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TOWARDS ACCURATE ESTIMATION OF CROP WATER REQUIREMENT WITHOUT THE CROP COEFFICIENT Kc: NEW APPROACH USING MODERN TECHNOLOGIES†

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ABSTRACT

Modern technologies to measure actual evapotranspiration, Eta, were implemented at an experimental farm near Bologna, Italy. Large Aperture Scintillometer and Eddy Covariance instruments were installed. The results showed significant differences between actual evapotranspiration measured by the Eddy Covariance and Scintillometer when compared with the potential reference evapotranspiration, ETo, calculated from meteorological data using Penman-Monteith equation and the crop potential evapotranspiration, ETc, which is based on the ETo and the crop coefficient, Kc. The ETc and ETo showed higher values than those of ETa obtained by Eddy Covariance and Scintillometer. On average the actual evapotranspiration measured by Eddy Covariance and Scintillometers for the cropping seasons 2014 and 2015 represented 45 and 35% of the ETo or the ETc, respectively.

The ETo, or the ETc, represent the atmospheric water demand while fundamentally, the crop water requirement should be based on crop water demand better represented by the actual evapotranspiration. At present, the results indicate that the actual crop water requirement based on the modern technologies could save at least 50% of irrigation water for this region. Another benefit is that these modern technologies do not need the crop coefficient Kc, which for many irrigation practitioners is difficult to obtain.

KEY WORDS: crop water requirement; Eddy Covariance; Scintillometry; actual

† Vers une estimation précise des besoins en eau des cultures sans recourir aux coefficients culturaux : une nouvelle approche utilisant des technologies modernes

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evapotranspiration; water saving; crop coefficient Kc.

RÉSUMÉ

Les technologies modernes pour mesurer l'évapotranspiration réelle, Eta, ont été mises en place dans une ferme expérimentale près de Bologne (Italie), à savoir: scintillomètre à large ouverture et mesure des fluctuations turbulentes (Eddy Covariance). Les résultats ont montré des différences significatives entre l'évapotranspiration réelle mesurée par Eddy Covariance et par Scintillométrie d'une part, par rapport à l'évapotranspiration potentielle de référence, ETo, d'autre part. Cette dernière est calculée à partir de données météorologiques en utilisant l'équation de Penman-Monteith et l'évapotranspiration potentielle de la culture, ETc, qui est basée sur ETo et le Coefficient cultural, Kc. ETc et ETo ont montré des valeurs plus élevées que celles de ETa obtenues par Eddy Covariance et Scintillométrie. En moyenne, l'évapotranspiration réelle mesurée par Eddy Covariance et Scintillométrie pour les saisons de cultures 2014 et 2015 représentait 45 et 35% de l'ETo ou de l'ETc respectivement.

ETo, ou ETc, représentent la demande d'eau atmosphérique alors que, fondamentalement, l'exigence d'eau de la récolte devrait être basée sur la demande en eau des cultures mieux représentée par l'évapotranspiration réelle. À l'heure actuelle, les résultats indiquent que l'exigence réelle d'eau d'une récolte basée sur les technologies modernes pourrait économiser au moins 50% de l'eau d'irrigation pour cette région. Un autre avantage est que ces technologies modernes n'ont pas besoin du coefficient cultural Kc, qui pour de nombreux praticiens de l'irrigation est difficile à obtenir.

MOTS CLÉS : besoins en eau des cultures ; Eddy Covariance; scintillométrie ; évapotranspiration réelle ; économie d'eau ; coefficient cultural Kc.

INTRODUCTION

Accurate estimation of irrigation water requirement could save water and minimize losses, allowing more land to be irrigated and subsequently more food to be produced. Irrigation practitioners commonly determine the crop water requirements (CWR) by different methods: hydrological methods, such as soil water balance or soil moisture deficit (SMD), weighing Lysimeters, Class A pan, plant physiology based methods, such as sap flow, and analytical methods using physically based or locally derived empirical equations.

Estimates of reference crop evapotranspiration (ETo*)* from meteorological data (radiation, wind speed, temperature and relative humidity) are widely used by irrigation engineers to define crop water requirements. ETo, has been defined as the rate at which water, if readily available, would be removed from the soil and plant surface of a specific crop, arbitrarily called a reference crop. This reference crop is either grass or alfalfa. The potential evapotranspiration for a cropped area (ETc) is quantified through the multiplication of ETo with a crop coefficient, Kc.

In agriculture, ETc is the maximum possible evapotranspiration rate under the prevailing meteorological conditions, while the actual evapotranspiration, ETa is soil moisture availability dependant. ETa is the actual evapotranspiration of the amount of water that is available under the current level of soil moisture, not the amount of water that can evaporate if the soil contains an unlimited amount of available water.

The reference evapotranspiration (ET_0), represents the environmental demand for evapotranspiration, a reflection of the energy available to evaporate water, the wind available to transport the water vapour into the atmosphere and the atmospheric vapour pressure deficit.

Eddy Covariance (EC) is a direct method of measuring actual evapotranspiration. In this technique fast fluctuations of vertical wind speed are correlated with fast fluctuations in atmospheric water vapour density. This method directly estimates the transfer of water vapour/evapotranspiration from the land/canopy surface to the atmosphere. The Eddy Covariance approach is considered to be a direct and accurate method to measure both latent heat (LE) (i.e. evapotranspiration) and sensible heat (H) fluxes (Rana and Katerji, 2000).

The instrument is commonly used for greenhouse gas emissions, e.g. carbon dioxide and methane emission monitoring, measuring water loss by evapotranspiration, and instantaneous water and radiation use efficiency measurements. Novel uses include carbon sequestration and capture monitoring and measuring of landfill gas emissions into the atmosphere, emissions of gases displaced by hydraulic fracturing into the atmosphere, gas leak detection and location, methane emission from permafrost regions, and reactive trace gas exchange flux measurement.

Scintillometry technique is another method to quantify the surface energy flux. In this technique, the scintillation of a transmitted optical or radio wave signal in conjunction with standard meteorological measurements is used to calculate sensible heat flux (Meijninger *et al*., 2002; Savage, 2009; Saiman *et al*., 2011; Bouin *et al*., 2012; McJannet *et al*., 2013). Latent heat flux is more commonly calculated as the residual of the energy balance. However, Guyot *et al*. (2009) determined the latent heat flux using Scintillometry and water balance.

A Scintillometer consists of a transmitter and a receiver where an optical or radio wave signal is transmitted to the receiver across a path length, sometimes over a few kilometres. The signal transmitted is usually scattered by the turbulent atmosphere (Meijninger *et al.*, 2002). The sensed intensity fluctuations, or scintillations, of the signal are analysed at the receiver, and expressed as a refractive index of air (Meijninger *et al*., 2002).

In their study, Evans *et al*. (2012) investigated the application of Scintillometry over a 2.4 km path of heterogeneous mixed agriculture on undulating topography in Berkshire, United Kingdom. A large aperture Scintillometer, LAS was compared with four EC stations measuring sensible and latent heat fluxes over different vegetation (cereals and grass) which when aggregated were representative of the LAS source area. Using spatially aggregated measurements of net radiation and soil heat flux with sensible heat flux from the LAS, the areal averaged latent heat flux was calculated as the residual of the surface energy balance. The correlation between the latent heat fluxes (evapotranspiration) obtained by EC and LAS demonstrated that Scintillometry is an accurate method for the landscape-scale estimation of evapotranspiration over heterogeneous complex topography.

Rosenberry *et al*. (2007) compared fifteen different methods to determine evapotranspiration on a small mountain lake in the USA. They found that only three evapotranspiration methods that include available-energy and aerodynamic terms (combination methods) provided the best comparisons against the measured evapotranspiration using Bown Ratio Energy Budget (BREB) evapotranspiration measured at Mirror Lake. Kashyap and Panda (2001) found that the ETo obtained by several methods including the FAO-Penman-Monteith, Penman, Hargreaves, Blaney Criddle and Turc was in general higher than the ETo obtained from lysimeters. In addition, they also reported that the crop coefficient Kc measured values were lower than those reported by Allen *et al*. (1989). The calculated high ETo and high Kc led to higher estimation of crop water requirement when compared with the measured values of ETo and Kc.

The crop water requirement calculation in the Gediz Basin of western Turkey was examined by Beyazgu *et al*. (2000), using six methods to estimate the ETo and comparing them with the actual ET obtained from water balance supported by soil moisture measurements. They found significant differences among the different equations and concluded that the water balance updated with measured soil moisture content was more promising.

Eddy Covariance (EC) was used to estimate the crop coefficient of drip irrigated tomato in the Jordan Valley (Amayreh and Al-Abed, 2005). The EC was used to estimate the crop evapotranspiration (ETc), then the crop coefficient Kc was calculated as a ratio between ETc and the ETo obtained by the FAO modified version of Penman Monteith equation (Allen *et al*., 1989). They found that the Kc values obtained using the EC were, on average, 36% lower than those reported by FAO (Allen *et al*., 1998). Higher Kc values would lead to significant impact on the estimation of crop water requirements and hence irrigation management of tomato crop, the major irrigated crop in the Jordan Valley.

A similar study to obtain the crop coefficient was conducted by Xinhua *et al*. (2009) in

North Central Florida to measure Bahiagrass evapotranspiration rates using an Eddy correlation system. Daily K_c values were calculated using the ratio of measured ET_c obtained by EC to the estimated ET_o from meteorological data. Suyker and Verma (2009) used the EC to measure the evapotranspiration and water productivity of maize–soybean cropping systems. In Portugal, Paço *et al*. (2006) measured the evapotranspiration over a 3 to 4 year old orchard using the EC. They reported that FAO-56 Penman-Monteith equation (Allen *et al*., 1998) overestimated crop evapotranspiration when compared with the EC.

ET obtained by EC was compared with ET obtained by large scale weighing lysimeters for maize grown in 2009 in China (Ding *et al*., 2010). There was only 3% difference between the two methods. Ding *et al*. (2010) stated that the EC method can be applied to accurately estimate ET in the arid region of China. A study at Logan's Dam in southeast Queensland, Australia, was conducted by McJannet *et al*. (2011). The ET of the Scintillometer over a transect covering the whole dam was compared to the ET measured by EC placed at the centre of the dam. The results showed an excellent agreement between the ET obtained by EC and Scintillometer.

The Scintillometer was used over a heterogeneous land surface and comparable results with the EC were obtained by Meijninger *et al*. (2006). They stated that the Scintillometry technology can be used to estimate ET at a scale of several kilometres.

In a Field experiment in the central region of Morocco with mostly orchards, Ezzahar *et al*. (2009) concluded that the Scintillometers have the potential to provide an estimate of large-scale evapotranspiration.

No evidence was found in literature that the Eddy Covariance or Scintillometers were tested for their suitability to estimate crop water requirement at field scale, nor that they were employed for agriculture water management. The aim of this work is to test the robustness, reliability and suitability of the Large Aperture Scintillometer (LAS) and Eddy Covariance (EC) to determine the crop water requirements based on measurements of actual evapotranspiration.

MATERIALS AND METHODS

The experimental field is located nearby the village of Mezzolara di Budrio (Bologna, Italy) in the plain of the Po valley (44º34´ N, 11º32´ E). The field is part of the Consorzio Bonifica CER's experimental farm. The Scintillometer and Eddy Covariance instruments have been installed in the CER's experimental farm (Figure 1) and measurements started at the beginning of the 2014 irrigation season and continued for two years (2014-2015).

Scintillometer (transmitter left-receiver right) Eddy Covariance

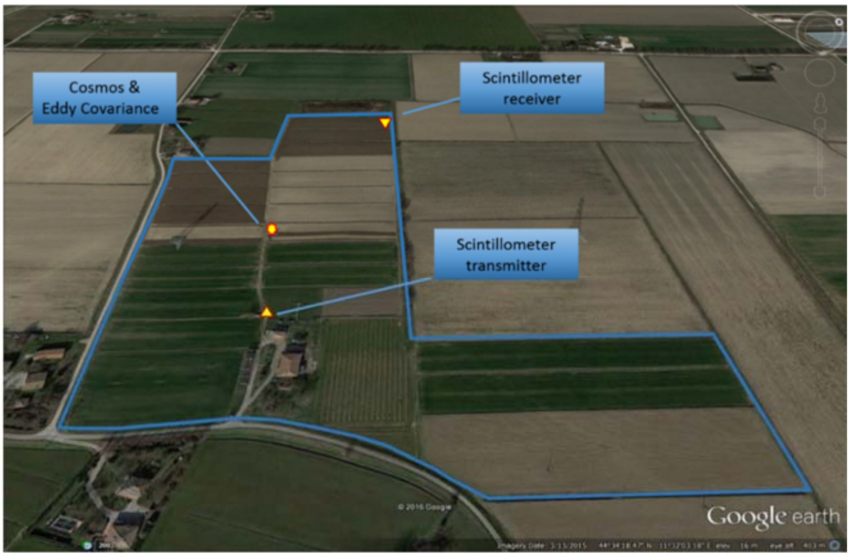

Figure 1. Experimental site and instruments locations

The soil is typical of the Po valley lowland with a high content of silt and fine sand. The soils of the valley are normally deep without noticeable soil particle size (> 2 mm). The detailed soil's physical and chemical parameters are given in Table I.

Crop rotation is typically bi- or tri-annual, including in sequence: winter wheat and an horticultural crop (potato or processing tomato) and maize or sorghum in case of a tri-annual rotation. The crops rotated in the period 2013-2016 are reported as percentage of the total cropped area in Table II.

The irrigation season normally starts end of May and ends late August/early September. The irrigation systems used were: Reel Sprinkler Machine equipped with Gun or Boom; Drip irrigation and solid Set Sprinklers (Table III).

The Eddy Covariance's area of measurement is of the order 100 m x 20 m for typical daytime and is a narrow ellipse shape footprint on the ground upwind of the EC mast location. The footprint analysis is expected to show the percentage contribution of each crop type. It is important to bear in mind that the crop type(s) measured for their ETa vary with wind direction.

Table. I. Soil physical and chemical parameters

Parameter, units	Average
Sand, %	32
Silt, %	50
Clay, %	18
pH, log H^-	8.27
$CaCO_3$ Total, %	13.5
$CaCO_3$ Active, %	3.1
N Total, %	0.06
K Exchangeable, meq/100g	0.34
P (Olsen), meq/100g	5.49
CEC, meq/100g	21.6

Table II. The crop rotation during 2013-2016

Crop	Percentage of the total cropped area in			
	2013	2014	2015	2016
Winter Wheat	46.4	32.1	43.0	39.3
Maize	21.4	21.4	28.7	21.4
Sorghum	18.0	28.7	0.0	14.3
Processing Tomato	7.1	7.1	7.1	14.3
Orchards	0.0	3.7	3.7	3.7
Sunflower	0.0	0.0	10.7	0.0
Constructed Wetland	3.7	3.7	3.7	3.7
Weather Station	3.7	3.7	3.7	3.7
Total	100%	100%	100%	100%

Table III. The land cover and the method of irrigation

Crop	Sprinkler-solid set system	Drip system	Supplementary irrigation. (reel-gun-boom sprinkler systems)	Not irrigated
Winter wheat				X
Sorghum			X	X
Sunflower			X	X
Orchards		X		
Maize	X	X		
Processing Tomato	X	X		

There have been a few problems with the system due to the relatively hot and dry conditions, also, few data were lost due to precipitation affecting the open-path infra-red gas analyser of the Campbell Scientific IRGASON EC sensor. Therefore, there are some small data gaps due to technical issues.

The Scintillometer can be considered as ground-based remote sensing, with no sensors in the field, only a beam of light above the field. More significantly, the Scintillometer offers a much larger sampling volume and statistically reliable fluxes can be measured in a few minutes, compared to 30 mins for EC. The area influencing the measurement (Figure 2) has been calculated in line with the dominant wind direction (Figure 3).

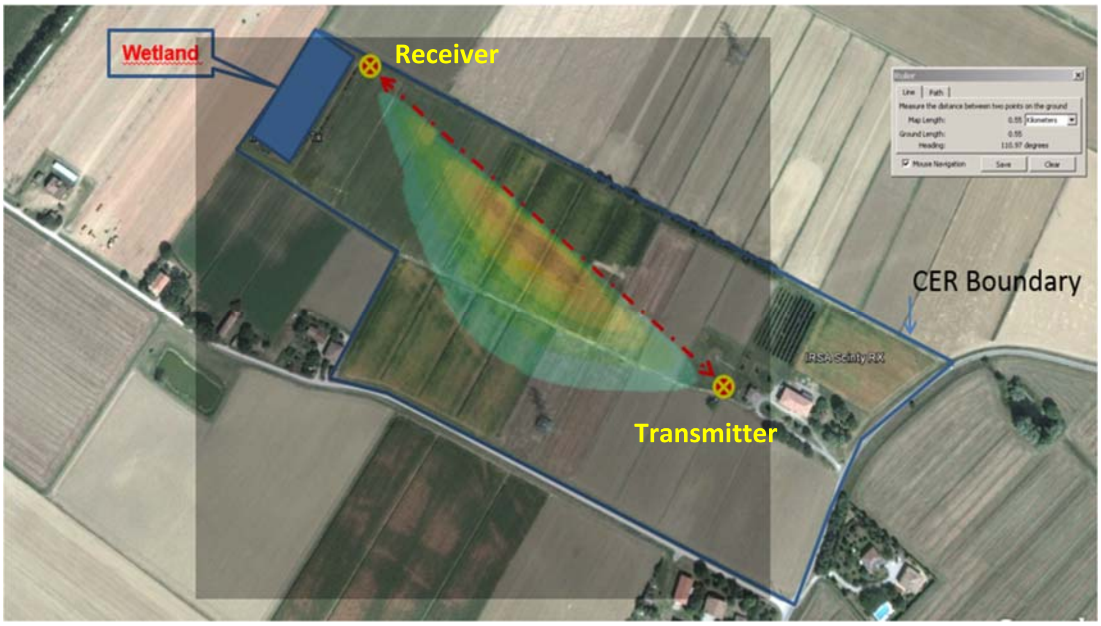

Figure 2. The Scintillometer footprint at the CER experimental farm (Mezzolara). Contribution to Eta increases from green to yellow to red areas

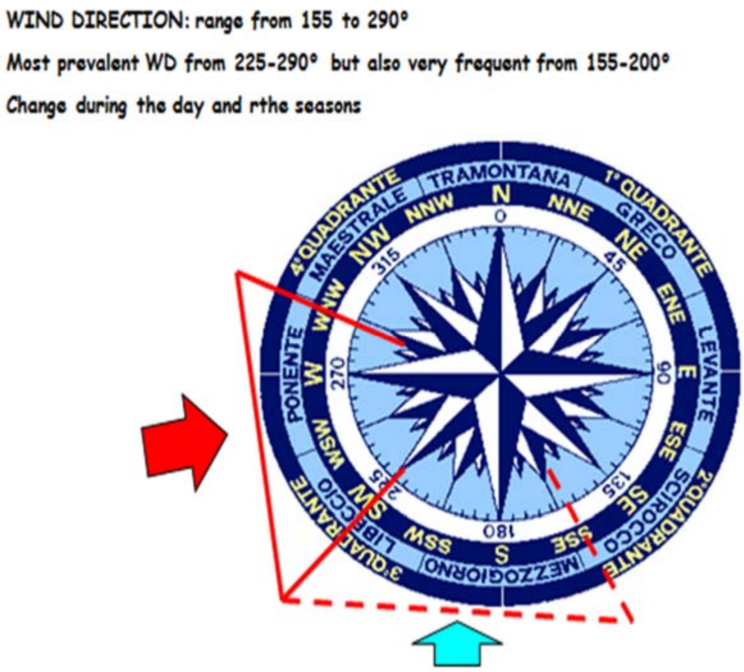

Figure 3. Prevailing wind direction influencing Eddy Covariance and Scintillometer measurement (Mezzolara), footprint

RESULTS AND DISCUSSION

The very low winter evapotranspiration rates are of course limited by the available energy from the sun, as the solar radiation decreases in winter, the evapotranspiration correspondingly decreases. The reference Penman-Monteith evapotranspiration, ETo and the maximum/potential crop evapotranspiration, ETc were compared with the actual evapotranspiration, ETa measured by Eddy Covariance and Scintillometer.

The ETa values are expected to reflect the footprint analysis which disaggregate crop types, such that ETa can be assigned to specific crops. The reference evapotranspiration, ETo, and the measured actual evapotranspiration, ETa_{Scinty} and ETa_{Eddy} are shown together in Figure 4. Eddy Covariance and Scintillometer are not directly comparable, given the much larger footprint of the Scintillometer. Therefore, they are measuring different proportions of each crop type and are not expected to be the same, but will be highly correlated and perhaps bounded by one another.

It is very interesting to see that despite the above caveats, the ET_{Scinty} and ETa_{Eddy} are quite similar in magnitude much of the time, demonstrating the real value of these technologies. ETa measured by Eddy Covariance and Scintillometer were compared with the reference evapotranspiration ETo calculated by Penman Monteith Equation (FAO-modified equation, Allen *et al*., 1998) as shown in Figure 4.

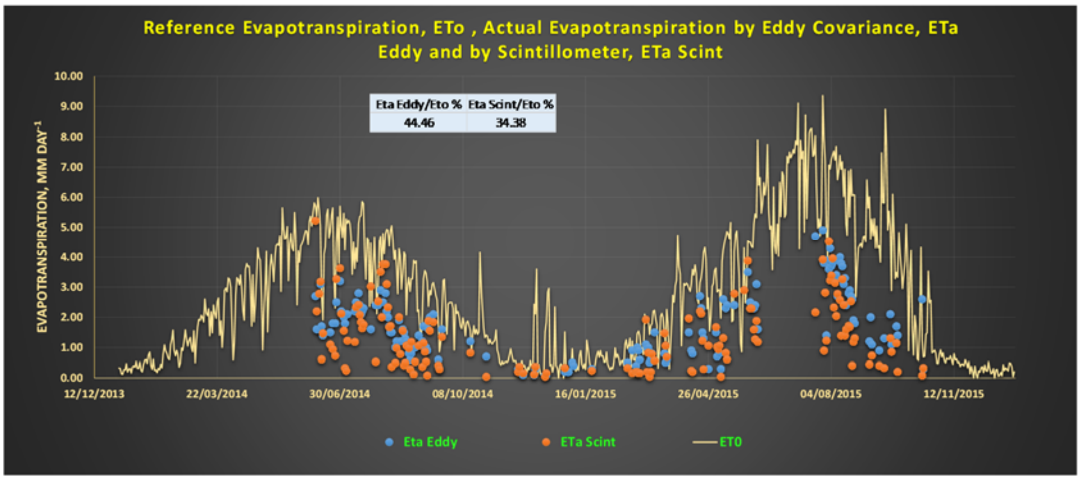

Figure 4. Comparison between actual evapotranspiration measured by Eddy Covariance and by the Scintillometer versus the reference evapotranspiration calculated by Penman-Monteith equation

Figure 4 shows that the Eddy Covariance and Scintillometer results are close to each other and both are below the reference evapotranspiration. The ratios of cumulative values over the observation period of actual evapotranspiration obtained by Eddy Covariance and Scintillometer to the cumulative reference evapotranspiration are 44.5% and 34.4%, respectively.

In order to calculate the crop evapotranspiration, which is the product of the reference evapotranspiration, (ETo) and the crop coefficient (Kc), one needs to know the relative contribution of each crop in the footprint of the Eddy Covariance and Scintillometer instruments. This is followed by estimating the weighted mean Kc value for each day based on the relative contribution of each crop in the footprint area. The contribution of the different crops within the Eddy Covariance footprint to the total actual evapotranspiration is shown in Figure 5a,b for 2014 and in Figure 6a,b for 2015.

Once the weighted mean crop coefficient Kc is calculated, the crop evapotranspiration ETc was calculated as a multiplication of ETo and the weighted mean of the crop coefficient. Figure 7 shows overall results of the actual evapotranspiration as measured by Eddy Covariance and Scintillometer compared with the calculated reference evapotranspiration (ETo) and the calculated crop evapotranspiration (ETc). The figure shows clearly that the ETa of Eddy Covariance and Scintillometer are significantly lower than the calculated ETo and ETc.

On average for the 2014 and 2015 cropping seasons, the actual evapotranspiration of Eddy Covariance and Scintillometers represent 45 and 35% of the ETo or ETc, respectively, (Figure 7). These are quite significant differences.

It should be noted that there was a hail event in 2015 at the end of the wheat growing season. This did not largely affect the wheat but resulted in re- transplanting maize and tomato, one week after the event. In comparison with 2014, the actual evapotranspiration measured in 2015 by Eddy Covariance and Scintillometer might have relatively more contribution from bare soil evaporation and less transpiration from a relatively smaller canopy. However, the ratio of ETa of both Eddy Covariance and Scintillometer to either ETo or ETc remained similar to those of 2014.

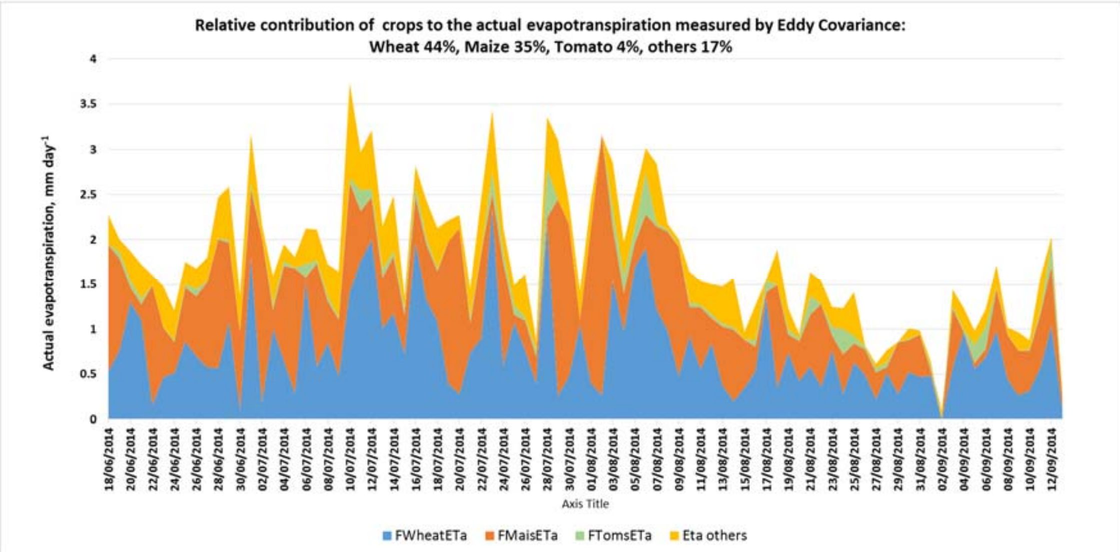

Figure 5a. Actual evapotranspiration, ETa, measured by Eddy Covariance and the relative contribution of the crops within the footprint to the total ETa for the 2014 season

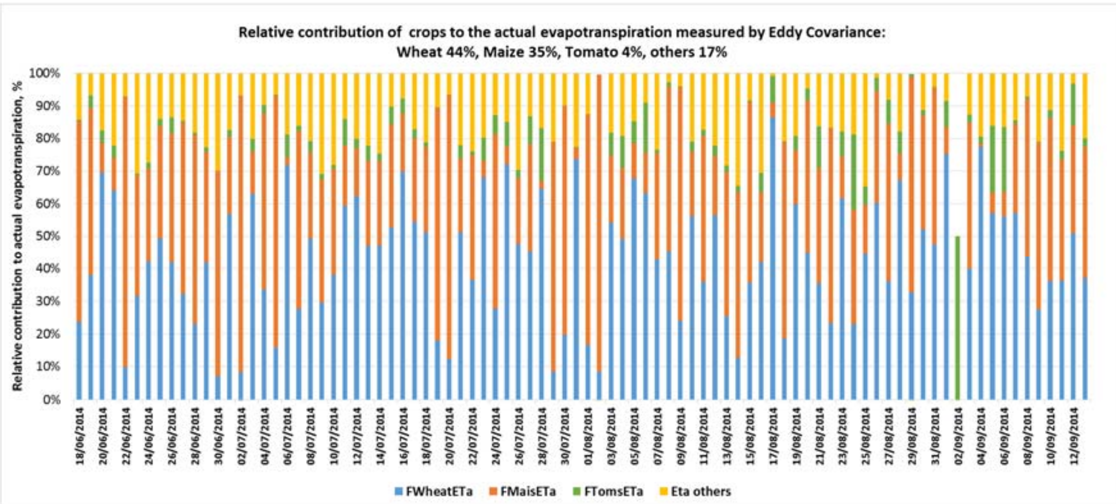

Figure 5b. Actual evapotranspiration, ETa, measured by Eddy Covariance and the % contribution of the crops within the footprint to the total ETa for the 2014 season

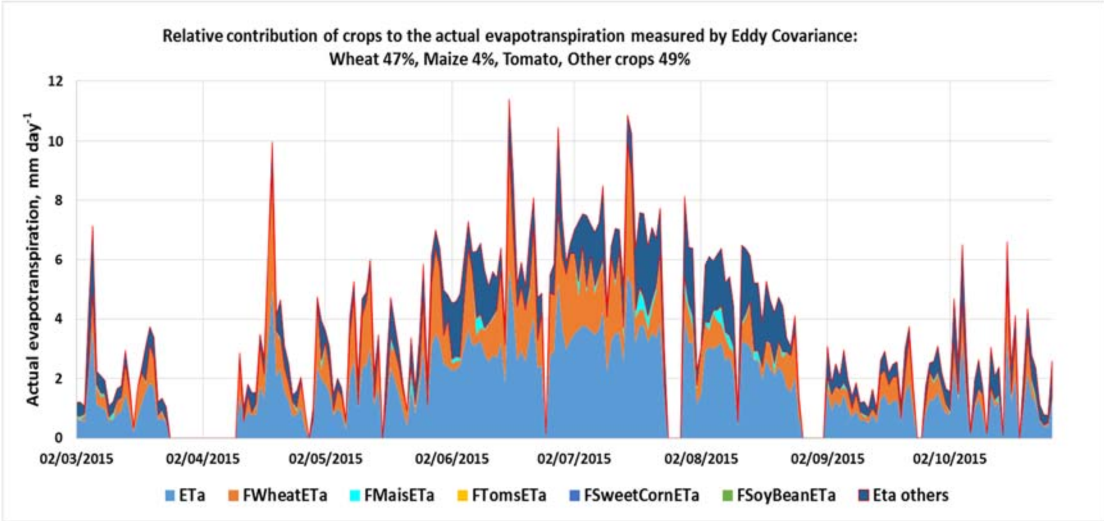

Figure 6a. Actual evapotranspiration, ETa, measured by Eddy Covariance and the relative contribution of the crops within the footprint to the total ETa for the 2015 season

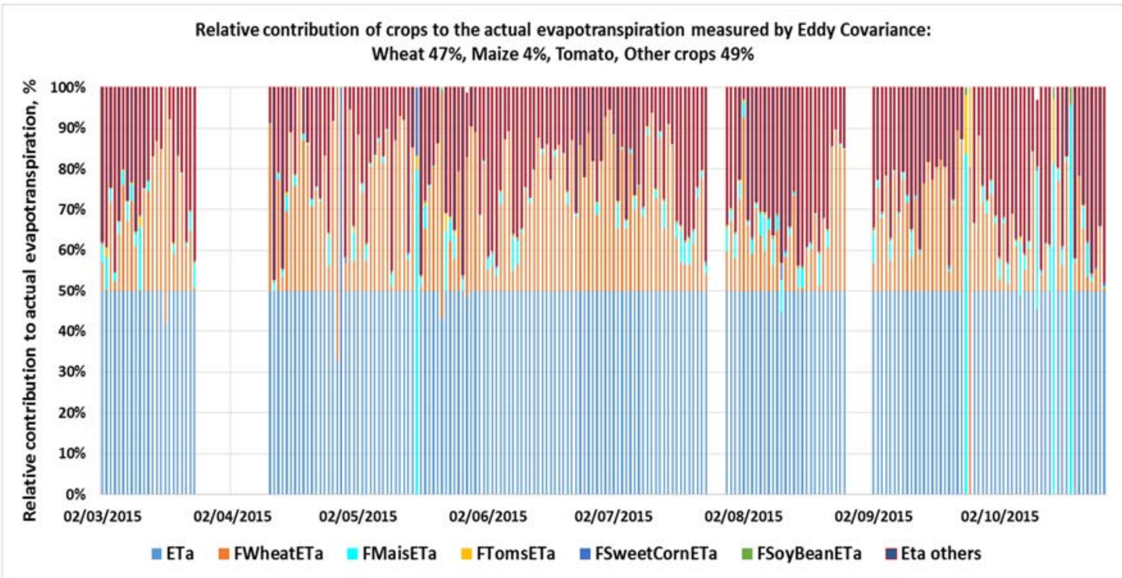

Figure 6b. Actual evapotranspiration, ETa, measured by Eddy Covariance and the % contribution of the crops within the footprint to the total ETa for the 2015 season

These results show a potential water saving in irrigation should the crop water requirement be based on actual measured evapotranspiration rather than the widely used classical methods that depend on calculating the reference evapotranspiration, ETo or the crop evapotranspiration, ETc from meteorological data. ETo is evapotranspiration at potential rather than actual level and the ETo would represent the atmospheric demand rather than the crop demand for water. The exact percentage of water saving will differ between seasons and crops but will always be actual irrigation water requirement. At present, based on data of two growing seasons, the indication is the ETa is around 35 to 45% of the ETc, which is used globally to estimate the crop irrigation requirement.

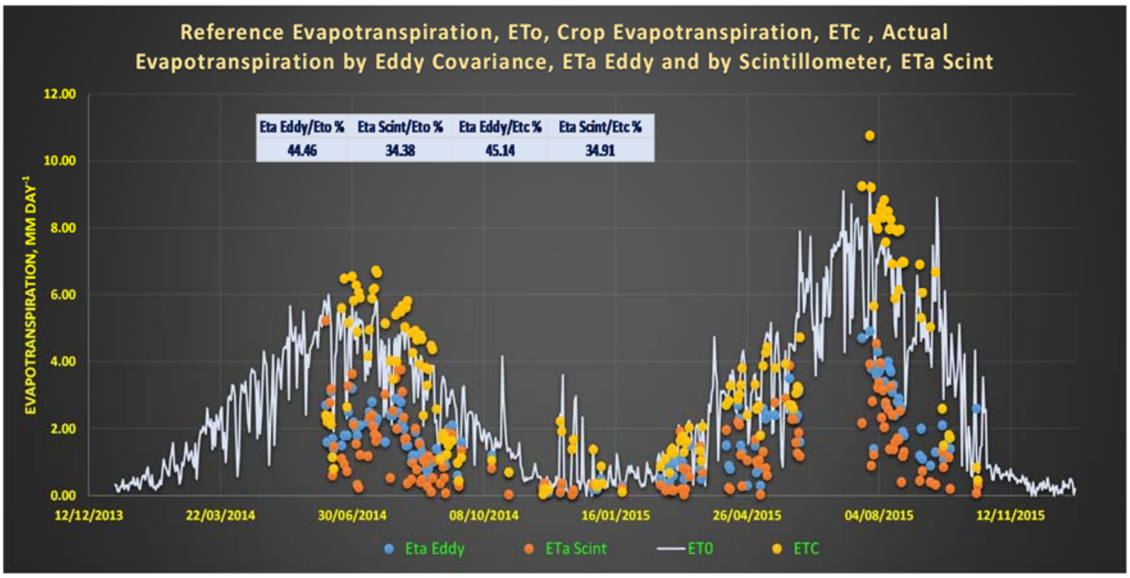

Figure 7. Comparison between actual evapotranspiration measured by Eddy Covariance and Scintillometer, reference evapotranspiration estimated from Penman-Monteith equation and crop evapotranspiration calculated from ETo and the weighted mean of the crop coefficient Kc

CONCLUSION

The results showed significant differences between actual evapotranspiration values measured by the new technologies of Eddy Covariance and Scintillometer when compared with the worldwide used potential reference evapotranspiration calculated from meteorological data using Penman-Monteith equation, ETo, and the crop evapotranspiration, ETc, based on the ETo and the crop coefficient, Kc. The ETc and ETo showed higher values than those of ETa obtained by Eddy Covariance and Scintillometer. On average the actual evapotranspiration of Eddy Covariance and Scintillometers for the cropping seasons 2014 and 2015 represented 45 and 35% of the ETo and ETc, respectively. These are quite significant differences.

These results indicate that there is a potential for water saving in irrigation should the crop water requirement be based on actual measured evapotranspiration rather than the calculation based on the widely-used Penman –Monteith equation and possibly other methods calculating potential evapotranspiration, not the actual evapotranspiration. Calculating the reference evapotranspiration, ETo, or the crop evapotranspiration, ETc, from meteorological data, produces potential evapotranspiration that would represent the atmospheric demand for water rather than the crop demand for water. Accurate crop water requirement should be based on crop and soil demand not on atmospheric demand for water. The exact percentage of water saving by using these new technologies, the Eddy Covariance and Scintillometer, will differ between seasons and crops but will always be actual irrigation water requirement. At present, with results from two cropping seasons, the indication is that the actual crop water requirement, based on the new technology could save at least 50% of irrigation water estimated by the commonly used methods for potential evapotranspiration such as Penman – Monteith equation. Another benefit is, these modern technologies of measuring the actual evapotranspiration do not need the crop coefficient Kc, obtaining Kc is a major problem to many irrigation practitioners.

Doubling food production by 2050 requires efficient water use to double the food production from the same amount of water. Accurate estimate of crop irrigation requirement based on actual evapotranspiration is the way forward.

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