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Estimation and Application of Bowen Ratio Fluxes over Crop Surfaces – An Overview

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ABSTRACT

Bowen-ratio (β) is defined as the ratio of sensible heat flux (H) to the latent heat flux (LE) from a surface and its values varies from 0.1 over tropical oceans to greater than 10 over deserts. The Bowen ratio - energy balance (BREB) method is the simple yet most practical method for estimating latent and sensible heat fluxes from any surface. It is estimated from the principle of conservation of energy and combines measurement of temperature and vapour pressure gradients apart from net radiation (Q_n) and soil heat flux to give estimate of energy and mass fluxes over a surface. If advection is negligible and β is small and positive, this method measures the surface fluxes accurately. This method is useful in estimating evapotranspiration (ET) over canopy in various stages of crop growth as well as LE/Q_n, which is a better indicator of crop water demand than either crop coefficient or crop factor. In semi-arid environment, ET estimation over the crop surface with non-exchanging psychrometer is comparable to the lysimetric measurements.

Key words: Advection, bowen-ratio, crop coefficient, crop factor, energy balance, eddy diffusivity, evapotranspiration, latent heat, sensible heat

Introduction

Energy is the driving force for all physical, chemical and biological activities in the biosphere. The quantity and the form of energy available in a system determine the efficiency of the system. Total energy available over a crop surface and partitioning of this energy into different components such as sensible heat, latent and soil heat fluxes determine the crop production. Therefore, a thorough understanding of the radiation balance over a crop canopy and the accurate estimation of different components of net radiation over the crop surface assume a great significance. The concept of Bowen-ratio (Bowen, 1926) is widely used in the agrometeorological research. Bowen ratio-energy balance (BREB) method is a micrometeorological method derived by combining Bowen-ratio with energy balance equation of the earth's surface (Tanner, 1960). This method has been used to estimate energy (both latent as well as sensible parts) and mass (ET) fluxes, quantify water use of crop (Cargnel *et al.* 1996), calculate crop coefficients (Malek and Bingham, 1993), evaluate crop water use models (Todd *et al.* 2000), measurement of emission of trace gases like methane (Chan *et al.* 1998) and nitrous oxide etc., from the soil/crop surface, to measure of carbon dioxide assimilate rate in crops (Chan *et al.* 1998) and energy balance studies above the crop surface (Hatfield, 1990 and Mokate *et al.* 1995).

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Bowen-ratio (β) and its measurement

The ratio of sensible heat flux (H) and latent heat flux (LE) from a surface is known as Bowen-ratio and can be expressed as -

$$\beta = \frac{H}{LE}$$

The sensible heat flux and latent heat flux can be expressed in terms of vertical gradient of average air temperature and vapour pressure as shown below:

$$H = \rho_a . C_p . K_h . dT/dz$$

$$LE = \rho_a . (\varepsilon/P) . L . K_w . de/dz$$

Where,

ρ_a	=	Density of air ($1.145*10^{-3}$ g/cm^3)
C_p	=	Specific heat of air at constant pressure (0.24 cal/g/^{0}C)
ε	=	Ratio of molecular masses of water vapour and dry air (0.622)
P	=	Atmospheric pressure (mb)
K_h & K_w	=	Eddy diffusivity of water vapour and sensible heat (m^2s^{-1})
L	=	Latent heat of evaporation (580 cal/ cm^3)
e	=	Evaporation (cm/day)
de/dz	=	Vertical vapour pressure gradient
dT/dz	=	Vertical temperature gradient

Therefore,

$$\beta = \frac{H}{LE} = \frac{\rho_a.C_p.K_h.dT/dz}{\rho_a.\varepsilon/P.L.K_w.de/dz} \quad (1)$$

$$= \frac{C_p*P}{\varepsilon.L} * \frac{K_h}{K_w} * \frac{dT}{de} * \quad (2)$$

According to the Reynolds's analogy $K_h = K_w$

$$\text{Therefore, } \beta = \gamma.1.\frac{dT}{de} \quad (3)$$

(Where γ is phychromatic constant)

The data required for estimating Bowen-ratio of a surface are the vertical temperature and vapor pressure gradients. Aspirated psychrometer, consisting of dry bulb and wet bulb thermometer sensors are generally used to measure the air temperature and vapor pressure gradients.

Bowen-ratio over natural surfaces

Bowen-ratio is an index that can give idea about the climate of a place and the nature of under lying surfaces under various climatic conditions. It may be either positive or negative. It is positive when both the sensible heat and latent heat fluxes are away from or towards the surface i.e., in same direction. Generally during daytime, β remains positive. Negative β is common during night when sensible heat flux is downward but the evaporation still continues. In presence of advection, during daytime also β may be negative. Under such conditions sensible heat is consumed rather than generated by the surface under consideration. In situations when β is greater than unity, more amount of energy is partitioned into sensible heat than the latent heat meaning more energy is dissipated into the atmosphere as sensible heat rather than latent heat from the surface. This type of situations are found over dry surfaces like deserts where water is a limiting factor for evaporation where the climate is relatively dry and warm. On the other hand, when sufficient water is there in the surface, more amount of energy is partitioned into latent heat as compared to the other components of the net radiation. In such situations when β is less than unity, the climate is relatively cool and moist. Values of β over some surfaces are listed below (Oak, 1978).

Surfaces	β value
Tropical oceans	0.1
Tropical wet jungles	0.1-0.3
Temperate forest and grass lands	0.4-0.8
Semi arid areas	2.0-6.0
Deserts	> 10.0

Bowen-ratio energy balance method (BREB) for estimation of energy and mass fluxes

The Bowen-ratio energy balance method is the simplest and most practical method for estimating latent heat, sensible heat and evaporation fluxes from a surface. The accuracy of this method has been reviewed by many workers (Tanner, 1960; Sinclair *et al.* 1975, Kim *et al.* 1989, Dugas *et al.* 1991, Prueger *et al.* 1997 and Todd *et al.* 2000). This method is based on the principle of conservation of energy which also combines the concept of Bowen-ratio.

The simplified energy balance equation for the earth surface is expressed as -

$$Qn = H + LE + G \quad (4)$$

$$\Rightarrow H = Q_n - LE - G \quad (5)$$

$$\Rightarrow \frac{H}{LE} = \frac{Q_n - G}{LE} - 1 \quad (6)$$

$$\Rightarrow \beta + 1 = \frac{Q_n - G}{LE} \quad (7)$$

$$\Rightarrow LE = \frac{Qn - G}{1 + \beta} \quad (8)$$

Equation (1) is used in BREB method for estimating different energy fluxes from a surface. In this method, the measurements of net radiation, air temperature and humidity gradients and soil heat flux are used to give the estimate of evapotranspiration. The measurements of air temperature gradient and humidity gradients are done with BREB apparatus (Varshneya, 2001).

Assumptions in BREB method

The BREB method relies on several assumptions (Fritschen and Simpson, 1989), which are considered during measurement of fluxes by the BREB method. The assumptions are -

i) transport of entities is assumed to be one dimensional with no horizontal gradient.

ii) measuring sensors assumed to be located within sub-layer where fluxes are assumed to be constant with height.

iii) the surface is assumed to be homogeneous with respect to sources and sinks of heat, water vapour etc.

iv) the ratio of turbulent exchange coefficients for heat and vapour is assumed to be 1 i.e., $K_h = K_w$

The first two assumptions are satisfied only when adequate upwind fetch is available. A fetch to height-above-surface ratio is 100:1 is often considered a rule of thumb (Rosenberg *et al.* 1983). When β is small and positive a ratio as low as 20:1 is considered adequate (Heilman *et al.* 1989).

Bowen-ratio approach in estimating gas fluxes over a surface

BREB method was also used to measure fluxes of the different gases like CO_2 and CH_4 from crop or soil surface by Chan *et al.* (1998), who described the theory of estimating CH_4 flux from the peat land ecosystem which is discussed below.

$$F_{CH_4} = \frac{K_{mc}.dc}{dz} \quad (9)$$

Where;

F_{CH_4} = Methane flux.

K_{mc} = Eddy diffusivity coefficient of methane.

dc/dz = Concentration gradient of methane.

Since, $LE = \rho_a.\varepsilon/P.\ L.\ K_w.\ de/dz$ (10)

According to Reynolds analogy the eddy diffusivity of water vapour (K_w) is equal to the eddy diffusivity of methane (K_{mc}). Therefore in equation (iii) K_w can be replaced with K_{mc}. Thus extending Reynolds analogy to equation (i) and (iii) the eddy diffusivity of methane can be estimated. Once the value of eddy diffusivity of methane is obtained, the flux of this gas from any surface can be calculated from the equation (ii).

Advantages and disadvantages of BREB method

Bowen-ratio energy balance method is gaining popularity because of improvement in portable acquisition system of field data, sensor accuracy and precession. The advantages of the BREB method include-its straightforward and simple measurements; it requires no information about the aerodynamics characteristics of the surface of interest; it can integrate fluxes over large area (100 to 1000 of square meters); it can integrate fluxes on fine time scale (less than one hour) and it can provide continuous and unattended measurements (Todd *et al.* 2000). The disadvantages of this method include-sensitivity to the biases of instruments which measures gradients and energy balance terms; the possibility of discontinuous data when the Bowen-ratio approaches -1.0 and the requirement of adequate fetch to ensure adherence to the assumptions to the method (Todd *et al.* 2000).

Reliability assessment of BREB method

Error analysis to determine reliable and correct value of Bowen-ratio as well as to identify the conditions when the BREB method fails is important. Perez *et al.* (1999) identified the five different conditions on the basis of analysis of data collected in the period from 1991 to 1994 in four different sites in semi arid climate in Spain when BREB method failed. They also classified the errors in estimation of fluxes by BREB method. The types of errors identified are listed below.

Conditions	Type of error
Qn - G > 0; $\Delta e > 0$ and $\beta < -1 + \varepsilon$	A
Qn - G > 0, $\Delta e < 0$ and $\beta > -1 + \varepsilon$	B
Qn - G < 0, $\Delta e > 0$ and $\beta > -1 - \varepsilon$	C
Qn - G < 0, $\Delta e < 0$ and $\beta < -1 - \varepsilon$	D
Rapidly changing T and e	E

Here, Δe = Vapour pressure difference between lower and upper measurement level.

ε = Error interval, (excluded interval of β values around - 1).

= $0.019/\Delta e$

Different type of errors (A, B, C, D and E) occur under following situations:

Early morning and late afternoon, when heat fluxes changes their sign.

During rainfall and irrigation with low values of Δe.

When Qn - G is very low.

During night, when Δe is negative (condensation).

Bowen-ratio and flux estimation

In advective conditions and when β is negative, BREB method cannot give accurate measurements of fluxes of different entities. This method estimates the fluxes accurately only in a small range of Bowen-ratio. As the value of Bowen ratio increases or decreases from that range, the estimation error also increases. The estimation errors of BREB method at different β values are listed below as reported by Panna Lal (1986).

i) When β value < 1, the estimation error is < 10%.

ii) When β value < 0.3, the estimation error is < 5%.

iii) When β value is positive and near to zero the estimation error is minimum.

iv) When β value is -1, the estimation error is 100%.

v) Safe range of β value for flux estimation = - 0.3 to 0.3.

Comparison of BREB method with Eddy correlation technique

Eddy correlation technique (Swinbank, 1951) is a micrometeorological method use to measure vertical energy and mass fluxes from a surface. This method is based on the fact that water vapour and energy are transported in the vertical direction by the upward and downward motion of small parcels of air or eddies. Dugas *et al.* (1991) compared the performance of BREB method with eddy correlation technique. They estimated the latent heat and sensible heat fluxes in the atmospheric boundary layer over irrigated spring wheat by both BREB and eddy correlation methods. The estimated sensible and latent heat fluxes were more when measurement of fluxes was done by BREB method as compared to eddy correlation technique (Table 1).

In the observation days, the values of β were positive and small for most of the time of the day. The difference between Q_n-G and LE+H was more, when measurements were taken by eddy correlation technique in both the days of observation. On the other hand this gap was insignificantly lower when measurements were taken by BREB method. Therefore, they concluded that the flux estimation was more accurate in BREB method as compared to eddy correlation technique (Fig 1).

Energy balance over crop canopy and crop factor (K_f)

The seasonal trend of energy balance over irrigated wheat at various growth stages was studied

Table 1. Average energy flux density (Wm^{-2}) calculated from Bowen-ratio energy balance method (BR) and eddy correlation (EC) instrumentation

Day(1989)	Hours (h)	LE		H	
		BR	EC	BR	EC
A	7.30 - 17.00	560	436 (77%)*	- 178	- 146 (82%)
B	7.30 - 18.00	399	266 (67%)	- 45	- 31 (69%)

*Percentage of that estimated by BREB method

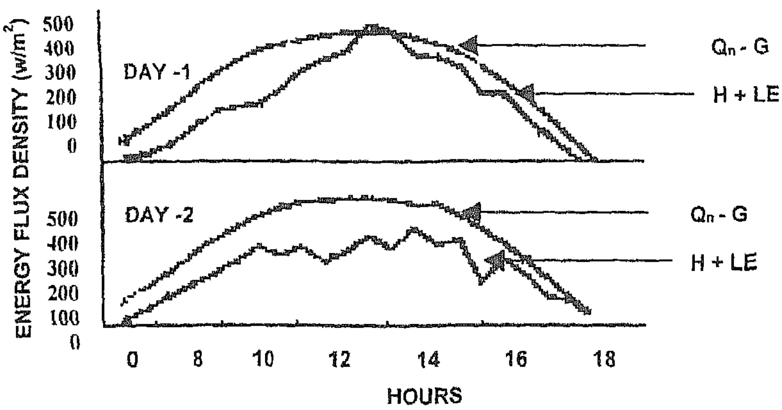

Fig. 1. Half hourly averages of available energy (Qn - G) and the sum of eddy correlation sensible heat and latent heat (H+ LE)

by using BREB method (Mokate *et al.* 1995) in CASAM, Pune. In the days of observations during emergence (E), crown root initiation (CRI) and tillering (T) stages, the sensible heat advection was negligible, 71 to 86 per cent of net radiation was partitioned in to latent heat flux (LE) and 13 to 21 per cent in to soil heat flux (G). The latent heat flux in the observation days at jointing (J), flowering (F), soft dough (SD) and hard dough (HD) stages were 95, 108, 100 and 112 percent of the net radiation, respectively. The contribution of sensible heat advection in increasing evapotranspiration in these days was 5, 13, 5 and 9% respectively (Fig 2).

Evapotranspiration, crop coefficients (ET/PET) and crop factors (ET/Pan evaporation) estimated for various crop growth stages are presented in Table 2. The crop coefficients were estimated using PET calculated by modified Penman formula. The PET was less than the estimated ET in the early stages of crop growth (when soil coverage was less) indicating under estimation of PET. The crop factors at various growth stages suggested that crop water demand was the maximum at the jointing stage, where as it should be at the flowering stage. Thus both the crop coefficient and the crop factor were not the good indicator of crop water demand. On the other hand, LE/Q_n increased from 0.71 to 1.12 from emergence to hard dough stage and then it declined to 0.40 at maturity stage. Therefore, they concluded that the LE/Qn was a better indicator of crop water demand than either crop coefficient or crop factor.

Instruments for measuring Bowen Ratio

a) ***Energy Balance Bowen Ratio Station (EBBR):*** The Energy Balance Bowen Ratio (EBBR) system produces 30 min estimates of the vertical fluxes of sensible and latent heat at the local surface. Flux estimates are calculated from observations of net radiation, soil surface heat flux and the vertical

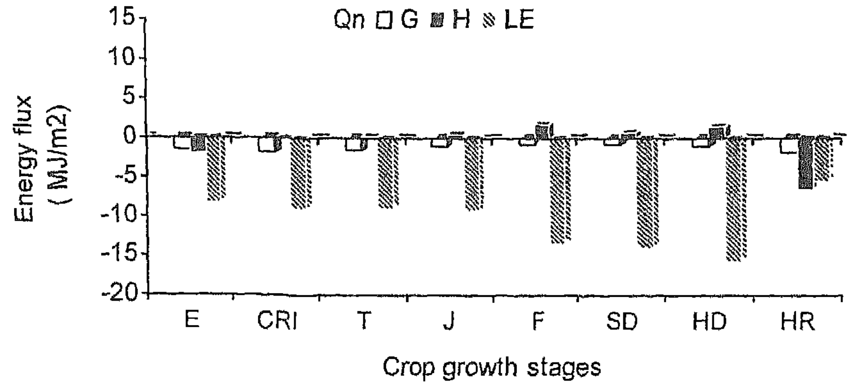

Fig. 2. Energy balance components at various growth stages of wheat estimated by BREB method (HR represents the harvesting)

Table 2. Total daily - LE/Q_n, Kc and K_r in different growth stages of wheat

Growth stages	Qn ($MJ/m^2/d$)	ET (mm/d)	- LE/Q_n	Kc	K_r
Emergence	11.71	3.5	0.71	1.04	0.70
CRI	10.89	3.7	0.83	1.21	0.89
Tillering	10.58	3.8	0.86	1.41	1.03
Jointing	9.71	3.9	0.95	1.26	1.26
Flowering	12.55	5.9	1.08	1.64	1.13
Soft dough	13.90	6.3	1.00	1.58	1.17
Hard dough	14.11	7.1	1.12	1.40	1.10
Harvest	13.73	2.3	0.40	0.42	0.32

gradients of temperature and relative humidity. Meteorological data collected by the EBBR are used to calculate bulk aerodynamic fluxes, which are used in the Bulk Aerodynamic Technique (BA) EBBR value-added product (VAP) to replace sunrise and sunset spikes in the flux data. A unique aspect of the system is the automatic exchange mechanism (AEM), which helps to reduce errors from instrument offset drift.

b) ***Eddy Correlation Flux Measurement System (ECOR)*** : Eddy correlation is the most direct micrometeorological technique for measuring turbulent fluxes in the surface layer of the atmospheric boundary layer. It is direct in that it involves fewer assumptions than other methods. Some remaining assumptions are that sensors have fast response and the measurement site is horizontally homogeneous enough to avoid measurement problems associated with adjective fluxes and terrain-induced flow distortion.

The eddy-correlation computation of sensible heat flux is the product of the volumetric heat capacity of air and the covariance between vertical wind speed and air temperature. The covariance between vertical wind speed and air temperature is separately entered as and the latent heat flux is calculated as the product of the latent heat of vaporization and the covariance between vertical wind speed and humidity.

The eddy correlation (ECOR) flux measurement system provides *in situ*, half-hour measurements of the surface turbulent fluxes of momentum, sensible heat, latent heat and carbon dioxide. The fluxes are obtained with the eddy covariance technique, which involves correlation of the vertical wind component with the horizontal wind component, the air temperature, the water vapor density, and the CO_2 concentration. Instruments used are

- A fast-response, three-dimensional (3-D) wind sensor (sonic anemometer) to obtain the orthogonal wind components and the speed of sound (SOS) (used to derive the air temperature).
- An open-path infrared gas analyzer (IRGA) to obtain the water vapor density and the CO_2 concentration.

The ECOR systems are deployed at the locations where other methods for surface flux measurements (e.g., energy balance Bowen ratio systems) are difficult to employ, primarily at the north edge of a field of crops.

c) ***A simple devise*** : Panna Lal (1986) designed a simple yet reliable instrumental setup to measure the water vapor and wind fluxes over bare field as well as over cropped surface. The setup consisted of thermocouple thermometers and simple anemometers placed at different heights on a mast. From these fluxes, the Bowen ratio is calculated.

Lysimetric measurement vs. BREB method

The performance of BREB method and Lysimeter in estimating evapotranspiration was compared by Prueger *et al.* (1997). The estimation of ET by lysimeter and simple Bowen-ratio system was made in 1993 and 1994 over lentil crop in semi arid climate. The trends of cumulative ET in both the systems were similar (Fig. 3a). In the first year (1993) up to 210 Julian Day (JD), there was no difference between lysimetric estimation and estimation by BREB system, where as there after there was significant difference between the two systems. In the second year (1994) up to 185 JD, there was no difference between two systems, but there after significant difference was observed between them. Difference was more in first year

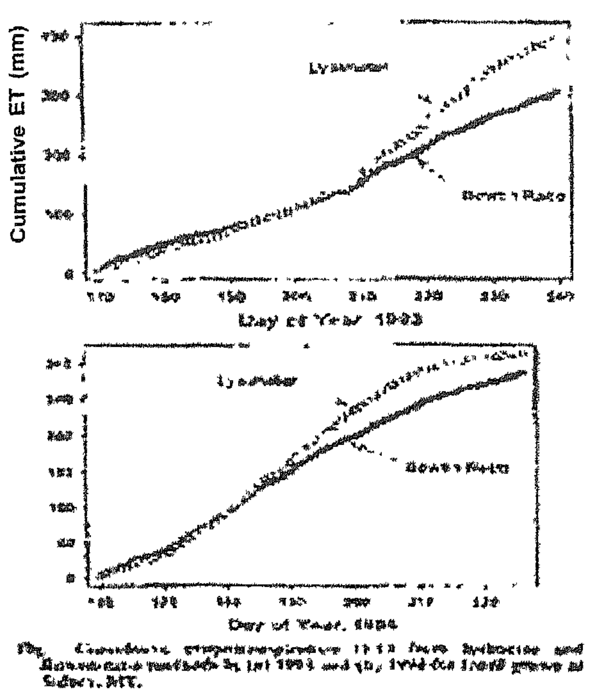

Fig. 3a. Cumulative evapotranspiration (ET) from lysimeter and Bowen-ratio methods in (a) 1993) and (b) 1994 for lentil grown at Sidney, MT

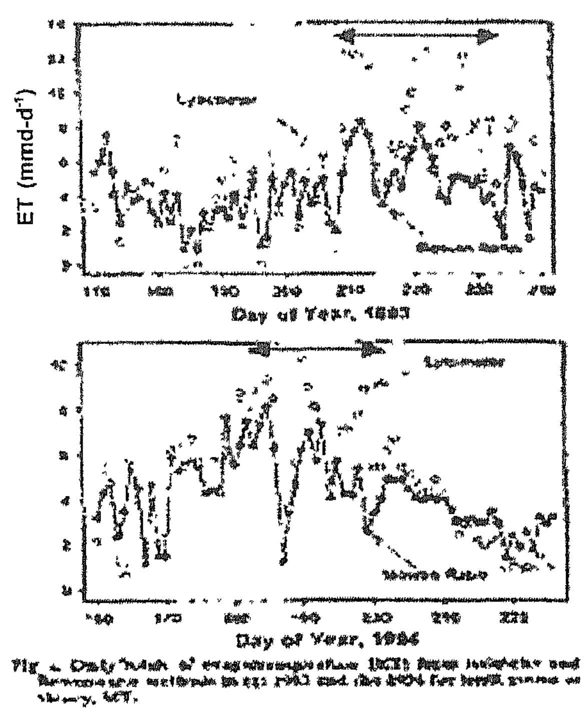

Fig. 3b. Daily totals of evapotranspiration (ET) from lysimeter and Bowen-ratio methods in (a) 1993 and (b) 1994 for lentil grown at Sidney, MT

than in the second year. In the first year, lysimeter ET was 6.01 mm d^{-1} and Bowen-ratio ET was 4.3 mm d^{-1}, where as in the second year ET were 4.9 and 4.5 mm d^{-1} as measured by lysimeter and Bowen-ratio system respectively. There were no significant differences in daily total of ET from lysimeter and Bowen-ratio systems up to 210 and 185 JD in the first and the second year, respectively (Fig. 3b). Differences were more prominent in both the year when there was rainfall. Precipitations during growing seasons from planting to harvesting were 367 and 227 mm in the first and the second year, respectively. During first crop season, soil water content of the lysimeter was greater than the field after large precipitation events around 210 JD, even though the lysimeter was drained. After this day, lysimeter ET exceeded than that was measured by Bowen-ratio system. Agreement was closure in the second year when precipitation was near normal and there was no excess soil water in the lysimeter.

Cumulative ET totals after rainfall events from the lysimeter was more as compared to the Bowen-ratio estimation because after large precipitation soil moisture inside lysimeter was more relative to the field and more water was available for ET. More over, heavy rainfall caused some foliage extended beyond the edge of the lysimeter rim and increasing the area of net radiation capture relative to actual lysimeter area, there by more amount of energy was available for evaporation. Cumulative ET totals from the lysimeter were reflective of the seasonal precipitation patterns. Differences between the lysimeter and Bowen-ratio occurred when there was excess precipitation and inadequate drainage from lysimeter. From their studies, they concluded that Bowen-ratio system can provide satisfactory estimates of daily and seasonal ET and can be used to estimates ET in semiarid climates.

Performance of BREB method in the advective environment

Todd *et al.* (2000) compared the latent heat flux of irrigated alfalfa crop estimated by the BREB method with that measured by lysimeter over a growing season in the semi-arid advective environment. They compared the mean values of ET measured by the two lysimeter and two BREB systems, which were exposed to the greater fetch (Fig. 4). Estimation of ET by lysimeter was higher than Bowen-ratio estimation when β value was negative or both latent and sensible heat fluxes were toward the surface (during night). There was no difference in ET estimation by both lysimeter and BREB system, when β values were between 0 and 0.3. However, when β value was greater than 0.3, BREB estimation was higher than that of lysimeter estimation.

They also compared two BREB systems (Sys - 1 and Sys -2) installed in opposite side of the field

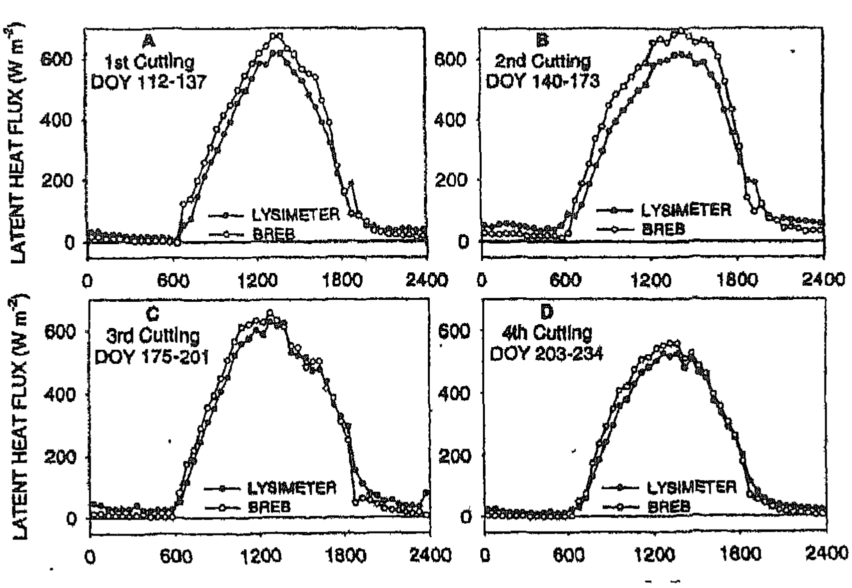

Fig. 4. Mean daily latent heat flux as measured by lysimeter and estimated by BREB method

in two days (north and south). In the first day (day - 1) there was sensible heat advection and system - 1 was exposed to greater fetch. The day was hot, dry and windy when the latent heat flux exceeded the available energy. On this day, the greatest difference between the two systems in estimating ET was observed (Table 3). On the other hand, on day - 2 there was no sensible heat advection and both the systems estimated more or less equal ET.

The relative difference between BREB and lysimetric measurement of LE increased as β either decreases from 0 or increases from 0.3 and when β value was between 0 and 0.3 and there was no advection the BREB method performs well in semi arid condition.

Table. 3. LHF estimated by two BREB systems

BREB Systems	Wind direction	LE/Q_n-G	LHF (w/m^2)
Day-1 (219 DOY)			
Sys - 1(N)	S-SW	1.32 ($LE>Q_n$-G)	492
Sys - 2 (S)			553
Day-2 (224 DOY)			
Sys - 1(N)	N-NW	1.02 ($LE = Q_n$-G)	361
Sys - 2 (S)			357

Estimation CH_4 flux from peat land ecosystem by BREB method

Methane flux from peat land surfaces were estimated by BERB method and closed chamber method by Chan *et al.* (1998). The flux rates obtained by both methods were compared using nine time points over three days at a peat land site and the mean fluxes obtained by both methods was of same magnitude (2.43-5.88 mg CH_4 m^{-1} h^{-1}) (Table 4). Mean fluxes obtained by chamber method were not significantly different (P>0.05) than the fluxes obtained from BERB method on sampling dates. Three days averages obtained from two methods were also very much similar. However, temporal variability of methane fluxes was much more in case of BREB method as compared to closed-chamber method.

Table 4. Comparison of CH_4 fluxes determined using closed chamber and BREB method

Day	Time (h)	Methane flux ($mg\ m^{-2}\ h^{-1}$) Closed chamber method	BREB Method
Day - 1	0900	4.21	1.97
	1250	3.08	0.88
	1700	2.92	4.94
	Mean	**3.14**	**2.43**
Day - 2	0900	5.46	2.02
	1250	7.18	1.25
	1700	5.01	12.00
	Mean	**5.88**	**5.09**
Day - 3	0900	4.94	-3.94
	1250	4.86	12.2
	1700	5.59	0.48
	Mean	**5.13**	**2.92**
	3 Day Mean	**4.18**	**3.48**

Conclusions

Bowen ratio method is simple, accurate and requires less instrumentation for measurement or estimation of energy and mass fluxes over different surfaces including crops and soils. This method is widely used in agriculture. However, this method has some limitations under arid and humid conditions where fluxes and mass exchange are under or over estimated. Bowen-ratio system can provide satisfactory estimates of daily and seasonal ET and can be used to estimates ET in semiarid climates

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