lysimeter field was more homogeneous) to develop the crop coefficients (K_c) of important agricultural crops. If K_c, which is the ratio of measured crop ET to reference crop ET, is developed using faulty (non-representative) measured data, then it results over or under irrigation, which is not considered good for agricultural water management.

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CHAPTER 4

Model Development for Surface Resistance (r_s) of Alfalfa

Overview

In chapter two, different crop evapotranspiration (ET) models that have been developed to date were summarized and also the advantage of one step ET estimation over the two step ET estimation was pointed out. In order to calculate actual crop ET in one step process, canopy surface resistance to vapor transfer (r_s) needs to be known a priori. A new approach is suggested to estimate daily variable r_s, as a function of either leaf area index (LAI) or crop height (h_c). Another alternative is also suggested to estimate daytime hourly variable r_s; which depends on weather and biophysical variables including aerodynamic resistance (r_a), canopy temperature (T_c) and vapor pressure deficit (VPD).

The modelled r_s was then used for hourly computation of alfalfa ET using the Penman-Monteith (PM) equation. The alfalfa ET using the daily variable r_s is abbreviated here as $ET_{rs\ (LAI)}$ or $ET_{rs\ (hc)}$ and using the hourly variable r_s is abbreviated as ET_{hourly_rs}. The PM equation with r_s as suggested by Allen et al. (1989) was also used to calculate hourly alfalfa ET rates, which is abbreviated here as $ET_{conventional\_rs}$. The statistical analysis suggested that $ET_{rs\ (LAI)}$ or $ET_{rs\ (hc)}$ was superior compared to the $ET_{conventional\_rs}$ when data of all crop heights were included. When the data was grouped as crop height (h_c) less than or greater than 25 cm, then the performance of $ET_{rs\ (LAI)}$ or $ET_{rs\ (hc)}$ was much better than $ET_{conventional\_rs}$ when h_c was less than 25 cm and slightly better when h_c was greater than 25 cm. The value of r_s for alfalfa as computed by the Allen et al.

procedure was found to be grossly underestimated when h_c was less than 25 cm, which resulted in higher hourly alfalfa ET rates (20% in 2009 and 41.5% in 2010) when compared with the measured lysimeter ET rates. However, when the $ET_{rs\,(LAI)}$ or $ET_{rs\,(hc)}$ was used for h_c <25cm, in 2009, the underestimation of ET was around 7%; whereas in 2010, the overestimation of ET was around 7%. The performance of $ET_{conventional\_rs}$ in 2010 for h_c <25 cm was poor as the Nash-Sutcliffe coefficient of efficiency was negative. The performance of ET_{hourly_rs} was also superior compared to the $ET_{conventional\_rs}$ for crop heights greater than 35 cm. When larger datasets were used, the modelled r_s performed better than the conventional r_s in estimating alfalfa ET rates.

INTRODUCTION

The global competition for fresh water resources is increasing day by day. Agriculture has been the largest sector of water consumption in most countries. With the increase in human population and increase in urbanization and industrialization, water availability for the agricultural sector is slowly decreasing with time. Over irrigation and under irrigation both are considered negative for optimum yield. When there is over irrigation, plants will have difficulty in root growth and root respiration; leaching problems; and in the worst case, some plants can even lodge due to poor stability in the submerged condition. Hence not only the water is wasted, also the productivity decreases with over irrigation. On the other hand, with under irrigation, plants are water stressed, which also results in low yield. In order to have the good yield, there should be proper water application on agricultural fields. Proper water application requires accurate estimation of crop evapotranspiration (ET). Evapotranspiration represents the loss of water from the earth's surface through the combined processes of evaporation (from soil and plant surfaces) and plant transpiration (internal evaporation) (Allen et al., 2005).

There are different ET determination techniques available. Some of them are lysimetry, eddy covariance, scintillometry, Bowen Ratio method, remote sensing methods and various ET estimation models as have been discussed in Chapter two. Among them, the lysimetric technique is considered the most precise method as it directly measures the evaporated water from the control volume using the soil water balance method. The lysimetric and the eddy covariance methods are the only methods considered as direct methods of measuring ET. This study focuses on the one step ET estimation technique, which is only possible after modelling the surface resistance (r_s) term in PM ET model. This study focuses on the development of a surface resistance model and then validating the model using the measured alfalfa lysimeter data.

Evapotranspiration process

In an agricultural field, evaporation from soil surface and transpiration from plant canopy are difficult to distinguish, hence it is common to use a common term, evapotranspiration (ET) to represent both evaporation and transpiration. When the canopy cover is low, evaporation is the main contributor of ET whereas when the canopy cover is high, transpiration plays the main role.

During the process of transpiration, water is transported from the soil through plant systems towards the atmosphere. If there is no soil water scarcity, during the daytime, stomata in the leaf fully open for carbon dioxide assimilation (photosynthesis process) and water is lost into the atmosphere during the process, which is called transpiration. However, if there is water shortage, stomata don't fully open, which limits the transpiration rate and also affects the photosynthesis rate. Previous research has shown that there is a strong correlation between crop growth and the rate of transpiration (Seckler, 2003). Hence the process of transpiration is necessary for plants in order to complete the photosynthesis process. Transpiration also helps to cool plants under extremely high temperatures and it also helps in the movement of sap, nutrients and moisture from the roots to the leaves (Seckler, 2003).

Aerodynamic equation of heat fluxes

The energy available for a given system is utilized either to heat the system itself or to change the state of water from liquid to vapor. When the temperature of the system is changed, it is referred as sensible heat flux (H) and when the liquid water changes to vapor, it is referred as latent heat flux (LE). The sensible heat flux can be defined as in equation (4.1) below (such as used in Chehbouni et al. 1997; and Chavez et al., 2010).

$$H = \frac{\rho C_p (T_o - T_a)}{r_a} \tag{4.1}$$

where, H is the sensible heat flux (W/m^2), ρ is the air density (kg/m^3), C_p is the specific heat of air at constant pressure (J/kg/K), T_o is the aerodynamic temperature (K), T_a is the air temperature (K) and r_a is the aerodynamic resistance to heat transfer (s/m). The latent heat flux can be defined as in equation (4.2) (such as used in Chehbouni et al., 1997; and Lhomme et al., 1994).

$$\lambda ET = \frac{0.622\, \lambda\, \rho}{P}\ \frac{e_s(T_o) - e_a(T_a)}{(r_a + r_s)} \tag{4.2}$$

where, λET is the latent heat flux (W/m^2), T_o is the aerodynamic surface temperature (°C), T_a is the air temperature (°C), e_s is the saturation vapor pressure (kPa), e_a is the actual vapor pressure (kPa), λ is the latent heat of evaporation (J/kg), ρ is the density of moist air (kg/m^3), P is the atmospheric pressure (kPa), r_a is the aerodynamic resistance (s/m) and r_s is the bulk surface resistance of the canopy (s/m). If we divide both sides of the equation by λ, then we obtain ET flux in kg/(m^2.s). In order to obtain the ET rates in common units like mm/h or mm/d, then it should be divided by the density of water (which can be approximated as 1,000 kg/m^3) and multiplied by 3.6×10^6 (for hourly unit) or $3.6 \times 10^6 \times 24$ (for daily unit).

Latent heat of evaporation (λ) to calculate evaporation flux (in mm per hour or mm per day) can be calculated using equation (4.3) (Harrison, 1963):

$$\lambda = 2.501 - 0.002361\, T_a \tag{4.3}$$

where T_a is the air temperature in °C, the unit of λ being MJ/kg.

The main challenge to directly use equation (4.1) and (4.2) to find H or LE is the calculation or measurement of T_o. It is not easy to calculate or even measure T_o. The variable T_o is the surface aerodynamic temperature, which occurs within the canopy (Figure 4.1). For a full cover canopy, its location is considered to be at a height approximately equal to "Z_o + d" from the ground surface, where Z_o is the roughness length for momentum transfer (m) and d is the zero plane displacement height (m). However, for sparser crops, the above statement may not be true (Shuttleworth and Wallace, 1985). The variable Z_o is approximated as ten per cent of the crop height (for a uniform and homogeneous cover), whereas d is approximated as two third of the crop height (Arya, 2001). Hence the occurrence of T_o within the canopy can be approximated as somewhere close to 75 per cent of the crop height. Yang and Friedl (2002) developed a parameterization for the roughness length of momentum and heat transfer and also the zero plane displacement height incorporating the canopy crown density and structure. The authors claimed that their method was able to account for site – to – site differences in roughness lengths that arise from canopy structural properties.

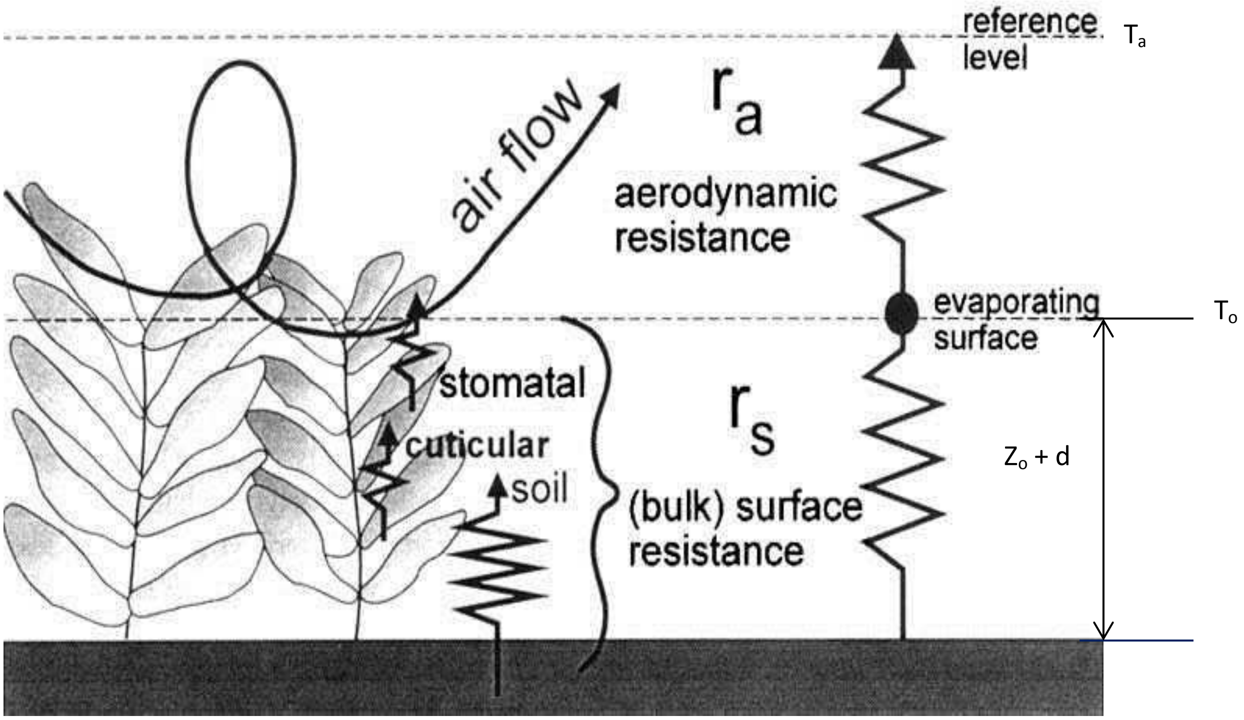

Figure 4.1: A diagram showing the location of aerodynamic temperature (T_o) within the crop canopy as well as the bulk surface resistance and aerodynamic resistance for water vapor flow (Source: FAO 56 by Allen et al., 1998)

Energy balance equation

The main source of energy on earth comes from the sun through solar radiation. Some portion of the incoming solar radiation is reflected to the atmosphere and some is absorbed by earth. Only the portion which is absorbed is in fact the useable energy, which is also called as net radiation

(R_n). Net radiation (R_n) is considered approximately equivalent to the sum of soil heat flux (G), sensible heat flux (H) and latent heat flux (LE). For hourly computation of ET, G needs to be included, however, for daily computation; G is insignificant and neglected in the calculation. It is considered that for daily computation, the amount of soil heat flux that goes to the ground and that comes from the ground approximately cancels each other. For a plant surface, some energy is also used by the plant for the physiological process of photosynthesis and some is stored within the canopy, but these are considered insignificant.

Penman Monteith equation

As T_o is a very difficult parameter to measure, calculate or estimate, Penman (1948) found a way to calculate ET without using T_o. He used the relationship of saturation vapor pressure versus temperature. He used a parameter "Δ" which is the slope of the saturation vapor pressure versus temperature curve. He defined Δ as $\delta e_s / \delta T$ evaluated at air temperature (T_a). Penman first developed an equation for evaporation of water from a free water surface, and then Monteith (1965) later introduced some crop resistance terms, to be applicable for the crop communities.

The Penman-Monteith (PM) equation follows a single – layer or 'big leaf' approach, where single surface resistance and single aerodynamic resistance terms represent the transport properties of the cropped surface (Allen et al., 2005). The PM equation has been considered a robust method to calculate reference ET. Both the ASCE-EWRI Standardized reference ET equation (Allen et al., 2005) and the FAO 56 reference ET equation (Allen et al., 1998) are based on the PM equation. PM equation is a combination equation, which uses both an aerodynamic term or component and a land surface energy balance component. The PM equation is as follows (Monteith, 1981; Allen et al., 1998):

$$\lambda E = \frac{\left(\Delta(R_n - G) + \rho C_p(e_s - e_a)/r_a\right)}{\Delta + \gamma(1 + r_s/r_a)} \tag{4.4}$$

where Δ is the slope of the saturation vapor pressure versus temperature curve evaluated at air temperature, e_s is the saturation vapor pressure at 2 m height (kPa), e_a is the actual vapor pressure at 2 m height (kPa) and γ is the psychrometric constant (kPa). Under wet canopy condition, r_s in the equation (4.4) is considered zero, which also refers to maximum possible ET, or, in other words, potential ET (Monteith, 1965; Thom and Oliver, 1977; Alves et al., 1998; Todorovic, 1999; Allen et al., 2005; Shuttleworth, 2007; Lascano and van Bavel, 2007; Lascano et al., 2010; Li et al., 2009 and Polhamus et al., 2012).

In all of the above mentioned models, the knowledge of r_s is necessary to obtain accurate ET estimation. If r_s is known, then direct one step ET estimation of crop is possible. The current trend is to first calculate the reference ET (which is either the grass or alfalfa reference surface) and then multiply it with the appropriate crop coefficients (K_c) to calculate the actual crop ET. In chapter two, it has been shown that the cumulative errors associated with the fixed surface resistance reference ET and the crop coefficients can be significant. The solution to this problem is to directly calculate r_s for different crops. By doing so, the error can be reduced to a great extent. The surface resistance models that are available are still in developmental phase (Section 8, Ch. 2). Hence there is a need to either further develop those models or develop a new model for surface resistance. This study was focused on developing a new model to estimate r_s for alfalfa based on several weather variables.

Why alfalfa crop?

Alfalfa is considered a major hay crop, so this is a food source of many livestock. In Western United States including Colorado, it is one of the major crops. It consumes a significant amount of water. Alfalfa is also a reference crop used by the ASCE to estimate the reference crop ET. Precise estimation of reference crop ET is a very important step to quantify actual water requirement of other important crops. Thus the direct calculation of r_s for alfalfa not only provides information on actual water requirement for alfalfa, but will also be helpful to accurately estimate water requirements of other important crops.

(Bulk) Surface Resistance (r_s)

The 'bulk' surface resistance describes the resistance of vapor flow through the transpiring crop and evaporating soil surface (Allen et al., 1998). Hence r_s integrates both stomatal resistance and soil resistance. Alves and Pereira (1999) mentioned that since r_s is the bulk surface resistance, the procedure adopted by Jarvis model just to calculate stomatal resistance is not enough to obtain the surface resistance. However, for the full cover canopy, when evaporation from the soil is not large, the r_s is close to the compound resistance of all leaves (r_l) in parallel (Irmak et al., 2008). Hence for the full cover canopy condition, bulk surface resistance (r_s) approximates the canopy resistance (r_c).

There are two general approaches in measuring r_s. The first approach is the top down approach where ET is measured first by using a measurement device such as lysimeter and then r_s is obtained by inverting the ET equation (either using the PM equation or the aerodynamic equation). Several authors have used the top-down approach to obtain r_s, for example, Russell

(1980), Katerji and Perrier (1983), Alves et al. (1998), Alves and Pereira (2000). The second approach is directly measuring the stomatal resistance/conductance and then integrating it to the whole canopy to obtain the bulk canopy resistance, which is also called the bottom up approach. In case of partial canopy condition, also the soil resistance (r_{soil}) should be accounted while integrating to get the r_s. Several authors have used this bottom up approach in obtaining r_s, for example, Choudhury and Idso (1985), Irmak and Mutibwaa (2009, 2010), Irmak et al. (2008) and Mutibwaa and Irmak (2010, 2012). Irmak et al. (2008) scaled up leaf stomatal resistance to canopy resistance as a function of photosynthetic photon flux density (PPFD) for corn canopy. The authors showed a strong relationship between leaf stomatal resistance and PPFD, however, they cautioned to use their method to obtain r_s when there is partial canopy cover.

Both top down and bottom up approaches have their own advantages and disadvantages. In case of the top down approach, in order to get the reliable r_s, the measured ET should be very accurate along with R_n, G, T_a, RH and r_a (if the PM equation is used) or the measured ET as well as the H, T_a and r_a should be very accurate (if aerodynamic equation is used). For the bottom-up approach, first of all, the porometer readings should be accurate to get the stomatal resistance and then the precise estimation of leaf area index is needed to integrate the stomatal resistance to the canopy level. For the partial canopy condition, the bottom up approach seems more tedious, as it also has to incorporate the soil resistance.

Objectives

It has been mentioned that the current practice of calculating actual crop ET (two step process), which is by calculating the reference crop ET first and then multiplying it with the crop coefficient (K_c), can give significant error. Hence the objective of this chapter was to develop a new model (one step Et calculation process) for alfalfa r_s: daily variable r_s and hourly variable r_s, and then implement it in the full-version PM equation (Equation 4.4) to get alfalfa ET rates and then assess its performance by comparing with measured lysimeter alfalfa ET data. Another objective was to investigate if the modeled r_s improved the alfalfa ET estimation with respect to the conventional r_s approach.

MATERIALS AND METHODS

Study Area

The following study area was chosen for this study: Colorado State University (CSU) Arkansas Valley Research Center (AVRC) near Rocky Ford, Colorado.

The geographic coordinates of the site is 38° 2’ N and 103° 41’ W and the elevation is 1,274 m above mean sea level. There are two large precision weighing lysimeters, one is a crop lysimeter (CL) and the other is a reference lysimeter (RL). The dimension of the crop lysimeter field is 160 m by 250 m and the field and lysimeter were covered with alfalfa from 2008 to 2012. A large monolithic weighing lysimeter (3 m × 3 m × 2.4 m) was located in the middle of the CL field. As part of the instrumentation in the field, there was a net radiometer (Q 7.1 net radiometer, REBS, CSI, Logan, Utah, USA), two infra-red thermometers (IRT Apogee model SI-111, CSI, Logan, Utah, USA) to measure crop radiometric surface temperature, soil heat flux plates (REBS model HFT3, CSI, Logan, Utah, USA) buried in the ground in the lysimeter box, at 10 cm depth, along with soil temperature and soil water content sensors, for the estimation of soil heat flux at the ground surface. The field was irrigated with a furrow irrigation system using siphons and a head ditch.

The average annual maximum temperature is 21.1° C (70° F). The average annual minimum temperature is 2.4° C (36.3° F). The long-term average annual precipitation at the site is 301 mm (11.85 inches) with approximately two-thirds of the annual total occurring from May through September. The total average annual snowfall is 589 mm (23.2 inches). The average date of the last spring frost (0° C or 32° F) occurs at about May 1, and the average date of the first fall frost occurs October 5. Thus, the average length of the growing season for warm-season crops like corn is 158 days as cited by Berrada (2011).

Description of weighing lysimeter

The crop lysimeter (Figure 4.2) is a large precision weighing lysimeter. Berrada (2011) has given a complete description regarding this lysimeter. The lysimeter consists of an inner soil monolith tank with monolith dimensions of 3 m × 3 m × 2.4 m and an outer containment tank. A load cell (22.7 kg capacity; Interface, Inc. model SM-50) that is connected to a Campbell Scientific CR7 records the mass of the inner tank and soil. It is connected to a lever assembly with a mechanical advantage of 100, which multiplies the effective load cell capacity to 2270 kg. Load cell readings are recorded in millivolts per volt (mV/V) and converted to equivalent mass values using the field calibration. The calibration equation of the load cell was $y = 685.4\,x - 142.9$ (where, y is mass in kilograms and x is the load cell output in mV/V), with standard deviation of the mass measurements less than 0.02 %. A change of 1 mV/V in the load cell output is equivalent to a water depth change of 76.1 mm on the lysimeter, which is simply obtained by dividing 685.4 by

9, where 9 m^2 is the evaporative area of the lysimeter. Andales (personal communication) corrected the effective evaporative surface area of the lysimeter by including the half thickness of the rubber seal, which separates the monolith interior wall from the external retainer wall of lysimeter. By doing so, the effective lysimeter surface area increases to 9.18 m^2 from previous 9 m^2 and so the calibration coefficient changes from 76.1 to 74.6 mm / (mV/V). Hence changes in load cell output are multiplied by 74.6 to obtain the amount of water lost by ET or amount of water gained through precipitation or irrigation. Al Wahaibi (2011) showed that there was some lodging of alfalfa from the lysimeter box and used a procedure to account for the increased surface area, which has been adopted in this study.

Figure 4.2: A picture showing CL Field and the large lysimeter as well as a weather station situated at the center of the field (Picture courtesy: Lane Simmons)

Soil moisture and crop height measurement

Soil volumetric water content was measured by using the neutron attenuation method. Two access tubes were installed inside the monolith and four were installed immediately outside the lysimeter. A CPN 503 DR neutron probe was used to measure the soil water content (% by volume) at 0.1, 0.3, 0.5, 0.7, 0.9, 1.1, 1.3, 1.5, 1.7 and 1.9 m depths in the soil profile (Berrada, 2011). The calibration of the neutron probe was performed according to the method suggested by Evett et al. (2003) as cited by Berrada (2011).

Crop height measurement was done every week in both weighing lysimeters. In CL, four harvests of alfalfa was possible every year from 2008 to 2011, while in 2012, only 2 harvests were possible as the field was getting transitioned from alfalfa to corn. A linear interpolation was then performed to get the daily crop height from the measured weekly crop height.

Methodology to obtain r_s

In this study, instead of inverting the PM equation using measured ET data to obtain r_s, aerodynamic equation of ET was used. The reason behind this was to reduce the possible measurement/estimation error in R_n, G and Δ which is essential in the PM equation.

The surface energy balance equation is the backbone of all the ET estimation equations. It states that the sum of the net radiation (R_n), soil heat flux (G), sensible heat flux (H) and latent heat flux (LE) is zero. There are also other energy terms, such as heat stored or released in the plant canopy, or the energy used in metabolic activities, however, as these terms are small compared to the R_n, they can be considered negligible (Allen et al, 1998; Colaizzi et al., 2014). The energy balance can be written as in equation (4.5).

$$R_n - G - H - \lambda ET = 0 \tag{4.5}$$

where,

R_n = net solar radiation (W/m^2)

G = soil heat flux (W/m^2)

H = sensible heat flux (W/m^2)

λET = latent heat flux (W/m^2)

Aerodynamic equations for H and LE are already defined in equations (4.1) and (4.2).

Substituting H and LE in equation (4.5), we get,

$$R_n - G - \frac{\rho C_p (T_o - T_a)}{r_a} - \frac{0.622\, \lambda\, \rho}{P}\ \frac{e_s(T_o) - e_a(T_a)}{(r_a + r_s)} = 0 \tag{4.6}$$

Then the equation for r_s can be obtained as in equation (4.7):

$$r_s = \frac{0.622 \lambda \rho (e_s(T_o) - e_a)}{P\ (R_n - G - \frac{\rho C_p (T_o - T_a)}{r_a})} - r_a \tag{4.7}$$

Equation (4.7) can also be written as:

$$r_s = \frac{0.622\lambda\rho(e_s(T_o) - e_a)}{P \times LE} - r_a \tag{4.8}$$

Equation (4.8) was used to estimate actual r_s values for alfalfa crop. LE was obtained using measured lysimeter ET data and then applying the conversion procedure from hourly ET to LE as discussed above. T_o was obtained using equation (4.9).

$$T_o = \frac{H \times r_a}{\rho \times C_p} + T_a \tag{4.9}$$

where, H in equation (4.9) was obtained from large aperture scintillometer (LAS). Atmospheric pressure (P) in equation (4.8) was calculated using the site elevation (Burman et al., 1987 as cited in Allen at al., 2005).

$$P = 101.3\left[\frac{293 - 0.0065z}{293}\right]^{5.26} \tag{4.10}$$

where z is the weather site elevation above mean sea level in meters.

Density of moist air in equation (4.9) was calculated using equation (4.11) (Ham, 2005).

$$\rho = \frac{P}{R_d T_a}\left[1 - \frac{0.378\, e_a}{P}\right] \tag{4.11}$$

where, R_d is the dry air constant, which is 287.04 J/Kg/K.

Many researchers use the crop surface temperature (T_s) which is recorded by infrared thermometer as a surrogate of aerodynamic temperature (T_o) to calculate H and LE (See equations 4.1 and 4.2). However, the use of T_s as a surrogate for T_o can cause serious error in the estimation of ET as these temperatures in most of the cases will be different. Alves et al. (2000) have shown that the difference of T_o and T_s can be as great as 7 ° C even at the neutral atmospheric condition (neutral here refers to the condition when T_s and T_a are very close).

In equation (4.8), r_a is obtained using the following equation, which was developed for neutral atmospheric condition, i.e., when temperature, atmospheric pressure, and wind velocity distributions follow nearly adiabatic conditions (no heat exchange) (Allen et al., 1998).

$$r_a = \frac{\ln\left((z_m - d)/z_{om}\right)\ln\left((z_h - d)/z_{oh}\right)}{k^2 u_z} \tag{4.12}$$

where,

z_m = height of wind measurement (m),

z_h = height of humidity measurement (m),

z_{om} = roughness length governing momentum transfer, which is estimated to be 0.123 h_c, where h_c is the crop height (m),

z_{oh} = roughness length governing heat transfer, which is estimated to be 0.0123 h_c (m),

d = zero plane displacement height, which is estimated to be 0.67 h_c (m),

k = von Karman's constant, which is approximately 0.41,

u_z = wind speed at height z (m/s).

Equation (4.12) may be used for well-watered reference crop condition as in the reference condition, heat exchange is small, and therefore stability correction is normally not required

(Allen et al., 1998). However, under non-standard conditions, the assumption of neutral atmospheric condition is invalid. Hence it is necessary to perform atmospheric stability correction especially for non-standard field conditions.

Choudhury et al. (1985) developed a method to perform atmospheric stability correction for aerodynamic resistance, which has been used in this research. According to Choudhury et al., the equation for r_a for stable atmospheric conditions is:

$$r_a = \frac{\ln\left(\frac{z_m - d}{z_{om}} - \Psi *\right)\ln\left(\frac{z_h - d}{z_{oh}} - \Psi *\right)}{k^2 u_z} \tag{4.13}$$

where,

$\Psi* = \{B - (B^2 - 4\alpha C)^{1/2}\}/(2\alpha)$

$\alpha = 1 + \eta$

$\eta = 5(Z - d)g(T_o - T_a)(T_a U^2)\backslash$

$B = ln\left(\frac{Z-d}{Z_o{}'}\right) + 2\eta ln\left(\frac{Z-d}{Z_o}\right)$

$C = \eta\left\{ln\left(\frac{Z-d}{Z_o}\right)^2\right\}$

where, T_o is the aerodynamic temperature (K) which can be approximated by surface temperature measured by IRT to calculate η ; and Z is the height of wind speed/temperature measurement which is 2 m in this research.

When Ψ* is less than -5, then it should be set to -5.

For unstable atmospheric condition, the equation for r_a is:

$$r_a = \frac{\ln\left(\frac{z_m - d}{z_{om}}\right)\ln\left(\frac{z_h - d}{z_{oh}}\right)}{k^2 u_z (1 + \eta)^{3/4}} \tag{4.14}$$

Daily Variable Surface Resistance (r_{s_daily})

Surface resistance (r_s) was estimated using the procedure described in the previous section, which is referred to as observed r_s. Then commonly available weather or crop variables such as air temperature (T_a), relative humidity (RH), vapor pressure deficit (VPD), solar radiation (R_s), net solar radiation (R_n), crop height (h_c), and leaf area index (LAI) were plotted against the observed r_s to assess if there is any relationship. LAI was calculated based on the crop height data (Allen et al., 1989).

$$LAI = 5.5 + 1.5\ln(h_c) \tag{4.15}$$

where, h_c is the crop height in meter.

Irmak and Mutibwaa (2010) used a multiple linear regression approach to model surface resistance for a nonstressed maize canopy and showed that the PM model incorporating their modelled r_s agreed well with the Bowen Ratio measured ET rates. Tolk (1992) also used similar technique to model r_s using LAI, T_a, T_s and R_s for corn and claimed R^2 of 0.53 and 0.7 for pre-anthesis and post-anthesis stages respectively.

Data from 7/7/2009 to 9/24/2009 of CL was used to obtain observed r_s values for alfalfa. Large aperture scintillometer (LAS) was deployed in the alfalfa field during that period, which was essential to measure sensible heat flux (H) enabling estimation of surface aerodynamic temperature (T_o). Only the hourly daytime data (from 9 a.m. to 6 p.m.) was then selected.

Conventional r_s

The equation given by Allen et al. (1989) was also used to calculate r_s, which is referred to as conventional r_s. This r_s was based on the leaf area index and bulk stomatal resistance, which is as follows:

$$r_s = \frac{r_l}{0.5\,LAI} \tag{4.16}$$

where, r_l is the bulk stomatal resistance taken as 100 s/m (for daily ET estimation). However, to approximate the hourly r_s values as provided in the ASCE Standardized equation, r_l for the daytime was fixed as 67 s/m and for the nighttime as 444 s/m. By doing so, when the LAI is close to 4.5, which is when alfalfa height is close to 50 cm, r_s approaches 30 s/m in the daytime and 200 s/m in the nighttime (which is the ASCE recommended values for the r_s for alfalfa reference crop). Since conventional r_s depends on LAI, it is constant for a specific day, but changes to some extent during the season.

ET estimation using the PM equation incorporating the modelled r_s

After developing the r_s model, it was then incorporated in the PM equation to calculate hourly ET in 2009. Data from 6/9/2009 to 10/5/2009 of CL was used for this purpose. Then it was also tested for 2010. Data from 6/3/2010 to 10/14/2010 of CL was used for 2010. Also the PM equation with conventional r_s was used to calculate ET in both years. Both ET rates were then compared with measured lysimeter ET data.

Evaluation Criteria

Several performance indicators were used to evaluate the PM model with conventional r_s and PM model with daily/hourly variable r_s. Both of these models were compared with the measured lysimeter ET. Hourly measured ET data was used for the evaluation process. The performance indicators that have been used are as follows:

Slope and y-intercept: The slope and y-intercept of the least squares regression line can indicate how well simulated data matched measured data (Moriasi, 2007). A slope of 1 and y-intercept of zero indicate that the model perfectly reproduces the magnitudes of the measured data (Wilmott, 1982). The slope and y-intercept are commonly examined under the assumption that measured and simulated values are linearly related, which implies that all of the error variance is contained in simulated values and that measured data are error free (Wilmott, 1982).

Co-efficient of determination (R^2): This is a measure of the proportion of variance in measured data that is explained by a model. It allows one to determine the certainty of making a prediction from a model. It ranges between 0 and 1, with a value of 1 being the optimal. Mathematically, R^2 is obtained by using equation (4.17).

$$R^2 = \frac{\left(\sum_{i=1}^{n}(O_i - \overline{O})^2 (M_i - \overline{M})\right)^2}{\sum_{i=1}^{n}\left(O_i - \overline{O}\right)^2 \sum_{i=1}^{n}\left(M_i - \overline{M}\right)^2} \tag{4.17}$$

where, O is the observed or measured (lysimeter in this case) and M is the predicted or derived (ET equation with variable r_s in this case) value. The bars above the variables indicate mean values.

Mean Bias Error (MBE): This indicator is usually used to calculate the mean model bias or mean over or under prediction. MBE is obtained by averaging the difference between predicted and measured values. Positive values indicate model over-estimation bias, and negative values indicate model under-estimation bias (Willmott, 1982), and zero indicate that there is no bias.

$$MBE = \frac{1}{n}\sum_{i=1}^{n}(M_i - O_i) \tag{4.18}$$

Percentage Mean Bias Error (%MBE): This indicator is same as mean bias error, except it is expressed in percentage. It is clearer by expressing some errors in percentage than in the absolute terms. It is calculated by dividing the MBE with the average measured values and then multiplying by 100.

$$\%MBE = \frac{MBE}{\frac{1}{n}\sum O_i} \times 100 \tag{4.19}$$

Root Mean Squared Error (RMSE): This is a commonly used error index statistic. A smaller RMSE value indicates a smaller error spread and variance and therefore a better model performance. It measures the magnitude of the spread of errors. It is calculated by squaring the differences between predicted and measured values, then averaging them and finally taking the square root of the average.

$$RMSE = \sqrt{\frac{1}{n}\sum_{i=1}^{n}(M_i - O_i)^2} \tag{4.20}$$

Percentage Root Mean Squared Error (%RMSE): This indicator is also the percentage expression for root mean squared error. Like %MBE, this indicator is also calculated by dividing RMSE with the average measured values and then multiplying by 100 (Lei, 1998).

$$\%RMSE = \frac{RMSE}{\frac{1}{n}\sum O_i} \times 100 \tag{4.21}$$

Index of agreement: Index of agreement is how close the model values agree with the measured values. It can be obtained by using equation (4.22). The index of agreement of 1 indicates a perfect agreement between the measured and predicted values, and zero indicates no agreement at all (Wilmott, 1982).

$$d = 1 - \frac{\sum_{i=1}^{n}(y_i - x_i)^2}{\sum_{i=1}^{n}(y_i' - x_i')^2} \tag{4.22}$$

where, d is the index of agreement, y_i and x_i are the calculated and the measured values respectively; $y_i' = y_i - x'$ and $x_i' = x_i - x'$ and N is the total number of observations.

Nash-Sutcliffe Coefficient of Efficiency (NSCE): This is usually used to assess the predictive ability of a model. To determine NSCE, the sum of absolute squared differences between the predicted and observed values, normalized by the variance of the observed values is subtracted from 1. NSE values range between -∞ and 1. The closer the model efficiency is to 1, the more accurate the model is, with values above zero indicating an acceptable performance level, while values less than zero indicate unacceptable performance (Nash and Sutcliffe, 1970; Moriasi et. al., 2007). NSE is obtained by using equation (4.23).

$$NSE = \frac{\sum_{i=1}^{n}(O_i - \overline{O})^2 - \sum_{i=1}^{n}(M_i - O_i)^2}{\sum_{i=1}^{n}\left(O_i - \overline{O}\right)^2} \tag{4.23}$$

where, M is the model estimation value, O is the measured or observed value and n is the number of observations.

RESULTS AND DISCUSSIONS

Observed r_s vs conventional r_s

Figures 4.3 and 4.4 show the timeseries chart in 2009 of observed r_s and conventional r_s respectively. The harvest took place on 7/15 and 8/24, where the peak in r_s (up to 700 s/m) can be observed. However, the peak of conventional r_s is only around 80 s/m. When the crop height is low, r_s is grossly underestimated using the conventional r_s approach, hence it is expected to get high ET values, as lower r_s results in higher ET values. Hence it is not practical to use the conventional r_s approach to estimate ET rates for alfalfa when the crop height is short. A new approach to estimate alfalfa r_s is therefore necessary.

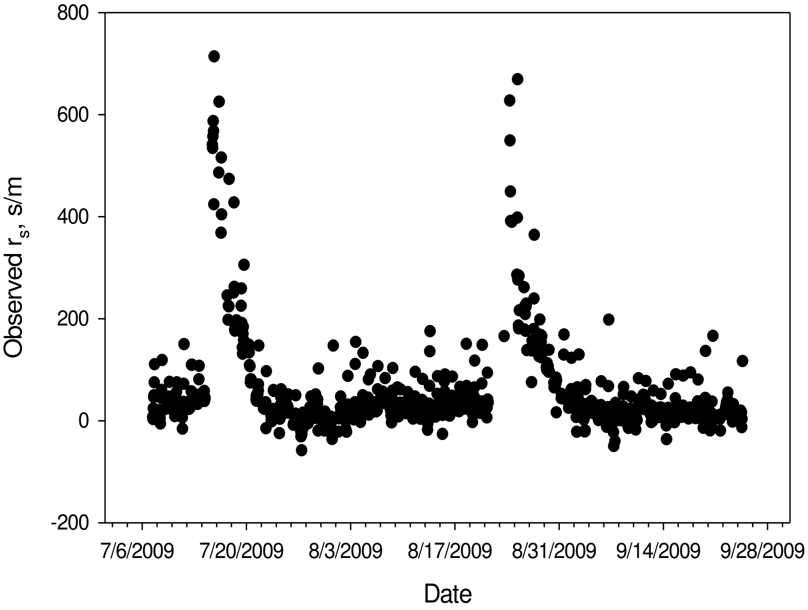

Figure 4.3: Variation of alfalfa r_s (observed) throughout the season in 2009. Note that harvest took place on 7/15 and 8/24, where peak r_s can be observed.

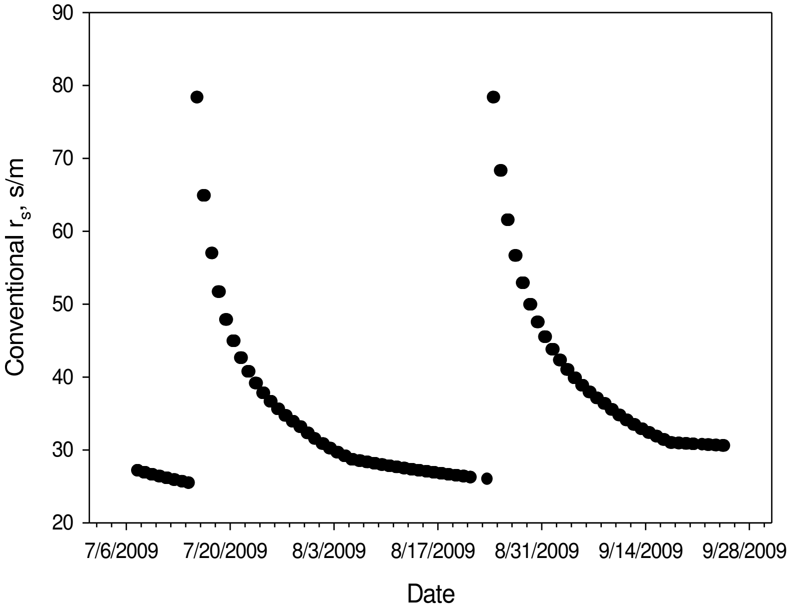

Figure 4.4: Variation of alfalfa r_s (using the conventional approach) throughout the season in 2009.

Relationship of observed r_s with different variables considering all crop height data

Figure 4.5 shows the relationship of r_s with leaf area index (LAI). It can be observed that there is a strong correlation of r_s and LAI for a polynomial equation of a 3rd order (cubic equation) as R^2 is as high as 0.83. Figure 4.6 shows the relationship of r_s with crop height (h_c). Again for the fifth order polynomial equation, there is good R^2 of 0.82. As LAI was computed (not measured) as a function of crop height, similar R^2 was possibly obtained. It can be observed from Figures 4.5 and 4.6 that when the crop height/LAI reached maximum, then r_s started decreasing. It is possible because of the leaf aging for alfalfa (see Figures in Appendix). On 8/4/2010, crop height was 0.48 m (Figure A2) whereas on 8/18/2010, crop height was 0.52 m (Figure A3). As LAI was calculated based on the crop height, its magnitude should be larger on 8/18 compared to 8/4. However, if we carefully observe on the actual pictures, the crop surface is greener on 8/14 (more ground cover) than on 8/18. Alfalfa leaf ages when it is near to the harvest date (which was on 8/23).

Figure 4.7 shows the relationship of r_s with incoming solar radiation (R_s) and Figure 4.8 shows the relationship of r_s with net solar radiation (R_n). In both cases, R^2 is very low. Figure 4.9 shows the relationship of r_s with vapor pressure deficit (VPD). The R^2 in this case was close to 0.1. Figure 4.10 shows the relationship of r_s with air temperature (T_a), R^2 being 0.06. Similarly Figure 4.11 shows the relationship of r_s with aerodynamic resistance (r_a), R^2 is very low, almost close to zero. Figure 4.12 shows the relationship of r_s with relative humidity (RH), R^2 being close to 0.1.

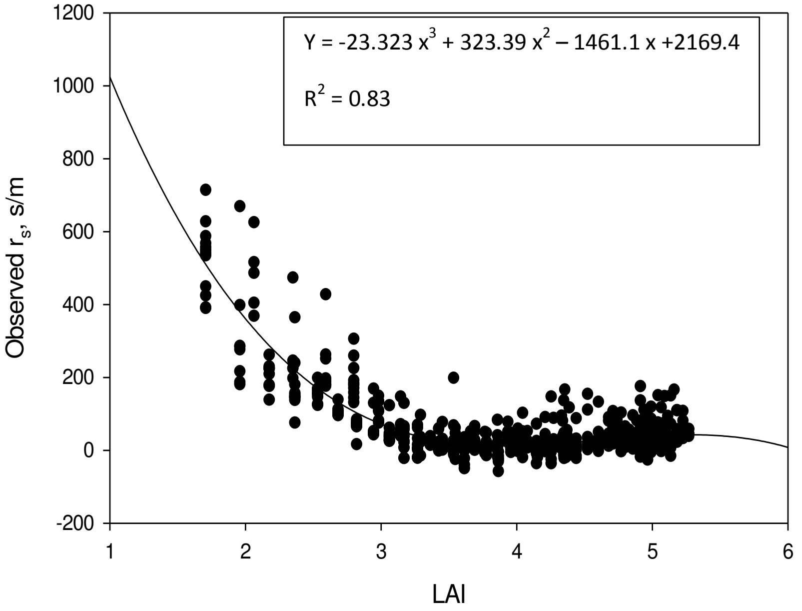

Figure 4.5: Relationship of r_s and leaf area index (LAI)

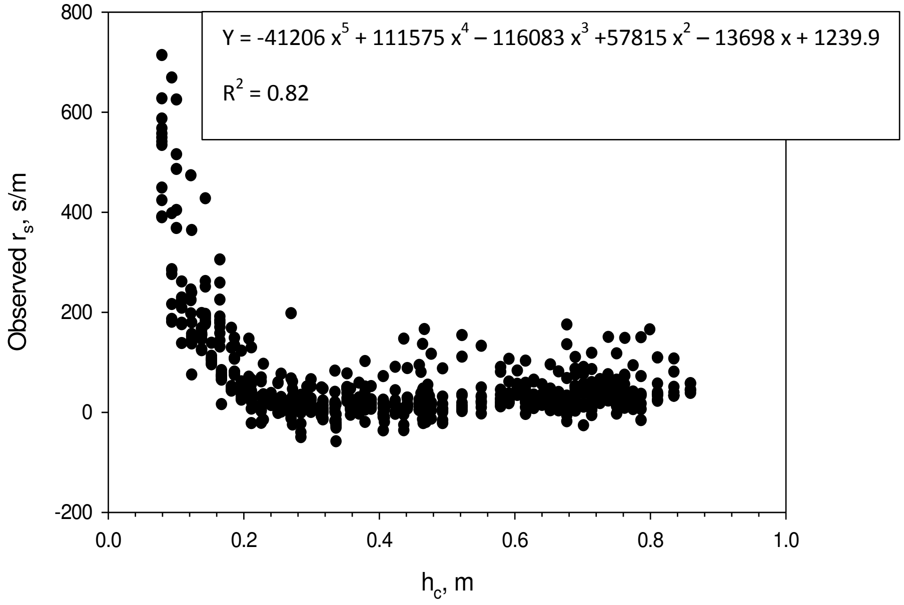

Figure 4.6: Relationship of r_s and crop height (h_c)

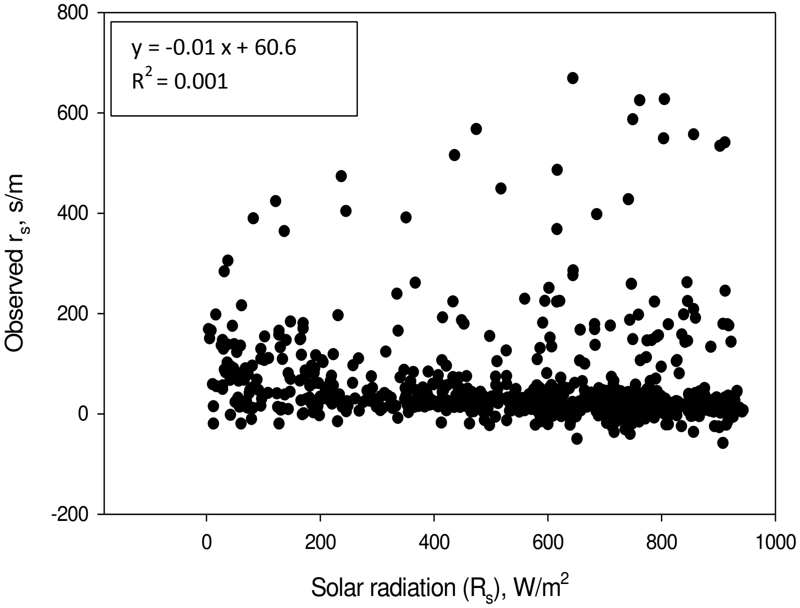

Figure 4.7: Relationship of r_s and solar radiation (R_s)

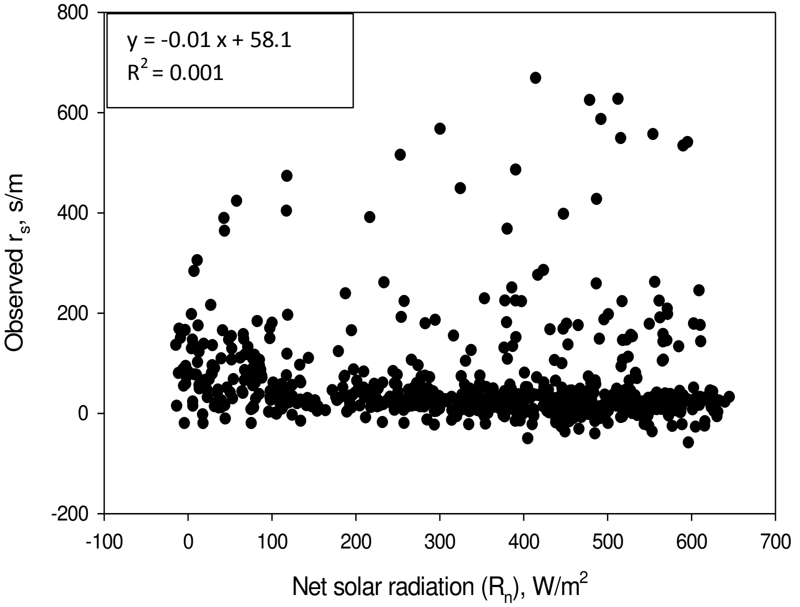

Figure 4.8: Relationship of r_s and net solar radiation (R_n)

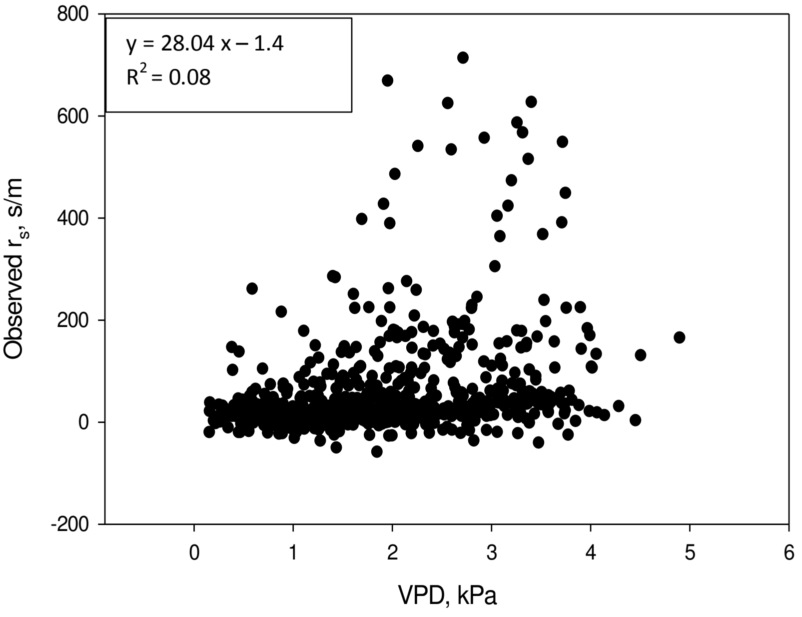

Figure 4.9: Relationship of r_s and VPD

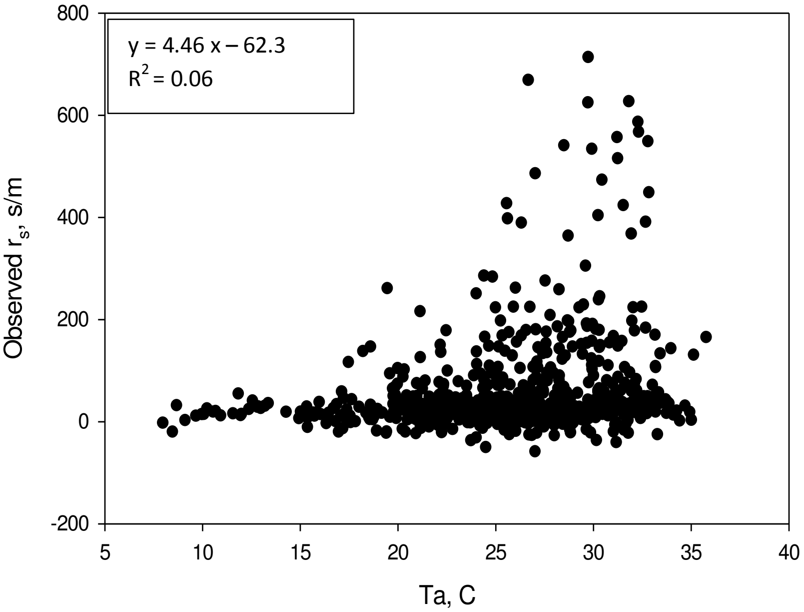

Figure 4.10: Relationship of r_s and T_a

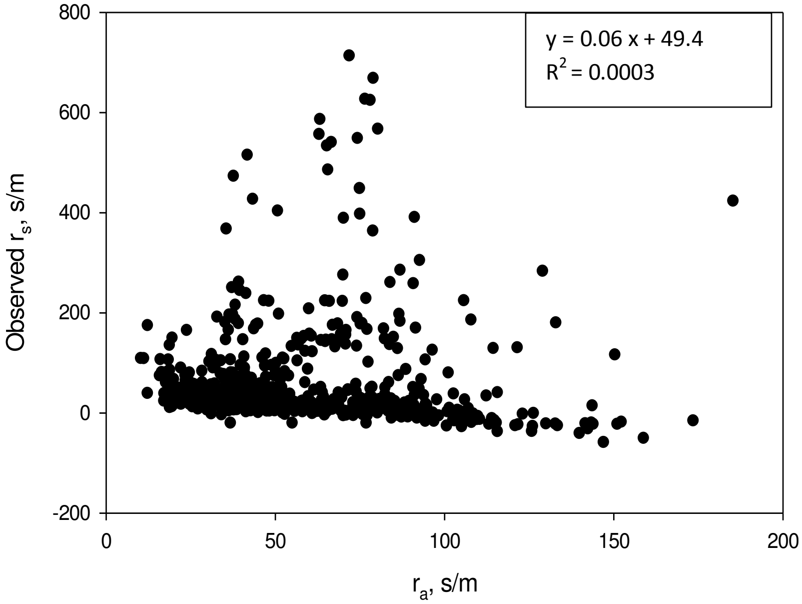

Figure 4.11: Relationship of r_s and r_a

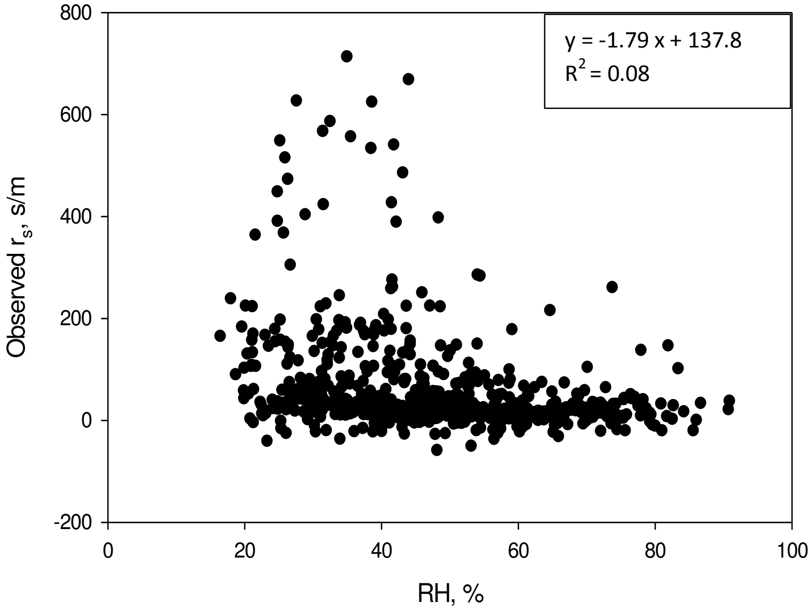

Figure 4.12: Relationship of r_s and RH

DAILY VARIABLE SURFACE RESISTANCE (r_{s_daily})

When all of the alfalfa crop data was used as shown in the Figures from 4.5 to 4.12, only the LAI or crop height showed strong correlation with r_s. Hence the cubic equation for LAI or the fifth order polynomial equation for h_c was used to calculate r_s. As r_s was calculated as a function of LAI or h_c, which doesn't change throughout the day, but it changes throughout the season, this r_s is termed as r_{s_daily}. Although this is termed as r_{s_daily}, this r_s is only the average of the daytime r_s data, it doesn't include nighttime data, or in other words, this r_s can only be used in hourly equation, not in the daily equation (since the other variables in the daily equation is the average of the 24 hour data).

$$r_{s\_daily} = - 23.323\ LAI^3 + 323.39\ LAI^2 - 1461.1\ LAI + 2169.4\ (R^2 = 0.83) \qquad (4.24)$$

$$r_{s\_daily} = - 41206\ h_c^5 + 111575\ hc^4 - 116083\ h_c^3 + 57815\ h_c^2 - 13698\ h_c + 1239.9\ (R^2 = 0.82) \qquad (4.25)$$

In order to use equations (4.24) or (4.25), one needs to know the alfalfa crop height. If the user has the measured data, there is no problem. However, if there is no measured data available, he/she can use a quadratic equation to obtain crop height as shown in the Appendix (Figure A10).

$$h_c = - 0.0003\ DAH^2 + 0.0268\ DAH + 0.03\ (R^2 = 0.99) \qquad (4.26)$$

where DAH is the days after harvest.

Performance of r_{s_daily} in PM equation

The modeled daytime average r_s (using equations 4.24 and 4.25) was then implemented in the PM equation using hourly data for both years 2009 and 2010. Also the conventional r_s was implemented for both years. The objective was to evaluate the performance of all of these methods. Figure 4.13 was produced from year 2009 when the modeled $r_{s\,(LAI)}$ was implemented in the PM equation and then compared to the measured hourly lysimeter ET. Similarly Figure 4.14 was when the modeled $r_{s\,(hc)}$ was used and Figure 4.15 was when the conventional r_s was used. For the modeled $r_{s\,(LAI)}$, the slope was 0.87, intercept was 0.05 with very good R^2 of 0.92. The mean bias error was close to zero (- 4%), root mean square error was 0.08 mm/h (13.8 %). The index of agreement was 0.98, which is considered very good. Also the Nash-Sutcliffe coefficient of efficiency was 0.91, which is considered good as well. Similarly for the modeled $r_{s\,(hc)}$, the slope was 0.89, intercept was 0.04 and R^2 was 0.92. Again the mean bias error was close to zero (-3.8%), root mean square error was 0.08 mm/h (13.7%). The index of agreement and the Nash Sutcliffe coefficient of efficiency were 0.98 and 0.91 respectively. Hence the performance of $r_{s\,(LAI)}$ and $r_{s\,(hc)}$ are comparable. However, for the conventional r_s, the slope was only 0.79, intercept was 0.1 and R^2 of 0.81. The mean bias error was zero and the root mean square error was 0.11 mm/h (20.3 %). The index of agreement was 0.94 and Nash-Sutcliffe coefficient of efficiency was 0.81. From the statistical point of view, all of the indicators except MBE were better for the modeled r_s with respect to the conventional r_s.

Similarly Figure 4.16 shows the comparison of the PM ET using modeled $r_{s\,(LAI)}$ with the measured lysimeter ET in 2010. The slope was 0.86, intercept was 0.08 and very good R^2 of 0.88. The mean bias error was zero, root mean square error was 0.1 mm/h (15.8%), the index of agreement was 0.97 and the Nash-Sutcliffe coefficient of efficiency was 0.88. The statistical indicators suggest that the PM equation with modeled $r_{s\,(LAI)}$ performed quite well. Figure 4.17 shows the comparison of the PM ET using modeled $r_{s\,(hc)}$ with the measured lysimeter ET in 2010 and the performance of both of these models are quite comparable as in 2009. Figure 4.18 shows the comparison of PM ET using fixed r_s with the measured lysimeter ET in 2010. In this case, slope was 0.72, intercept was 0.17 and R^2 was 0.7. The mean bias error was zero, root mean square error was 0.15 mm/h (25.4%), index of agreement was 0.91 and the Nash-Sutcliffe coefficient of efficiency was 0.7. The statistical analysis revealed that modeled r_s (which is a variable r_s) performed superior compared to the fixed r_s when implemented in the PM equation.

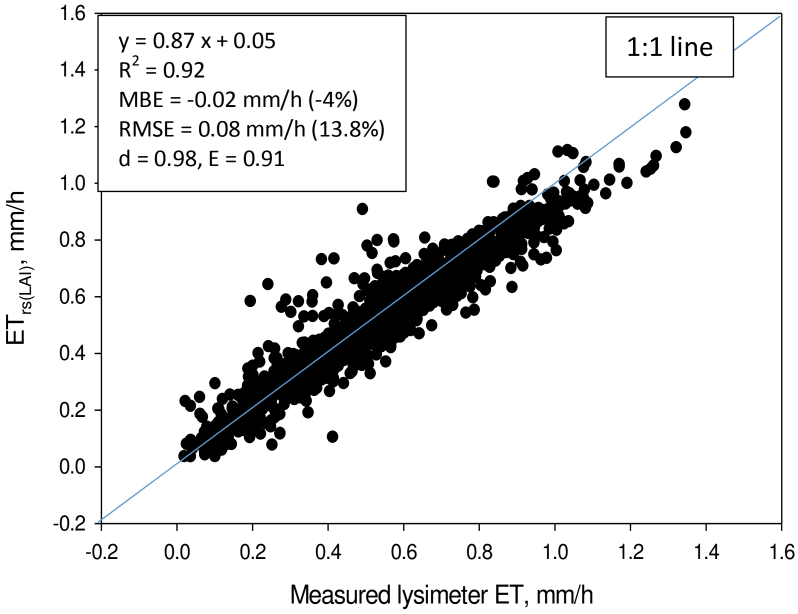

Figure 4.13: Comparison of PM ET using modeled r_s (LAI) with measured lysimeter alfalfa ET in 2009

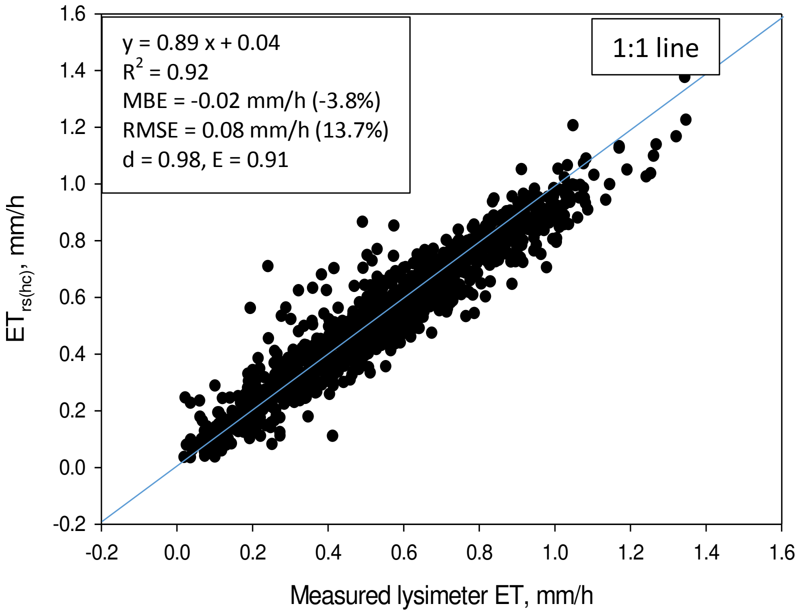

Figure 4.14: Comparison of PM ET using modeled r_s (hc) with measured lysimeter alfalfa ET in 2009

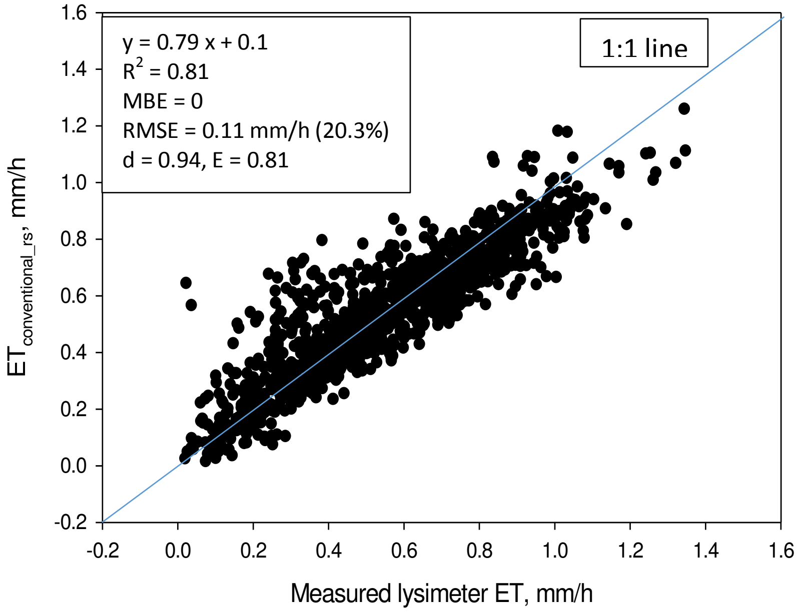

Figure 4.15: Comparison of PM ET using conventional r_s with measured lysimeter alfalfa ET in 2009

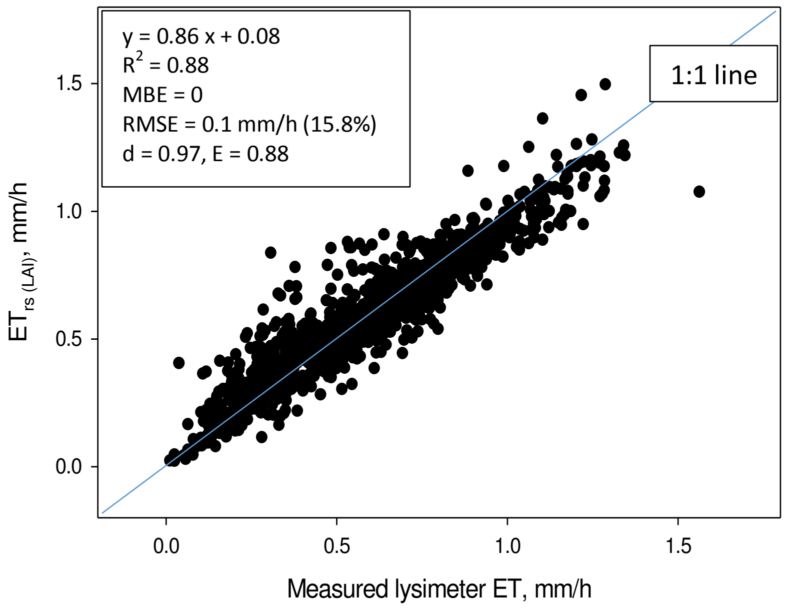

Figure 4.16: Comparison of PM ET using modeled r_s (LAI) with measured lysimeter alfalfa ET in 2010

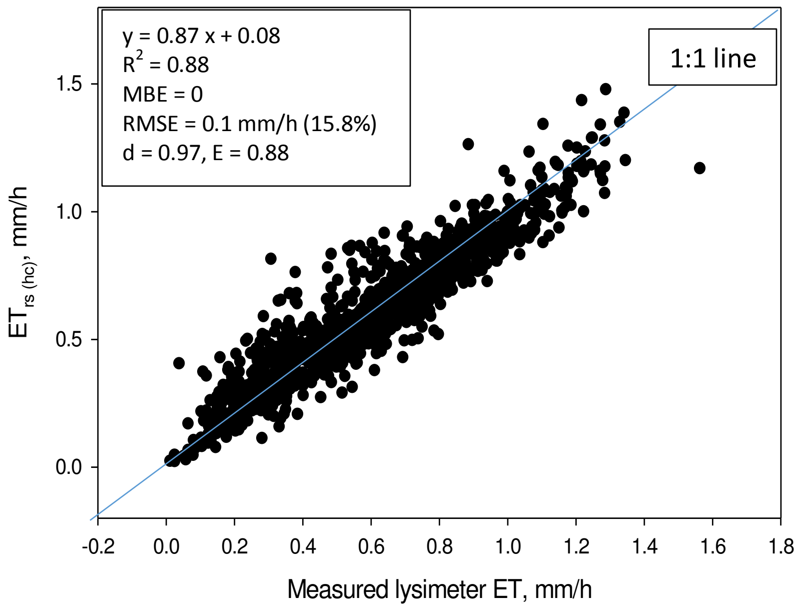

Figure 4.17: Comparison of PM ET using modeled r_s (hc) with measured lysimeter alfalfa ET in 2010

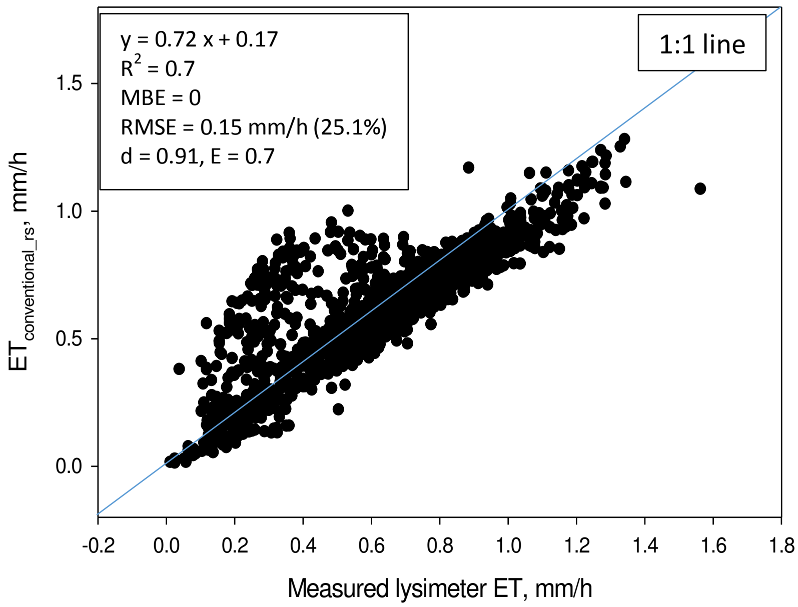

Figure 4.18: Comparison of PM ET using conventional r_s with measured lysimeter alfalfa ET in 2010

Performance of the model when $h_c < 25$ cm and when $h_c > 25$ cm

When all of the datasets were used, then it was found that PM ET with modeled r_s was superior to the PM ET with conventional r_s. When conventional r_s was used, there was a clear ET overestimation for lower ET values whereas ET underestimation for higher ET values as suggested by Figures 4.15 and 4.18. It was observed that those overestimations especially occurred when alfalfa crop height (h_c) was less than or equal to 0.25 m. Hence, for both years, the datasets were grouped into $h_c < 25$ cm and $h_c > 25$ cm. Figure 4.19 shows the comparison of PM ET using modeled $r_{s\ (LAI)}$ with the measured lysimeter ET when $h_c < 25$ cm for year 2009. The slope was 0.84, intercept was 0.04 and R^2 was 0.86. The mean bias error was -0.03 mm/h (-7.4 %), RMSE was 0.08 mm/h (20.7%), index of agreement was 0.95 and the Nash-Sutcliffe coefficient of efficiency was 0.84. Similarly Figure 4.20 shows the comparison of PM ET using modeled $r_{s\ (hc)}$ with the measured lysimeter ET when h_c <25 cm for year 2009. Again the performance of $r_{s\ (LAI)}$ and $r_{s\ (hc)}$ were comparable. Similarly Figure 4.21 shows the comparison of PM ET using fixed r_s with the measured lysimeter ET when h_c < 25 cm for year 2009. The slope in this case was 0.71, intercept was 0.2 and R^2 was only 0.57. The mean bias error was 0.08 mm/h (19.8%), which means significant overestimation by the equation. The root mean square error was 0.16 mm/h (39.9%), index of agreement was 0.84 and the Nash-Sutcliffe coefficient of efficiency was 0.39. The statistics revealed that the modeled variable r_s performed much better compared to the conventional r_s as all of the indicators were better for the modeled variable r_s.

Figure 4.22 shows the comparison of PM ET using modeled $r_{s\ (LAI)}$ with the measured lysimeter ET when h_c >25 cm for year 2009. The slope in this case was 0.85, intercept was 0.07 and R^2 was 0.92. The mean bias error was close to zero, root mean square error was 0.08 mm/h (12.7%), index of agreement was 0.97 and the Nash-Sutcliffe coefficient of efficiency was 0.91. The statistics infer that the PM ET with daily variable r_s (modeled r_s) performed quite well for h_c >25 cm as well. Similarly Figure 4.23 shows the comparison of PM ET using modeled $r_{s\ (hc)}$ with the measured lysimeter ET when h_c >25 cm for year 2009, resulting in similar performance as with $r_{s\ (LAI)}$. Figure 4.24 shows the comparison of PM ET using fixed r_s with the measured lysimeter ET when h_c >25 cm for year 2009. The slope of the regression line was 0.85, intercept was 0.05 and the R^2 was 0.87. The mean bias error was -0.04 mm/h (-6.5%), root mean square error was 0.1 mm/h (16.6%), index of agreement was 0.96 and the Nash-Sutcliffe coefficient of efficiency was 0.85. For h_c >25 cm, even the conventional r_s performed satisfactorily. When the performance of the modeled r_s versus conventional r_s was evaluated, the modeled r_s performed slightly better as the mean bias error was close to zero (instead of around -6.5% for fixed r_s), root mean square error was 0.08 mm/h, or12.7% (instead of 0.1 mm/h, or 16.6%) and the Nash Sutcliffe coefficient of efficiency improved from 0.85 to 0.91.

Figure 4.25 shows the comparison of PM ET using modeled $r_{s\ (LAI)}$ with the measured lysimeter ET when crop height was less than 25 cm for year 2010. The slope of the regression line was 0.72, intercept was 0.15 and the R^2 was 0.58. The mean bias error was 0.03 mm/h (7.1%), root mean square error was 0.14 mm/h (31.9%), index of agreement was 0.87 and the Nash-Sutcliffe coefficient of efficiency was 0.53. It means that the equation with modeled r_s is slightly overestimating ET. Similarly Figure 4.26 shows the comparison of PM ET using modeled $r_{s\ (hc)}$ with the measured lysimeter ET when crop height was less than 25 cm for year 2010, depicting similar statistical results as $r_{s\ (LAI)}$. Figure 4.27 shows the comparison of PM ET using conventional r_s with the measured lysimeter ET when h_c <25 cm for year 2010. The slope of the regression line was 0.59, intercept was 0.35 and the R^2 was 0.32. The value of intercept is too large and the R^2 is too low. The mean bias error was 0.18 mm/h (41.5%), which is too high, in other words, it over predicted actual ET rate by 41.5%. The root mean square error was 0.26 mm/h (61.3%), which is simply unacceptable. Again the index of agreement was 0.65 and the Nash Sutcliffe coefficient of efficiency was -0.74. As the Nash Sutcliffe coefficient of efficiency is a negative value, the PM ET using conventional r_s is considered unacceptable when h_c was less than 25 cm for year 2010.

Figure 4.28 shows the comparison of PM ET using modeled r_s (LAI) with the measured lysimeter ET when crop height was larger than 25 cm for year 2010. The slope of the regression line was 0.89, intercept was 0.06 and the R^2 was 0.92. The mean bias error was - 0.02 mm/h (-2.6%) and root mean square error was 0.08 mm/h (12%). The index of agreement was 0.98 and the Nash-Sutcliffe coefficient of efficiency was 0.92. The statistical indicators suggest that the developed $r_{s\,(LAI)}$ model worked quite well when implemented in the PM equation when h_c was larger than 25 cm. Similarly Figure 4.29 shows the comparison of PM ET using modeled $r_{s\,(hc)}$ with the measured lysimeter ET when crop height was larger than 25 cm for year 2010, again resulting similar performance as $r_{s\,(LAI)}$. Figure 4.30 shows the comparison of PM ET using conventional r_s with the measured lysimeter ET when crop height was larger than 25 cm for year 2010. The slope of the regression line was 0.86, intercept was 0.04 and the R^2 was 0.92. The mean bias error was -0.05 mm/h (-8%) and the root mean square error was 0.1 mm/h (14.5%). The index of agreement was 0.97 and the Nash-Sutcliffe coefficient of efficiency was 0.88. It can be inferred that even the fixed r_s performed satisfactorily when the crop height was larger than 25 cm in 2010. However, the bias was reduced when using the modeled r_s and also the slope of the regression line was improved, RMSE dropped and also the Nash Sutcliffe coefficient of efficiency improved from 0.88 to 0.92.

When all of the crop heights were considered, the mean bias error was close to zero when $ET_{conventional\_rs}$ was compared with measured lysimeter ET (Refer Figures 4.15 and 4.18). Actually what happened was there was significant overestimation of ET when crop height was less than 25 cm (20% in 2009 and 41.5% in 2010) and some underestimation of ET when h_c was greater than 25 cm in height (6.5% in 2009 and 8% in 2010) when $ET_{conventional\_rs}$ was used . These two biases cancelled out and the mean bias error came close to zero when all of the data was considered.

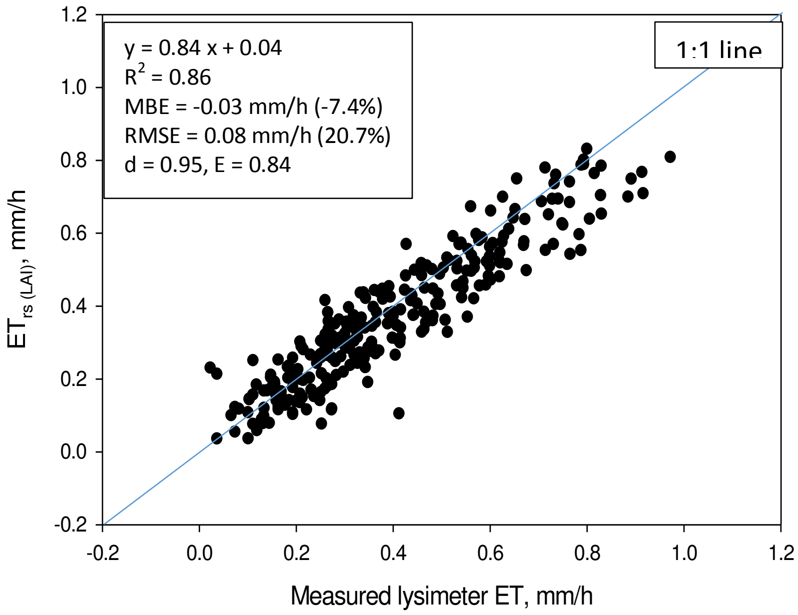

Figure 4.19: Comparison of PM ET using modeled r_s (LAI) with measured lysimeter alfalfa ET in 2009 when $h_c < 25$ cm

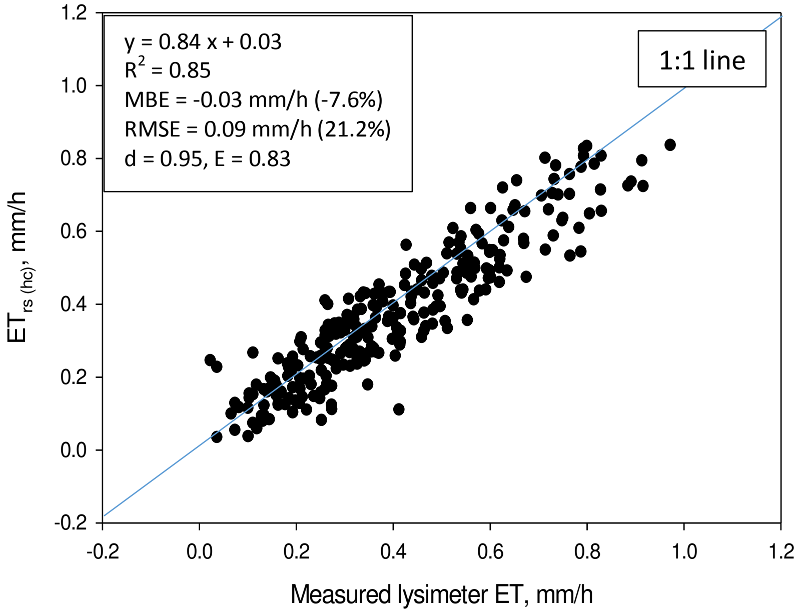

Figure 4.20: Comparison of PM ET using modeled r_s (h_c) with measured lysimeter alfalfa ET in 2009 when $h_c < 25$ cm

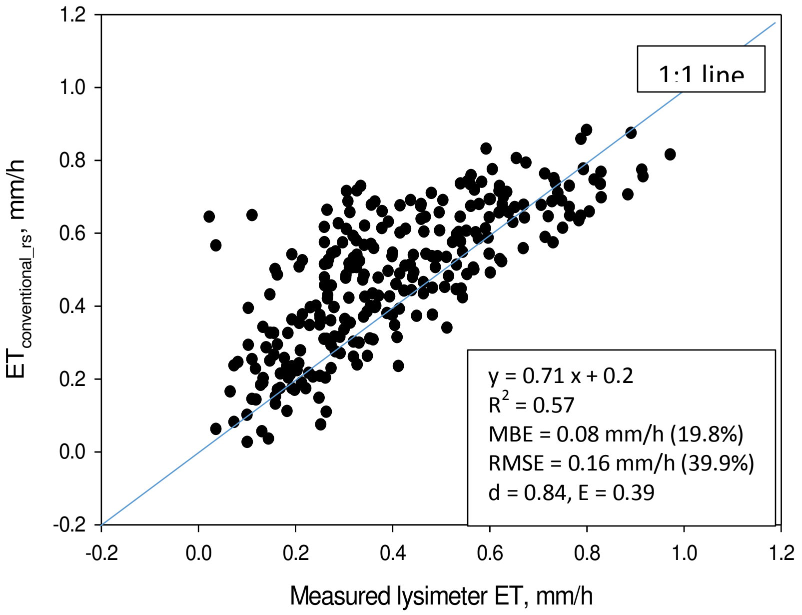

Figure 4.21: Comparison of PM ET using conventional r_s with measured lysimeter alfalfa ET in 2009 when $h_c < 25$ cm

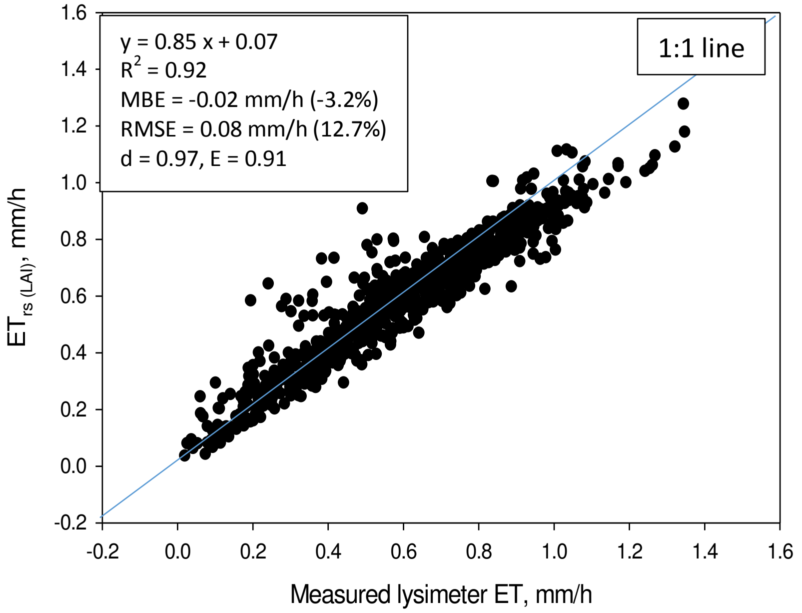

Figure 4.22: Comparison of PM ET using modeled r_s (LAI) with measured lysimeter alfalfa ET in 2009 when $h_c > 25$ cm

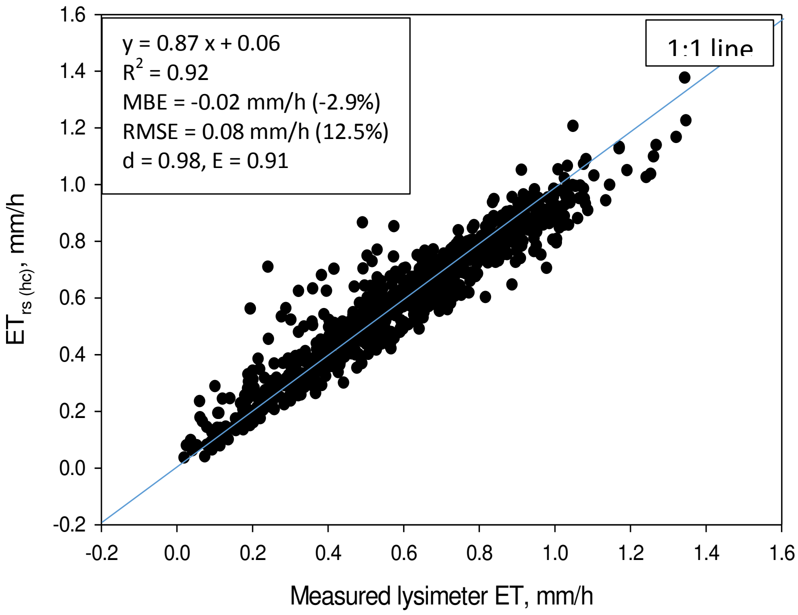

Figure 4.23: Comparison of PM ET using modeled r_s (h_c) with measured lysimeter alfalfa ET in 2009 when $h_c > 25$ cm

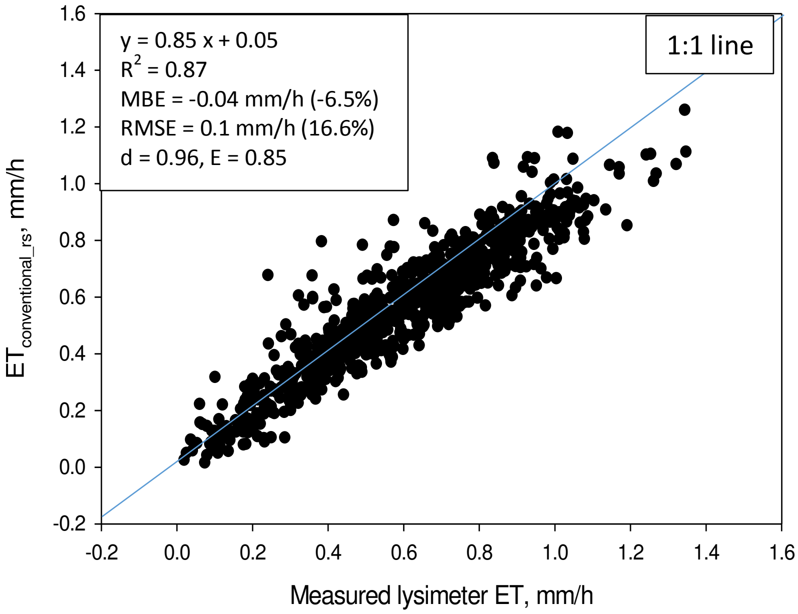

Figure 4.24: Comparison of PM ET using conventional r_s with measured lysimeter alfalfa ET in 2009 when $h_c > 25$ cm

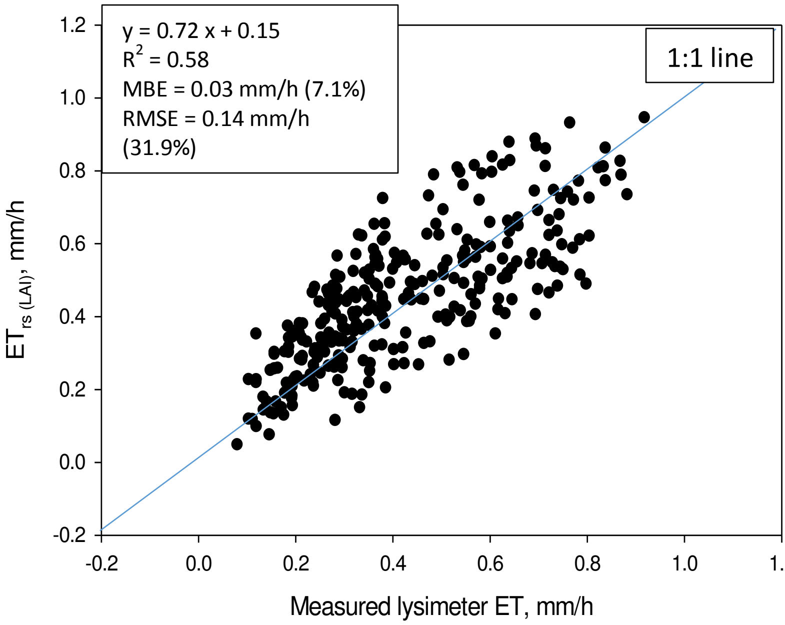

Figure 4.25: Comparison of PM ET using modeled r_s (LAI) with measured lysimeter alfalfa ET in 2010 when $h_c < 25$ cm

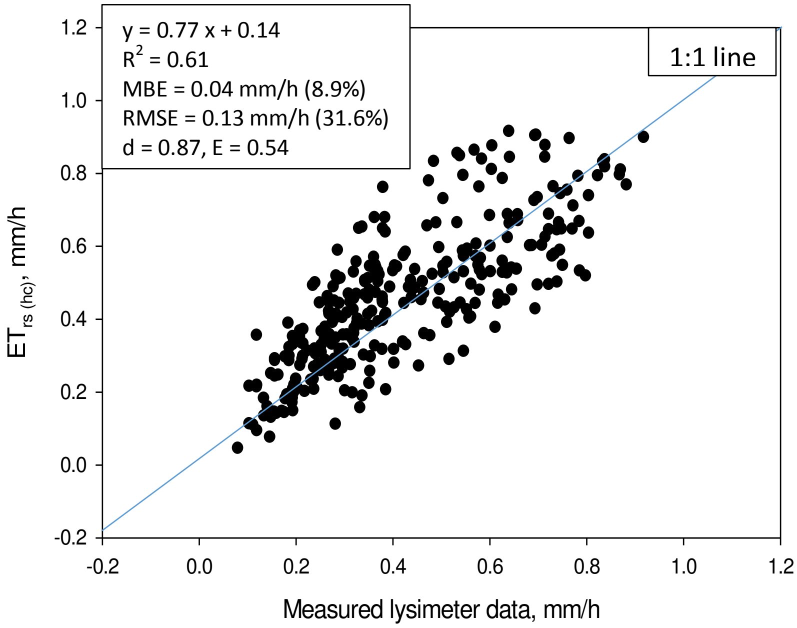

Figure 4.26: Comparison of PM ET using modeled r_s (h_c) with measured lysimeter alfalfa ET in 2010 when $h_c < 25$ cm

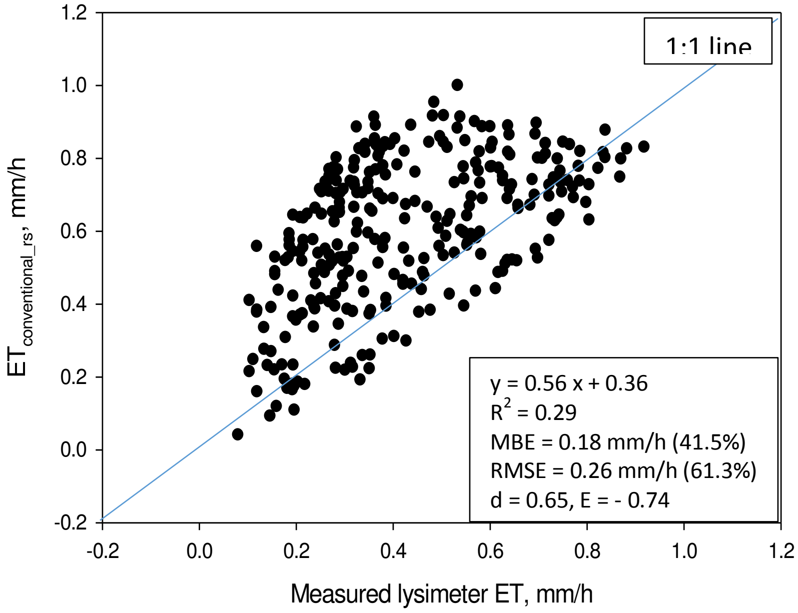

Figure 4.27: Comparison of PM ET using conventional r_s with measured lysimeter alfalfa ET in 2010 when $h_c < 25$ cm

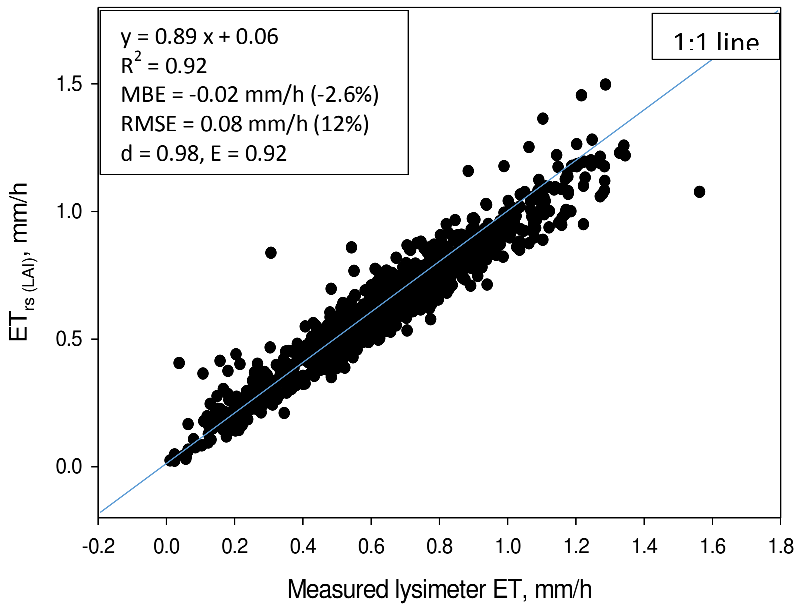

Figure 4.28: Comparison of PM ET using modeled r_s (LAI) with measured lysimeter alfalfa ET in 2010 when $h_c > 25$ cm

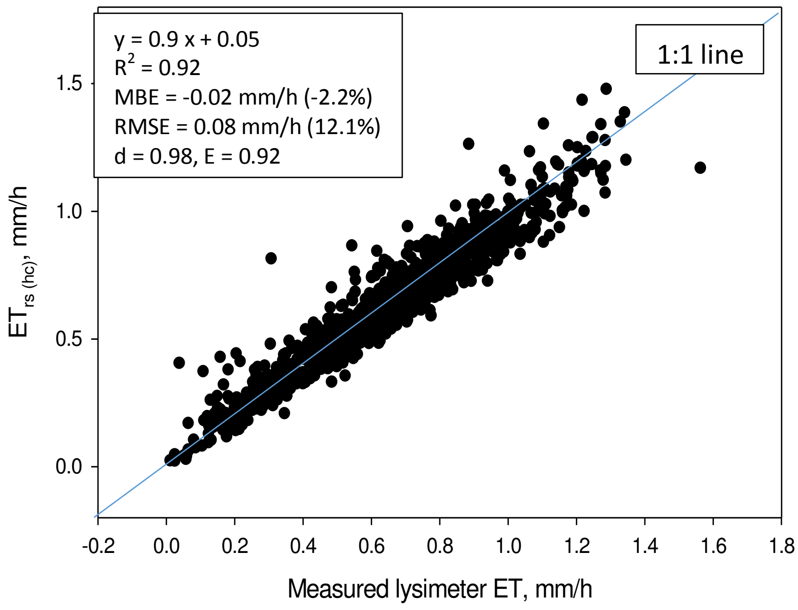

Figure 4.29: Comparison of PM ET using modeled r_s (h_c) with measured lysimeter alfalfa ET in 2010 when h_c > 25 cm

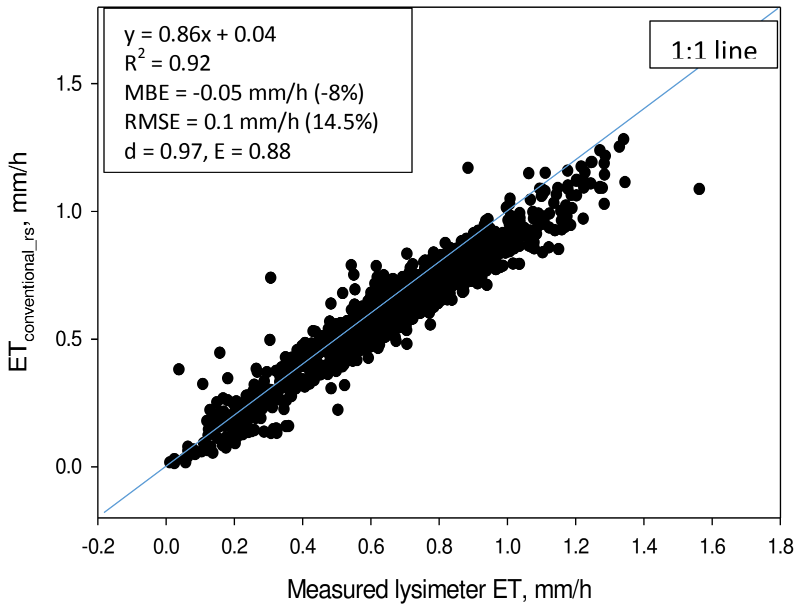

Figure 4.30: Comparison of PM ET using conventional r_s with measured lysimeter alfalfa ET in 2010 when h_c > 25 cm

Performance of modelled rs_daily for compiled dataset

It is important to examine how the model performs for a larger dataset. Since the model was developed from 2009 data, it was not included; and only data from years 2010 to 2012 were used for this analysis. Figure 4.31 shows the comparison the PM ET using conventional r_s with measured lysimeter ET. The slope of the linear regression line was 0.65, intercept was 0.21 and R^2 was 0.68. Similarly MBE was -0.02 mm/h (-3.6%) and RMSE was 0.19 mm/h (28.8%). The index of agreement was 0.89 and Nash-Sutcliffe coefficient of efficiency was 0.68. The performance of PM ET equation was improved when using modelled r_s,. Figure 4.32 shows the comparison of PM ET using modelled $r_{s\,(LAI)}$ with measured lysimeter ET and Figure 4.33 shows the comparison of PM ET using modelled $r_{s\,(hc)}$ with measured lysimeter ET. The slope of the linear regression line was 0.76 and intercept was 0.16 with R^2 as 0.81, when modelled r_s were used. Similarly MBE was close to zero, RMSE was 0.15 mm/h, index of agreement was 0.94 and Nash-Sutcliffe coefficient of efficiency was 0.8. Hence it can be observed that all of the statistical indicators were improved when modelled r_s was used instead of the conventional r_s in the PM equation.

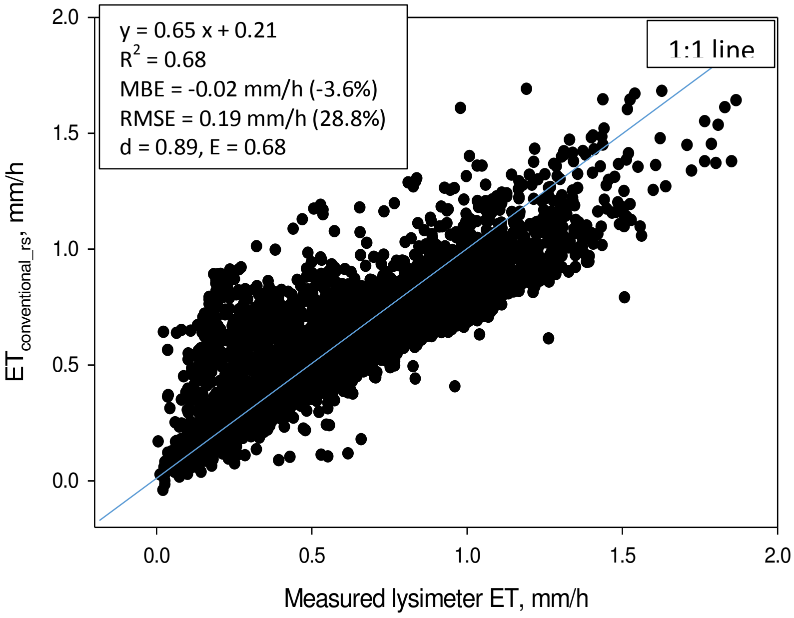

Figure 4.31: Comparison of PM ET using conventional r_s with measured lysimeter alfalfa ET for compiled dataset

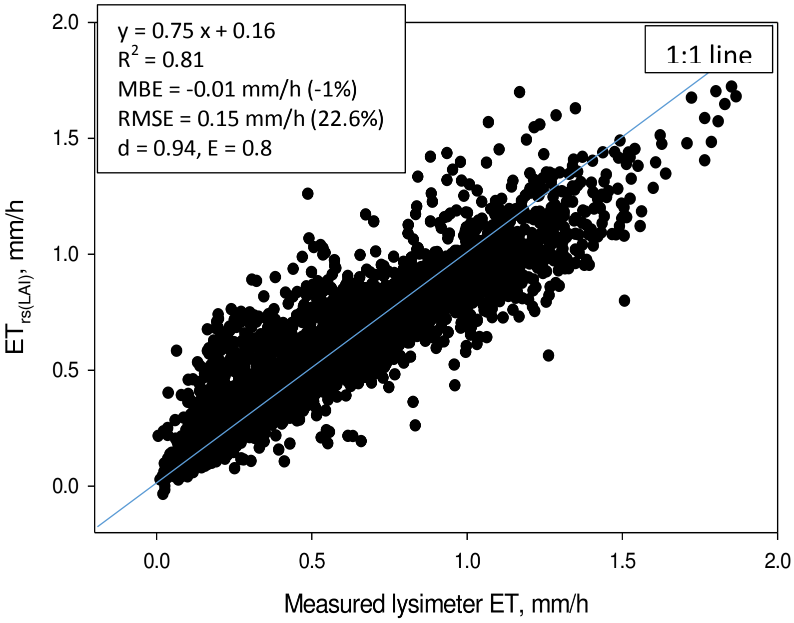

Figure 4.32: Comparison of PM ET using modelled $r_{s\ (LAI)}$ with measured lysimeter alfalfa ET for compiled dataset

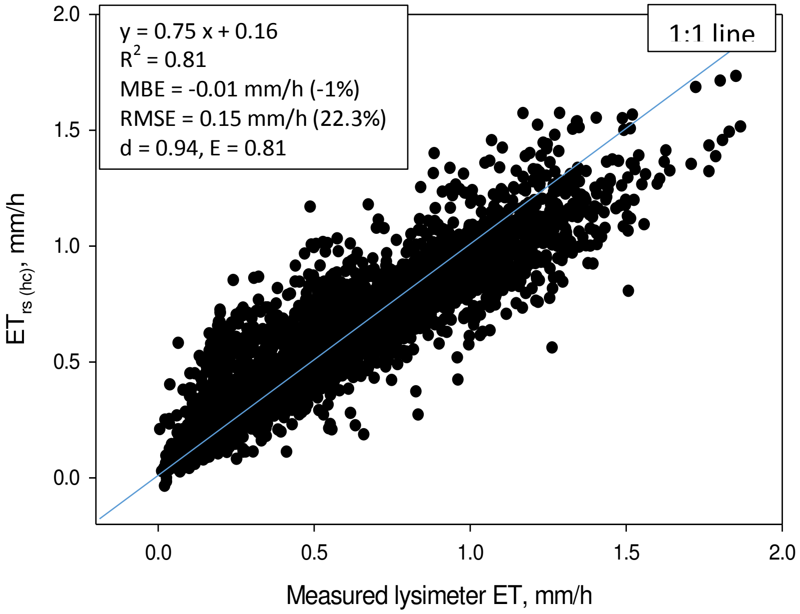

Figure 4.33: Comparison of PM ET using modelled $r_{s\ (hc)}$ with measured lysimeter alfalfa ET for compiled dataset

Typical diurnal pattern of r_s

The value of r_s is larger at nighttime and smaller at daytime. According to the ASCE Standardized Reference ET equation procedure (ASCE EWRI, 2005), r_s for alfalfa reference surface is fixed for the daytime as 30 s/m and for the nighttime as 200 s/m whereas r_s for grass reference surface is fixed as 50 s/m and for the nighttime as 200 s/m. On a typical day for reference alfalfa crop condition, the following plot can be obtained for conventional r_s and indirectly measured r_s (which is named here as observed r_s) throughout the day.

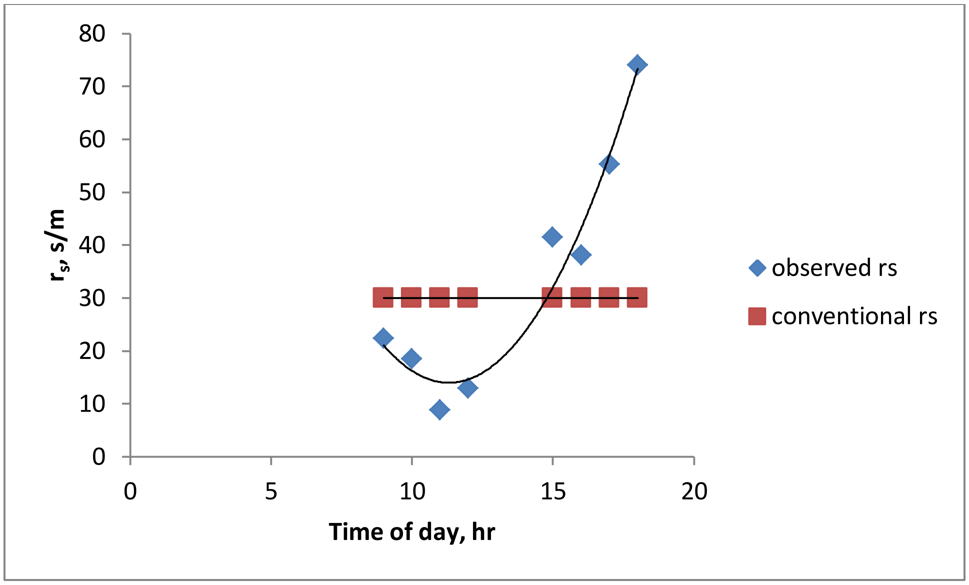

Figure 4.34: Diurnal pattern of r_s on reference alfalfa crop condition

In Figure 4.34, in case of observed r_s, r_s decreases until around noon time, then it increases. On the other hand, conventional r_s has a fixed constant value for all daytime hours. Because of this, there can be considerable error while estimating ET using the fixed r_s approach. The cumulative error in estimating daily or monthly or even seasonal ET using the fixed r_s approach can be significant. Hence it is important to consider the hourly variable r_s approach in estimating reference ET.

HOURLY VARIABLE SURFACE RESISTANCE (r_{s_hourly})

Daily variable r_s as a function of LAI or crop height worked well for estimating alfalfa ET rates. However, it can be hypothesized that perhaps the hourly variable r_s may even provide better result as previous studies have shown that r_s in fact changes throughout the day. Canopy temperature (T_c) is considered an important parameter to govern r_s especially for the full canopy cover condition. Excess T_c can cause stress in crop which may result in increase of r_s. T_c was calculated using the relation given by Norman et al. (1995) which is as follows:

$$T_R{}^4 = f_{VR} T_C{}^4 + (1 - f_{VR}) T_S{}^4 \tag{4.27}$$

where T_R is the radiometric surface temperature, f_{VR} is the fraction of vegetation appearing in the radiometer field of view (or per cent canopy cover) and T_s is the soil surface temperature.

There were 5 days of data available in 2010 when the nadir lysimeter field images were taken, from which canopy cover (in %) was estimated. The images were taken on July 26, August 4, August 18, September 13 and September 27 (See Appendix). The minimum crop height on those five days was 36 cm. It can be observed that when the canopy cover (CC) was larger, the field seemed to be greener, which means the presence of healthy leaves transpiring at potential level. As observed r_s was impacted by both LAS and lysimeter data (see Eq. 4.8), the data was excluded when the discrepancy in LE from these instruments exceeded 100 W/m^2. Also there were some instances where negative r_s was observed under very large r_a (>80 s/m) condition and as negative r_s has no physical meaning, they were excluded too. Alves et al. (1998) also had issue with negative r_s and they tried to solve the issue by calculating r_a from top of the canopy instead of the height d + z_{oH}, which results in lower r_a. In this study, this was not done because it was thought that r_a was also used to obtain T_o using the measured H data from LAS; and lowering r_a will also lower T_o. However, in the future studies, this could be an option to deal with negative r_s. Again only the daytime data (from 9 a.m. to 6 p.m.) was used for the analysis. Since crop height was close to the reference crop height (which is 50 cm) in all these days, the atmospheric stability correction on r_a was not performed to obtain observed r_s using equation (4.8).

Sensitivity analysis of PM equation to r_s

It is very important to know the impact of r_s on the PM equation as we are using the PM equation in estimating actual crop ET. For this purpose, some arbitrary values were chosen for different variables used in the PM equation. The chosen values were as follows:

$R_n = 623.9$ W/m^2

RH = 43 %

$T_a = 18.7$ °C

$r_a = 15$ s/m

$r_s = 30$ s/m

Soil heat flux (G) was calculated as 4% of R_n. Then equation (4.4) was used to calculate hourly alfalfa ET. The other variables were calculated following the procedure listed in ASCE manual (Allen et al., 2005). The calculated ET was 0.79 mm/h. Then all other variables being same, r_s was increased to 40 s/m to see its impact on ET. New ET was then 0.70 mm/h (11.1 % reduction in ET). Similarly when r_s was decreased to 20 s/m, ET was then 0.90 mm/h (14.3% increase in ET). It can be observed that r_s plays a significant role in accurately estimating ET when r_a is low or when it is windy condition.

In the above example, all other variables being same, r_a was then increased to 100 s/m (to simulate calm weather condition). When r_s was 30 s/m, calculated ET was 0.65 mm/h. Similarly when r_s was changed to 40 s/m, then ET was calculated as 0.64 mm/h (only 2.7% reduction in ET). Likewise when r_s was 20 s/m, calculated ET was 0.67 mm/h (only 2.8% increase in ET).

When R_n or RH was changed, there was no impact in percentage change in ET by changing r_s. However when T_a was increased, the percentage difference in ET by change in r_s slightly dropped. Similarly when T_a was decreased, the percentage difference in ET due to the change in r_s slightly increased.

It was found from this analysis that when the magnitude of r_a is small, the accuracy in r_s plays a big role in the accuracy of ET estimation. However when the magnitude of r_a is large, the accuracy in r_s plays a less significant role in accuracy of ET estimation.

Relationship of observed r_s with different variables when h_c >35cm

Figure 4.35 shows the relation of observed r_s and LAI and Figure 4.36 shows the relation of r_s and crop height. The correlation is not strong unlike in the case of using all datasets (see Figures 4.5 and 4.6). For the daily averaged r_s, data from after harvest to before harvest was considered, so we were able to get a good trend of r_s with respect to LAI or crop height. However, in this case, only 5 days of data were available with crop height greater than 35 cm. Again as pointed out earlier, the per cent canopy cover in some cases was higher when the crop height was relatively shorter, so r_s in this case is not expected to have strong relation with LAI or crop height. Figure 4.37 shows the relation of r_s and VPD, with R^2 of 0.51. It can be observed that when VPD increased, r_s also increased, with some exponential growth trend. Alves and Pereira (1999) also found the similar result, however, with linear trend. Figure 4.38 shows the relation of r_s and T_c, R^2 being 0.41. Again in this case, r_s increased when T_c increased, with some exponential trend. The increase in T_c might create some crop stress, resulting in partial stomatal closure. Figure 4.39 shows the relation of r_s and r_a with a very strong relation, R^2 being 0.57. In this case, it was found that when r_a is smaller, r_s is larger and vice-versa with logarithmic trend. Alves and Pereira (1999) also showed similar results, however with linear relation. Again it is possible that when r_a is smaller (or very windy condition) then stomata could have been partially closed. It can be observed that the correlation of r_s with r_a and VPD was not good when all crop height data was used (see Figures 4.9 and 4.11). However, the correlation was improved when the crop height greater than 35 cm was used. This is possible because when the crop height is low, r_s is high all the time, impacted less by r_a and VPD. Hence when all of the crop height data was used, the low correlation of r_s with r_a and VPD for low crop height impacted the overall correlation.

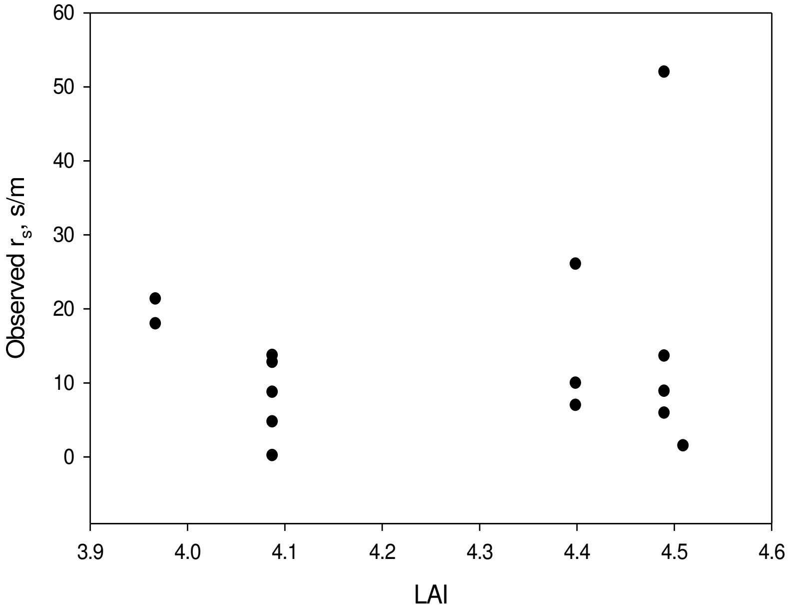

Figure 4.35: Relationship of r_s and LAI

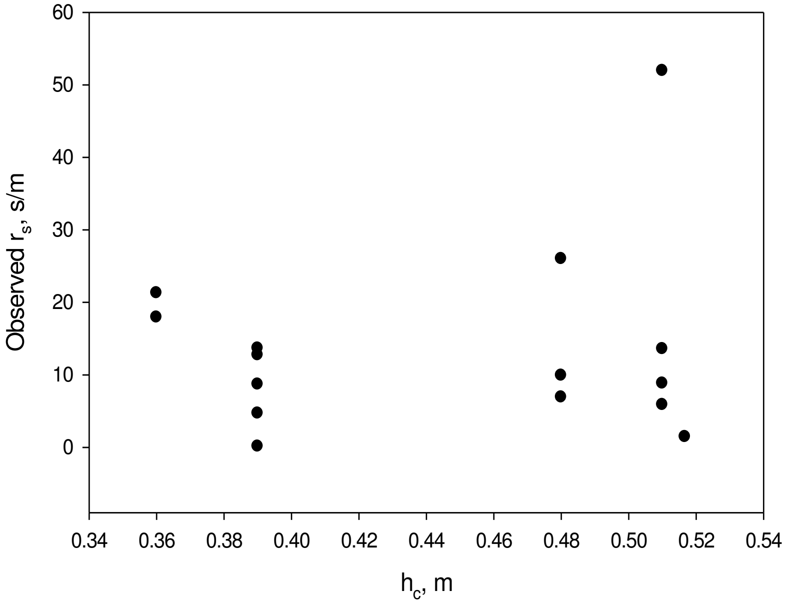

Figure 4.36: Relationship of r_s and crop height (h_c)

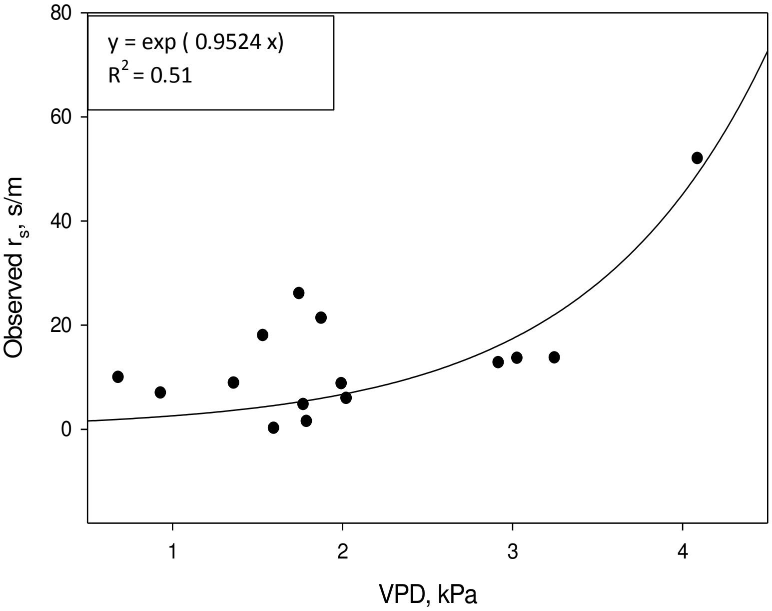

Figure 4.37: Relationship of r_s and VPD

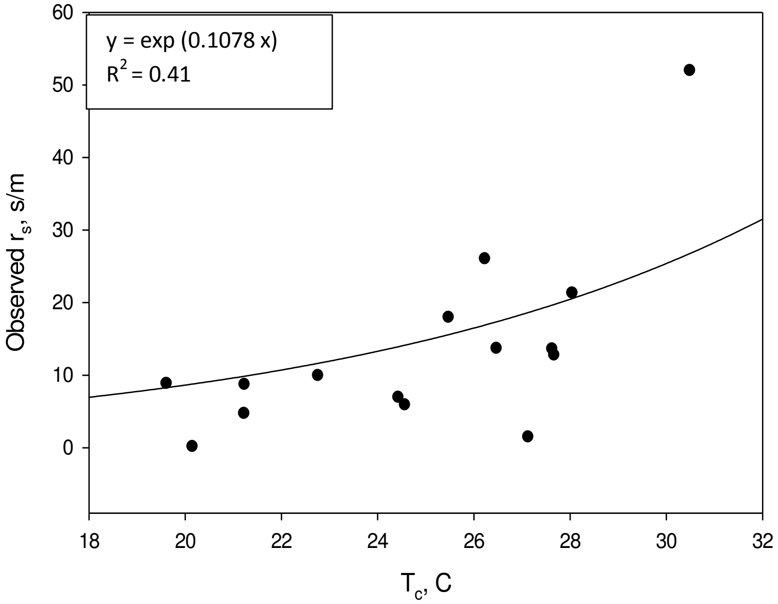

Figure 4.38: Relationship of r_s and T_c

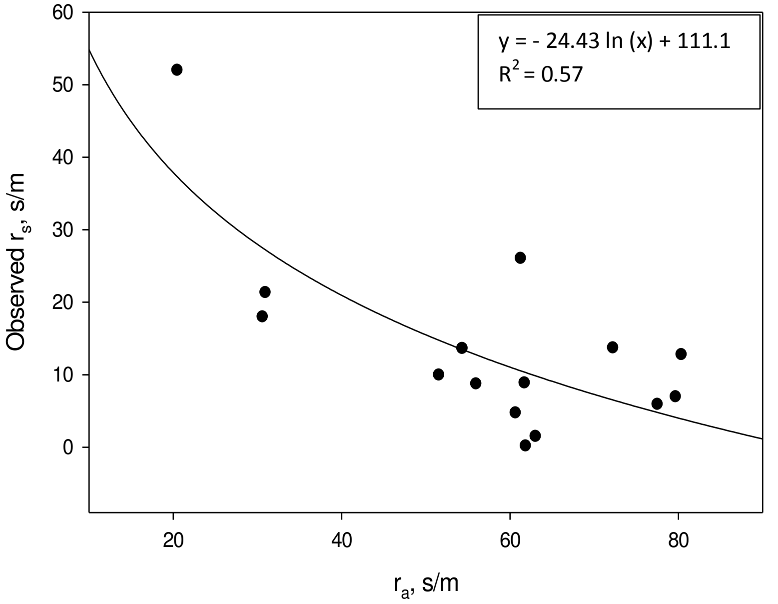

Figure 4.39: Relationship of r_s and r_a

Variables r_a, T_c and VPD were selected to calibrate r_s. A multiple regression was performed using these variables. Since there were only 5 days of data available, all of the data were used for the calibration purpose. The following calibration model was obtained:

$$r_s = -14.6 \ln(r_a) + 0.54 \exp(0.1078\, T_c) + 0.41 \exp(0.9524\, VPD) + 59.1 \quad (R^2 = 0.81) \tag{4.28}$$

Figure 4.40 was obtained when the calibrated r_s model was plotted against the observed r_s. It can be observed that the modelled r_s followed the observed r_s closely having slope of the regression line as 0.81 and also R^2 as 0.81.

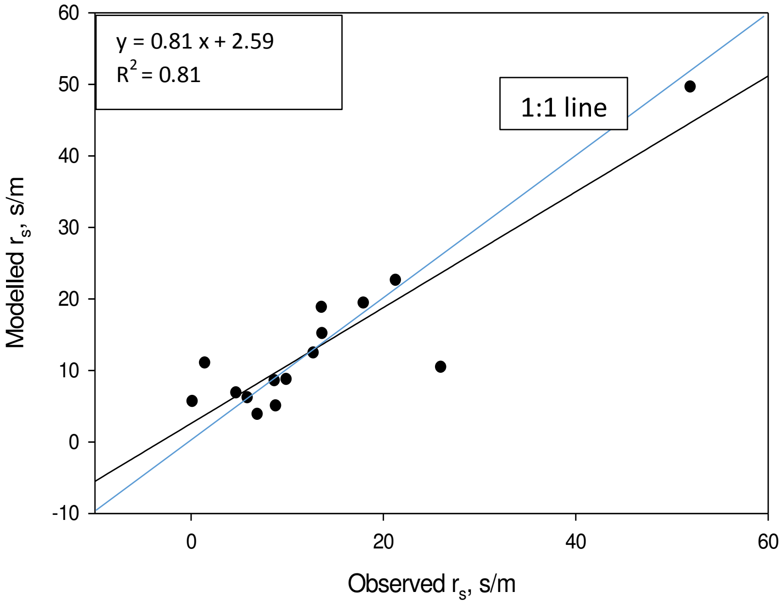

Figure 4.40: Comparison of modeled r_s with observed r_s

After calibrating the r_s, then it was implemented in the PM equation for those five days. Figure 4.41 shows the comparison of PM ET using hourly modeled r_s with measured lysimeter ET. The comparison is quite good as the slope of the regression line was 0.93, intercept was 0.05 and R^2

was 0.95, mean bias error of 0.01 mm/h (1.1%), root mean square error of 0.04 mm/h (6.3%), index of agreement being 0.99 and Nash-Sutcliffe coefficient of efficiency being 0.95. Similarly Figure 4.42 shows the comparison of PM ET using conventional r_s with measured lysimeter ET. In this case, slope of the regression line was 1.09, intercept was - 0.08 and R^2 was 0.93. Hence the slope of the regression line was significantly different from one and also the intercept was significantly different from zero. The mean bias error was -0.02 mm/h (- 3.7%), root mean square error was 0.06 mm/h (9.7%), index of agreement was 0.97 and the Nash-Sutcliffe coefficient of efficiency was 0.88. It suggests that even the performance of conventional r_s was good, however, the performance of PM modeled ET was improved when using the hourly variable modeled r_s (as the MBE was dropped from -3.7% to 1.1%, root mean squared error dropped from 9.7% to 6.3% and also the improvement on index of agreement and Nash-Sutcliffe coefficient of efficiency was observed).

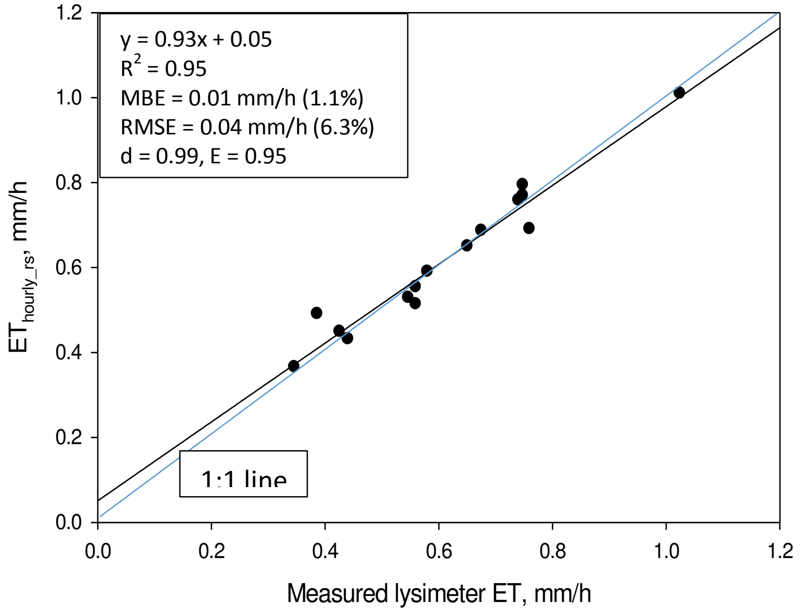

Figure 4.41: Comparison of PM ET using hourly modeled r_s with measured lysimeter alfalfa ET

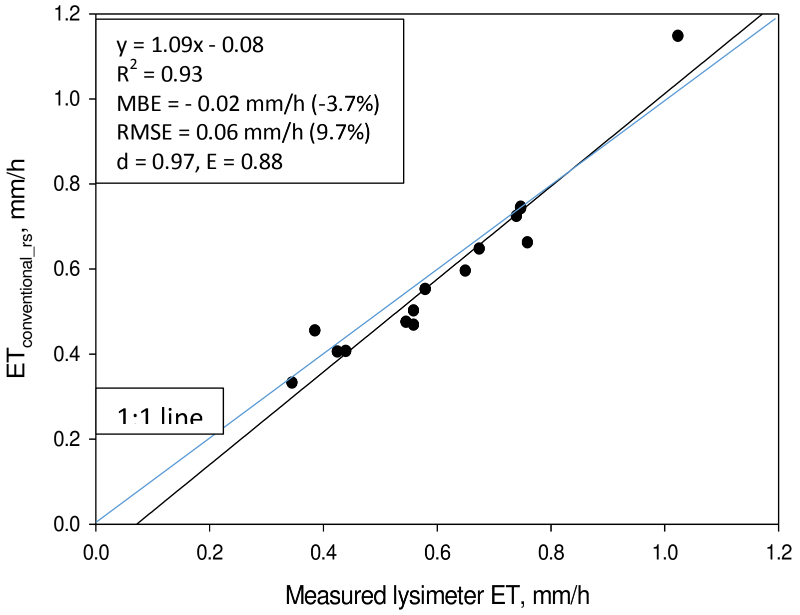

Figure 4.42: Comparison of PM ET using conventional r_s with measured lysimeter alfalfa ET

CONCLUSION

The surface resistance (r_s) for alfalfa crop could be estimated as a function of LAI or crop height (h_c). The alfalfa h_c data if not available, could be estimated using the information of days after harvest as shown in this study. Just after the alfalfa harvest, it was found that r_s was underestimated almost 10 times when the conventional r_s were used, which led to the overestimation of ET. Both sets of r_s models: r_s (LAI) or r_s (h_c) was found to be superior compared to the conventional r_s in estimating alfalfa ET. The RMSE dropped from 0.11 mm/h (20.3%) to 0.08 mm/h (13.7%) in 2009 and from 0.15 mm/h (25.1%) to 0.1 mm/h (15.8%) in 2010 when modeled r_s was used instead of the conventional r_s in the PM equation. However, mean bias error was zero in both years when even the conventional r_s was used, which was misleading. In fact, when the data was classified into 2 sets with crop height greater than and less than 25 cm, it was found that $ET_{conventional\_rs}$ overestimated excessively when $h_c < 25$ cm and underestimated when $h_c > 25$ cm. In 2009, for $h_c < 25$ cm, $ET_{conventional\_rs}$ overestimated measured ET by 20% and in 2010, the overestimation was 41.5%. Similarly, for $ET_{conventional\_rs}$, in 2009, when $h_c > 25$ cm, the underestimation of ET was 7% whereas in 2010, it was 8%. The performance improved when r_s (LAI) or r_s (h_c) was used resulting underestimation of 7% when $h_c < 25$ cm and 3% when $h_c > 25$ cm in 2009 whereas overestimation of 9% when $h_c < 25$ cm and underestimation of 2% when $h_c > 25$ cm in 2010. When larger datasets (including 2010, 2011 and 2012 data) were used, the RMSE dropped from 0.19 mm/h (28.8%) to 0.15 mm/h (22.3%) when modelled $r_{s\,(hc)}$ was used instead of the conventional rs.

The surface resistance (r_s) model as a function of LAI or h_c outputs constant r_s throughout the day, which was also able to improve the ET estimation compared to the conventional approach. As r_s in fact varies throughout the day, depending on the weather and biophysical variables, a better model would be the hourly variable model. Keeping that in mind, r_s was calibrated based on r_a, T_c and VPD. The PM ET_{hourly_rs} improved the ET estimation compared to the $ET_{conventional\_rs}$ as the MBE was dropped from – 3.7% to 1.1%, root mean squared error dropped from 9.7% to 6.3% and also the improvement on index of agreement and Nash-Sutcliffe coefficient of efficiency was observed.

The sensitivity analysis of PM equation to r_s was performed. It was found that when r_a was low (windy condition), PM ET was very sensitive to r_s. However, when r_a was large (calm condition), PM ET was not very sensitive to r_s. Hence from irrigation water management perspective, more energy should be invested to find r_s when r_a is low rather than high r_a condition.

The knowledge of r_s is important to estimate crop water requirement. The conventional r_s method didn't seem to work to estimate alfalfa ET rates especially when the crop height was small. The developed r_s (LAI) or r_s (h_c) as shown in this study will be a good tool for farmers or irrigation engineers to estimate alfalfa ET rates. If they have crop percent canopy cover data available, then the modeled hourly r_s could be used to better approximate the ET rates when the crop height is taller than 35 cm.

RECOMMENDATIONS

- It is recommended to use the r_s (LAI) or r_s (h_c) as shown in this study for hourly daytime ET calculation for alfalfa crop. The performance of r_s (LAI) or r_s (h_c) is quite superior compared to the conventional r_s in estimating alfalfa ET rates throughout the season.
- It is recommended to use the hourly variable r_s as modelled in this study for hourly daytime ET calculation for alfalfa crop. The use of the variable r_s, which is a function of the weather and biophysical variables (r_a, T_c and VPD), is capable of accommodating the change in the evaporative demand.
- Similar approach in modeling r_s could be implemented for other important crops to enable one-step ET estimation.
- The conventional r_s model needs to be improved especially for alfalfa crop height less than 25 cm, as the model showed larger error when alfalfa crop height was low.

LIMITATIONS

The hourly variable r_s model may not work when the crop height is less than 35 cm. The study is limited to the data from Southeastern Colorado, which is considered as a semiarid climate. Hence the user should be cautious before implementing the model in other climatic conditions.

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CHAPTER 5

Effective daytime surface resistance (r_s) value for alfalfa reference crop in Southeast Colorado

Overview

The knowledge of surface resistance (r_s) of crops plays an important role in accurate evapotranspiration (ET) estimation using the Penman-Monteith (PM) model. In the ASCE Standardized PM equation, the value of r_s has been fixed as 30 s/m for alfalfa reference crop for hourly daytime calculation. The parameter C_d in the equation, which was based on r_s, has been standardized as 0.25 for hourly daytime calculation for alfalfa reference crop. This study found that using the recommended value of r_s as 30 s/m underestimated ET by approximately 10 percent in both 2009 and 2010 when compared with the measured alfalfa reference ET from a precision weighing lysimeter. The r_s value of 10 s/m was found to yield the best PM ET rates when compared with lysimeter data. In 2009, when $r_s = 30$ s/m was used, RMSE of 0.08 mm/h (15.3%) and MBE of -0.05 mm/h (- 9.9%) was observed. Instead, when $r_s = 10$ s/m was used, then RMSE of 0.06 mm/h (11.4 %) and MBE of zero was observed. Similarly in 2010, when $r_s = 30$ s/m was used, RMSE of 0.09 mm/h (14.1%) and MBE of -0.06 mm/h (- 9.6%) was found. Again when $r_s = 10$ s/m was used, then RMSE of 0.06 mm/h (10.1%) and zero MBE was found. The surface resistance of 10 s/m corresponds to the C_d value of 0.09 for hourly calculation. Hence it is recommended to use the value of C_d as 0.09 instead of the ASCE recommended 0.25 to find the alfalfa hourly ET rates for the semiarid climatic condition in southeast Colorado. This finding is also expected to produce more realistic K_{cr} curves (crop coefficients based on alfalfa reference crop) of important field crops for similar climatic conditions.

INTRODUCTION

Accurate quantification of irrigation water requirement is crucial for agricultural water management. Crop evapotranspiration (ET), or consumptive water use, is the primary component of the irrigation water requirement. The most commonly used method to estimate crop ET is first to calculate reference crop ET and then multiply it with the appropriate crop coefficients (K_c). Hence the accuracy in obtaining reference crop ET and the use of K_c both have impact on accurate estimation of crop ET or irrigation water requirement in general. This study is focused on the reference crop ET estimation.

Allen et al. (2005) recommends either grass (short crop) or alfalfa (tall crop) to be a reference crop. The recommended height for grass is 12 cm and alfalfa is 50 cm. In order to be in reference condition, the reference crop needs to be well watered, healthy, actively growing and representing an expanse of at least 100 m of the same or similar vegetation. The value of surface resistance (r_s) recommended by the ASCE Standardized equation for hourly daytime data use for the alfalfa crop is 30 s/m and for nighttime hourly data is 200 s/m. Several researchers have reported that PM equation underestimates measured ET in arid and semiarid climates (Rana et. al., 1994; Steduto et. al., 1996; Pereira et. al., 1999; Todorovic, 1999; Ventura et. al., 1999; Sellers, 1965; Lecina et. al., 2002; Lascano and van Bavel, 2007). It may be possible that the recommended value of surface resistance to calculate alfalfa reference ET is not representative (Lascano et al., 2010; Evett et al., 2012). Subedi et al. (2016) recommended adjusting the value of r_s used in the ASCE Standardized equation for the arid and semiarid condition. During daytime, r_s plays a significant role in ET estimation, hence, accurate value of r_s must be chosen. However, during nighttime, as ET rate is small, r_s doesn't play a significant role in ET estimation. Hence this study is only focused on daytime data. It is very important to assess if the recommended daytime surface resistance of 30 s/m is reasonable for the semiarid climatic conditions in Colorado. This study is also intended to find the effective value of r_s for alfalfa to obtain the PM equation ET rates which best agree with the lysimeter measured ET rates for alfalfa reference crop.

MATERIALS AND METHODS

This study was conducted at the Colorado State University (CSU) Arkansas Valley Research Center (AVRC) near Rocky Ford, Colorado. Details of the lysimeter instrumentation used for this research have already been provided in the previous chapter. Data from 2009 and 2010 was used for this study. Data was selected when the crop height was close to 50 cm (more specifically from 45 to 55 cm) and when there was no soil water stress to satisfy the assumptions of the ASCE Standardized equation. Data from the second, third and fourth alfalfa cutting cycles were included in both the years. First cutting cycle data was excluded as it was not representative of other cutting cycles. Previous studies have shown that in the first cutting cycle, unlike in other cutting cycles, the ET rates measured from lysimeter are lower compared to the PM equation even in the reference condition (Subedi et al., 2016; Gleason, 2013). Data from June 25th to September 29th (6/25 to 6/27, 8/1 to 8/4, 9/17 to 9/29) were included in 2009 and data from June 20th to October 13th (6/20 to 6/24, 8/2 to 8/22 and 9/17 to 10/13) were included for 2010. Only the daytime data (from 9 a.m. to 6 p.m.) were included as the objective was to assess the surface resistance for the daytime condition.

Equation (5.1) is the full version Penman-Monteith (PM) equation which is based on a big leaf model, that is, whole plant canopy is considered as a big leaf.

$$\lambda ET = \frac{\left(\Delta(R_n - G) + \rho C_p(e_s - e_a)/r_a\right)}{\Delta + \gamma(1 + r_s/r_a)} \tag{5.1}$$

where,

λET = latent heat flux (W/m^2)

Δ = slope of saturation vapor pressure-temperature curve (kPa/°K)

R_n = calculated net radiation at the crop surface (W/m^2)

G = soil heat flux density at the soil surface (W/m^2)

ρ = air density (kg/m^3)

C_p = specific heat capacity of air at constant pressure, J/kg/°K

e_s = saturation vapor pressure, kPa

e_a = actual vapor pressure, kPa

r_a = aerodynamic resistance, s/m

γ = psychrometric constant, kPa/°K

r_s = bulk surface resistance, s/m

Equation (5.1) can be converted into equation (5.2) to obtain the desired ET rates in mm per hour or mm per day.

$$ET = \frac{\left(\Delta(R_n - G) + \rho C_p(e_s - e_a)/r_a\right)}{(\Delta + \gamma\left(1 + \frac{r_s}{r_a}\right))(\rho_w \times \lambda \times D)} \tag{5.2}$$

where ρ_w is the density of water in kg/m^3, λ is the latent heat of evaporation in J/kg and D is the conversion coefficient. For hourly calculation, D equals $(3.6\times10^6)^{-1}$ and for daily calculation, D equals $(86.4 \times 10^6)^{-1}$. ASCE Standardized equation has adopted a fixed value of λ for reference condition, which is 2.45 MJ/kg.

Direct implementation of equation (5.2) to calculate crop ET is not easy as it is difficult to obtain r_s for different crops. In soil water stress conditions, the direct implementation of equation (5.2) to calculate ET is even more challenging as r_s becomes highly variable. To address these problems, Allen et al. (2005) recommended using ASCE Standardized equation, which was based on full-version PM equation to first calculate reference crop ET and then use suitable crop coefficients to estimate non-stressed crop ET. In FAO 56 paper, Allen et al. (1998) has published crop coefficient (K_c) values for various field crops based on grass reference and also developed a method to calculate actual crop ET under soil water stress conditions using a water stress coefficient (K_s). Equation (5.3) is the ASCE Standardized equation which is applicable for both grass and alfalfa reference crops.

$$ETsz = \frac{0.408\,\Delta\,(R_n - G) + \,\gamma\,C_n\,u_2\,\frac{e_s - e_a}{T_a + 273}}{\Delta + \gamma(1 + C_d\,u_2)} \tag{5.3}$$

where,

ET_{sz} = standardized reference crop evapotranspiration for short crop (grass) (ET_{os}) or tall crop (alfalfa) (ET_{rs}) surfaces, mm/h

R_n = calculated net radiation at the crop surface, $MJ/m^2/h$

G = soil heat flux density at the soil surface, $MJ/m^2/h$

T_a = air temperature, °C

U_2 = wind speed at 2 m height, m/s

C_n = numerator constant, which is 66 for hourly alfalfa ET

C_d = denominator constant, which is 0.25 for hourly alfalfa ET

Neutral atmospheric condition has been assumed for reference condition. In the reference condition, heat exchange is small, and therefore stability correction is normally not required (Allen et al., 1998). Equation (5.4) was used to calculate the aerodynamic resistance (r_a) (Thom, 1975) while deriving the ASCE Standardized equation (Allen et al., 2005).

$$r_a = \frac{\ln((z_m - d)/z_{om})\ln((z_h - d)/z_{oh})}{k^2 u_z} \tag{5.4}$$

where,

z_m = height of wind measurement (m),

z_h = height of humidity measurement (m),

z_{om} = roughness length governing momentum transfer, which is estimated to be 0.123 h_c, where h_c is the crop height (m),

z_{oh} = roughness length governing heat transfer, which is estimated to be 0.0123 h_c (m),

d = zero plane displacement height, which is estimated to be 0.67 h_c (m),

k = von Karman's constant, which is approximately 0.41,

u_z = wind speed at height z (m/s).

In this study, all the input variables were calculated as recommended in the ASCE Standardized handbook. Then equation (5.2) was used to obtain alfalfa ET rates in mm/h. The ET rates were then compared with the measured lysimeter ET rates. Different r_s values with r_s = 0, 1, 2, 3,…………30 s/m were used. For all the r_s values, statistical indicators like root mean square error (RMSE), mean bias error (MBE) and coefficient of determination (R^2) were used. Then the effective r_s value, that resulted in reference ET values that agreed best with the measured lysimeter ET was selected for the studied years.

Evaluation Criteria

Several performance indicators were used to evaluate the PM model with different r_s values by comparing it with the measured ET rates from the weighing lysimeter. Hourly measured ET data was used for the evaluation process. The performance indicators that have been used are as follows:

Slope and y-intercept: The slope and y-intercept of the best-fit regression line can indicate how well simulated data matched measured data (Moriasi et al., 2007). A slope of 1 and y-intercept of zero indicate that the model perfectly reproduces the magnitudes and measured data (Wilmott, 1982). The slope and y-intercept are commonly examined under the assumption that measured and simulated values are linearly related, which implies that all of the error variance is contained in simulated values and that measured data are error free (Wilmott, 1982).

Co-efficient of determination (R^2): This is a measure of the proportion of variance in measured data that is explained by a model. It allows one to determine the certainty of making a prediction from a model. It ranges between 0 and 1, with a value of 1 being the optimal. Mathematically, R^2 is obtained by using equation (5.5).

$$R^2 = \frac{(\sum_{i=1}^{n}(O_i - \overline{O})^2(M_i - \overline{M}))^2}{\sum_{i=1}^{n}\left(O_i - \overline{O}\right)^2 \sum_{i=1}^{n}\left(M_i - \overline{M}\right)^2} \tag{5.5}$$

where, O is the observed or measured (lysimeter in this case) and M is the predicted or derived (ET equation with different r_s in this case) value. The bars above the variables indicate mean value.

Mean Bias Error (MBE): This indicator is usually used to calculate the mean model bias or mean over or under prediction. MBE is obtained by averaging the difference between predicted and measured values. Positive values indicate model over-estimation bias, and negative values indicate model under-estimation bias (Willmott, 1982), and zero indicate that there is no bias.

$$MBE = \frac{1}{n}\sum_{i=1}^{n}(M_i - O_i) \tag{5.6}$$

Percentage Mean Bias Error (%MBE): This indicator is same as mean biased error, except it is expressed in percentage. It is clearer by expressing some errors in percentage than in the absolute terms. It is calculated by dividing the MBE with the average measured values and then multiplying by 100.

$$\%MBE = \frac{MBE}{\frac{1}{n}\sum O_i} \times 100 \tag{5.7}$$

Root Mean Squared Error (RMSE): This is a commonly used error index statistic. A smaller RMSE value indicates a smaller error spread and variance and therefore a better model performance. It measures the magnitude of the spread of errors. It is calculated by squaring the differences between predicted and measured values, then averaging them and finally taking the square root of the average.

$$RMSE = \sqrt{\frac{1}{n}\sum_{i=1}^{n}(M_i - O_i)^2} \tag{5.8}$$

Percentage Root Mean Squared Error (%RMSE): This indicator is also the percentage expression for root mean squared error. Like %MBE, this indicator is also calculated by dividing RMSE with the average measured values and then multiplying by 100 (Lei, 1998).

$$\%RMSE = \frac{RMSE}{\frac{1}{n}\sum O_i} \times 100 \tag{5.9}$$

RESULTS AND DISCUSSION

All of the variables in equation (5.1) were calculated as recommended in the ASCE Standardized equation for tall reference crop (alfalfa). Since only the daytime data was used, the value of r_s used for the reference condition was 30 s/m as recommended by the equation. Figure 5.3 shows the comparison of ASCE Standardized ET with measured lysimeter ET in 2009 and Figure 5.4 shows the comparison in 2010. In both the years, it is evident that the equation underestimated ET by approximately 10 per cent.

The objective of this chapter was to find the optimum value of r_s which better agrees with lysimeter ET. In Table 5.1, data from 2009 was used. Since there was underestimation from equation, lower r_s values would justify more reasonable ET estimation. Hence the values used for r_s were chosen from 0 to 30 s/m. Zero surface resistance would indicate that the canopy is basically in wet condition (Monteith, 1981). The optimum r_s would result in lowest root mean square error, lowest mean bias error and high R square. From Table 5.1 and Figure 5.1, it can be observed that the optimum r_s is somewhere around 10 s/m as RMSE was 0.06 mm/h (11.4 %) and MBE was zero with high R^2 (0.95). When r_s of 30 s/m was used as recommended in ASCE Standardized equation, RMSE was 0.08 mm/h (15.3%) and MBE was -0.05 mm/h (- 9.9%).

Similarly, in Table 5.2 and Figure 5.2, data from 2010 was used. In 2010 also, the optimum r_s was somewhere around 10 s/m as RMSE was 0.06 mm/h (10.1%) and MBE was zero with R^2 (0.95) close to one. When r_s of 30 s/m was used as recommended by the ASCE Standardized equation, RMSE was 0.09 mm/h (14.1%) and MBE was -0.06 mm/h (- 9.6%).

In both the studied years, r_s of 10 s/m agreed better with lysimeter ET compared to the ASCE recommended r_s of 30 s/m for alfalfa reference crop. Figure 5.5 and 5.6 shows the comparison of PM ET (with r_s of 10 s/m) with the measured lysimeter ET in 2009 and 2010 respectively. It can be observed that most of the points in Figures 5.5 and 5.6 followed more closely to the 1:1 line compared to Figures 5.3 and 5.4.

In the ASCE Standardized equation (Eq. 5.2), constant C_d in the denominator accounts for the surface resistance (r_s). In fact, C_d stands for the term $\{r_s / (r_a \times u_2)\}$, where u_2 is the wind speed measured at 2 m height. For alfalfa, r_a equals approximately $\{110 / u_2\}$ by using equation (5.4) for the reference crop height (that is, 50 cm) (See Appendix for the calculation). Hence, C_d should equal r_s / 110. From this study, r_s of 10 s/m resulted in better performance in ET estimation, the corresponding C_d should then be equal to 10/110 or 0.09. In other words to calculate the hourly alfalfa reference crop ET for the semiarid climatic condition like Colorado, the recommended value of C_d should be 0.09 instead of 0.25 as suggested by Allen et al. (2005).

Al Wahaibi (2011) in his PhD dissertation showed that the crop coefficient for alfalfa (K_{cr}), with alfalfa reference crop frequently exceeded 1.2, sometimes even exceeding 1.3. Crop coefficient is the ratio of actual crop ET (measured by the lysimeter) to the reference crop ET (calculated using the ASCE Standardized equation for tall reference crop). The upper limit of K_{cr} for alfalfa should be around one. It might go up to 1.1 in cases when the alfalfa height is significantly taller than the standardized alfalfa reference crop height of 50 cm. However, it is a concern when the K_{cr} value reaches 1.3. The correction in the value of C_d in the ASCE Standardized equation as shown by this study will help to lower the value of K_{cr} and to develop more realistic K_{cr} curves for important field crops.

Table 5.1: Statistical indicators for different r_s values in 2009

r_s	RMSE	MBE	Slope, intercept	R^2
0	0.07 (13.7%)	0.02 (4.2%)	0.92, 0.07	0.92
1	0.07 (13.3%)	0.02 (3.6%)	0.92, 0.06	0.93
2	0.07 (12.9%)	0.02 (3.0%)	0.91, 0.06	0.93
3	0.07 (12.6%)	0.01 (2.5%)	0.91, 0.06	0.93
4	0.07 (12.3%)	0.01 (1.9%)	0.91, 0.06	0.94
5	0.07 (12.0%)	0.01 (1.4%)	0.91, 0.06	0.94
6	0.06 (11.8%)	0 (0.9%)	0.90, 0.06	0.94
7	0.06 (11.7%)	0 (0.4%)	0.90, 0.06	0.94
8	0.06 (11.5%)	0 (-0.2%)	0.90, 0.06	0.94
9	0.06 (11.5%)	0 (-0.7%)	0.89, 0.05	0.94
10	**0.06 (11.4%)**	**0 (-1.2%)**	**0.89, 0.05**	**0.95**
11	0.06 (11.4%)	-0.01 (-1.7%)	0.89, 0.05	0.95
12	0.06 (11.4%)	-0.01 (-2.1%)	0.89, 0.05	0.95
13	0.06 (11.5%)	-0.01 (-2.6%)	0.88, 0.05	0.95
14	0.06 (11.5%)	-0.02 (-3.1%)	0.88, 0.05	0.95
15	0.06 (11.5%)	-0.02 (-3.6%)	0.88, 0.05	0.95
20	0.07 (12.5%)	-0.03 (-5.8%)	0.86, 0.04	0.95
25	0.07 (13.8%)	-0.04 (-7.9%)	0.85, 0.04	0.95
30	0.08 (15.3%)	-0.05 (-9.9%)	0.84, 0.03	0.95

Table 5.2: Statistical indicators for different r_s values in 2010

r_s	RMSE	MBE	Slope, intercept	R^2
0	0.08 (13.0%)	0.04 (6.4%)	1, 0.04	0.93
1	0.08 (12.6%)	0.04 (5.7%)	0.99, 0.04	0.93
2	0.08 (12.1%)	0.03 (5.1%)	0.98, 0.04	0.94
3	0.07 (11.7%)	0.03 (4.4%)	0.98, 0.04	0.94
4	0.07 (11.4%)	0.02 (3.8%)	0.97, 0.04	0.94
5	0.07 (11.0%)	0.02 (3.2%)	0.97, 0.04	0.94
6	0.07 (10.8%)	0.02 (2.6%)	0.96, 0.04	0.94
7	0.07 (10.5%)	0.01 (2.0%)	0.95, 0.04	0.94
8	0.06 (10.3%)	0.01 (1.4%)	0.95, 0.04	0.95
9	0.06 (10.2%)	0 (0.8%)	0.94, 0.04	0.95
10	**0.06 (10.1%)**	**0 (0.2%)**	**0.94, 0.04**	**0.95**
11	0.06 (10.0%)	0 (-0.4%)	0.93, 0.04	0.95
12	0.06 (9.9%)	-0.01 (-0.9%)	0.93, 0.04	0.95
13	0.06 (10.0%)	-0.01 (-1.5%)	0.92, 0.04	0.95
14	0.06 (10.1%)	-0.01 (-2.0%)	0.92, 0.04	0.95
15	0.06 (10.2%)	-0.02 (-2.5%)	0.91, 0.04	0.95
20	0.07 (11.0%)	-0.03 (-5.0%)	0.89, 0.04	0.95
25	0.07 (12.4%)	-0.05 (-7.4%)	0.87, 0.04	0.95
30	0.09 (14.1%)	-0.06 (-9.6%)	0.84, 0.04	0.95

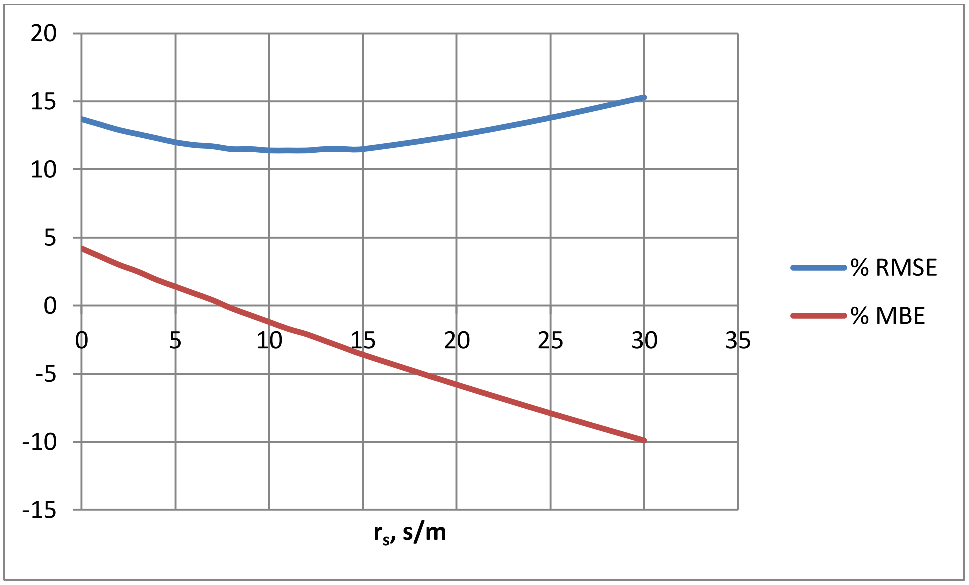

Figure 5.1: Percentage RMSE and MBE for different r_s values in 2009

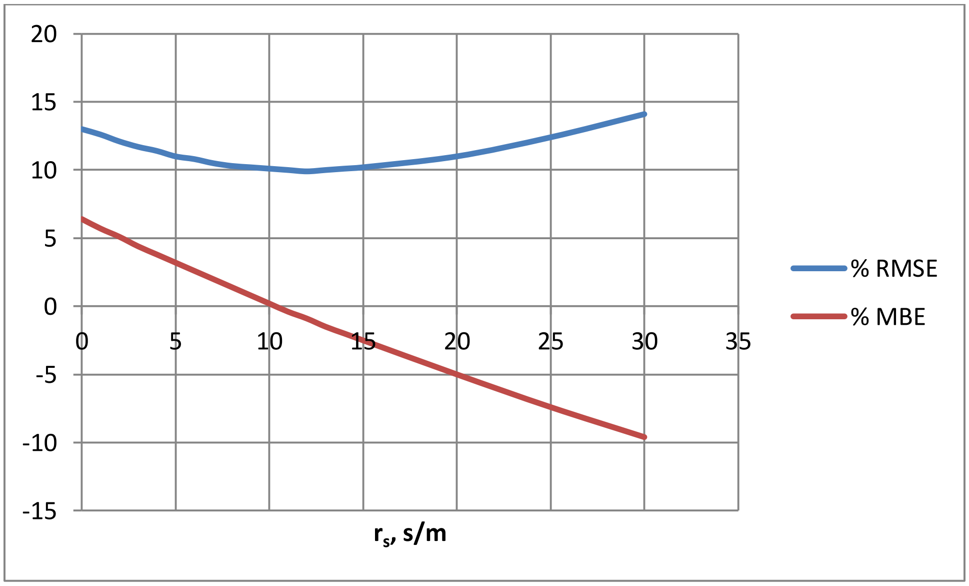

Figure 5.2: Percentage RMSE and MBE for different r_s values in 2010

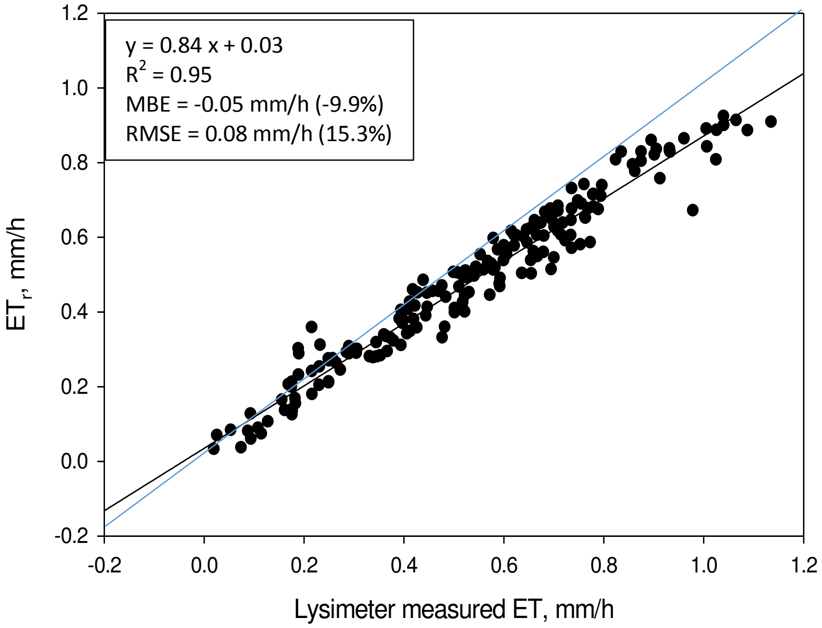

Figure 5.3: Comparison of PM equation ET (using r_s = 30 s/m) with measured lysimeter ET in 2009

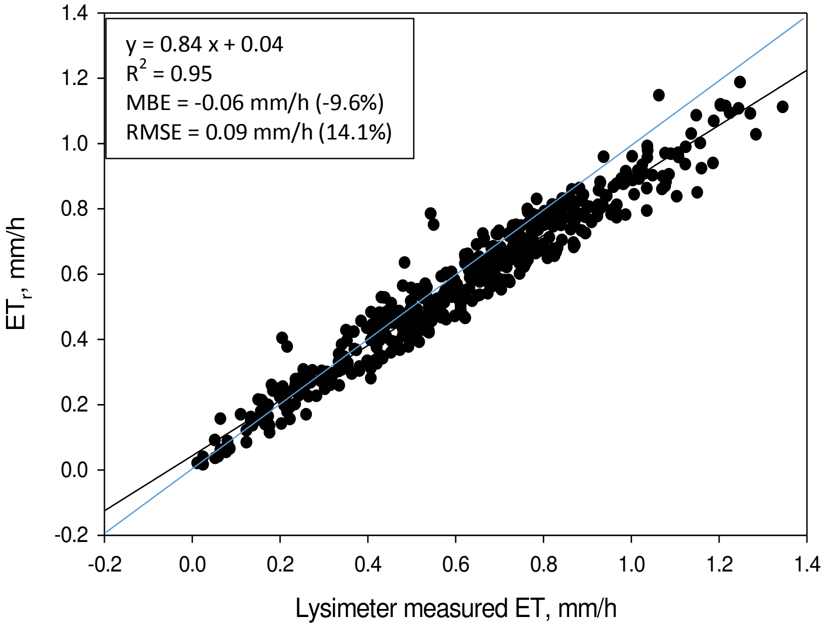

Figure 5.4: Comparison of PM equation ET (using r_s = 30 s/m) with measured lysimeter ET in 2010

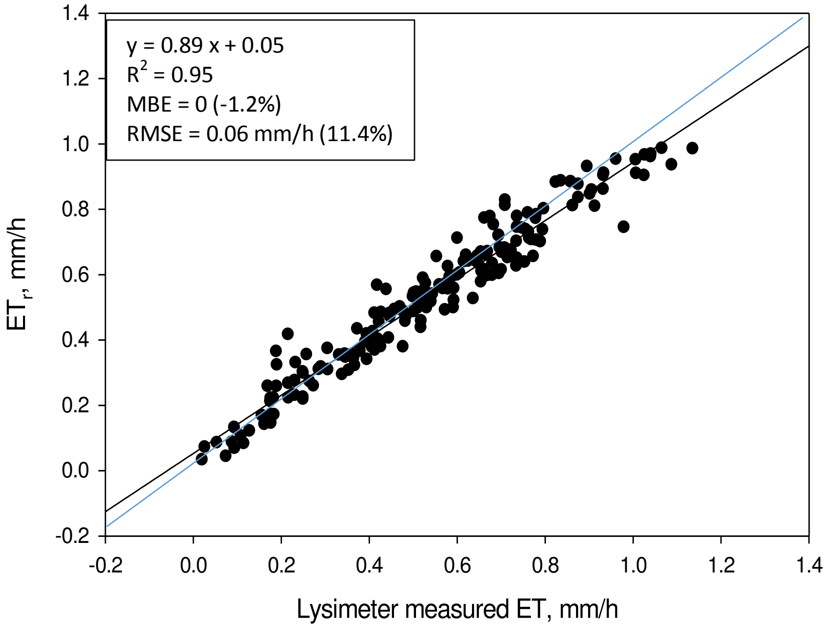

Figure 5.5: Comparison of PM equation ET (using r_s = 10 s/m) with measured lysimeter ET in 2009

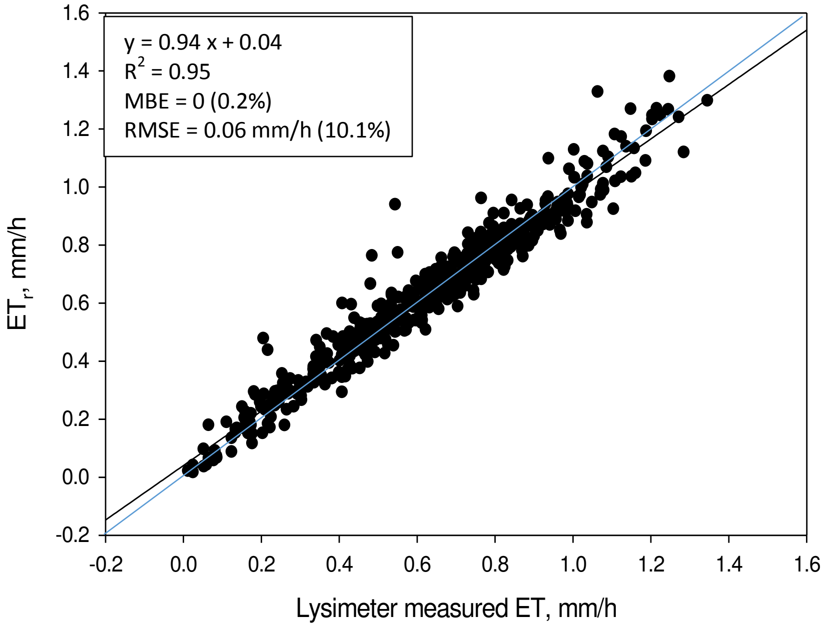

Figure 5.6: Comparison of PM equation ET (using r_s = 10 s/m) with measured lysimeter ET in 2010

CONCLUSION

ASCE recommended value for daytime surface resistance for tall reference crop (which is 30 s/m) yielded lower reference ET when compared with the measured lysimeter ET. On the other hand, the optimum value of r_s that minimized differences between calculated and lysimeter alfalfa reference ET was found to be around 10 s/m. The performance of the equation improved when r_s of 10 s/m was used instead of the recommended 30 s/m. In 2009, when r_s = 30 s/m was used, RMSE of 0.08 mm/h (15.3%) and MBE of -0.05 mm/h (- 9.9%) was observed. Instead, when r_s = 10 s/m was used, then RMSE of 11.4 % and MBE of zero was observed. Similarly in 2010, when r_s = 30 s/m was used, RMSE of 0.09 mm/h (14.1%) and MBE of -0.06 mm/h (-9.6%) was observed. Again when r_s = 10 s/m was used, then RMSE of 0.06 mm/h (10.1%) and zero MBE was observed.

Since C_d in the ASCE Standardized equation includes the assumed value of r_s, the value of C_d in the equation for tall reference crop (alfalfa) should be 0.09 (which corresponds to r_s of 10 s/m) instead of 0.25 (which corresponds to ASCE recommended r_s of 30 s/m) for the semiarid climate in southeast Colorado.

RECOMMENDATIONS

The value of C_d for the tall reference crop (alfalfa) ET for hourly data was found to be 0.09 for the semiarid condition as in Colorado. Hence it is recommended to use this value instead of the ASCE recommended value of 0.25 for the semiarid condition in southeast Colorado to better predict alfalfa reference crop ET. It is also recommended to assess the value of C_d for tall reference crop (alfalfa) in other climatic conditions and for short reference crop (clipped grass) in different climatic conditions.

LIMITATIONS

This study was based on the data from Southeastern Colorado (which is considered as semiarid climate). Hence the result may not be applicable to other climatic conditions especially in humid and sub humid conditions.

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CHAPTER 6

Conclusion and Recommendations

CONCLUSION

The overall objectives of this dissertation were to model surface resistance for alfalfa reference crop and to find an effective value of the surface resistance of alfalfa in the ASCE Standardized Reference ET equation. The specific objectives were as follows:

- To explore different ET estimation methods to date and find a gap in the existing methods (Chapter 2)
- To compare lysimeter measured ET with ET measured using micrometeorological methods; to find under what conditions these measured ET can be very different (Chapter 3)
- To model surface resistance for alfalfa reference crop and investigate if the modeled r_s performed better compared to the conventional approach (Chapter 4)
- To find an effective value of r_s for alfalfa and recommend the value of C_d in the ASCE Standardized Reference ET equation for the tall reference crop (Chapter 5)

Based on this dissertation work, the following conclusions can be drawn:

- Lysimeter ET can be representative of the field ET if the field is uniform in soil moisture and crop biomass.

- Lysimeter ET cannot be representative of the field ET if the field is heterogeneous, or in other words, if there is large spatial differences in soil moisture and crop biomass in the field.
- A cubic equation for surface resistance (r_s) as a function of LAI and a fifth order polynomial equation for r_s as a function of crop height (h_c) were developed. If the alfalfa h_c data was not available, a simple procedure to calculate h_c based on days after harvest (DAH) was developed. The full-version PM equation (Monteith, 1965) was then used to implement the modeled r_s. It was found that PM equation using the modeled r_s worked better than the PM equation using the conventional r_s. Using this approach, r_s doesn't change throughout the day, however it changes throughout the season as it is a function of LAI or h_c. The modeled $r_{s\,(LAI)}$ or $r_{s\,(hc)}$ significantly improved the alfalfa ET estimation when the crop height was less than 25 cm and slightly improved the ET estimation when the crop height was larger than 25 cm when compared to the conventional r_s approach.
- Hourly variable r_s was also developed using weather and biophysical variables. A multiple regression was used to calibrate r_s using aerodynamic resistance (r_a), canopy temperature (T_c) and vapor pressure deficit (VPD). It was found that PM equation using hourly variable r_s values were closer to the measured lysimeter ET when compared to the PM equation using the conventional r_s. Sensitivity analysis of PM equation to r_s revealed that the equation is more sensitive to r_s when r_a is low (windy condition) and vice-versa.
- ASCE-EWRI Standardized PM Equation for tall reference crop underestimated measured lysimeter ET by about 10 per cent in both 2009 and 2010. However, when the value of alfalfa daytime hourly r_s was changed from the standardized 30 s/m to 10 s/m, there was no bias using the equation and also the root mean square error dropped

considerably. Hence the parameter C_d used in the equation, which is a surrogate for term r_s, should be changed from the recommended 0.25 to 0.09 for the semi-arid conditions in southeast Colorado.

RECOMMENDATIONS

The following recommendations are given based on this research:

- In order to make lysimeter ET representative of the field ET, uniform irrigation to the whole field is recommended. This can be effectively done by using drip or sprinkler irrigation instead of furrow irrigation. It is also necessary to have the uniform crop height and density both inside and outside the lysimeter.
- While developing the crop coefficient (K_c), it is recommended to maintain the homogeneous surface condition in the lysimeter field. It is also recommended only to use good year data (when most of the times there is homogeneous surface condition inside and outside the lysimeter) to develop the K_c for a particular crop.
- The daily/hourly r_s models improved the ET estimation for alfalfa. Hence it is recommended to use these r_s models instead of the conventional model to find alfalfa water requirement.
- It is also recommended to test the performance of the models in other climatic conditions, particularly humid and sub-humid.
- It is recommended to change the value of C_d in the ASCE Standardized equation for tall reference crop from recommended 0.25 to 0.09 to better simulate the measured ET for similar semi-arid climatic conditions like southeast Colorado.

APPENDICES

Appendix A1: Shuttleworth Model

Shuttleworth (2006) developed an equation for crop coefficient (K_c) which is as follows:

$$K_c = \left[\frac{\frac{R_c^{50}}{u_2} + \frac{D_{50}}{D_2} r_{clim}}{\frac{302}{u_2} + \frac{D_{50}}{D_2} r_{clim}}\right]\left[\frac{(\Delta + \gamma)\frac{302}{u_2} + 70\gamma}{(\Delta + \gamma)\frac{R_c^{50}}{u_2} + \gamma(r_s)_c}\right] \qquad (1)$$

where,

R_c^{50} = aerodynamic coefficient for a crop of height h_c at blending height of 50 m,

U2 = wind speed at 2 m height,

D50 = vapor pressure deficit at blending height of 50 m (kPa),

D2 = vapor pressure deficit at 2 m height (kPa),

r_{clim} = climatological resistance = $\frac{\rho c_p D}{\Delta(R_n - G)}$ (s/m)

$(r_s)_c$ = surface resistance of crop (s/m)

The equation to calculate R_c^{50} in equation (1) is given by:

$${R_c}^{50} = \frac{1}{(0.41)^2} ln\left[\frac{(50 - 0.67h_c}{(0.123h_c)}\right] ln\left[\frac{(50 - 0.67h_c}{(0.0123h_c)}\right] \frac{ln\left[\frac{(2 - 0.08)}{0.0148}\right]}{ln\left[\frac{(50 - 0.08)}{0.0148}\right]} \qquad (2)$$

The equation to calculate r_{clim} in equation (1) is given by:

$$r_{clim} = \frac{208}{u_2}\left[\frac{\alpha[\Delta + \gamma(1 + 0.337u_2)]}{\Delta + \gamma}\right] - 1 \qquad (3)$$

where, α is the Priestley – Taylor coefficient, which is equal to 1.26.

The equation to calculate $\left(\frac{D_{50}}{D_2}\right)$ in equation (1) is given by:

$$\left(\frac{D_{50}}{D_2}\right) = \left[\frac{(\Delta+\gamma)302 + 70\gamma u_2}{(\Delta+\gamma)208 + 70\gamma u_2}\right] + \frac{1}{r_{clim}}\left\{\left[\frac{(\Delta+\gamma)302 + 70\gamma u_2}{(\Delta+\gamma)208 + 70\gamma u_2}\right]\left[\frac{208}{u_2}\right] - \frac{302}{u_2}\right\} \quad (4)$$

The equation to calculate surface resistance $(r_s)_c$, according to Shuttleworth is given by:

$$(r_s)_c = \frac{{r_s}^1}{{K_c}^{FAO}} - {r_s}^2 \quad (5)$$

Where, K_c^{FAO} is the different Kc values of different crops published in FAO 56 document, r_s^1 and r_s^2 are given by:

$$ {r_s}^1 = \left(\frac{\frac{R_c^{50}}{u_2} + \left(\frac{D_{50}}{D_2}\right)^{pref}(r_{clim})^{pref}}{\frac{302}{u_2} + \left(\frac{D_{50}}{D_2}\right)^{pref}(r_{clim})^{pref}}\right) \times \left(\frac{(\Delta^{pref}+\gamma)\frac{302}{u_2} + 70\gamma}{\gamma}\right) \quad (6)$$

$$ {r_s}^2 = \frac{(\Delta^{pref}+\gamma)}{\gamma}\frac{R_c^{50}}{u_2} \quad (7)$$

Where, Δ^{pref} is the value of Δ calculated at temperature T^{pref} (kPa/°C), T^{pref} being the air temperature when the value of K_c^{FAO} was derived (°C)

and $\left(\frac{D_{50}}{D_2}\right)^{pref}$ is the value of $\left(\frac{D_{50}}{D_2}\right)$at T^{pref}

$(r_{clim})^{pref}$ can be obtained from equation (3) as:

$$(r_{clim})^{pref} = 104\left[1.26\frac{[\Delta^{pref} + 1.67\gamma]}{\Delta^{pref}+\gamma}\right] - 1 \quad (8)$$

Appendix A2: Figures showing alfalfa condition in selected days

Figure A1: Nadir photo of the lysimeter surface taken on 7/26/2010 (h_c = 0.36 m, CC = 70.8%) (Picture courtesy: Dr. Allan Andales and Lane Simmons)

Figure A2: Nadir photo of the lysimeter surface taken on 8/4/2010 (h_c = 0.48 m, CC = 85.9%)
(Picture courtesy: Dr. Allan Andales and Lane Simmons)

Figure A3: Nadir photo of the lysimeter surface taken on 8/18/2010 (h_c = 0.52 m, CC = 80.8%)
(Picture courtesy: Dr. Allan Andales and Lane Simmons)

Figure A4: Nadir photo of the lysimeter surface taken on 9/13/2010 (h_c = 0.39 m, CC = 76.2%)
(Picture courtesy: Dr. Allan Andales and Lane Simmons)

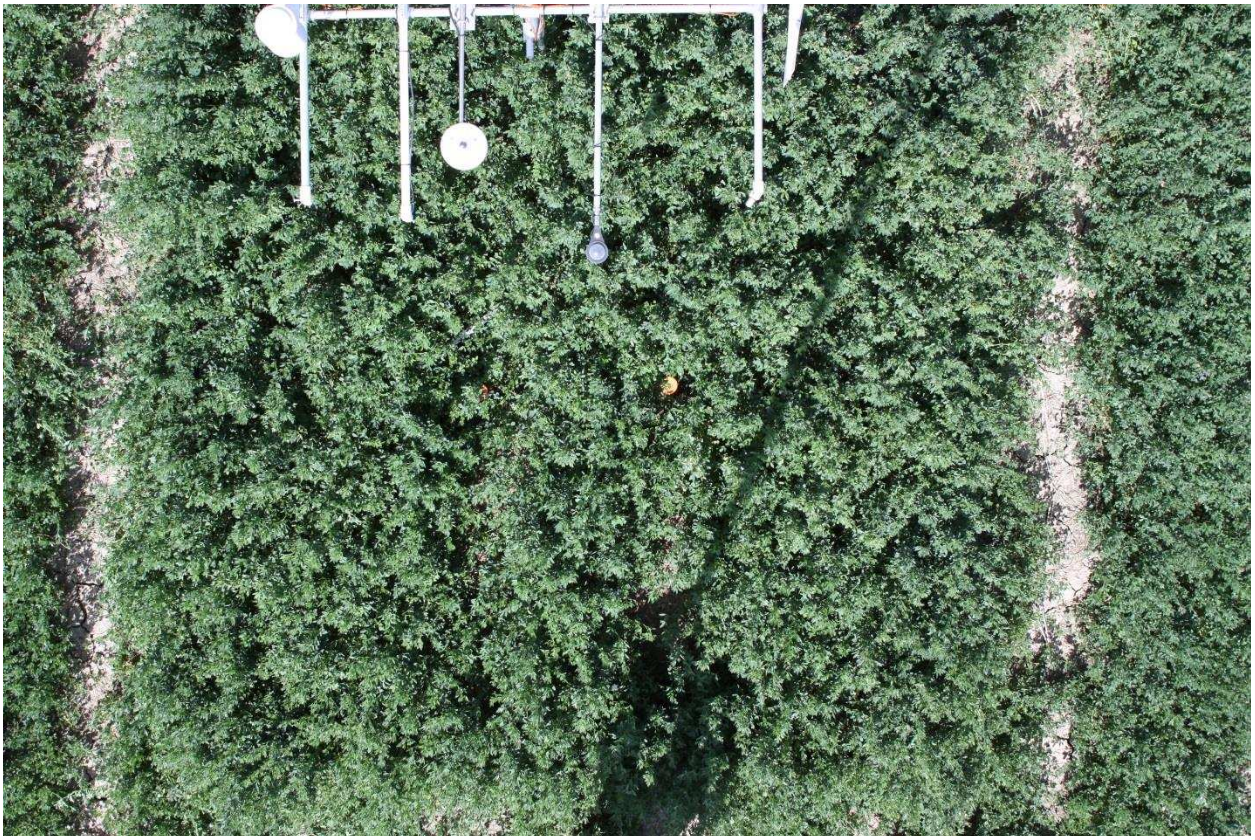

Figure A5: Nadir photo of the lysimeter surface taken on 9/27/2010 (h_c = 0.51 m, CC = 72.3%)
(Picture courtesy: Dr. Allan Andales and Lane Simmons)

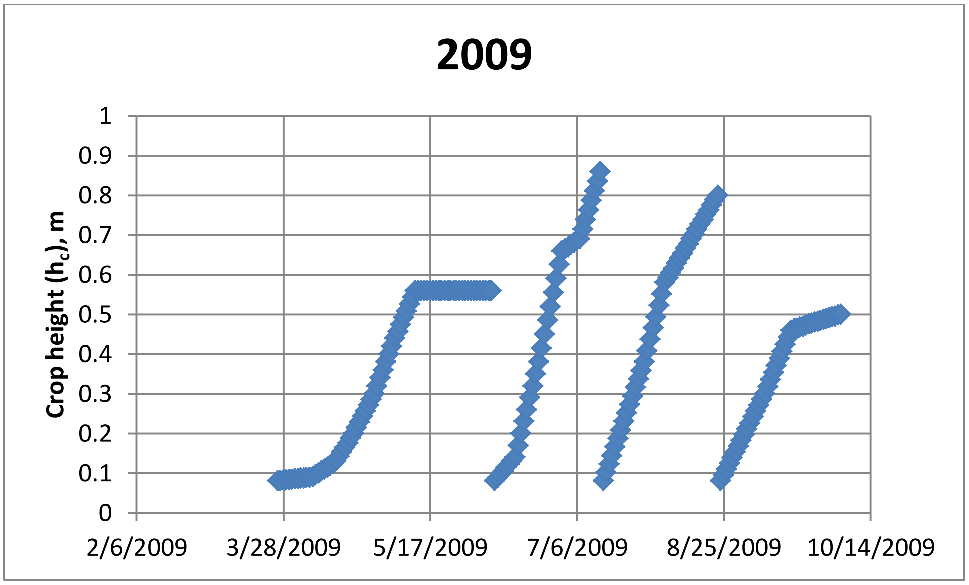

Figure A6: Time series of crop height data in 2009

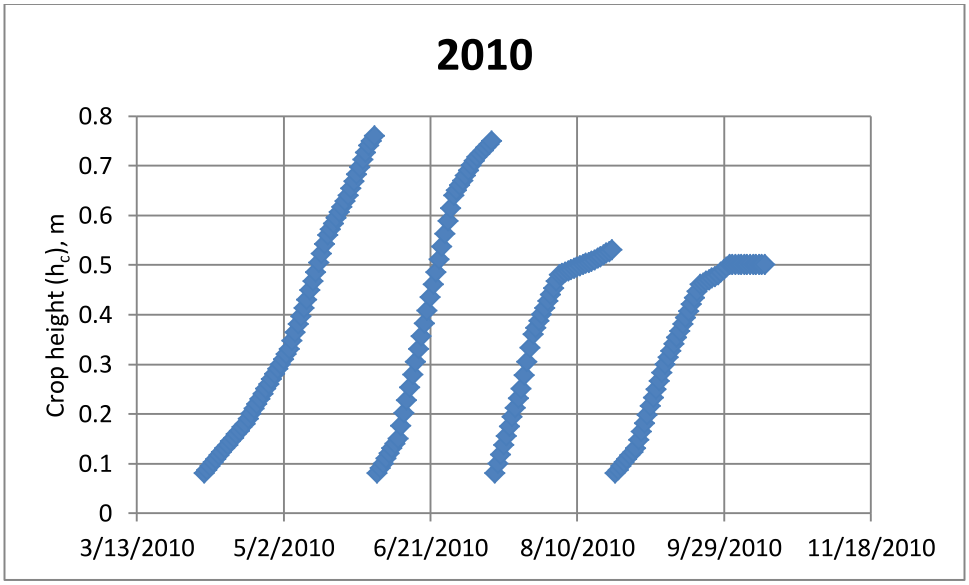

Figure A7: Time series of crop height data in 2010

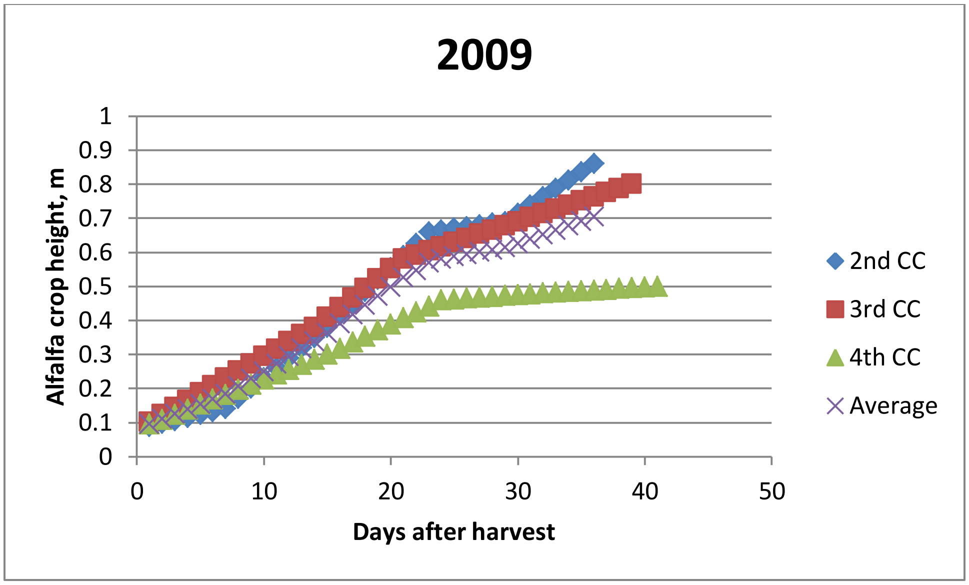

Figure A8: Alfalfa crop height versus days after harvest for different cutting cycles in 2009

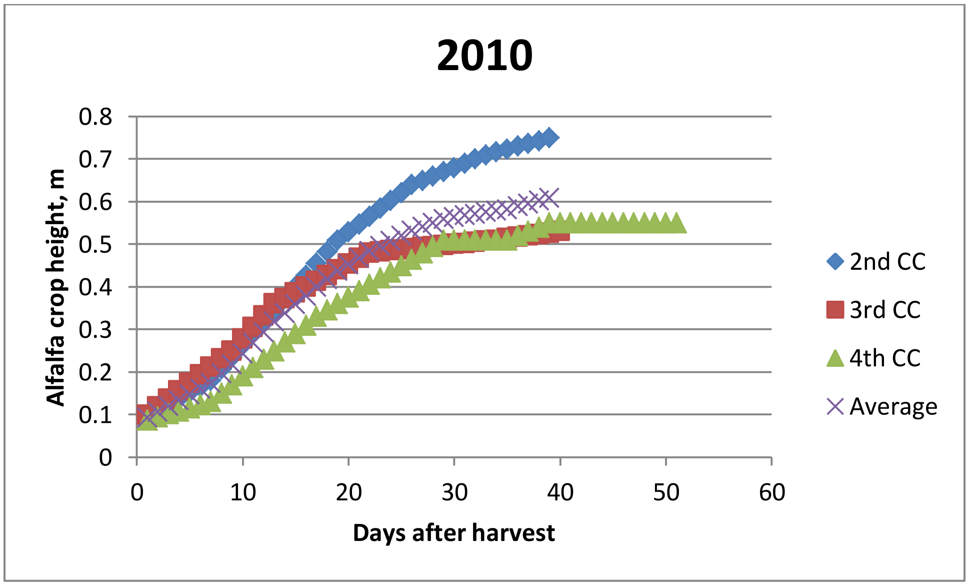

Figure A9: Alfalfa crop height versus days after harvest for different cutting cycles in 2010

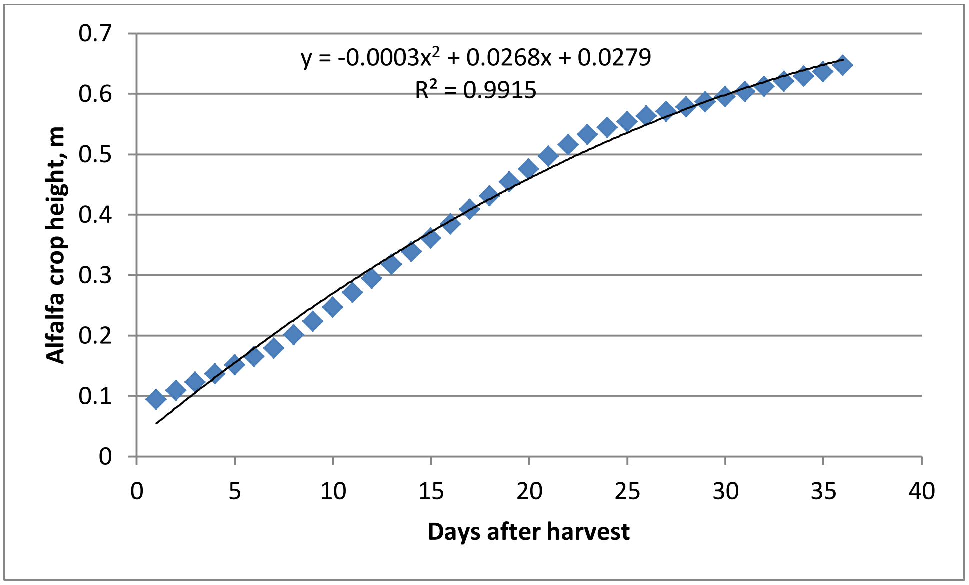

Figure A10: Alfalfa crop height versus days after harvest (Blue dots showing the measured data and black line showing regression line)

Appendix A3: Relationship showing aerodynamic resistance and wind speed for alfalfa reference crop

For the alfalfa reference crop, crop height (h_c) = 50 cm = 0.5 m.

$d = 0.67\ h_c = 0.67 \times 0.5 = 0.335$ m

$Z_{om} = 0.123\ h_c = 0.123 \times 0.5 = 0.0615$ m

$Z_{oh} = 0.1\ Z_{om} = 0.00615$ m

Height of wind speed/temperature measurement = 2 m

Hence from equation (4.3) in the text,

$$r_a = \frac{ln\left(\frac{2-0.335}{0.0615}\right) ln\left(\frac{2-0.335}{0.00615}\right)}{0.41^2\ u_2}$$

which can be simplified to,

$$r_a = \frac{109.91}{u_2} \approx \frac{110}{u_2}$$