Gradient distributions and flux profile relations above a rough forest

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SUMMARY

Temperature and humidity gradients above a sparse pine forest (400 trees per hectare) in Sweden were measured using movable sensors. Under daytime conditions the gradients were remarkably small with a median value of \( -0.007 \text{ K m}^{-1} \) for the potential temperature gradient and \( -3.8 \times 10^{-4} \text{ m}^{-1} \) for the specific humidity gradient. The range of inferred Bowen ratios was \( -0.3 \) to \( 1.8 \) with a median value of \( 0.72 \).

The starting point for the paper was a discrepancy between energy balance/Bowen ratio (EBBR) and water balance estimates of the forest evapotranspiration. There was no sign that insufficient fetch influenced the results but some evidence was obtained to suggest that the lowest measurement level, about one mean distance between trees above the mean tree level, was situated in a region of inhomogeneity in the heat and water flux field. Excluding this level from the calculations increased the inferred Bowen ratio by 30%. This change is not sufficient to account for the difference in estimates of evapotranspiration by the two methods. It is, however, concluded that the discrepancy could be explained by rather small, quite realistic errors in the gradient measurements.

1. INTRODUCTION

Evapotranspiration (ET) from vegetated surfaces is one of the least understood processes in the hydrological cycle. One step towards an increased understanding of the process is to obtain reliable estimates of ET with diurnal resolution from different types of vegetation. So far, the energy balance/Bowen ratio method (EBBR) has been considered the most suitable for 'direct' measurements of ET. For short crops the EBBR method has frequently been found successful. For forests comparisons between EBBR and other methods have not always been given mutually consistent results (e.g. Tajchman 1971; McNeil and Shuttleworth 1975; Thom et al. 1975; Roberts 1976; Grip et al. 1979). On the other hand, Nnyamah and Black (1977) found good agreement between EBBR and water balance (WB) estimates of ET, and Gay and Frischen (1979) concluded that the agreement between lysimetric and EBBR estimates of ET was excellent.

The starting point for this paper was a comparison between EBBR and WB estimates of ET for a sparse pine forest in central Sweden (Grip et al. 1979). Total ET during the period May 27 to Sept. 2, 1977, was about 350 mm as measured by the EBBR method and about 150 mm by the WB method. Agreement between the two methods need not, in theory, be perfect since the WB estimate is a strictly consumptive use whilst the EBBR measurements also include evaporation of dew and transpiration of water stored in the sapwood: a difference of about 10% between the two methods might, for this reason, be expected. When discussing these results, Grip et al. point out that further analyses of both EBBR and WB estimates are required. They suggest, however, that the EBBR estimate is the more erroneous and that the EBBR similarity principle may be one important source of error.

The EBBR measurements discussed by Grip et al. were evaluated in a straightforward manner without considering possible effects of insufficient fetch, extreme stabilities, etc., and the object of this paper is to make a more detailed analysis of the processes.

2. EXPERIMENTAL SITE

The Jädraås research site (60°49'N 16°30'E, 185 m) is situated on glacial sandy deposits in central Sweden. The mature 120-year-old forest (Pinus sylvestris L.) had a
mean height of about 16 m, a density of 400 trees per hectare and a basal area of 15.1 m²
per hectare in 1973 (Axelsson and Bräkenhielm 1980). The rather sparse canopy had a
crown density of 0.41 and a leaf area index (projected) of 2.6 (Lindroth and Perttu 1981).
The ground vegetation was a lichen-dwarf-shrub type. More than 95% of the roots were
situated in the upper 30 cm of the soil and plant-available water in this zone was about
50–55 mm (Jansson 1977). The ground water table was below 10 m over most of the
area.

The distance from the instrumental mast to the leading edge of the forest varied
between 400 and 1250 m. The ground-level differences over the area are less than 10 m.

3. INSTRUMENTATION

The temperature and humidity gradients were measured on a 50 m mast by using
one set of sensors which were moved to the different levels. The ventilated radiation
shield, containing a resistive temperature sensor and a capacitive humidity sensor, both
with time constants of about 15 s, was mounted on a trolley. The trolley was moved up
and down the mast by means of a motorized hoist. Normally the measurement cycle
included five levels (22, 24, 26, 28 and 30 m). One measurement of temperature and
humidity was performed each minute. To reduce possible influence on the gradients from
variation in background temperature and humidity, a fixed set of sensors was also used;
these sensors were placed in the middle of the profile. This technique to reduce possible
systematic errors in the measurement of the very small gradients was implemented using
two sets of equipment, directed towards the west and the east.

It was not possible to make measurements when the humidity was close to saturation.
The thin-film humidity sensor (Humicap, Vaisala OY, Finland) would have been severely
damaged if dew was allowed to form on it. To protect the sensor, a heater was mounted
inside the radiation shield some distance in front of the sensors. The heater was switched
on when the relative humidity rose above 95%.

The reference level for the energy balance measurements was chosen 27 m above
ground and accordingly net radiation was measured there. Measurements of air temperature
and humidity at 2 m were used to calculate the energy storage in the canopy air
below the reference level. Temperature measurements in stems and soil were used to
estimate the energy storage in vegetation and soil. All sensors were connected to a
computerized data collection and data base system (Engelbrecht and Svensson 1978).
Instrumentation and measurement programmes have been thoroughly described by
Perttu et al. (1977) and Lindroth and Norén (1979).

4. THEORY

One basic assumption behind micrometeorological methods for estimating evapo-
ration is that the evaporating surface is horizontal, homogeneous and large enough in
extent to have established a constant flux layer. These demands are necessary to ensure
that net fluxes of water and heat are entirely vertical and that horizontal advection has
a negligible effect. It is also essential that the measurements are carried out under
stationary conditions and within the constant flux layer of the vegetation. In practice,
these conditions are rarely completely fulfilled.

Neglecting advection and photosynthetic energy consumption, the energy balance
of a horizontal surface above the forest is given by

\[ R_n = LE + H + S \]  

(1)

where \( R_n \) is the net radiation, \( LE \) latent heat flux, \( H \) sensible heat flux and \( S \) rate of
change of energy storage. The ratio between sensible and latent heat fluxes, the Bowen ratio, is given by

\[
\beta = \frac{H}{LE} = \frac{c_p}{L} \left( \frac{K_h}{K_e} \right) \frac{\partial \theta}{\partial z} \frac{\partial q}{\partial z}
\]

(2)

where \(c_p\) is specific heat of dry air, \(L\) latent heat of vaporization, \(K_h\) and \(K_e\) turbulent exchange coefficients, \(\partial \theta/\partial z\) and \(\partial q/\partial z\) gradients of potential temperature and specific humidity.

Hence, assuming equality between the exchange coefficients for heat and water, the Bowen ratio can be calculated according to Eq. (2). Combining (1) and (2) gives

\[
LE = A/(1 + \beta)
\]

(3)

where \(A = R_n - S\) is available energy.

5. RESULTS

(a) Anomalies in heat and water flux field

The usual way of determining whether all measurement levels are within the constant flux layer is to plot potential temperature against specific humidity. A height-consistent flux-gradient relationship should be exposed by a proper linear behaviour. Here, scatter in the data made it quite impossible to decide which levels were significantly disturbed. Figure 1 demonstrates a typical behaviour of potential temperature versus specific humidity for the normal averaging period of one hour. Extending the averaging period to two hours did not substantially improve the situation.

Instead of using individual plots, the Bowen ratio was calculated using all five measurement levels. Then another Bowen ratio, using all but the lowest level (22 m), was calculated for the same periods. Plotting these variables against each other (Fig. 2) revealed a systematic difference. The less pronounced deviation when the Bowen ratios were negative, i.e. during slightly stable conditions, is also noticeable. Bowen ratios calculated for 24–30 m and 26–30 m did not, however, reveal any systematic deviation. It is plausible that the lowest level was situated within the so-called roughness sublayer (Raupach et al. 1980) and that the distortion was caused by horizontal inhomogeneity in heat and water flux fields. Raupach et al. show that the effect of horizontal inhomogeneity on the wind field remained up to a height \(D\) above the mean obstacle height, where \(D\) was equal to the interelemental spacing. The mean distance between the trees in the Jådraås forest was about 6 m and the mean tree height was about 16 m. The lowest measurement level was situated at 22 m, equal to the sum of tree height and mean distance between trees. This suggests that the criterion given for the wind field should be applied also for heat and water vapour.

The data in Figs. 2 and 3 are based on about 280 hour-mean values distributed over the 1977 growth season in situations when the net radiation was greater than zero. A separate investigation with atmospheric stability data (Richardson number, Ri) available showed that when net radiation was greater than zero and wind speed at the reference level (27 m) was above 0\(\cdot\)7 m s\(^{-1}\), 95% of the data was in the range \(-0\cdot01 < Ri < 0\cdot02\). Under daytime conditions \((R_n > 0)\), the wind speed at the reference level was rarely below 0\(\cdot\)7 m s\(^{-1}\), and accordingly positive net radiation values were used as indicators of near neutral conditions.

(b) Fetch

Fetch requirements of micrometeorological sites have been the subject of much
discussion. Recommendations vary from fetch–height ratios of 10 up to 200 or more (e.g. Dyer 1963; Bradley 1968; Panofsky and Townsend 1964; Pasquill 1972; Jarvis et al. 1976). Most of the experiments have been performed over surfaces of low roughness compared to that of forests and only a few allow for stability effects. In the absence of a consistent theoretical treatment of the fetch problem, possible advective effects were examined by direct analysis of the measurements.

During advection from an area outside the forest it was reasonable to assume that primarily the highest measurement level should be affected. If the surrounding areas had evaporation patterns clearly different from that of the forest, this should have been exposed when comparing Bowen ratios when the highest level was or was not included in the calculations. The data in Fig. 3 concern only near neutral conditions and the lowest level was excluded from the calculations. They are grouped with respect to different upwind distances to the leading edge of the forest. Despite the scatter in the data, no
Figure 2. Hourly Bowen ratios for all five sampling levels ($\beta_{22-30}$) plotted against Bowen ratios for which the lowest level is excluded in the calculations ($\beta_{24-30}$).

Figure 3. Hourly Bowen ratios with the top level excluded ($\beta_{24-30}$) compared with Bowen ratios where that level is included in the calculations ($\beta_{24-30}$). The three classes refer to upwind distance from the leading edge of the forest.

serious bias was found. It is concluded that the four highest levels were appropriate to use for calculations of heat and water fluxes by the EBBR method for this forest.

(c) **Gradients and Bowen ratio**

Based on about 400 hours of measurement, the median potential temperature
Figure 4. The distributions of potential temperature gradients (a), specific humidity gradients (b) and Bowen ratios (c). Number of data indicated on vertical axis.
<table>
<thead>
<tr>
<th>Forest/site</th>
<th>Country</th>
<th>Position</th>
<th>Species</th>
<th>Mean tree height (m)</th>
<th>Tree density No./ha</th>
<th>Leaf area index&lt;sup&gt;a&lt;/sup&gt;</th>
<th>Weather</th>
<th>Lowest meas. height (m)</th>
<th>Temp. grad. (K/m)</th>
<th>Humidity grad. (mb/m)</th>
<th>Bowen ratio</th>
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<tbody>
<tr>
<td>Triangle</td>
<td>Australia</td>
<td>35°18′S, 149°08′E</td>
<td>Pinus radiata</td>
<td>7.5</td>
<td>700</td>
<td>2.6</td>
<td>s</td>
<td>h</td>
<td>0.05</td>
<td>0.1</td>
<td>0.1-0.8</td>
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<tr>
<td>U.S.A.</td>
<td>36°00′N, 79°00′W</td>
<td>Pinus taeda</td>
<td>12.5</td>
<td>1700</td>
<td>s</td>
<td>h</td>
<td>s</td>
<td>0.1</td>
<td>0.4-1.4</td>
<td>0.2</td>
<td>0.4-1.2</td>
</tr>
<tr>
<td>Crane Prairie</td>
<td>U.S.A.</td>
<td>43°50′N, 121°45′W</td>
<td>Pinus contorta</td>
<td>7.0</td>
<td>600</td>
<td>3.1</td>
<td>s</td>
<td>h</td>
<td>0.4</td>
<td>0.6-2.0</td>
<td>0.45</td>
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<tr>
<td>Petawawa</td>
<td>Canada</td>
<td>46°03′N, 77°22′W</td>
<td>Pinus resinosa/strobus</td>
<td>22.0</td>
<td>600</td>
<td>s</td>
<td>s</td>
<td>s</td>
<td>0.5-1.3</td>
<td>0.2-3.1</td>
<td>0.3-1.3</td>
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<tr>
<td>Ebersberger</td>
<td>F.R.G.</td>
<td>47°55′N, 07°35′E</td>
<td>Pinus sylvestris</td>
<td>2.7</td>
<td>12 000</td>
<td>s</td>
<td>s</td>
<td>o</td>
<td>0.0</td>
<td>0.2-1.5</td>
<td>0.2-1.5</td>
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<tr>
<td>Eberswalde</td>
<td>F.R.G.</td>
<td>48°10′N, 11°50′E</td>
<td>Picea abies</td>
<td>27.5</td>
<td>800</td>
<td>8.4</td>
<td>s</td>
<td>s</td>
<td>0.5</td>
<td>0.5-1.6</td>
<td>0.3-1.2</td>
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<tr>
<td>U.B.C.</td>
<td>Canada</td>
<td>49°10′N, 122°48′W</td>
<td><em>Pseudosuga</em> menziesii</td>
<td>7.8</td>
<td>1700</td>
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<td>26</td>
<td>s</td>
<td>o</td>
<td>o</td>
<td>o</td>
<td>1.4</td>
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<td>0.5-2</td>
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<td>Thetford</td>
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<td>52°25′N, 00°39′E</td>
<td><em>Pinus sylvestris</em></td>
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<td>800</td>
<td>4.3</td>
<td>s</td>
<td>h</td>
<td>0.0-4</td>
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<tr>
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<td>Picea sylvestris</td>
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<td>s/o</td>
<td>h + 4</td>
<td>s</td>
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<td>0.0-4</td>
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<td>Fetteresso</td>
<td>U.K.</td>
<td>56°58′N, 02°24′W</td>
<td><em>Picea sitchens</em></td>
<td>11.5</td>
<td>4100</td>
<td>9.8</td>
<td>**</td>
<td>h</td>
<td>0.0-8</td>
<td>0.0-5</td>
<td>0.0-5</td>
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<td>Sweden</td>
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<td><em>Picea abies</em></td>
<td>22.0</td>
<td>1400</td>
<td>s</td>
<td>o</td>
<td>h + 7</td>
<td>0.0-3</td>
<td>0.0-4</td>
<td>0.0-7-1.9</td>
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<td>Jädraås</td>
<td>Sweden</td>
<td>60°49′N, 16°30′E</td>
<td><em>Pinus sylvestris</em></td>
<td>16</td>
<td>400</td>
<td>2.6</td>
<td>s/o</td>
<td>h + 8</td>
<td>0.0-4</td>
<td>0.0-7</td>
<td>0.0-7-1.8</td>
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<tr>
<td>Dundret</td>
<td>Sweden</td>
<td>67°08′N, 20°30′E</td>
<td><em>Pinus sylvestris</em></td>
<td>1.5</td>
<td>7000</td>
<td>s</td>
<td>o</td>
<td>o</td>
<td>0.0-2</td>
<td>0.0-5</td>
<td>0.0-2-0.7</td>
</tr>
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<sup>a</sup> Projected area basis. <sup>b</sup> Median value for sun radiation > 400 W m<sup>-2</sup>. <sup>c</sup> Median values for solar radiation < 400 W m<sup>-2</sup>. <sup>d</sup> = sunny, <sup>e</sup> = overcast. <sup>f</sup> = mean or median height.

Data from Jarvis et al. (1976) except for the Jädraås forest.
gradient was estimated as -0.007 K m\(^{-1}\), and the specific humidity gradient as -3.8 \times 10^{-6} \text{ m}^{-1} (Figs. 4(a), (b)). When the largest and smallest 10% of the values were excluded, potential temperature gradients lay between -0.020 and +0.003 K m\(^{-1}\) and specific humidity gradients between -8.0 \times 10^{-6} and -1.2 \times 10^{-6} \text{ m}^{-1}. These values generally seem much smaller than those of other forests (Table 1). The data in Table 1 were compiled from a review by Jarvis et al. (1976) plus results reported in this paper. It is not clear, however, to what circumstances the data of Jarvis et al. refer. Gradients of similar magnitude were also found in Jädraås but generally only for ‘fair’ weather conditions. The size of the gradients was normally well related to net radiation (Fig. 5).

![Figure 5. Potential temperature gradient (vertical) against net radiation (horizontal).](image)

The range of Bowen ratios extended from -0.3 to 1.8 with a median value of 0.72 (Fig. 4(c)), the elimination of the lowest level having resulted in an increase of the median Bowen ratio by 30% (from 0.55 to 0.72). For most forest sites, the daytime Bowen ratio from a dry canopy varies between 0.1 and 1.5 (Table 1). The result for the Jädraås forest is in quite good agreement with this although the range is a little larger, probably because some wet canopy situations were included.

6. Discussion

It has been suggested that close to a rough surface, such as that of a sparse forest, there is a region of anomalies in the heat and water flux field. The depth of this region is at least of the same order of magnitude as the mean distance between trees. Similar results have been reported for the wind field by, e.g., Mulhern and Finnigan (1978) and later by Raupach et al. (1980). Garratt (1978) studied the variation of non-dimensional functions of momentum and heat with height above a very rough surface and found that the depth of this region was about 4.5 and 3 times the height of the mean roughness elements for momentum and heat transfer, respectively. Hicks et al. (1979) objected to
these results arguing that the calculations were too sensitive to the choice of the displacement height. The implication for experiments above rough surfaces is that the measurement levels must be chosen with as much respect to the depth of the region of horizontal inhomogeneity as to the fetch. Apparently the recommendations for the wind field given by Raupach et al. should be applied also for heat and water flux measurements, i.e. the lowest measurements should be taken at a height of more than one interelemental spacing above mean tree level.

Jarvis et al. (1976) discussed the possible failure of one-dimensional models to predict forest fetch requirements. The ‘distance-constant’ proposed by these authors can be conservatively calculated for the Jädraås forest as approximately 200 m. Two or three ‘distance-constants’ correspond to 86% or 95% adjustment of the profiles to the new equilibrium. The measurements reported here are in agreement with this assumption. Consequently a fetch–height ratio of about 30% seems to be enough; at least for this forest. It is quite reasonable to assume that, for forests in general, this ratio should be smaller than for short vegetation because of more intense turbulence, which rapidly aids the development of a constant flux layer as well as keeping conditions near neutrality.

At Jädraås, elimination of the lowest measurement level increased the median Bowen ratio by about 30%. The effect of this is to decrease the implied evapotranspiration by about 10–15%. Returning to the discrepancy mentioned in the introduction, this brings the EBBR estimate down from 350 to about 300 mm. The WB estimate of ET, which can be considered as an ‘absolute’ measurement, has been subject to a renewed and detailed analysis. According to P-E. Jansson (personal communication, 1983) the original estimate (150 mm) is still the most likely. The soil water data could, however, with acceptable assumptions about variability of the unsaturated conductivity, be ‘stretched’ to accord with an estimate of ET of about 205 mm. Nevertheless, there is still a large difference, of at least 100 mm, between the two methods, which must be accounted for.

Little is known about the amount of dew that is formed on forest canopies. For leaves and artificial surfaces maximum amounts of 0.2 to 0.5 mm per night have been observed (Monteith 1963; Rosenberg 1974). Fritschen and Doraiswamy (1973) found that dew contributed as much as 29% of total ET in a Douglas fir forest, although this clearly is specific for the location of this forest. For the Jädraås forest it is energetically impossible to explain the discrepancy by dew formation alone, although about 35 mm might have fallen, assuming potential dewfall (Monteith 1963) every second night.

When the absolute values of temperature and humidity gradients are very small the Bowen ratio calculations are sensitive to errors in the measurement of gradients. From Eqs. (2) and (3) it can be shown that under median conditions (Bowen ratio ~0.7), combined systematic errors of +0.002 K m⁻¹ in the potential temperature gradient and of −1.0×10⁻⁴ m⁻¹ in the specific humidity gradient imply an uncertainty of about 25% in the ET estimate. Such an error in ET could almost ‘explain’ the discrepancy between EBBR and WB estimates reported by Grip et al. (1979). These assumed errors are smaller than those specified for the Jädraås measurements (Perttu et al. 1977).

Because of the almost impossible accuracy demands for determination of the gradients and the uncertainty about the amount of dew and sapwood water contributing to the EBBR measurements, it was not possible to identify the causes of the discrepancy. It is concluded that investigations into the question of failure/non-failure of the similarity principle should be based on direct turbulence measurements and also that Bowen ratio experiments above forest should be designed with the utmost care. Further investigations about dew formation in forests are also required.
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<th>Reference</th>
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