

Chapter (non-refereed)

Jarvis, P.G.; Stewart, J.B.. 1979 Evaporation of water from plantation forest. In: Ford, E. D.; Malcolm, D. C.; Atterson, J., (eds.) *The ecology of even-aged forest plantations*. Cambridge, Institute of Terrestrial Ecology, 327-350.

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EVAPORATION OF WATER FROM PLANTATION FOREST

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SUMMARY

The transpiration and evaporation of water from plantation forest is analysed with the aid of the Penman-Monteith equation.

When the canopy is dry, the rate of transpiration is generally restricted to less than 0.3 mm/h or 3 mm/day in summer and 0.03 mm/day in winter by the combined effects of saturation and stomatal conductance. When saturation deficits are small the stomatal conductance is high, but when saturation deficits are large, stomatal conductance is low as the result of stomatal closure. Consequently transpiration uses only about 40 per cent of the available energy and Bowen ratios are large and often over 2.

When the canopy is wet, evaporation is rapid because of the very high boundary layer conductance of forest canopies. Even though the available energy and the saturation deficits are very small, rates of over 0.3 mm/h are reached. Thus, the rate of evaporation often exceeds the rate of input of available energy and the Bowen ratio is negative as a result of the addition of sensible heat to the canopy.

Despite the much lower available energy and saturation deficits on rainy days than on sunny days, evaporation rates are often 2-3 times transpiration rates because low stomatal conductance reduces transpiration on fine days and high boundary layer conductance enhances evaporation on wet days. Hence long term rates of water loss from plantation forest by transpiration and evaporation depend upon the pattern of rainfall distribution and are much

larger where frequent rainfall keeps the canopy wet for much of the time.

Because the stomatal conductance of forest is lower than that of grassland, transpiration rates from forest are lower than rates from grassland in the same meteorological conditions despite differences in the albedos. However, rates of evaporation from wet forest canopies are very much higher than from wet grasslands because the boundary layer conductance of forest is much higher than that of grassland. Thus, long-term rates of water loss from forest may be more or less than losses from grassland, depending upon the proportion of time the canopy is wet and hence the pattern of rainfall distribution.

More precise evaluation requires better information on the stomatal and boundary layer conductances of different types of forest at different stages of development, and on interception loss and duration of canopy wetness in different climatic regions.

RÉSUMÉ

La transpiration et l'évaporation de l'eau dans les plantations forestières sont analysées à l'aide de l'équation de Penman-Monteith.

Quand le couvert est sec, le taux de transpiration est en général ramené à moins de 0.3 mm/h ou 3 mm/jour l'été, et à 0.03 mm/jour l'hiver, dû à la combinaison du déficit de saturation et de conductance stomatale. Lorsque les déficits de saturation sont faibles, la conductance stomatale est élevée, tandis que lorsqu'ils sont élevés la conductance stomatale est faible à cause d'une fermeture stomatale. Par conséquent la transpiration n'utilise que 40 per cent de l'énergie disponible et les rapports Bowen sont élevés et dépassent souvent 2.

Quand le couvert est mouillé, l'évaporation est rapide à cause de la conductance de la couche limite très élevée des couverts forestiers. Même dans le cas où l'énergie disponible et les déficits de saturation sont faibles, on arrive à des taux dépassant 0.3 mm/h. Ainsi, le taux d'évaporation excède souvent le taux d'absorption d'énergie disponible et le rapport Bowen est négatif à cause d'un léger apport de chaleur au couvert.

Malgré le fait que l'énergie disponible et les déficits de saturation sont plus faibles les jours de pluie que les jours de beau temps, le taux d'évaporation est parfois deux à trois fois plus élevé que le taux de transpiration parce qu'une faible conductance stomatale réduit la transpiration pendant les jours de beau temps et que la conductance élevée de la couche limite augmente l'évaporation les jours de pluie. Donc, il résulte que, dans les plantations forestières les taux à long terme de perte d'eau dûe à la transpiration et à l'évaporation dépendent de la distribution des chutes de pluie et sont bien plus importants dans le cas où le couvert reste mouillé la plupart du temps.

Puisque la conductance stomatale des forêts est plus faible que celle des prairies, le taux de transpiration des forêts est plus faible que celui des prairies, dans les mêmes conditions météorologiques malgré des albédos différents. Cependant, le taux d'évaporation des forêts à couverts mouillés est bien plus important que celui des prairies humides parce que la conductance de la couche limite des forêts est bien plus élevée que celle des prairies. Ainsi, le taux, à long terme, des pertes d'eau des forêts peut être, soit plus faible, soit plus élevé que celui des prairies, le tout dépendant du temps pendant lequel le couvert est mouillé et, par conséquent, de la distribution des chutes de pluie. Une meilleure évaluation nécessite plus de renseignements sur les conductances des stomates et la couche limite des différentstypes de forêts à des stades différents de développement, sur l'interception et le temps pendant lequel un couvert reste mouillé dans des régions de climats différents.

ZUSAMMENFASSUNG

Transpiration und Evaporation von Forstpflanzen wurden mit Hilfe der Penman-Monteith Gleichung analysiert.

Bei trockenem Kronendach beschränkt sich die Transpiration aufgrund des Zusammenwirkens von Sättigungsdefizit und Spaltöffnungsverhalten auf weniger als 0.3 mm pro Stunde oder 3 mm pro Tag im Sommer und 0.03 mm pro Tag im Winter. Bei niedrigen Sättigungsdefiziten besteht hohe

Regulierbarkeit der Spaltöffnungen, bei hohen Sättigungsdefiziten ist sie jedoch sehr gering, da dann die Spaltenöffnungen geschlossen sind. Folglich werden nur 40 Prozent der verfügbaren Energie durch die Transpiration ausgenützt und die Bowen-Quotienten sind gross, oft über 2. Bei nassem Kronendach ist die Evaporation intensiv aufgrund der hochliegenden Grenzschicht des Kronenraums. Auch bei knappem Energieangebot und sehr geringem Sättigungsdefizit werden Werte von über 0.3 mm pro Stunde erreicht. So übersteigt die Evaporationsrate oft den Input an verfügbarer Energie und das Bowenverhältnis wird durch die zusätzliche Wärme des Kronendaches negativ. Obwohl die verfügbare Energie und die Sättigungsdefizite an Regentagen viel geringer sind als an sonnigen, liegen die Evaporationsraten oft zwei- bis dreimal höher als die Transpirationsraten, da die geringe Regulierbarkeit der Spaltöffnungen bei schönem Wetter die Transpiration reduziert, während die hoch liegende Grenzschicht an Regentagen die Evaporation steigert. Die Langzeitraten des Wasserverlusts durch Transpiration und Evaporation in Forstpflanzungen hängen somit von der Art der Niederschlagsverteilung ab; sie sind viel grösser, wo häufiger Niederschlag das Kronendach die meiste Zeit nass hält. Da die Spaltöffnungsregulierung im Forst unter denselben meteorologischen Bedingungen und trotz unterschiedlicher Albedo geringer ist als bei Grasland, liegen auch die Transpirationsraten des Forsts niedriger. Andererseits sind jedoch die Evaporationswerte bei nassem Kronendach sehr viel höher als bei nassem Grasland, da die Grenzschicht im Wald viel höher liegt. So können also die Langzeitraten des Wasserverlusts im Forst grösser oder kleiner sein als bei Grasland, je nachdem wie lange das Kronendach nass ist - was natürlich von der Art der Niederschlagsverteilung abhängt. Zu einer präziseren Darstellung wären bessere Information über die Spaltöffnungsregulierung und die Grenzschicht bei verschiedenen Forsttypen in verschiedenen Entwicklungsstadien notwendig, ausserdem über den Interceptionsverlust und die Zeit der Kronenbefeuchtung in verschiedenen Klimazonen.

GENERAL PRINCIPLES

The driving force for the movement of water from the soil through the trees to the atmosphere is provided by the evaporation of water at the liquid - air interface within the leaves. The phase change followed by the diffusion of water molecules through the stomata is here called transpiration (E_T) to distinguish it from the evaporation of intercepted water on the surfaces of the foliage, twigs, branches and other parts of the trees (E_I). E is used when either or both E_T or E_I is intended.

The transpiration of evaporation of water from the foliage depends strongly upon the available energy (A), the saturation deficit of the air (D), the wind speed (U) and, to a lesser extent, on air temperature (θ). In addition, transpiration is strongly dependent upon the stomatal conductance (g_s) of the needles and evaporation on the structural characteristics of the canopy which influence the boundary layer conductance (g_a) in addition to the windspeed.

These variables were first put together through the application of the conservation of energy to exchange processes in crop canopies by H.L. Penman in 1948 and were first related explicitly in the manner used below by J.L. Monteith in 1965. As a result the following expression for transpiration has come to be known as the Penman-Monteith equation. It was first applied to the study of water loss from trees in plantations by A.J. Rutter in 1967.

$$\lambda E_T = \frac{sA + c_p \rho D g_a}{s + \gamma(1 + g_a/g_s)} \quad (1/m^2) \quad \dots(1)$$

$$1W/sq.m = 0.0015 \text{ kg}/(sq.m/h) = 0.0015 \text{ mm/h}$$

The physical parameters c , ρ , γ and λ , respectively the specific heat of air, the density of air, the psychrometric constant and the latent heat of vaporization of water, are all weak functions of temperature (see Table A3 in Monteith 1973). The parameter s is the slope of the curve relating the saturated vapour pressure of water (e_s) to temperature (i.e. $de_s/d\theta$) at the appropriate temperature and varies appreciably with temperature. For example, it has values of 0.61, 0.83, 1.45 and 2.44 mb/ $^{\circ}\text{C}$ at 5, 10, 20, and 30 $^{\circ}\text{C}$, respectively (Monteith 1973, Table A4).

In the case of evaporation of intercepted water from a completely wet canopy, rather than the transpiration of water which has passed through the plant, g_s becomes very large indeed (Shuttleworth 1976) and equation (1) becomes

$$\lambda E_I = \frac{sA + c_p \rho D g_a}{s + \gamma} \quad \dots(2)$$

Provided that the dependence of g_a on windspeed is known, evaporation can be calculated from this equation wholly from weather station data.

The Penman-Monteith equation can be applied to single leaves or extensive canopies. When applied to canopies, an approximation is involved since the derivation assumes identical sources and sinks of water vapour and heat, whereas this is unlikely to be the case in a canopy. However, comparisons with more complex models show that this approximation does not lead to serious error (Sinclair, Murphy & Knoerr 1976; Shuttleworth 1976).

The equation can be applied successfully over periods of weeks, days, hours or minutes provided that appropriate values of the variables are available. Application over short periods of time, such as an hour, is usually limited by the availability of hourly meteorological data and hourly measurements or reliable estimates of stomatal conductance, g_s .

The equation predicts that E will increase with increases in either available energy or saturation deficit or both. The influence of available energy and saturation deficit on E appears in the numerator as additive. In the past this has led to the description of evaporation as having a radiation dependent component and a windspeed or saturation deficit dependent component. This is convenient but somewhat artificial since the maintenance of a saturation deficit depends upon the input of energy into the system. However, the relative importance of available energy and saturation deficit in deriving E can readily be defined by the ratio of the two terms in the numerator of equation (1) or (2) as

$$J = c_p \rho D g_a / s_a \quad \dots(3)$$

Clearly the larger the boundary layer conductance, the larger will be the effect of saturation deficit on E . If both g_a and D are large, the deficit term may greatly exceed the radiation term. This is commonly the case for tall, rough vegetation like plantation forest when the canopy is dry. For dry canopies of coniferous plantations, J typically lies in the range 5-20.

This leads to a useful simplification of equation (1). In the first place, if J is large and transpiration is much more dependent on saturation deficit than on available energy, the radiation term can be neglected. Secondly, if the ratio g_a/g_s is also large, as will be seen later, the small terms in the denominator of equation (1) can be ignored. Thus the rate of transpiration can be approximated by

$$E_T = \frac{c_p \rho}{\lambda \gamma} \cdot D \cdot g_s = K \cdot D \cdot g_s \quad \dots(4)$$

where K is the factor for converting partial pressure of water vapour into mass concentration and has a value of $740 \times 10 \text{ kg}/(\text{cu.m mb})$ at a temperature of 20°C and atmospheric pressure of 1013 mb .

Equations (1) and (2) provide a means of determining the rates of transpiration and evaporation in particular circumstances. To demonstrate how the properties of plantation forests interact with the environmental variables, it is also convenient to express evaporation in terms of the sources of energy available to drive it:

$$A = \lambda E + C \quad \text{.....(5)}$$

where C is the convective exchange of sensible heat to or from the foliage. Two alternative parameters are commonly used to describe the partitioning of available energy: - the proportion of the available energy used in evaporation

$$\alpha = \lambda E / A \quad \text{.....(6)}$$

- the Bowen ratio, which is defined as

$$\beta = C / \lambda E \quad \text{.....(7)}$$

From equations (5) and (7) λE can also be written as

$$\lambda E = A / (1 + \beta) \quad \text{....(8)}$$

TRANSPIRATION FROM DRY CANOPIES

Measured mean hourly rates of transpiration from extensive plantations of Sitka Spruce in Scotland (Forest of Mearns) and Scots pine in Norfolk (Thetford Forest) can reach 0.3 mm/h (200 W/sq.m) but are more commonly in the range 0.1 to 0.2 mm/h (70 – 140 W/sq.m), depending on the weather and time of day. Daily rates can reach 3 mm/day in the summer but are more commonly about 2 mm/day in summer and 0.3 mm/day in winter.

These rates of transpiration account for the utilisation of only a small proportion of the available energy. On average during the daytime only 40 per cent of the available energy is used for transpiration; values of α are within the range 0.3 to 0.5 for many hours of observations at Forest of Mearns, and Thetford Forest. The daytime Bowen ratios are rarely less than 1 and frequently in the range 2–4, rising to even higher values during drought or periods of high temperature and low humidity. Such low rates of transpiration and the values of α and β are very different from what was expected ten years ago on the basis of experience with short vegetation such as agricultural crops and grasslands. The transpiration rate from such vegetation when well supplied with water may equal or

exceed the input of available energy; α for such vegetation is frequently in the range 0.8 to 0.9 and β in the range 0 to 0.5 (Penman, Angus & van Bavel 1967). That is to say, the rate of transpiration from short vegetation may commonly be two to three times larger than from plantation forest; or conversely, the rate of transpiration from plantation forest is only about 1/5 to 1/3 of the rate from crops and grassland.

To make useful generalizations about water use by plantation forests, we need, therefore, to consider the reasons for the low measured rates of transpiration, low values of α and high values of β .

As expressed in equation (1), the main variables determining the rate of transpiration are:

- the available energy, A
- the saturation deficit, D
- the boundary layer conductance, g_a
- the stomatal conductance, g_s .

In principle, the rate of transpiration could vary widely and reach very high values depending on the values of these variables. In practice, however, the range is restricted by the combinations of values of the variables which occur. These combinations depend both on the environmental variables and on the morphological and physiological properties of the foliage of the trees.

Available energy and saturation deficit

Net radiation over coniferous forest is about 75-90 per cent of the incident shortwave radiation (Jarvis, James & Landsberg 1976). For dense canopies which intercept most of the radiation, such as Sitka spruce at 4000 trees/ha, with a leaf area index of about 9, little radiation reaches the soil and in the middle of the day only about 5 per cent of the net radiation goes into storage. Thus the available energy can reach about 600 W/sq.m in summer. In more open stands such as Scots pine with a leaf area index of only 3 or 4, much more of the net radiation reaches the soil and also goes into storage in the stems and branches. Consequently the energy available to evaporate water from the canopy is rather less, reaching only about 400 W/sq.m.

The normal range of saturation deficits in temperate maritime climates is small. Over most of the British Isles, and particularly those parts in which forest plantations occur, saturation deficits only occasionally exceed 15 mb. The normal range of deficits throughout the year over the main areas of afforestation is 1-10 mb. Of course much larger deficits of up to 30 mb do occur commonly in the summer in more continental areas where plantations are grown.

Stomatal conductance

The maximum stomatal conductance of Sitka and Norway spruce forests canopies is about 0.02 m/s. The maximum conductance for Scots pine, lodgepole pine and Douglas fir is

somewhat less at about 0.01 m/s. However, measured conductances are usually less than these values, depending on the weather, the time of day and time of year. For comparison, the maximum stomatal conductances of crop canopies and grassland are somewhat larger (0.015 to 0.05 m/s).

The conductance of a canopy is the arithmetical sum of the conductances of all the individual needles. Thus it depends upon the number of needles present, i.e. on the leaf area index, and on the conductance of the individual needles. The conductance of a needle varies with the species, and depends upon the age of the needle and its position in the canopy, as well as upon the season, the time of day and the current weather. Because of the variation amongst needles in a canopy, the canopy conductance depends upon the proportion of needles of different properties which are present, i.e. on the partial leaf area indices of needles of different ages, position, branching etc.

The conductance of needles of conifers is low because of the occurrence of a meshwork of wax tubes in the stomatal antechambers (Jeffree, Johnson & Jarvis 1971). g_s is also much reduced on a daily and seasonal basis by the pronounced sensitivity of the stomata of many conifers to saturation deficit. This sensitivity is particularly marked in Sitka spruce (Grace, Malcolm & Bradbury 1975; Watts, Neilson & Jarvis 1976; Watts & Neilson 1978).

Boundary layer conductance

In comparison with diffusion through the stomata, the turbulent transfer of water molecules across the needles and shoot boundary layers and through the canopy to the air above is very effective. Consequently the boundary layer conductance is very large in relation to the stomatal conductance and hence can vary widely with little or no influence on transpiration. Values of g_a are typically 0.1 to 0.3 m/s which can be compared with the values of g_s of 0.02 m/s.

In addition, the large boundary layer conductance of plantation forest facilitates removal of sensible heat from the foliage with the consequence that leaf temperatures of conifers are seldom very different from air temperatures (Jarvis, James & Landsberg 1976). As a result of enhanced sensible heat transfer and low leaf temperatures, the transpiration rate is less than might otherwise be expected, α is smaller and β is larger. For comparison, g_a of crops and grassland is an order of magnitude lower (see under Evaporation from wet canopies), leading to lower sensible heat losses and higher leaf temperatures, both of which tend to push the transpiration rate up and β down.

In the absence of stomatal control, when the canopy is wet, the boundary layer conductance is a major factor determining the rate of evaporation and is considered later.

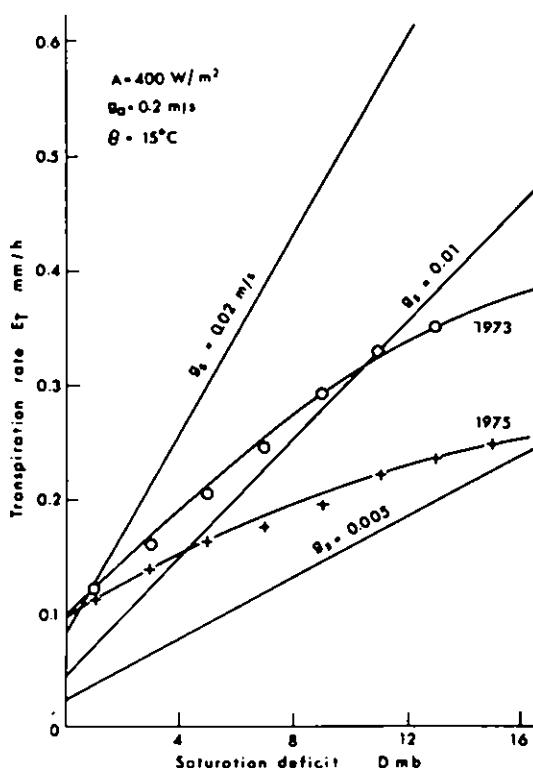


Fig. 1. The relation between transpiration rate and saturation deficit calculated from equation (1) for the conditions shown and three different values of g_s . The data points are medians of a large number of mean hourly values within saturation deficit classes for Sitka spruce at Forest of Mearns in June and July 1973 and 1975. The stand was thinned in 1974

Conclusions

From these figures and equation (1), we may estimate the rates of transpiration we would expect to find. For example, if g_s were to be maintained at 0.02 m/s on a fine summer day when $A = 600 \text{ W/sq.m}$ and $D = 15 \text{ mb}$, a transpiration rate of 0.9 mm/h, three times the maximum measured rate, would be expected, together with $\alpha > 0.9$ and a low value of β of about 0.1.

The question arises as to why the measured transpiration rates and values of α are so much lower than might be expected

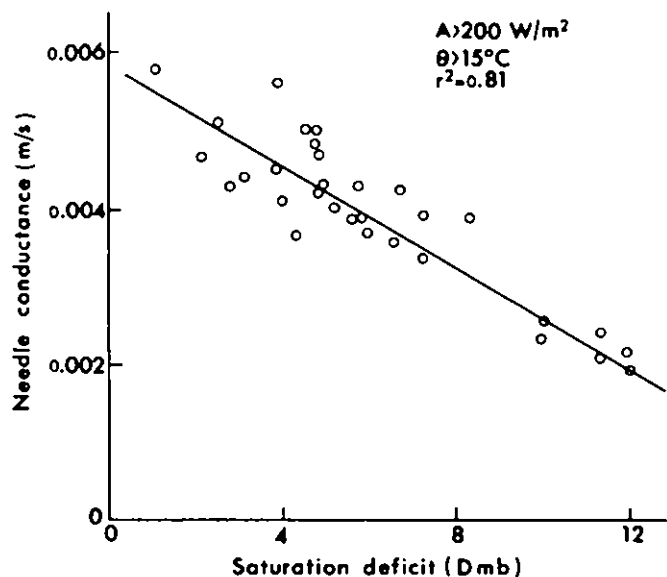


Fig.2. The relation between saturation deficit and stomatal conductance of 1-year-old needles of Sitka spruce in the upper part of the canopy, Forest of Mearns, summer 1972. Needle conductance expressed on a unit needle area basis.

and the Bowen ratios so much higher. The answer is made most clearly evident by reference to the simplification in equation (5). Essentially, E_T depends upon g_s and D . Stomatal conductance is large in humid, cool weather when deficits are small, but because of the small deficits transpiration is not large in any case. On the other hand, in warm, dry weather when the deficits are large, the stomatal conductance is small, because the stomatal conductance itself depends upon the deficit. Stomatal conductance and saturation deficit are never both large at the same time. Consequently transpiration never reaches the high rates expected.

Although the rate of transpiration does increase as D increases (Fig. 1), it does not increase to the extent that would be expected because g_s does not remain constant. During the course of a warm, summer day, g_s decreases as the saturation deficit gets larger (Fig. 2) and in extreme conditions may get so small that CO_2 uptake becomes zero or negative. Thus there is feedback in the needle which effectively prevents large rates of water loss being attained. Laboratory experiments show that this decrease in g_s results from the closing of stomata. Closure is not associated with

the development of large water stresses in soil, tree or leaf mesophyll, but is a specific response of the stomata to saturation deficit.

Influence of stage of development

Transpiration from dry canopies depends upon the stomatal conductance of the canopy. This in turn depends upon the accumulation of leaf area and development of a closed canopy, as well as upon the changing morphological and physiological characteristics of the needles and behaviour of the stomata. So far as we know, systematic studies of stomatal conductance of canopies have been made on about ten stands of five different species at varying stages of development in the U.K. No systematic studies of stage of development of g_s have been made or are in progress.

EVAPORATION FROM WET CANOPIES

The rate of evaporation of intercepted water from wet canopies can reach very high values. Rates are normally in the range 0.1 to 0.3 mm/h (70-210 W/sq.m) but can exceed 0.5 mm/h (340 W/sq.m) in the summer for short periods. The rate of evaporation often exceeds the rate of input of available energy, i.e. $\alpha > 1$, β negative. For example, the average of 245 measurements of evaporation rate over 20 min periods from a wet Scots pine canopy at Thetford was 129 W/sq.m and the corresponding average rate of available energy input was 102 W/sq.m (Stewart 1977).

At first sight this might appear surprising since canopies are wet, dew apart, either when it is raining or immediately after rain has ceased. In these circumstances it is usually cloudy so that the available energy is low. In addition, evaporation of the rain and intercepted water raises the humidity of the air and lowers its temperature, thus bringing the air closer to saturation. This combination of atmospheric conditions might be expected to result in low rates of evaporation of the intercepted water. The rates of evaporation are, of course, lower than would occur if saturation was not approached and irradiation remained high but they are nonetheless high for two reasons. In the first place, evaporation is not restricted by stomata, a large area of foliage and twig presenting a free water surface to the atmosphere at a temperature close to ambient. Secondly, because of the aerodynamic roughness of the canopy, turbulent mixing is very effective and the boundary layer conductance is very large (0.1 to 0.3 m/s), thus facilitating transfer of water vapour into atmospheres of even very high humidity.

If hourly rates of over 0.3 mm/h were sustained for twenty-four hours, very high daily rates of evaporation would result. However, the canopy rarely remains wet for long periods, because it dries out so rapidly and when it does remain wet for long periods, the humidity of the air

approaches saturation so that the rate of evaporation is depressed. Consequently daily rates of evaporation rarely exceed 6 mm/day.

Available energy and saturation deficit

In cloudy, rainy weather the available energy is small, often lying, in the range 50 to 150 W/sq.m. Nonetheless in the absence of restriction by the stomata, this can lead to an appreciable evaporation rate. Even if the air were to become completely saturated ($D=0$), equation (2) gives the proportion of available energy involved in evaporation as

$$\alpha = \lambda E / A = s / (s + \gamma) \quad \dots(9)$$

If the air were to be cooled to a dewpoint of 9°C for example, $\alpha = 0.5$ and E_x might be 0.08 mm/h. In practice, although the saturation deficit decreases as the air is cooled and humidified by evaporation, the air does not become saturated because of the influx of air which has previously passed over areas of lower vegetation where there has been a sufficient input of sensible heat to maintain a small saturation deficit. Many observations at Mearns and Thetford indicate that while the canopy remains wet, even after rainfall has ceased, the saturation deficit of the air above is less than 1 mb, compared with values of 10-25 mb in good weather when the canopy is dry. During rainfall the saturation deficit is usually also about 0.5-1 mb and evaporation goes on at similar rates.

Boundary layer conductance

The large boundary layer conductance is without doubt the most important feature of forest canopies leading to high rates of evaporation. The boundary layer conductance is large because the plantation surface is rough in an aerodynamic sense. This roughness derives in part from the spire-like structure of the canopy and from the height of the trees. The boundary layer conductance also depends on windspeed (Fig. 3) which is very rarely less than 0.5 m/s at tree top height. For these two reasons, the boundary layer conductance of coniferous forest canopies is very large both in relation to the stomatal conductance and in comparison with the boundary layer conductance of crops and grassland (Fig. 4). Typically, values of g_a for plantation forests are in the range of 0.1 to 0.3 m/s. Consequently, the saturation deficit, even when less than 1 mb, contributes substantially to the evaporation rate from coniferous forest plantations.

Curves B and C (Fig. 4) calculated from equation (2), show that even at small saturation deficits, rates of evaporation would be expected to exceed the available energy if the aerodynamic conductance is large enough. If the humidity and temperature of the air were not to adjust, evaporation would proceed at very high rates indeed as

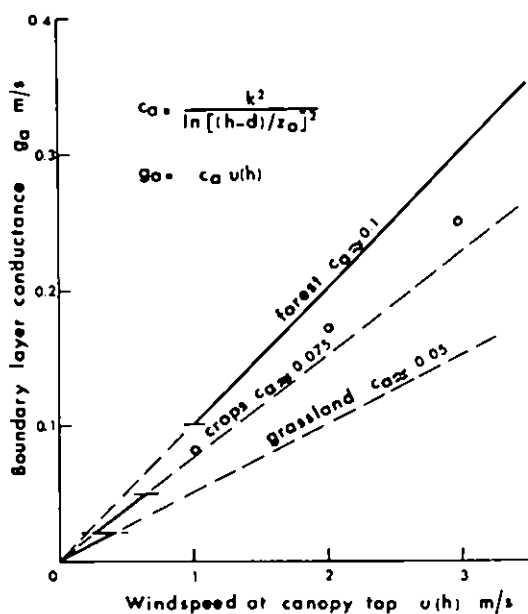


Fig. 3. The relation between boundary layer conductance and windspeed at the top of the canopy for plantation forests, cereal crops and grassland. Crop heights of 16, 1 and 0.3m were assumed. C is a non-dimensional canopy drag coefficient which is dependent upon the aerodynamic parameters z and d (Jarvis 1976). Heavy lines indicate typical ranges of values in the field. Data points are based on 66 mean hourly wind profiles measured with sensitive cup anemometers over Sitka spruce at Forest of Mearns.

indicated by curve A. However, these rates could not be supported without the abstraction of a great deal of heat from the ambient air, thus reducing D by cooling the air as well as by raising its humidity. The rate of evaporation of intercepted water will only become less than the available energy if the air approaches very close to saturation, or g_a decreases (Curve D). If the air were to become saturated (Curve E), then evaporation would proceed at a rate which was some fraction of A set by the dewpoint temperature as indicated by equation (9) above.

The 245 measurements of evaporation from the wet Scots pine canopy at Thetford mentioned previously are shown in Figure 5 in relation to the available energy (Stewart 1977). Also shown is the 1:1 line. The large number of points above the 1:1 line indicate that the evaporation rate was larger than the rate of input of available energy in the majority of

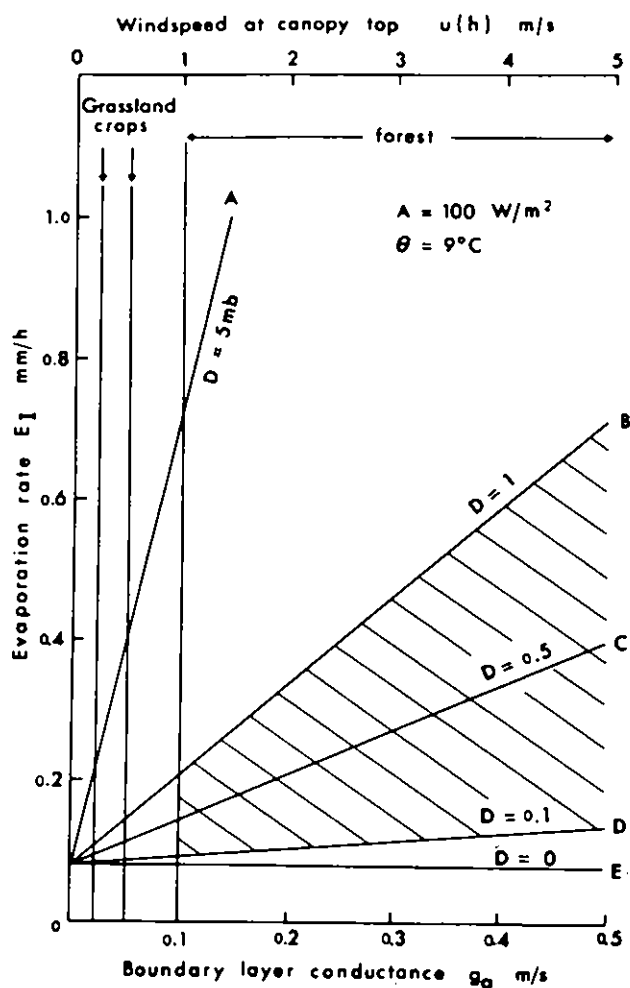


Fig. 4. The relation between evaporation rate, E_t , and boundary layer conductance calculated from equation (2) at a range of saturation deficits, D . The letters on the curves are explained in the text. Upper limits for the boundary layer conductance of grassland and crops are indicated by arrows at the top of the figure. The shaded area indicates the range of evaporation rates from wet forest canopies

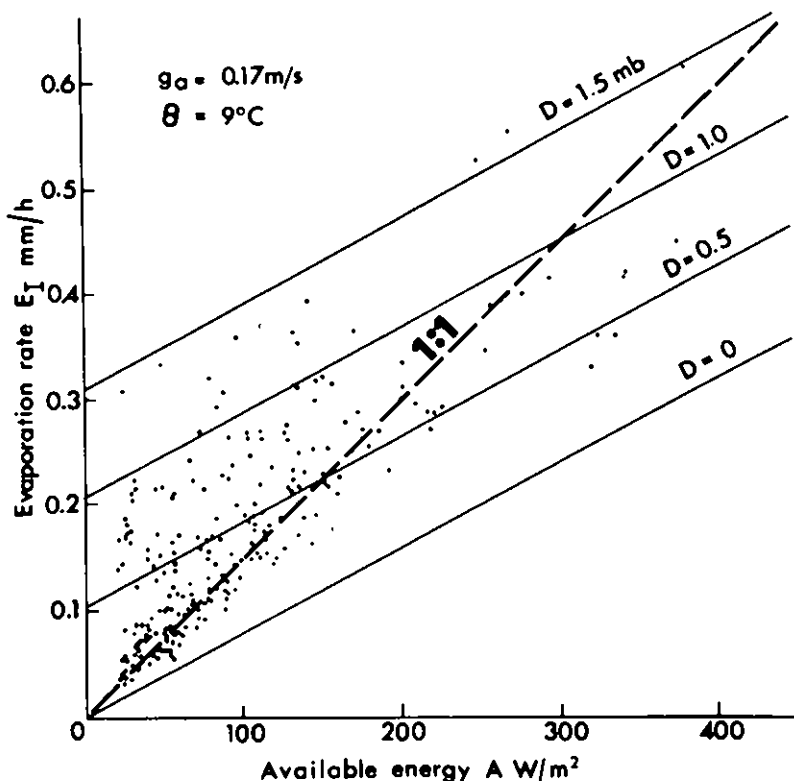


Fig. 5. The relation between evaporation rate and available energy ($A > 20 \text{ W/sq.m}$) for a wet Scots pine canopy at Thetford. The solid lines show the expected evaporation rates, calculated from equation (2) for the values of saturation deficit, D , shown by the lines. The dashed line (1:1) shows the line for evaporation rate equal to the available energy.

cases. The other four lines show the evaporation rates to be expected for the values of D given, and a temperature of 9°C . It is clear that $J (= c_p \rho D g_a / sA)$ has values of between 1 and 4 even when D is 0.5 to 1 mb and A is 50 to 150 W/sq.m . Thus even at these small saturation deficits, the high boundary layer conductance is responsible for substantially raising the evaporation rate above what would be expected from radiation alone.

Evaporation during rainfall

As a result of the high boundary layer conductance, evaporation from wet canopies goes on at high rates into

atmospheres of high humidity both when it is raining and after rainfall has ceased. It is not always appreciated that evaporation of intercepted water during rainfall accounts for a large proportion of the loss of intercepted water. This is illustrated with data provided by J.H.C. Gash (personal communication) in Table 1 which shows that about 30 per cent of the interception loss results from evaporation whilst rain is falling.

Table 1. The partitioning of the loss of intercepted water by evaporation from two plantations, one of Norway spruce in the Plynlmmon watershed and the other of Scots pine in Thetford Forest. The data were obtained from interception studies and micro-meteorological measurements and were kindly made available by J.H.C. Gash. For further details see Gash & Stewart (1977) and Gash (1979).

Evaporation occurring	Plynlmmon Norway spruce	Thetford Scots pine
From small storms (mostly during rainfall)	0.09	0.19
During wetting up the canopy	0.03	0.05
From saturated canopy during rainfall	0.26	0.34
After rainfall ceases	0.46	0.41
From trunks	0.16	0.01
TOTAL	1.00	1.00

Comparison with transpiration

Although large, the rates of evaporation are not so much larger than the rates of transpiration as might be expected simply from the absence of stomatal control, i.e. from equation (2) rather than equation (1), because, as the result of rain, the micrometeorological conditions are not the same as in fine weather. In rainy weather, cloud may reduce A to less than 100 W/sq.m, compared with values of 400 to 600 W/sq.m in fine weather, and D is reduced to less than 1 mb, compared with values of 10 to 25 mb in fine weather when the canopy is dry. A comparison between E_L and E_T , with g_a/g_s taken as 20, suggests that the rate of evaporation from a wet canopy would be over ten times that from a dry canopy in the same weather conditions. However, largely because of the small saturation deficits during and after rain, in practice the rate of evaporation from a wet canopy does not exceed two to

Table 2. Typical values of mean hourly and mean daily rates of transpiration and evaporation from coniferous forest plantations in summer and winter. The figures are based on micrometeorological measurements on Scots pine at Thetford Forest and on Sitka spruce at Forest of Mearns, and on interception studies on Norway spruce at Plympton (see Jarvis et al. 1976; Gash & Stewart 1977; Stewart 1977; Gash 1979).

	Transpiration E_T		Evaporation E_I	
	mm/h*	mm/day	mm/h	mm/day+
Summer	0.15	2	0.3	6
Winter	0.03	0.3	0.1	2.5

* for daylight hours only

+ in practice the canopy is rarely wet for 24 h.

three times that from a dry canopy in summer (Table 2).

Influence of stage of development

It might be expected that the surface roughness parameter of plantation canopies, and hence g_a , would vary with tree species, density of planting and stage of development of the stand. Up to 1975, fourteen published studies had been made on ten species in six countries by thirteen teams of investigators on fourteen stands of generally poorly defined structure and stage of development (Jarvis, James & Landsberg 1976). No systematic studies of the influence of stand characteristics on the aerodynamic properties of forest canopies have ever been made, despite the importance of these characteristics in the exchanges of water, CO_2 , heat and momentum; the last being also of some significance with regard to windblow!

ANNUAL WATER LOSS

As a result of the large differences in instantaneous rates of water loss from wet and dry canopies, long-term losses by evaporation and transpiration together (evapotranspiration) from plantation forest must depend upon the proportion of the time that the canopy is wet or dry, as well as upon the local climate and weather. Consequently, large differences in annual rates of evapotranspiration may be expected amongst areas with differing patterns of rainfall distribution with respect to time. If the rainfall is frequent, so that the canopy is almost continuously wet, very large amounts of water will be lost by evaporation. On the other hand, if the rainfall mostly comes in short, infrequent, heavy showers, or is very seasonal, the annual loss by evapotranspiration will be smaller because of the much lower

Table 3. The loss of water by transpiration and evaporation in 1975 from a plantation of Norway spruce in mid-Wales and Scots pine in East Anglia. The figures are based on micrometeorological and lysimetric measurements and data from automatic weather stations. Some of the data kindly provided by J.H.C. Gash. Further information is given by Calder (1977), Gash & Stewart (1977) and Gash (1979).

	Plynlimmon Norway spruce	Thetford Scots pine
Gross rainfall, mm	2002	650
Mean evaporation rate, mm/h	0.13	0.19
Mean rainfall rate*, mm/h	1.76	1.38
Proportion of time the canopy is wet	0.48	0.13
Transpiration loss, mm	340	350
Evaporation loss, mm	550	210
Total loss, mm	890	560

* for hours in which the rainfall exceeded 0.5 mm.

rates of loss by transpiration from dry canopies than by evaporation from wet ones

There is very little information available on the separate losses of water by transpiration and evaporation from forests in different climates, with which to support this hypothesis. Table 3 shows a comparison between such estimates for a Norway spruce plantation in the Plynlimmon watershed in mid-Wales and a Scots pine plantation in Thetford Forest in East Anglia, i.e. a comparison between a damp, oceanic site in the west and a dry, more continental site in the east of the country. At both sites the transpiration losses in 1975 were very similar, but over twice as much water was lost by evaporation from the Plynlimmon site than from Thetford because frequent rain kept the canopy wet there for a much larger proportion of the time.

This comparison is not only between regions of the country but is also between species, and indeed between stands of quite different age structure. This is the best we can do at present. We do not have the information to make comparisons between the same species in different regions, let alone the same species in stands at different stages of development or under different management regimes.

COMPARISON BETWEEN PLANTATION FOREST AND GRASSLAND

The main differences between plantation forest and grassland in characteristics affecting evapotranspiration lie

in

- the solar reflection coefficient (albedo);
- the stomatal conductance;
- the boundary layer conductance.

The mean daily albedo of plantation forest is generally in the range 0.10 to 0.15 (Jarvis, James & Landsberg 1976) in contrast with that of grassland and many crops which is about 0.25. This difference gives rise to about 10 per cent more net radiation over forest than over grassland and probably an equal amount more available energy.

The maximum stomatal conductance for plantation forest is about 0.02 s/m for dense canopies of spruce and about 0.01 s/m for pines and perhaps some other coniferous species. Some crops and grasslands may have somewhat higher values but a figure of 0.02 s/m is probably fairly representative for a sward well supplied with water. However, whereas the value for grassland may remain more or less constant during the day, unless drought intervenes, g_s for pine and spruce canopies may decline markedly during the day to much lower values leading to much lower transpiration rates.

The boundary layer conductance of plantation forest is typically within the range 0.1 to 0.3 s/m whereas g_a for crops is about 0.03 s/m and for grassland about 0.01 s/m. These large differences lead to substantial differences in the rate of evaporation of intercepted water from forest and grassland.

The estimated effects of these variables on water loss from wet and dry canopies are shown in Table 4.

Table 4. A comparison between the characteristics and components of evapotranspiration of dry and wet canopies of Scots pine at Thetford Forest and grassland experiencing the same meteorological conditions during twelve hours of daylight on two days in June 1973. $\theta = 15^\circ\text{C}$. Adapted from Stewart (1978).

	Canopy dry		Canopy wet	
	Scots pine	grass	Scots pine	grass
A MJ/sq.m	19.36	15.33	2.40	1.98
g_s m/s	0.01-0.003	0.02	-	-
g_a m/s	0.17	0.01	0.17	0.01
J	4.21	0.30	0.99	0.07
α	0.49	0.80	1.21	0.64
β	1.04	0.25	-0.17	0.56
Deficit term, mm	3.09	1.14	0.59	0.03
Radiation term, mm	0.73	3.75	0.60	0.49
Total, mm	3.82	4.89	1.19	0.52

Dry canopy comparison

The higher stomatal conductance of the grassland leads to

a much higher transpiration rate attributable to the radiation or available energy term than for the forest, despite the somewhat smaller amount of available energy. This is offset to a considerable degree by the much lower deficit term of the grassland than of the forest as a result of the differences in $g_a : J$ is 4.2 for the forest whereas it is only 0.3 for the grassland. However, the partitioning of energy by dry canopies is more dependent on g_s so that the daily total of transpiration by the grassland is 28 per cent higher than by forest and 80 per cent of the available energy goes into transpiration by the grassland as compared with only 49 per cent by the forest.

Wet canopy comparison

On days on which the canopies are wet all day, there is much less energy available because of the cloudy, rainy conditions.

The evaporation from the forest is twice that from the grassland, because the deficit term contributes as much as the radiation term, whereas the deficit term contributes almost nothing to evaporation from the grassland. Consequently evaporation from the forest exceeds the input of available energy, whereas evaporation from the grassland is much less than the available energy. Thus J is negative for the forest but +0.56 for the grassland.

CONCLUSIONS

Because of the high boundary layer conductance, rates of evaporation from wet plantation forest canopies are much higher than from grassland. On the other hand, the low stomatal conductance leads to lower rates of transpiration from forest than from grassland (Table 4). The figures in the table are for daylight hours only. It may be assumed that transpiration will be much reduced at night as a result of stomatal closure, as well as from lack of energy. If the needle stomata were to remain partly open, night time transpiration might also be appreciable. Evaporation from the canopy at night is likely to be at about the same rate as that attributable to the deficit term in day time, thus further enhancing the daily loss from forest, as compared with grassland. Thus, if wet and dry days occur with equal frequency, average daily rates of evapotranspiration might be about 5 per cent higher from forest than from grassland. However, the rate of evaporation from the wet forest canopy is so rapid that the forest canopy does not remain wet for long between showers, except in the wetter, more humid, western parts of the U.K. where rainfall is frequent and often continuous for long periods. In these areas forests lose more water than grassland because of the large amount of rainfall which is intercepted by the canopy and thence evaporated. Where the pattern of rainfall is markedly discontinuous, the

total evapotranspiration from forest is unlikely to exceed evapotranspiration from good quality grassland on deep soils, well supplied with water, because of the lower stomatal conductance of the forest. However, should the grassland experience drought, because of shallow rooting, or be composed of xerophytic species with low stomatal conductance, the total evapotranspiration from the forest probably will still be higher. A more exact assessment must await better information on the comparative rates of evaporation and transpiration from forest and grassland in different climatic areas. In view of the considerable amount of information obtained on evaporation and transpiration from forest over the last fifteen years, it is perhaps desirable now that the emphasis be shifted somewhat towards accurate estimation of evaporation and transpiration from grassland and heathland in upland locations.

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