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# Interception loss, throughfall and stemflow in a maritime pine stand.
## I. Variability of throughfall and stemflow beneath the pine canopy

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## ABSTRACT

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Patterns of spatial variability of throughfall and stemflow were determined in a maritime pine (*Pinus pinaster* Ait.) stand for two consecutive years. Data were obtained from 52 fixed rain gauges and 12 stemflow measuring devices located in a 50 m × 50 m plot at the centre of an 18-year-old stand. The pine trees had been sown in rows 4 m apart and had reached an average height of 12.6 m. The spatial distribution of stems had a negligible effect on the throughfall partitioning beneath the canopy. Variograms of throughfall computed for a sample of storms did not reveal any spatial autocorrelation of throughfall for the sampling design used. Differences in throughfall, in relation to the distance from the rows, were not consistently significant. In addition, the distance from the tree stem did not influence the amount of throughfall. The confidence interval on the amount of throughfall per storm was between 3 and 8%. The stemflow was highly variable between trees. The effect of individual trees on stemflow was significant but the amount of stemflow per tree was not related to tree size (i.e. height, trunk diameter, etc.). The cumulative sampling errors on stemflow and throughfall for a single storm created a confidence interval of between ±7 and ±51% on interception. This resulted mainly from the low interception rate and sampling error on throughfall.

## INTRODUCTION

Interception losses from various forest canopies under temperate climatic regimes have been reported for a range of species during the last three decades.

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Following Rutter's approach (Rutter et al., 1971), some applications of physical models for interception (Calder, 1977; Gash, 1979; Massman, 1983; Mulder, 1985; Dolman, 1987) have given rise to simulations of interception losses from hardwood (Pearce and Rowe, 1981; Dolman, 1987; Nizinski and Saugier, 1988) and coniferous stands (Rutter et al., 1975; Gash and Morton, 1978; Gash et al., 1980). Validation of the models used is generally carried out by comparing a set of simulated values with a set of observed values for interception loss, the latter being determined from the canopy water balance by the difference between gross rainfall and throughfall plus stemflow. However, few reports take into account the sampling error of the measured data such as, for example, the gross rainfall, throughfall, stemflow and subsequent error on interception. Nevertheless, significant sampling errors on stemflow and throughfall may be expected in most cases, as demonstrated by previous studies concerning the spatial variability of throughfall and stemflow (Aussenac, 1970; Kimmins, 1973; Ford and Deans, 1978; Lloyd and Marques, 1988). Throughfall is defined here as the amount of rainfall transmitted beneath the canopy, originating from either dripping leaves and branches or direct transmission from above the canopy. As the canopy structure has been shown to determine the spatial distribution of the sources of water input to the soil of a forest stand (Aussenac, 1970; Ford and Deans, 1978; Lloyd and Marques, 1988; Durocher, 1990, the sampling errors depend mainly on the canopy structure of the stand. For a leaf area index (LAI) of between four and ten, different spatial patterns of throughfall and stemflow have been reported for coniferous forest stands (Aussenac, 1970; Kimmins, 1973; Ford and Deans, 1978; Johnson, 1990). This problem has never been studied in the case of row-seeded stands of fast-growing species in southern Europe, which are characterized by the alignment of crowns in rows, a slight crown overlap and a low LAI value. In these stands, the interception rate is expected to be low, and the estimation of throughfall and stemflow must be considered before further modelling of rainfall partitioning and interception losses. Moreover, very few studies have been carried out to investigate the effects of storm size on the spatial variability of throughfall and stemflow. As the sensitivity of throughfall to canopy structure parameters is related to the amount of gross rainfall per storm (Gash, 1979), it would appear necessary to take the latter into account in the assessment of spatial throughfall variability.

This paper represents a preliminary study of interception loss and rainfall partitioning in a maritime pine stand. It reports the results of a study of the variability of throughfall and stemflow in a stand in southwest France and suggests some implications for the estimation of interception losses. Throughfall and stemflow were determined from June 1987 to December 1989 using a fixed rain gauge sampling design. The spatial autocorrelation of throughfall measurements beneath the canopy was assessed by computing the variograms of throughfall for a range of storms. The spatial distribution of throughfall in relation to stem location was estimated by variance and regression analyses. The variability of stemflow was also assessed. A subsequent study (Loustau et al., 1992) will examine an application of Gash's analytical model (1979) for the set of data obtained in this study.

## MATERIALS AND METHODS

### *The experimental site*

The Bray forest is located 20 km southwest of Bordeaux (0°46′W; 44°–42′N) at an altitude of approximately 60 m above sea-level. The mean annual temperature and mean annual rainfall in Bordeaux (1950–1980) were 12.5°C and 920 mm respectively. Prevailing winds were from the west, particularly during rainfall events. Pines were seeded in rows 4 m apart in 1970. In 1988 they had reached an average height of 12.6 m and had been thinned to a density of approximately 800 trees $ha^{-1}$. The mean height of the living crown base was 6 m. The LAI had been estimated to have a value of three (Diawara et al., 1991). The tree crowns were contiguous or slightly overlapping above the rows, leaving a path of approximately 1 m width between rows. The percentage of overlapping crown projected area was estimated visually to be 5–10% on a sample of 20 trees for the winter of 1988. As a result of wind action, tree trunks, and consequently crowns, were bent towards the east. Measurements of stemflow and throughfall were made in an area of 50 m × 50 m located within a 16 ha stand. The stand was surrounded by similar stands, giving a fetch of more than 1 km to the west and 0.6 km for other directions (Fig. 1).

### *Instrumental design*

#### *Rainfall*

The gross rainfall was assumed to be normally distributed over the stand and was estimated from the arithmetic mean of values obtained from 12 funnels similar to those used for throughfall measurements. The funnels were located in tracks of 15 m width bordering the stand (Fig. 1). The standard error on gross rainfall was less than 3%. Therefore, it was assumed that spatial variability of gross rainfall over the experimental area was negligible. This estimate of gross rainfall was not significantly different ($\alpha = 0.05$, $t$-test) from the values given by a rain gauge located at 2 m above the canopy, close to the centre of the stand.

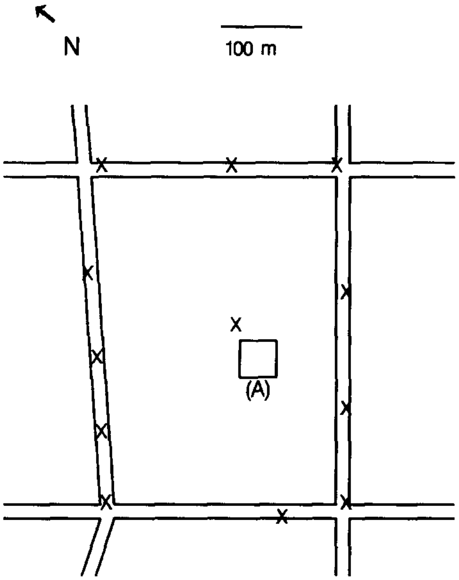

Fig. 1. Location of rain gauges ( × ) used for gross rainfall determination, at the boundaries of the stand. The 50 m × 50 m area used for throughfall measurements is represented by the square (A).

*Throughfall*

Throughfall was determined from mid-June 1987 to April 1989 with 52 sharp-edged rubber funnels (30 cm diameter). Each funnel was fitted into a 10 l polyethylene container and placed at a height of 80 cm above the soil surface. These gauges had been previously calibrated against a standard meteorological rain gauge. Measurements were recorded either after each storm or every 2 weeks. For the entire data set obtained, single storms corresponded to 33 measurements whereas two or more storms combined corresponded to 38 measurements. The former were used for variograms, variance and regression analyses of throughfall and stemflow. The entire data set was used only for grouping cumulative throughfall throughout the season and for further modelling procedures (Loustau et al., 1992).

*Stemflow*

Stemflow was measured simultaneously with throughfall. A wired rubber hose, 3 cm in diameter, was used to make spiral-type stemflow gauges, 1.50 m in length. The troughs were pressed against the stem with an adjustable stretcher and tightened closely to the trunk with a rubber seal. Each channel formed two loops around a stem at an angle of approximately 45° to the horizontal and was connected to an 80 l plastic container.

## *Sampling design and data analysis*

### *Throughfall*

To investigate the effect of tree distribution within rows on the spatial variability of throughfall, throughfall collectors were partitioned into four zones as shown in Fig. 2. In each zone, 12 funnels were randomly located at a fixed position, except for the row stratum, called 'R', where 16 gauges were placed under the assumption that variability was higher close to the trees. To assess the effects of storm features on spatial variability of throughfall, collectors were kept at the same position throughout the experiment.

Data analysis was performed in two sets. The first analysed the spatial dependence of the throughfall measurements by computing the throughfall semi-variograms (calculated as half the mean squared difference of throughfall of paired sample measurements) for seven selected storms. When the spatial independence of the measurements was demonstrated, the second analysis was carried out. This involved an analysis of variance and comparison of means to evaluate the distribution pattern of throughfall among the four zones. Finally, according to the distribution of throughfall, the mean throughfall and its confidence interval were estimated for each storm.

### *Stemflow*

Stemflow was measured on 12 trees which, because of their dimensions (diameter at breast height, height, diameter under the lowest living whorl), were considered a representative sample of the whole stand (see Table 4 below). As storms could not be considered as independent replicates for stemflow, the individual tree effects on stemflow were analysed by an analysis of variance based on rank (procedure ANOVA, Statistical Analysis Systems Institute (SAS), 1987). In addition, interaction with the amount of gross rainfall per storm was examined. This interaction between the effects of trees and effect of gross rainfall was tested by analysing continuous-by-class effects with the general linear model procedure (SAS, 1987). The relationship between stemflow and tree dimensions, i.e. diameter at 1.3 m height, total height and diameter under the last living whorl, was analysed by multifactorial regressional analysis. Assuming a normal distribution of stemflow in the stand, the mean stemflow and its confidence interval ($\alpha = 0.05$) were estimated from a $t$-test for each storm.

### *Estimation of interception*

The interception loss for each storm was estimated by the difference between gross rainfall and the sum of throughfall and stemflow. Assuming the

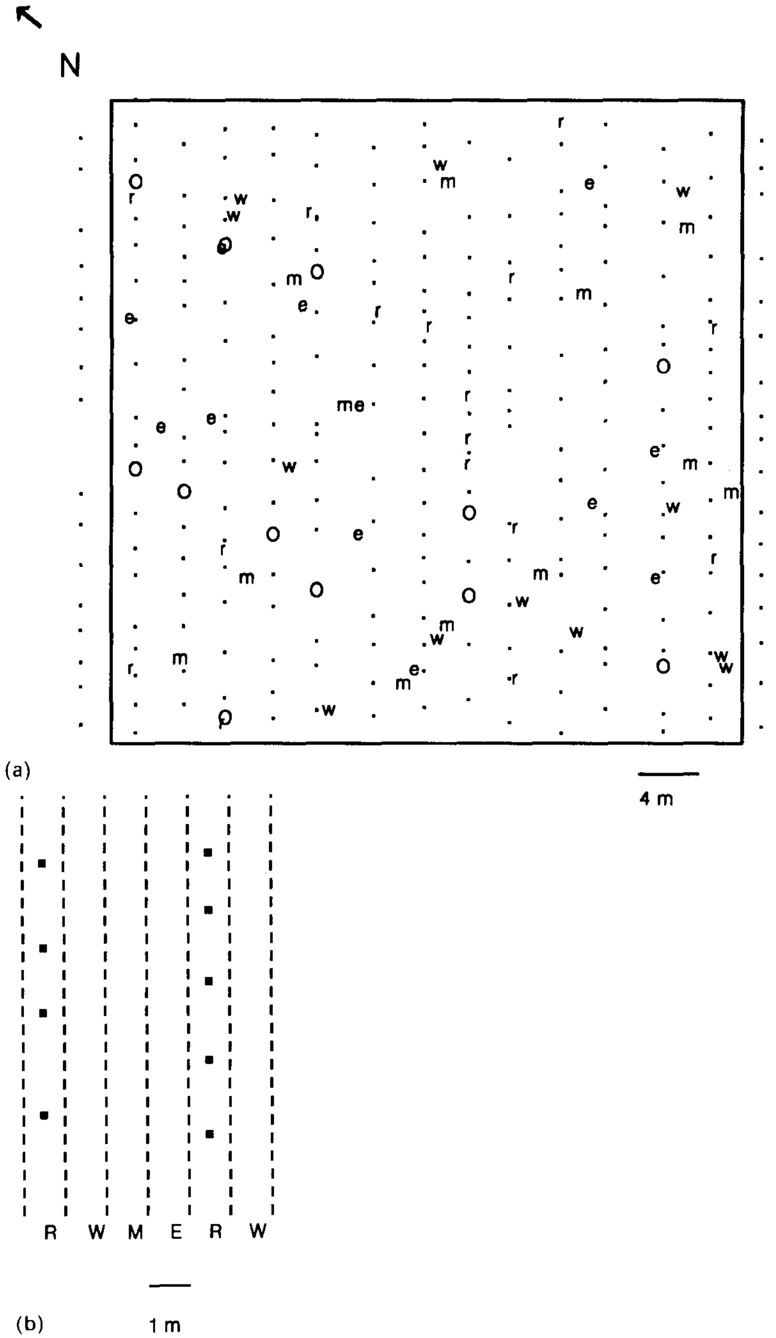

Fig. 2. (a) Locations of 52 rain gauges (r, m, e, w according to their stratum) and the 12 stemflow gauges (O), the former being used for throughfall estimation. ●, Tree stems. (b) Delimitations of the four zones within the experimental area: R: rows; W and E: west and east sides of the path, respectively; M: middle of the path. ■, Tree stems.

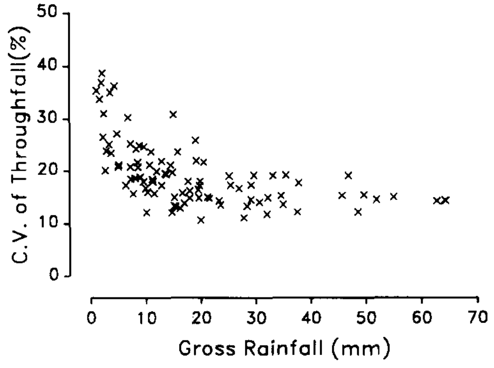

Fig. 3. Relationship between the throughfall coefficient of variation and rainfall for the entire data set.

independence of determinations of throughfall and stemflow, the standard error on the estimate of interception loss was computed as the root sum of the variances of throughfall and stemflow. The confidence intervals on interception estimates ($\alpha = 0.05$) were then computed, assuming that interception was estimated from a random sample with more than 30 degrees of freedom.

The statistical analyses were performed using various SAS Institute procedures (UNIVARIATE, GLM, REG and NPAR1WAY) (SAS, 1987), available on micro-PC, and Geo-EAS (EMS Laboratory, Office of Research and Development, 1988) software for variograms.

## RESULTS

### *Variability of throughfall*

The spatial variability of throughfall was higher for light storms, and decreased asymptotically as gross rainfall increased (Fig. 3). Each of the seven computed variograms had a horizontal linear shape, as shown in Fig. 4 for a range of gross rainfall values. The shape of the variograms did not reveal any structure of spatial autocorrelation between the measurements of throughfall, from the global variograms shown here, or from any single direction (not shown). This means that the variance of throughfall did not show consistent variation as the distance between two points of throughfall measurements was increased. Therefore, the measurements of throughfall for each collector were assumed to be independent of each other. On the assumption that the seven selected storms were representative of the 33 single storm measurements, this assumption was applied to the entire data set.

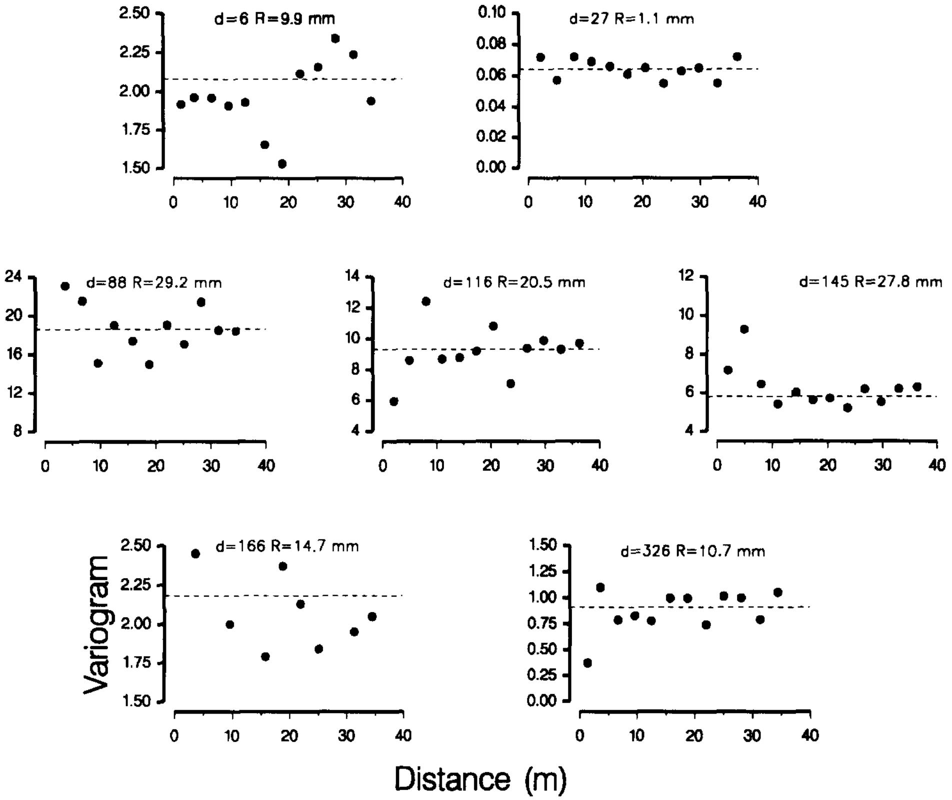

Fig. 4. Global variograms of throughfall for seven selected storms. Julian day (d) and gross rainfall (R) are indicated in the upper part of each graph. The first two points for each variogram were computed from less than 30 pairs of values and therefore should not be considered. Total variance of throughfall is represented by a dashed horizontal line.

For each of the 33 storms, an analysis of variance (ANOVA) was performed to examine the effect of zones on the variability of throughfall. Significant differences in throughfall were found for some storms but no consistent pattern of throughfall distribution between zones was revealed. The throughfall over the path (zone M) was highest for small storms and lowest for large storms, but this difference was not significant (Table 1). The resulting cumulative differences were not significant for any season (Table 2). Furthermore, a non-normal distribution (Shapiro and Wilk's test, $\alpha = 0.05$) was significant only for four out of 32 storms. Therefore, even when significant differences between zones were found, the row effect was not sufficient to create a significant non-normal distribution. A linear regressional analysis of throughfall against distance to the nearest stem was performed for the seven selected storms. No relationship was found between

TABLE 1

Spatial partitioning of throughfall among four zones for 33 single storm events

| Class of storms | No. of events | Mean throughfall (mm) | | | |
|---|---|---|---|---|---|
| | | W | M | E | R |
| < 5 mm | 7 | 1.69 | 1.92 | 1.88 | 1.62 |
| 5–15 mm | 11 | 8.69 | 8.34 | 8.70 | 8.38 |
| > 15 mm | 15 | 21.4 | 20.4 | 21.9 | 21.6 |

W, E: western and eastern sides of row, R: row, M: middle of the path. No significant differences between zones were found.

throughfall and distance to the nearest tree stem ($r^2 = 0.04$, dof = 51). The arithmetic mean of the 52 throughfall measurements was within 78 and 86% of the gross rainfall throughout the experiment. The mean confidence intervals of estimated throughfall were computed for the events where a normal distribution of throughfall could be assumed. These intervals lay within ±3 and ±8% of the mean, 21 out of 28 being less than ±5% (Table 3).

### *Variability of stemflow*

The stemflow coefficient of variation has a tendency to decrease asymptotically with increase in gross rainfall (Fig. 5), as observed for throughfall. Tree size characteristics of trees, mean stemflow per storm and rank for stemflow are given in Table 4. Large differences were revealed in stemflow between

TABLE 2

Spatial partitioning of throughfall among four zones for the experimental period: cumulative seasonal totals per zone (all events)

| Year | Season | Total rainfall (mm) | Cumulative throughfall (mm) | | | |
|---|---|---|---|---|---|---|
| | | | W | M | E | R |
| 1987 | Summer | 267 | 222 | 208 | 213 | 213 |
| 1988 | Winter | 623 | 500 | 478 | 527 | 520 |
| | Summer | 425 | 342 | 335 | 315 | 325 |
| 1989 | Winter | 245 | 192 | 181 | 197 | 192 |
| | Summer | 416 | 353 | 333 | 340 | 337 |

W, E: western and eastern sides of row, R: row, M: middle of the path. No significant differences between zones were found.

TABLE 3

Estimates of gross rainfall, throughfall and stemflow (mm) and their confidence intervals ($\alpha = 0.05$) for 32 single storms, (the confidence intervals are given as percentages of the estimate)

| Year | Date | Rainfall (mm) | Throughfall (mm) | Stemflow (mm) |
|---|---|---|---|---|
| 1987 | 177[a] | 0.3 | 0.1 | 0 |
| | 245 | 5.0 | 3.8 ± 4.8 | 0.05 ± 35 |
| | 250 | 2.0 | 1 ± 6.7 | 0 |
| | 285 | 35.0 | 28.4 ± 3.1 | 0.76 ± 24 |
| | 303 | 17.0 | 15.2 ± 4.1 | 0.28 ± 28 |
| | 314 | 23.3 | 20.6 ± 4.2 | 0.83 ± 27 |
| | 316 | 11.5 | 9.6 ± 4.4 | 0.56 ± 24 |
| | 321 | 29.1 | 24.8 ± 4.2 | 1.70 ± 18 |
| | 327 | 16.2 | 14.6 ± 3.9 | 0.50 ± 22 |
| 1988 | 6 | 9.9 | 8.3 ± 4.8 | 0.48 ± 25 |
| | 15 | 8.0 | 6.6 ± 5.3 | 0.19 ± 29 |
| | 18 | 4.7 | 3.2 ± 7.0 | 0.08 ± 25 |
| | 26 | 10.9 | 7.2 ± 4.9 | 0.18 ± 27 |
| | 27[a] | 1.1 | 0.7 | 0.0 |
| | 29 | 23.6 | 20.2 ± 3.8 | 1.57 ± 25 |
| | 33 | 14.5 | 10.4 ± 5.0 | 0.63 ± 21 |
| | 34 | 1.7 | 1 ± 8.0 | 0.0 |
| | 35[a] | 3.3 | 2.4 | 0.0 |
| | 40 | 8.6 | 6.4 ± 5.4 | 0.80 ± 20 |
| | 41 | 11.2 | 8.6 ± 4.7 | 0.88 ± 18 |
| 1988 | 88 | 29.2 | 24.2 ± 4.9 | 20.9 ± 24 |
| | 99 | 32.1 | 27.5 ± 3.1 | 0.55 ± 39 |
| | 116 | 20.5 | 15.1 ± 5.6 | 0.47 ± 23 |
| | 127 | 11.9 | 8.5 ± 4.3 | 0.11 ± 50 |
| | 145 | 27.8 | 23.7 ± 2.8 | 0.95 ± 25 |
| | 148 | 8.8 | 6.5 ± 6.7 | 0.03 ± 65 |
| | 153 | 15.1 | 10.8 ± 5.7 | 0.12 ± 55 |
| | 166 | 14.7 | 12.6 ± 3.3 | 0.35 ± 33 |
| | 169 | 19.5 | 5.8 ± 4.4 | 0.41 ± 28 |
| | 326[a] | 10.7 | 7 | 0.04 ± 44 |
| 1989 | 66 | 19.8 | 15.6 ± 4.5 | 0.83 ± 18 |
| | 104 | 62.7 | 52.6 ± 3.9 | 2.63 ± 16 |

[a] Storms where the throughfall value distribution deviated significantly from the normal distribution (Shapiro and Wilk's test, $\alpha = 0.05$).

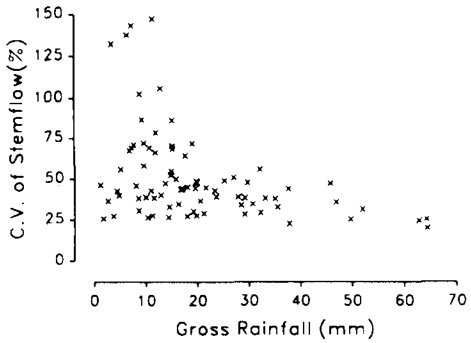

Fig. 5. Relationship between the stemflow coefficient of variation and rainfall for the entire data set.

individual trees. As no interaction between the effect of individual trees and rainfall was found for the 33 single storms examined, an ANOVA was also performed on the entire data set which included composite events. The results of the ANOVA for this data set were not significantly different from the results of the ANOVA for the single storms data set. The individual tree effect on the ranking for stemflow was significant ($\alpha = 0.05$), and interaction with rainfall remained non-significant (Table 5). Therefore, individual features of

TABLE 4

Size characteristics, mean stemflow and rank for stemflow of trees sampled in 1987–1989 (all events)

| Number | Height (m) | DBH (m) | Diameter under last living branch (m) | Mean stemflow (l) | Rank |
|---|---|---|---|---|---|
| 1 | 11.4 | 0.19 | 0.12 | 7.3 | 6 bc |
| 2 | 12.3 | 0.19 | 0.13 | 9.1 | 2 b |
| 3 | 12.3 | 0.24 | 0.15 | 7.1 | 7 bc |
| 4 | 11.4 | 0.20 | 0.14 | 8.4 | 3 bc |
| 5 | 11.6 | 0.20 | 0.09 | 7.6 | 5 bc |
| 6 | 11.6 | 0.19 | 0.12 | 7.9 | 4 bc |
| 7 | 12.8 | 0.19 | 0.12 | 6.4 | 8 bc |
| 8 | 11.2 | 0.17 | 0.09 | 6.1 | 9 bc |
| 9 | 11.0 | 0.17 | 0.10 | 5.9 | 10 c |
| 10 | 10.5 | 0.13 | 0.07 | 10.7 | 1 a |
| 11 | 11.3 | 0.18 | 0.11 | 5.5 | 11 c |
| 12 | 10.7 | 0.16 | 0.10 | 5.2 | 12 c |

DBH, diameter at breast height.

Ranks followed by the same letter are not significantly different ($\alpha = 0.05$) (Newman–Keul's test).

TABLE 5

Two-way analysis of variance for testing the effect of trees, gross rainfall and interaction on the rank for stemflow

| Source of variation | Degrees of freedom | Sum of squares | *F* value |
|---|---|---|---|
| Trees | 11 | 802 686 | 1.9* |
| Gross rainfall | 1 | 53 754 358 | 1398** |
| Interaction | 11 | 31 035 | 0.18 |

* Significant at the 5% level.
** Significant at the 1% level.

trees appeared to play a role in determining the amount of stemflow. However, no significant relationship could be found between the stemflow of a tree and its size characteristics. The high variability of stemflow resulted in large confidence intervals, e.g. 16–65% on the estimate of the mean stemflow (Table 3).

### *Estimation of interception*

No relationship was revealed between the confidence interval on the interception estimate and the amount of gross rainfall per storm (Fig. 6). The confidence intervals on interception loss per storm were on average ±23% of the estimate. The errors on stemflow and throughfall accounted for approximately 5% and 95% of the total error respectively (Table 6).

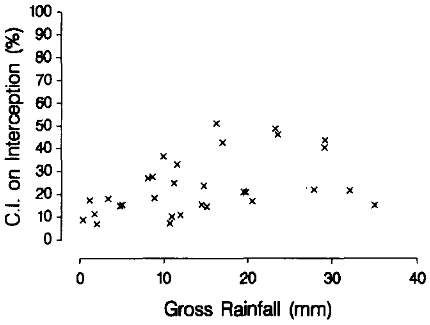

Fig. 6. Relationship between the confidence interval (one side) on interception (as percentage of the mean) and the amount of gross rainfall for 33 single storms.

TABLE 6

Estimated interception, confidence interval (α = 0.05) and error partitioning between throughfall and stemflow (as percentage of the variance of interception)

| Year | Date | Rainfall | Interception (mm) and confidence interval (%) | Error contribution (%) | |
|---|---|---|---|---|---|
| | | | | Throughfall | Stemflow |
| 1987 | 177[a] | 0.32 | 0.26 | | |
| | 245 | 4.99 | 1.16 ± 16 | 100 | 0 |
| | 250 | 1.99 | 0.96 ± 7 | 100 | 0 |
| | 285 | 35 | 5.86 ± 15 | 96 | 4 |
| | 303 | 17 | 1.46 ± 43 | 98 | 2 |
| | 314 | 23.3 | 1.81 ± 48 | 94 | 6 |
| | 316 | 11.5 | 1.32 ± 33 | 92 | 8 |
| | 321 | 29.1 | 2.59 ± 40 | 93 | 7 |
| | 327 | 16.2 | 1.10 ± 51 | 97 | 3 |
| 1988 | 6 | 9.9 | 1.11 ± 36 | 93 | 7 |
| | 15 | 8.0 | 1.28 ± 26 | 98 | 2 |
| | 18 | 4.7 | 1.48 ± 15 | 99 | 1 |
| | 26 | 10.9 | 3.46 ± 10 | 98 | 2 |
| | 27[a] | 1.1 | 0.39 | 100 | 0 |
| | 29 | 23.6 | 1.79 ± 46 | 82 | 18 |
| | 33 | 14.5 | 3.42 ± 15 | 95 | 19 |
| | 34 | 1.7 | 0.68 ± 11 | 99 | 1 |
| | 35[a] | 3.3 | 0.89 | | |
| | 40 | 8.6 | 1.34 ± 27 | 86 | 14 |
| | 41 | 11.2 | 1.70 ± 24 | 89 | 11 |
| | 88 | 29.2 | 2.87 ± 43 | 87 | 13 |
| | 99 | 32.1 | 3.98 ± 22 | 95 | 5 |
| | 116 | 20.5 | 4.94 ± 17 | 99 | 1 |
| | 127 | 11.9 | 3.31 ± 11 | 98 | 2 |
| | 145 | 27.8 | 3.12 ± 22 | 90 | 10 |
| | 148 | 8.8 | 2.33 ± 18 | 99 | 1 |
| | 153 | 15.1 | 4.15 ± 15 | 99 | 1 |
| | 166 | 14.7 | 1.74 ± 24 | 94 | 6 |
| | 169 | 19.5 | 3.27 ± 21 | 98 | 2 |
| | 326[a] | 10.7 | 3.6 | | |
| 1989 | 66 | 19.8 | 3.34 ± 21 | 96 | 4 |
| | 104 | 62.7 | 7.54 ± 27 | 96 | 4 |

[a] Storms where the throughfall value distribution deviated significantly from the normal distribution (Shapiro and Wilk's test, α = 0.05). For these storms, error on throughfall and on interception loss were not estimated.

## DISCUSSION

### *Throughfall variability*

Our results demonstrate the spatial independence of throughfall measurements for the sampling scheme used, although the actual spatial structure of throughfall cannot be inferred. The spatial independence of throughfall measurements allows the measured values of throughfall to be considered as a random sample beneath the canopy. This has two consequences. First, as far as normality of the throughfall distribution values could be tested, the arithmetic mean of the values of throughfall given by the rain gauge network may be considered as the best estimate of the throughfall for the experimental plot. For our data set, the confidence interval on the mean throughfall was between ±3% and ±10% (Table 3). This sampling error is acceptably low and in the range reported by Kimmins (1973) for a similar sample size. Second, this independence satisfies one of the prerequisites of variance or regressional analysis and thus validates further statistical analyses.

As observed previously for various species (Aussenac, 1970; Kimmins, 1973), the throughfall coefficient of variation decreases asymptotically with increase in gross rainfall (Fig. 3). The amount of throughfall in a given location of a coniferous stand is related to the local value of various canopy structure parameters (Aussenac, 1970; Ford and Deans, 1978; Johnson, 1990). Depending on the structure of the canopy, different patterns of spatial variability of throughfall are thus observed under coniferous forest canopies. In a sitka spruce plantation, Ford and Deans (1978) found the highest values of throughfall between trees within the same row and close to the tree stems, for storms of 20–40 mm rainfall. Johnson (1990) found a positive correlation between the amount of throughfall and distance from the stem in sitka spruce stands. Aussenac (1970) reported similar results for different canopies.

The throughfall beneath a plant canopy may be partitioned into two components: the free throughfall and the throughfall sensu stricto, originating respectively from direct transmission of rainfall to the ground and water dripping from the canopy. For small storms, the free throughfall is the most important component (Rutter et al., 1971; Gash, 1979), as the throughfall originates mostly from rain falling to the ground without striking any canopy element. Therefore, the spatial variability of throughfall should be related to the spatial variability of the free throughfall coefficient for small storms. When gross rainfall increases, dripping from the canopy becomes increasingly important (Rutter et al., 1971; Gash, 1979; Calder and Wright, 1986) and so therefore the spatial variability of throughfall should become more sensitive to the spatial variability of the distribution of canopy drip points and storage capacity. For the heaviest storms, once canopy saturation is reached, each drip point becomes fully efficient and distribution of throughfall is the result of only the spatial distribution of drip points.

The spatial variability pattern of throughfall shown under our experimental conditions may be considered consistent with the following hypothesis.

(1) For small storms, the higher variability of throughfall (Fig. 2), as well as the slight differences in throughfall between strata (Table 1), may be explained by the spatial variation of the degree of canopy opening. The interception analysis and simulation of these data with Gash's analytical model (1979) show that throughfall is more sensitive to the free throughfall coefficient for small storms (Loustau et al., 1992). This analysis was performed on a per stand basis but conclusions may be extended to single point measurements of throughfall. Unfortunately, no point measurements of the free throughfall coefficient and the canopy storage capacity are available for this stand. However, the distribution pattern of throughfall for small storms appears to be consistent with this hypothesis: the most watered stratum for small storms that corresponding to the path (E and M). Similarly P. Courcoux (unpublished results, 1982) found a high correlation between measured values of throughfall and the degree of canopy closure beneath a maritime pine canopy. Aussenac (1970) also showed this relationship for various species.

(2) For larger storms, no relationship between throughfall distribution and stem location or strata delimitation was found. Hence, the distribution of stems in arrays would not have resulted in a differential distribution of the dripping points and canopy storage capacity in the stand. This conclusion may also be confirmed by the normal distribution of throughfall for most storms.

The spatial distribution pattern of throughfall therefore appeared to be fairly uniform. Noticeable variations occurred only for the smallest storms, and for this reason had little effect on the distribution of the water input from throughfall within the stand (Table 2). However, we are not at present able to confirm the hypothesis of a uniform distribution of throughfall in the experimental area because the pattern revealed may also result from an under-sampling of throughfall. As compared with the 52 measurement points used here, Ford and Deans (1978) used 104 measurement points for assessment of the spatial variability of throughfall beneath a dense sitka spruce canopy and were able to detect significant variations of throughfall related to the distance from the nearest tree stem for heavy storms.

### *Stemflow*

Crockford and Richardson (1990) reported the main factors influencing the stemflow for a given tree. Only a few of these factors are related to tree size. As the effect of individual trees on the rank for stemflow was significant (Table 4), our results suggest that size-independent factors, e.g. tree bending, branching angle and the number of flow path obstructions, may be significant. However, the stemflow was different only for four trees of the sample, and individual relationships between gross rainfall and amount of stemflow were not significantly different. Consequently, the size-independent factors influenced the stemflow production of trees only slightly. For other coniferous species, Aussenac (1970) and Ford and Deans (1978) also found that tree size parameters did not explain adequately the stemflow variations between stems. As far as the stemflow variability could be inferred from our data, the reduction of the confidence interval of estimated mean stemflow below ± 10% would require an increase in sample size of between four- and six-fold, which would result in an unmanageable sample size of more than 40 stems.

### *Implications for estimating the interception loss*

As the purpose of the present experiment was to investigate the effect of the size of storms on the variability of throughfall stemflow and interception, the gauges were not relocated throughout the measurement period. Despite an acceptable accuracy in the estimate of throughfall, the relative error created on the interception loss estimate per storm was high (Fig. 6). This is mainly due to the low interception rate and sampling errors on throughfall (Table 6), which demonstrates that the throughfall was under-sampled in the present experiment. To reduce the confidence interval on the interception estimate to below 10%, a six-fold increase in the throughfall sampling rate is required. Two alternatives are possible. The most usual method consists of periodically relocating the gauges beneath the canopy. This improves the accuracy on cumulative estimates of throughfall and interception but does not increase the accuracy of determinations based on a single storm. This method should be useful for long-term monitoring of throughfall but has little to offer for assessment of either the temporal or spatial variability of throughfall. It may be inferred from the present results that a confidence interval on interception below 10% may be expected after six consecutive relocations of the 52 gauges, giving a total number of 312 points. The alternative is to increase the sampling rate of throughfall using appropriate gauges, such as plastic film or troughs. Plastic film gauges have been shown to be of limited suitability for long-term surveys, but they offer an adequate method for accurate determinations of throughfall on a single storm basis (Teklehaimanot et al., 1991). Troughs would probably be of value for increasing the accuracy of throughfall measurements under sparse canopies in a manageable way, both for determinations based on a single storm and for long-term experiments.

## CONCLUSIONS

This experiment demonstrated that the spatial distribution of throughfall beneath a maritime pine canopy was insensitive to the spatial distribution of stems. The passage of rainfall through the canopy did not induce a significant departure from a normal spatial distribution. Such a distribution pattern might be attributed at present to the low LAI and to the distribution of foliage within the three crowns, but further investigations are required to describe the spatial variability of throughfall with a higher resolution and to test the uniform distribution hypothesis under consideration. The stemflow per tree was highly variable and was not related to tree size. The low interception rate resulted in large relative errors, ±23% on average, on the interception estimate per storm. The sampling error on throughfall was the major error component of the interception estimate. Accurate determination of interception loss for a given storm from canopy water balance would consequently require a larger throughfall sampling rate.

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## REFERENCES

Aussenac, G., 1970. Action du couvert forestier sur la distribution au sol des precipitations. Ann. Sci. For., 27: 383–399.

Calder, I.R., 1977. A model of transpiration and interception loss from a spruce forest in Plynlimon, central Wales. J. Hydrol., 33: 247–265.

Calder, I.R. and Wright, I.R., 1986. Gamma ray attenuation studies of interception from Sitka spruce; some evidence for an additional transport mechanism. Water Resour. Res., 22: 409–417.

Crockford, R.H. and Richardson, D.P., 1990. Partitioning of rainfall in a eucalyptus forest and pine plantation in southeastern Australia: II stemflow and factors affecting stemflow in a dry sclerophyll eucalypt forest and a *Pinus radiata* plantation. Hydrol. Processes, 4: 145–155.

Diawara, A., Loustau, D. and Berbigier, P., 1991. Comparison of two methods for estimating the evaporation of a *Pinus pinaster* (Ait.) stand: Sap flow and energy balance with sensible heat flux measurements by an eddy covariance method. Agric. For. Meteorol., 54: 49–66.

Dolman, A.J., 1987. Summer and Winter rainfall interception in an oak forest. Predictions with an analytical and a numerical simulation model. J. Hydrol., 90: 1–9.

Durocher, M.G., 1990. Monitoring spatial variation of forest interception. Hydrol. Processes, 4: 215–229.

EMS Laboratory, Office of Research and Development, 1988. Geo-EAS (Geostatistical Environment Assessment Software). US Environmental Protection Agency, Las Vegas, NV, 89 193-3478.

Ford, E.D. and Deans, J.D., 1978. The effects of canopy structure on stemflow, throughfall and interception loss in a young sitka spruce plantation. J. App. Ecol., 15: 905–917.

Gash, J.H.C., 1979. An analytical model of rainfall interception by forests. Q. J. R. Meteorol. Soc., 105: 43–45.

Gash, J.H.C. and Morton, A.J., 1978. An application of Rutter's model to the estimation of the interception loss from Thetford Forest. J. Hydrol., 38: 49–58.

Gash, J.H.C., Wright, I.R. and Lloyd, C.R., 1980. Comparative estimates of interception loss from three coniferous forests in Great Britain. J. Hydrol., 48: 89–105.

Johnson, R.C., 1990. The interception, throughfall and stemflow in a forest in highland Scotland and the comparison with other upland forests in the U.K. J. Hydrol., 118: 281–287.

Kimmins, J.P., 1973. Some statistical aspects of sampling throughfall precipitation in nutrient cycling studies in British Columbian coastal forests. Ecology, 54: 1008–1019.

Lloyd, C.R. and de O. Marques, F.A., 1988. Spatial variability of throughfall and stemflow measurements in Amazonian forest. Agric. For. Meteorol., 42: 63–73.

Loustau, D., Berbigier, P. and Granier, A., 1992. Interception loss, throughfall and stemflow in a maritime pine stand. II. An application of Gash's analytical model of interception. J. Hydrol. in press.

Massman, W.J., 1983. The derivation and validation of a new model for the interception of rainfall by forest. Agric. Meteorol., 28: 261–286.

Mulder, J.P.M., 1985. Simulating interception loss using standard meteorological data. In: B.A. Hutchison and B.B. Hicks (Editors) The Forest–Atmosphere Interaction. D. Reidel, Dordrecht, pp. 177–197.

Nizinski, J. and Saugier, B., 1988. Mesures et modèlisation de l'interception nette dans une futaie de chênes. Acta Oecol. Oecol. Plant., 9: 311–329.

Pearce, A.J. and Rowe, L.K. 1981. Rainfall interception in a multi-storied, evergreen mixed forest: estimates using Gash's analytical model. J. Hydrol., 49: 341–353.

Rutter, A.J., Kershaw, K.A., Robins, P.C. and Morton, A.J., 1971. A predictive model of rainfall interception in forests. I. Derivation of the model from observations in a plantation of Corsican Pine. Agric. Meteorol., 9: 367–384.

Rutter, A.J., Morton, A.J. and Robins, P.C., 1975. A predictive model of rainfall interception by forests, 2. Generalization of the model and comparison with observations in some coniferous and hardwood stands. J. Appl. Ecol., 12: 367–381.

Statistical Analysis Systems Institute, 1987. SAS/STAT Software. SAS Institute, Cary, NC.

Teklehaimanot, Z., Jarvis, P.G. and Ledger, D.C., 1991. Rainfall interception and boundary layer conductance in relation to tree spacing. J. Hydrol., 123: 261–278.