Evaluation of an enclosed portable chamber to measure crop and pasture actual evapotranspiration at small scale

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Abstract

An enclosed portable chamber was constructed and calibrated to measure actual evapotranspiration (ET) from crop and pasture and then evaluated against established methods that are used to determine evapotranspiration. The chamber was equipped with variable speed electric fans to mix the air within the chamber during each ET measurement. The most appropriate fan speed was investigated.

Pasture ET measured using the enclosed portable chamber compared well with predicted water loss using the water balance method for a six day period during winter 1997 in Armidale (NSW, Australia). Mean cumulative pasture ET for the six day period was 5.75 mm and 5.89 mm measured with the enclosed portable chamber and soil profile water loss respectively.

Wheat ET measured using the enclosed portable chamber was compared with that estimated by the Bowen Ratio (BR) method for a two day period in the early growth stages of the crop. Mean ET using the enclosed portable chamber was 2.4 mm/day compared with 2.3 mm/day using the BR method.

Results from the enclosed portable chamber method showed sensitivity to the choice of fan speed. A slow fan speed that produced an air velocity of 2.7 km/hr, gave the closest agreement with the Bowen Ratio method (2.3 versus 2.2 mm/day) for the wheat crop.

The main attractions of the enclosed portable chamber method include: (1) its suitability for ET measurement within small areas (<1m^2), which enables ET measurement from individual plant communities within small areas; (2) its main principles of measuring the actual water flux from transpiring vegetation rather than inferring it from climatic parameters; (3) the speed by which an instantaneous ET rate is obtained (less than one minute);

(4) instantaneous ET measurement can be repeated throughout the day from the same plant communities; and (5) the portability of the enclosed portable chamber. ET measurement using the enclosed portable chamber method may be combined with the existing soil water balance models for comparing alternative crop and pasture systems in terms of their water balance.

Key words**:** evapotranspiration, enclosed portable chamber, Bowen Ratio, water balance, pastures.

Introduction

An efficient means of measuring crop and pasture evapotranspiration (ET) is required to assess and optimise the water balance in agricultural systems. No single method of ET determination is likely to be ideal for all circumstances. Depending on the availability of data, common methods may infer potential ET through either a direct measure of evaporation from an evaporation pan or an indirect estimate using, for example, the Penman equation (Penman 1948; and 1963). Actual ET determination is more difficult (Holmes and Watson, 1967); direct measurements such as with lysimetry and micrometeorological techniques are available, but are expensive and not always feasible for use in conjunction with agronomic trials (Stannard, 1988). The cost and complexity of large lysimeter installations are often prohibitive, and micro-lysimeters are more suited to measurement of bare soil evaporation (Boast and Robertson, 1982). Micrometeorological methods are impractical to apply with plot or small paddock - scale field experiments, because of error from advection. For example, the Bowen Ratio method requires a fetch-to-height ratio ranging from 10:1 (Panofsky and Townsend, 1964) to 200:1 (Dyer, 1965) with an average recommended fetch-to-height ratio of 100:1 (Rosenberg et al., 1983). The water balance method is also difficult to apply successfully in some circumstances, particularly during wet periods and where shallow water tables are present creating uncertainty about direction of water movement.

Portable chambers have been used to measure ET from small areas of vegetation (Greenwood and Beresford, 1979; Puckridge, 1978, Reicosky and Peters, 1977; Reicosky et al., 1983). Ventilated chambers have been widely used to measure evapotranspiration of single trees (Leuning and Foster, 1990), forest (Greenwood and Beresford, 1979; Greenwood et al., 1982; Greenwood et al., 1985a), and grazed pasture (Greenwood et al., 1985b, Clifton and Taylor, 1995). However, the use of ventilated chambers for ET measurement has been criticised on the basis that net radiation and microclimate within the chamber may not be representative of that outside the chamber. Net radiation inside a perspex chamber was estimated to be about 95% of that outside (Greenwood and Beresford, 1979). Other studies found that the significant reduction of net radiation and microclimate inside a ventilated chamber could reduce the transpiration rates by up to 30% at around midday (Leuning and Foster, 1990; Denmead et al., 1993). Ventilated chambers used in these studies were held in place for a long period.

Portable, enclosed chambers made of Mylar film or plexiglass have been used to measure evapotranspiration from crops (Reicosky and Peters, 1977; Reicosky et al., 1983) and evaporation from soil and litter (McJannet et al., 1996). Reicosky et al. (1983) compared a portable chamber and a weighing lysimeter when measuring ET of alfalfa, and concluded that although the irradiance inside the chamber was reduced by 8-10%, ET measured by the chamber was comparable with that measured with the weighing lysimeter. In a large fallow experimental field at Wagga Wagga, McJannet et al. (1996) compared soil evaporation measured using a range of methods including a dome shaped chamber, microlysimeter, Bowen Ratio, and Eddy correlation. A reasonable agreement was obtained between soil evaporation values measured by dome, microlysimeter, and micrometeorological techniques. These studies implied that the portable chamber could provide a reasonable measure of field evapotranspiration.

Stannard (1988) reported a design of a portable chamber that can be used to determine ET from different vegetation types within a small area. This design has been used by McJannet et al. (1996) to measure ET of soil and litter beneath mountain ash forest, which suggested the need of further study on the most optimum fan speed to be used with the dome. In this current study, the design proposed by Stannard (1998) is adopted with some modification. The principal of operation of the enclosed portable chamber is that an increase of vapour density inside the portable chamber is determined while over vegetation. Vapour density measurement continues only for a period less than one minute. Measurement stops before evapotranspiration reduces from plants responding to increased vapour or CO_2 concentration within the chamber. Small rotating fans with variable speed are used to mix the air and water vapour within the chamber thus ensuring representative sampling by the single temperature and humidity sensors. The increase of vapour density within the chamber is proportional to the ET. Measurements are repeated at various times throughout the day before the series of instantaneous rates are used to infer daily ET.

The objectives of this paper are: (a) to describe the design and internal calibration of a portable chamber to measure evapotranspiration; (b) to evaluate the suitability of the chamber to measure pasture and crop evapotranspiration; (c) to evaluate the most suitable fan speed to be used with the enclosed portable chamber and (d) to explore the potential application of the measured ET data by the enclosed portable chamber in the development of a simple model to describe ET using soil water data and solar radiation. The evaluation of the enclosed portable chamber method to measure ET was undertaken by comparing it with other established methods for measuring ET. The first comparison was for ET from a range of pastures estimated using the soil water balance equation. The second comparison was for ET from winter wheat obtained using the Bowen Ratio method during which the most suitable fan speed within the enclosed portable chamber was investigated.

Methods

Design, operation, data processing and calibration of the enclosed portable chamber

Design

The schematic construction of the ET chamber is presented in Figure 1. The basic design and calibration of the enclosed portable chamber used in this study followed that of Stannard (1988), except that the hemispherical perspex dome was 0.67 m in diameter compared with 1.06 m. A Vaisala HMP 35A combination temperature and humidity sensor was mounted inside the chamber to monitor internal atmosphere and a second sensor was mounted outside to sense ambient conditions. The factory calibration provided by Vaisala was used for both of these sensors. The sensors were connected to a Campbell Scientific Data logger (model 21X) and PC208 software was used to store and retrieve data. Two fans, each of 80 mm in diameter, were used to mix air and water vapour within the chamber. Fan speed was regulated using a rheostat control resulting in air velocities of 2.7, 4.9, and 10.8 km/hr inside the chamber. A lead acid battery powered the data logger and sensors. The chamber as used in the field is shown in Figure 2.

For ease of use on rough ground, the instrumented chamber and associated equipment were mounted on a light steel-framed trolley. This enabled one person to operate the apparatus. The chamber was equipped with a hand-operated crank that enabled it to be lowered and raised. When not in use and during movement between measurement areas, the chamber was raised 100 mm above the ground. A strip of flexible foam (5 cm thick) was attached to the base of the chamber to seal it onto the soil surface.

Procedure for measuring ET

The following steps were undertaken to make an instantaneous ET measurement with the portable chamber:

(a) Environmental conditions at measurement time were recorded based on visual observation (e.g. wind, cloud, and sunshine).

(b) The chamber was raised and tilted with the fans running to ensure that the air under the chamber was representative of ambient conditions. The readings from the internal and external sensors were compared to confirm similarity between conditions within the chamber and outside. It took between 3 to 4 minutes for the chamber atmosphere to equilibrate with the atmosphere.

(c) The fan speed was set at the desired level.

(d) The chamber was lowered over the vegetation with the foam strip firmly laid on the soil surface.

(e) The air humidity and temperature inside and outside the chamber were logged at two-second intervals for a period of one minute following Stannard (1988) to obtain an instantaneous rate of ET. It was assumed that within this short measurement period, there was no microclimate change inside the chamber and that saturation vapour pressure was not attained. A program was written for the data logger to set the beginning and the end of each measurement.

(f) The chamber was then raised, and moved to the next location in the plot or field and the measurement sequence was repeated.

(g) To obtain cumulative daily ET of particular vegetation, measurements for that vegetation were repeated at an hourly or half-hourly interval throughout the day. Half-hourly intervals are desirable but number of measurement areas and distance between areas may lengthen this.

Each measurement was conducted at one point per plot at any given time, so there could be a 2-3 minute difference between two consecutive measurements depending on the distance between the two sampling locations. At completion of a series of measurements, the PC208 data logger support software was used to retrieve the data.

Procedure for calculating instantaneous ET rates and cumulative daily ET

Relative humidity and temperature data were used to calculate the rate of vapour density increase inside the chamber according to the procedures outlined by McJannet et al. (1996). This includes calculations of the saturation vapour pressure, partial vapour pressure, vapour density, slope of the straight line from the plot of vapour density versus time, instantaneous ET rate for each measurement, and total daily ET (mm).

The saturated vapour pressure (e_s), partial vapour pressure (e), and vapour density (ρv) inside the dome were calculated following CSIRO DWR (1994):

Saturation vapour pressure (Pa),

$$e_s = 6.11213 f(P) \exp\left(\frac{17.5043t}{241.2 + t}\right)$$ Equation 1

where,

t is temperature in °C, and $f(P)$ is assumed to be a constant value (100.4718) related to atmospheric pressure.

Partial vapour pressure, e (Pa) was calculated using relative humidity (RH) information

$$e = \frac{RH e_s}{100} \qquad \text{Equation 2}$$

Vapour density, ρv (g/m^3), was calculated using:

$$\rho v = \left(\frac{0.622e}{R_d T} \right) 1000 \qquad \text{Equation 3}$$

where R_d is the gas constant (287.04 J/kg/K) and T is temperature in degrees Kelvin. The factor 0.622 is the ratio of the molecular weights of water (g/mol) and of dry air (Rosenberg et al. 1983; CSIRO DWR, 1994).

The slope of the straight-line section from the plot of vapour density inside the dome against time was obtained using the least-squares method. The straight-line section usually lay within the first 5 to 26 seconds of measured data (Figure 3). This slope value is used in the modified (Stannard, 1988) equation (Equation 4) to calculate the instantaneous rate of ET (mm/hr) at a particular time of the day.

$$ET = 3.6 \frac{MVC}{A} \qquad \text{Equation 4}$$

where *ET* is ET (mm/hr), *M* is the slope of the constant slope section ($g/m^3/sec$), *V* is the volume inside the chamber (m^3), *C* is the calibration factor to account for vapour absorption by the chamber material (unitless), *A* is the area of land surface covered by the chamber (m^2) and 3.6 is a conversion factor, to convert grams of water/m^2/sec to an hourly rate of mm/hr.

The area under the curve produced by plotting the time of day against hourly ET rates is the daily cumulative evaporation (mm).

Calibration of the chamber material

The materials used to construct the chamber were moderately hydrophilic, and required calibration to account for error due to vapour absorption. The calibration procedure also corrected for possible error caused by poor mixing of air inside the chamber and possible sensor error (Stannard, 1988).

The chamber materials were calibrated following Stannard's (1988) procedure prior to field measurement. The procedure involved boiling water in a beaker beneath the chamber at a range of rates while recording the weight of water loss with time. The increase in vapour density inside the chamber was monitored using the combination humidity and temperature sensor. The loss of water from the beaker was compared with the increase in vapour density within the chamber.

Water was boiled inside a 1000 ml beaker using a small 110-Volt heating coil on top of a top loading-digital balance (range 0 to 3000g, readability to 0.01 g). The heating coil was clamped on a ringstand (no part of the coil or ringstand touched the beaker), and was connected to a variable voltage source. The steady state evaporation rate was determined at five voltage settings (40, 50, 60, 70, 80 volts) by timing weight loss on the balance display for a one minute period. These voltage settings produced approximate boiling rates ranging from 0.2 to 3.0 g/min.

At each of the voltage settings, the weight of water loss from the beaker, the humidity, and temperature inside the chamber were recorded at five second intervals for a period of two minutes. Vapour gain inside the dome was measured at three fan speeds (resulting in air velocities of 2.7, 4.9, and 10.8 km/hr) at each boiling rate. Measurements for each combination of boiling rate and fan speed were repeated three times.

The weight of water loss was plotted against time for each measurement to obtain the vapour production rate, which was the slope of the straight-line section. Similarly, vapour gain was plotted against time to obtain the vapour accumulation rate. The vapour accumulation rates were then plotted against the vapour production rates (Figure 4), and the slope of the fitted line passing through the origin (1.534) is the calibration factor used in calculating the instantaneous ET rate (Equation 4).

Evaluation of ET measured using the enclosed portable chamber method with those using other methods

To evaluate the enclosed portable chamber method for measuring ET, it was compared with two other methods. The first comparison was against the water balance method under pasture and the second comparison was against the Bowen Ratio technique for a winter wheat crop.

Comparison of the enclosed portable chamber method with the water balance method

A comparative study between the enclosed portable chamber and the soil water balance method to obtain pasture ET was undertaken at field site (Big Ridge 2) at the CSIRO "Chiswick" Pastoral Research Station near Armidale on the Northern Tablelands of New

South Wales, Australia (31^{o}31’S, 150^{o}39’E, 1060 m above sea level) (Schafer, 1980) during winter 1997. The area has a cool temperate climate with mean minimum and maximum air temperature of 0^{o}C and 26.1^{o}C for winter (July) and summer (January) respectively. Frosts are common between May and September and temperatures as low as -10^{o}C have been recorded (Hartridge, 1979). Mean annual rainfall is 795 mm and is summer dominant, with sixty percent of the rain falling between October and March (George et al.,1977).

The soil type was a Brown Chromosol (Isbell, 1996), derived from sedimentary material but also influenced by basaltic colluvium, transported from the upper slopes. It had a strongly differentiated profile (duplex soil), with a sandy clay loam A-horizon and medium to heavy clay B-horizon. The A2-horizon was generally bleached, indicating extensive leaching (highly permeable). The texture contrast between the A and B horizon (horizon boundary at around 40 cm) may induce subsurface lateral flow when the A horizon is saturated (McLeod, 2002).

Comparison of chamber ET and predicted ET using the water balance equation was conducted under two replicates of three different pasture types. The pasture types were: (a) degraded [pasture dominated by annual species originating from an improved phlaris+white clover pasture that was grazed for 26 years at medium to high stocking rates of 13.75 to 17.5 Merino ewes/ha], (b) phalaris [pasture originating from a low stocking rate of 10 Merino ewes/ha for the same period], and (c) the phalaris+white clover pasture [phalaris dominant pasture that was re-sown with the white clover (cv. Huia) in 1994 (1kg/ha) by direct drilling following an application of the herbicide gramoxone (at 1.5 L/ha) (Scott et al.,2000)]. These pastures were continuously grazed, with starting stocking rates of 7.5, 12.5, and 17.5 dse/ha for the degraded, phalaris, and phalaris/white clover pastures, respectively. Stocking rates were varied depending on the availability of forage.

ET was measured with the enclosed portable chamber at hourly or half-hourly intervals from sunrise to sunset over a 6 day period from 15/7/97 to 20/7/97. The measurements were conducted over pasture around NMM access tubes (2 access tubes for each of the three pasture types), positioning the centre of the dome over the access tube. The position of the chamber was maintained at the same location for each hourly or half-hourly measurement throughout the 6 day period. The daily changes in soil profile water storage (0-130 cm) were measured for six consecutive days using a neutron moisture meter (NMM) and Time Domain Reflectometry (TDR). Profile soil water potential near the neutron probe access tube was measured with a bank of field tensiometers using the double puncture technique (Greenwood and Daniel, 1996) to check the likelihood of deep drainage or subsurface lateral flow along the boundary of A and B horizons.

Climate data (air temperature, relative humidity, solar radiation, rainfall, etc.) were recorded on site using an automatic weather station so that potential evapotranspiration (PET) can be calculated using the Priestley-Taylor equation (Priestley and Taylor, 1972).

The cumulative pasture evapotranspiration obtained with the two methods were compared using a linear mixed model, fitted using the ASREML statistical program (Gilmour et al.,1999). The fixed terms in this model included methods of ET measurement, pasture types, and the interaction between these two terms, and the random term was location (sampling area). The significance of the random term was determined by comparing twice the change in the log-likelihood to Chi-square distribution value (df=1; the critical value for significance was 3.84). Significant difference between methods and the treatment effects ($P<0.05$) on pasture ET was assessed using the Wald test (an approximate F-test), and the mean comparison was conducted using the least significant difference (LSD).

Comparison of the portable chamber method against the Bowen Ratio method

The energy balance method provides a convenient and reliable way of assessing crop ET, by inferring it from other measured parameters (WMO, 1966; Monteith, 1973; Faulkner and Evans, 1981). Accurate electronic instrumentation is necessary, but the method may be adapted to facilitate the simple use of two sets of wet and dry bulb thermometers, a net radiometer and a soil heat flux plate. Assuming that the photosynthesis term is negligible, the net radiation at the earth's surface can be expressed as:

$$R_n = H + LE + G \qquad \text{Equation 5}$$

where R_n is net radiation (i.e. net of short wave solar radiation and long wave earth radiation), H is the sensible heat exchange between the earth's surface and the air above it, E is evaporation, L is latent heat of vaporization and G is the heat flux in the surface layer of the earth. Both R_n and G can be easily measured using electronic devices, but H is difficult to measure. Consequently, Bowen (1926) proposed the use of the ratio of the sensible heat and latent heat fluxes (Bowen Ratio), β, in the calculation of surface evaporation:

$$\beta = \frac{H}{LE} \qquad \text{Equation 6}$$

where,

$$H = \rho C_p K_h (dT/dz) \qquad \text{Equation 7}$$

$$LE = \rho L K_e (dq/dz) \qquad \text{Equation 8}$$

and ρ is density of air, C_p is specific heat of air at constant pressure, K_h is the coefficient for eddy diffusion of sensible heat, K_e is the coefficient for eddy diffusion of latent heat, dT/dz is the temperature gradient above the crop, and *dq/dz* is the specific humidity gradient above the crop.

For crop ET, the coefficients of sensible and latent heat are assumed to have the same value, although this may be invalid under unstable conditions and advective heating. However, in close proximity to the crop surface the effects of buoyancy are reduced and the assumption holds (WMO, 1966). Therefore the following expression can be derived (Faulkner, 1992):

$$\beta = \gamma \frac{(T_1 - T_2)}{(e_1 - e_2)} \qquad \text{Equation 9}$$

where γ is the psychometric constant (the value taken as 0.66 mb/^{o}C) and *e* is the vapour pressure (partial pressure of the water vapour in the atmosphere). By recording wet and dry bulb temperatures at two reference heights (1 and 2) the temperature gradient (T_1-T_2) and the vapour pressure gradient (e_1 - e_2) may be measured. Normally reference height 1 would be at the crop/vegetation canopy surface and height 2 would be 0.5 to 0.8 m above the crop.

The final equation for the Bowen Ratio becomes (Faulkner, 1992):

$$ET = \frac{R_n - G}{L(1 + \beta)} \qquad \text{Equation 10}$$

ET measurement by both the enclosed portable chamber and the Bowen Ratio methods were conducted in the centre of a large field of actively growing winter wheat near Moree, in northern New South Wales Australia on 19 and 20 August 1997. The wheat crop was 10 weeks old and approximately 20 cm high. ET was measured using the enclosed portable chamber half-hourly from 11:00 to 17:00 at a single location. The Bowen Ratio unit and the chamber apparatus were about 100 cm apart during the measurement, and when not in use, the chamber was kept away from the Bowen Ratio unit to minimise disturbance to the Bowen Ratio unit.

The comparison was conducted on a wheat crop because the Bowen Ratio method requires a fetch area of equal or greater than 100 times vegetation height (Rosenberg et al., 1983), with uniform vegetation. This is to ensure that disturbance from turbulence caused by taller vegetation is minimised. Therefore the evaluation of the enclosed portable chamber method against the Bowen Ratio method had to be conducted in a large area of uniform vegetation.

For the comparison study between the enclosed portable chamber and Bowen Ratio method, the DREAM system (Direct Reading Evapotranspiration Assessment Monitor), a Bowen Ratio unit developed and described in detail by Faulkner (1992), was used to measure the inputs required to determine the Bowen Ratio (Equation 9) and then the corresponding ET (Equation 10). The DREAM system recorded: (a) Net radiation R_n (Mj/m^2), measured using a net radiometer situated 0.96 m above the crop canopy; (b) Ground heat flux, *G*, measured using a soil heat flux plate buried 5 mm beneath the soil surface; (c) Temperature within and above the crop canopy (T_1 and T_2); and (d) Humidity within and above the crop canopy (RH_1 and RH_2). Two pairs of aspirated wet and dry bulb platinum resistance thermometers were situated just above the crop canopy and 1.3 m higher to obtain a temperature difference greater than 0.2^{o}C and so the Bowen Ratio (Faulkner, 1992). An Easidata data-logger attached to the DREAM system recorded measurements every 30 minutes.

The determination of the optimum fan speed to use with the chamber was included during this evaluation study. The fans used to mix air and water vapour within the chamber were operated to give three air velocities of 2.7, 4.9 and 10.8 km/hr so that the effect on ET could be determined. These fan speeds will be referred to as Low, Medium and High respectively throughout this section.

Daily ET values obtained with the portable chamber and the Bowen Ratio methods were compared using the linear mixed model fitted with the ASREML statistical program (Gilmour et al. 1999). The fixed terms in this model was method, and the random term was date. Significant difference between methods ($P<0.05$) was assessed using the Wald test (an approximate F-test), and the comparison between treatment means was assessed using the least significant difference (LSD) at $P=0.05$.

To compare the shape of the hourly ET, a B-spline model (Chambers and Hastie, 1997) was fitted to the measured hourly ET obtained with the Bowen Ratio method and the enclosed portable chamber method with three fan speeds. This was conducted using the S-Plus statistical package (Becker et al.,1988). The B-spline model enabled a fuller comparison to be made as it not only describes the similarities or differences of the ET values, but also describes the shapes/profile of the daily ET curves. The preliminary plots suggested that four degrees of freedom would provide a smooth model to adequately summarise the data. The statistical model, after deleting any non-significant interactions is,

$$et_{ijt} = \beta_o + day + method_j \sum_{1}^{4} \beta_{jk} \times S_{kt} + \varepsilon_{ijt}, \varepsilon_{ijt} \sim N(0,\sigma^2) \qquad \text{Equation 11}$$

where

et_{ijt} is the observed ET from method j (j=1,…4) on day i (i=1,2) at time t,

day 1 and method 1 are constrained to be zero, so that the intercept represents the overall mean of Bowen Ratio, day 1,

day 2 is the day effect and methods 2,3,4 are the differences between the respective means at different fan speeds and method 1 (Bowen ratio),

S_{kt} is the value of the k-th basis function at time t,

ε_{ijt} is a normal random variable with zero mean and variance σ^2,

The spline coefficients indicate both similarities and differences amongst the methods with respect to the shape of the profile over time. Overall mean differences (or vertical shifts) are described by method and day effects.

The entire set of spline coefficients are necessary to define the curve and whilst there is a considerable overlap of the basis functions S_k, k = 1 to 4; they mostly refer to the following range of time; basis S_1 for time range 11:00 to 14:00, S_2 for 12:00 to16:00, S_3 for 14:00 to 17:00, and S_4 for time range 15:00 to 17:00 hours.

Modelling of ET under pastures as a function of soil water content and solar radiation

Due to the laborious nature of the enclosed portable chamber, the development of a simple model to predict pasture evapotranspiration as function of soil water content and solar radiation was explored. This could be a useful tool to predict ET from these pastures when the actual measurement is not available.

Solar radiation (Watt/m^2) from 15 to 20 July 1997 at the Big Ridge 2 site was measured hourly for each day with extra half-hourly measurements at 11:30 and 12:30 to be confident of establishing peak radiation. The exact time of measurement was different for each plot. The radiation that was occurring when ET was sampled was determined by modelling radiation over time for each day using B-spline curves and using these models to predict radiation at each sampling time of ET, using a B-spline model with six base functions.

Preliminary plots of ET against radiation indicated that the standard deviation increased with the mean, which suggests that the ET observation follows a gamma distribution whose mean is a function of the radiation. However, ET is also influenced by the soil water in the plots, hence soil water was included in the model. A principal components analysis of soil water from all plots at 10, 20,30, 40, 50, 60, 80, 100 and 120 cm depths indicated that plot differences could be accounted for by the soil water content at 10, 20, 30 and 40 cm.

The statistical model to represent ET as a function of solar radiation is a generalised addition model (Chambers and Hastie, 1997), for a gamma distribution with log link function. The predictive part includes soil water content at 10, 20, 30, and 40 cm depths and solar radiation. After fitting the model, the fitted curve of ET versus radiation was calculated for the mean soil water at each depth, thereby correcting for initial differences in soil water content. The final B-spline model used was in the form of:

$$ET \sim bs(solar\ radiation,\ df=6) + d10\ cm + d20\ cm + d30\ cm + d40\ cm \qquad \text{Equation 12}$$

where,

ET is the predicted evapotranspiration, *bs* are the basis function (1-6). Soil water content at 10, 20, 30, and 40 cm depths are represented by *d10 cm, d20 cm, d30 cm*, and *d40 cm*, respectively.

Results and Discussion

Comparison with the soil water balance method

Soil water content and potential

Within the six-day period, no rainfall was recorded and no significant rainfall had been recorded in the previous two months. Profile soil water content (Figure 5) and soil water potential indicated that drainage beyond the depth of water content measurement and subsurface lateral flow at the horizon's boundary was not expected to occur during the 6 day period of ET comparison. Soil water potential values for 100 and 120 cm depths ranged from -46 to -26 kPa, while at 40 cm ranged from -56 to -30 kPa during the measurement period. Therefore all water lost from the soil profile between two consecutive times was considered to be mainly due to plant water extraction and soil evaporation. This enabled comparison of ET measured with the enclosed portable chamber to be made with that determined from change in profile water storage.

Pasture evapotranspiration

Daily pasture ET obtained by the enclosed portable chamber for the 6 day period ranged from 0.7 to 1.2 mm, while the daily value of potential evapotranspiration calculated using the Priestley-Taylor equation ranged from 1.6 to 1.8 mm. The average daily ET from each pasture type and the Priestley-Taylor evaporation rates during the 6 day period are presented in Figure 6. Pasture daily ET varied with date, which is due to climatic variations, particularly solar radiation and soil temperature at 75 mm (McLeod, 2002). Daily ET increases as solar radiation and soil temperature at 75 mm depth (data not shown) increases. Daily ET values obtained by the enclosed portable chamber were consistently within the expected range (below the potential ET rate).

Cumulative ET for the 6 day period obtained by the water balance method and the enclosed portable chamber for each pasture replicate is presented in Table 1. Total ET obtained with the water balance method is the difference between profile water storage of day 1 and day 6, while the cumulative ET obtained by the enclosed portable chamber is the sum of daily ET for the 6 day period. Comparison of the cumulative ET for the 6 day period was preferred to daily ET because error in calculating profile water storage using the NMM measurement could be as high as 6% (Sinclair and Williams, 1979). During winter the measurement error for soil water content by NMM on a daily basis might be larger than the expected ET. In most cases, a reasonable agreement was obtained between measured water loss and measured ET except for the phalaris pasture, replicate 2 (Phalaris 2, Table 1). In this replicate, the ET inferred from the water loss calculation seems inconsistent with the other replicate and substantially lower than the other treatments. The difference was thought to be due to random error in measuring the soil water content. For this replicate, profile water storage suddenly increased by 2.46 mm from day 5 to day 6 after a steady decrease from day 1 to day 5. The enclosed portable chamber method produced a more consistent set of ET values.

Comparison of the two methods suggested that the two methods were not different in measuring pasture ET ($P>0.05$, Table 2) and ET during winter measurement was not different between pastures ($P>0.05$, Table 2).

Comparison with the Bowen Ratio method

The Bowen Ratio and the enclosed portable chamber produced a similar pattern of hourly ET from 11:00 to 17:00 (Figure 7 a,c), being broadly consistent with the hourly net radiation (Figure 7 b,d). The hourly net radiation during the second day fluctuated more compared with the first day due to the presence of cloud. Discrepancies between the hourly ET rates predicted by the two methods occurred after 15:30 hours when the Bowen Ratio method gave higher ET values. This may be due to the sensitivity of the Bowen Ratio unit to capture the soil surface radiation during this period. The value of Bowen Ratio (β) can become negative under advective conditions, when the air above the crops is warmer than the air at soil surface. Faulkner (1992) found that the β value between 1 to -0.5 is required to calculate ET value (Equation 10) sensibly. In the present study the β value was as low as -0.70 after 16:00 for 19/8/1997 and -1.21 after 17:00 for 20/8/1997.

Where the two faster fan speeds are used with the enclosed portable chamber, ET rates are greater than those indicated by the Bowen Ratio method from 11:30 to 14:00 hours, particularly for the 19/08/1997. It is likely that at greater fan speeds, humid air trapped near the soil surface is disturbed by the fans and introduced into the atmosphere above the plants. This water vapour would then be erroneously considered as ET.

The divergence of ET readings between the enclosed portable chamber at greater fan speeds and the Bowen Ratio method occurred most noticeably from 11:30 to 14:00 hours, which coincided with the period of maximum radiation for the day. During this period the difference between humidity in the boundary layer and in the atmosphere above was likely to be greater than early or late in the day when the boundary layer humidity would tend to equilibrate with that in the atmosphere above. Thus, error from boundary layer disturbance with higher fan speeds was likely to be larger around the middle of the day, as the data suggest (McLeod et al., 1998).

Other factors are likely to contribute to the difference in the hourly ET values measured by the two methods. The data from the enclosed portable chamber are point measurements, collected over a period of seconds over a small area (0.35 m^2) and then aggregated, i.e. there is interpolation between measurement times. The Bowen Ratio method differs in that ET is determined at 10 minute time intervals before being averaged over a 30 minute period, and the ET is the average from a much greater fetch area. Therefore, the ET determination from the Bowen Ratio method is made over a much larger area compared to the enclosed portable chamber. The enclosed portable chamber method is a spot measurement that does not account for field variability. Stannard (1988) suggested that confidence in the ET value at a single site increases with frequency of measurements throughout the day. However, confidence in the ET value for a plant community increases as the number of sampling locations increases. Therefore a balance between frequency of measurement and number of sampling locations needs to be determined. In this comparison of methods, ET was only measured from one sampling point with three fan speeds at 30 minute intervals. The underlying assumption is that ET was uniform throughout the field.

The cumulative ET from 11:00-17:00 obtained using the Bowen Ratio, the portable chamber at Low, Medium and High fan speeds for each day was not significantly different (Table 3). However, ET measured at the lowest fan speed was closest to values determined by the Bowen Ratio method.

The risk of introducing humid air trapped by vegetation in a boundary layer is lessened at low fan speeds. Low fan speeds have previously been reported as giving the most uniform mixing of air inside the enclosed portable chamber (CSIRO, 1994; McJannet et al., 1996). Ideally, fan speed should produce air velocities within the chamber that generate sufficient mixing of air and vapour for sensor measurements to be representative, but without disturbing the naturally occurring boundary layer present at the time of measurement. For these reasons the lowest fan speed was adopted for further measurements.

Plots of the observed ET data and fitted B-spline model are presented in Figure 8. Associated with each curve is a point-wise 95% confidence interval of ± 0.023 mm/hr which, when applied to the curves, reveals the instances where predicted values from the different methods are similar or different. The summary of the main effects is presented in Table 4, while the spline coefficient is presented in Table 5.

The analysis of the B-spline model shows that the shapes of the hourly ET with time measured at three fan speeds with the enclosed portable chamber method are similar (Table 4). However, the shape of the hourly Bowen Ratio ET with time was different to those obtained with the enclosed portable chamber method with three fan speeds by its spline coefficient β_2, which describes the response between 12:00 and 16:00 (Table 4 and 5). Figure 8 shows that the instantaneous ET rates measured by the enclosed portable chamber continue to drop approaching zero toward the end of the day, which implies that night time evapotranspiration is negligible. This is consistent with previous study with the enclosed portable chamber (Stannard, 1988). In contrast, the ET rates obtained by the Bowen Ratio did not appear to go toward zero the end of the day. It seems that the Bowen Ratio unit is influenced by other factors toward the end of the day. The Bowen Ratio unit may be sensitive to the heat released when the earth surface is cooling and interpreted it as available energy for evapotranspiration, and would continuously predict appreciable ET rates. This could lead to overestimation of overall daily ET. Night time irrigated lucerne ET estimated by the Bowen Ratio method have been reported to be a significant proportion (up to14%) of total daily ET (Malek, 1992).

Modelling of ET under pastures as a function of soil water content and solar radiation

The predicted ET curve (using the B-splines with six basis functions) and its 95% pointwise confidence interval for predicted values are plotted against solar radiation in Figure 9. Also plotted are the observed ET values, corrected to mean soil water content. The coefficients for each basis function in the B-spline model and for soil water content (on the log scale) and its respective standard errors are presented in Table 6.

Although the effect of soil water content on evapotranspiration was shown to be statistically different, they are of lesser magnitude than the effect due to solar radiation. During winter in Armidale, it is likely that pasture evapotranspiration rate is controlled by atmospheric demand rather than by water availability. This may not be the case during spring or summer.

The potential for modelling development from the measured ET, solar radiation and soil water content data shown in this study may overcome the need for daily ET measurement. The speed and portability of the enclosed portable chamber used in this study would enable spot measurement of ET rates to be conducted during selected periods throughout the year.

Scotter et al. (1979) proposed a simple linear model to predict pasture ET as a function of soil water deficit. The disadvantage of this approach is that the model parameters need to be derived from profile water storage data during an extended period of drying cycle. Otherwise, the relationship between soil water deficits is not satisfactory. In addition, it uses the same function throughout the year, disregarding the seasonal effect on pasture evapotranspiration. This could lead into incorrect estimation of actual ET. When ET is directly measured at the same time as the soil water measurement, such as in this study, these problems can be avoided. The ET prediction could be fine tuned with direct ET measurement using the enclosed portable chamber.

Conclusions

The enclosed portable chamber to measure evapotranspiration from pasture and crop was constructed. The calibration factor obtained to account for vapour absorption by the chamber material was 1.534. The enclosed portable chamber was compared successfully against two other commonly used methods to predict evapotranspiration. A reasonable agreement was obtained when the enclosed portable chamber ET was compared with the estimated ET using profile water loss (water balance method) from three pasture types during winter 1997 with the range of the total daily pasture ET between 0.7 and 1.2 mm. A good agreement was obtained when ET measured by the enclosed portable chamber method was compared with that measured by the Bowen Ratio method on a large wheat paddock.

There was no significant difference between ET measured by the Bowen Ratio and the enclosed portable chamber method at three different fan speeds. However, the lowest fan speed that resulted in an air velocity of 2.7 km/hr inside the chamber was preferred as it would cause least disturbance to the surface boundary layer, and the resulting ET was closest to ET values obtained by the Bowen Ratio unit.

The advantage of the enclosed portable chamber over other available methods to predict evapotranspiration includes its basic principle of measuring the actual flux of water from the transpiring vegetation rather than inferring it from climatic parameters. The enclosed portable chamber has shown to be fast and reliable, reproducible, and comparable with other techniques. It is suitable to measure ET from different vegetation within a small area or to measure evaporation from bare soil, litter and understorey. This ability would enable segregation between transpiration and evaporation.

However, the use of the enclosed portable chamber to measure ET is laborious and time consuming, so daily use is impractical. ET data obtained by the enclosed portable chamber can be used to develop a model to predict ET based on other information including soil water data and instantaneous (modelled) radiation data.

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Table 1. Cumulative pasture ET calculated using the measured profile water storage and the enclosed portable chamber method from 15/7/97 to 20/7/97.

Pasture*	Cumulative ET (mm)	
	Water balance method	Portable chamber method
Degraded 1	5.45	6.19
Degraded 2	6.41	6.05
Phalaris 1	7.04	5.19
Phalaris 2	3.45	5.78
Phal+WC 1	6.16	5.48
Phal+WC 2	6.81	5.79

*Number following pasture type is the number of the replicate.

Table 2. Average values of cumulative ET for each pasture type measured by the enclosed portable chamber method and water balance method from 15 to 20 July 1997.

Pasture	Cumulative ET (mm)	
	Water balance method	Portable chamber method
Degraded	5.93	6.12
Phalaris	5.24	5.48
Phalaris+white clover	6.48	5.64
$LSD_{0.05}$	2.5	

[a]Values followed by the same letter are not significantly different at P=0.05

Table 3. Mean ET of wheat crop measured by the Bowen Ratio and portable chamber method with three different fan speeds from 11:30 to 17:00 on the 19 and 20 August 1997.

	BR	Fan speeds with the portable chamber		
		Low	Med	High
ET (mm/day)	2.30[a]	2.22[a]	2.39[a]	2.51[a]

Table 4. Summary of the main effect of the method comparison on ET

Main factor	Value (mm/hour)	Std.error (mm/hour)	t	Pr (t)
Bowen Ratio day 1	0.3925	± 0.039	10	<0.001
Bowen Ratio day 2	0.336	± 0.00875	-6.3	<0.001
Portable chamber-Low	0.34458	± 0.05375	-0.9	0.4
Portable chamber-Medium	0.3908	± 0.055416	-0.02	0.98
Portable chamber-High	0.40458	± 0.059166	0.2	0.84

Table 5. The spline coefficients of each method and their standard errors.

Basis function	Time range	Coefficient	BR	Fan speeds the portable chamber with		
				Low	Med	High
S_1	11-14	β_1	2.87(1.90)	1.81(1.80)	2.65(1.90)	2.18(2.06)
S_2	12-16	β_2	-0.88(1.58)	3.12(1.57)	2.15(1.56)	5.38(1.55)
S_3	14-17	β_3	-2.03(.72)	-2.14(1.60)	-2.5(1.69)	-4.12(1.77)
S_4	15-17	β_4	-2.15(.19)	-3.55(1.16)	-5.25(1.18)	-5.90(1.24)

Value inside the parentheses is the standard error of the coefficient.

Table 6. The spline coefficients of the B-spline used to predict ET from solar radiation and soil water content (Equation 12).

Basis function	Factors	Coefficient	t-value
BS_1	Solar radiation	0.19(0.23)	0.82
BS_2	Solar radiation	1.45(0.12)	11.92
BS_3	Solar radiation	1.72(0.16)	10.59
BS_4	Solar radiation	1.85(0.11)	15.61
BS_5	Solar radiation	2.11(0.13)	16.06
BS_6	Solar radiation	2.18(0.12)	17.53
	d10 cm	0.009(0.004)	2.15
	d20 cm	0.018(0.009)	-2.10
	d30 cm	0.018(0.008)	2.26
	d40 cm	0.009(0.004)	-2.19

Value inside the parentheses is the standard error of the coefficient.

Figure captions:

Figure 1.The schematic diagram of the chamber construction redrawn from Stannard (1988).

Figure 2. The enclosed portable chamber for measuring ET used in this study.

Figure 3. The increase in vapour density (g/m^3) inside the enclosed portable chamber during the one minute measurement period. The slope of the straight line section between 5 and 26 second represents the vapour accumulation rate and was used to calculate the instantaneous ET rate.

Figure 4. Plot of the vapour accumulation rate and vapour production rate to provide the calibration factor for vapour absorption by the chamber material.

Figure 5. Changes in soil profile water content from 15/07/1997 to 20/07/1997 under each pasture type.

Figure 6. Mean daily evapotranspiration under degraded, phalaris, and phalaris+white clover pastures from 15/7/1997 to 20/7/1997. The vertical bars indicate the LSD value at P=0.05 for each measurement date.

Figure 7. Hourly ET rates measured by the Bowen Ratio (BR) method and the portable chamber method from 11:00 to 17:00 for the 19 and 20 August 1997 (a,c). The lower diagrams (b,d) show the corresponding hourly net radiation.

Figure 8. B-spline models of the ET rates measured by Bowen Ratio and portable chamber method at three fan speeds from (a) 11:00 to 17:00 on 19/8/1997 and from (b) 11:30 to 17:00 on 20/08/1997. The lines are the predicted ET value with the B-spline model, while the points are the measured values.

Figure 9. Daily pasture ET (mm) as a function of solar radiation adjusted to mean initial soil water content (swc).

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