Comparative studies of evaporation from Pinus nigra and Pseudotsuga menziesii, with particular reference to air and stomatal resistances.

A thesis submitted for the Degree of Doctor of Philosophy in the University of London

by

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LONDON, S.W.7.

June 1969

ABSTRACT

A comparison has been made of some of the factors that determine evaporation in forest stands of Corsican pine and Douglas fir. The trees were about 75ft. high on adjacent sites in Yateley Heath Wood, Hampshire.

Measurements were made of rainfall, throughfall and stemflow. Throughfall was measured by 5in. gauges and by troughs (about 40ft. x 3in.) which discharged into rainfall recorders. The troughs were calibrated against the 5in. gauges.

Evaporation of intercepted water was estimated in showery weather, after canopy saturation, as the difference between gross rainfall and net rainfall for individual showers during storms, which provided estimates of evaporation rates for periods of from one to several hours.

The canopy air resistance was calculated by dividing the vapour concentration gradient by the evaporation rate. The gradient was obtained from measurements of leaf temperature and dewpoint above the canopy.

Annual interception losses were about 37% of

rainfall in Corsican pine with insignificant stemflow, and 42% in Douglas fir where stemflow contributed about 7% to net rainfall.

Canopy saturation values were estimated in two parts as foliage and trunk saturation values. They were 0.9mm. and 0.05mm. for Corsican pine and 1.2mm. and 0.9mm. for Douglas fir.

The air resistance at a wind speed of 3m/sec. was 0.03sec./cm. in Corsican pine and 0.02sec./cm. in Douglas fir. In Corsican pine there was a linear relationship with the inverse of wind speed.

The calculated flux of sensible heat to the Corsican pine canopy was consistent with measured evaporation rates and solar radiation conditions.

The significance of these measurements in forest evaporation was considered. Throughfall was predicted in Corsican pine during individual rain storms. Calculated and measured ratios of interception losses agreed reasonably well. The importance of stomatal resistance was considered in relation to a soil water balance made by the Forestry Commission and some preliminary observations were made with a diffusion porometer.

CONTENTS

I. INTRODUCTION

The Importance of Forest Evaporation

Evaporation from forest trees forms an important part of the forest water balance. The balance may be summarised by the equation :

$$P = E + R \pm \Delta S \quad (1)$$

where : P = Precipitation
E = Evaporation
R = Run-off inclusive
ΔS = Change in water storage in the soil

In this equation Evaporation includes evaporation from the soil surface and understory. This is a small fraction of the total evaporation when there is complete ground cover by the canopy.

Run-off, in conditions when surface run-off is negligible, normally occurs when the soil is at field capacity, but it is usually unimportant at other times. The quantity stored in the profile depends on the physical characteristics of the soil and the depth of the profile. Thus, in a given climate on a particular soil, the evaporation determines the water content of the soil and the amount of run-off.

Evaporation is, therefore, an important factor in the ecology of the tree. It also has economic importance because forests are frequently found on water catchment areas, where evaporation represents water lost from the catchment.

Man may directly influence the water balance of an area through the evaporation term. This may be done by altering the vegetative character of the forest by the normal forestry activities of thinning and felling, or by changing the tree species in the forest (Douglass, 1967; Hibbert, 1967; Ladefoged, 1963; Rogerson, 1967; Wilm and Dunford, 1948). A better understanding of the factors controlling forest evaporation will help when making decisions concerning forest management in catchment areas.

The Evaporation Process

Evaporation is the vaporisation of liquid water, which requires about 590 calories of energy for every gram of water evaporated. This energy may be gained from radiation, or by turbulent exchange of sensible heat in the atmosphere, or by conduction from a warmer soil and warmer parts of the trees.

For the process to continue there must be an adequate supply of water and transport of the vapour away from the liquid surface.

There are two sources of water in forest canopies. These are the water in the leaf mesophyll and the water that wets the leaf surfaces following a period of rain. The water supply in the mesophyll is maintained by the plant under conditions of adequate soil water content. The surface water (or intercepted water) on the wet canopy is a limited quantity and of variable occurrence.

The transport of vapour from the liquid surface is a diffusion process in still air and becomes increasingly governed by turbulent exchange with increasing wind speed. The rate of diffusion (evaporation rate) in still air is given by

$$E = \frac{de}{dz} \cdot d \qquad \text{(Sutton, 1953)} \qquad (2)$$

where : d = diffusion coefficient of water vapour in air, (cm^2/sec)

$\frac{de}{dz}$ = the gradient of absolute humidity, (gms/cm^3)

E = Evaporation rate ($gms/cm^2/sec$).

In turbulent air, neglecting the small molecular diffusion term

$$E = \frac{de}{dz} \cdot K \qquad \text{(Van Wijk, 1963)} \qquad (3)$$

where : K = Eddy diffusivity, (cm^2/sec).

These equations may be written :

$$E = (\text{absolute humidity difference}) \times \frac{\text{Diffusivity term}}{\text{path length}} \quad (4a)$$

or

$$E = \frac{(\text{absolute humidity difference})}{\text{Resistance}} \quad (4b)$$

by analogy with Ohms law, where

$$\text{Resistance} = \frac{\text{Path length}}{\text{Diffusivity term}}$$ (Slatyer, 1967).

If E is measured in gms/cm^2/sec and the specific humidity in gms/cm^3, then the resistance is measured in sec/cm units and corresponds to the time taken for one cm^3 of air above the canopy to exchange vapour with one cm^2 of surface. (Monteith, 1965)

Evaporation Pathways

The evaporation pathway may be characterised by a resistance term as shown above. In the case of evaporation of intercepted water the resistance is that of the turbulent air between the wet leaf surface and the point above the canopy at which the absolute humidity of the air is measured. This air resistance is given the symbol, ra.

The air within the leaf is generally assumed to be saturated, though this is open to question, (Heath, 1959). But Cox and Boersma (1967) have shown that the error in making this assumption is small. If this assumption is accepted, the transpiration pathway consists of the air between the mesophyl cells, in substomatal cavities, in the stomatal pores and the turbulent air in the canopy. The additional resistance due to the leaf is associated mainly with the stomata and called the stomatal resistance, rs. The total resistance to transpiration is then (ra + rs).

The air resistance varies with windspeed following changes of the eddy diffusivity. The wind profile above a rough canopy, under neutral conditions, may be written :

$$U = \frac{u^*}{k} \ln\left(\frac{z - d}{zo}\right) \qquad \text{(Sutton, 1953)} \qquad (5)$$

where : U = wind speed at height z
u*= friction velocity
k = Von karman constant
z = height
d = zero plane displacement
zo = roughness length

Then, assuming equivalence of the eddy diffusivity for momentum and water vapour, Penman and Long (1960) showed that latent heat of Evaporation is :

$$\frac{K^2 \rho c (eo - e)u}{(\ln(z - d)/zo)^2} \qquad (6)$$

where : ρc = Specific heat of air

eo = Vapour pressure at zero plane

e = Vapour pressure above crop

and from the definition of resistance the air resistance is given by :

$$ra = \frac{1}{K^2 u} \ln\left(\frac{(z - d)}{zo}\right)^2 \qquad \text{(Montieth, 1965)} \qquad (7)$$

If the roughness length and zero plane displacement remain constant with wind speed, ra is inversely related to wind speed.

The stomatal resistance is determined by the response of the plant to the prevailing meterological conditions and the soil water status. The value of rs generally shows diurnal variation (Montieth, 1965) and seasonal variation (Rutter, 1967).

Methods of Estimating Air and Stomatal Resistances

The air resistance may be determined from measurements of wind speed at several levels above the canopy, from which the parameters in equation (7) may be calculated.

The wind profile above tall trees is difficult to measure, but it has been done by Baumgartner (1956, 1957) for a young pine forest; Boelter, Brooks and Kepner (in Poppendick, 1949) over an orange orchard, and by Gisborne (in Poppendick, 1949) over Idaho forests. Kung (1961) tested these determinations, where there were sufficient anemometers, by making duplicate measurements using the odd or even numbered anemometers. He concluded that wind data at less than four levels was inconclusive, and that at least seven levels are required to reliably establish the roughness parameters.

The stomatal resistance of a forest canopy has not been estimated directly, but measurements per unit leaf area have been made by calculation from measurement of geometry and numbers of stomata (Bange, 1953; Lee and Gates, 1964; Penman and Schofield, 1951; Rutter, 1968) and by measuring evaporation rates and vapour pressure gradients for individual leaves (Holmgren et al, 1965; Knoerr, 1967; Parkhurst and Gates, 1967; Rutter, 1967b).

Monteith (1965) said that values of rs per unit leaf area may be converted to values for the canopy by dividing by the leaf area index (Watson, 1947).

Rutter (1967) used this method for determining canopy values of both ra and rs in a stand of Scots pine. This procedure assumes that the canopy consists of a number of units of leaf area index, whose resistances are in parallel. This neglects the increased path length at lower levels in the canopy, and the fact that the pathways from each leaf layer coincide at the top of the canopy. A more realistic approach was suggested by Waggoner and Reifsnyder (1968). They considered the total canopy resistance to consist of resistances between the foliage and air within layers of the canopy, and the resistances between the layers, as shown in Fig.1. Such an approach required detailed knowledge of the distribution of foliage within the canopy.

Monteith (1963, 1965) has developed a method of determining a surface or stomatal resistance from profiles of wind, humidity and temperature measured above crops. Where these are the same shape, Monteith suggests that values of humidity and temperature obtained by extrapolating the profiles to the zero plane may be used as values at the 'effective surface' of the crop. The resistance may then be calculated as before from the vapour pressure gradient divided by the

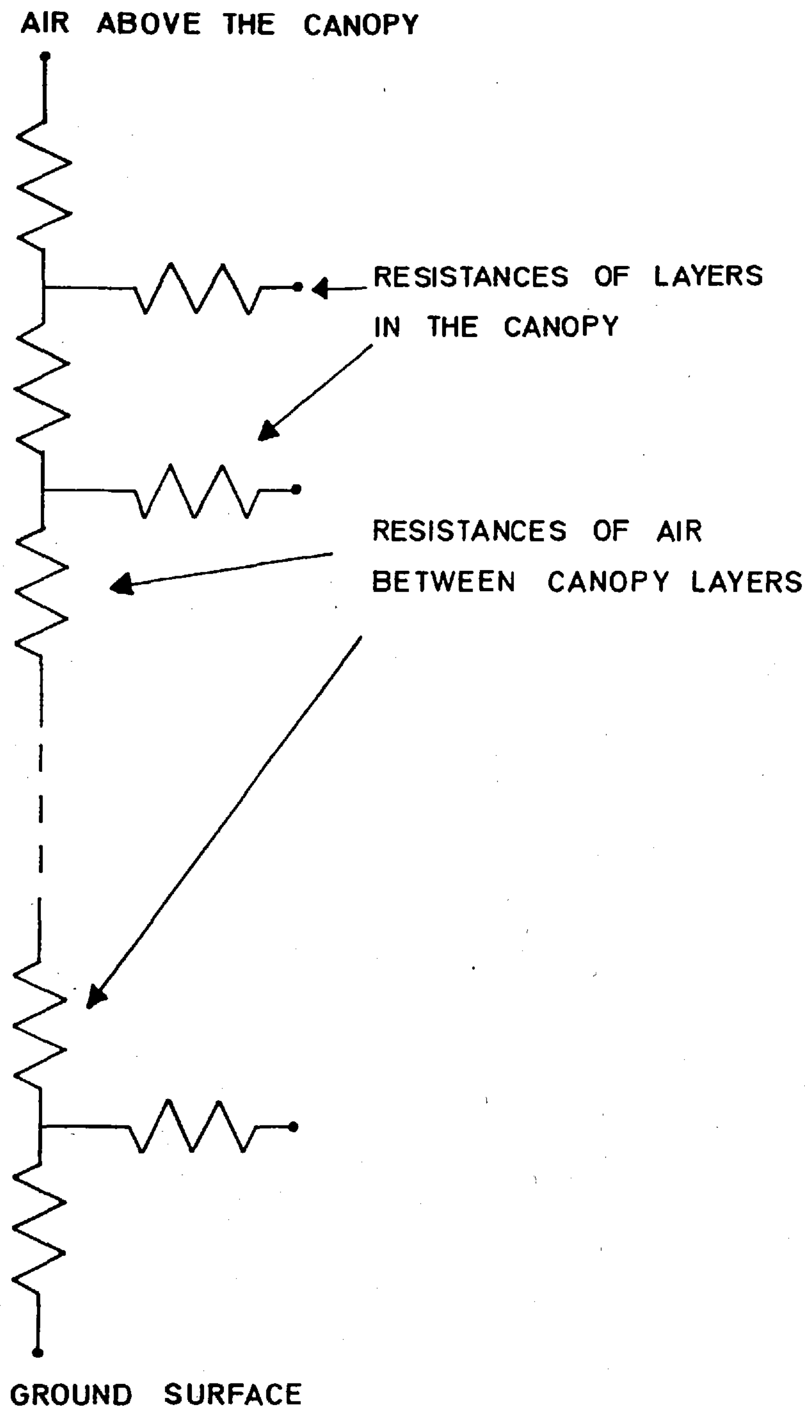


FIG. 1 The arrangement of resistances within a vegetative canopy visualised by Waggoner and Reifsnyder.

evaporation rate.

This approach has been adversely criticised by Tanner (1963) and Philip (1966), who say that the extrapolation of the profiles is not justified in conditions where the size and distribution of sources and sinks of heat, water vapour and momentum are not the same. Monteith (1965), however, has said that this criticism is irrelevant when measurements are made above the canopy where the established profiles are the same shape.

In view of the difficulty of determining ra and rs for forest canopies, new methods of determining these quantities would be very valuable. Impens, Stewart and Allen (1967) and Linacre (1967) have described methods of determining ra and rs in corn crops based on leaf temperature measurements made on transpiring and non-transpiring leaves, and on leaf temperature measurements following strong illumination. A new method of measuring the air resistance of a forest canopy will be described in a later chapter.

Energy Balance Approach

The calculation of evaporation using equation (4b) requires a knowledge of the temperature of the water surface, or of the leaf surface in the case of transpiration, which is not available from standard meteorological observations. Penman (1952) and Monteith (1965) have developed expressions for calculating the evaporation rate using resistance terms and meteorological data from a consideration of the energy balance of a wet surface.

The following equation, derived by Monteith for an open water surface,

$$E = \frac{\Delta H + \rho c \frac{(e^* - e)}{ra}}{\Delta - \gamma} \tag{8}$$

where : E = Evaporation rate

Δ = Slope of saturated vapour pressure curve at air temperature

H = Net radiation

γ = Psychrometer constant

ra = Resistance

e* = Vapour pressure of saturated air at air temperature

e = Vapour pressure of air

eliminates the measurement of surface temperature, and the net radiation and saturation deficit of the air may be determined from standard meteorological measurements (Penman, 1963).

When the value of ra for a forest is used, the calculated evaporation rate is for intercepted water. In addition, Monteith (1965) showed that the transpiration rate may be calculated if the equation is modified to include the stomatal resistance. Thus, the transpiration (E_T) rate is given by :

$$\frac{\Delta H + \rho c \frac{(e^* - e)}{ra}}{\Delta - \gamma \left(\frac{ra + rs}{ra} \right)} \qquad (9)$$

A similar modification of Penman's (1952) formula was successfully used by Businger (1956) and Tanner and Pelton (1960); Rutter (1967) has shown that evaporation from a stand of Scots pine could be accounted for, using this formula and measured resistances.

Importance of Interception

Water intercepted on forest canopies has been considered as a wasted quantity because it never reaches the ground to replenish soil moisture or stream flow, (Patric, 1966; Hirata, 1929; Law, 1956). This view neglects the possible interaction between evaporation of intercepted water and transpiration. As evaporation is determined by the energy available, evaporation of intercepted water may be associated with a reduction of transpiration. This view is supported by the work of Burgy and Pomeroy (1958) who found that the evaporation rate from grasses with artificially wetted surfaces was the same as from grasses with dry leaves. This result was later substantiated by McMillan and Burgy (1960).

Rutter (1967), however, found that the evaporation rate of intercepted water in a Scots pine stand was about four times as great as the transpiration rate in similar conditions. Similar findings of Sykes (1960) and Wells (1963), who used potted tree seedlings or detached shoots and leaves, have been reported by Leyton et al (1967).

Helvey (1967), Patric (1966) and Rutter (1963) have reported interception losses in winter months that exceed calculated estimates of open water evaporation, which indicate high evaporation rates for intercepted water. Rutter (1968) showed that in forest stands, where ra is usually much smaller than rs, the transpiration rate is primarily determined by the stomata and that because ra is small the evaporation of intercepted water is several times faster than transpiration in the same environmental conditions. Thus, the reduction in transpiration loss (assuming transpiration stops when the canopy is wet) due to the evaporation of intercepted water is less than the interception loss. As a result, the forest evaporates an amount in excess of that which would have occurred if there were no intercepted water and transpiration proceeded at the potential rate.

The recent review of American interception studies, by Zinke (1967), quotes annual interception values for *Pinus* species of 12% - 28% of the rainfall, and values of 20% - 44% for *Pseudotsuga menzesii*. Zinke quotes other high values of 58% for *Picea abies* and 33% for *Thuja plicata* and some low values of 7% - 20% for deciduous trees. Ovington (1954) found values of 36% - 54% for conifer trees and 21% - 34% for deciduous trees. Leyton et al (1967) found interception of 48% of annual rainfall in a plantation of *Picea abies* near Oxford. Helvey and Patric (1965), in a review of interception in hardwoods in the Eastern United States, reported interception of from 5% - 34% of rainfall.

As these figures were obtained in different climates they cannot be compared directly, but they show that interception losses may form an important part of the water balance of forests.

The Interception Process and Terminology Used

A small fraction of the rain falling on a dry canopy falls directly through or splashes off the canopy surfaces to reach the ground as throughfall, while the remainder is intercepted by the canopy. When the canopy is wet, water dripping from the leaves forms the bulk of throughfall. Some intercepted water drains down the branches and trunks to reach the ground as stemflow. Net rainfall is given by the sum of throughfall and stemflow. The difference between gross and net rainfall gives the interception loss. This is made up of the evaporation that occurred during the storm and the amount of water that wets the leaf surfaces (the canopy saturation value) which evaporates at the end of the storm. Evaporation occurring during a storm is most important in showery weather, as a significant amount of evaporation may occur in a short dry period between showers. Thus the interception loss depends on the canopy saturation value, the incidence of rainfall and the canopy air resistance.

Present Work

Unpublished measurements of soil water status by the Forestry Commission suggest that the annual evaporation from a Corsican pine stand was greater than from an adjacent stand of Douglas fir. The work, to be described, was started to see if this result could be confirmed and the reasons for the difference found. It was carried out on the Forestry Commission sites, where the differences were found.

The problem was approached by making an analysis of the interception process in the two stands and calculating the canopy saturation values. A method of determining the canopy air resistance from measurements of the evaporation rate of intercepted water was developed. At present a complete analysis of the evaporation of the two stands is not possible as the stomatal resistance has not been measured. The effect of the stomatal resistance and transpiration pathway has been considered in theoretical terms, and a few comparative observations were made using a diffusion porometer. A completed water balance is not possible, but some conclusions may be made.

II. THE EXPERIMENTAL SITES AND RAINFALL MEASUREMENTS

The Sites

The experimental work was carried out in part of Yateley Heath Wood, Map Ref. SU.798/580, near Farnborough, Hampshire. Experimental sites were set up in plantation stands of Corsican pine (*Pinus nigra*) and Douglas fir (*Pseudotsuga menziesii*) which were separated by less than 300 yds. (275m.).

The Corsican pine was forty years old in 1966 and was last thinned in 1959 leaving 660 trees per hectare with a mean height of about 65ft. (20m.). The Douglas fir was forty-one years old and last thinned in 1953. By 1966 some trees had been suppressed leaving about 666 living trees per hectare, with a mean height of about 80ft. (24m.).

The sites were close to the centre of Yately Heath Wood and surrounded by plantations of Scots pine (*Pinus sylvestris*), Corsican pine and a smaller area of Douglas fir, all of which were of similar height to the experimental stands. There was an area of marshy ground containing scattered Scots pine and Silver birch (*Betula pendula*) growing to a height of

20-30ft. (6-9m.) on the northern side of the Corsican pine stand. Otherwise plantation conditions extended for at least 1/3 mile (0.5km.) and mostly for 2/3 mile (1 km.) around the sites.

The sites were at about 300ft. (92m.) above sea level with higher ground to the North and West and lower ground to the East. The exposure of the two stands was judged to be similar except when the wind was from the South West when the Corsican pine was sheltered by the Douglas fir.

Sectional aluminium alloy towers were erected in each stand to give access to the canopy. There were two towers, 60ft. (18.3m.) high, in the Corsican pine, from which part of the foliage of six trees could be reached. At the top of one of these towers a Stevenson screen was mounted. An integrating anemometer was erected to a height of 6ft. above the tree tops.

In the Douglas fir there were two 66ft. (20m.) high towers which were connected to each other by bridges 20ft. long at heights of 54ft. and 60ft. Parts of the foliage of six trees could be reached in this stand also.

Rainfall Measurement

Rainfall was measured at three sites to assess the areal variability over the forest. Three 5in. (12.7cm.) gauges were used, with rims about 30cm. above the ground, and one 8in. (20.3cm.) natural siphon recording rain gauge with its rim about 50cm. above the ground. The recording gauge was situated with a 5in. gauge in a clearing (site 1) about 50m. from the northern edge of the Corsican stand. The clearing was about 15 x 30m. and surrounded by trees up to a height of 25m. There were a few trees scattered about the clearing, but none of these was nearer than its height to the gauges. A second site (site 2) was about 750m. North East of the Corsican pine stand, and about 150m. across. It was a disused nursery, with some trees 50-100cm. high remaining and much open grassland. There were also two small plots of trees 10-15m. high. There was no tree closer than three times its height to the gauges. This site was thought to have the best exposure.

A third site (site 3) was set up in June 1967. It was about 750m. South West of the Corsican pine site. It was 50m. across and surrounded by trees about 15m. high. The gauge was on a bank at the side of a forest ride, with the nearest tree at a distance about equal to its height away.

A comparison of the catch of the three gauges is shown in Table 1. The annual catch of the first two sites differs by 1.2mm. and there is no consistent monthly difference. Individual daily catches usually differed by less than 0.5mm. and the occasions when the difference exceeded this were often noticed to be during showery weather. Similar small differences were found between the three sites over a six month period. No attempt was made to assess or allow for the systematic error inherent in the use of a rain gauge (Penman, 1963; Rodda, 1967).

From these comparisons it was assumed that a realistic estimate of rainfall over the experimental sites could be made using the catch of the gauges at the first site. In the following work this site alone has been used to estimate the rainfall. This choice was made because, i) there were small differences between the sites; ii) site 1 included the recording gauge; and iii) it was nearest to the two stands and therefore thought to be the most reliable during showery weather.

TABLE 1. Comparison of rainfall measured at the three sites.

PERIOD	RAINFALL (mm.)		
	Site 1	Site 2	Site 3
June 1966	68.3	63.3	
July	64.2	71.4	
Aug.	56.8	57.1	
Sep.	12.8	13.3	
Oct.	132.5	128.6	
Nov.	60.4	59.9	
Dec.	56.1	56.1	
Jan. 1967	55.3	56.1	
Feb.	57.9	58.0	
Mar.	62.3	62.6	
Apr.	38.1	37.9	
May	116.6	115.6	
JUNE 1966 - MAY 1967	841.3	839.9	
June 1967	49.9	47.8	48.2
July	38.6	42.8	36.3
Aug.	58.0	57.2	58.4
Sep.	60.8	58.4	56.6
Oct.	137.3	137.6	138.5
Nov.	52.8	52.5	52.1
JUNE - NOV. 1967	397.4	396.3	390.1

Measurement of Throughfall

The throughfall in each of the two stands was measured using twelve randomly positioned 5in. gauges and a 40ft. (12.5m.) long trough emptying into a recording gauge.

1) 5in. gauges

The 5in. gauges were positioned in a marked out area of about 450m^2. A table of random numbers (Fisher and Yates, 1963) was used to give co-ordinates of their positions. Each gauge was sited carefully with a tape measure. The gauges were moved to a new position after about 40mm. of rain outside the stand.

Errors of Measurement

Observations of a single day's throughfall had standard errors which varied from 4% to 17% of the mean in the Corsican pine, and 5% to 23% of the mean in the Douglas fir. Table 2 shows the standard errors of monthly totals of throughfall for both stands, together with the number of positions of the gauges during each month. Moving the gauges reduced the co-efficient of variation (standard error of the mean, per cent) for a six month period to 2.4% of the mean in the Corsican pine, and 2.7% of the mean in the Douglas fir. This is in keeping with the findings of Wilm (1943); Law (1957); Reynolds and Leyton (1961) and Rutter (1963).

TABLE 2. Rainfall, throughfall (with standard errors) measured with 5in. gauges and number of gauge patterns for six months from June to November 1966

Period (1966)	Rainfall (mm)	Throughfall and standard error (mm)		No. of gauge pat-terns
		Corsican pine	Douglas fir	
June	68.3	47.71 ± 2.45	45.08 ± 2.42	1
July	64.2	37.03 ± 2.13	35.45 ± 2.16	2
Aug.	56.8	47.10 ± 1.77	35.33 ± 2.69	2
Sep.	12.8	4.26 ± 0.22	3.79 ± 0.29	1
Oct.	132.5	95.79 ± 2.39	83.75 ± 3.21	3
Nov.	60.4	27.81 ± 0.98	21.85 ± 0.98	2
JUNE - NOV.	455.0	259.69 ± 6.24	225.25 ± 6.06	8

The errors for the Douglas fir are generally greater than for the Corsican pine. This is attributed to the nature of the canopy. The Douglas fir forms an uneven canopy which is dense near the trunks and thin between the trees, while the Corsican pine forms a more open canopy, with a more even cover.

2) The trough

The first trough was set up in the Corsican pine in April 1967 and the second in the Douglas fir in June 1967. They were 12.5m. long, 6.5cm. wide and 15cm. deep, with a U-shaped cross section. They were made of aluminium in 6ft. sections (1.8m.). Each trough sloped from a height of 4ft. (1.2m.) at its distal end, to 2ft. (0.6m.) where it discharged into the rain gauge. The lower end was shaped to form a funnel from which a short length of tubing connected the trough to a natural siphon recording rain gauge. All joints in the trough were sealed using a bitumastic plastic.

Throughfall was prevented from entering the gauge directly by a cover, and in the funnel of the gauge there was a layer of gauze to prevent debris entering the float chamber. Adjacent to the gauge a pit was dug for a reservoir to collect the water that siphoned out of the gauge. This served as a check during high intensity rainfall when the recorder traces tended to merge. The arrangement of the apparatus is shown in Plate 1.

In the Corsican pine the trough was placed in a position that was judged to be representative of the stand. In the Douglas fir a position was chosen at random. This was done by selecting co-ordinates of two positions from a table of random numbers. The first was used as the site of the recording gauge and the second used to select the direction in which the trough extended from the gauge.

Calibration of the Troughs

The troughs were calibrated by fitting a regression to throughfall measured by the 5in. gauges against the trough reading. Daily catches of throughfall were used in most cases, but some catches were for occasions when there were two or three days of continuous rainy weather with no opportunity to empty the gauges. Figs. 2 and 3 show the data and fitted line for each trough. During the period available for calibration the moved gauges were in eleven different random patterns of distribution in the

PLATE 1 The trough and rainfall recorder in the Corsican pine.

FIG. 2 Trough calibration in the Corsican pine. The fitted line is $y = 0.0501x + 0.06$.

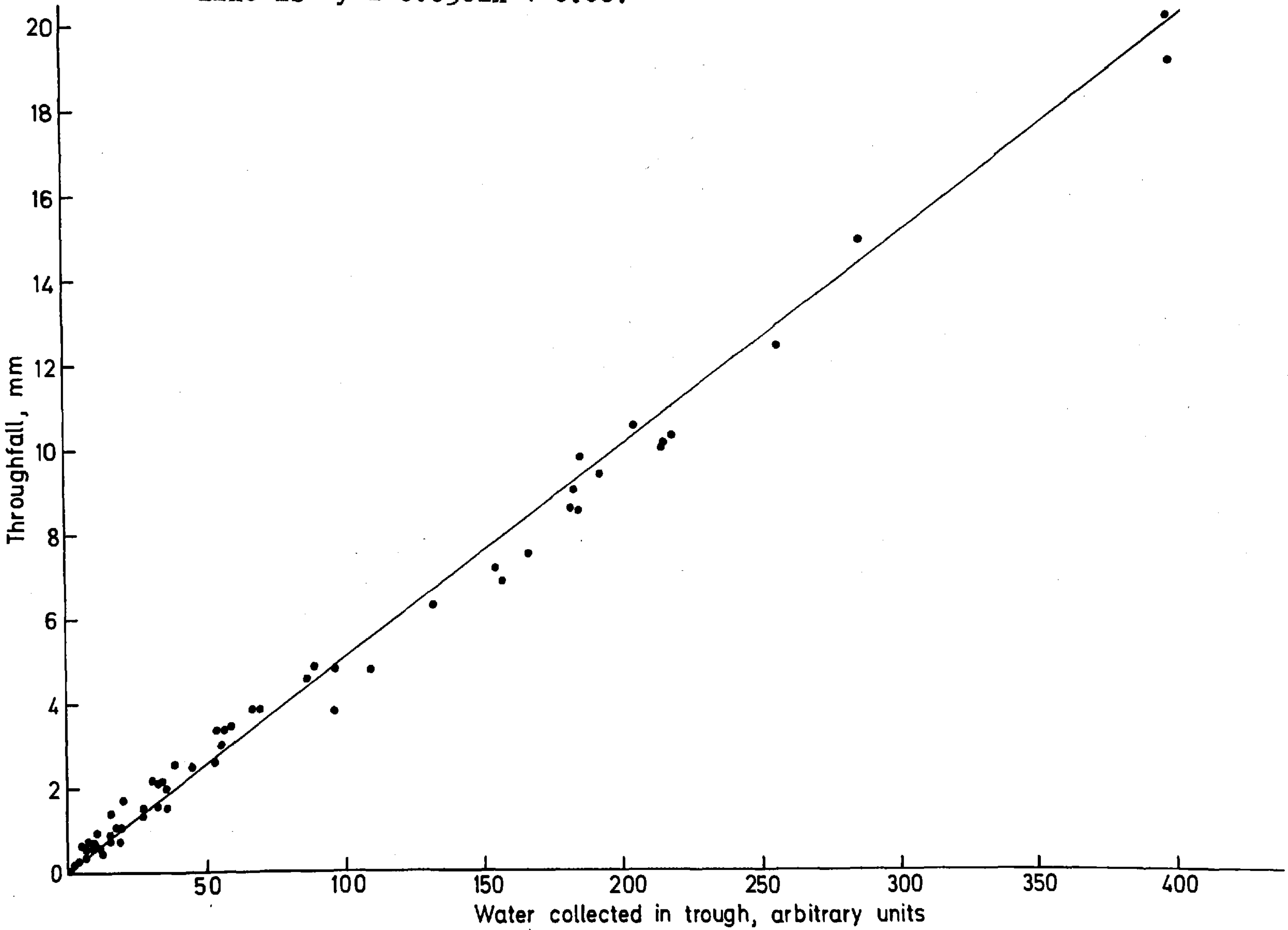
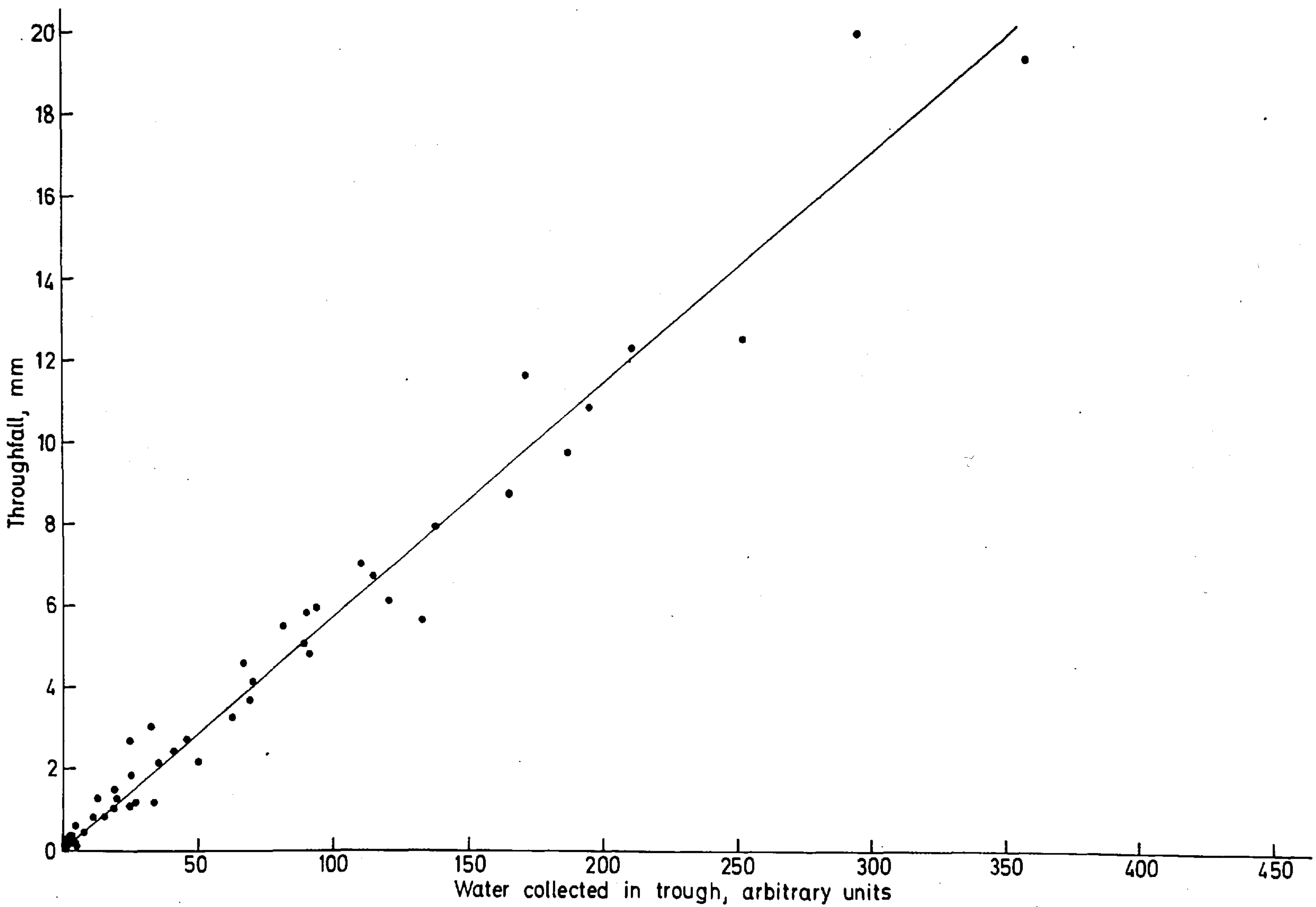


FIG. 3 Trough calibration in the Douglas fir. The fitted line is $y = 0.0570x + 0.09$.



Corsican pine and nine in the Douglas fir. The line has the mean slope of the individual lines for the different gauge patterns, and is drawn through the general mean. The lines are :

$$\text{Corsican pine} \quad y = 0.0501\,x + 0.06 \tag{10}$$

$$\text{Douglas fir} \quad y = 0.0570\,x + 0.09 \tag{11}$$

where : y = expected throughfall
x = trough reading

An analysis of covariance was made to obtain the variance of the regression coefficient and the mean $\bar{y}$. The analysis is shown in Table 3. The standard error of an estimate of y is given by :

$$\text{standard error} = \sqrt{\left(\frac{S^2y}{N} + \frac{S^2r(x - \bar{x})^2}{\sum(x - \bar{x})^2}\right)} \tag{12}$$

where : S^2y = Variance of mean $\bar{y}$
N = Number of samples
S^2r = Variance of regression coefficient b
x = Trough reading
$\bar{x}$ = Mean x

For the Corsican pine at $x = \bar{x} = 79.16$,
$y = 4.03 \pm 0.065$mm.

and at $x = 250$
$y = 12.62 \pm 0.117$mm.

TABLE 3. A summary of the analysis of covariance made on the data from troughs and throughfall gauges in Corsican pine and Douglas fir.

		D.F.	Residual S.S.	M.S.	
CORSICAN PINE					
A	Total Data	69	16.958	0.2468	
B	Variation about common regression (individual lines pooled)	59	13.976	0.2369	F=1.680 N.S.
A-B	Variation about adjusted means (difference between elevation of individual lines)	10	2.981	0.2981	
C	Sum of deviations from individual lines	49	8.875	0.1811	F=0.908 N.S.
B-C	Difference between the slope of individual lines	10	5.101	0.5101	
DOUGLAS FIR					
A	Total Data	52	32.192	0.6191	
B	Variation about common regression (individual lines pooled)	44	24.660	0.5605	F=1.258 N.S.
A-B	Variation about adjusted means (difference between elevation of individual lines)	8	7.532	0.9415	
C	Sum of deviations from individual lines	36	20.520	0.5700	F=2.82**
B-C	Difference between the slope of individual lines	8	4.140	0.5175	

For the Douglas fir at $x = \bar{x} = 67.73$,

$y = 3.95 \pm 0.132$mm.

and at $x = 200$

$y = 11.49 \pm 0.213$mm.

The analysis shows that the standard error of throughfall measured with the calibrated trough compares favourably with the standard error of daily catches using the 5in. gauges. In the Corsican pine stand, for the days that have standard errors calculated, never has one been found lower than 0.2mm. and only once has there been one as little as 0.4mm. in the Douglas fir.

Tests Made on the Trough

The depth of throughfall required to wet the trough was estimated by spraying a known volume into the trough, with a garden spray, and collecting the runoff. The estimated quantity was less than 0.02mm. The calculated lines suggest slightly higher values. This may be due to the distribution of throughfall within the stand, and to the fact that the trough collected fallen needles although it was cleaned out daily. Both of these factors were greater in the Douglas fir, where the trough ran close to the trunk of three trees and where the leaves fall more or less throughout the year.

The time taken to wet the trough was estimated by spraying water onto it at the top end and noting the time taken for water to run into the gauge. It was less than three minutes for both troughs. The time taken for the trough to drain after being thoroughly wetted was 10 to 15 minutes. Most of the water drained out in the first 5 minutes.

Measurement of Stemflow

A stemflow gauge was set up on six trees in each stand. In order to represent the different sizes of tree in the stand, the trees within the working area were grouped together in ascending order of circumference at chest height, so that there were six groups containing equal numbers of trees. One tree was then selected at random from each size group.

Construction of the Gauge

First, loose bark was cleared in a band about 15cm. across spiralling about 1.3 times round the trunk. Using a round backed rasp or coarse file, a groove was made near the top edge of this band to open up any channels in deeper layers of the bark. Bitumastic plastic was spread over the cleared band

and pressed into the groove and surrounding cracks to fill them. On the lower half of the prepared band a length of plastic covered rope (clothes line) was fixed in a spiral with a nail at each end. The lower end of the rope passed into and through the side of a short length of 2.5cm. diameter P.V.C. tubing. The bitumastic plastic was used to seal any gaps that occurred. The lower end of the P.V.C. tube was fitted with a cork and connected to a 30 litre reservoir by a short length of rubber tubing. In the Douglas fir it was necessary to have two reservoirs per trunk.

The plastic rope formed a channel which collected water running down the trunk and emptied it into the P.V.C. tube. The gauge seemed to work satisfactorily, but as a precaution a side wall was added to the channel to prevent possible loss by water flowing over the rope. The side wall was built up of short lengths of heavy duty polythene, held in place by a layer of bitumastic plastic. No increase in catch was noticed after this had been done, but an extensive comparison was not made. The gauges were tested and later checked from time to time by

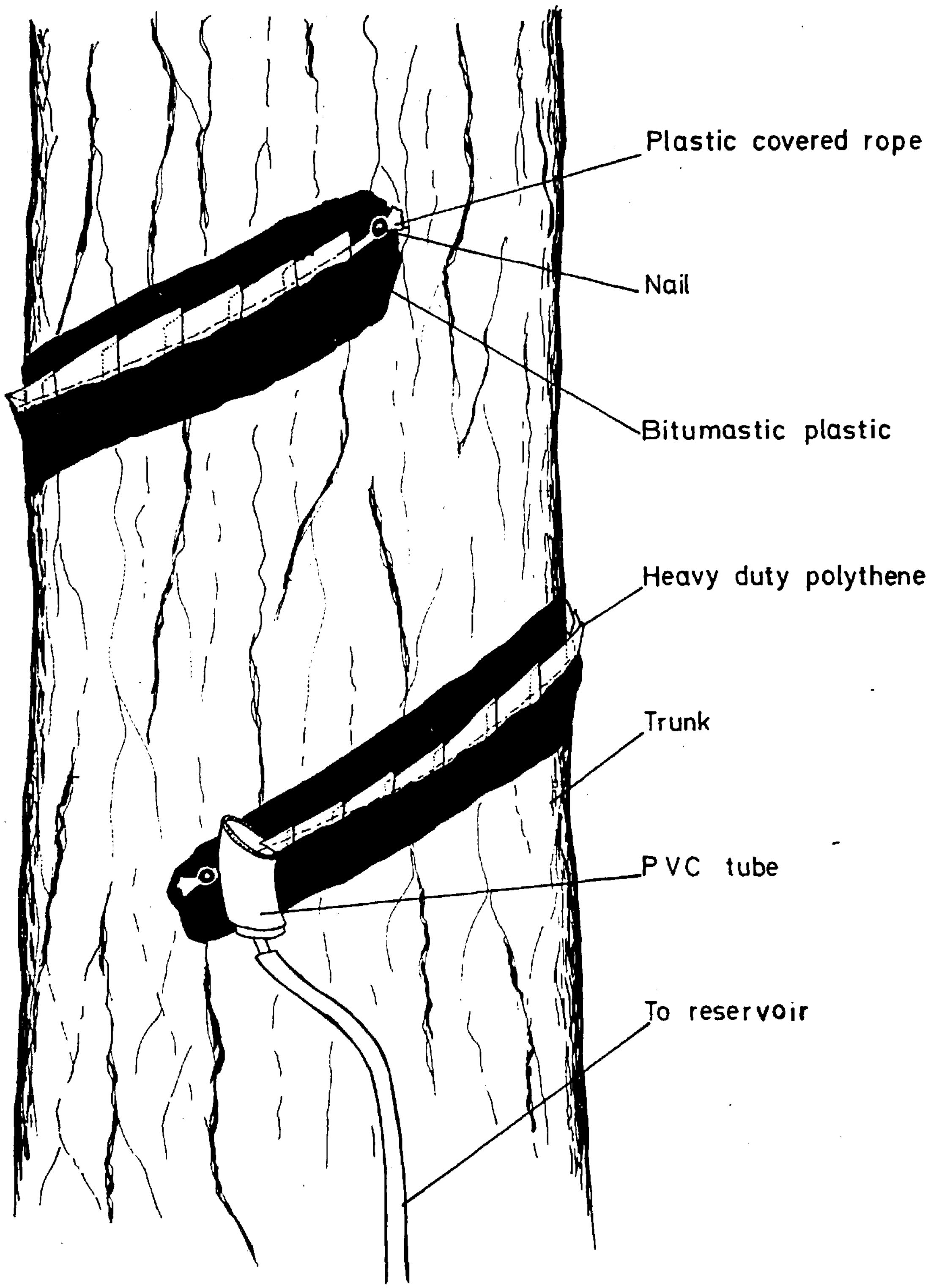


FIG. 4 Diagram showing construction of the stemflow gauges.

spraying water onto the trunk above the gauge. They were also seen working during rain on several occasions.

Errors of Measurement

Table 4 shows the standard errors of stemflow measurements for a period of four months. The stemflow is very variable and has a high standard error, which is not proportionately reduced for longer periods as the gauges were not moved. When assessing the errors of total throughfall, the error of stemflow measurement in absolute amount is small compared with the total throughfall, as is shown in Table 4.

TABLE 4. Rainfall, stemflow (with standard errors) and standard errors as % total throughfall for 4 months, in Corsican pine and Douglas fir.

	Rain (mm)	Stemflow (mm)	Stemflow % Total Throughfall
Corsican pine			
Aug.	56.8	0.04 ± 0.03	0.1%
Sep.	72.8	Nil ± -	
Oct.	132.5	0.53 ± 0.20	0.2%
Nov.	60.4	0.26 ± 0.09	0.3%
AUG - NOV	322.5	0.83 ± 0.29	0.2%
Douglas fir			
Aug.	56.8	3.59 ± 2.10	5.4%
Sep.	72.8	0.49 ± 0.39	9.1%
Oct.	132.5	7.47 ± 2.64	2.9%
Nov.	60.4	2.66 ± 0.87	3.5%
AUG - NOV	322.5	14.20 ± 5.51	3.5%

III. ANNUAL INTERCEPTION LOSSES

The interception loss is the difference between rainfall and the sum of throughfall and stemflow. The measured rainfall, throughfall and stemflow are shown for three six-month periods in Table 5. The throughfall was measured with the 5in. gauges. The table shows that throughfall was greater in the Corsican pine by about 10% of the rainfall. Stemflow contributed little to the total throughfall in the Corsican pine, but was about 7% of the rainfall in the Douglas fir. The stemflow in the Douglas fir compensates for the smaller throughfall, so that the interception losses of the two stands differ by about 4%. For the year from December 1966 to November 1967 the interception losses were 37.4% of the rainfall in the Corsican pine and 41.6% of the rainfall in the Douglas fir.

Seasonal Difference

The monthly totals of rainfall, throughfall and stemflow are shown in Fig. 5. The stemflow for June and July 1966 has been estimated from succeeding data. The figure shows that throughfall was consistently greater, and net rainfall usually greater,

TABLE 5. Rain, Throughfall, Stemflow, Net Rainfall and Interception Losses for three 6 month periods for Corsican pine and Douglas fir

Period	June '66 to Nov '66	Dec '66 to May '67	June '67 to Nov '67
Rainfall (mm.)	395.0	386.3	397.4
CORSICAN PINE			
Throughfall (mm.)	268.2	225.5	262.2
Stemflow (mm.)	1.7	2.2	1.7
Net rainfall (mm.)	269.9	227.7	263.9
Interception loss (% Rain)	31.7	41.1	33.6
DOUGLAS FIR			
Throughfall (mm.)	232.1	185.6	213.2
Stemflow (mm.)	25.4	30.6	29.2
Net rainfall	257.5	216.2	242.4
Interception loss (% Rain)	34.8	44.1	39.0

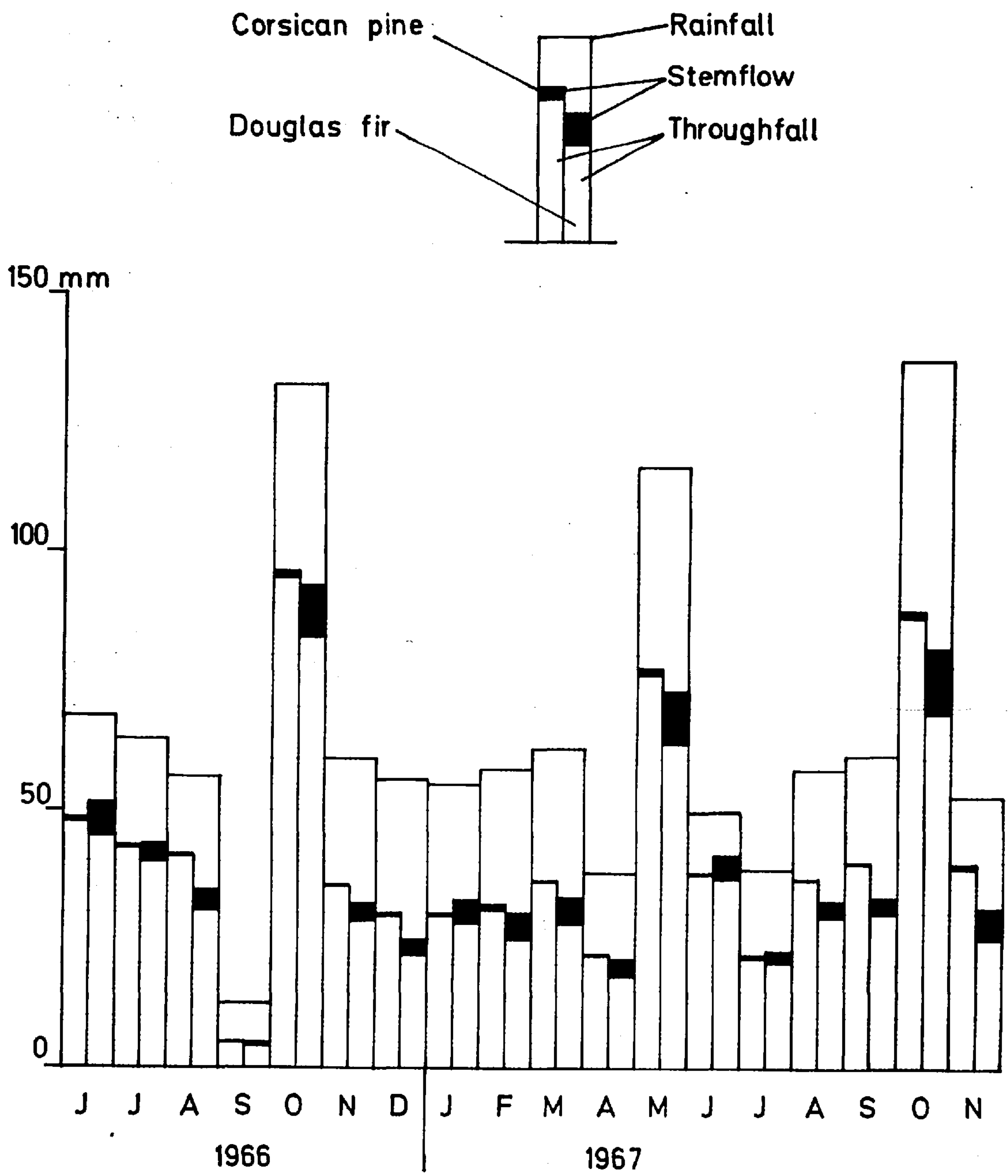


FIG. 5 Monthly totals of rainfall, throughfall and stemflow in Corsican pine and Douglas fir.

in the Corsican pine but that in some months (June and July 1966 and 1967, January 1967) the net rainfall in the Douglas fir equalled or exceeded that in the Corsican pine.

The records for individual storms show that between June 1966 and November 1967 there were only nine occasions when throughfall in the Douglas fir exceeded that in the Corsican pine. Of these, seven occurred in June and July and one on May 30th 1967, and one after three days of rain at the beginning of October 1967. Of the seven occasions in June and July six were preceeded by at least one dry day. The gauges were in four different patterns when these measurements were made, so the differences were probably not due to a bias in the distribution of the gauges. Both the greater daily throughfall and the greater monthly net rainfall in the Douglas fir, in June and July, appear to be explicable in terms of seasonal changes in canopy weight and form, and will be discussed further below.

The greater net rainfall in the Douglas fir in January 1967 has no obvious explanation. Most of the rain occurred in the last two weeks of the month, when there was rain on thirteen consecutive days, and the greater throughfall in the

Douglas fir during this period may have been due to the canopy not drying completely between the periods of rain. It was often noticed that this stand remained wet after the Corsican pine had dried. There may also have been a bias in the gauge distribution in either stand as the gauges were not moved during the period.

Seasonal Changes in the Canopy

The forest canopy is observed to consist of a number of years of leaf growth. In June 1967 this number was estimated by counting the number of years of growth still retaining leaves on sample shoots that showed a current year's growth. For each year of growth recorded an estimate was made of the proportion of the original shoot that remained on the tree. In the Corsican pine there were 3 3/4 years of growth and 5 years in the Douglas fir, excluding the current year in each case.

The seasonal changes in the canopy were determined by estimating the production of new leaves and the fall of old leaves.

Leaf Production

In the Corsican pine the length of the new leaves was measured at intervals from June until

August 1967. Growth began early in June and continued until August. During June the leaves were closely bunched together, so that the new shoot was the shape of an inverted cone. By the end of July the extension rate of the leaves was reduced, and the leaf bearing stem began to elongate, thus separating the leaf pairs so that they projected at right angles to the stem.

In the Douglas fir the date of opening of the leaf buds and the date that they were fully open was recorded. On individual trees the buds were fully opened in about two weeks. The buds began opening in the last week of May on the earliest trees and all the trees had fully grown shoots before the end of June.

Leaf Fall

Leaf fall was sampled by fourteen randomly placed tins, approximately 30cm. square and 15cm. deep, in both stands. These were emptied and placed at new random positions each month. Fig. 6 shows the mean (of two years) monthly leaf fall in units of leaf area index, assumed to be equal to total annual production, together with the estimated leaf growth and the net changes in the foliage for both stands.

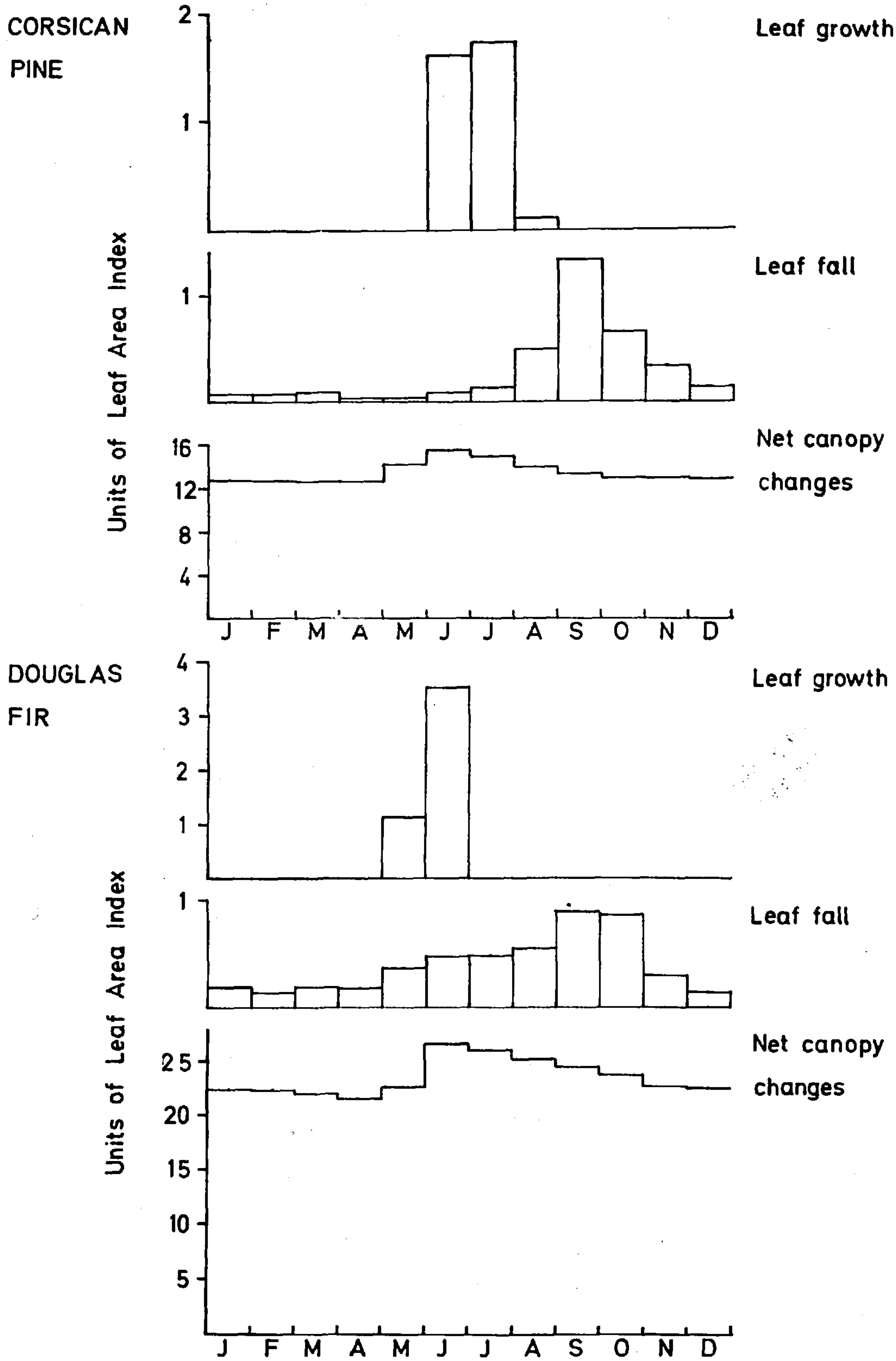


FIG. 6 The course of leaf growth, leaf fall and net canopy changes in Corsican pine and Douglas fir.

Total Foliage Weight

The total foliage weight in June was taken as 3 3/4 years of leaf production in the Corsican pine and 5 years in the Douglas fir, excluding the current year's growth. The leaf growth per month was added to these figures and the leaf fall was subtracted to give the estimate of monthly foliage changes.

The total foliage weights in January were 14,000 kg/ha and 16,500 kg/ha, but these figures do not reflect the leaf areas of the canopies as the Corsican pine leaf is thicker than that of the Douglas fir.

Leaf Area Index

The leaf area index was determined by estimating the mean surface area of individual leaves and the number of leaves in the canopy per unit of ground area. The surface area was calculated from measurements made with a microscope eyepiece micrometer and the number of leaves in the canopy was estimated by counting the number in the monthly leaf fall collection. The estimates of leaf area index were 12.9 for the Corsican pine and 23.5 for the Douglas fir.

The Corsican pine shows a marked peak in the canopy weight during June, July and August which is due to the separation of the period of leaf growth and leaf fall. There is a smaller peak in the Douglas fir, partly because leaf fall occurrs throughout the year and partly because there is always an additional year of leaves present in the canopy.

Throughfall Differences Associated with the Changes in the Canopy

The increase in the canopy of the Corsican pine in June, July and August would be expected to present a greater leaf area for interception and evaporation of intercepted water in showery weather. Both of these effects would reduce the throughfall relative to that in the Douglas fir. In addition, during June the bunched leaves of the new shoot in the Corsican pine may retain more water than a mature shoot. It was observed that the new shoots channel water into their centres where it was trapped, forming many drops at the points of contact of the individual leaves. On mature shoots rain runs down the upper leaves, onto the stems and down the lower leaves to form drops at their tips. Thus, only about half of the leaves of mature shoots retain drops.

The Douglas fir shoot opens quickly and the half opened shoot does not differ so markedly from the mature shoot as it does in the Corsican pine. Seasonal changes in canopy saturation capacity will be considered in the next chapter.

Seasonal Course of Throughfall

Monthly throughfall and stemflow as a percentage of the rainfall is shown in Fig. 7. The throughfall shows no marked change through the year. The absence of an increase in throughfall during winter months suggests that the evaporation rate of intercepted water is not significantly slower in winter.

Similar results were obtained by Rutter (1963) and Rennie (1956) quoted by Reynolds and Henderson (1967). Leonard (1967), however, has suggested that a higher viscosity and surface tension at lower temperatures may increase the canopy saturation value in the winter months. But Rutter (1966) has shown that the evaporation rate of intercepted water in these months may be many times the estimated rate for an open water surface calculated by Penman's (1956) formula.

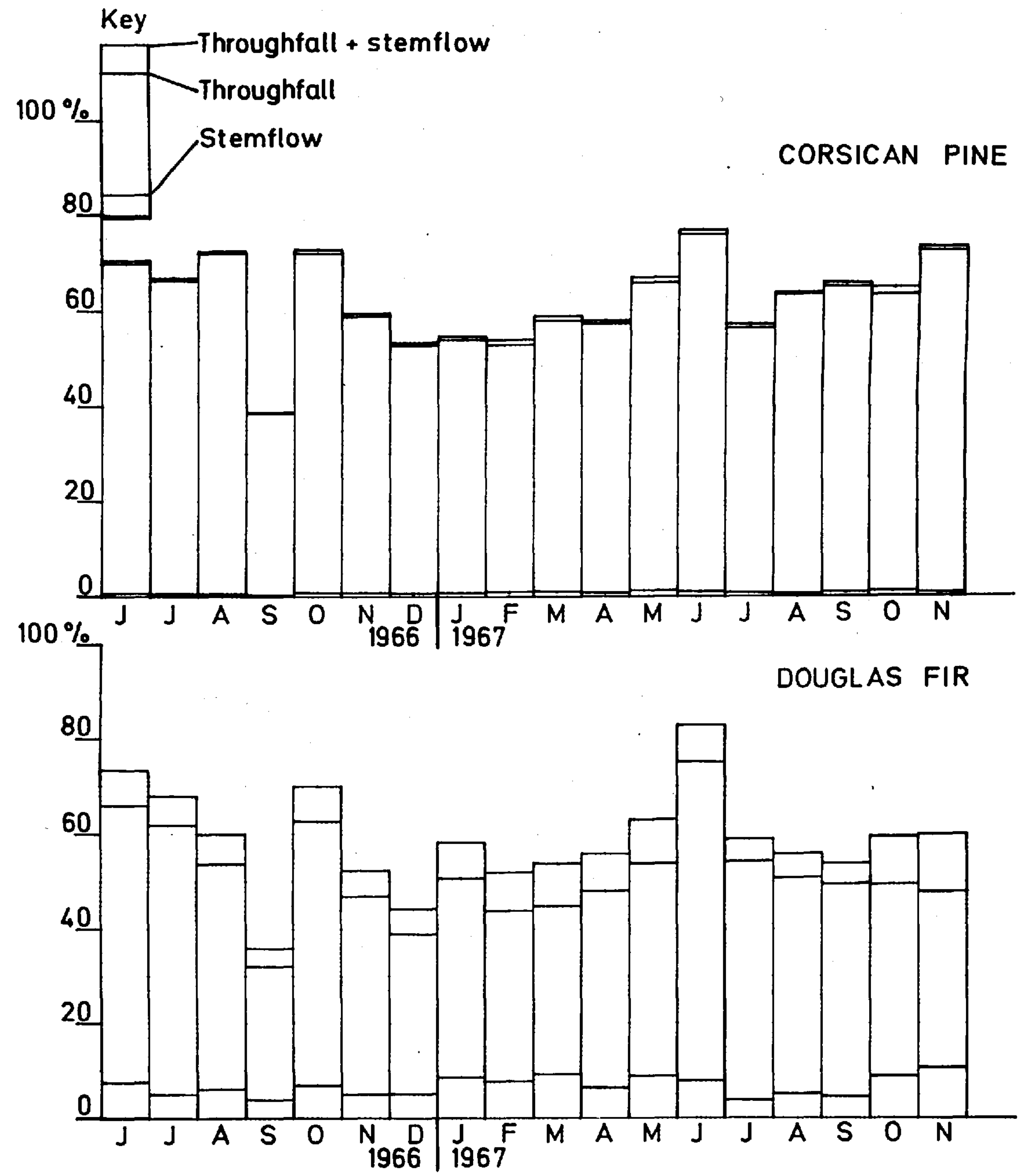


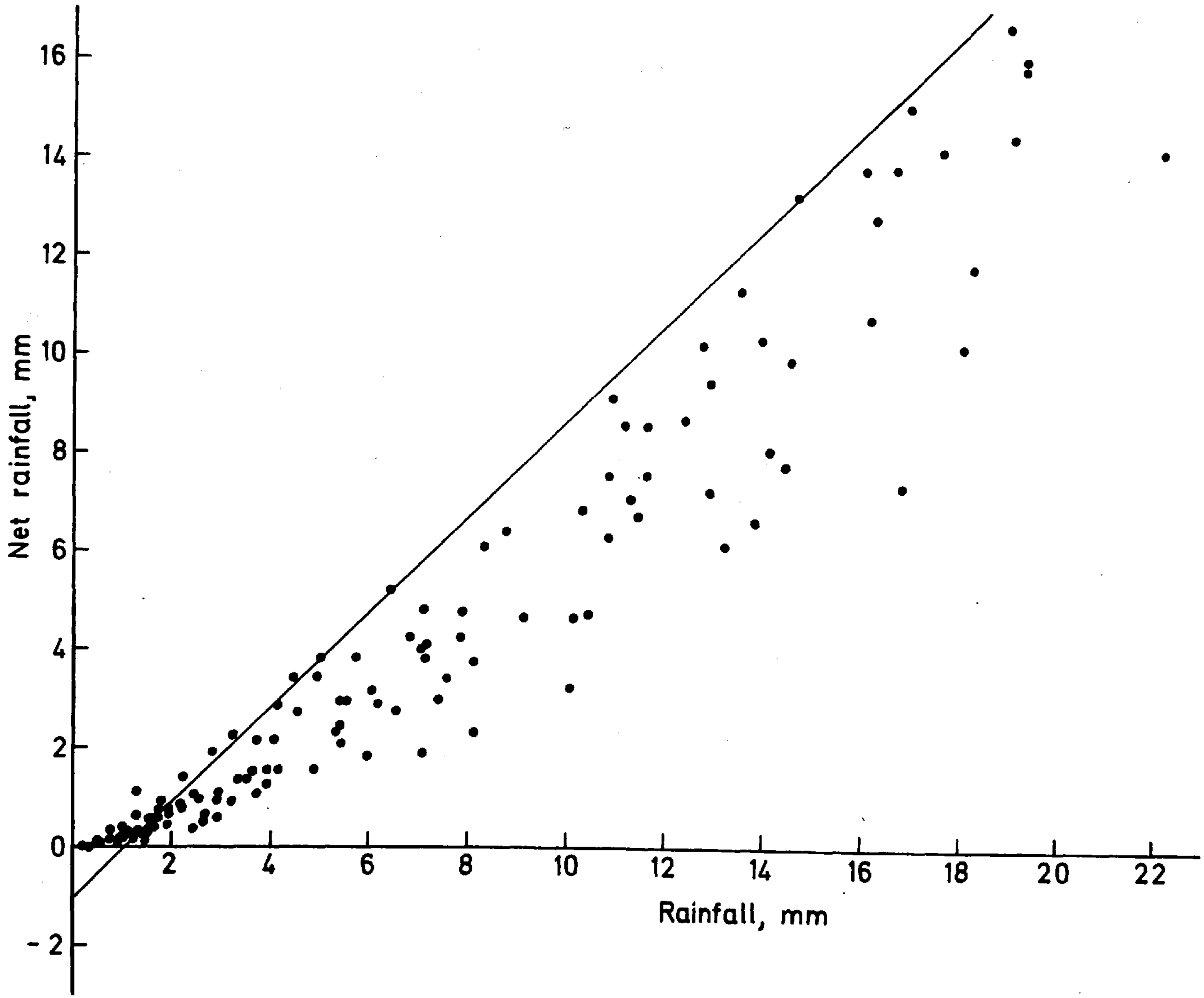
FIG. 7 Monthly throughfall and stemflow shown as a fraction (%) of the monthly rainfall in Corsican pine and Douglas fir.

IV. ESTIMATION OF CANOPY SATURATION VALUES

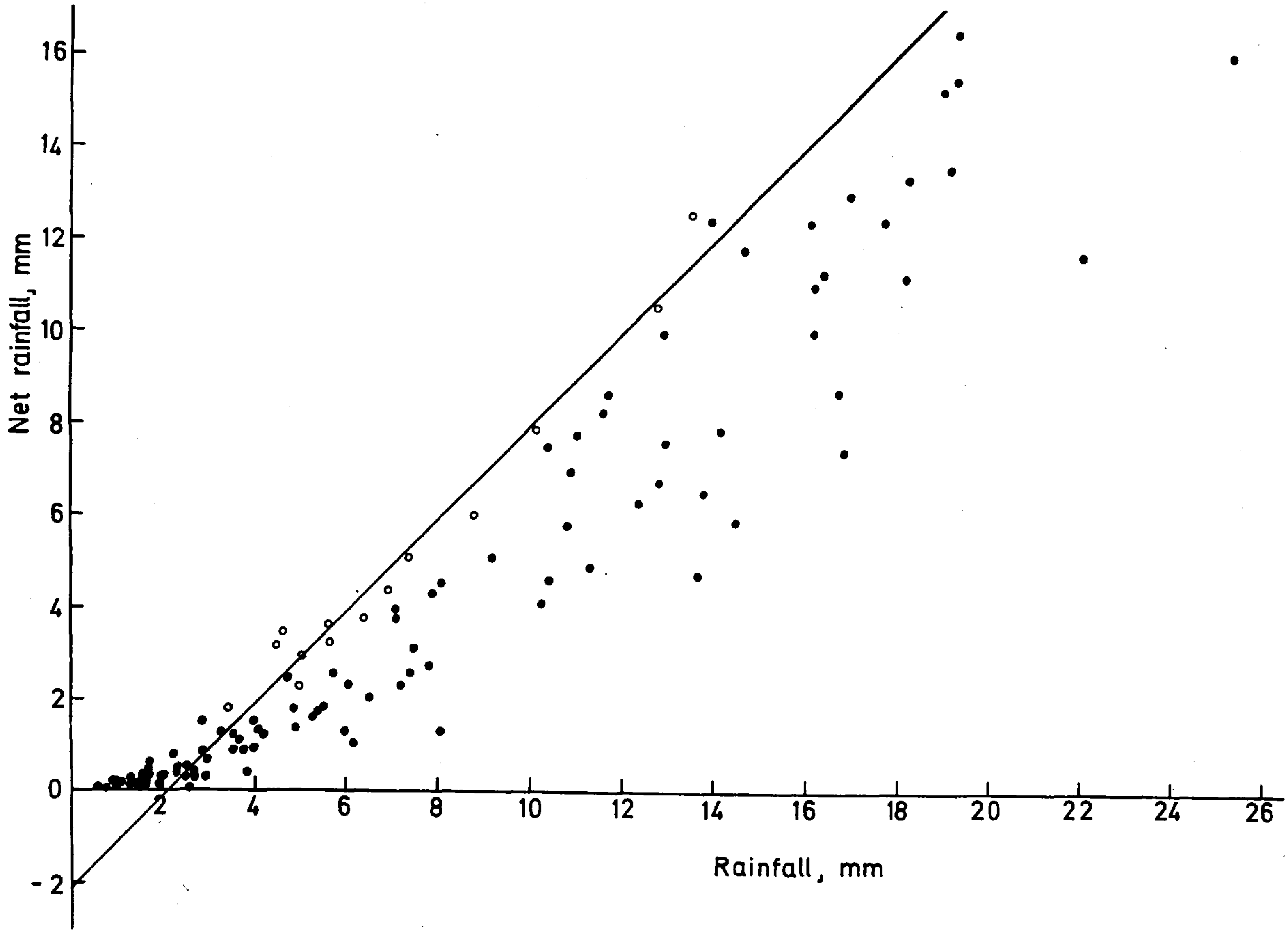
The canopy saturation value is the amount of rain required to completely wet the canopy. The most common method of determining this value is from rainfall and throughfall data, presented as in Figs. 8 and 9. Wilm and Niederhof (1941) fitted a linear regression to such data and extrapolated the line to give an estimate of the canopy saturation value at zero throughfall. Reynolds and Leyton (1963) pointed out that this gives a biased estimate if data from small storms is included. Rutter (1963) fitted a regression to points above the inflection, representing storms large enough to completely saturate the canopy. He suggested that the interception loss in a 24 hour period is determined by the canopy saturation value, the size of the individual showers and the amount of evaporation between showers.

As the data of Figs. 8 and 9 was, at best, collected on a daily basis, the points may represent several wetting and drying cycles, and evaporation may contribute considerably to the interception loss. This difficulty has been discussed by Leyton et al (1967) who suggested, that in the absence of data for

FIG. 8 Net rainfall, measured by 5in. gauges and stemflow gauges, plotted against rainfall for Corsican pine.



<u>FIG. 9</u> Net rainfall, measured by 5in. gauges and stemflow gauges, plotted against rainfall for Douglas fir.



single storms, a line be fitted through the points of maximum rainfall, excluding the data from small storms. This procedure has been followed here.

The inflection that occurs when the canopy becomes saturated should be recognisable as a double inflection. The first occurs when the leafy parts of the canopy are saturated and the second when the trunks are saturated and stemflow begins. There may be a considerable difference between the rainfall required to reach these critical values for tall trees. The position of these inflections was considered when fitting lines to the throughfall data.

The Corsican pine data (Fig. 8) contains several points that indicate the line to be drawn, but in the Douglas fir data (Fig. 9) there is no clearly indicated line. The records show that the circles in Fig. 9 include abnormally high proportions of stemflow, probably due to the trunks remaining wet from a previous storm. While the canopy usually dried within 24 hours, the trunks often remained wet for two or three days. To overcome this difficulty, throughfall and stemflow were considered separately. The difficulty was not apparent in the Corsican pine because stemflow contributes very little to net rainfall and the trunks usually dried within 24 hours.

Throughfall Data and Estimation of Foliage Saturation Values

Throughfall measured with the 5in. gauges is shown plotted against rainfall in Figs. 10 and 11. Each point represents a 24 hour period or longer as the gauges were not emptied on mornings when it was raining or when the canopy was wet during showery weather. In Figs. 12 and 13, the throughfall was measured with the trough. The points represent, as nearly as possible, single storms. A storm was assumed to be a period of rain during which the canopy did not dry completely. The canopy was assumed to have dried when the trough indicated no further dripping from the leaves.

The estimate of the saturation value given at zero throughfall for the Corsican pine is 1.0mm. from both sets of data. The estimate from the trough data is obtained from fewer measurements. Good agreement is also found for the Douglas fir, where estimates of 1.4mm. and 1.5mm. are obtained. These values represent the depth of rain required to wet the parts of the canopy that form drips that fall to the ground. The leaves constitute the bulk of this category, but some parts of the branches may be

FIG. 10 Throughfall, measured by 5in. gauges, plotted against rainfall for Corsican pine.

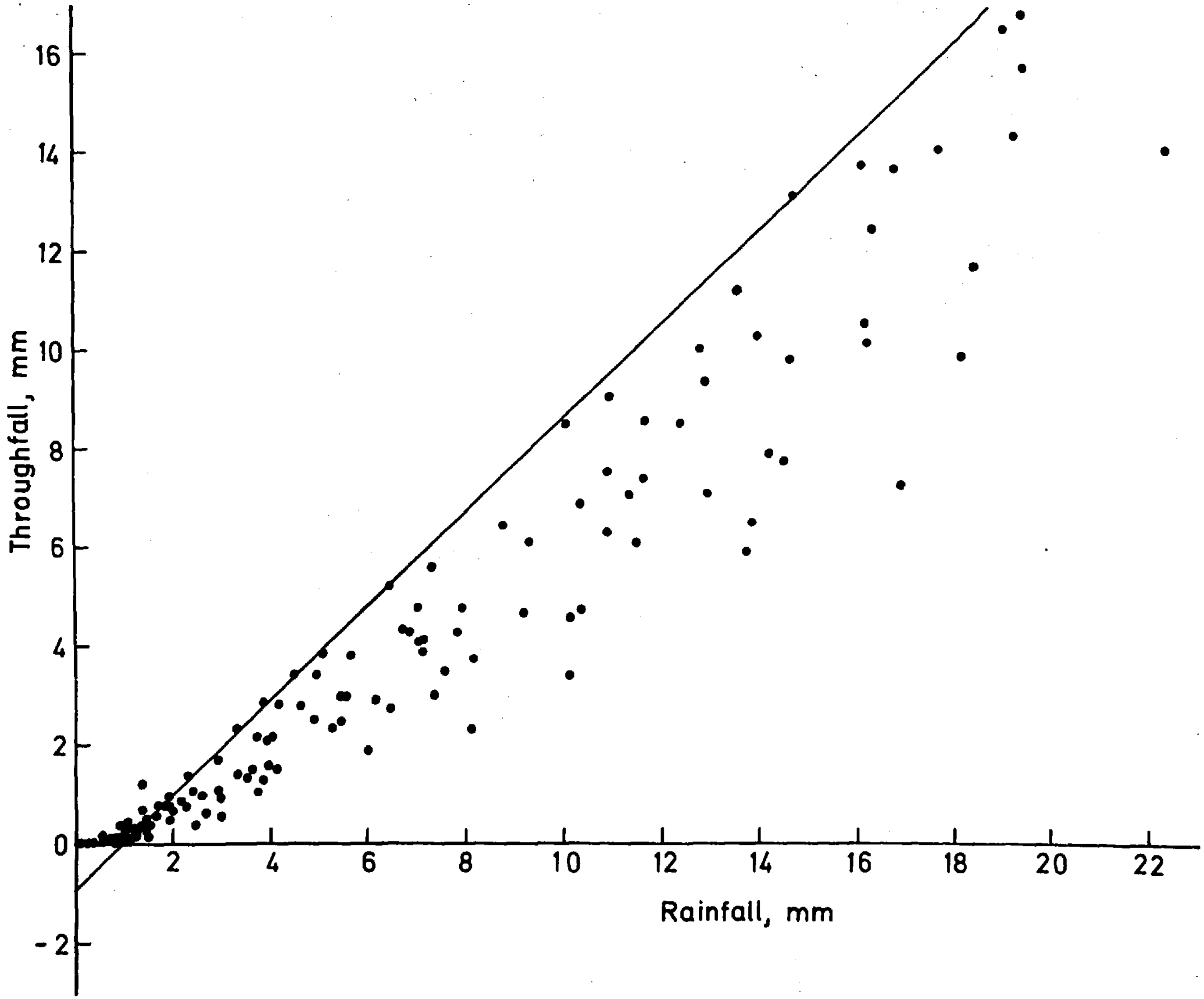


FIG. 11 Throughfall, measured by 5in. gauges, plotted against rainfall for Douglas fir.

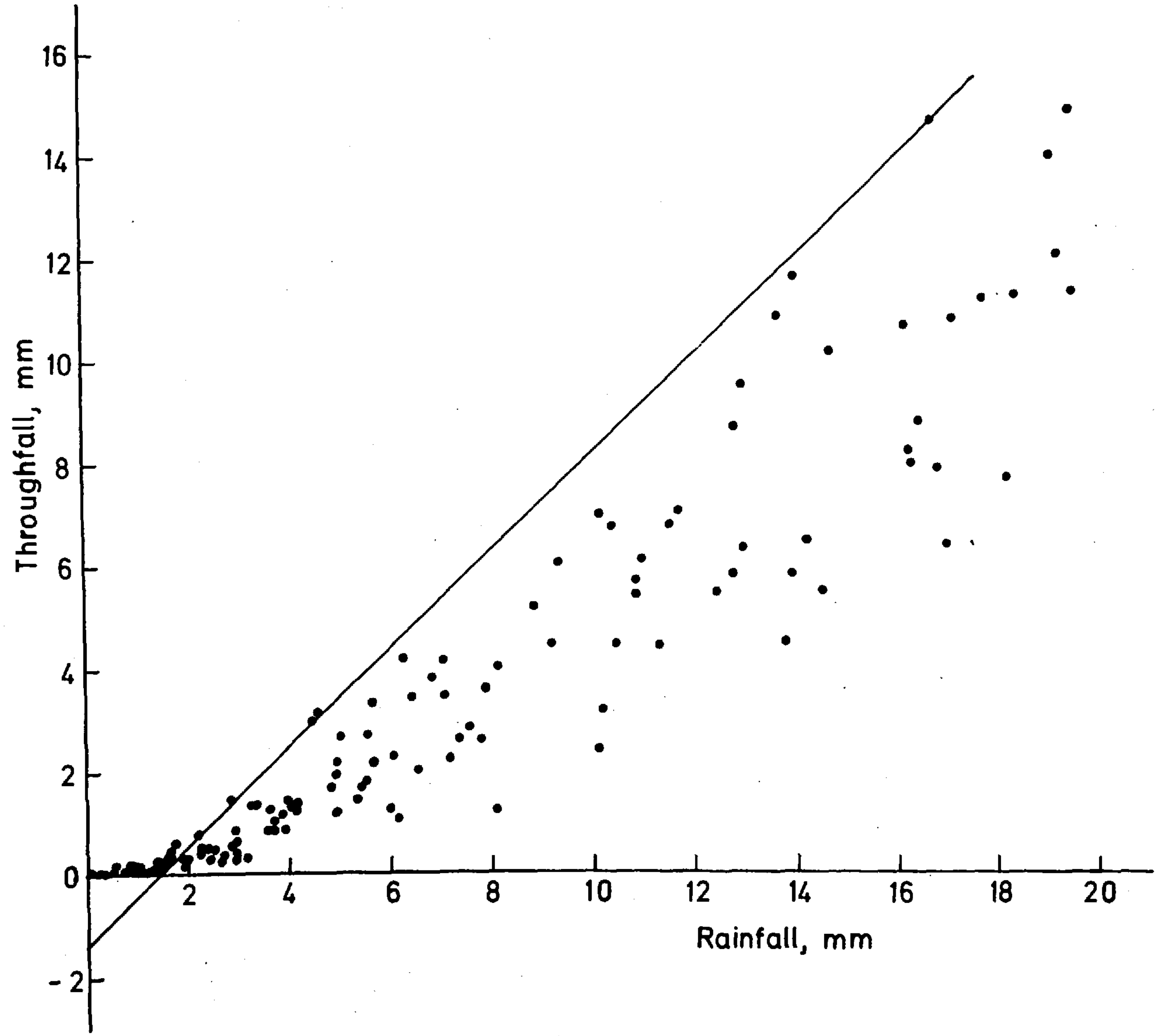
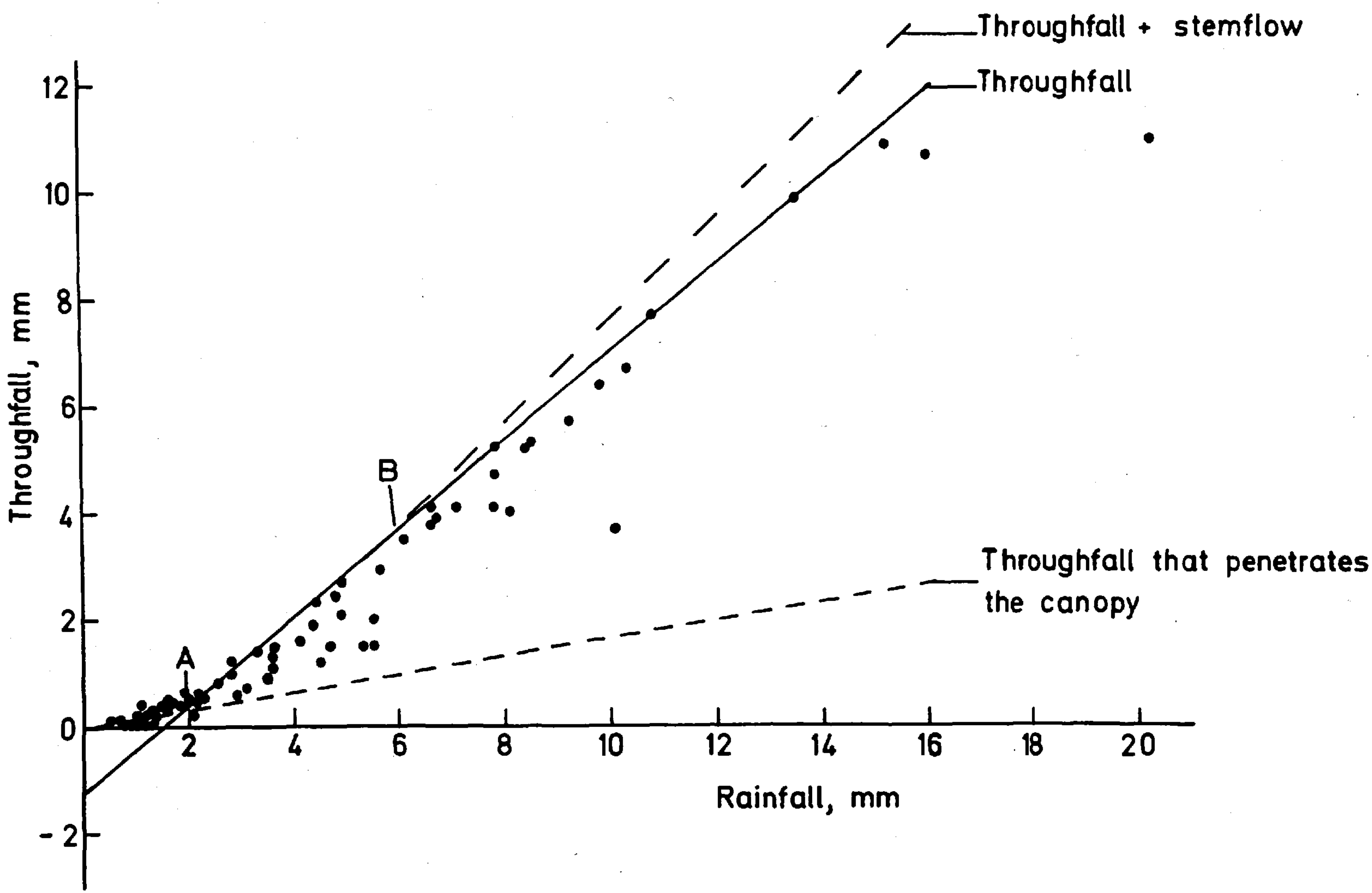


FIG. 13 Throughfall measured by the trough plotted against rainfall for Douglas fir. A and B mark the inflections due to saturation of foliage and trunks.



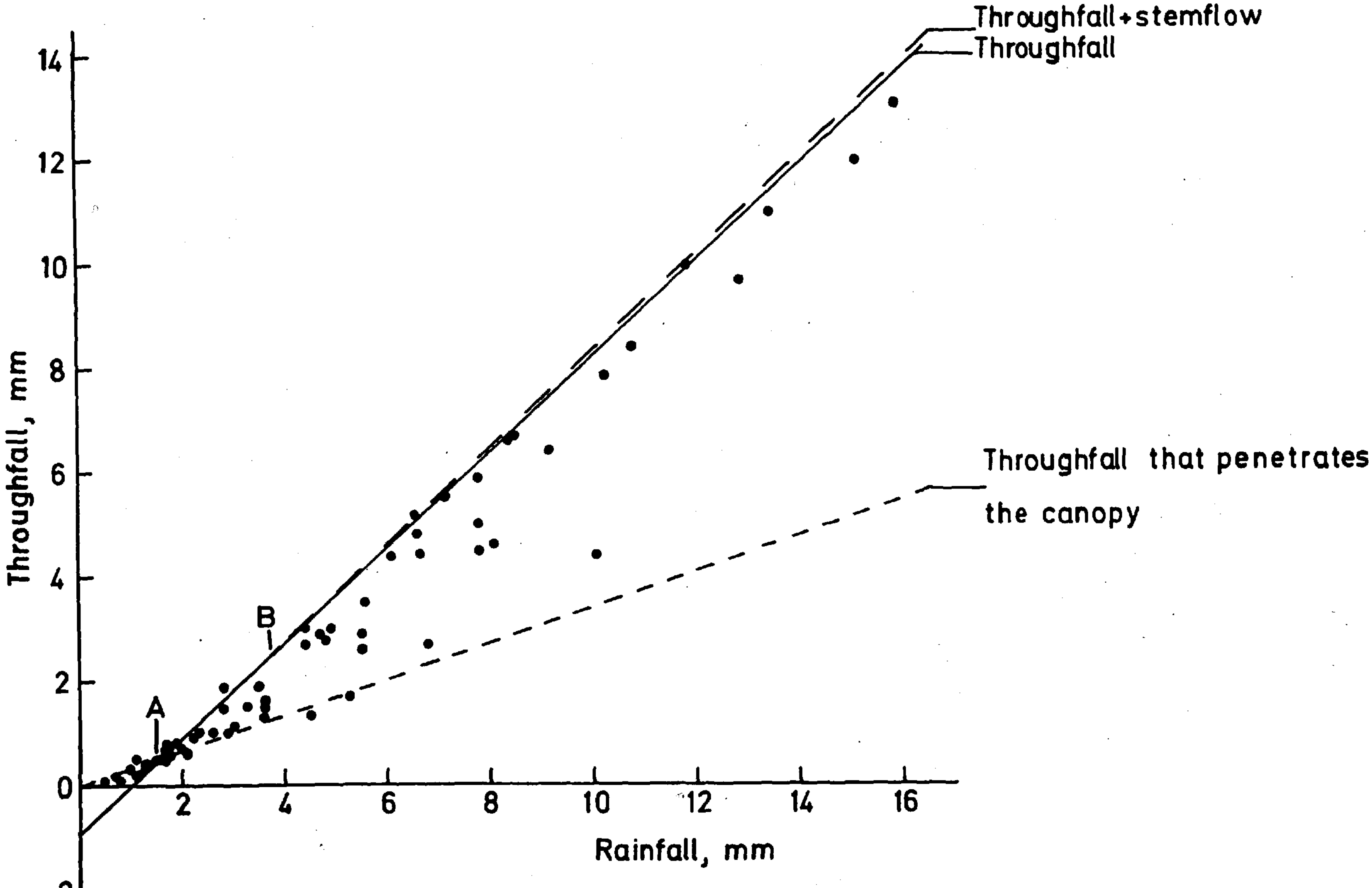


FIG. 12 Throughfall measured by the trough plotted against rainfall for Corsican pine. A and B mark the inflections due to saturation of foliage and trunks.

included. These saturation values are referred to as 'foliage saturation' values. The quantity of water retained on the foliage is determined from the intercept on the throughfall axis. This is found to be 0.95mm. for the Corsican pine, in both cases, and 1.3mm. from the gauge data and 1.2mm. from the trough data in the Douglas fir.

<u>Stemflow and Estimates of</u>

<u>Trunk Saturation Values</u>

Stemflow and rainfall data for selected storms are shown in Fig. 14. The points represent stemflow for approximately 24 hour periods that were preceded by at least one dry day; only storms that exceeded 8mm. of rain were used. The error due to the trunks remaining wet was minimised by selecting storms that occurred in the summer months.

A linear regression was fitted to the data because the scatter could not be entirely attributed to drying during the storm or to the trunks remaining wet from a previous storm. The lines are :

Corsican pine $y = 0.012x - 0.05$ (13)

Douglas fir $y = 0.150x - 0.89$ (14)

The lines are shown in Fig. 14. They indicate that

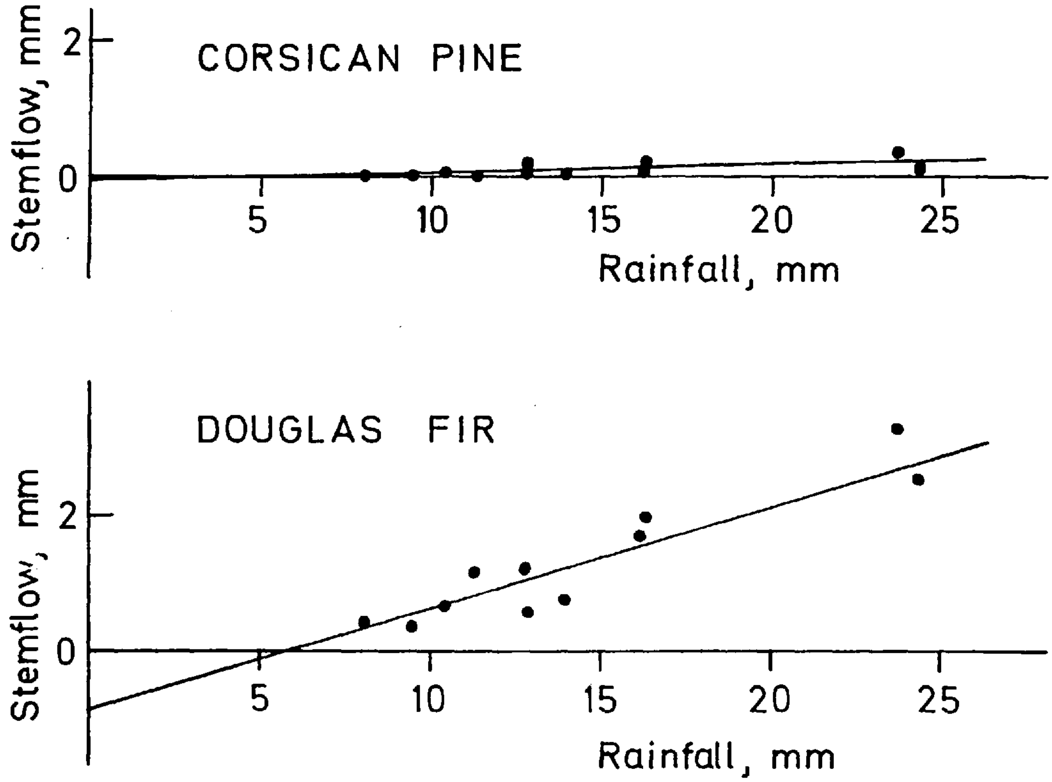


FIG. 14 Stemflow for selected storms plotted against rainfall in Corsican pine and Douglas fir.

4.2mm. of rain is required to cause stemflow in the Corsican pine and 6.0mm. in the Douglas fir. These values correspond to the crown saturation of Reynolds and Henderson (1967) and the position of the second inflection in the throughfall data. An estimate of the depth of water that is required to saturate the trunks was obtained from these regressions. It was assumed that the proportion of rain reaching the trunks is constant throughout a storm and that it could be estimated from the slopes of the regression lines in Fig. 14. The estimates of trunk saturation obtained are 0.05mm. for the Corsican pine and 0.89mm. for the Douglas fir. These estimates include branches and some leaves that channel water to the trunks. Leaves on the leading shoots probably contribute to the stemflow but they represent a small proportion of the canopy.

The value of 0.05mm. for the Corsican pine does not represent a true saturation value of all the trunk surface because the trunks were only observed to be completely wetted on two occasions in two years. Usually they were wetted on one side only, which often seemed to be due to interception of throughfall on the side exposed to wind. The channelling of water from branches to the trunk seemed unimportant in this stand.

Partition of Throughfall

The inflections in the throughfall data represent the beginning of dripping from the canopy and the beginning of stemflow. Throughfall for small storms is not zero as some rain penetrates openings in the canopy and some may bounce off the foliage. Figs. 10 to 13 show that from 1/10 to 1/4 of the rainfall penetrates the canopy in the Corsican pine, and less than 1/10 in the Douglas fir.

The contribution of stemflow and rain that penetrates the canopy to net rainfall is shown in Figs. 12 and 13 where stemflow, determined from the regression, has been added to the throughfall line. The two inflections are marked A and B in the figures. The inflection due to the beginning of stemflow B is of little significance in the Corsican pine, but neglecting it in the Douglas fir would cause an appreciable error. The slope of the computed net rainfall line in Fig. 13 for the Douglas fir is 0.98 , in good agreement with an anticipated unity.

Canopy Saturation Values

The estimated depth of water required to saturate the complete canopy in the Douglas fir is 2.1mm. of which 1.2mm. wets the foliage and 0.9mm. wets the trunks. The net rainfall data for the Corsican pine in Fig. 8 shows that a depth of 1.0mm. is required to wet the canopy. This is 0.05mm. greater than for the foliage alone and is in agreement with the stemflow regression (Equation 13).

A further estimate of canopy saturation in the Douglas fir was made using net rainfall of single storms taken from the trough data (Fig. 15). The stemflow for each storm was estimated by distributing measured stemflow, which may have been a total for more than one storm because there was no recording device for stemflow, proportionally with the rainfall. This procedure probably overestimated the stemflow. The estimate of canopy saturation is 2.2mm. and the line has a slope of 1.04 which may indicate the error due to estimating the stemflow. A line drawn with a slope of unity on Fig. 9, through a canopy saturation value of 2.1mm. is in moderate agreement with the data.

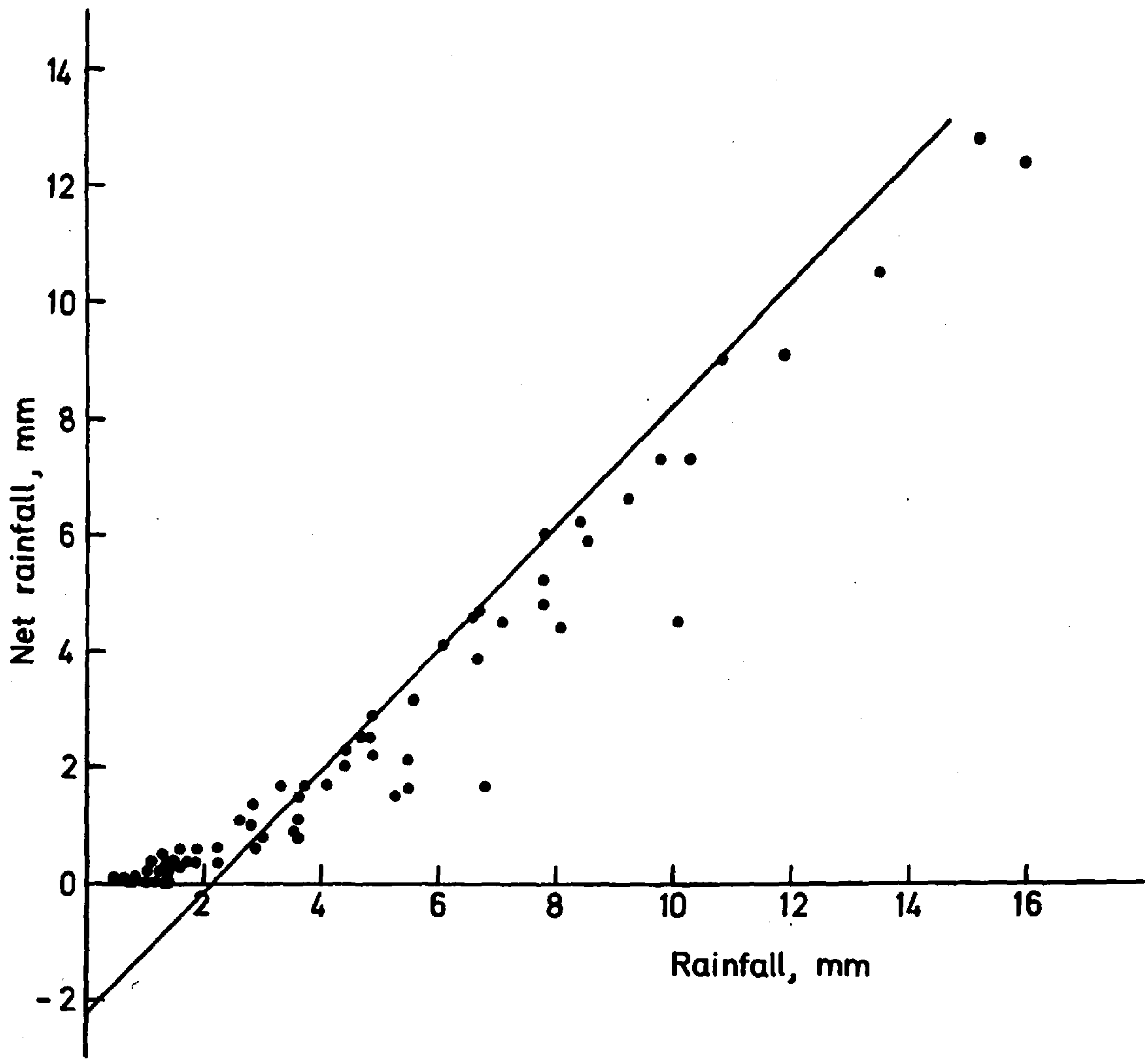


FIG. 15 Net rainfall, measured by the trough and stemflow gauges, plotted against rainfall for Douglas fir.

Estimate of Foliage Saturation from Periods of Continuous rain

A further estimate of the foliage saturation value was made by selecting measurements of throughfall for periods of continuous rain that began with the canopy dry. Each storm was great enough to saturate the leafy part of the canopy and several were the beginning of longer showery periods of rain; these storms were assumed to have ended after the first dry period, and an estimate was made of the amount of throughfall that would have drained from the leaves in the absence of further rain. The estimate was made by comparison with the end of the rainy period and added to the measured throughfall for the period under consideration. The amount was small after dry periods of more than 1/4 hour. Stemflow was neglected to avoid errors involved in proportioning or predicting it. The storms occurred between October and April, during which period there was little change in the canopy weight.

Linear regressions were fitted to the throughfall against rainfall data. The data and calculated lines are shown in Figs. 16 and 17.

The lines are :

$$\text{Corsican pine} \quad y = 0.96x - 0.9 \qquad (15)$$

$$\text{Douglas fir} \quad y = 0.80x - 1.2 \qquad (16)$$

where y = throughfall
x = rainfall

These lines give an estimate of 0.9mm. and 1.4mm. for the foliage saturation values in the Corsican pine and Douglas fir corresponding to 0.9mm. and 1.2mm. depth of water. The standard errors of the regression intercepts were calculated to assess the errors of the estimates which are shown below :

Corsican pine 0.9 ± 0.08mm.

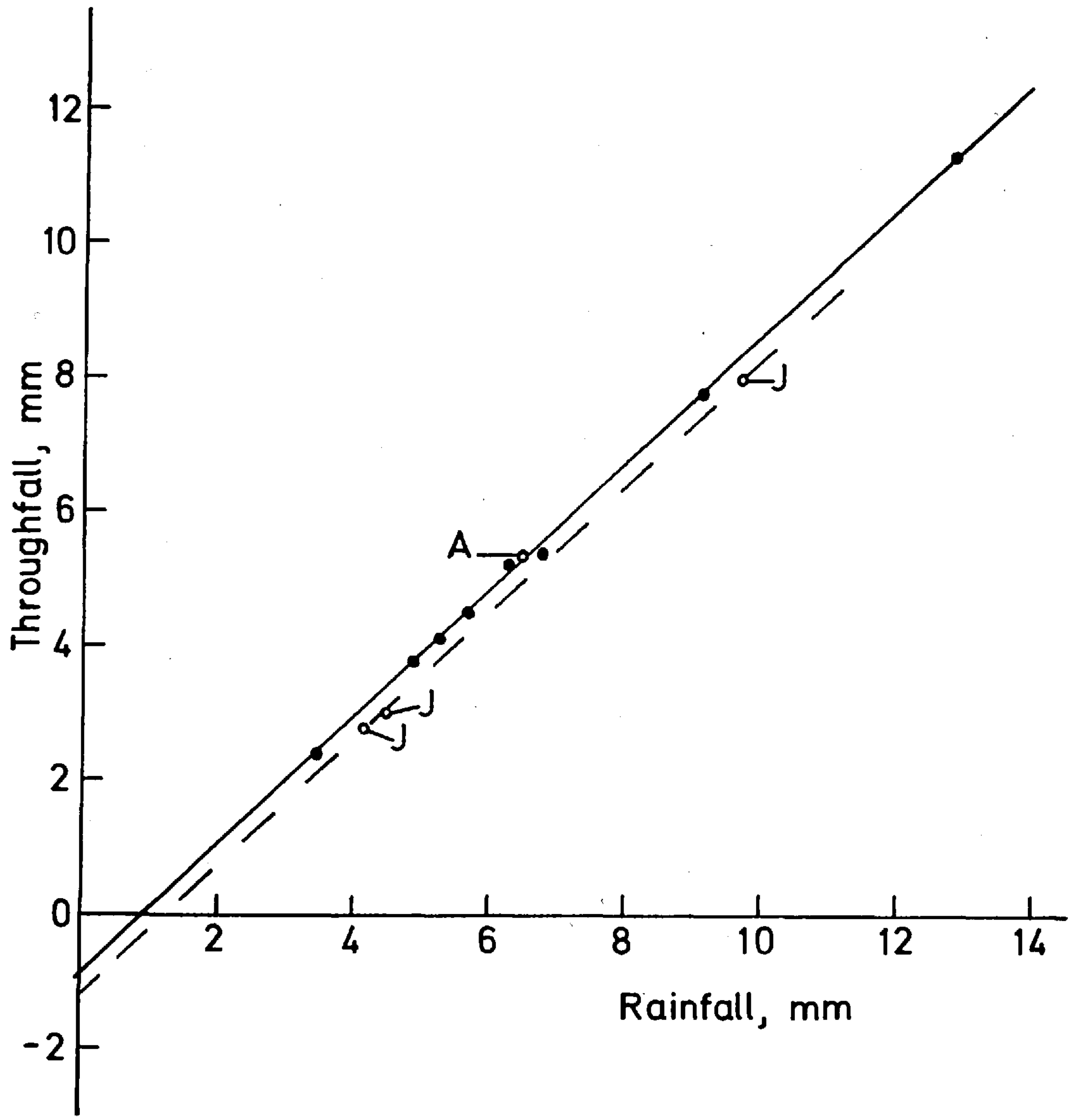
Douglas fir 1.2 ± 0.13mm.

These results are in good agreement with the previous results.

Seasonal Variation of Canopy Saturation Value

There were three storms of continuous rain in June and one at the beginning of August 1967 that were suitable for estimating the foliage saturation value. These are shown for the Corsican pine in Fig. 16. During June the saturation value increased

FIG. 16 Throughfall during storms of continuous rain plotted against rainfall for Corsican pine.



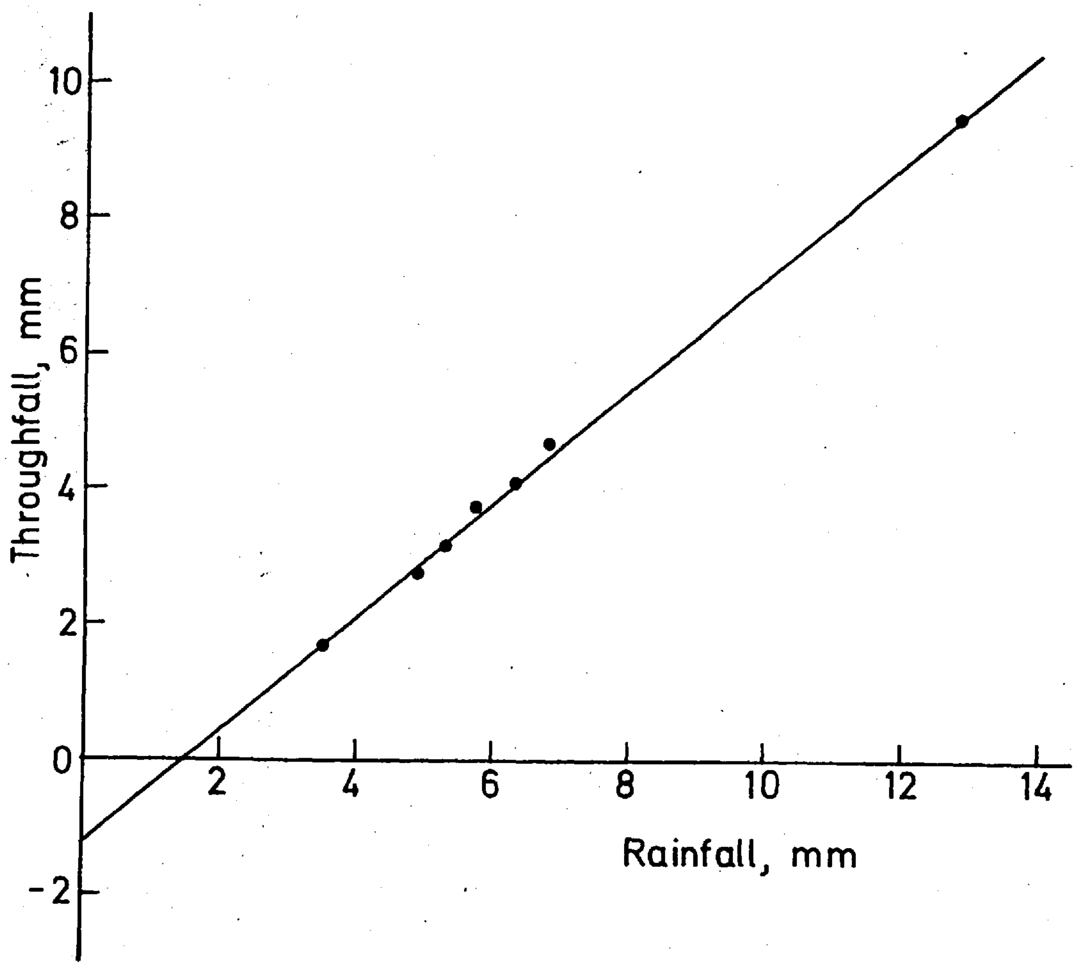


FIG. 17 Throughfall during storms of continuous rain plotted against rainfall for Douglas fir.

to 1.1mm., which is close to the winter value for the Douglas fir. At the beginning of August, when the canopy has a greater leaf area than in June, the value was 1.0mm. This seems to support the suggestion that there is an increase in canopy saturation which is related to the arrangement of leaves in the new shoot.

Although the trough was installed in the Douglas fir at the end of June the results for the first two months were unreliable because the greater amount of leaf fall in this stand blocked the trough and gauge on several occasions. There was no further trouble when the trough was cleaned out daily. The records that were made suggest that there was little difference in saturation values between June and August, but they do not start early enough to indicate changes due to the growth of the new shoots.

There is, therefore, an indication of a larger saturation value in the Corsican pine in June, which may account for lower throughfall in this month relative to the Douglas fir, to which attention was drawn in the preceeding chapter.

V. THE DETERMINATION AND SIGNIFICANCE OF EVAPORATION DURING RAIN STORMS

The total interception loss from a given storm consists of the water remaining on the canopy at the end of the storm, together with the amount evaporated during the storm (Horton, 1919). Methods of estimating canopy saturation values have been discussed; basically they consist of selecting those storms in which evaporation during the storm is minimal. However, in most storms interception loss considerably exceeds the estimate of canopy saturation value, and in this chapter a water balance for the canopy will be used to estimate the contribution to the total interception loss made by evaporation during storms.

Method

Rainfall and throughfall were determined for fifteen-minute periods, during selected storms, from the recording gauges at Site 1 and with the trough in each stand. Sample records from these gauges are shown in Plate 2. Periods of fifteen minutes were found to be the most satisfactory as

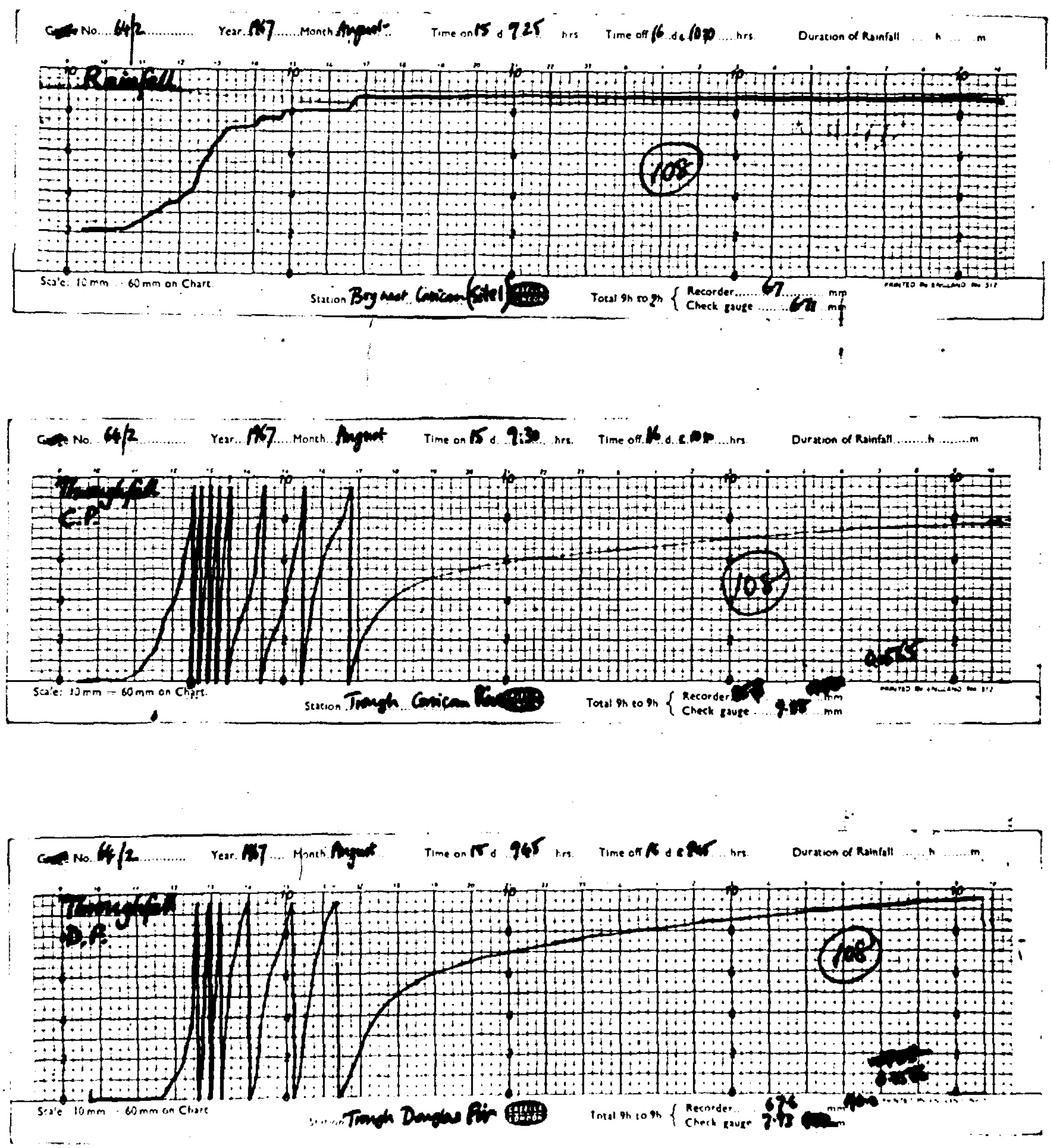


PLATE 2 Sample recorder charts from Site 1 and the troughs in the Corsican pine and Douglas fir.

the errors, due to setting the individual clocks and the time taken for water to run out of the trough, were minimised. The difference between the throughfall and rainfall was calculated for each period and was termed the 'crude interception loss'. This quantity represents the rainfall that failed to reach the ground as throughfall and consists of water retained on the canopy surfaces, stemflow and evaporative losses. Subtraction of stemflow from the crude interception loss gives the 'corrected interception loss'. This distinction is drawn because there are certain errors in partitioning the total stemflow for a storm into fifteen minute periods.

Fig. 18 shows data for a storm recorded in April 1968 plotted cumulatively. The storm began with 6.8mm. of rain and ended with 0.9mm. of rain after a dry period of 3 1/2 hours.

The Course of Throughfall During the Storm

At the beginning of the storm the throughfall is small, and the interception loss is nearly equal to the rainfall. This has often been reported for small storms (Law, 1957; Ovington, 1954; Reynolds and Henderson, 1967).

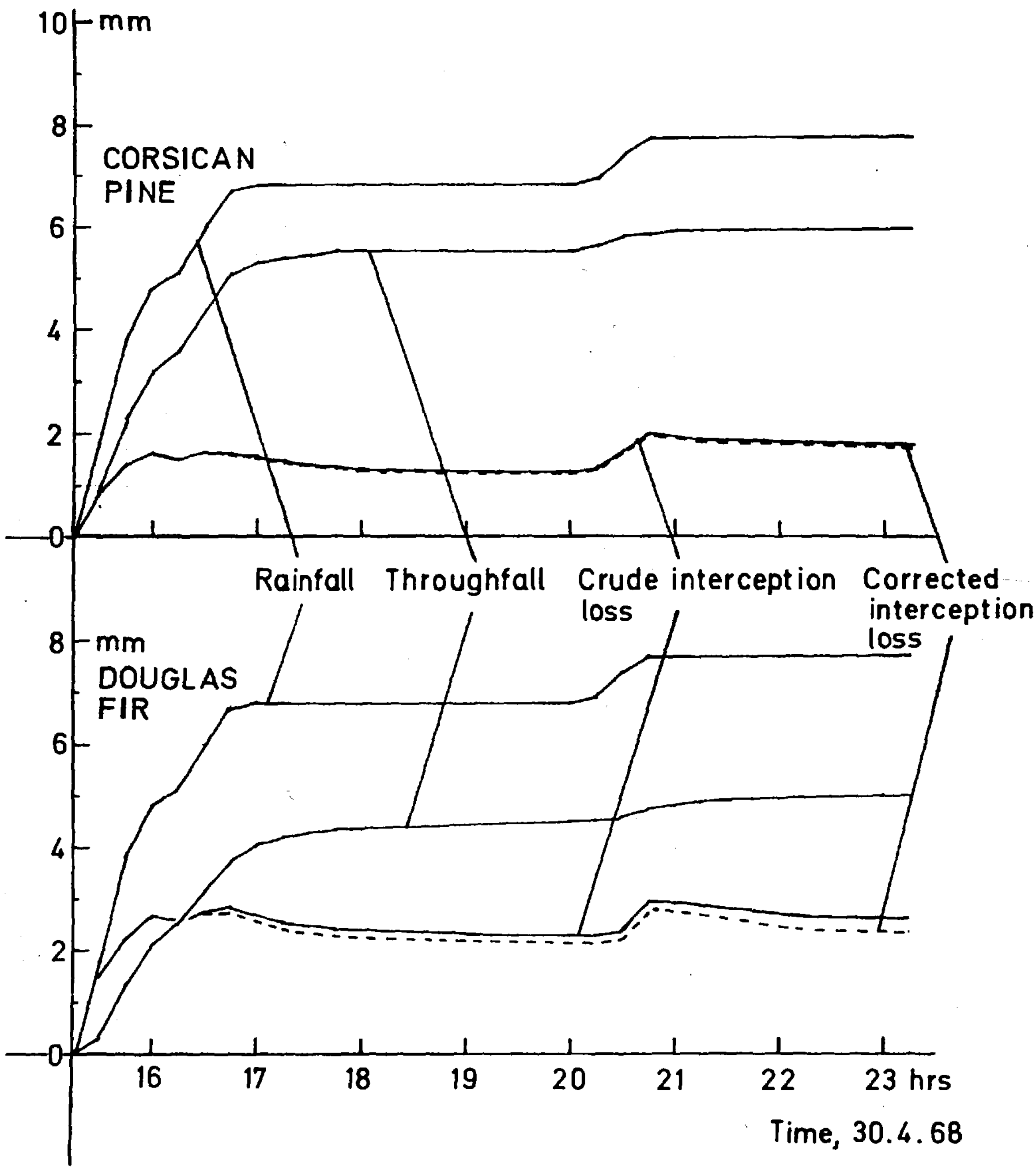


FIG. 18 Rainfall, throughfall and interception losses in Corsican pine and Douglas fir on 30 April 1968.

During the second half of the first period of rain the interception loss was nearly constant in both stands. This indicates that the canopies were saturated and the throughfall was equal to the rainfall. The slight rise (16.30 - 16.45 hrs.) of the crude interception loss in the Douglas fir may be accounted for by stemflow, which, according to the stemflow regression (Eq. 14), began after 6.0mm. of rain had fallen. It amounted to 0.1mm. during the fifteen minutes (16.30 - 16.45 hrs.) when 0.7mm. of rain fell. The corrected interception loss is also shown in the figure.

During the dry period the interception loss decreased. This was due to the canopies dripping after the rain had ceased. By 20.00 hrs. the rate of drip was negligible, and at this point the crude interception loss (1.3mm. for the Corsican pine, 2.3mm. for the Douglas fir) is expected to equal the sum of the canopy saturation value and the stemflow, providing there was no evaporation during the rain. The expected stemflow was 0.03mm. for the Corsican pine and 0.1mm. for the Douglas fir. The estimated canopy saturation values are 1.3mm. for the Corsican pine, and 2.2mm. for the Douglas fir. These values, which are higher than expected, lead to the conclusion that some intercepted water evaporated during the first part of the storm. The occurrence of evaporation during rain will be considered further below.

The second period of rain was assumed to re-saturate the canopies, although the rain did not last long enough for this to be clearly indicated by the throughfall data. After the rain, the crude interception loss increased by 0.4mm. in the Corsican pine and 0.3mm. in the Douglas fir. Stemflow contributed less than 0.01mm. in the Corsican pine and 0.1mm. in the Douglas fir. The unaccounted increase in interception loss, which amounts to 0.4mm. in the Corsican pine and 0.2mm. in the Douglas fir, is concluded to be due to evaporation during the dry period. The total interception loss for the storm is 1.7mm. for the Corsican pine and 2.4mm. for the Douglas fir. Thus the total evaporative loss during the storm was about 0.6mm. in the Corsican pine and 0.3mm. in the Douglas fir. The accuracy of an estimate of evaporative loss obtained in this way is dependent on the accuracy with which the canopy saturation value is known. However, determination of the evaporation during the dry period simply required that the canopy was saturated at the beginning of the dry period and re-saturated after the second fall of rain.

Water Retained in the Canopy During Rain

The drip from the canopy when rain has ceased indicates that during the rain a greater quantity than the canopy saturation value is retained on the canopy. This has previously been shown by Grah and Wilson (1944). The amount retained may be visualised as being a balance between the rate of rainfall and the rate of drip from the canopy. As the rainfall intensity increases the temporary retention on the canopy increases. This has been observed in the canopy and is shown by the throughfall records for single storms. In very heavy rain the needles in the Corsican pine have been seen surrounded by a depth of water approaching their thickness (1 - 2mm.). When the rainfall abated the water drained from the leaves leaving only a thin film of water.

There is an indication of the canopy retention changing with rainfall intensity in Fig. 18. When the intensity fell for fifteen minutes at

16.00 hrs. the crude interception loss decreased, but increased to its previous value when the rainfall intensity increased again.

Fig. 19 shows a storm in which there was a constant rainfall intensity for much of the storm. During this time the crude interception loss remained constant but fell as the rainfall intensity decreased at the end of the storm. The decrease is more marked in the Douglas fir when the stemflow is taken into account.

Fig. 20 shows a storm with varying intensity rainfall. The interception loss is shown to vary with the changing rainfall intensity, and shows signs of remaining constant when the rainfall intensity is constant at 01.30, 02.30, 04.00 and 04.30 hrs.

Measurement of Evaporation Rate

The evaporative loss during a storm depends on the proportion of the surface area of the canopy that is wet, and the potential rate of evaporation. The latter is determined by meteorological conditions for a particular forest, and may be estimated as the rate of evaporation of intercepted water in a period when all of the canopy surfaces are wet. The choice of a suitable period and the determination of the

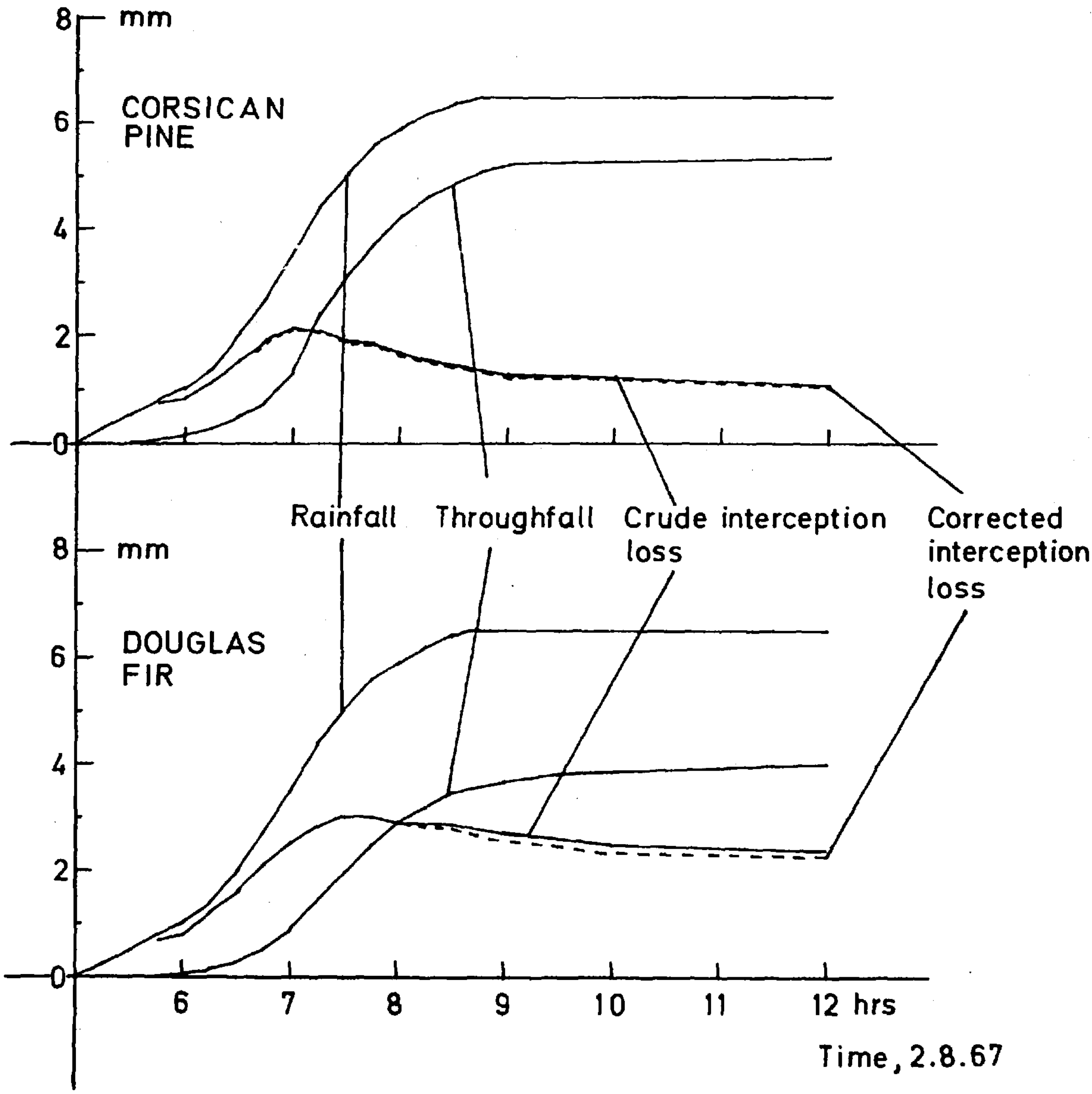


FIG. 19 Rainfall, throughfall and interception losses in Corsican pine and Douglas fir on 2 August 1967.

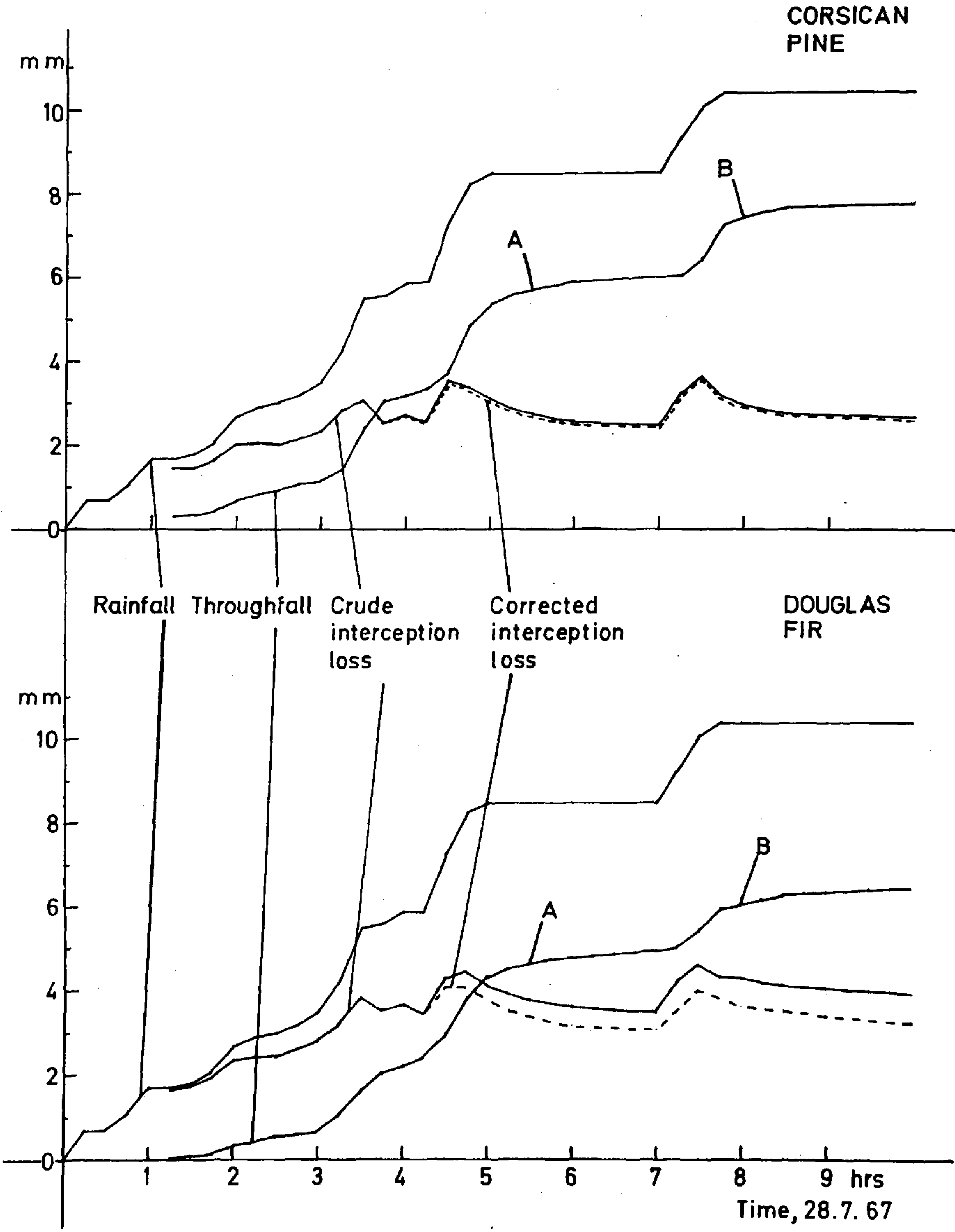


FIG. 20 Rainfall, throughfall and interception losses in Corsican pine and Douglas fir for 28 July 1967.

evaporation rate are described below.

The period used should follow a point in the storm when the canopy is fully saturated and should be short enough not to allow large parts of the canopy to dry completely. The period is chosen so that :

1) it begins and ends with the same amount of water in the canopy, and
2) it includes a period of rain that exceeds the loss by evaporation.

Such a period is shown for both stands in Fig. 20, which will be used as an example. The points A and B (representing the beginning and end of the period) were chosen so that the rates of drip were the same. To fulfill condition 1), it is assumed that the rate of drip is related to the water retained on the canopy and that equal rates of drip correspond to equal amounts of water in the canopy. As there was drip throughout the period marked, it is assumed that the canopy did not dry extensively during it. Fulfilling condition 2) the rain in the second period was 2mm. which exceeds the interception loss between A and B.

The gains and losses of water in the canopy are equal for the period marked; the rain is the source of gain and throughfall, drip and evaporation are the losses. As all of these, except the evaporation, are measured, this may be estimated as the difference between the gain and losses. The evaporation rate is found by dividing the loss by the length of the period. This method avoids making a distinction, at the end of a period of rain, between throughfall and drip and the difficulties experienced when estimating the length of a dry period between rain showers. These difficulties are mainly due to the fact that rain often begins and ends as drizzle or light sporadic rain, as seen in Fig. 19.

In the example shown for the Corsican pine in Fig. 20 the rainfall was 1.9mm. and the throughfall was 1.7mm. In this stand stemflow was negligible for small amounts of rain, so that 0.2mm. was evaporated in 2 1/2 hours or 0.08mm./hr. There was 1.4mm. of throughfall and 0.3mm. of stemflow in the Douglas fir. Thus, there was a similar rate of evaporation of 0.2mm. in 2 1/2 hours in this stand also. In practice these measurements were made directly on the recorder charts, where the accuracy was not restricted to points at 15 minute intervals.

A comparison of the rates of evaporation of intercepted water during the same storms is shown in Table 6. A detailed comparison of the two stands will be made in the next chapter.

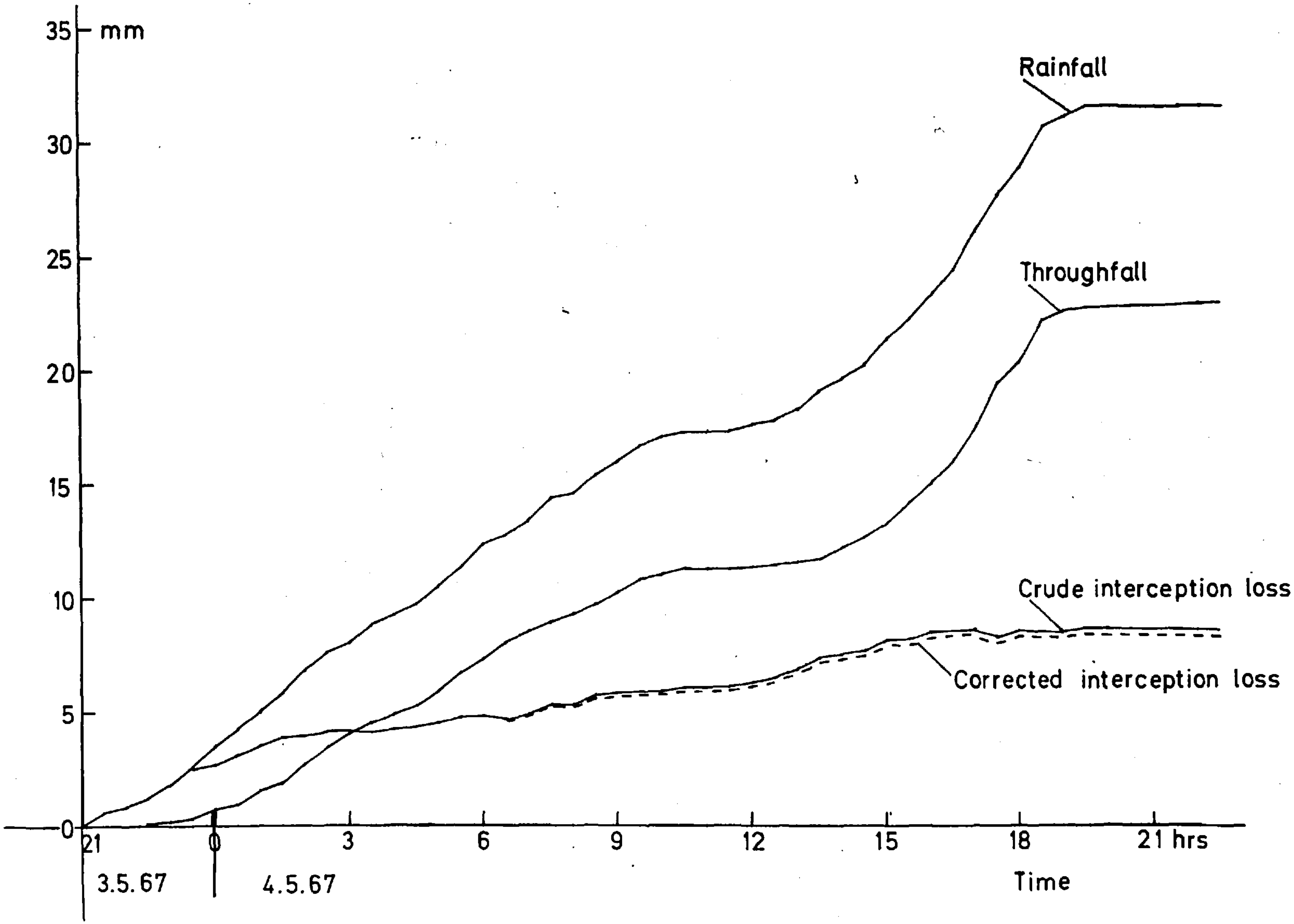
Evaporation During Rain

It was suggested above that evaporation may occur during rain as well as in rainless periods during storms. Further evidence for this was obtained during a storm in May 1967, shown in Fig. 21. There was continuous rain for eight hours after canopy saturation, but the interception loss continued to increase and the increase was more than could be accounted for by stemflow.

Fig. 22 shows a storm when data for both stands was obtained. The crude interception loss at the end of the storm, even after drip, is higher than during the period of light rain in the middle of the storm. The increase is not accounted for by stemflow and it was concluded that evaporation occurred during the rain.

Leonard (1967) has suggested that a high rate of evaporation may be expected at the beginning of a storm, before the air in the canopy is fully saturated. This view is supported here because the

FIG. 21 Rainfall, throughfall, and interception loss in Corsican pine during May 3/4 1967.



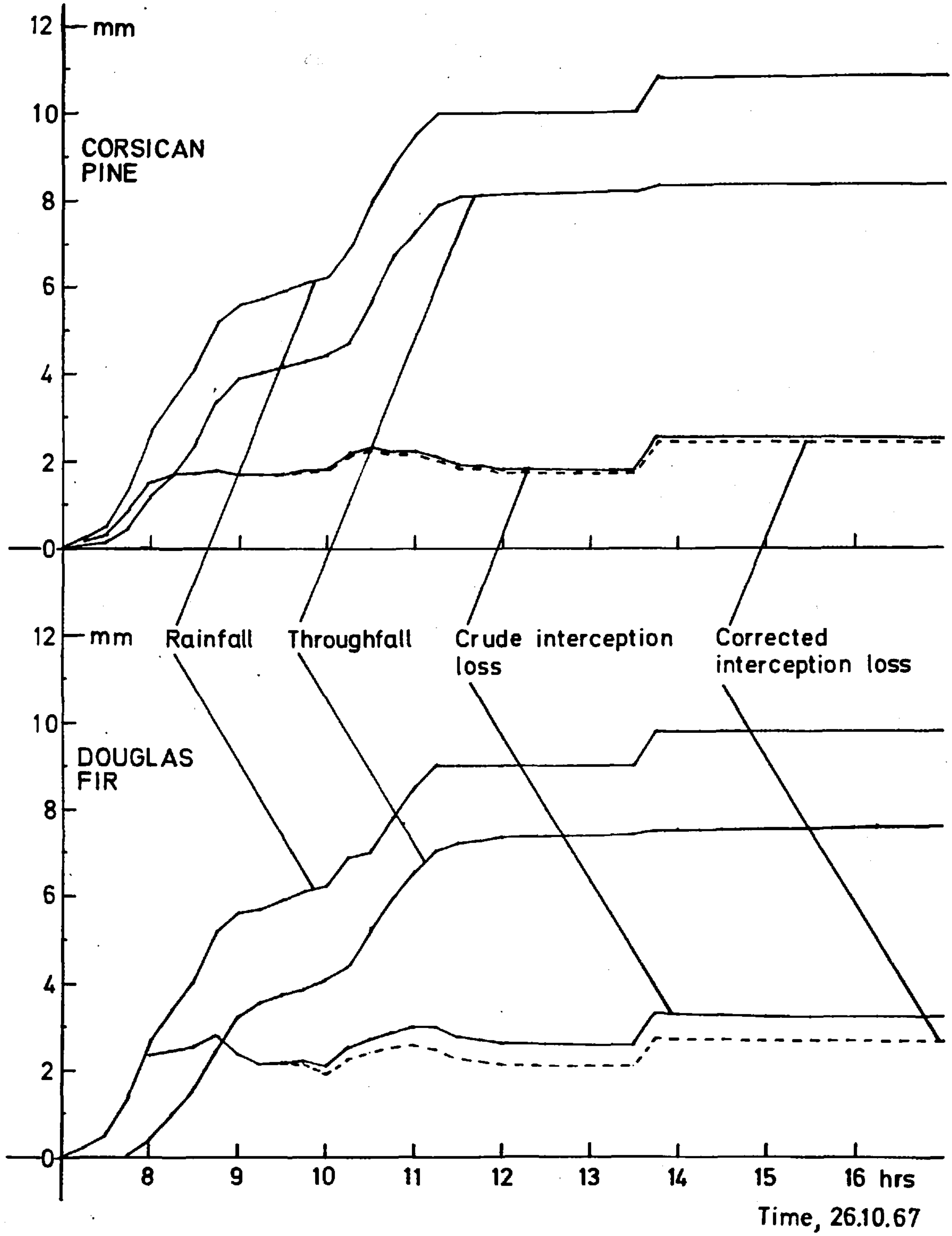


FIG. 22 Rainfall, throughfall and interception losses in Corsican pine and Douglas fir on 26 October 1967.

air humidity measured above the Corsican pine stand has been observed to rise only slowly following the beginning of rain. Fig. 23 shows the course of the vapour pressure gradient and leaf and air temperatures during a storm. Figs 21 and 22 indicate that evaporation occurred during rain when the canopy surfaces were fully saturated, and the air within the canopy may have been expected to be saturated. Spot measurements of humidity during rain, made above the Corsican pine stand with a whirling psychrometer, have frequently indicated that the air is not saturated. For this reason it is assumed that the increasing interception loss shown during the rain is due to evaporation, and not to some other unrecognised loss.

This chapter has shown that the evaporation of intercepted water during a storm is an important part of the total interception loss of a forest, and that the evaporation is not confined to dry periods between rain showers. The relationship of the evaporation rate with meteorological conditions and the physical properties of the canopy will be considered in the next chapter.

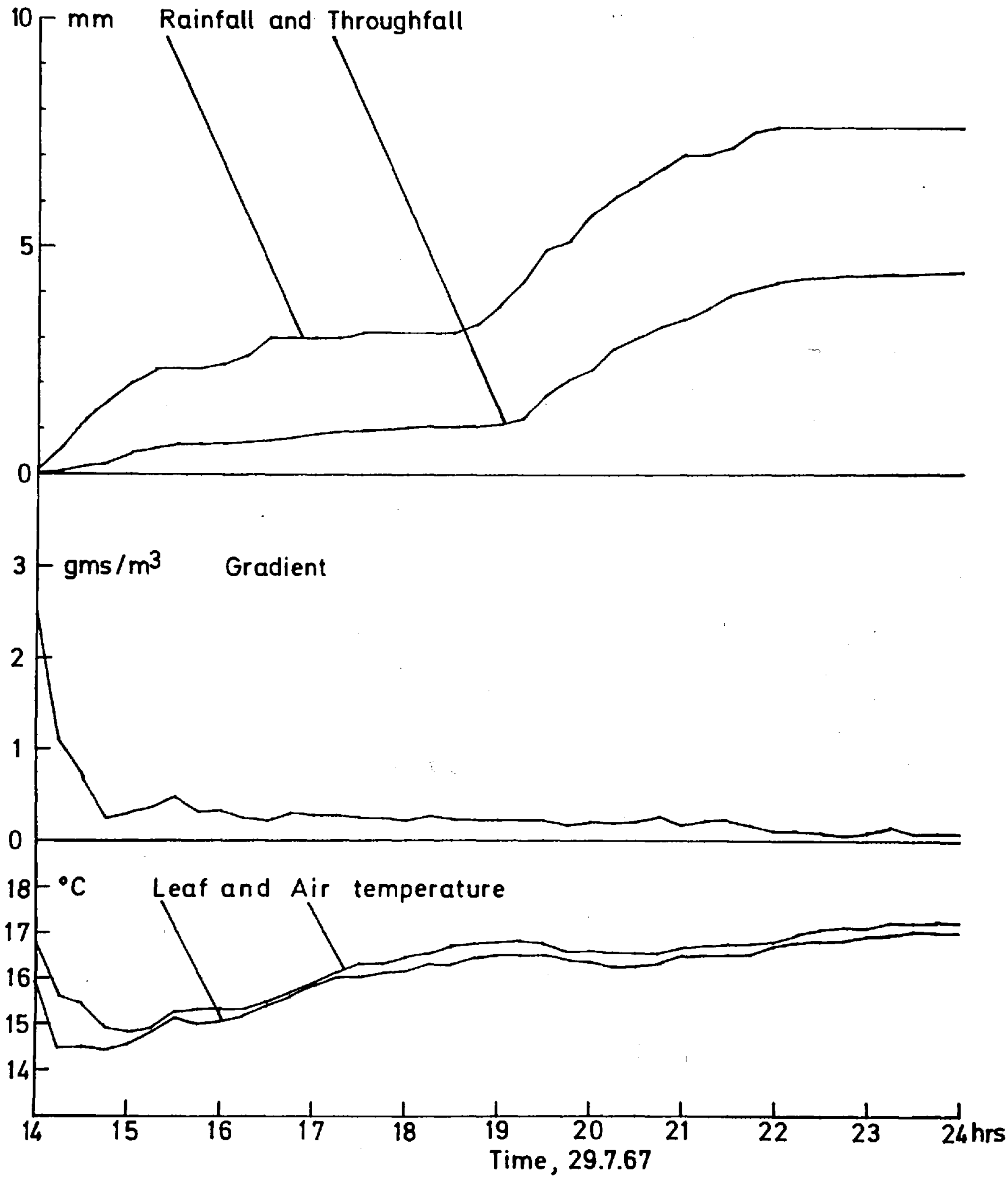


FIG. 23 The course during a single storm of vapour pressure gradient, and leaf and air temperatures in Corsican pine.

TABLE 6. Showing the rate of evaporation of intercepted water determined at the same time in Corsican pine and Douglas fir.

Date	Time and Duration of Estimate	Evaporation Rate (mm./hr.)	
		Corsican pine	Douglas fir
1967			
July 29	1600 - 1730	0.17	0.07
	1730 - 2300	0.27	0.24
July 30	0100 - 0415	0.23	0.16
Aug. 15	1400 - 1700	0.05	0.02
Oct. 16	1830 - 2015	0.54	0.17
Oct. 27	0900 - 1130	0.17	0.09
Oct. 28	1230 - 1645	0.15	0.15
Nov. 1	1130 - 1600	0.04	0.09
Nov. 5	2130 - 2300	0.14	0.06
1968			
Apr. 30	1745 - 2100	0.11	0.07

VI. MEASUREMENT OF AIR RESISTANCE

The evaporation pathway for intercepted water consists of the air in the boundary layer surrounding the wet surfaces, the air within the canopy and the air above the canopy. Evaporation occurs when there is a water vapour concentration gradient between the air at the wet surface and the air above the canopy. In still air water vapour moves by diffusion alone, but in turbulent air turbulent transfer occurs, which is a faster and more important process. In turbulent air diffusion may be neglected. The air resistance (ra) can be calculated from :

$$ra = \frac{\text{the vapour concentration gradient}}{\text{water vapour flux (evaporation rate)}} \qquad (17)$$

when the evaporation rate is determined by the method described in the last chapter.

In free air turbulence increases with the wind speed (Sutton, 1953) and the air resistance decreases with the increasing turbulence (by definition in the Penman formula). If the aerodynamic roughness of the canopy remains constant the air resistance is inversely related to the wind speed above the canopy (Monteith, 1965). The air resistance has been calculated over a range of wind speeds for both the Corsican pine and the Douglas fir.

Method

Equation 17 shows that the mean water vapour concentration gradient and the evaporation rate are required to calculate the air resistance. The evaporation rate from wet leaves was determined by the method described in the last chapter. The vapour concentration gradient was calculated as the difference between the mean vapour concentration in the air above the canopy and the vapour concentration of saturated air at the mean leaf temperature. The vapour concentration above the canopy was calculated from wet and dry bulb temperatures above the stand.

The temperature measurements were made with thermistor probes and recorded on a miniature chart recorder made by Grant Instruments (Developments) Ltd. Toft, Cambridge, which recorded each of twelve probes, for 12 seconds, once in 3 1/2 minutes.

The air humidity was measured just above the leading shoots in the Corsican pine and at the highest practicable position in the Douglas fir.

In this stand the trees extended further above the top of the towers so that the height of the leading shoots was not known exactly. The point at which the humidity was measured was judged to be level with the leading shoots of most trees. In the Corsican pine the wet and dry bulb thermistors were shielded from the sun by a white horizontal plate fixed above them, but were otherwise in the free air and aspirated by natural wind. In the Douglas fir air was drawn down a tube from the sampling height by a battery driven pump (Charles Austin Ltd.) and pumped over the wet and dry bulb thermistors.

Leaf temperature measurements were made using fine catheter probes. The thermistor bead was mounted at the end of a nylon tube about 1mm. in diameter. The probes were fixed to the leaves with fine fuse wire, as shown in Fig. 24. Eight probes were positioned at random at two levels in the canopy by first numbering the trees, branches and shoots and then selecting them using a random number table (Fisher and Yates, 1963). Their random distribution was changed three times in the Corsican pine, but was not changed during the more limited observations in the Douglas fir.

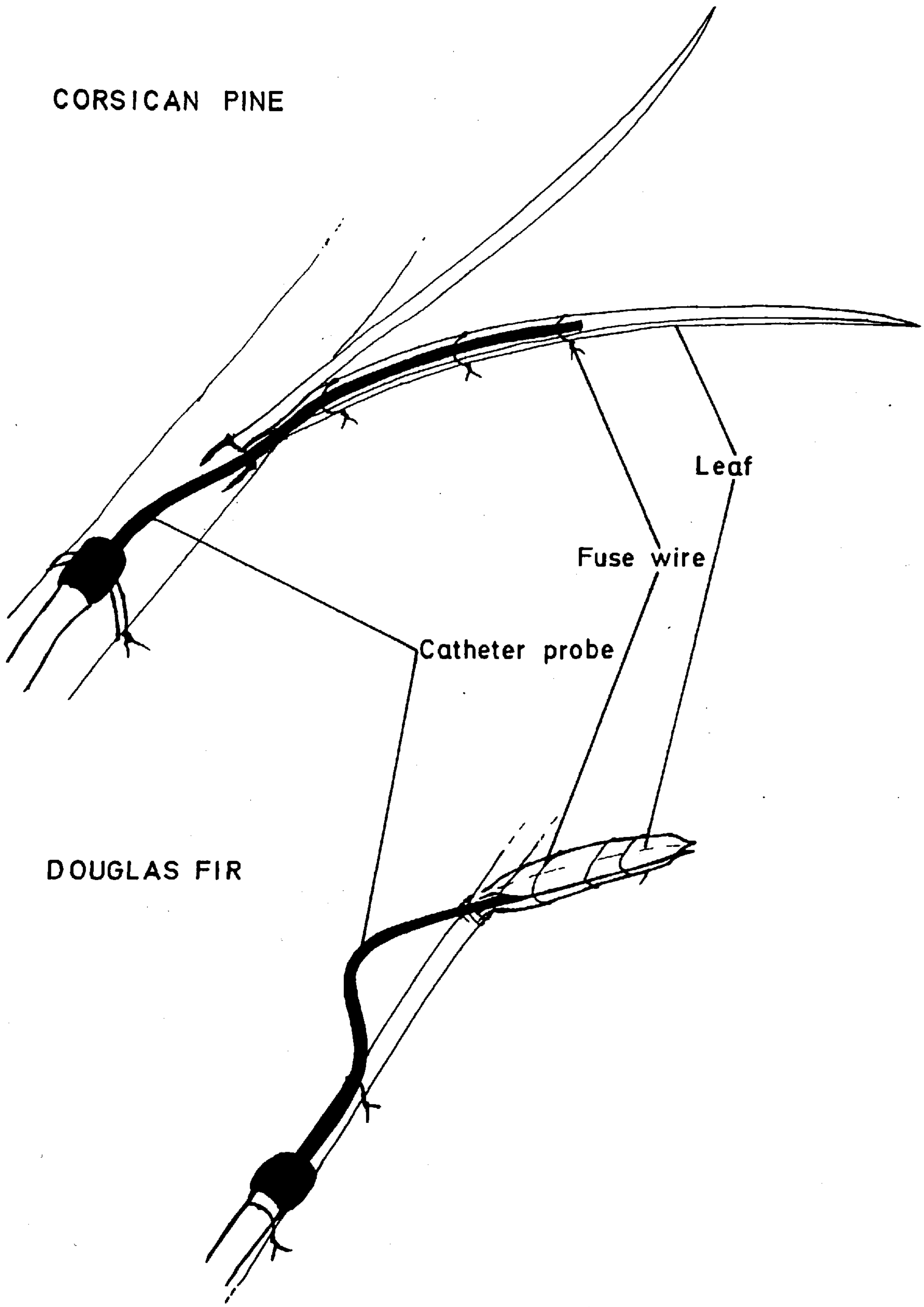


FIG. 24 Diagram showing method of fixing thermistor probes to leaves.

The daily wind run was measured by an integrating anemometer about 6ft. (2 metres) above the tallest tree near the towers in the Corsican pine. The anemometer was raised each year to keep its relationship with the canopy constant. The wind speed for periods of a few hours were obtained by proportioning the total wind run in a day according to the hourly wind run recorded at South Farnborough, about 5 miles (8 kilometres) away. This information was provided by the Meteorological Office at Bracknell.

The Reliability of the Measurements

1. Rainfall and Throughfall

The rainfall recorded at Site 1 was assumed to be the true rainfall over the stands; justification for this assumption is that the measured variability of rainfall at three sites in the forest was small, and Site 1 was very close to the Corsican pine and sheltered from the wind. The latter point probably minimised errors in the catch of a rain gauge due to turbulence over the orifice, and the former points suggest that the catch at Site 1 was a reasonable estimate of the rain over both the stands.

The throughfall over a short period within a storm was determined from the slope of the trough calibration lines (Eqs. 10 and 11). The slopes and standard errors were 0.05 ± 0.00058 and 0.057 ± 0.00133. Thus the standard errors were 1.2% and 2.3% of the slope, with a corresponding error in the estimate of throughfall. The size of the error in an average storm was 0.03mm. in the Corsican pine, and 0.01mm. in the Douglas fir (see Tables 7 and 8)

2. <u>Temperature Measurements</u>

All the thermistor probes were carefully calibrated against a standard probe in a water bath. This was done four times during the period that measurements were made, but no drift in calibration was detected. The temperatures were recorded to the nearest 0.1°C. in the Corsican pine, and 0.025°C. in the Douglas fir, after the recorder was modified.

The leaf temperatures recorded by the thermistor probes were compared, in the laboratory, with measurements made with fine thermocouples. The comparisons were made by fixing a fine copper/constantan thermocouple and thermistor probe together on a single detached leaf. It was found that on a dry leaf, in still air, enclosed in a dark box, the thermocouple detected a warming of the thermistor while it was recording. This was due to the current passing through it from the recorder, and amounted to 0.13°C. This was noticeable on the recorder trace as well. No warming was detected on a wet leaf in similar conditions and was not found at all in a gentle breeze.

On a wet leaf, in still air, the thermistor probe gave a reading of up to 0.5°C. higher than the thermocouple. This was, no doubt, due to the size of the probe and the large temperature gradient at the surface caused by a relative humidity of about 40% in the laboratory air. When this was increased to 70% there was no detectable difference between the thermistor and the thermocouple. It was concluded that under the conditions in which the probes were used, i.e. on wet leaves in an atmosphere with a high humidity, they adequately measured the leaf temperature. When the probe was fixed between a pair of needles it agreed with the thermocouple measurements under all conditions. This technique was used in the Douglas fir.

The variability of the leaf temperatures within the wet canopy was investigated in the Corsican pine. No consistent differences were found between eight different probe positions on a single branch at the top of the canopy. The difference rarely exceeded 0.2°C. The mean leaf temperature of branches at the top and bottom of the wet canopy, measured at the same time, were also found to be similar. This uniformity of leaf temperatures in the wet canopy was supported by all further measurements made in the canopy.

During longer dry periods between showers, but with the leaves remaining wet, the leaf temperature at the top of the canopy sometimes rose about 0.5°C. above those at the lower level. This was assumed to be due to strong radiation at the top of the canopy which did not penetrate to the lower levels. A larger rise in temperature was only found on occasions when the canopy dried significantly at the top.

During sunny spells in June and July, when the canopy was dry, a rise of 2.0°C. to 5.0°C. above air temperature was often recorded at the top of the canopy. At the lower level leaf temperature usually remained close to the air temperature. The leaf temperatures were generally more variable on dry days, but were uniform at night and under overcast conditions.

From these results it was concluded that under the conditions in which they would be used, i.e. in dull, cloudy weather when the canopy was wet, the eight probes adequately sampled leaf temperatures in the canopy.

3. Humidity Measurements

The ability of natural aspiration to give accurate wet and dry bulb temperatures in the Corsican pine was checked frequently with a whirling psychrometer; measurements were made between 09.00 and 10.00 hrs. when the daily visit was made. More extensive tests were made on a still day, when the humidity measured by natural aspiration of the wet and dry thermistor probes was compared with measurements made with the same probes aspirated with a small fan. No difference was found between the naturally aspirated and the artificially aspirated measurements. These measurements also agreed with those made using a whirling psychrometer. The low wind speed necessary for full ventilation of the wet bulb was consistent with the small size of the thermistor probes and the natural turbulence of the atmosphere.

The aspiration in the Douglas fir was tested using fine thermocouples in the same air stream as the thermistor probes. The construction of the wet and dry bulb thermocouples and the air flow was such that the maximum wet bulb depression was obtained. (Monteith, 1954; Penman, 1955). The thermistor measurements agreed with the thermocouple measurements.

4. <u>The Evaporation Rate</u>

The evaporation rate measured in the way described in the last chapter was assumed to be the potential evaporation rate, i.e. that occurring when the canopy was fully saturated and occurred from all surfaces. If there was very rapid evaporation or a long period between showers, part of the canopy may have become dry and the evaporation would no longer be at the potential rate. This would cause an over-estimate in the value of the air resistance. Such an overestimate may be avoided by making a careful selection of the periods used to estimate the evaporation rate. The criteria for making such a selection were based on the following observations made in the canopy during showery weather.

When rain ceased, the excess water in the canopy drained down the leaves and formed a drop at the lowest point. Judging by the rate of drip from a leaf, the flow over the leaf surface became slower as the film of water on the surface decreased in thickness. The surplus water in the canopy makes good the loss by evaporation until the canopy retains only the minimum quantity of water required to wet the leaf surfaces. This quantity has been estimated earlier as the canopy saturation value. At this point the thickness of water on the leaf surfaces is assumed to be roughly equal to the equivalent film thickness calculated by Leyton et al (1967) and Merriam (1961). The calculated equivalent film thickness for the two stands was 0.070mm. for the Corsican pine and 0.051mm. for the Douglas fir. This was based on canopy saturation values of 0.9mm. and 1.2mm. and leaf area indices of 12.9 and 23.5 for the Corsican pine and Douglas fir respectively.

However, the water film over the leaf surfaces is not of uniform thickness. The upward projecting tips are covered by a thin film only and are the first parts to dry. This was most noticeable at the top of the canopy, which is subject to direct radiation and is not partly re-wetted by the dripping canopy above. In showery weather the canopy has been seen partly dry at the top while still dripping below.

This condition was detected in the records by noting the rise in temperature of the leaves at the top of the canopy which occurred in strong sunlight. Where these conditions were found, the period was not used to calculate a value of the air resistance. This procedure helps to ensure that the rates of drip used to identify suitable periods for calculating the air resistance correspond to similar canopy conditions.

Thus, suitable periods are those following high intensity rainfall when the canopy retains an excess of water which may evaporate without leaving a dry surface. Periods of many short showers with short dry spells between, or periods of continuous light rain, provide equally suitable estimates of evaporation. Examples of each type of drying period have been used to calculate the air resistance of the canopies. The dry period, 11.15 to 13.30 hrs., shown in Fig. 22 (last chapter) is an example of a period that was discarded due to high temperatures at the top of the canopy.

Results

The results are shown in Tables 7 and 8.

TABLE 7. The measurements of Rainfall (mm), Net Rainfall (mm), Vapour gradients (gms/cm^3 x 10^{-6}) used to determine the air resistance for Corsican pine.

Date 1967	Time	Rain (mm)	Net Rain (mm)	Evap (mm)	Grad gm/cm^3 x 10^{-6}	ra sec/cm	Wind Speed m/sec
May 4	1045-1945	15.30	11.70	3.60	0.28	0.025	4.67
Jun 23	1720-2030	1.35	1.01	0.34	0.14	0.047	1.92
Jun 24	1540-1608	1.35	1.16	0.19	0.39	0.022	2.39
Jly 29	1555-1729	0.70	0.29	0.41	0.20	0.028	2.91
	1730-2300	4.65	3.40	1.25	0.14	0.022	3.48
Jly 30	0100-0415	0.65	0.12	0.53	0.11	0.024	3.45
Aug 15	1357-1708	1.55	1.42	0.13	0.20	0.176	0.46
Aug 19	0900-1100	3.50	3.39	0.11	0.21	0.137	0.81
Oct 16	1830-2015	2.00	1.02	0.98	0.33	0.021	6.00
Oct 28	1230-1350	0.45	0.23	0.22	0.34	0.074	1.33
	1350-1550	2.20	1.98	0.22	0.21	0.069	1.13
	1550-1645	0.25	0.13	0.12	0.19	0.052	1.83
Nov 1	1130-1600	2.60	2.43	0.17	0.05	0.048	3.20
Nov 5	2130-2258	0.40	0.20	0.20	0.16	0.042	2.60
Oct 27	0903-1125	4.50	4.15	0.35	0.16	0.039	2.99

TABLE 8. The measurements of Rainfall (mm), Net Rainfall (mm), Vapour gradients (gms/cm^3 x 10^{-6}) used to determine the air resistance for Douglas fir.

Date 1968	Time	Rain (mm)	Net Rain (mm)	Evap (mm)	Grad gm/cm^3 x 10^{-6}	ra sec/cm	Wind Speed m/sec
Apr 17	2215-0945	3.10	2.70	0.40	0.050	0.052	1.8
Apr 30	1740-2105	0.90	0.64	0.26	0.130	0.061	1.5
May 4	0140-0545	0.30	0.23	0.07	0.105	0.022	2.6
May 8	1430-1620	0.90	0.42	0.48	0.150	0.020	2.8
	1620-1910	0.55	0.28	0.27	0.105	0.040	2.1
May 10	2300-0105	0.45	0.24	0.21	0.040	0.015	3.4

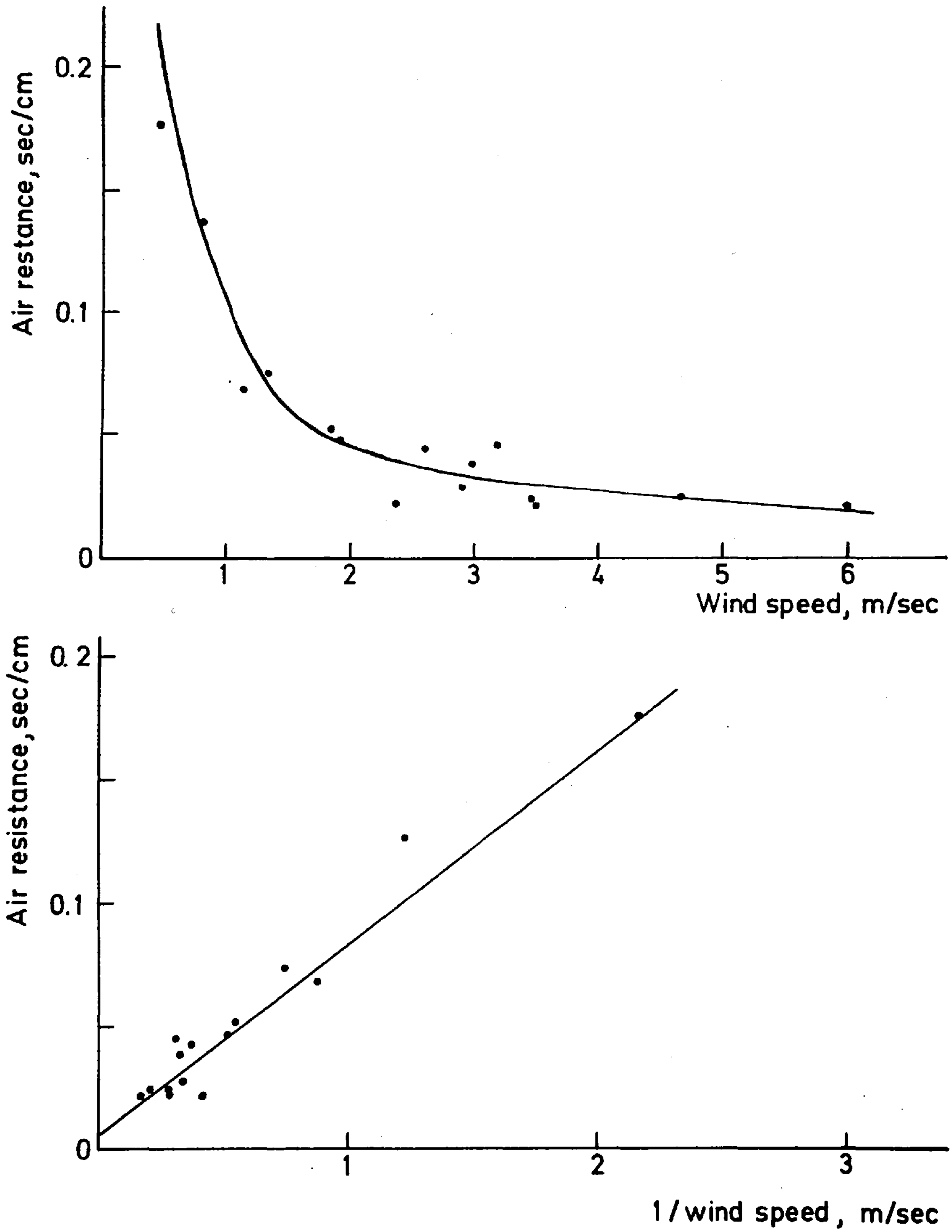


FIG. 25 Graphs of air resistance against wind speed and 1/wind speed for Corsican pine.

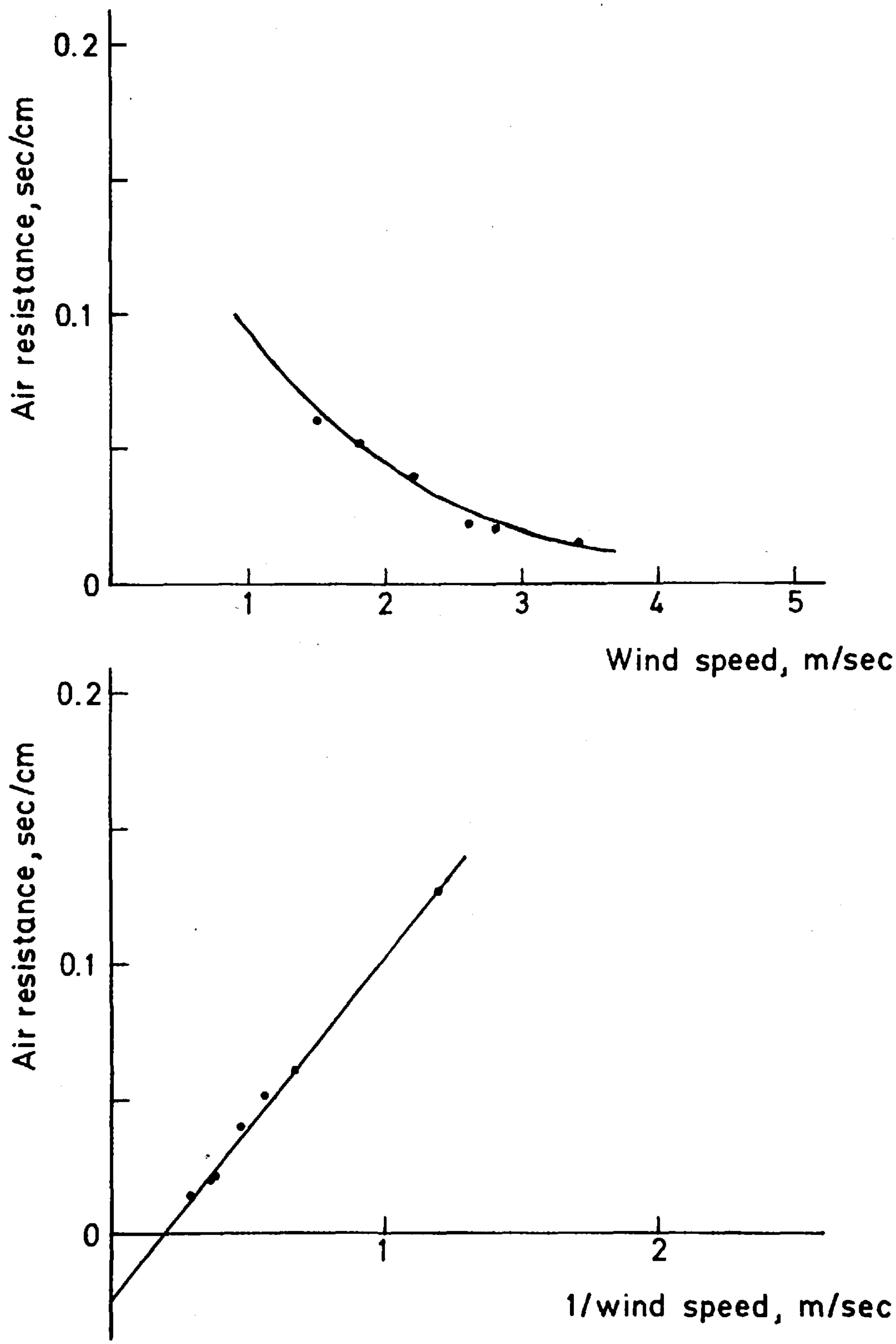


FIG. 26 Graphs of air resistance against wind speed and 1/wind speed for Douglas fir.

Figs. 25 and 26 show the calculated air resistance plotted against wind speed and the inverse of wind speed. The calculated regression lines drawn on the figures are :

$$\text{Corsican pine} : y = 0.0836x + 0.006 \quad (18)$$

$$\text{Douglas fir} : y = 0.130x - 0.024 \quad (19)$$

where x = 1/Wind Speed

y = Air Resistance

The standard error of the regressions is a measure of the random errors in the data. They are 0.012 for the Corsican pine and 0.004 for the Douglas fir. Thus, on only one in twenty occasions is the error greater than 0.024 in the Corsican pine and 0.008 in the Douglas fir.

Variation of Air Resistance with Wind Speed

If the aerodynamic roughness of the canopy remains constant the air resistance plotted against the inverse of the wind speed should give a straight line that passes through the origin. In the case of the Corsican pine there is no significant difference between the intercept of the calculated line and zero. This is interpreted as meaning the roughness does not vary with wind speed. In the Douglas fir the intercept of the calculated line is significantly less than zero, which from the limited data indicates a change in roughness as the wind speed increases.

These conclusions were supported qualitatively by observations in the canopy. In the Corsican pine the trees only swayed gently in strong winds and wind was felt to move through the depth of the canopy even in light winds. In the Douglas fir the wind did not move through the canopy in the same way until the wind speed was moderate. The trees swayed in light winds and the branches shook vigorously in moderate winds. In strong winds the trees swayed ten to fifteen feet off centre. The vigorous shaking of the branches at high wind speeds in the Douglas fir may have caused more rapid mixing of the canopy air, which accounted for the low resistance in these conditions.

Direct comparison of the values obtained for the two stands should be made with caution. It was not certain that there was no additional gradient above the points at which the humidity was measured and these points may not have had the same relationship with the total gradient in each stand.

Sensible Heat Flux

As the exchange coefficients of heat and water vapour are approximately equal, the air resistance derived from evaporation studies may be used to calculate the flux of sensible heat to the canopy from :

$$\text{flux (cals./cm.}^2\text{/sec.)} = \frac{\rho c \text{ (Temp. gradient (}^{\circ}\text{C.))}}{ra} \quad (20)$$

where : ρ = density of air

c = specific heat of air

This has been done for the Corsican pine where the air temperature above the stand was measured. Table 9 shows the results in cals./cm.^{2}/sec. and as an equivalent evaporation rate. The measured evaporation rate is also shown.

Storms 103 B, 103 C, 133 and 144 occurred at night when sensible heat flux is the major source of energy for evaporation, and on these occasions the calculated evaporation rate and the measured rates agree quite well except in Storm 133. This storm shows a large discrepancy for which there is no clear explanation. It is possible that part of the canopy may have dried completely during the dry periods as

TABLE 9. Showing calculated heat flux with equivalent and measured evaporation rates

Date/time 1967		Rain Storm No.	Temp. gradient °C.	Air resistance sec/cm	Heat flux cals/cm/sec	Equiv. Evap. rate gm/cm²/sec $\times 10^{-6}$	Meas. Evap. rate gm/cm²/sec $\times 10^{-6}$
4. May	11-2000	73	0.06	0.025	6.8	1.2	11.1
23. June.	17-2000	92	0.21	0.047	13.0	2.2	3.0
24. June.	15-1600	93	0.10	0.022	13.2	2.2	17.6
29. July.	16-1700	103A	0.05	0.028	5.4	0.9	7.3
	17-2300	B	0.25	0.022	33.2	5.6	6.3
	01-0400	C	0.15	0.024	18.2	3.1	4.5
15. Aug.	14-1700	108	0.07	0.176	1.1	0.2	1.1
19. Aug.	09-1100	110	0.18	0.137	3.8	0.6	1.5
16. Oct.	18-2000	133	0.27	0.021	39.0	6.3	15.6
27. Oct.	09-1200	137	0.10	0.039	7.4	1.3	4.1
28. Oct.	12-1400	139A	0.13	0.074	5.1	0.9	4.6
	13-1600	B	0.20	0.069	8.4	1.4	3.1
	16-1700	C	0.15	0.052	8.5	1.4	3.6
1. Nov.	11-1600	142	0.10	0.048	6.0	1.0	1.0
5. Nov.	21-2300	144	0.29	0.042	20.0	3.4	3.8

the wind speed was very high. This drying could not be detected from the thermistor readings in the absence of strong radiation. Storm 92 occurred in the late afternoon and early evening and here, also, there is good agreement between the calculated and measured rate of evaporation. Storm 93 was short and heavy on an otherwise hot June day. Under such strong radiation conditions, solar radiation may be expected to supply most of the energy for evaporation as is indicated. The results generally indicate a greater solar energy input during the summer months than in October and November.

In this chapter a method of calculating the air resistance of a forest canopy has been described, and the estimate has been used to calculate the sensible heat flux to the forest. The results show reasonable agreement with the measured evaporation rates and the climatic conditions.

VII. THE CONTRIBUTION OF INDIVIDUAL ASPECTS OF FOREST EVAPORATION TO THE TOTAL EVAPORATION

The total evaporation from a forest canopy consists of the interception loss and transpiration. The interception loss may be further divided into evaporation occurring during rain and evaporation occurring after the end of rain storms when the wet canopy dries. In this chapter the contribution of these separate parts to the total evaporation will be considered in relation to the measurements described in the preceding chapters.

In given environmental conditions evaporation from a wet canopy is determined by the air resistance, itself a function of both wind speed and canopy structure. Assuming that the radiation balances of the Corsican pine and Douglas fir give rise to similar gradients of water vapour in similar conditions, the rate of evaporation of intercepted water in these stands will be related to their air resistances. The measured resistances for wind speeds of less than 2.5m./sec. are similar for both stands, but at higher wind speeds the air resistance in the Douglas fir was lower than that in the Corsican pine. The mean monthly wind speeds were mostly between 1.5 and 2.5m./sec. Thus, for much of the time the air resistance of the two stands did not differ greatly.

The amount evaporated from the canopy after the end of a storm is determined by the canopy saturation value. The estimated values for the Corsican pine and the Douglas fir differ by about 0.3mm. This is expected to increase the total interception loss of the Douglas fir by an amount dependent on the number of times the saturated canopy dries. The time taken for the canopy to dry depends on the air resistance in the same way as evaporation during rain. The importance of this time is that, together with the length of storms, it determines the time available for transpiration, assuming that transpiration does not occur while the leaf surfaces are wet.

The transpiration rate is determined by the stomatal resistance in addition to the air resistance, and the total transpiration is determined by the rate and the time available. The value of stomatal resistance may vary with species; (Holmgren et al, 1965; Knoerr, 1967; Lee and Gates, 1964; Rutter, 1967).

The stomatal resistance of the Corsican pine and the Douglas fir have not been measured adequately, but during the course of the present work a diffusion porometer, similar to that of van Bavel et al (1965) and Stiles (described in Meidner and Mansfield, 1968), has been developed for use on leaves of pine and Douglas fir. It has not been used for routine measurements, as only a rough calibration of the instrument has so far been made, but comparative measurements have been made on a few occasions.

<u>Calculated Monthly Totals of Evaporation</u>

The role of these factors in determining total evaporation is demonstrated by calculating monthly totals of evaporation in representative climatic conditions, using Monteith's elaboration of Penman's equation (Eq. 9). The calculations are for three sample thirty day months when net radiation was -0.4, 2.2 and 4.4 equivalent mm./day. Vapour pressure deficits consistant with observations for months with these radiation conditions were assumed. It was further assumed that there were ten storms in each month which saturated the canopies. This is the average number of days per month that 1mm. or more of rain fell at South Farnborough (the nearest station to the site).

To take account of evaporation that occurred at times other than after the end of saturating rain storms, periods during which evaporation of intercepted water occurred were assigned to each month. The length of these periods were chosen to give realistic values of interception loss. The values of air resistance that have been used are 0.02, 0.04 and 0.06 sec./cm. The value of 0.04 sec./cm. is close to the mean monthly value for both stands.

A value of stomatal resistance was chosen to suit the radiation conditions, based on the values found by Rutter (1967) for Scots pine, and from figures tentively derived from a soil water balance for both the Corsican pine and Douglas fir sites provided by the Forrestry Commission. Canopy saturation values of 0.9mm. and 1.2mm. were chosen to represent the Corsican pine and Douglas fir. It may be noted here that the size of the canopy saturation value affects the number of saturating rain storms per month which in turn affects the estimated time that evaporation occurs from a wet canopy. The size of storm that saturates the two stands, and therefore the number of times the saturation value is evaporated, is probably similar here because the Corsican pine has a less dense canopy and allows a greater part of the rainfall to penetrate the canopy before saturation. In the Douglas fir the water drains from one branch to the next from top to bottom of the canopy, so that it is more efficiently wetted than the Corsican pine. This factor may also tend to increase the interception loss of storms that do not saturate the canopies.

The interception loss of the foliage was calculated as the sum of ten saturation values and the evaporation that occurred from the wet canopy. The transpiration was calculated from the transpiration rate and the time available, following Rijtema (1965) and Rutter (1967). The total monthly evaporation was estimated as the sum of these two factors; the figures are shown in Table 10.

The table shows that monthly transpiration is not markedly influenced by changes in air resistance, whereas the interception loss is clearly related to the air resistance. The significance of the air resistance in the monthly figures depends on the rainfall climate. When rainfall is predominantly showery with substantial evaporation during rain storms (the equivalent of one or more days evaporation

TABLE 10. Calculated interception losses, transpiration and total evaporation for three sample months, when ten saturating storms occurred in conditions appropriate for the time of year.

JANUARY (assumed to have 30 days)

Net Radiation = - 0.4 equiv. mm/day

Saturation deficit of air = 0.6 mb.

rs = 3.0 sec/cm.

	ra sec/cm.	No. of days canopy is wet (excluding drying time at end of storms). CORSICAN PINE C.S.V.*= 0.9mm.			DOUGLAS FIR C.S.V.*= 1.2mm.		
		1/2	1	4	1/2	1	4
Interception loss (mm)	0.02	14.01	19.02	49.08	17.01	22.02	52.08
	0.04	11.46	13.91	28.64	14.46	16.91	31.64
	0.06	10.61	12.22	21.88	13.61	15.22	24.88
Transpiration (mm)	0.02	3.43	3.31	2.95	3.40	3.30	2.98
	0.04	3.31	3.19	2.82	3.25	3.19	2.83
	0.06	3.20	3.08	2.72	3.09	3.03	2.67
Total evaporation (mm)	0.02	17.44	22.33	52.03	20.41	25.32	55.06
	0.04	14.77	17.10	31.46	17.71	20.10	34.47
	0.06	13.81	15.30	24.60	16.70	18.25	27.55

* C.S.V. = Canopy Saturation Value

TABLE 10. (cont.)

APRIL

Net Radiation = 2.2 equiv. mm/day

Saturation deficit of air = 2.4 mb.

rs = 1.0 sec/cm.

	ra sec/cm.	No. of days canopy is wet (excluding drying time at end of storms).					
		CORSICAN PINE C.S.V.*= 0.9mm.			DOUGLAS FIR C.S.V.*= 1.2mm.		
		1/4	1/2	1	1/4	1/2	1
Interception loss (mm)	0.02	18.39	27.78	46.56	21.39	30.78	49.56
	0.04	13.84	18.69	28.37	16.84	21.69	31.37
	0.06	12.34	15.65	22.30	15.34	18.65	25.30
Transpiration (mm)	0.02	44.84	44.46	43.70	44.73	44.35	43.59
	0.04	44.18	43.81	43.05	43.99	43.61	42.85
	0.06	47.04	46.62	45.81	46.74	46.33	45.52
Total evaporation (mm)	0.02	63.23	72.24	90.26	66.12	75.13	93.15
	0.04	58.02	62.50	71.42	60.83	65.30	74.22
	0.06	59.38	62.27	68.11	62.08	64.98	70.82

* C.S.V. = Canopy Saturation Value

TABLE 10. (cont.)

JUNE

Net Radiation = 4.4 equiv. mm/day

Saturation deficit of air = 4.1 mb.

r_s = 1.0 sec/cm.

	ra sec/cm.	No. of days canopy is wet (excluding drying time at end of storms).					
		CORSICAN PINE C.S.V.*= 0.9mm.			DOUGLAS FIR C.S.V.*= 1.2mm.		
		1/4	1/2	1	1/4	1/2	1
Interception loss (mm)	0.02	22.25	35.50	62.00	25.25	38.50	65.00
	0.04	15.97	22.93	36.85	18.97	25.93	39.85
	0.06	13.87	18.74	28.48	16.87	21.74	31.48
Transpiration (mm)	0.02	77.77	77.11	75.80	77.64	76.98	75.67
	0.04	77.35	76.69	75.38	77.11	76.45	75.14
	0.06	77.25	76.59	75.27	76.90	76.24	74.92
Total evaporation (mm)	0.02	100.02	112.61	137.80	102.89	115.48	140.67
	0.04	93.32	99.62	112.23	96.08	102.38	114.99
	0.06	91.12	95.33	103.75	93.77	97.98	106.40

*C.S.V. = Canopy Saturation Value

from the wet canopy) it has the greatest influence, and when the rainfall occurs more often as continuous rain with little evaporation from the wet canopy it has a smaller influence.

These figures show clearly that the interception loss of a forest is related to the rainfall climate, so that the common practice of expressing the interception loss as a percentage of the rainfall as, for example, in the review of interception studies by Zinke (1967), has little significance when making comparisons between species in different rainfall climates. The rainfall climate in which the measurements were made should be carefully considered.

The relative importance of the interception loss compared with transpiration is greatest in winter months. This is due to the presumed high stomatal resistance and corresponding low transpiration rate.

The effect of increasing the canopy saturation value by 0.3mm. has little effect throughout the year. The absolute size of the difference depends on the number of times the canopy was saturated, and its relative importance depends on the time of year and the amount of evaporation occurring during storms.

The reduction in time available for transpiration does not compensate for the increased interception loss, which reflects the fact that the evaporation of intercepted water is many times faster than transpiration.

Comparison of the Interception Losses in the Douglas Fir and Corsican Pine

The figures in Table 10 take no account of the contribution to throughfall of stemflow, and consequently calculated estimates of foliage interception loss cannot be compared with the measured values. To make such a comparison the measured interception losses have been modified to remove the influence of stemflow. The modified interception loss was calculated as the difference between throughfall and rainfall, excluding the part that contributed to stemflow. This was estimated from the stemflow regressions (Eqs. 13 and 14) as 0.15 of rainfall for the Douglas fir and 0.012 of rainfall for the Corsican pine. The mean foliage interception loss of the Douglas fir, calculated in this way, is 91% of that of the Corsican pine. The calculated figures in Table 10 do not agree with this value. In every case the foliage interception loss in the Douglas fir is greater than in the Corsican pine. This discrepancy could be due to errors in foliage saturation, stemflow regression and air resistance, or to different radiation balances in the two stands.

As all the estimates of the foliage saturation show it to be greater in the Douglas fir, it seems unlikely that this is the source of the discrepancy. The annual stemflow in the Douglas fir is many times that of the Corsican pine, where it is an insignificant amount, suggesting that the proportion of rainfall contributing to stemflow is greater in the Douglas fir. A possible undetected error may be the absorption of significant amounts of water, which would otherwise reach the ground as stemflow, by the Corsican pine trunks. This seems unlikely because of the arrangement of the branches and foliage which seem to channel water away from the trunks. Water has never been seen to flow over branch and trunk surfaces in the Corsican pine in the way that it does in the Douglas fir. It was concluded that errors in the stemflow regressions did not explain the discrepancy.

A further possibility is that the estimates of air resistances are incorrect. As described above (Chapter VI) this may be due to inadequate measurement of the humidity gradients.

Another important factor, so far overlooked, may be different air resistances for different parts of the canopy. In the Corsican pine the foliage is uniformly arranged throughout with each shoot similarly ventilated. In the Douglas fir the foliage hangs from the branches, forming dense leaf masses whose interior is poorly ventilated. The leaves within the leaf masses may be expected to have a higher air resistance than the rest of the canopy. This view is supported by the fact that while the exposed parts of the canopy appear to dry at a similar rate to the Corsican pine, the leaves within the dense foliage remain wet for a much longer time.

To allow for this possible factor, the interception loss has been calculated for the Douglas fir assuming that half of the intercepted water evaporated at half the calculated rate. The monthly estimates calculated in this way are compared with figures for the Corsican pine in Table 11. They show that the estimate for the Douglas fir is about 95% of

TABLE 11. Modified calculation of evaporation for Corsican pine and Douglas fir, when allowance is made for the suspected higher air resistance of the inner parts of the Douglas fir canopy and for the contribution of stem evaporation.

	JAN.	APRIL		JUNE	
No of days canopy was wet	4	1		1/2	
ra	0.04	0.04		0.04	
rs	3.0	2.0	1.0	1.0	0.5
<u>CORSICAN PINE</u>					
C.S.V.*=0.9mm.					
Interception loss (mm)	28.64	28.37		22.93	
Stem evap (mm)	0.22	0.22		0.15	
Transpiration (mm)	2.82	22.24	43.05	76.69	140.26
Total evap. (mm)	31.68	50.83	71.64	99.77	163.34
<u>DOUGLAS FIR</u>					
C.S.V.*=1.2mm.					
Interception loss (mm)	26.73	26.53		22.46	
Stem evap (mm)	3.47	3.42		2.46	
Transpiration (mm)	1.37	23.99	39.79	77.03	111.21
Total evap. (mm)	31.57	53.94	69.74	101.95	136.13

*C.S.V. = Canopy Saturation Value

that for the Corsican pine, which is close to the 91% obtained from the modified throughfall measurements.

The evaporation from the 15% of the canopy which, it is assumed, contributes to stemflow when it is wet has been estimated as a proportion of the evaporation from the rest of the canopy. It is assumed that this part of the canopy is mostly the woody branches and the top part of the trunk, and that this has a similar air resistance to the rest of the canopy. This additional evaporation is shown in Table 11.

The total interception loss in the Douglas fir obtained in this way is a little less than 111% that of the Corsican pine, which is the mean measured value. The water intercepted on the lower part of the trunk may account for an additional quantity, depending on the number of times the trunks were saturated. This number is difficult to estimate because the trunks may remain wet for several days and only a small part of the rainfall contributes to stemflow. It was judged that less than one in four of the storms that saturate the canopy also saturate the trunks, but no allowance for this has been made in Table 11.

The radiation balance of the two stands depends on the absorbtion, reflection and emission characteristics and the effective areas involved (Tibbals et al, 1964). The absorbtivity and emissivity of long waves are taken to be the same, and Gates and Tantraporn (1952) found that it was nearly uniform for most leaves. The reflection coefficient, or albedo, is a measure of the short wave absorbtion; the value of the albedo depends on the spacing of the leaves, as the reflected radiation may be absorbed by other parts of the canopy (Monteith, 1959; Tibbals et al, 1964). Rutter (1967) quotes albedos measured by Angstrom (1925), Barry and Chambers (1966), Baungartner (1967), Budyko (1956) and Stanhill et al (1966) for coniferous forests which vary from 0.10 to 0.20, the majority being between 0.10 and 0.15.

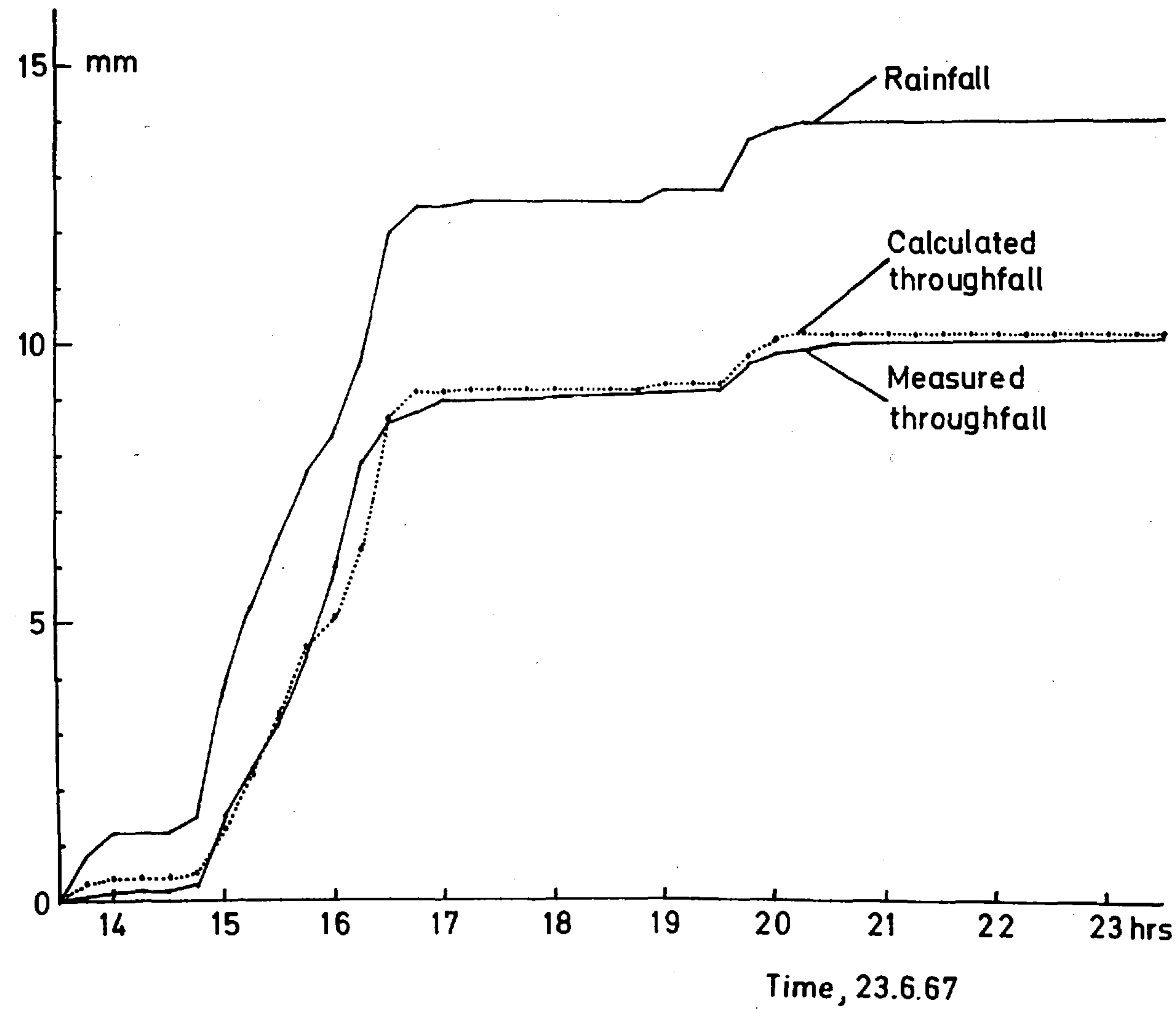
While the radiation exchange coefficients may be similar for the Corsican pine and the Douglas fir, the effective leaf areas and the canopy microclimates may be expected to differ. Further work is needed to determine the nature and extent of this difference.

Evaporation During Individual Rain Storms

The measured values of canopy saturation value and air resistance have been used with rainfall and water vapour concentration gradients to predict throughfall during single rainstorms in the Corsican pine. The method used was based on a calculated water balance for the canopy which was made each 1/4 hour of the storm. A small fraction of the rainfall was assumed to fall through the canopy until the canopy was saturated, when throughfall was assumed to equal the rainfall less the evaporation loss. The evaporation loss from the saturated canopy was calculated using the estimate of air resistance appropriate for the wind speed and the measured water vapour concentration gradient. The evaporation when the canopy was only partly saturated was estimated by simple proportion. A sample storm is shown in Fig. 27.

The graph of throughfall obtained was compared with the measured throughfall from the trough recorder. The comparison showed that while the total throughfall after a showery period of rain could be predicted fairly well, there were errors caused by the ability of the canopy to retain more than the saturation value, and the dripping of the canopy when

FIG. 27 Rainfall, measured throughfall and predicted throughfall for a storm on 23 June 1967.



rain stopped. Methods for dealing with these difficulties are being developed, which depend on developing expressions to relate the water held in the canopy to the rainfall intensity, and to relate the drip from the canopy to the water held in the canopy.

Transpiration Resistances

The transpiration pathway consists of the canopy air and the pores of the stomata, characterised respectively by the air resistance and stomatal resistance.

The air resistances were estimated from the rate of evaporation of intercepted water, which involves both leaf surfaces. In the Corsican pine the stomata are on both surfaces, so that the air resistance for transpiration is the same as the estimated value. In the Douglas fir the stomata occupy two strips forming about 2/3 of the area of the underside of the leaves. The air resistance for transpiration has been estimated on a leaf area index basis following Monteith (1965) and Rutter (1967).

The leaf area index including both leaf surfaces is 23.5 for the Douglas fir and the air resistance per unit of leaf area index is 23.5 times the measured air resistance, assuming that the total canopy resistance consists of 23.5 parallel resistances. On a similar basis, the total air resistance for transpiration consists of 7.8 resistances in parallel, giving a total resistance of $\frac{23.5}{7.8}$ times the measured air resistance.

The underside of the leaves are the least exposed parts which were assumed, above, to have a high air resistance associated with poor ventilation. Accordingly the resistance per unit of leaf area index used to derive the transpiration resistance was doubled for the purpose of the calculations in Table 11, which gave a value for the canopy of 0.24 sec./cm., which is six times greater than for the Corsican pine. Despite this large difference the calculated transpiration shown in Table 11 shows only a small reduction compared with the Corsican pine. This is a further demonstration of the insignificance of air resistance in determining transpiration rate when it is small compared with the stomatal resistance, (Rutter, 1968).

Stomatal Resistances

The measured interception losses in the two stands differ by less than 5%, so if, as unpublished water balances made by the Forestry Commission suggest, there is any difference in water use of the two stands it is probably due to different stomatal behaviour. A few observations may be made concerning possible differences.

The total leaf area index of the Corsican pine was 12.9, which indicates that the ratio of stomatal area in the Douglas fir and the Corsican pine are 12.9 : 7.8. Therefore, for the same canopy stomatal resistance the resistances per unit leaf area in the Douglas fir is expected to be about 60% of that of the Corsican pine. The resistances per unit leaf area were compared on a few occasions, with the diffusion porometer. The rough calibration of the instrument was based on the reading obtained with a wet filter paper substituted for a leaf. The resistance that this reading indicated was assumed to be that of the air in the chamber, which was calculated from the chamber dimensions. Resistances for leaves were obtained by comparison with this resistance.

The comparisons suggested three ways in which the canopies may differ. First, the stomata in the Corsican pine opened in early spring, when those in the Douglas fir remained closed. It was often possible, in April, to obtain readings in the Corsican pine but not in the Douglas fir. Secondly, in hot June sunshine measurements made at the top of the Douglas fir canopy, in direct sunshine, indicated a lower stomatal resistance per unit of leaf area than in the Corsican pine. The estimates of stomatal resistance were 1-3 sec./cm. in the Douglas fir, and 5-7 sec./cm. in the Corsican pine. Thirdly, measurements made in the lower canopy gave more variable results. In the Douglas fir, where the lower parts were in shade, the resistance rose to 10 sec./cm. or more. The Corsican pine showed a similar tendency, but less marked. Typical estimates were between 5 and 10 sec./cm. The values of stomatal resistance quoted are rough estimates only.

General Conclusions

Table 11 shows that by making some assumptions about the canopy characteristics, the relationship of the calculated interception losses agrees with the measured value. The assumptions involved when deriving the air resistance for transpiration do not have an important effect on the estimate of transpiration, because of the greater importance of the stomatal resistance in determining this. The assumption that half of the intercepted water evaporates at half of the calculated rate is arbitrary and, while it may be quantitatively inaccurate, observation suggests that this aspect must be considered to obtain a complete description of the evaporation.

A factor that has not been considered is the fall in the evaporation as the canopy dries, due to the decreased area of wet leaf present. In both stands the top of the canopy dries fastest, but the slower drying of the lower parts is more marked in the Douglas fir. In the Corsican pine the evaporation of intercepted water may be accompanied by transpiration as parts of the canopy dry, assuming transpiration begins when the leaf surface is dry. In the Douglas fir transpiration may not start until a considerable part of the canopy is dry because the surfaces that dry first do not contain stomata.

From these few considerations it is clear that it is not possible to treat the canopy as a single surface with certain measured characteristics to obtain a full account of evaporation. The contribution of the individual parts of the canopy must be considered. This point has also been made by Knoerr (1967) who investigated the radiation balance of individual leaves and related it to their position in the canopy. He found that the top of the canopy may act as a radiation sink, and the bottom as a sink for sensible heat. This was also found by Idso and Baker (1967). Baungartner (1967) drew attention to the effects of different microclimates in different canopies.

Waggoner and Reifsnyder (1968) were able to synthesise gradients of temperature and humidity within herbaceous canopies by assuming that the air resistance could be described as shown earlier in Fig. 1. It seems that this may adequately represent the Corsican pine canopy where there is no marked variability of leaf exposure at a particular level. In the Douglas fir it may be necessary to visualise each leaf surface resistance as two or more parallel resistances to take account of the position of leaves within a layer.

Denmead (1964) has investigated the evaporation pathway in a canopy of Pinus radiata in terms of apparent diffusivities at different heights in the canopy. He found a decline in the apparent diffusivity at lower levels in the canopy, which was greatest at the top, and that the evaporation sources within the canopy were distributed roughly in proportion to the distribution of the foliage. This was supported by Knoerr (1967) and is consistent with the rate at which the wet foliage dried within the Corsican pine canopy.

The important role of stomatal resistance in determining transpiration, and the importance of transpiration in the total water use, indicate that further work is needed in this field. The porometer is a useful tool for this purpose, despite its unsuitability as a recording instrument. Its use may also necessitate a more detailed analysis of the environment within the canopy.

Effects of Tree Morphology

The morphology of the trees affects the canopy saturation value, stemflow, air resistance and stomatal behaviour.

The leaf area index of the Douglas fir is nearly twice that of the Corsican pine, but the canopy saturation value is only 30% greater. The explanation of this may be that there are relatively few free leaf ends at which drops form in the Douglas fir, because most leaf tips touch adjacent leaves due to the hanging nature of the branches. In the Corsican pine the branches are more or less horizontal and adjacent leaves do not touch. This provides many sites for drop formation, which are larger than those observed in the Douglas fir. The drops are surprisingly stable even in moderate winds, and thus contribute to the estimate of canopy saturation value.

The effect of morphology on stemflow has been mentioned earlier. The dense nature of the Douglas fir canopy seems to shelter the trunks from the air above the canopy, so that the wet trunks dry slowly. This allows increased stemflow caused by the trunks remaining wet between storms. A shorter stand may show a further increase in the contribution of stemflow.

The role of morphology in determining air resistance is not clear. The variation with wind speed seems to be related to the shaking of the canopy in the Douglas fir. This may be visualised as increasing the ventilation of the internal leaves of the branches, and thus reducing the resistance rather than causing a change in the whole canopy.

At light to moderate wind speeds the air resistances of the canopies were similar, an unexpected result for such dissimilar canopies which appeared to be ventilated to different extents. The Douglas fir was a taller stand but on the evidence presented by Rutter (1968) this could be expected to give a difference of only 0.003 sec./cm. at 3m./sec.

The low resistance in the Douglas fir may be due to the higher leaf area index. The resistance per unit leaf area index is higher in the Douglas fir, which is consistent with poorer ventilation.

The final important aspect of morphology concerns the distribution within the canopy of the environmental conditions that govern the stomatal behaviour. The conditions in the Corsican pine appear to favour a uniform distribution of stomatal activity, while the shading of the lower parts of the canopy in the Douglas fir causes variable stomatal activity. Further work on this aspect is needed and should prove very rewarding.

ACKNOWLEDGEMENTS

I thank Professor A. J. Rutter for introducing me to Forest Hydrology; his advice and encouragement together with his ready help in the forest are gratefully acknowledged.

I am grateful to the Forestry Commission for the use of their sites at Yateley Heath Wood and for generous help and provision of data from the Research Branch at AliceHolt. Thanks are also due to the staff of the Forest Office for their co-operation and collection of daily rainfall data.

I thank Mr. W. Stiles for his help with the porometer and the Meteorological Office for access to the South Farnborough wind records; Mrs. M. Maby who typed the stencils and Mr. H. Devitt who did the photographic work; the staff and students of Imperial College for much help, advice, criticism and encouragement.

The patience and forbearance of my wife was outstanding.

This work was supported by a Research Grant from the Science Research Council for which grateful acknowledgement is made here.

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