

Comparison of an isotopic method and the Penman-Monteith equation for estimating transpiration from Scots pine

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The Penman-Monteith equation was used with measured values of stomatal conductance and leaf area, in conjunction with weather station measurements of net radiation, vapor pressure deficit, and wind speed to calculate the transpiration rates of two Scots pine (*Pinus sylvestris* L.) stands of widely different densities. Transpiration was compared with water uptake estimated from ³²P radioisotope movement through trees of known conducting area and water content. Uptake consistently lagged behind transpiration throughout the day. From dawn to dawn, however, uptake and transpiration were in close agreement as a result of recharge during the night.

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L'équation de Penman-Monteith a été utilisée avec des valeurs mesurées de la conductance stomatique ainsi que l'aire foliaire conjointement avec des données météorologiques de station de la radiation nette, du déficit de tension de vapeur et de la vitesse du vent pour calculer les taux de transpiration de deux peuplements de pin d'Ecosse (*Pinus sylvestris* L.) de densités très différentes. La transpiration a été comparée avec l'absorption hydrique estimée à partir de l'entraînement du radioisotope ³²P dans des arbres dont l'aire de conduction et la teneur en eau étaient connues. Toutefois, au début de chaque journée l'absorption et la transpiration étaient en accord suite à l'hydratation nocturne.

Introduction

Canopy stomatal conductance, measured with a porometer, can be used in the Penman-Monteith equation (Monteith 1965) with meteorological variables to calculate rates of transpiration from forests (Rutter 1975). This method requires a dry canopy, measurement of leaf area density, and an appropriate procedure in the choice of shoots to be sampled.

An alternative method for estimating transpiration rates injects radioactive isotopes into the sapwood of individual trees and subsequently measures the velocity of the isotope up the stems (Owston et al. 1972). This method requires a knowledge of the conducting area in the individual trees and an estimate of the change in stored water in the sapwood (Waring et al. 1979). However, when this method is compared against an independent estimate of transpiration, an excellent agreement has been noted (Waring and Roberts 1979).

In this study, these two methods were used to measure simultaneously transpiration rates on two forest plots of Scots pine (*Pinus sylvestris* L.) in

northeastern Scotland. Results over short intervals of a few hours and cumulative estimates over periods of 24 h are compared for the two techniques.

Methods

The two plots of Scots pine were part of a spacing experiment in Roseisle Forest, part of the Forestry Commission's Laigh of Moray Forest in northeastern Scotland (58° N latitude, 4° W longitude). The trees were planted in 1936 and have been thinned to maintain differences in spacing. In 1977, transpiration was measured on the two plots with the most contrasting spacings, plots 1 and 2 with 608 and 3281 trees ha⁻¹. Table 1 summarizes the characteristics of the trees on both plots.

The Penman-Monteith equation

Hourly rates of transpiration, E_{PM} , were calculated from the Penman-Monteith equation as

$$[1] \quad E_{PM} = \frac{sA + \rho c_p D g_a}{\lambda[s + \gamma(1 + g_a/g_c)]}$$

where A is net radiation, D is saturation deficit, g_a is canopy boundary-layer conductance (calculated as $g_a = 0.1 \cdot u_h$, where u_h is the wind speed (metres per second) at canopy height, h (Jarvis et al. 1976)), and g_c is canopy stomatal conductance. The constants, s , λ , c_p , ρ , and γ , are the slope of the saturated vapor pressure curve with temperature, the latent heat of evaporation of water, the specific heat of air at constant pressure, the density of moist air, and the psychrometric constant, respectively. The constant s depends strongly on temperature; the others are weak functions of temperature. Daily transpiration was calculated by summing the hourly values for each canopy.

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TABLE 1. Summary of characteristics of the two forest plots (from Whitehead 1978)

Plot	No. of trees/ha	Tree height ± SE ^a (m)	Basal area, OB ^b (m ² ·ha ⁻¹)	Standing volume ^c (m ³ ·ha ⁻¹)	Sapwood basal area ^d (m ² ·ha ⁻¹)	Leaf area index ^e
1	608	15.0±0.3	26.6	168	21.0	2.4
2	3281	15.0±0.2	57.7	365	39.8	3.1

^aStandard error (SE) from measurements on 10 trees on each plot.

^bDetermined from outside bark (OB) diameter measurements on all trees on each 0.1-ha plot.

^cTotal stemwood volume estimated from Forest Mensuration Handbook (Hamilton 1975).

^dEstimated from proportion of sapwood determined by coring 20 randomly selected trees on each plot.

^eEstimated from linear correlation with sapwood basal area (Whitehead 1978).

Hourly mean values of net radiation, wind speed, and wet and dry bulb temperatures were obtained from the records of an automatic weather station (Strangeways 1972) situated 2 m above the canopy on plot 2.

On 30 days throughout the season, stomatal conductance of shoots was measured on both plots at 2-h intervals using a null-balance diffusion porometer (Beardsell et al. 1972). Five shoots from each of three levels and two age-classes in each canopy were measured during daylight hours. At the end of each 1-week measurement period, the shoots were removed and their projected areas measured using an optical planimeter (model No. LI-3000, LiCOR Instrument Corp., Lincoln, NE).

Total canopy stomatal conductance was calculated from the sum of the products of the mean shoot conductance and the leaf area index of each class of foliage (Jarvis et al. 1976; Watts et al. 1976). The distribution of foliage area between the classes of foliage had been previously determined (Whitehead 1978).

Radioisotope ³²P

The preparation of the isotope, injected as a solution of 1 mCi (3.7 × 10⁷ Bq) of ³²P orthophosphate in dilute hydrochloric acid, and the injection procedure have been described by Waring and Roberts (1979). During each period of measurement, five trees on each plot were injected with ³²P. The rates of isotope movement were followed up the stem at approximately 2-h intervals during the day with a portable scaler ratemeter. We monitored up to a height of 7 m which was still below any living branches.

The volume of water, Q , moving through each 1-m long segment of stem each day was calculated from [2] (Waring and Roberts 1979):

$$[2] \quad Q = \frac{l}{t} A_s \left[\frac{\rho_t - \rho_d}{\rho_w} - B \left(1 - \frac{\rho_d}{\rho_{l,c}} \right) \right]$$

Q is determined by knowing the rate at which a pulse of isotope moves through a known distance, l , through a measured cross-sectional area of sapwood, A_s , of specified water content and density in time t . Four density measures are required: ρ_t , ρ_d , ρ_w , and $\rho_{l,c}$ which correspond to the fresh density, dry density, the density of water, and the density of the lignin and cellulose in the sample, 1530 kg·m⁻³ (Siau 1971).

The cross-sectional area of sapwood between the point of injection and 7 m above ground level was estimated at 1-m intervals from two cores extracted at right angles across the stem with an increment borer. By holding the cores against the sunlight, sapwood showed as a translucent band whereas the heartwood was opaque.

Sapwood cores were extracted at dawn each day of measurement to determine ρ_t and ρ_d (Waring et al. 1979). B , the fraction of the water content which is bound to the cell walls, was estimated as 0.2 from the equilibration of pieces of Scots pine wood above a graded series of salt solutions maintained at a constant temperature (Waring et al. 1979).

Over a given day, ρ_t was assumed constant although it does vary somewhat (Waring et al. 1979). If the sapwood segment

through which water moves in a specified period has a constant water content and density between measurements, and if isotope movement is uniform throughout, the average volume flux of water, \bar{Q} , through the segment over the interval t can be calculated as

$$[3] \quad \bar{Q} = \frac{V_{sw}}{t} \bar{\phi}_a$$

where V_{sw} is the volume of sapwood in the segment, and $\bar{\phi}_a$ is the average volume fraction of free water. The total volume flow of water through a stem during a day was calculated from [3] knowing the volume of sapwood through which the isotope passed and the free water contents of the appropriate segments.

The transpiration rate, E_t , for each plot was calculated by multiplying the flux of water per unit of sapwood basal area of a tree by the sapwood basal area of the stand (21.0 and 39.8 m²·ha⁻¹ for plots 1 and 2, respectively). With five trees available from each plot, a mean transpiration rate with a standard error could be calculated.

Results

Although transpiration rates were measured on 30 days using the Penman-Monteith equation, complete data when the foliage remained dry from dawn until dusk were only available on 10 days. Isotope movement was monitored on 25 days throughout the season, but some days included times when the foliage was wet and others when the isotope pulse extended beyond 7 m in height. Complete days when isotope measurements were taken at approximately 2-h intervals and for which comparable canopy measurements existed occurred for both plots on two occasions, 1 May and 6 July 1977 (Julian dates 121 and 187).

On 1 May, estimated transpiration was less than half that on 6 July because of differences in evaporative demand (Figs. 1 and 2). Throughout both days, the cumulative uptake of water through the boles lagged significantly behind that transpired from the canopy on both plots. Only with recharge of the boles late in the evening and through the night did uptake and transpiration approach a balance for the day.

The estimates of transpiration by the two methods were significantly correlated when compared over a period of 24 h from dawn to dawn as shown in Fig. 3. Although the regression equation indicates a 9% lower estimate of transpiration

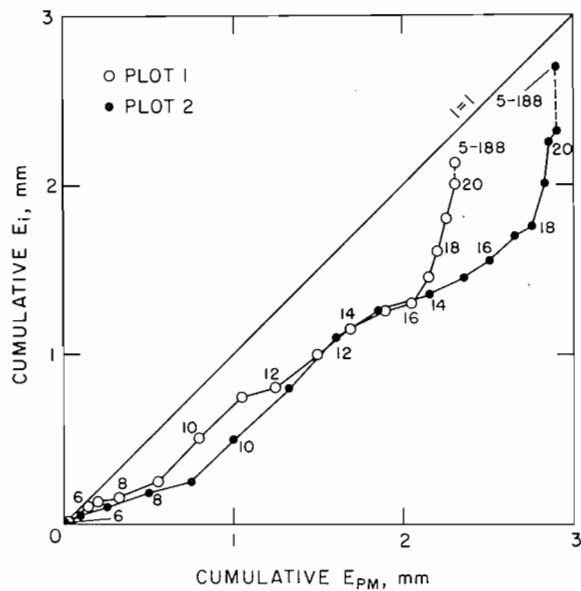


FIG. 1. Comparison of cumulative hourly estimates of transpiration by the isotopic method (E_i) and the Penman-Monteith equation (E_{PM}) for Julian day 187, 1977. Hourly values are indicated on the curves.

by the isotopic method, this difference is not statistically significant at the 95% confidence interval, and it could easily be attributed to a $\pm 2\%$ variation in sapwood relative water content from dawn to dawn (Waring et al. 1979).

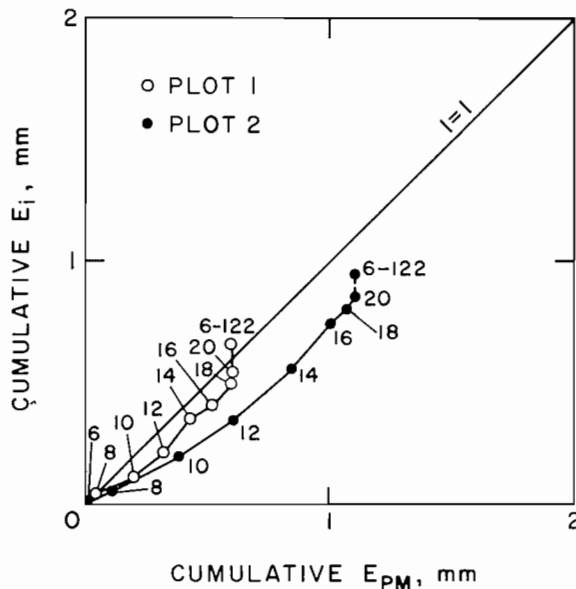


FIG. 2. Comparison of cumulative bi-hourly estimates of transpiration by the isotopic method (E_i) and the Penman-Monteith equation (E_{PM}) for Julian day 121, 1977. Bi-hourly values are indicated on the curves.

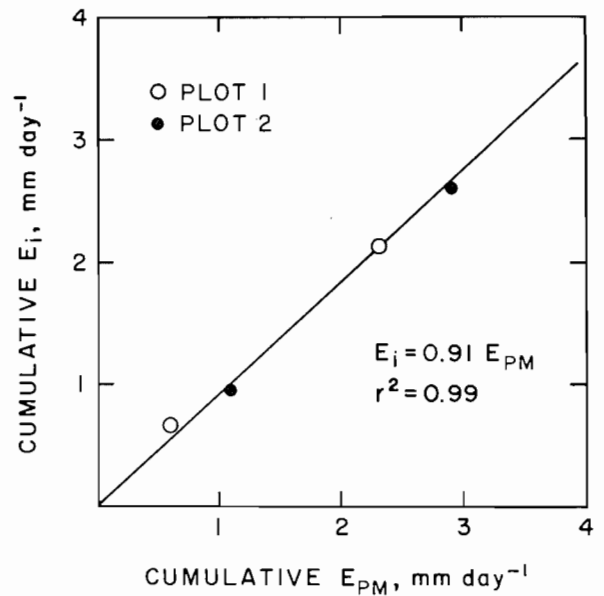


FIG. 3. Relationship between cumulative daily transpiration estimates made with the Penman-Monteith equation (E_{PM}) and the isotope method (E_i) for Julian days 121 and 187 on plots 1 and 2. The standard error of estimate, $S_{y \cdot x}$, for the regression is 0.12.

Discussion

On a basis of total daily transpiration, the two methods closely agreed. The slightly lower estimates of transpiration by the isotopic method, although not statistically significant, may reflect absorption as the pulse progressed through the bole. If some ^{32}P is absorbed the apparent rate of the pulse would be less than that of the water.

Withdrawal of water from storage in the boles might explain the cumulative discrepancies between the estimates of transpiration by the two methods. Evidence suggests that water was withdrawn from storage throughout most of the day (Figs. 1 and 2) and that uptake probably occurred at night. A net reduction in stored water of less than 2% relative water content would account for about a 5% difference in water uptake estimated by the two methods. Such small changes were less than could be identified by diurnal sampling of increment cores (Waring et al. 1979). More precise estimates of changes in storage may be possible by increasing the number of cores sampled and by determining precisely the volume of each core.

On the research site, the conducting tissue only reached and remained at saturation for a period of less than 10 very wet days (Waring et al. 1979). Internal storage appeared to change whenever the trees transpired appreciably. Thus, without accurate measurement of the changes in storage during

the day, the isotopic method or related heat-pulse method (Doley and Grieve 1966; Swanson 1972; Lassoie et al. 1977) are likely to be poor estimators of diurnal variation in transpiration rate.

The possibility of using radioactive isotopes routinely to estimate daily transpiration is small because of related health hazards. The assumptions made in calculating water flux through the stems should, however, apply to velocity estimates made from the heat-pulse method. Further investigations are warranted to demonstrate whether velocity measurements based on the heat-pulse method (when corrected for net changes in storage, wood density, and effective conducting area) correspond to independent estimates of daily transpiration.

Methods based upon the flow of water through stems do have the advantage of not requiring canopy measurements or precise knowledge of meteorological conditions. Moreover, they offer the possibility of calculating transpirational losses during days when the canopy is partly wet. Such methods may also offer a means of estimating water loss from mixed forests growing on steep slopes where canopy exchange processes are difficult to calculate.

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