APPLICABILITY OF BOWEN RATIO ENERGY BALANCE METHOD IN FETCH LIMITED CONDITIONS

APLIKOVATELNOST METODY BOWENOVA POMĚRU V PODMÍNKÁCH S LIMITOVANÝM FETCH

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ABSTRACT

Water plays a key role in the climatic processes of the Earth. In terrestrial ecosystems the main component of water loss is evapotranspiration. One of the standard techniques used to measure evapotranspiration indirectly is the Bowen ratio energy balance method (BREB). This study focuses on the quantification of errors caused by insufficient fetch (upwind distance from the edge of investigated cover) using data from two BREB systems obtained through intensive summer 2012 campaign. The measurement took advantage of one mobile and one fixedly positioned BREB systems employed at turf grass cover from the prevailing north-west wind direction surrounded by broadleaved trees, poplar stoolbed dirty road and buildings at experimental station in Domanínek near Bystřice nad Pernštejnem. Surprisingly, the results showed no significant systematic deviation between the reference BREB with sufficient 180 m long fetch and mobile BREB positioned at fetches between 10 to 100 m. Moreover, it was not found any impact of the fetch on non-systematic errors leading to the conclusion that the fetch did not have any effect on the overall data quality and consistency. One of the explanations may be very similar response to soil moisture conditions of the selected contrasting living ecosystems and thus their similar Bowen ratios.

Key words: evapotranspiration, Bowen ratio energy balance method, limited fetch

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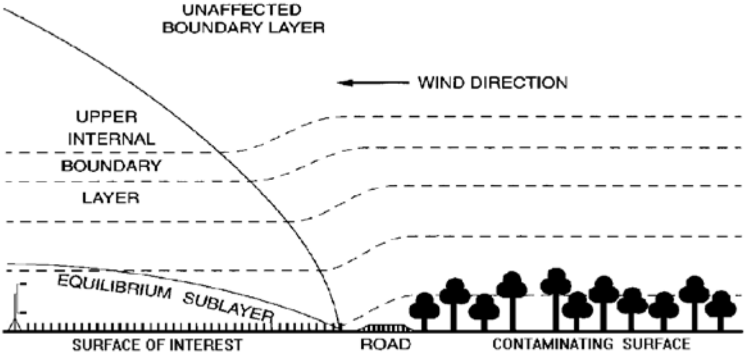
INTRODUCTION

Water plays a key role in the climatic processes of the Earth. Quantitative expression of all water within ecosystem can be described as water balance. In terrestrial ecosystems the main component of water loss is evapotranspiration (ET). One of the standard techniques to measure LE indirectly is the Bowen ratio energy balance method (BREB) (Heilman and Brittin, 1989). The BREB determines latent and sensible heat fluxes. The surface area that accounts for some large percentage of the measured flux (say more than 90 %) is called the source area of the measurement, and the horizontal distance from the sensor to the upwind discontinuity is called the fetch. The fetch divided by the sensor height is the fetch-to-height ratio. The surface downwind of the discontinuity is the surface of interest (Stannard, 1997). As Heilman and Brittin (1989) explain, as air moves downwind, after a change in surface roughness, it forms an internal boundary layer whose thickness increases with the fetch. For BREB it is required that temperature and humidity gradients are measured within the internal boundary layer that is in equilibrium with the surface (Heilman and Brittin, 1989). Fig. 1 shows the schematic of field layout, equilibrium sublayer and internal boundary layer using Stannard´s (1997) picture.

Figure 1 Schematic of field layout for determining Bowen-ratio fetch requirements and approximate boundary layers (adapted from Stannard, 1997)



To ensure that measurements are made in the equilibrium layer the described minimum fetch-to-height ratios have been ranging from 10:1 (Panofsky and Townsend, 1964) to 200:1 (Dyer, 1965). General agreement considers the ratio 100:1 to be sufficient for the most measurements (Rosenberg et al., 1983) According to Heilman and Brittin (1989) calculations indicate that BREB may be less sensitive to inadequate fetch conditions when the Bowen ratio is small. It is often reality that a site has not sufficient size. The micrometeorological measurements of LE are often affected to some degree by errors arising from limited fetch. Practically, fetch is often limited, and the measurements are somewhat affected by fluxes of sensible heat and water vapour from an upwind contaminating surface i.e. in this case dirt road, broadleaf trees, and buildings. That is why this study has been focusing on applicability of Bowen ratio energy balance method in fetch limited conditions. In particular, this study aims to deal with two hypotheses:

1) The measured evapotranspiration of the grass is increasing downwind from the possibly drier area due to the rising of equilibrium layer (Fig. 1).
2) As the wind blows along homogenous cover (turf grass) the overall data quality and consistency increases with fetch.

MATHERIALS AND METHODS

This study takes advantage of BREB method which is based on rearrangement of the surface energy balance equation (Bowen, 1926). The surface energy balance equation is given by: $R_n - G = H + LE$, where R_n is the net radiation flux, G is soil heat flux, H and LE are sensible heat and latent heat fluxes respectively (all in W m^{-2}), neglecting the energy used in photosynthesis and stored in canopy (Guo et al., 2007). The LE is basically evapotranspiration expressed in energy units ($LE = \lambda ET$). The Bowen ratio is defined as the ratio of sensible (H) and the latent (LE) heat flux: $\beta = \frac{H}{\lambda ET}$ and based on the flux gradient relationship $\beta = \frac{\gamma K_H}{K_{LE}} \frac{\partial T}{\partial e}$, where γ is psychrometric constant (0.066 kPa $°C^{-1}$), K_H and K_{LE} (m^2 s^{-1}) are eddy diffusivity for temperature and water vapour respectively, ∂T and ∂e are the vertical difference in temperature (°C) and water vapour (kPa) respectively. According to the Bowen ratio similarity principle $K_H = K_{LE}$ and that is why they can be left out from the calculation. The combination of energy balance and BREB is then following equation: $\lambda ET = \frac{R_n - G}{1 + \beta}$. To divide the available energy between the sensible- and the latent-heat fluxes the temperature and humidity is measured at two heights above a surface (Savage, 2010). In this study the temperature and humidity were measured at two heights 0.4 m and 2 m above the surface using one mobile and one fixedly positioned BREB systems (EMS Brno, Czech Republic) employed at turf grass cover from the prevailing north-west wind direction surrounded by broadleaved trees, poplar stoolbed, dirty road and buildings. The experiment took place at an experimental field of the experimental station in Domanínek near Bystřice nad Pernštejnem in an area of the Czech-Moravian Highlands (Czech Republic, 49° 31´ N, 16° 14´ E and altitude 530 m a.s.l.). The lawn was cut periodically to maintain 5−6 cm height of the turf grass. The data has been obtained through intensive summer 2012 campaign since 4th July to 10th October 2012. Before the meteorological stations were placed in the field for the first time all sensors were calibrated in the laboratory. After that, the BREB systems were placed next to each other on the grassland of experimental station in Domanínek in order to ensure the laboratory calibration was successful. This “field calibration” produced highly satisfactory results too. Subsequently, the mobile BREB system was moved to distance 10 m from the edge of homogenous cover (fetch = 10 m). Gradually, once in a week or two weeks (depending on the wind direction and occurrence of the anticyclonic weather conditions) this station was transferred to collect data from all fetches: 20, 25, 30, 40, 50 and 100 m. The dates and time of changes is showed in table 1 on the next page. Afterwards the data were calculated following BREB methodology and the suspicious data were removed according Guo et al. (2007). The remaining outliers were finally deleted graphically after visual control. In these calculations also data from another station were used. This station is positioned 100 m south from the fixedly positioned reference station and equipped with other auxiliary instrumentation - for more detail see Fischer (2012). Subsequently, the gathered data were filtered according to required wind directions between 230–300° from which the reference BREB was facing the longest fetch around 180 m.

Table 1 Dates and time of changing fetch and number of measured values

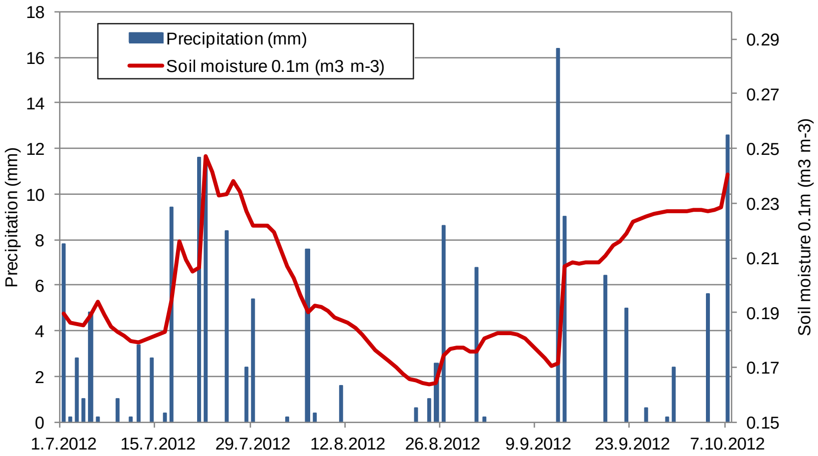
Number	Fetch (m)	Date	Time	N
1	10	11.7.	18:20	169
2	25	31.7.	9:15	84
3	40	10.8.	10:00	25
4	50	15.8.	9:14	51
5	100	23.8.	13:30	79
6	10	29.8.	10:10	28
7	20	6.9.	10:20	61
8	30	17.9.	17:20	27
9	50	27.9	10:05	58
10	100	4.10.	9:20	28
The end of experiment		10.10.	10:00	

The evapotranspiration was calculated for three different BREB stations. Fixedly positioned BREB station with long fetch was considered as reference values. The LE was compared with the LE based on the data from the mobile station. The fetch of this station was being changed according to Tab. 1. The third BREB system placed nearby with limited 5 m fetch surrounded by bare soil with emerging weeds (maximum coverage was estimated to 10 %) served for confrontation.

RESULTS AND DISCUSSION

In order to evaluate the dryness of the environment during the experiment the precipitation was compared with the long term average. The actual values are shown in following graph (Fig. 2). According to the long term average between 1981 and 2010 mean monthly precipitation in Domanínek in July is 75.48 mm whereas this summer it was 3.0 % lower. In August it was 57.6 % lower than the long term average 69.41 mm and in September 20.0 % lower than the typical 50.28 mm.

Figure 2 Graph of precipitation (mm) in daily sums and soil moisture in 0.1 m (m^3 m^{-3})



Figures 3, 4 and 5 show the examples of calculated LE for all three BREB stations in different weather conditions. Fig. 1 displays LE during wet conditions after rain. It can be mentioned that the difference between fixedly positioned BREB, mobile station with fetch 100 m, and BREB station with limited fetch 5 m is barely noticeable. On the other hand, while the weather conditions were drier the difference is much clearer as it is visible in the Fig. 5 when the mobile station had fetch 20 m. Fig. 4 shows the conditions in between.

Figure 3 Diurnal dynamics of evapotranspiration during wet conditions after precipitation and fetch 100 m

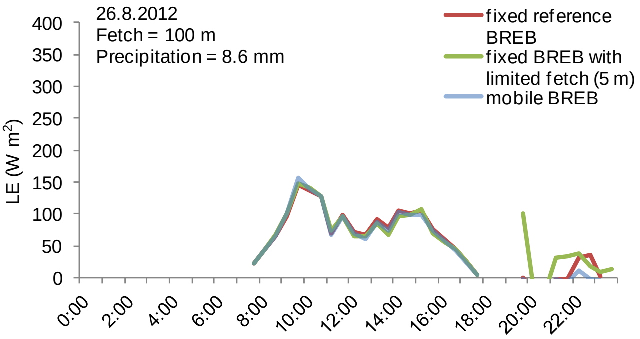


Figure 4 Diurnal dynamics of evapotranspiration during mild conditions and fetch 25 m

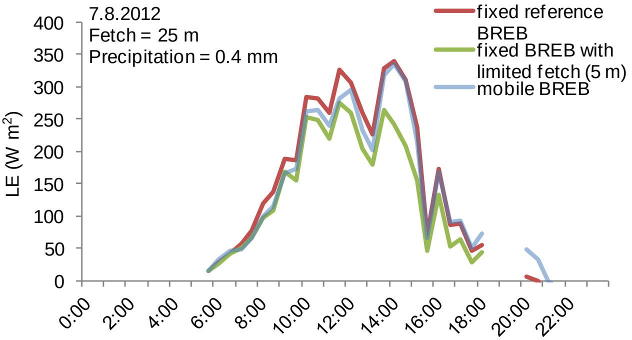
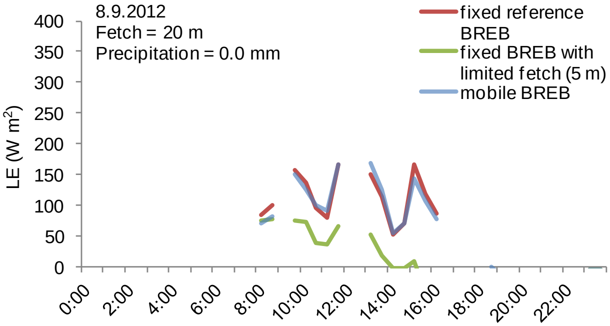


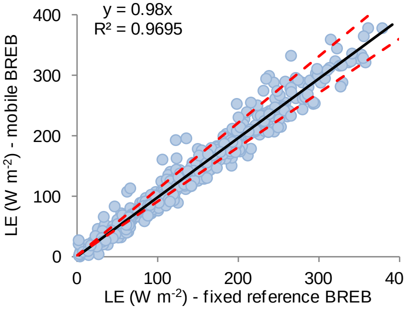
Figure 5 Diurnal dynamics of evapotranspiration with dry conditions and fetch 20 m

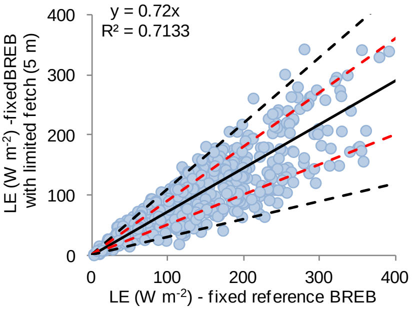


Because of described results it can be stated that precipitation and subsequently soil moisture have considerable effect on the importance of fetch if LE is calculated. After the rain when the soil is refilled with water LE of reference, mobile and also fixed station with limited fetch, are basically the same. It means that in these conditions fetch itself does not play the key role for estimation of LE. On the other hand, when the weather conditions are dry the difference between fixed station with limited fetch and two other stations is emphasized (Fig. 5). Theoretically, if the two covers were more contrasting (irrigated lawn against dry bare soil) the effect of fetch would be more significant. In this part of article it can be summarized that the expected underestimation of calculated LE with shorter fetch in comparison with long fetch is negligible during wet conditions and even fetch shorter than 20 m can results in underestimation less than 10 %. This is also shown in the following Fig. 6 and 7. In the Fig. 6 the comparison of LE of fixed reference and mobile BREB system during the whole period is displayed. Linear regression line has slope 0.98 (2 % underestimation) and in the picture it is black. Two red dashed lines stand for the slope 1.1 and 0.9 to demonstrate that the majority of values from the mobile BREB deviate mostly by ±10 % from those measured at the fixed reference BREB.

Figure 6 Comparison of LE of fixed reference and mobile BREB, black linear regression line has slope 0.98, red dashed lines depict the slope 1.1 and 0.9.

Figure 7 Comparison of LE of fixed reference and fixed BREB with limited fetch (5 m), black line has slope 0.72, red dashed lines have slope 0.9 and 0.5, and black dashed lines 1.1 and 0.3.





The graph in Fig. 7 shows the relation of LE (W m^{-2}) of fixed reference and fixed BREB with limited fetch. Two red dashed linear regression lines have slopes 0.9 and 0.5 which shows that most of the values for fixed BREB with limited fetch are underestimated between 10 and 50 %. This is a result of the short 5 m fetch where the grassland is surrounded by bare soil. Overall, there is underestimation of 28 % (slope 0.72) Two black dashed lines have slopes 1.1 and 0.3 and are displayed to demonstrate that fixed BREB system with limited fetch overestimate up to 10 % but there are also values underestimating more than 70 % although, there are not many of them. In general the underestimation station with short fetch occurs when the bare soil around the lawn is dry. In contrary, during wet conditions values calculated for short fetch can be very comparable with the ones for long fetch (fixed reference).

Furthermore, the LE from mobile BREB system and fixed station with long fetch were compared using statistical variables coefficient of determination (R^2), slope of linear regression line, mean bias error (MBE) and root mean square error (RMSE) according to Willmott (1982). The results are shown in subsequent figures (Fig. 8–10). It is obvious that even the random error (expressed as R^2 and RMSE) is not affected by the length of fetch. In other words, it means that fetch influences neither the data consistency nor their quality.

However, slow increase of the coefficients of determination (Fig. 8) and the slopes of linear regression lines (Fig. 9) can be observed, nevertheless, these trends are not statistically significant. Though, there is an unexpected result within the 10 m long fetch. This might be due to the sudden change of aerodynamical roughness caused by the transition from the area with high roughness (trees and shrubs) to the short aerodynamically smooth grass cover resulting in enhancement of the eddy diffusivities in a few first meters. Although the eddy diffusivities for temperature and water vapour are expected to be the same (Stannard, 1997) and thus enhanced by the same portion, the latent heat flux is generally much higher in such kind of environmental conditions and therefore its absolute values will be more increased by this eddy diffusivity enhancement. Apart from the change of roughness another explanation can be seen in the fact that if the wind is bringing drier air it can cause higher LE at the edge of the lawn. This is well known as so called edge effect (Oke, 1987).

Figure 8 The coefficients of determination

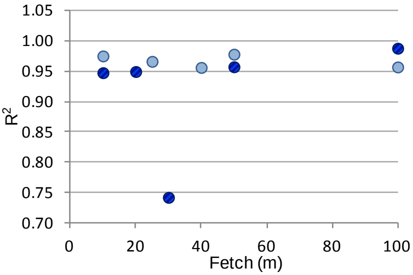


Figure 9 The slopes of linear regression lines

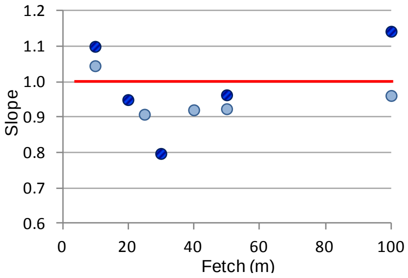


Figure 10 Root mean square errors (%)

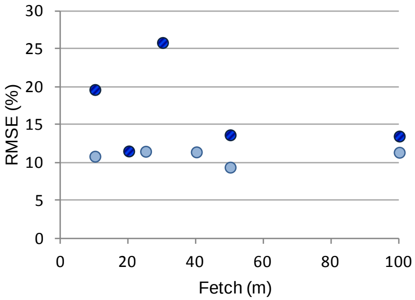
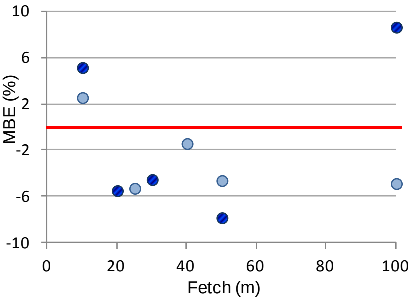
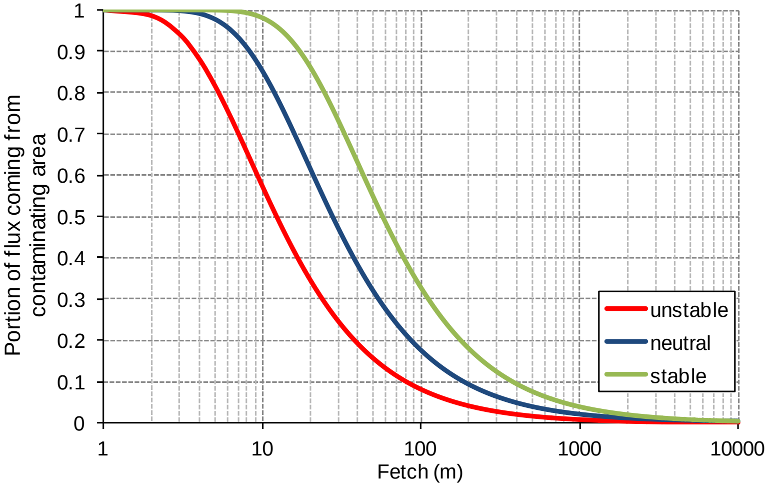


Figure 11 Mean bias errors (%)



Apparently, obtained results do not confirm given hypotheses at all. According to footprint models (see e.g. Hsieh et al. 2000) the effect of the contaminating area is decreasing downwind from the leading edge as it is shown in Fig. 12. This is in addition influenced by the stability of atmosphere. During the diurnal conditions which are typically unstable shorter fetch is needed compared to the night (stable conditions). In such type of conditions fluxes measured at 10 m long fetch should be contaminated roughly by 60 %, whereas at fetch 50 m by 15 %, and finally at fetch 100 by less than 10 %.

Figure 12 Footprint model according to Hsieh et al. (2000) describing portion of flux coming from contaminating area with respect to fetch under different atmospheric stability conditions



In order to observe similar results as those from the footprint model more contrasting covers would be needed. Since the BREB method relies on the equality of the eddy diffusivity of water vapour and temperature as a consequence of the same source of heat and water vapour (Stannard, 1997) this can be also violated by the sudden change of the surface features. To avoid the difficulties in interpretation different method like direct eddy covariance (EC) would be useful to reveal the answers to these issues. Considering the financial costs there is an option to use only one mobile EC system which can be firstly calibrated against the fixed reference BREB system and consequently moved to different fetches according to the scheme described in this study.

Taking into account overall complication with the interpretation and the need for additional measurement to make the results more generally valid, it seems that indeed the fetch to height ratio for BREB method is not so critical and probably lays closer to the values 10:1–20:1 given by Panofsky and Townsend (1964) or Heilman and Brittin (1989) and Stannard (1997) rather than the values 100:1-200:1 which are generally more deep-rooted and accepted within the scientific community.

CONCLUSIONS

The hypotheses of this study were not confirmed. The results showed no significant systematic deviation between the reference BREB with sufficient 180 m long fetch and mobile BREB positioned at fetches between 10 to 100 m. One of the explanations may be very similar response to soil moisture conditions of the selected covers resulting in similar Bowen ratios. Likewise, the difference between the soil moisture of the area of interest and the upwind area was not big enough to be detected in the results.

Moreover, there was not found any impact of the fetch on non-systematic errors. This leads to the conclusion that the fetch did not have any effect on the overall data quality and consistency. From the above mentioned it can be concluded, in the relatively wet environments typically with rather low Bowen ratio of all surrounding fields, the fetch is not so critical issue and produce comparable errors as the instruments themselves.

However, different method would be very desirable to reveal more of the mystery of such results. The direct eddy covariance method is suggested as a solution because it is often adopted to check the validity of other indirect methods. Considering the costs of this system a solution could be using only one mobile EC system. It might be firstly calibrated against the fixed reference BREB system and then moved to different fetches according to the scheme described in this study. Further experiments would uncover answers to many issues arising from this study.

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