Chapter 7
Evapotranspiration of Wheat in a Hilly Topography: Results from Measurements Using a Set of Eddy Covariance Stations

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Abstract Several methods allow the determination of evapotranspiration (ET), either by direct measurement or by estimation from weather data. The most used estimation method is the FAO56 (FAO-PM), based on the concept of reference evapotranspiration (ETo) and crop coefficient (Kc). The eddy covariance technique (EC) developed for measurement of convective fluxes between land surface and the atmosphere is commonly used to estimate ET. However, these methods were established under standard conditions in flat terrain, and their use in hilly areas is questionable. In this work, the variability of ETo and ET measured by EC and energy balance (EB) in a hilly area of northern Tunisia is studied for different relief configurations. The experiment was conducted using a meteorological (M), and three EC-EB measurement stations in three wheat fields. Two stations were installed on opposite slopes of a ridge with apposing aspects and moderate slopes (A, B), and one station was installed in a flat site (C). Results of monitoring during the mid-season of wheat growth showed similar ETo levels in all sites for hourly and daily time steps with relative RMSE in the range 0.03–0.08 compared to M. Average ET values in sloping fields (A, B) were, respectively, 15% and 10% lower than in (C). However, hourly values of ET/ETo obtained from EC measurements were smaller than FAO-Kc, contrarily to those based on the EB method.

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List of Acronyms and Abbreviations

EB	Energy Balance
EC	Eddy covariance
ET	Evapotranspiration
ET_EC	Evapotranspiration estimated by Eddy covariance technique
ET_EB	Evapotranspiration estimated by Energy Balance equation
ETo	Reference evapotranspiration
FAO-56	Food and Agriculture organization, paper 56
FAO-Kc	Kc recommended by FAO-56 bulletin, Table 12
FAO-PM	FAO Penman–Monteith equation
G	Soil heat flux
H	Sensible heat flux
ITC	The integral turbulence characteristics test
Kc	Crop coefficient
LAI	Leaf Area Index
LE	Latent heat flux
Min	Minute
Rn	Net radiation
ST	The steady-state test

Introduction

Methods used for determination of ET are based on weather and crop observations or simulation models. Among these methods there is: (i) the FAO-56 formulation (Allen et al. 1998) which uses the concept of reference evapotranspiration multiplied by a crop coefficient (Kc), (ii) the methods based on the soil water balance and, (iii) the methods based on combinations of the energy balance (EB) and sensible and latent heat flux measurements, such as the eddy covariance technique (EC). In the EC method, vertical wind speed and air temperature/humidity are measured with high frequency and used directly to estimate the convective fluxes of latent (LE) and sensible (H) heat between land surfaces and the atmosphere (Van Dijk et al. 2004). EC systems are often used for testing and calibrating remote sensing-based energy balance models, although several authors reported their systematic underestimation of ET and energy closure problem (Twine et al. 2000; Evett et al. 2012a, b).

Nevertheless, in spite of experimental and instrumental progresses, datasets of EC measurements often experience large portions of missing data. The average data loss in EC systems attributed to maintenance operations, sensitivity of the sensors to

rainfall, and to the method itself which requires spatial and temporal stability of flows, is typically over 35% during a year (Falge et al. 2001). Quality assessment criteria were developed in order to reject inconsistent measurements. The stationarity over 30-min time interval and the spatial homogeneity of turbulence tests are usually applied and result in smaller datasets (Foken and Wishura 1996; Hammerle et al. 2007; Rebmann et al. 2005).

Moreover, most methods for ET estimation are developed and validated in standard conditions and typically for flat areas. Little attention has been given for the hilly catchments, despite the fact that hilly topography is prevailing in large agricultural areas (Hammerle et al. 2007; Feigenwinter et al. 2008; Rana et al. 2007). Hilly topography has an effect on water and energy fluxes in terms of: (i) net and global radiations which are more important on slopes facing south (Raupach and Finnigen 1997; Holst et al. 2005), (ii) soil moisture, which is dependent on the slope, vegetation and the distance from the valley (Tromp van Meerveld and McDonell 2006; Hugo et al. 2013), (iii) wind, which has a speed and vertical profile dependant on the slope and aspect (Raupach and Finnigen 1997). The representativeness of weather or flux data used for ETo and ET estimation is therefore highly dependent on the location of the measurement station. The aim of this work is to assess ET variability in a hilly area of the south Mediterranean and the sensitivity of ETo and ET of a wheat crop to slope.

Materials and Methods

Experimental Site

The experiment was carried out in a small rain-fed agricultural catchment in the Cap Bon region, northeast Tunisia (Fig. 7.1). Simultaneous measurements of energy
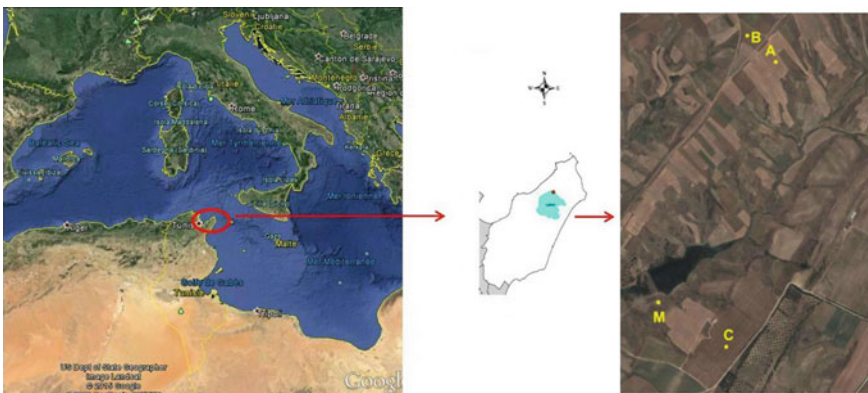
Fig. 7.1 Location of the experimental site and position of the flux (A, B, C) and standard weather (M) stations, Cap Bon, Tunisia

Table 7.1 Location of experimental fields and measurement stations

Field label	Coordinates	Crop	Slope (°)	Aspect (°)	Altitude (m)
A	N36°52'50.2" E10°52'33.1"	Wheat	5.3	152	153
B	N36°52'54.8" E10°52'27.8"	Wheat	6.0	300	155
C	N36°52'12.6" E10°52'40.5"	Wheat	Flat field	–	130
M	N36°52'13.0" E10°52'09.0"	Standard meteorological station			108

fluxes and climatic factors required by the FAO-PM equation were performed in three cereal fields: two stations (A, B) were installed on opposite sides of a ridge on slopes of 5 and 6° respectively, and a station was installed in a flat area (C).

Data from a meteorological station (M), located approximately 100 m southwest of a reservoir at the outlet of the catchment was used for determining ETo (Table 7.1).

The climate in the area is a sub-humid Mediterranean with annual rainfall (P) and reference evapotranspiration (ETo) of 600 mm and 1300 mm, respectively. Traditional and semi-intensive rain-fed agriculture based on cereals (durum wheat, bread wheat, barley, oat, triticale), and legumes (chickpeas, fava beans) are prevailing in the region with landscape organization and land use determined by relief and soil fertility.

Measurements of energy flux terms, and climatic factors were performed in the three fields (A, B, C) and in the weather station (M) from December 2012 to June 2013. However, only the period Mars 7–31, corresponding to simultaneous data availability in all stations and to mid-season stage of wheat growth is considered in this work.

Fields were sown during the same period (December 1, A&B and December 10 for C) and commonly used fertilization and weed control practices were applied in order to have similar growth.

Data Acquisition

Each flux measurement station was equipped with a CR3000 datalogger (Campbell Scientific, USA) and measurement sensors allowing determination of the energy balance (EB) terms. Sensible (H) and latent (LE) heat fluxes, were determined by ECPACK software (Van Dijk et al. 2004) using 20 Hz data of wind vertical velocity, temperature, and air humidity generated by sonic anemometers (CSAT3, Campbell Scientific, USA) and Krypton hygrometers (KH20, Campbell Scientific, USA). Net radiation (Rn) and soil heat flux (G) were measured in each site by a differential radiometer (NR01, Hukesflux, NL) and three soil heat flux sensors

(HPF01, Hukesflux, NL). The stations were also equipped with thermo-hygrometer sensors (HMP45C, Vaisala, FL) in order to determine humidity and air temperature useful in calculating ETo.

The meteorological station (M) provided measurements of solar irradiance (SP100 pyranometer Skye, UK); air temperature and humidity (HMP45C probe, Vaisala, FL); wind speed (A100R anemometer, Vector Instruments, UK); and wind direction (W200P wind vane, Vector Instruments, UK). All instruments had been calibrated by the manufacturer and were connected to a CR10X datalogger (Campbell Scientific, USA) which calculates and stores average values over 30-minute time intervals.

Data Processing and Quality Assessment

The entire set of instrumental and double rotation corrections available in the ECPACK library were applied (Van Dijk et al. 2004). Moreover, Rn measurements were corrected for slope effects using the procedure proposed by Holst et al. (2005).

Quality assessment was applied to H and LE values as proposed by Foken and Wichura (1996) and revisited by Rebmann et al. (2005), considering temporal stationarity (ST) and integral turbulence characteristics (ITC) and used to reject low quality data.

The Penman–Monteith equation (Allen et al. 1998) was used to determine hourly and daily ETo using data obtained at the three sites and at the weather station. Eddy covariance ET (ET_EC = LE) and energy balance ET (ET_EB = Rn-G-H) were determined with hourly time steps in the three sites.

Results and Discussion

Experimental Conditions and Quality Assessment

The average wind speed value recorded during the experiment (4.1 m/s) is twice the global average (Allen et al. 1998). The rainfall during the period January–March 2013 (232 mm) was well distributed and above average cumulated ETo resulting in good soil moisture conditions.

ET_EC and ET_EB were calculated at hourly time steps. Quality assessment was used to identify invalid data using ST and ITC criteria. Records corresponding to maintenance and missing data due to rainfall or condensation were also discarded.

The rejected ET_EC data by quality assessment tests during the cropping season represented 23%, 27%, and 16%, respectively, for fields A, B, and C. The percentages do not consider missing data due to power failure, maintenance and KH20 sensor stops during rainfall events. A relatively greater percentage of good quality
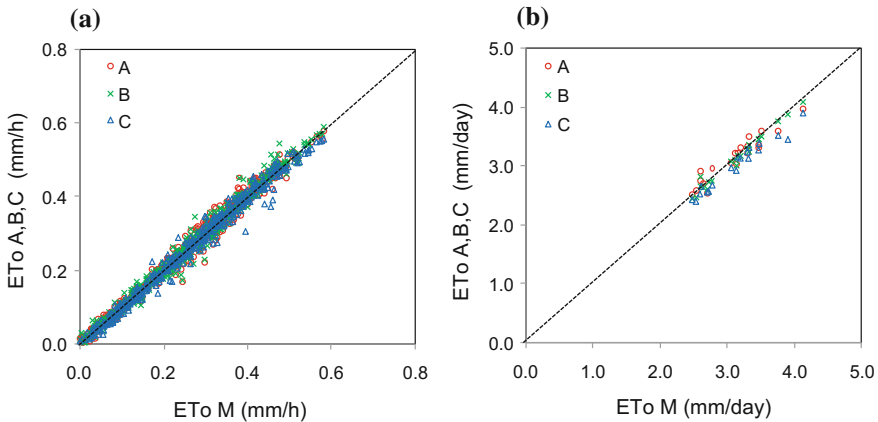
Fig. 7.2 Reference evapotranspiration calculated on hourly **a** and daily **b** time steps using weather data measured in wheat fields A, B, and C as related to ETo derived from standard weather station data M, during the period March 07–31, 2013

data was observed in flat field. Falge et al. (2001) reported an average annual percentage of good quality data of 65%. In contrast, data of sensible heat flux (H) in the three sites had better quality with only 8–9% of the data rejected by quality control tests.

Sensitivity of ETo to Crop Cover and Slope

A comparison between hourly ETo calculated using weather data measured at the meteorological station and in the wheat fields is given in Fig. 7.2. LAI values of 1.4, 2.2, and 1.3 observed, respectively, in sites A, B, and C seem to have relatively small impact on ETo estimations.

Average values of daily ETo calculated from data recorded in M, A, B, and C sites during the period March 07–31 were, respectively, 3.12, 3.08, 3.15, and 2.92 mm/day. High correlation was observed between ETo calculated using meteorological station data and those measured in the wheat fields, with R^2 more than 0.98 for daily and hourly values (Fig. 7.2). The regression lines between ETo of wheat fields (A, B, C) and meteorological station (M) had slopes in the range of 0.98–1.00. Relative root mean square deviations between ETo of site M and those of A, B, C were, respectively, 0.06, 0.07, and 0.06 for daytime hourly data and 0.05, 0.03 and 0.08 for daily data. This suggests that ETo determined using data of a standard weather station, and those measured on cultivated fields with LAI around 2 and with low slopes (5–6°) are comparable.
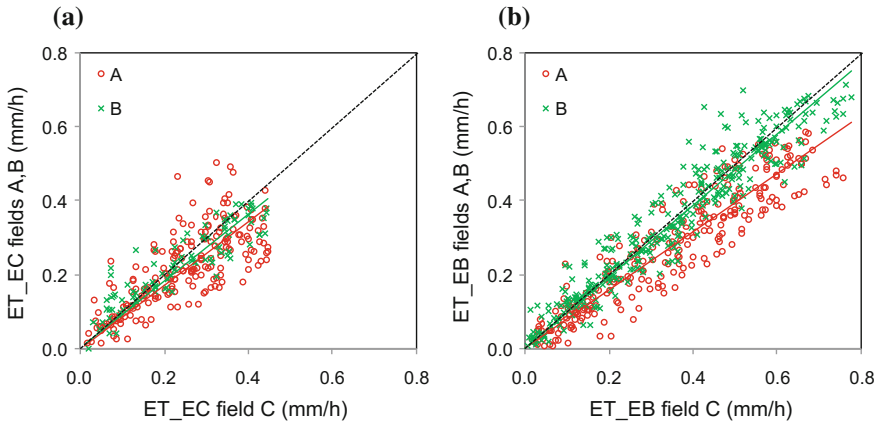
Fig. 7.3 Values of hourly ET observed on sloping fields (*A* and *B*) as function of those observed in flat condition (*C*) during the period March 07–31, 2013, using eddy correlation (**a**) and energy balance (**b**) methods

Impact of Slope on ET of Wheat

A comparison of hourly ET values measured by the eddy covariance and energy balance over the mid-season stage (March 07–31) between sloping fields (A, B) and flat field (C) is given in Fig. 7.3. Average value of ET in the flat field during the considered period was 4–22% higher than in the sloping sites. Values obtained with EC method in sloping fields A and B were, respectively, 15% and 10% lower than in C. However, better correlation between flat and sloping fields is observed with EB method.

Coefficients of determination for comparison of ET values observed at hilly sites (A and B) with those observed in (C) were, respectively, 0.89 and 0.93 for EB method, whereas for EC they were 0.54 and 0.74.

Maximum observed hourly ET during the period March 07–31, corresponding to mid-season stage, was around 0.55 mm/h for EC and 0.79 mm/h for EB.

Hourly and Daily Crop Coefficient of Wheat in Sloping Area

Hourly Values of ET/ETo Ratio
Hourly ET estimations by EC and EB at the three sites (A, B, C) during mid-season stage are represented in Fig. 7.4 versus ETo measurements in the respective site. The ratio ET/ETo, which represents the crop coefficient Kc for well watered conditions, is the slope of the linear regression line between ET and ETo.

The regression line slopes of Fig. 7.4a corresponding to ET determined by eddy covariance were 0.82, 0.86, and 0.96, respectively, for A, B, and C sites, well below

(a)

(b)
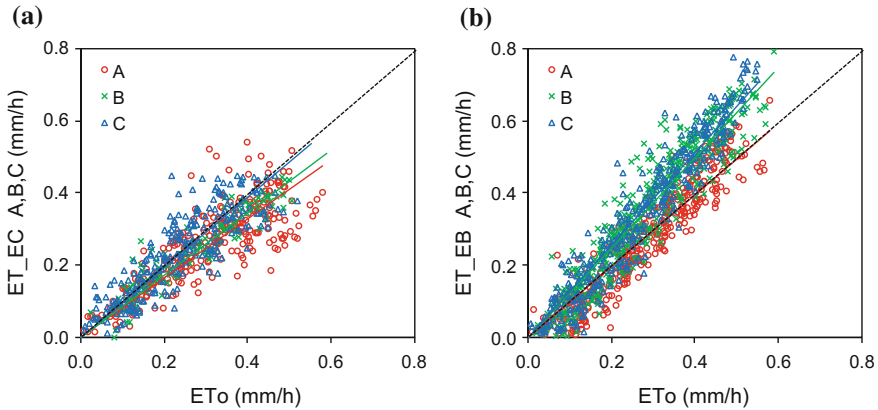
Fig. 7.4 Hourly ET values of wheat estimated by EC (**a**) and EB (**b**) methods in sloping (*A* and *B*) and flat (*C*) fields as related to ETo estimations using the FAO-PM equation in the corresponding site, during the mid-season stage of wheat (March 07–31, 2013)

values suggested by FAO (1.15) for mid-season stage. In contrast, ET determined by energy balance is closer to FAO levels with an ET/ETo ratio of 0.98, 1.24, and 1.27, respectively, for A, B, and C sites (Fig. 7.4b). This difference can be explained by a systematic underestimation of ET by the EC method and the closure problem in the surface energy balance, reported in the literature to be in the range of 10–30% (Twine et al. 2000). The relatively smaller crop coefficient in A would be the consequence of less exposure to dominant wind resulting in a lower mean daytime wind speed (4.18 m/s) compared to B (5.09 m/s) and C (4.53 m/s) and less vegetative vigor in term of height (45 cm for A vs. 57 cm for B) and LAI (1.4 for A vs. 2.2 for B).

Daily Values of ET/ETo as Compared to FAO-Kc

Daily ET values could not be determined for EC method because the high proportion of missing and rejected data by quality assessment. However, the lower percentage of rejected data for sensible heat (8–9%) allowed determination of ET using the energy balance equation. Considering that rejection rate is smaller during daytime and that global radiation and ETo during the period 8 h–19 h were found to represent, respectively, 99% and 93% of daily totals, daily ET was taken as the total of hourly values between 8 h and 19 h.

Figure 7.5 shows daily values of ET_EB in the three wheat fields as compared with ETo measured at each site during mid-season stage of wheat.

Fig. 7.5 Daily ET values of wheat estimated by energy balance equation (ET_EB) in sloping (*A*, *B*) and flat (*C*) fields versus ETo determined at each site during the period March 07–31, 2013
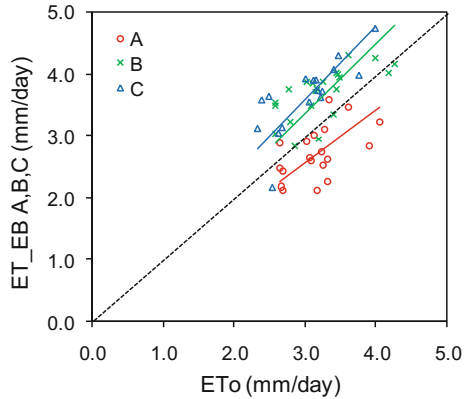
The slopes of the linear regression lines are, respectively, 0.85, 1.15, and 1.20 for A, B, and C sites. These are similar to hourly values; however, the observed slope for site A (0.85) seems to be too low compared to typical FAO-Kc values.

Conclusion and Perspectives

This work concerned assessment of evapotranspiration of cultivated fields in a hilly Mediterranean region. The slope and aspect effects on estimation of reference and actual evapotranspiration of a wheat crop were approached through field experiments involving three eddy covariance stations and a standard weather station. Results show that for slopes of 5–6° and LAI values around 2; relief and crop cover had only small effects on reference evapotranspiration estimates, suggesting the possibility of measuring ETo outside the standard conditions. Hourly Kc estimates determined as the ratio between ET_EC and PM-ETo were below values given by FAO, nevertheless better consistency was observed when ET was estimated by energy balance; this may be explained by the fact reported by several authors suggesting that the EC method overestimates the available energy and underestimates the convective energy. Also, despite the high volume of data recorded using the EC method, the percentage of LE data rejected by quality control tests was considerably greater than the percentage of H data rejected, particularly in sloping fields. Gap filling would have to be systematically used in order to generate daily values needed for operational use in agriculture.

References

Allen RG, Pereira LS, Raes D, Smith M (1998) Crop evapotranspiration—guidelines for computing crop water requirements—FAO irrigation and drainage paper 56. Food and Agriculture Organization of the United Nations, pp 465

Evett SR, Schwartz, RC, Howell TA, Baumhardt RL, Copeland KS (2012a) Can weighing lysimeter ET represent surrounding field ET well enough to test flux station measurements of daily and sub-daily ET? Adv Water Resour 50:(79–90)

Evett SR, Kustas, WP, Gowda, PH, Anderson, MC, Prueger, JH, Howell, TA (2012b) Overview of the bushland evapotranspiration and agricultural remote sensing EXperiment 2008 (BEAREX08): A field experiment evaluating methods for quantifying ET at multiple scales. Adv Water Resour 50:(5–19)

Falge E, Baldocchi D, Olson, RJ, Anthoni P, Aubinet M, Bernhofer C, Burba G, Ceulemans R, Clement R, Dolman H, Granier A, Gross P, Gru¨nwald T, Hollinger D, Jensen N-O, Katul G, Keronen P, Kowalski A, Ta Lai C, Law BE, Meyers T, Moncrieff J, Moors E, Munger JW, Pilegaard K, Rannik U, Rebmann C, Suyker A, Tenhunen J, Tu K, Verma S, Vesala T, Wilson K, Wofsy S (2001) Gap filling strategies for defensible annual sums of net ecosystem exchange. J Agric Meteorol 107:(43–69)

Feigenwinter C, Bernhofer C, Eichelmann U (2008) Comparison of horizontal and vertical advective CO2 fluxes at three forest sites. Agric Meteorol 148:12–24

Foken T, Wishura B (1996) Tools for quality assessment of surface-based flux measurements. J Agric Meteorol 78:83–105

Hammerle A et al (2007) Eddy covariance measurements of carbon dioxide, latent and sensible energy fluxes above a meadow on a mountain slope. Bound-Layer Meteorol 122:397–416

Holst T, Rost J, Mayer H (2005) Net radiation balance for two forested slopes on opposite sides of a valley. Int J Biometeorol 49:275–284

Hugo AG, Enrique R, Colin Cikoski C, Bruce J, Rafael L, Erkan I (2013) On the observed ecohydrologic dynamics of a semiarid basin with aspect-delimited ecosystems. Water Resour Res 49:1–22

Rana G, Ferrara RM, Martinelli N, Personnic P, Cellier P (2007) Estimating energy fluxes from sloping crops using standard agrometeorological measurements and topography. Agric Meteorol 146:116–133

Raupach MR, Finnigan JJ (1997) The influence of topography on meteorological variables and surface-atmosphere interactions. J Hydrol 190:182–213

Rebmann C, Göckede M, Foken T, Aubinet M, Aurela M, Berbigier P, Bernhofer C, Buchmann N, Carrara A, Cescatti A, Ceulemans R, Clement R, Elbers JA, Granier A, Grünwald T, Guyon D, Havránková K, Heinesch B, Knohl A, Laurila T, Longdoz B, Marcolla B, Markkanen T, Miglietta F, Moncrieff J, Montagnani L, Moors E, Nardino M, Ourcival JM, Rambal S, Rannik U, Rotenberg E, Sedlak P, Unterhuber G, Vesala T, Yakir D (2005) Quality analysis applied on eddy covariance measurements at complex forest sites using footprint modelling. Theor Appl Climatol 80(2–4):121–141

Tromp-van-Meerveld HJ, McDonnell JJ (2006) On the interrelations between topography, soil depth, soilmoisture, transpiration rates and species distribution at the hillslope scale. Adv Water Resour 29:293–310

Twine TE, Kutas WP, Norman JM, Cook DR, Houser PR, Prueger JH, Starks PJ, Wesley ML (2000) Correcting eddy-covariance flux underestimates over a grassland. Agric Meteorol 103:279–300

Van-Dijk A, Moene AF, DeBruin HAR (2004) The principles of surface flux physics; theory, practice and description of the ECPACK library. In: Meteorology and Air Quality Group. Netherlands