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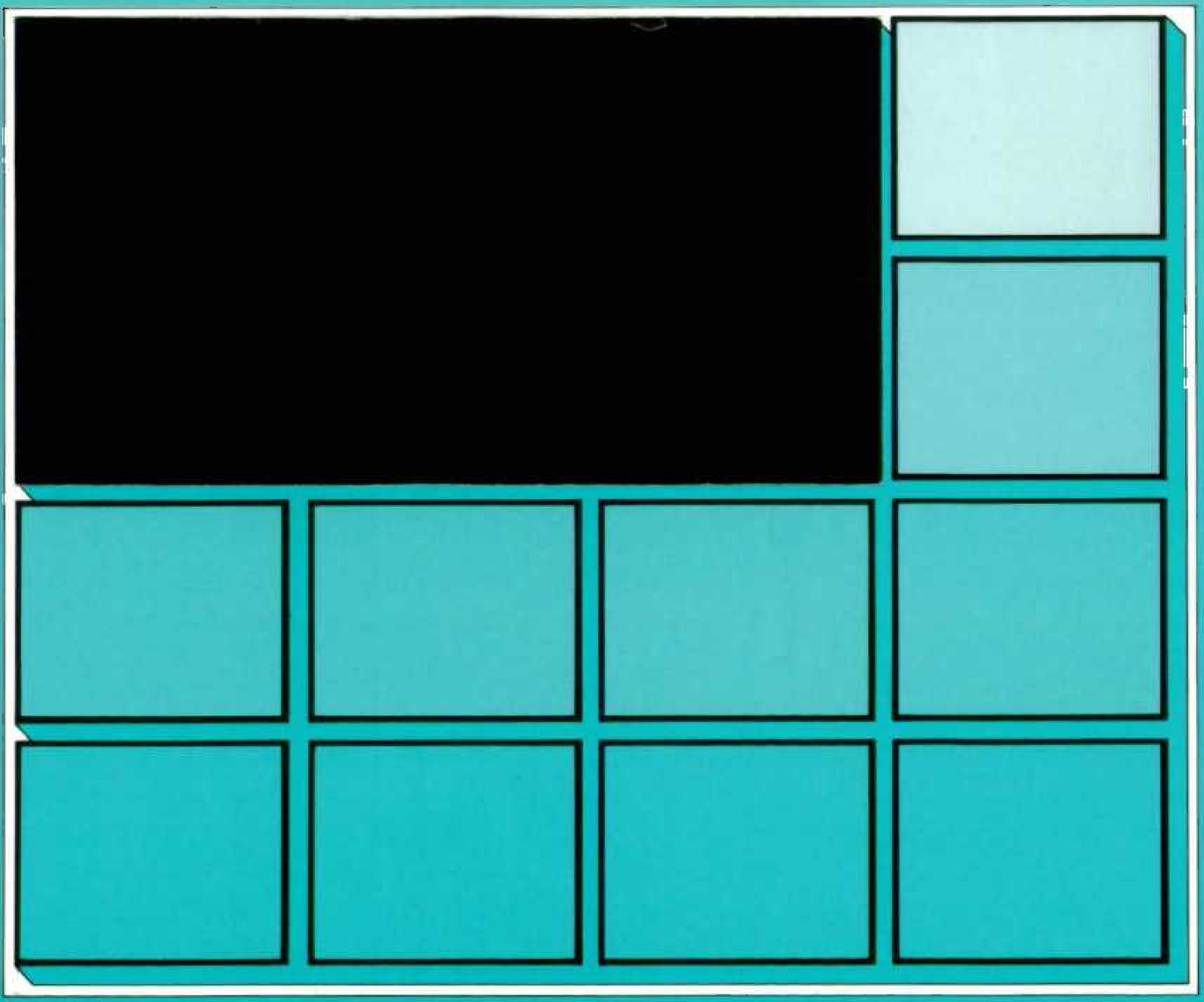

The Hydrological Impacts of Broadleaf Woodland in Lowland Britain

INSTITUTE OF HYDROLOGY REPORT
TO THE
NATIONAL RIVERS AUTHORITY

Report No. 2, October 1990

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Contents

1. Executive summary

In the past year data collection has continued at the Black Wood site. The storms of January and February 1990 caused major damage. Most of the damage was restored promptly. Only the 'edge effect' experiment proved irrepairable and has been discontinued.

In April and May 1990 a second experiment was set up in Northamptonshire. The objective of this site is to provide additional information on Ash plantations in a range of environments. The data collection from this site has gone smoothly through the summer of 1990.

Like 1989 the summer of 1990 has been extremely dry which has provided a second good data set on the effect of drought on forest evaporation. Unfortunately the interception experiments have suffered and we are still short of observations describing the interception of a leafed canopy.

An analysis of the first year's hydrological observations of interception, transpiration and soil moisture and chemical assays of stemflow, throughfall and rainfall has been made. A good start has been made on the development of a water use model, and a clear picture of chemical fluxes through the forest is emerging. The main conclusions are:

The interception ratio was 12% for the leafed period and 11% for the unleafed period at Black Wood for 1989.

The plant physiological measurements indicate a transpiration loss (June to September 1989) of 299.4 mm and 308.4 mm for the ash and beech respectively.

The transpiration is below the Penman potential rate, this is particularly marked at high rates.

The soil moisture measurements show transpiration rates within 10% of those estimated from the plant physiology. There is 20% more soil water depletion beneath the ash than the beech.

Chemical gradients are observed close to the forest edge (<50m) for sea salt components, such as sodium, magnesium and chloride, which are supplied directly from the atmosphere.

There is only a very small chemical gradient near the forest edge for components, such as potassium and nitrogen, which are cycled through the vegetation.

The stemflow plus throughfall chemical fluxes are higher than the rainfall counterparts. In components which are cycled, this difference can be up to 300%. For components which are not cycled much lower values are observed (away from the forest edge).

There is no evidence for changes in chemical fluxes following the extensive storm damage in February 1990.

1. Atmospheric ammonia levels are typically 2 to 5 ppm although during February and March 1990 average values were about 21 ppb. Atmospheric nitrogen oxide levels varied between 3 and 25 ppb: maximum values occured in November 1989 and minimum values occured in January 1990.

2. Background

It is expected that there will be an increase in hardwood plantations in the next decade as a response to pressure to reduce agricultural surpluses. Work by the Institute of Hydrology in the north and west of the UK has shown that coniferous afforestation can lead to large decreases in water yield and substantial changes in the runoff chemistry. While it is likely that the water use from deciduous trees is larger than agricultural crops and the scavenging of pollutants is greater, very little is known about these processes. In upland Britain the difference between rainfall and evaporation is large while in lowland Britain this difference is small, consequently the water available for river flow and aquifer recharge is very sensitive to small changes in evaporation.

The future nature of plantation in Britain will be deciduous hardwoods in small blocks scattered in a mosaic over the countryside. This poses a number of scientific questions: firstly edge effects may be important, leading to an enhancement of the evaporation from and the transfer of atmospheric pollutants to the canopy. Secondly the evaporation from the ground vegetation will be higher than in a coniferous forest, especially in the spring. Thirdly in lowland Britain the trees are likely to be water stressed in the summer months.

The project 'The Hydrological Impacts of Hardwood Plantation in Lowland Britain' was started in September 1988 to address the problems outlined above. The project's specific objectives are:

a) to assess the hydrological effects of small-scale hardwood plantations in lowland Britain by studying the evaporative processes (interception and transpiration);

b) to assess the hydrochemical effects both temporally and spatially by determining the chemistry associated with rainfall, throughfall and stemflow.

The main products of the research will be: 1) to provide a proven *hydrological model to calculate the effects of afforestation in all regions of* lowland Britain; 2) to provide new information on the hydrochemistry of deciduous plantation especially chemical gradients arising from edge effects.

The project was originally funded by the Department of the Environment, the Department of Rural Affairs and the Natural Environmental Research Council. In April 1990 the National Rivers Authority took over the funding from the

Department of the Environment. Following a meeting of the project steering group in October 1989 the title of the project was changed to "The Hydrological Impacts of Broadleaf Woodland in Lowland Britain".

In September 1988 a national symposium entitled "The Hydrological Impacts of Hardwood Plantation in Lowland Britain" was held at Wallingford. In March and April 1989 the first sites were set up at Black Wood in Hampshire. A review of the symposium, a detailed description of the Black Wood sites and an overview of the first summer's observations were presented in the first annual report (Report number 1). One contribution to the symposium was a detailed literature review of the water use of broadleaf forest, this has now been prepared as a paper and is presented in Appendix 1.

3. Activities in the last 12 months (September 1989 to September 1990)

At Black Wood the routine measurements of soil moisture, rainfall and throughfall chemistry and meteorology have continued. As planned, the plant physiological work has been limited at this site to measurements of leaf area index.

During the severe storms in January and February 1990, the Black Wood plantations were badly damaged. The worst damage was along the western edge of the plantation, 7 of the 15 interception sites were destroyed or greatly modified. The main water use sites, which are near the centre of the plantation, suffered only minor damage. The edge effect experiment has however been severely disrupted. Investigations were made to re-site the damaged sites but it was felt that the western edge of the forest is now so uneven that any results would be ambiguous. Where possible the monitoring of all sites has continued with an aim to determine the effect on the scavaging of pollutants of the modification of the forest.

A major effort in the last year has gone into the establishment of new water use sites in an ash plantation at Old Pond Close in Northamptonshire. It was felt that a new site was desirable, firstly, to extend the range of environmental conditions, the new site is on clay whereas Black Wood is on chalk, and secondly, to investigate a more extensive ash plantation, the ash plantation at Black Wood is of limited area. Water use observations were started at Old Pond Close in May 1990. A site description and a sample of results are presented in (sections 8 and 9).

It is hoped to collaborate with the Field Drainage Experimental Unit (FDEU) at this site. The FDEU plan to install a small flume to measure the surface runoff from a segment of the plantation.

Considerable progress has been made on modelling the transpiration. A multi-layer transfer model has been written and the predictions from this for Black Wood 1989 are presented in section 6. This model will provide the basis for the water use calculations for all the sites to be investigated within this programme.

Analysis of the Black Wood chemistry has progressed smoothly (section 7) although the assessment of the chemical fluxes through the forest is not yet complete. During 1989 field trials of modified gas tubes for improved determination of sulphur oxide have progressed well.

4. Black Wood interception measurements

The measurements from the plastic-sheet net-rainfall gauges in the ash and beech plantations have continued throughout the last year. The networks of stemflow and throughfall measurements have also been maintained; however the three transects nearest the forest edge were severely affected by the damage to the forest in the storms in late January and early February. A number of the instrumented sites were completely destroyed while at others the exposure has changed. The two transects well within the forest (and the plastic-sheet net-rainfall gauge) suffered only minor damage. The main interception experiments have continued while the edge effect experiment has terminated. However measurements at the storm damaged sites have continued to investigate the interception (and most particularly the chemistry) at storm damaged sites.

A comprehensive set of winter interception data have been collected but the data in the leafed period is sparse because of the dry summers of 1989 and 1990. It is proposed that data collection will continue for a further year.

The interception results from 2 May 1989 and 2 February 1990 have been analysed and the preliminary findings are presented in a draft paper in Appendix 2. The main conclusions are:

(a) average net rainfall is relatively constant with distance from the forest edge (20 to 350 metres; monitoring nearer than 20 metres from the edge proved impracticable);

(b) interception loss averages about 12% in the leafed and 11% in the unleafed periods;

(c) the stemflow increases as a proportion of the net rainfall from 2% in the leafed to 6% in the unleafed period;

(d) a network approach is important for assessing interception losses: localised rainfall inputs are observed; systematic differences are seen between similar localities.

5. Black Wood soil moisture measurements

The soil moisture measurements at the ash and the beech plots have been maintained throughout 1990. The storm of the 25 January caused only minor damage to the soil moisture network, a tree was uprooted near to tube 05 on the beech plot, measurements have continued at this tube and there appears to be only a minor effect on the soil water pattern. In March the frequency of visits was reduced from weekly to fortnightly to release manpower for the setting up and data collection at the Old Pond Close site. The effect on soil moisture measurements has not been serious, with only a small loss of detail. The effect on the tensiometer measurements has been important, at high tensions the mercury columns only last a week before breaking. A review of the tensiometer measurement cycle will be made.

As reported in Report No. 1 by August 1989 a large soil moisture deficit, of at least 250 mm, had built up during the dry summer of 1989. Figure 5.1 shows the monthly rainfall at the beech site through the winter of 1989/90 and summer 1990. October, December, January and February all exceeded 100 mm with a total winter rainfall (October to March) of 572 mm. In contrast the summer of 1990 has again been exceptionally dry with a total rainfall (April to August) of 120 mm, with only June approaching the long-term average for the month.

The total water content for the top 2.4 m (average of five tubes) are shown in Figure 5.2 for the ash and beech sites. The soil water started increasing in October 1989 and continued to increase from December 1989 until a maximum in mid-February 1990. The soil dried steadily from March through to August (1990) with a levelling off during June (when 51 mm of rain fell).

As is characteristic with chalk sites a simple plateau (see Figure 5.2) corresponding to a field capacity is not found. The soil water potential measurements show that below the beech saturation was not reached until 9 February, the potential then decreased (became more negative) through late February and early March, during which time, the water content measurements suggest, some drainage from the profile took place (approximately 50 mm). The ash site presents a slightly different picture, the potential measurements suggest that the soil profile did not completely wet up below 120 cm (Figure 5.3). However through late February and early March there is a similar water content pattern to the beech, this suggests that some drainage did occur during this period. Chalk maintains a relatively high water conductivity when it has a low (negative) water potential and so drainage through the chalk is still possible. However the extraction of a small amount of water lowers the water potential considerably and it is unlikely that there is a great deal of drainage from the chalk. The drainage which took place between February and March most probably came from the soil layer in the top 50 cm.

Through the summer period most of the depletion of soil moisture takes place in the top 2.5 m (Figures 5.4 and 5.5). There is some depletion below this level but it is of the order 0.01 to 0.02 Moisture Volume Fraction and only constitutes about 10% of the total.

The water use can be estimated from the pattern of soil moisture, unfortunately it is difficult to distinguish between the effects of drainage and transpiration. Prior to leaf emergence the transpiration from the forest will be essentially zero. Therefore before May losses can be ascribed to drainage. At the beginning of May all depths show water potentials below -400 cm of water and it seems unlikely that significant drainage could continue. After May all losses can be ascribed to transpiration. This crude procedure is not completely satisfactory and more work is required on the water movement in the chalk.

The soil moisture depletion (DS), the rainfall (R), the interception loss (I) (assuming a 12% interception ratio) and the calculated transpiration (T),

$$T = DS + R - I$$

are shown in Table 5.1 for May to September 1989 and May to August 1990. It can be seen that the transpiration losses through these two summers are much larger than the interception losses (although through the winter the transpiration losses will be small while the interception losses will be considerable, 11% of rainfall, see Appendix 1). These were also two particularly dry summers. The transpiration calculated for the ash is larger than the beech by 30 to 50 mm over the season. This may be the effect of the understorey.

Table 5.1 Changes in soil moisture May to September (mm).

	1989	1990
Start date	4/5/89	2/5/90
Finish date	28/9/89	30/8/90
Change in soil moisture (DS):		
Beech	216.5	191.6
Ash	252.2	249.3
Rainfall (R)	142.3	101.3
Interception (I)	17.1	12.1
Transpiration (T) :		
Beech	341.7	280.8
Ash	377.4	338.5

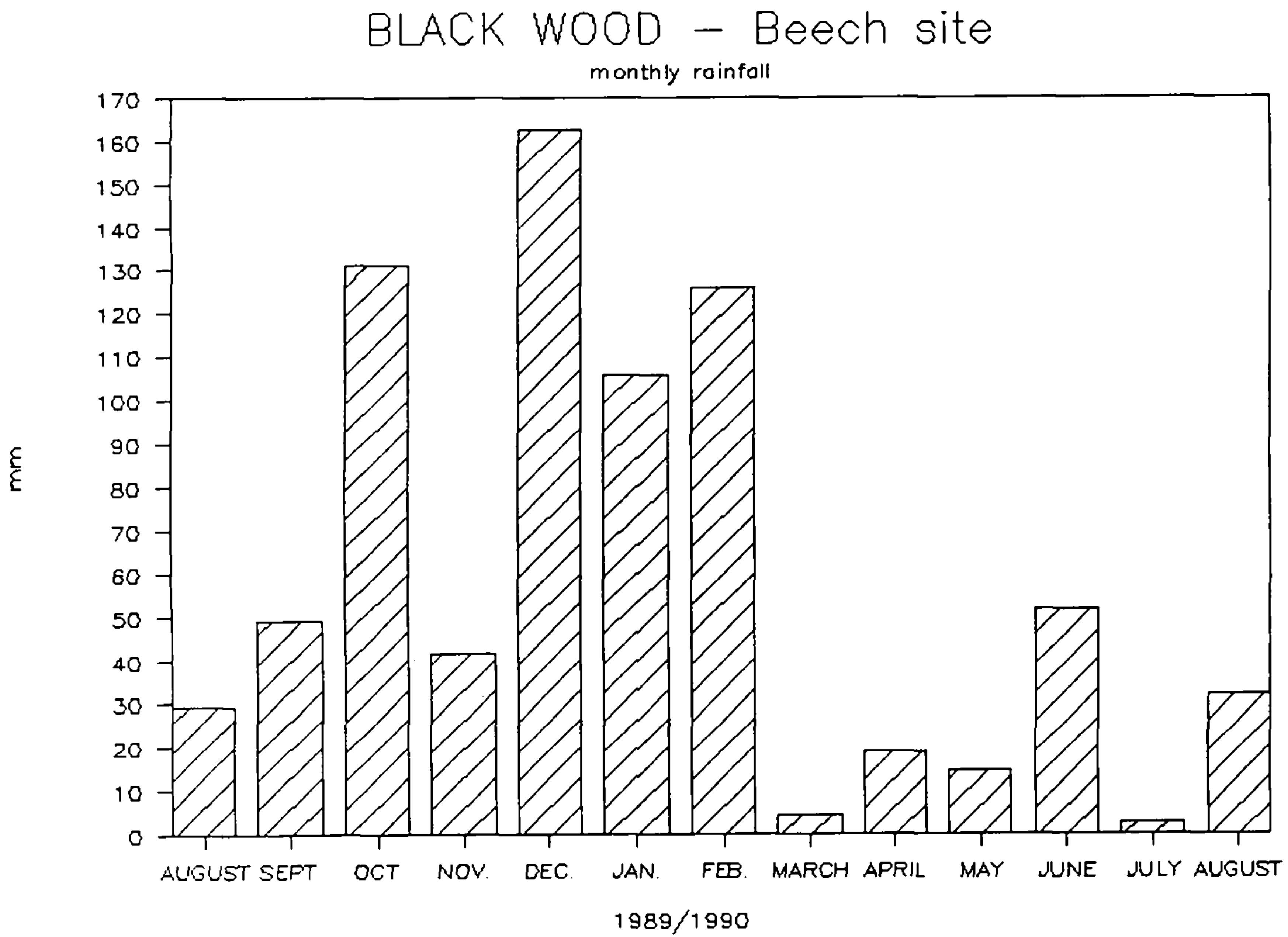

Figure 5.1 Monthly rainfall at the Black Wood beech site

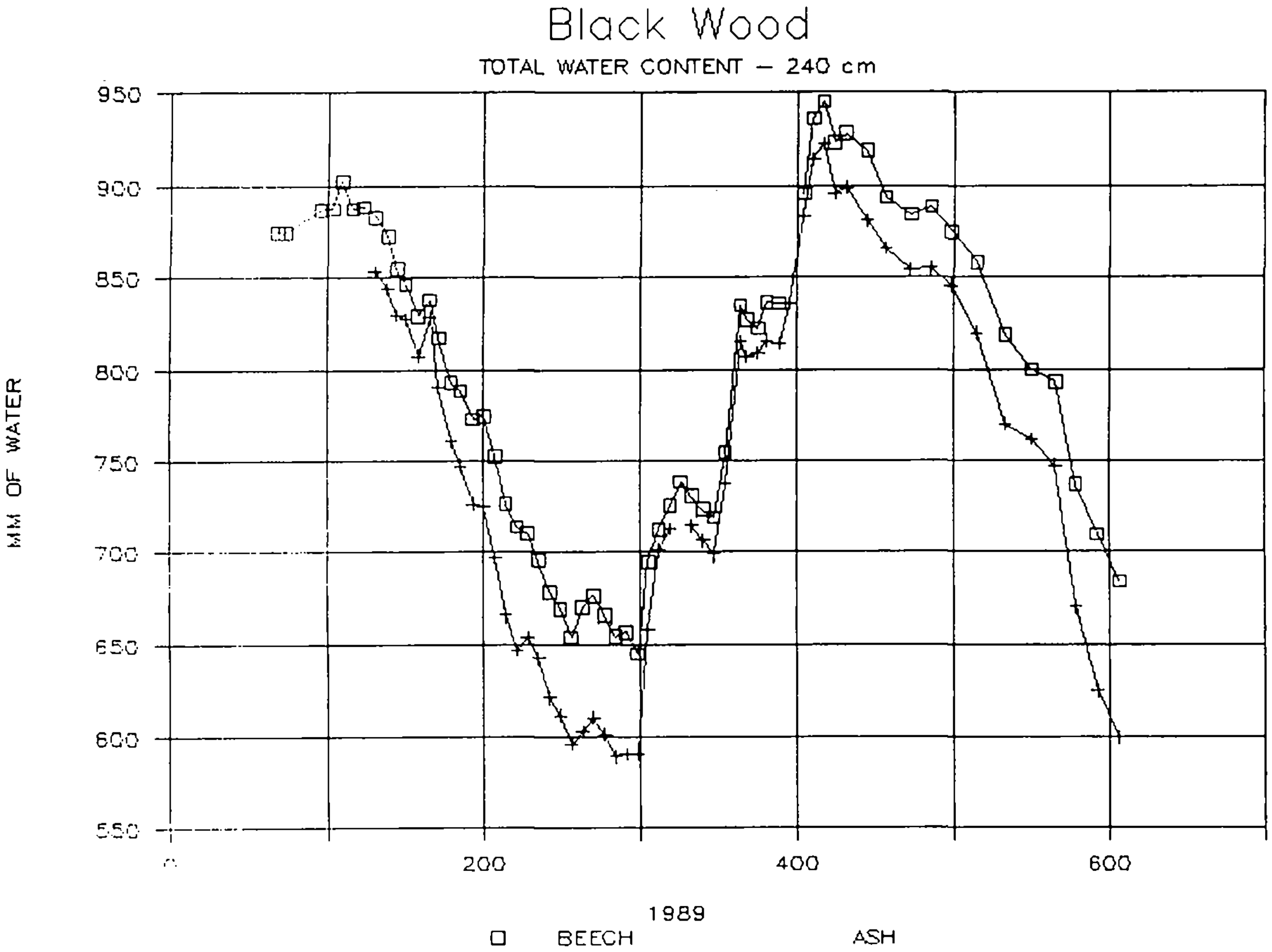

Figure 5.2 Total water content from the ash and the beech sites

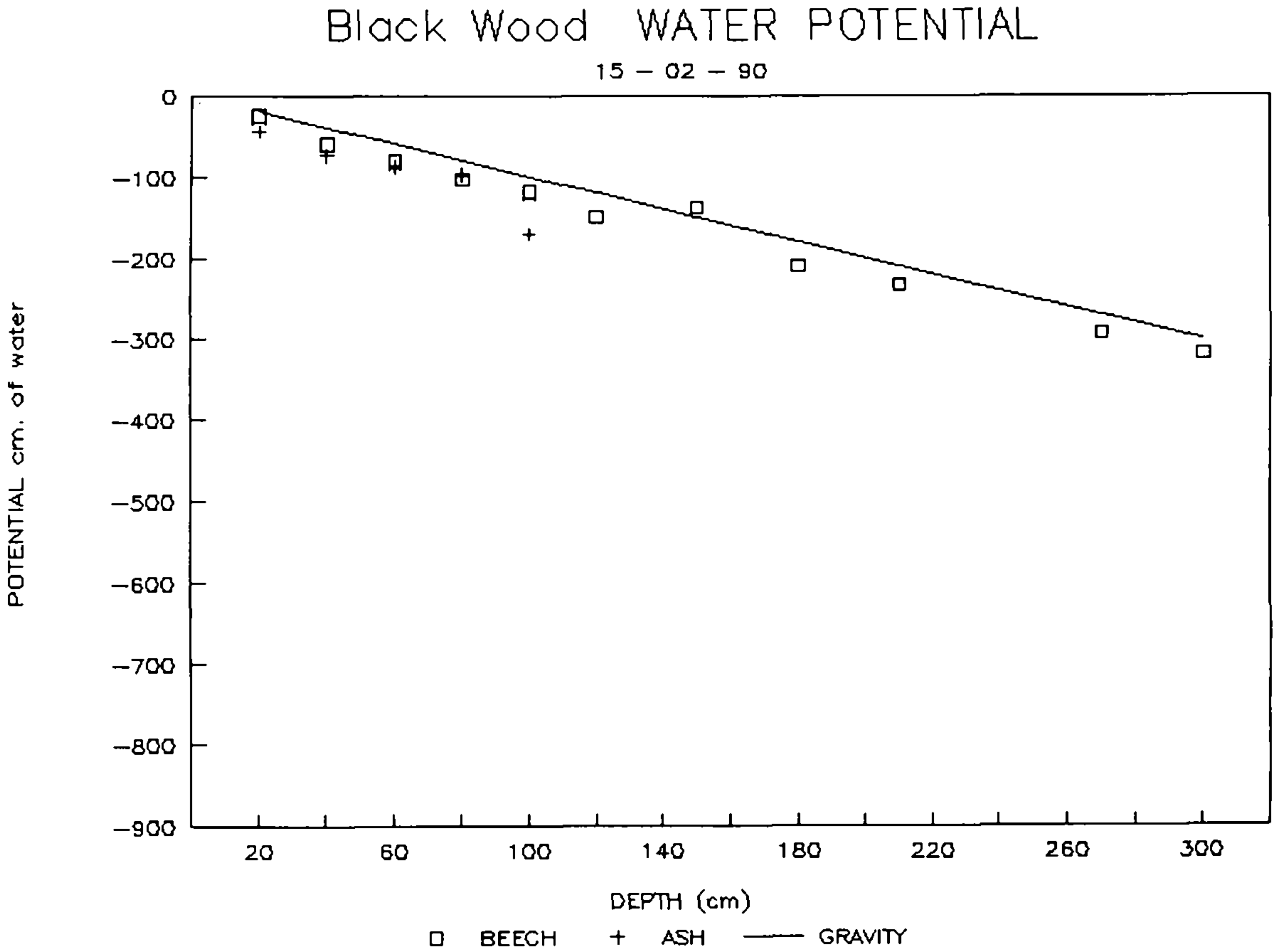

Figure 5.3 Soil water potential from the ash and beech sites 15 February 1990

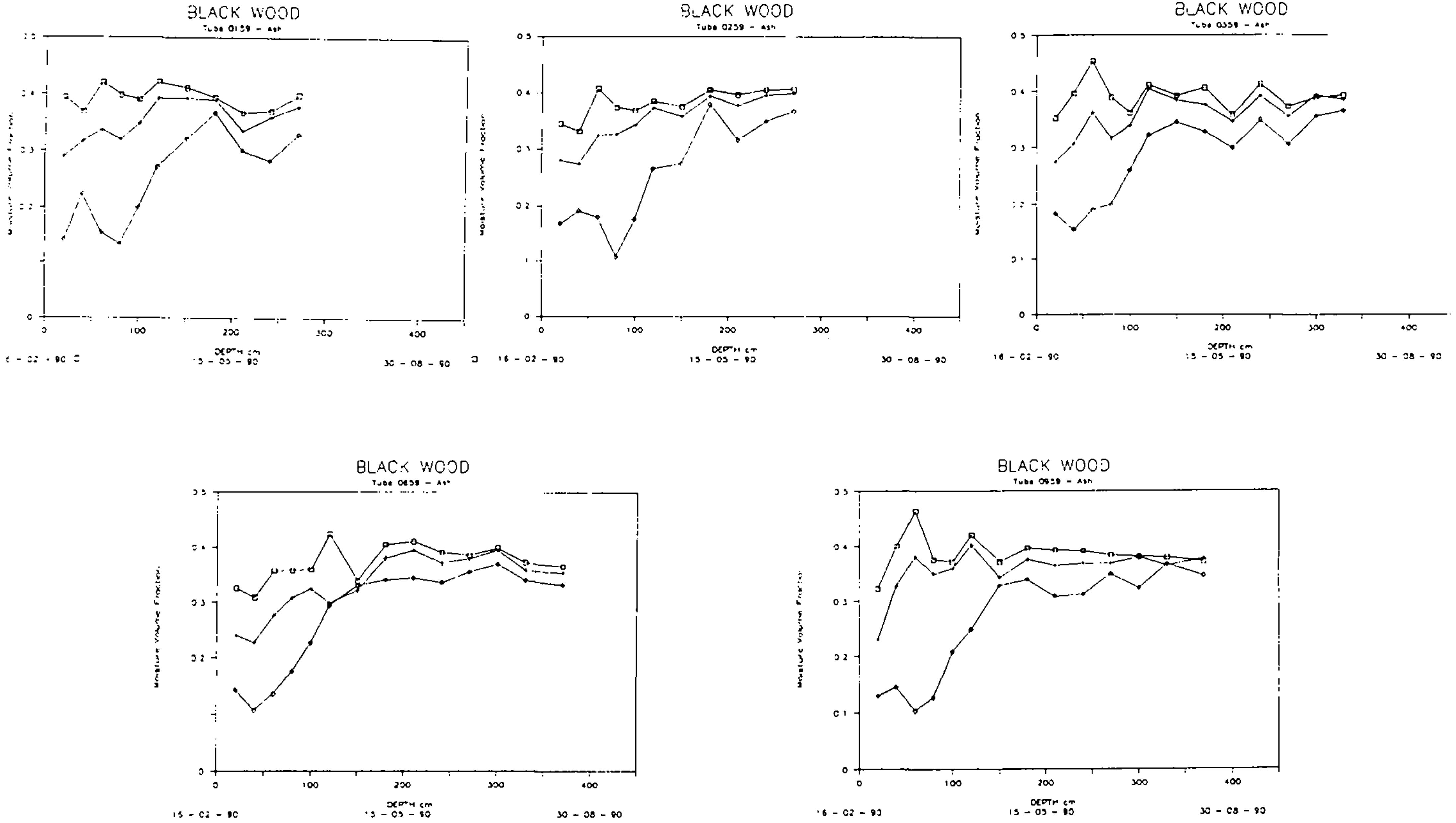

Figure 5.4 Soil moisture profiles from the ash site

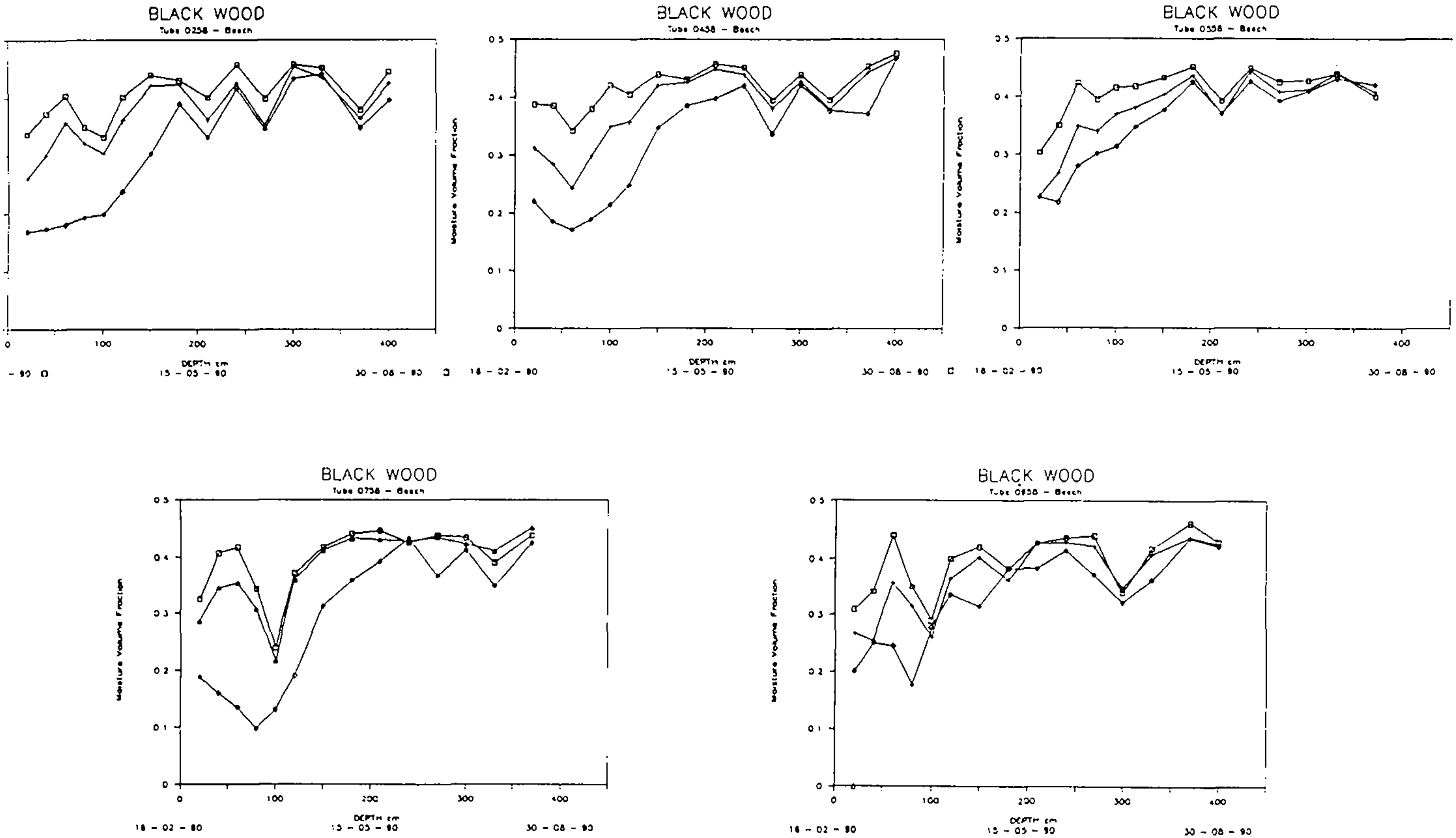

Figure 5.5 Soil moisture profiles from the beech site

The soil moisture measurements will continue during the coming year; as previously mentioned a priority for this work must be a more detailed study of the water movement in the chalk to separate the depletion due to drainage from that due to transpiration.

6. Black Wood plant physiology 1989

The Observations

During 1989 measurements of leaf gas exchange (stomatal conductance (G_s) and net photosynthesis) and leaf water potential were made at the beech, ash and understorey sites on the following dates.

Table 6.1 Plant Physiology measurement days

Ash	Beech	Understorey
23.5.89	16.5.89	18.5.89
8.6.89	1.6.89	25.5.89
21.6.89	15.6.89	14.6.89
4.7.89	27.6.89	19.7.89
18.7.89	12.7.89	8.8.89
2.8.89	1.8.89	22.8.90
15.8.89	14.8.89	
31.8.89	30.8.89	
12.9.89	19.9.89	

Stomatal conductance and leaf water potential data was measured at three levels through the canopy for both the beech and ash stands. For the understorey stomatal conductance data is available from three species: dogs mercury, hazel and bramble.

The summer of 1989 was characterised by below average rainfall which produced substantial soil moisture deficits beneath the ash and beech stands. However, a seasonal change in stomatal conductance was not observed in either the ash or beech. (Appendix 3: Progress Update, Report No. 1.) The maximum stomatal conductance is similar in both the ash and beech (350 and 320 $mmolm^{-2}s^{-1}$ respectively) and in all cases shows a gradual fall throughout each measurement day. A consistent pattern also emerges in the fall of stomatal conductance through the canopy of both species.

A lower maximum value of stomatal conductance (100 $mmolm^{-2}s^{-1}$) was measured in the three understorey species, which were affected by the decreased soil moisture.

Leaf litter from 20 randomly placed litter trays in both the ash and beech plots were collected during September 1989 to November 1989 inclusive. The average Leaf Area Index (LAI) for each species for each month is given in Table 6.2.

Table 6.2 Leaf area index of the ash and beech plots

Month	Ash	Beech
September 1989	0.14	0.07
October 1989	1.40	1.86
November 1989	0.66	2.23
Total LAI	2.20	4.16

The LAI from the understorey was sampled from 5 randomly located positions on the ash litter plot on 25 May 1989. The average LAI for each plot was 1.908, 1.806, 2.396, 1.414 and 2.622 with a mean of 2.029.

The Model

A four layer model based on the Penman-Monteith formulation has been used to produce daily values of transpiration from both the ash (including the understorey) and the beech plots. The model requires hourly values of solar and net radiation, dry bulb temperature, specific humidity deficit and windspeed. These have been provided by the above beech canopy and the ash understorey automatic weather stations. The model also needs a knowledge of the following:

the distribution of leaf area index within the canopy;

the extinction of net radiation within the canopy;

the relationship between stomatal conductance and specific humidity deficit.

Leaf area index within the canopy

A typical canopy distribution uses a 1:2:1 basis for allocating the LAI between the layers and this has been used in the model. Table 6.3 shows the breakdown of LAI for each canopy level for both the ash and the beech. Canopy level 4 for the ash is the understorey. There is no understorey for the beech so the LAI is put to zero.

Table 6.3 Within canopy distribution of leaf area index

Canopy Level	Ash	ΣLAI	Beech	ΣLAI
1	0.547	0.547	1.041	1.041
2	1.095	1.642	2.082	3.123
3	0.547	2.189	1.041	4.164
4	2.029	4.218	0.0	4.164
Total	4.218		4.164	

Extinction of net radiation

The calculation of the extinction of net radiation through the canopy has been made using a simple exponential relationship, where

net radiation = exp (-K L)

and K = 0.5 (from other published work)

L = cumulative LAI above the level of interest

This distributes the net radiation through each canopy as shown in Table 6.4

Table 6.4 Within canopy distribution of net radiation

Canopy Level	Ash	Beech
1	0.245	0.406
2	0.324	0.385
3	0.105	0.085
4	0.326	0.0

Specific humidity deficits and stomatal conductance relationship

To investigate the influence of specific humidity deficit on stomatal conductance the data for each canopy level for the ash and the beech plots have been analysed by linear regression. Figures 6.1 and 6.2 show the regression lines fitted for each canopy level. All levels have statistically significant negative relationships between specific humidity deficit and stomatal conductance. Table 6.5 gives details of the linear regression statistics for each canopy level.

Table 6.5 Linear regression statistics for stomatal conductance (mmol m^{-2} s^{-1}) with specific humidity deficit (g kg^{-1}) for three canopy levels

Canopy level		Ash	Beech
Upper	a	264.825	295.994
	b	-14.38	-23.899
	v	-0.68	-0.791
Middle	a	196.174	196.37
	b	-12.11	-12.06
	v	-0.79	-0.575
Lower	a	171.49	138.156
	b	-11.11	-8.30
	v	-0.74	-0.54

The model has been run using data collected from 9 June 1989 to 26 September 1989, (the period for which detailed automatic weather station data is available). The transpiration values for the ash and beech are 299.4 and 308.4 mm respectively. Figure 6.3 shows the cumulative transpiration for the ash and the beech and the cumulative Penman evaporation. The transpiration is below the Penman potential rate, noticeably at high rates, Figure 6.4. This is the effect of the reduction of stomatal conductance with increasing specific humidity deficit taking place. As a comparison the calculated transpiration as used in Table 5.1 has been made for the period 9 June 1989 to 26 September 1989 and the results are shown in Table 6.6.

Table 6.6 Comparison of transpiration loss determined from soil moisture changes and the transpiration model for the period 09/06/89 to 26/09/89

	Ash	Beech
Rainfall (R)	127.1	127.1
Interception (I)	17.1	17.1
Δ DS	227.8	171.7
Transpiration from soil moisture losses (T)	339.7	283.6
Transpiration from model	299.4	308.4

There is a lack of agreement between the two estimates of transpiration at the 10% level. This may be a failing of the transpiration model: the most likely error comes from uncertainties in the LAI measurement. There are also

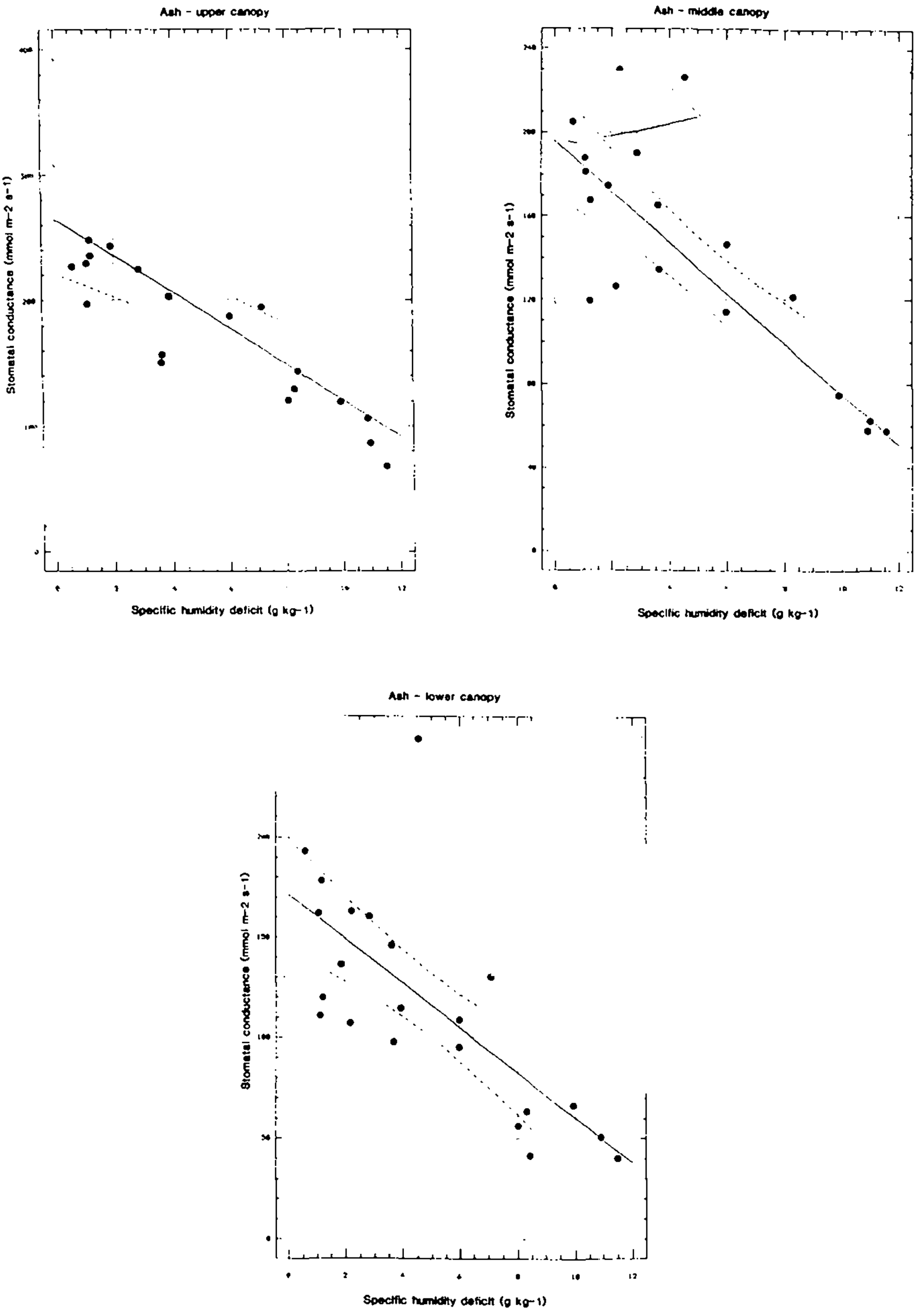

Figure 6.1 The relationship between stomatal conductance and specific humidity deficit for three canopy levels in the ash

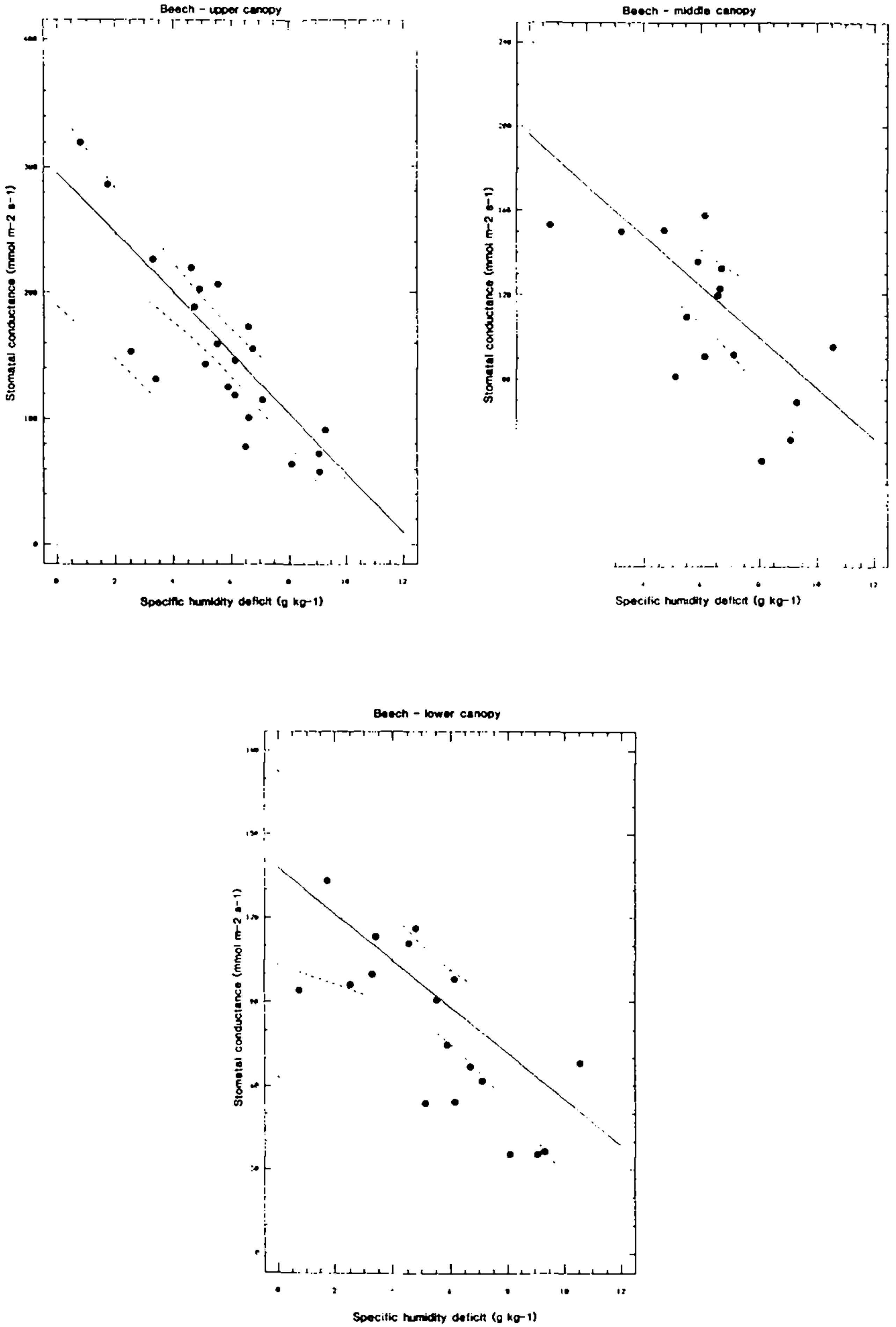

Figure 6.2 The relationship between stomatal conductance and specific humidity deficit for three canopy levels in the beech

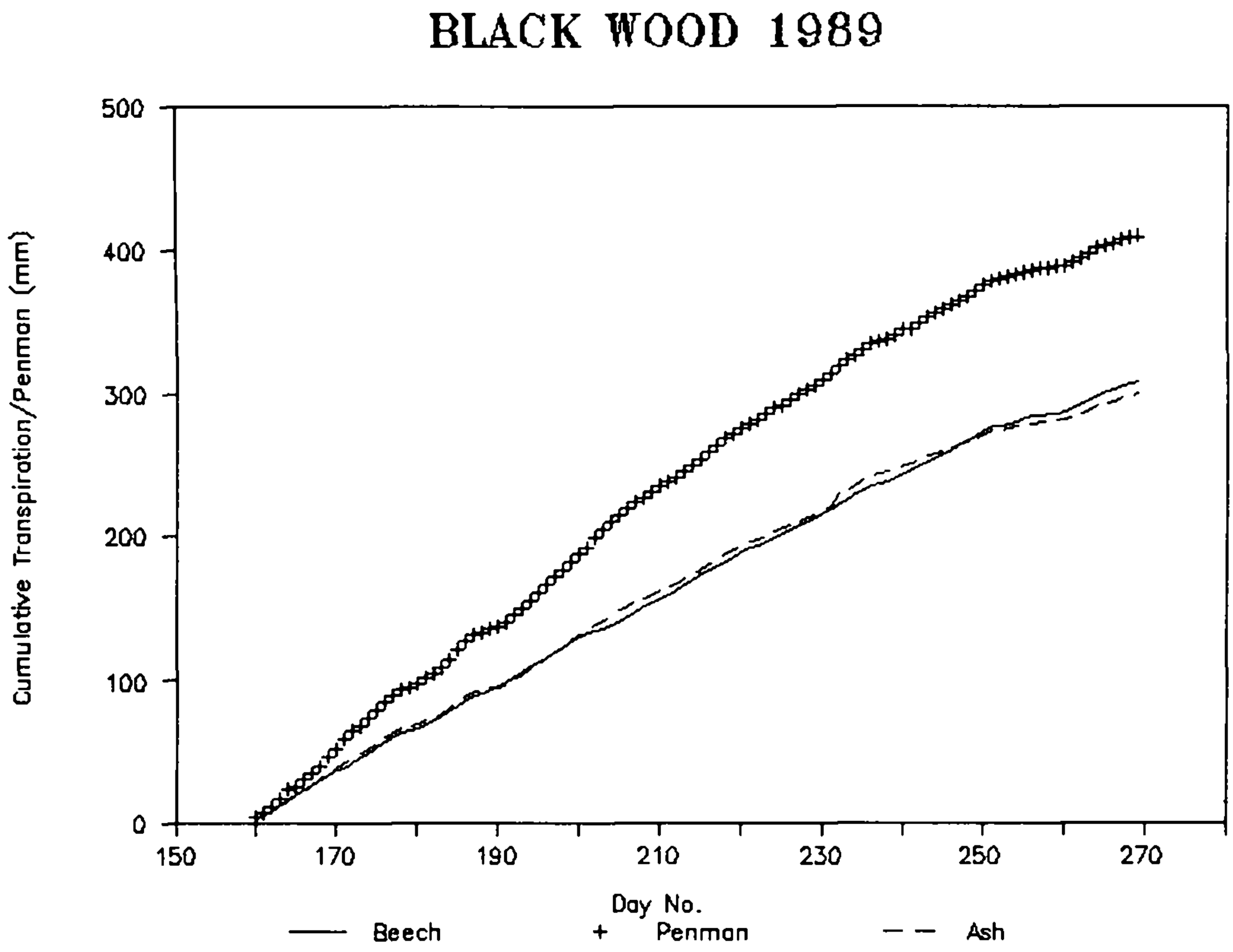

Figure 6.3 Comparison between cumulative Penman evaporation and cumulative transpiration from the ash and beech from the 4 layer transpiration model

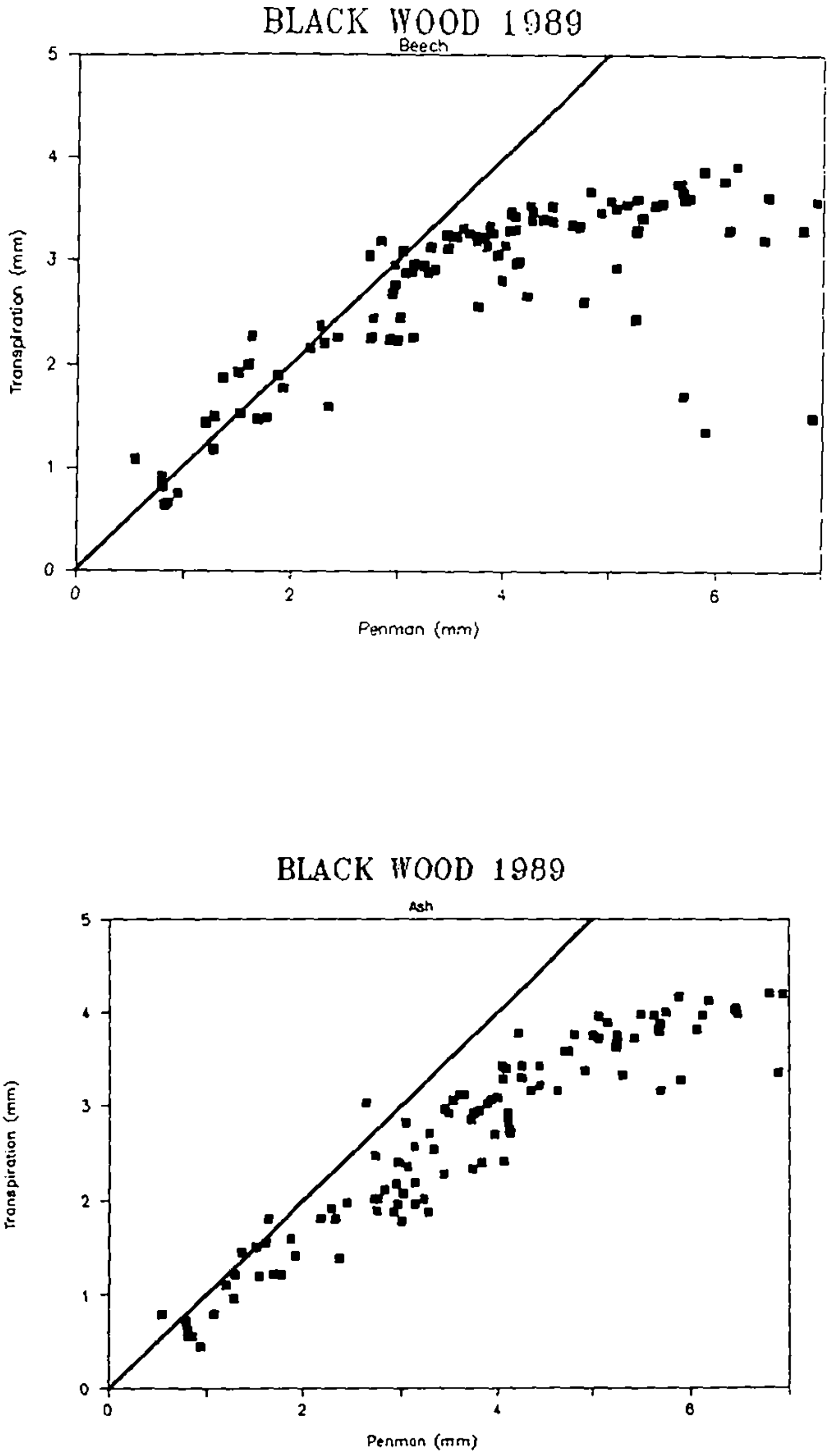

Figure 6.4 Relationship between Penman evaporation and ash and beech transpiration

uncertainties in the soil moisture method, in particular the neglect of drainage from the soil profiles during the summer months. Both areas have been identified for future work, see Section 11.

7. Black Wood chemistry

Monitoring of rainfall, stemflow and throughfall has continued in Black Wood since May 1989. Report No. 1 gave details of the network design, methods of sampling and chemical analysis.

Rainfall, stemflow and throughfall results

Over the past year and a half 52 collections have been made. For each collection 2 rainfall, 16 stemflow, and 16 throughfall samples have been analyzed: some 1768 determinations. An extensive data base has been established.

The detailed statistical analysis of the data required to assess the fluxes of chemicals through the forest is as yet incomplete. Extensive records are required to obtain representative information owing to the high variability in the data on a plot to plot basis. For this reason comparisons are made, initially, on a row to row basis to provide averaged variations.

Storm damage in February this year destroyed many trees near the forest edge (25% of the trees in the plots of the first 3 rows were lost). Remarkably, very similar interception and chemical flux results occur for the periods before and after the storm damage even though in some cases three of the four trees in a given plot were toppled in the gales (Figure 7.1). To avoid repetition, the general findings are presented, in the text, without reference to the storm damage in the first instance.

Major and minor element chemistry shows large variations with time. In general, concentrations and ranges in concentration are in the order stemflow > throughfall > rainfall (Tables 7.1 and 7.2). Within rainfall, sodium, magnesium and chloride are highly correlated ($r > 0.94$, $N = 52$) and this reflects the varying contributions of salts derived from oceanic sources: other chemical determinands show little inter-correlation. The presence of fairly high concentrations of sulphate, nitrate and calcium, together with the lack of correlation with the sea salt components, indicates the importance of pollutant sources for these components. Within the stemflow and the throughfall data a similar pattern emerges. For example, in the case of the sea salt components, high correlations occur ($r = 0.65$, $N = 416$): poor correlations occur for all the other components measured.

The contribution of throughfall dominates the chemical fluxes through the canopy: only about 4% of the net rainfall comes from stemflow while the increased element concentration in stemflow compared with throughfall is insufficient to make up this disparity.

Table 7.1 Rainfall, stemflow and throughfall concentrations for the major elements. All units are mg/l. Bracketed values indicate the range in concentration.

Element	Rainfall	Stemflow	Throughfall
Na	5.1	16.5	9.2
	(0.3-18.5)	(0.5-97.5)	(0.5-71.0)
K	0.6	4.8	3.2
	(0.0-3.7)	(0.6-59.1)	(0.2-55.7)
Ca	1.1	2.2	2.8
	(0.2-5.0)	(0.7-10.8)	(0.4-27.2)
Mg	0.6	1.7	1.4
	(0.0-2.2)	(0.0-11.6)	(0.1-8.5)
[illegible]	0.02	0.09	0.09
	(0.0-0.3)	(0.0-0.9)	(0.0-0.9)
	0.01	0.03	0.03
	(0.0-0.2)	(0.0-0.3)	(0.0-0.8)
Cl	8.8	29.9	17.8
	(0.0-32.5)	(1.0-172.0)	(1.0-136.5)
NO_2	0.06	0.07	0.17
	(0.0-4.3)	(0.0-20.1)	(0.0-14.7)
NO_3	2.1	2.3	4.3
	(0.0-11.5)	(0.0-46.7)	(0.0-57.3)
PO_4	0.12	0.07	0.48
	(0.0-2.8)	(0.0-2.9)	(0.0-14.1)
SO_4	5.1	12.2	9.0
	(1.5-16.5)	(3.5-64.0)	(3.0-45.5)
NH_4	1.3	1.4	2.4
	(0.0-15.6)	(0.0-26.6)	(0.0-74.0)

The flux of many chemical components through the forest canopy (stemflow plus throughfall) are highest nearest the forest edge (< 50 m). Comparison of flux data for each plot shows important systematic differences (Figure 7.1). The most extreme example of this occurs for manganese where differences of a factor of 2 occur for adjacent plots within the first row: straight line correlations occur when the event data for individual plots are graphed together (Figure 7.2). Sodium, chloride, magnesium, sulphate, calcium and strontium show a increased net flux at the forest edge of between 1.2 and 2 times the value observed further into the forest. In contrast, potassium, silicon, barium, zinc, phosphate, fluorine, ammonium, total nitrogen, nitrite, nitrate and hydrogen ion show little variation: manganese shows a minimum value 100 m from the forest edge; boron fluxes increase away from the edge.

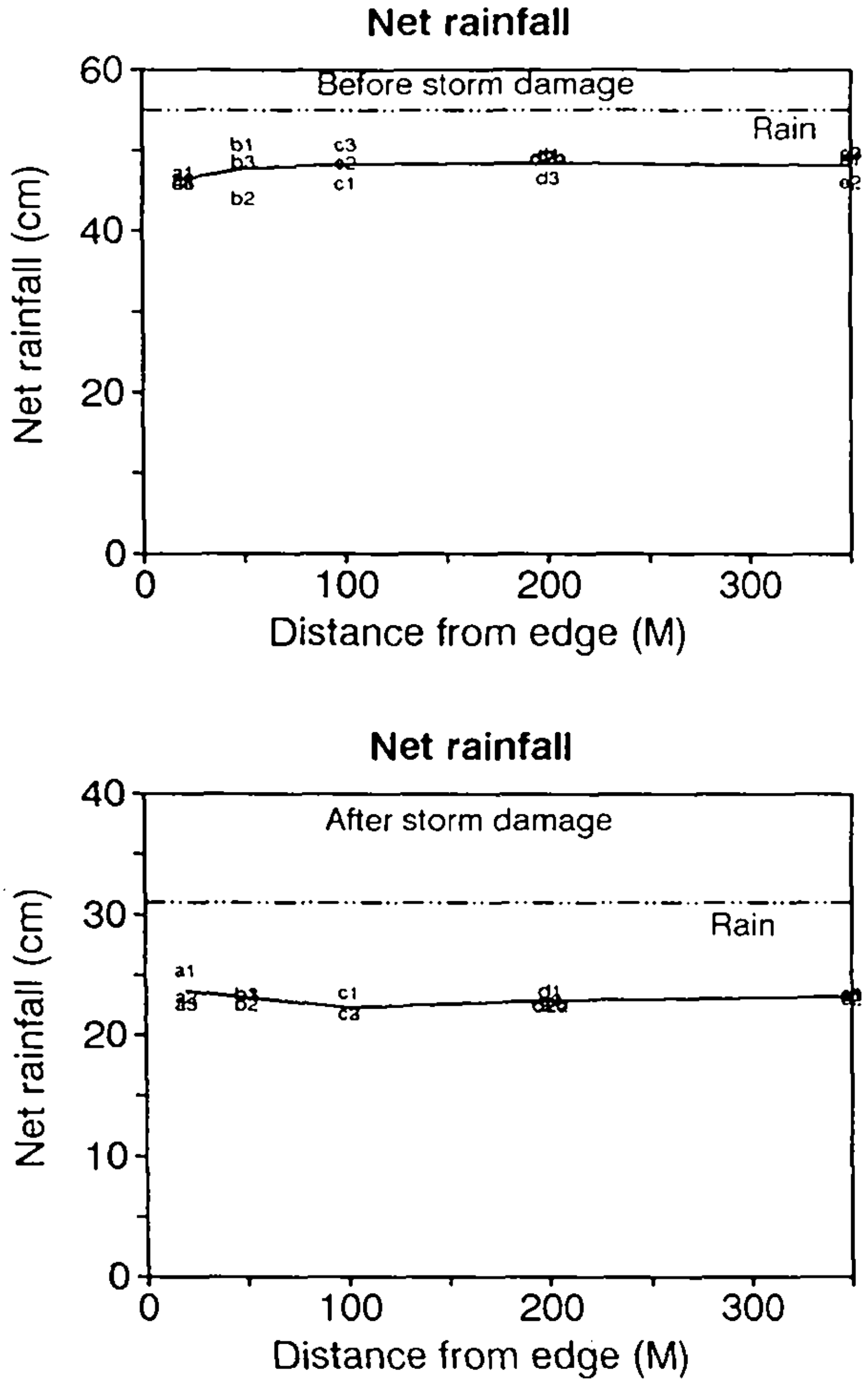

Figure 7.1 A compilation of diagrams depicting rainfall and stemflow plus throughfall fluxes for major, minor and trace elements with varying distance from a forest edge. Separate graphs are provided for the periods before and after storm damage (1/5/1989 to 2/2/1990 and 3/2/1990 to 21/8/1990). Chemical fluxes are provided, on each diagram, for the individual plots (the letters a to e give row locations and the associated number gives the position in the row) and the average for each row (joining lines).

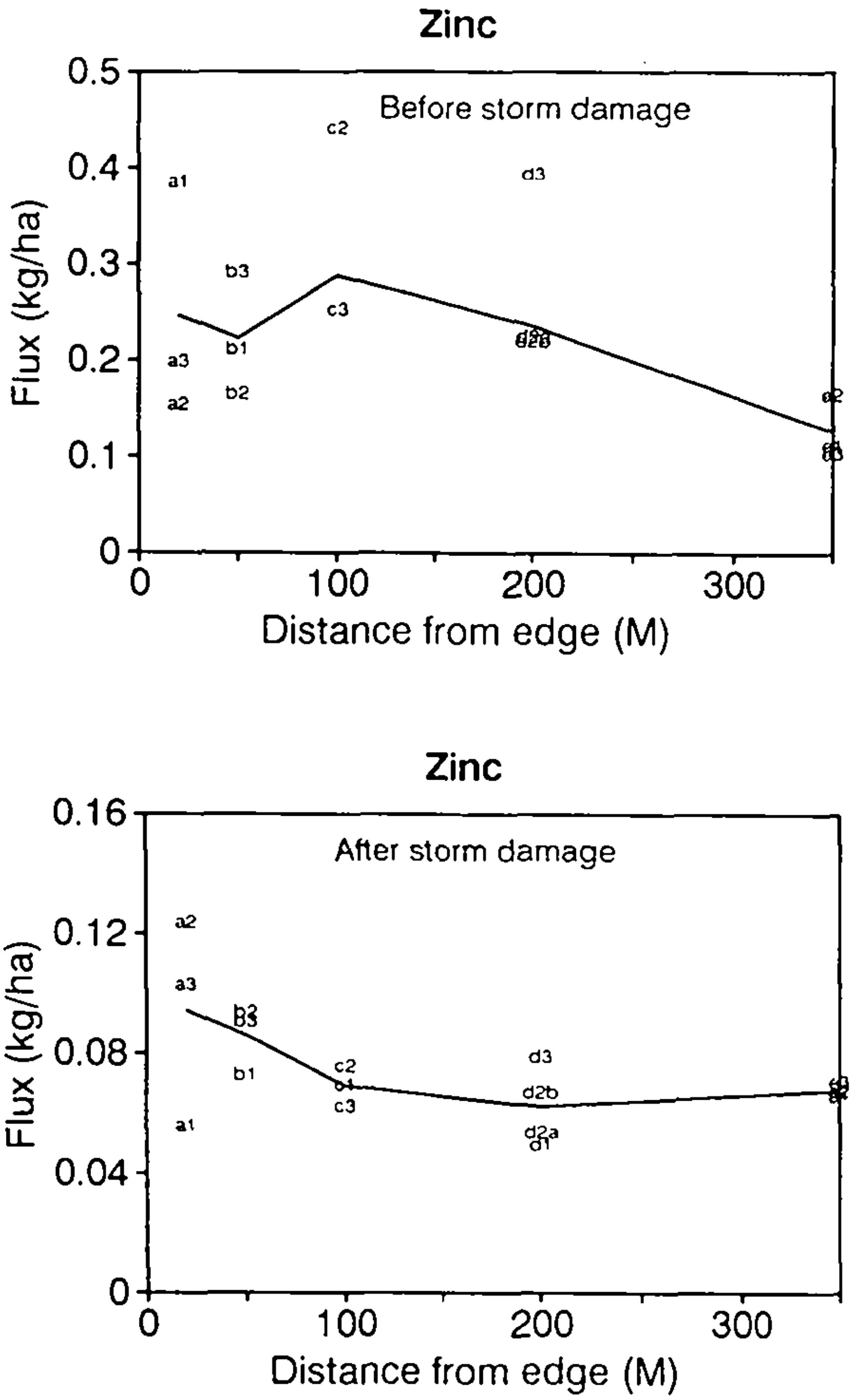
Zinc
Before storm damage
Flux (kg/ha)
0.5
0.4
0.3
0.2
0.1
0
0
100
200
300
Distance from edge (M)
a1
a2
a3
b1
b2
b3
c2
c3
d3
Zinc
After storm damage
Flux (kg/ha)
0.16
0.12
0.08
0.04
0
0
100
200
300
Distance from edge (M)
a1
a2
a3
b1
b3
c2
c3
d3
d2b
d2a
d1

Figure 7.1

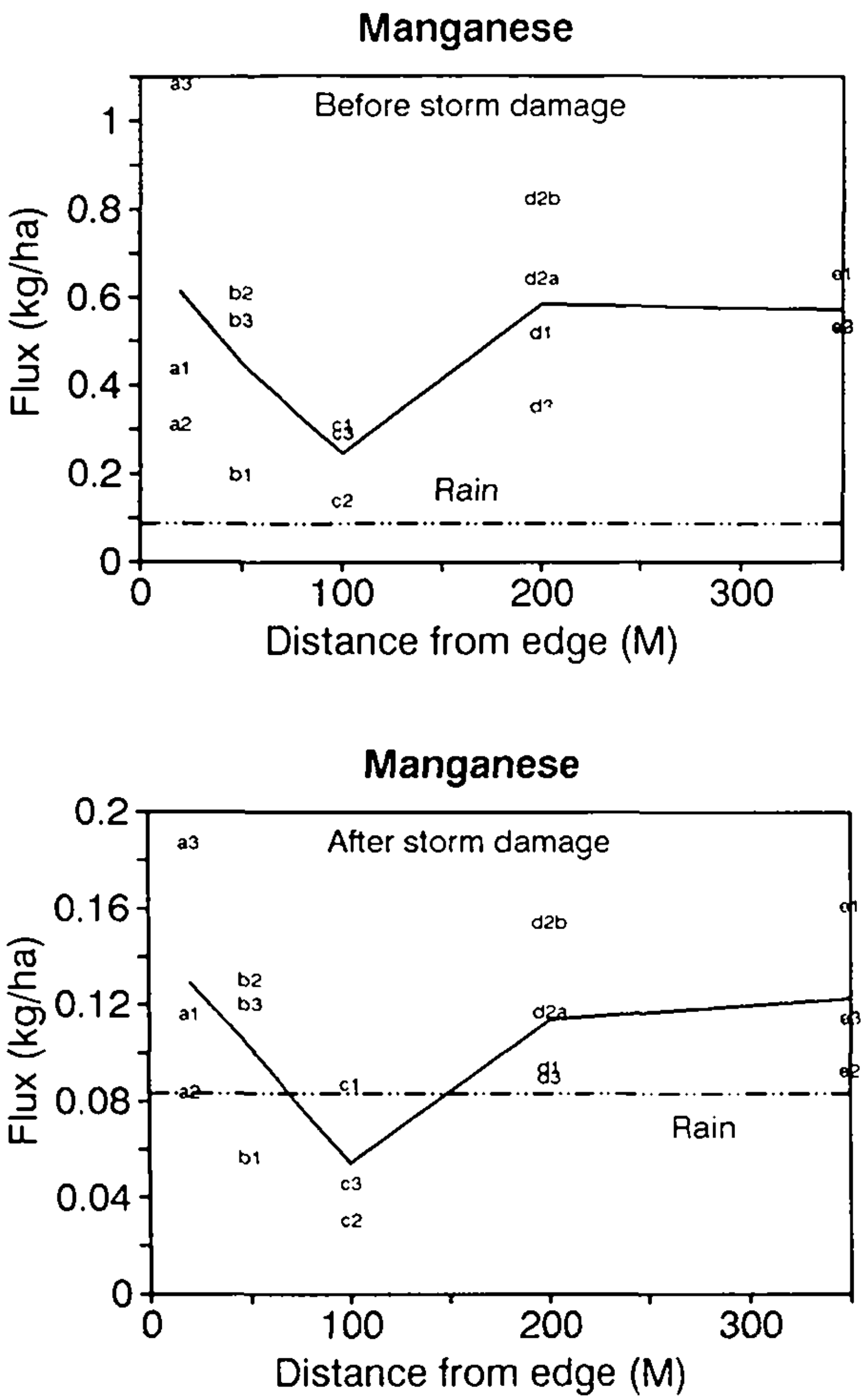
Manganese
Before storm damage
Flux (kg/ha)
1
0.8
0.6
0.4
0.2
0
a3
d2b
d2a
e1
b2
b3
d1
e3
a1
a2
c1
c3
d?
b1
c2
Rain
0
100
200
300
Distance from edge (M)
Manganese
After storm damage
Flux (kg/ha)
0.2
0.16
0.12
0.08
0.04
0
a3
e1
d2b
b2
b3
a1
d2a
e3
d1
d3
e2
a2
c1
Rain
b1
c3
c2
0
100
200
300
Distance from edge (M)

Figure 7.1

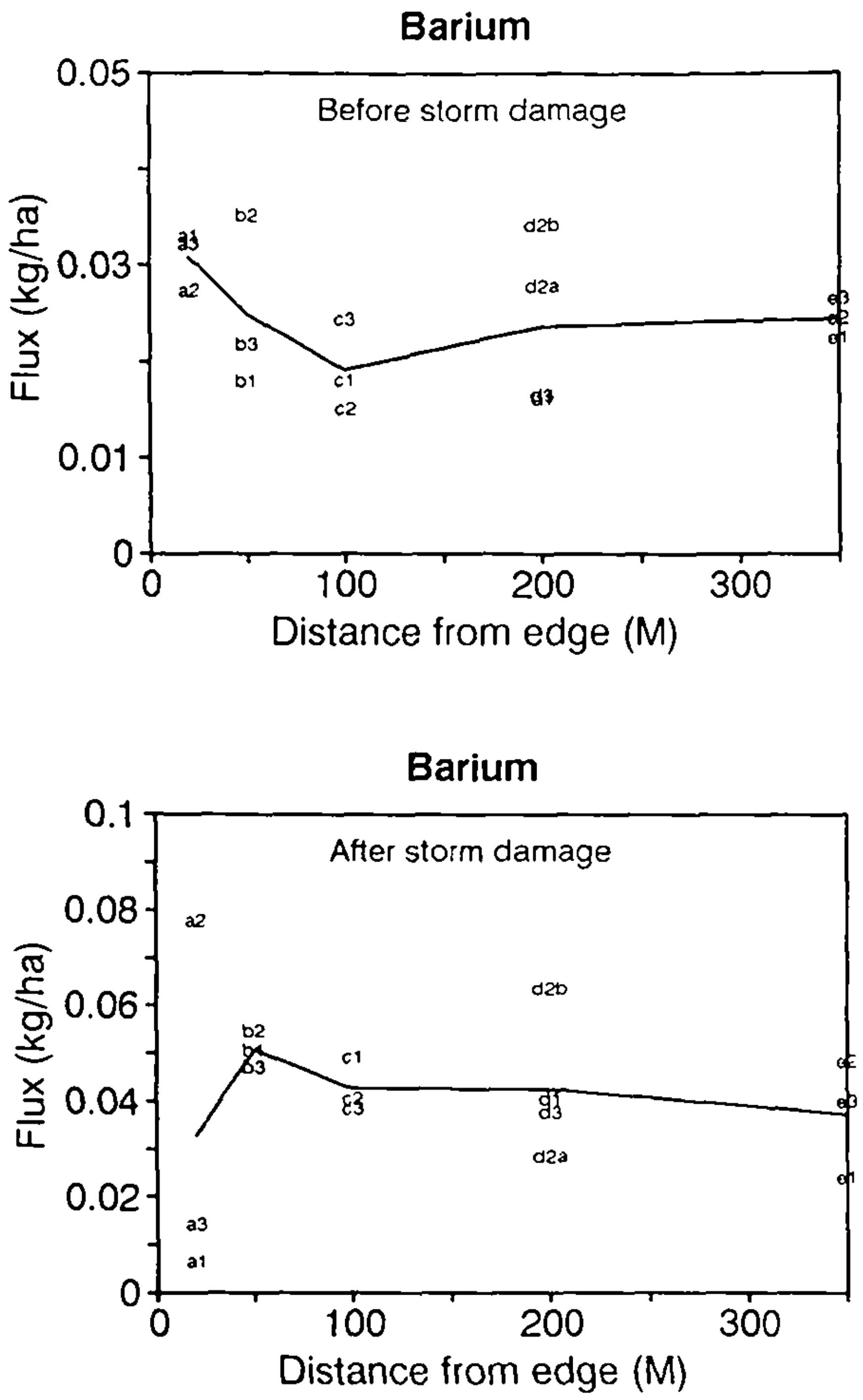
Barium
Before storm damage
Flux (kg/ha)
0.05
0.03
0.01
0
Distance from edge (M)
0
100
200
300
a1
a3
a2
b2
b3
b1
c3
c1
c2
d2b
d2a
d1
d3
e3
e2
e1
Barium
After storm damage
Flux (kg/ha)
0.1
0.08
0.06
0.04
0.02
0
Distance from edge (M)
0
100
200
300
a2
a3
a1
b2
b1
b3
c1
c2
c3
d2b
d1
d3
d2a
e2
e3
e1

Figure 7.1

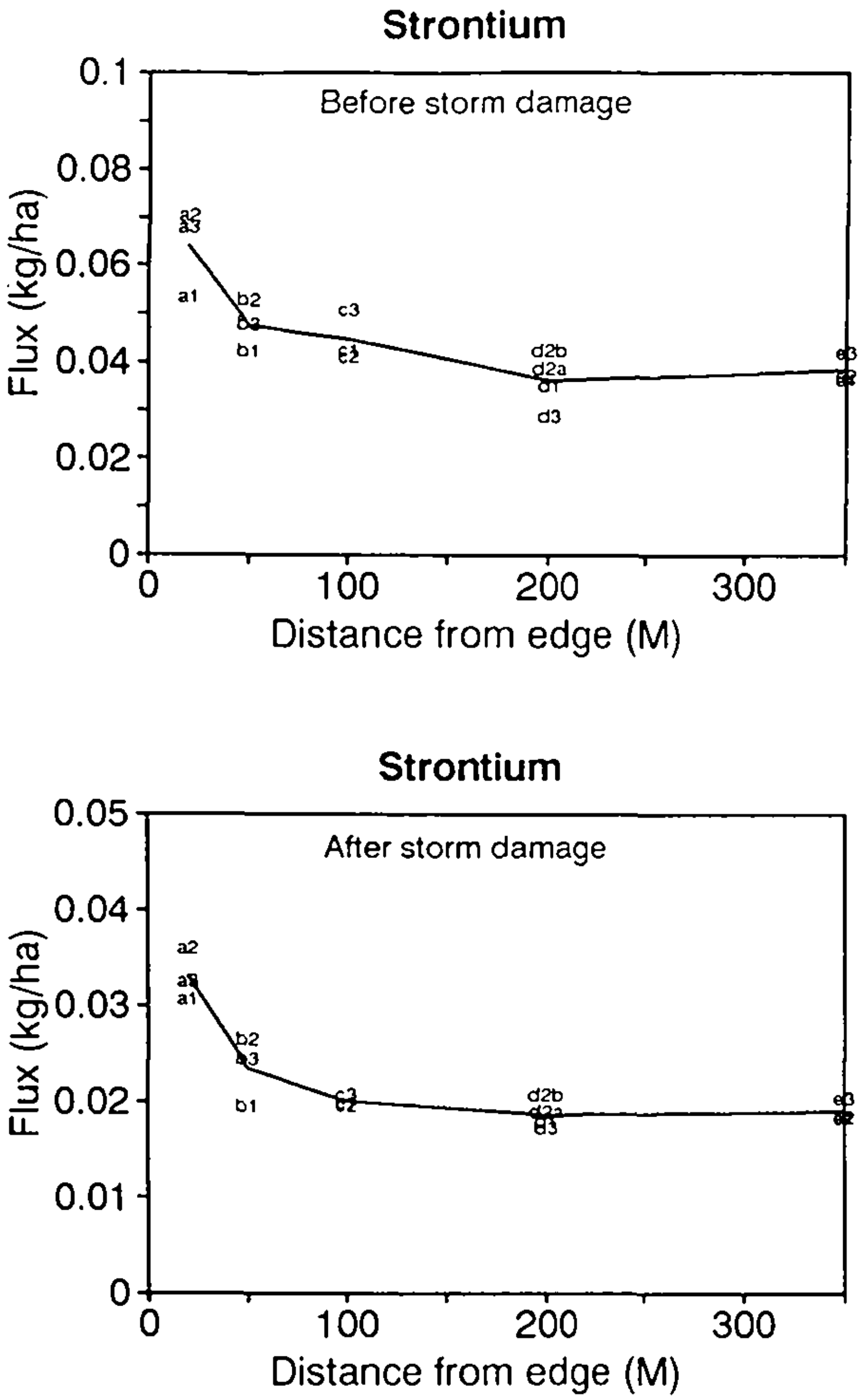
Strontium
Before storm damage
Flux (kg/ha)
0.1
0.08
0.06
0.04
0.02
0
a2
a3
a1
b2
b3
b1
c3
c2
d2b
d2a
d1
d3
e3
Distance from edge (M)
0
100
200
300
Strontium
After storm damage
Flux (kg/ha)
0.05
0.04
0.03
0.02
0.01
0
a2
a3
a1
b2
b3
b1
c3
c2
d2b
d2a
d3
e3
e2
Distance from edge (M)
0
100
200
300

Figure 7.1

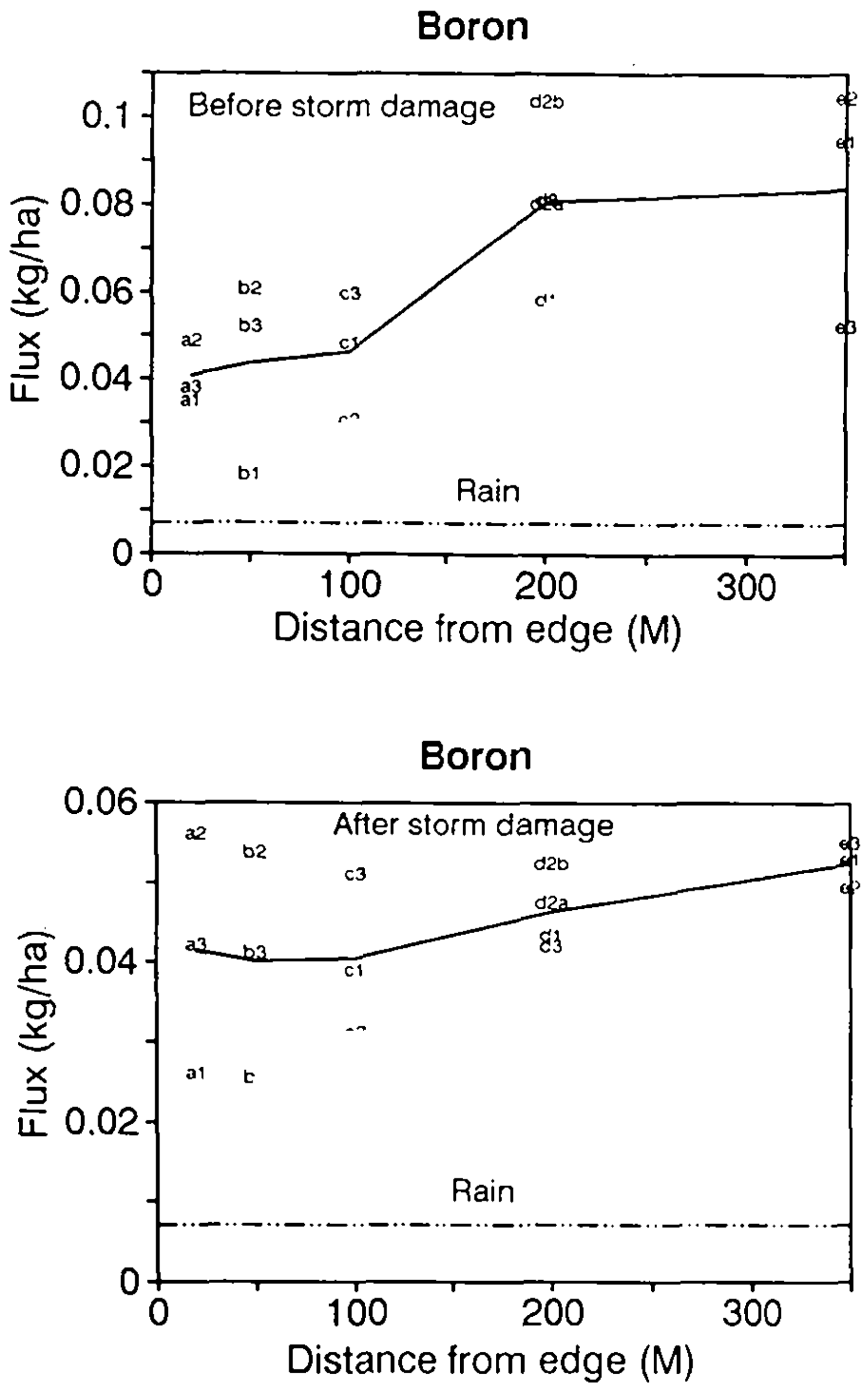
Boron
Before storm damage
Flux (kg/ha)
0.1
0.08
0.06
0.04
0.02
0
Distance from edge (M)
0
100
200
300
a2
a3
a1
b2
b3
b1
c3
c1
d2b
e2
e1
e3
Rain
Boron
After storm damage
Flux (kg/ha)
0.06
0.04
0.02
0
Distance from edge (M)
0
100
200
300
a2
a3
a1
b2
b3
c3
c1
d2b
d2a
e3
e1
Rain

Figure 7.1

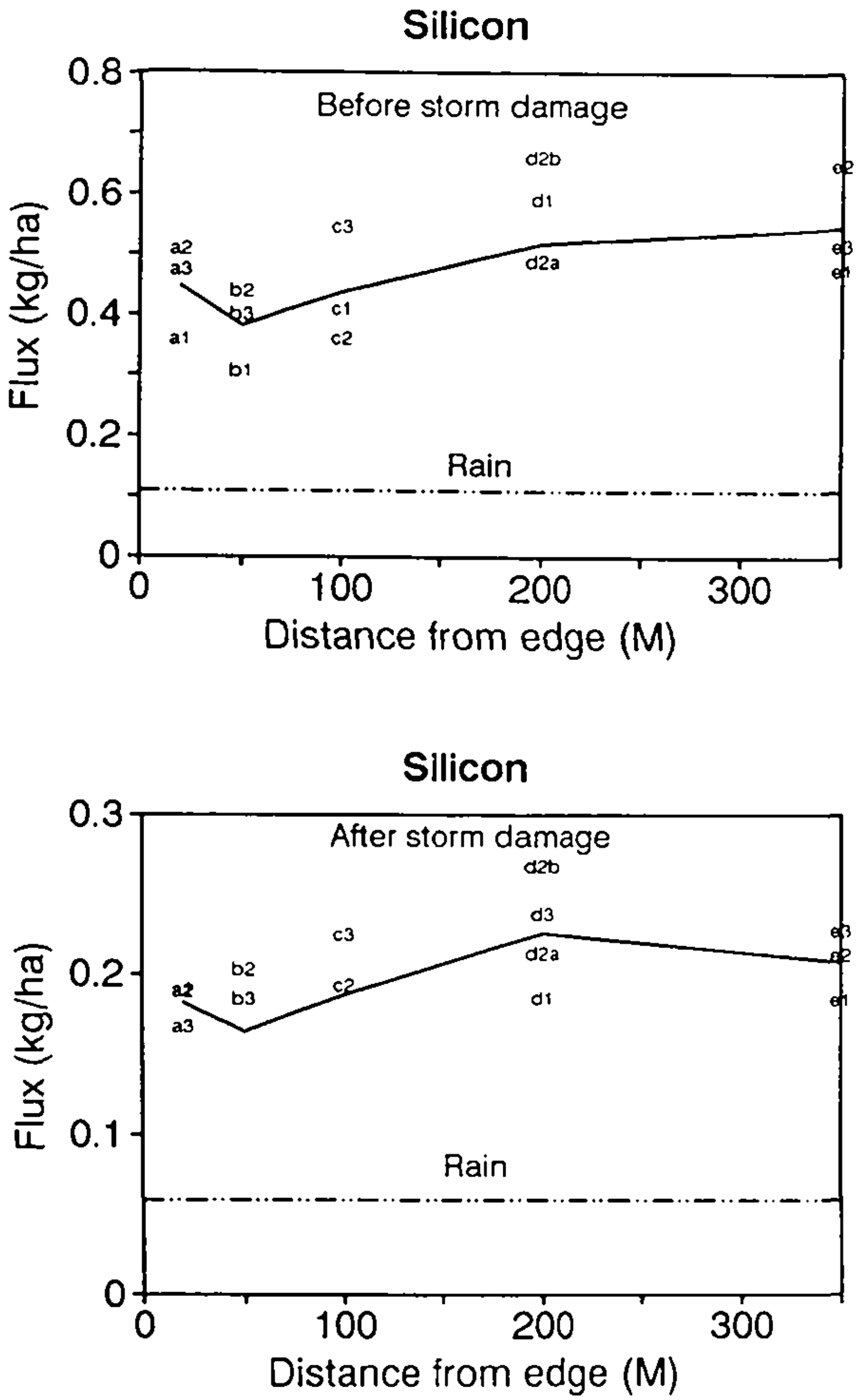
Silicon
Before storm damage
Flux (kg/ha)
0.8
0.6
0.4
0.2
0
d2b
e2
d1
c3
a2
a3
e3
d2a
e1
b2
b3
c1
a1
c2
b1
Rain
0
100
200
300
Distance from edge (M)
Silicon
After storm damage
Flux (kg/ha)
0.3
0.2
0.1
0
d2b
d3
c3
e3
e2
b2
d2a
a2
c2
b3
d1
e1
a3
Rain
0
100
200
300
Distance from edge (M)

Figure 7.1

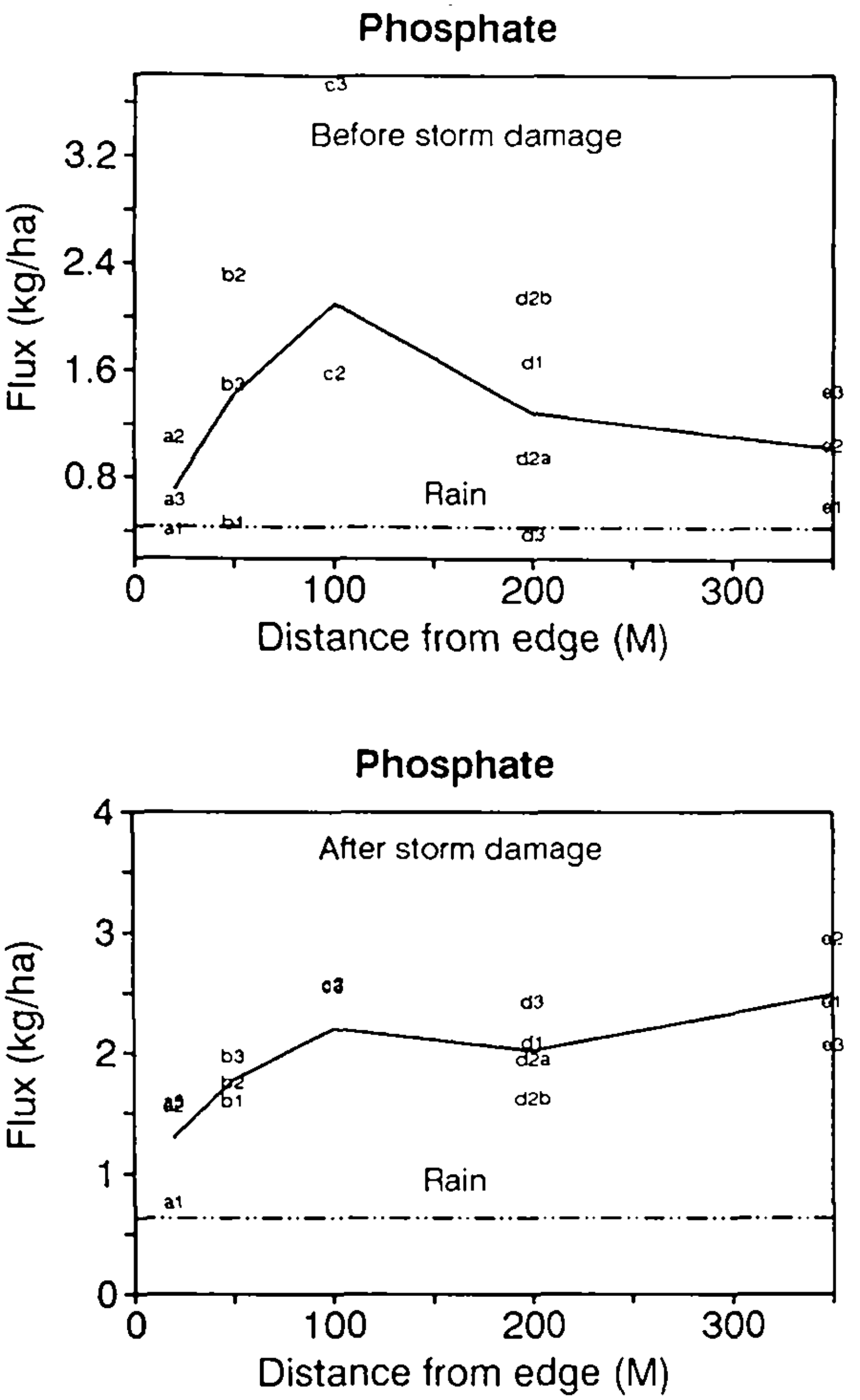
Phosphate
Before storm damage
Flux (kg/ha)
3.2
2.4
1.6
0.8
c3
b2
d2b
b3
c2
d1
e3
a2
e2
d2a
a3
Rain
e1
a1
b1
d3
0
100
200
300
Distance from edge (M)
Phosphate
After storm damage
Flux (kg/ha)
4
3
2
1
0
e2
c3
d3
e1
b3
d1
d2a
e3
a2
b2
b1
d2b
Rain
a1
0
100
200
300
Distance from edge (M)

Figure 7.1

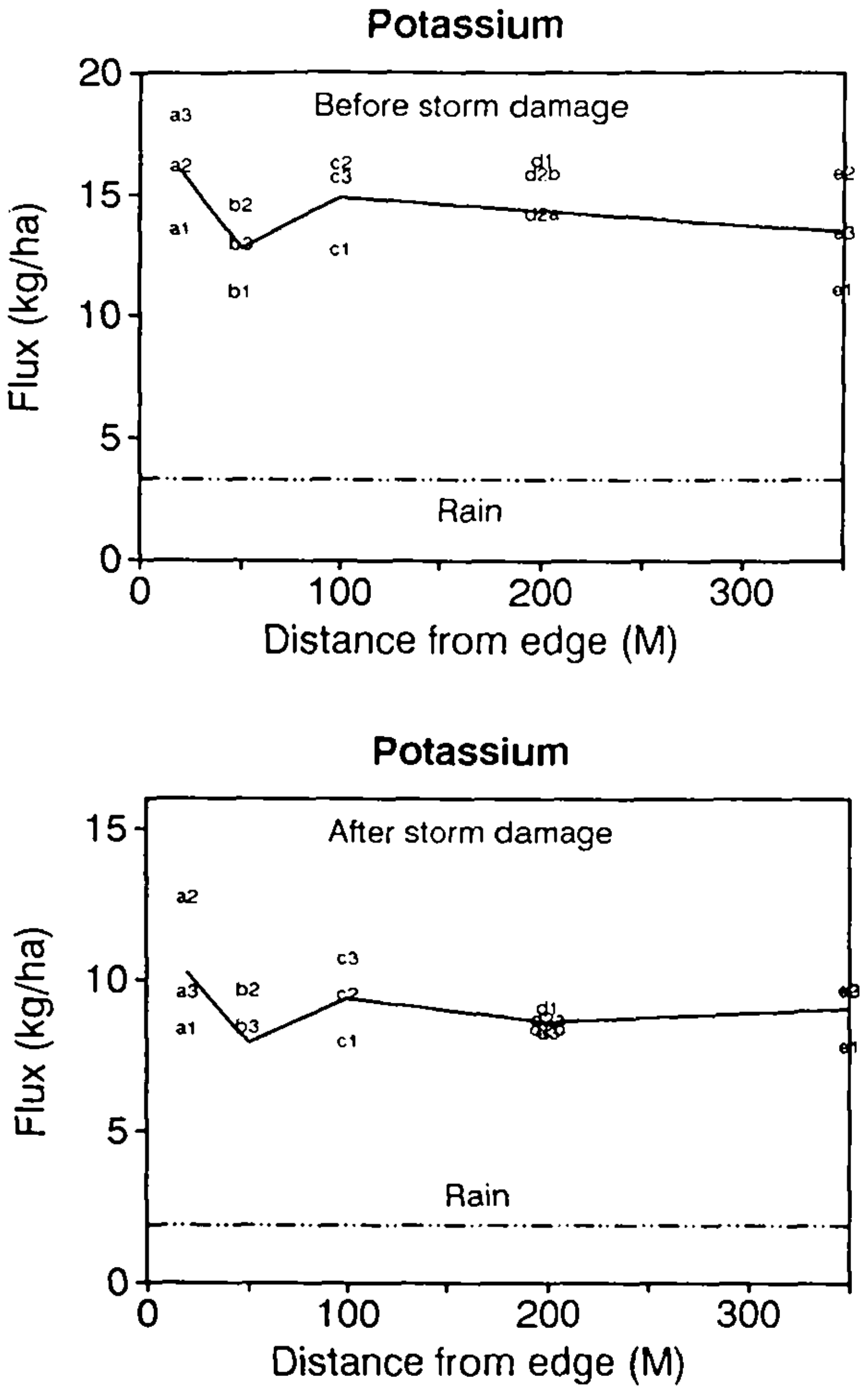
Potassium
Before storm damage
Flux (kg/ha)
20
15
10
5
0
a3
a2
a1
b2
b3
b1
c2
c3
c1
d1
d2b
d2a
e2
e3
e1
Rain
0
100
200
300
Distance from edge (M)
Potassium
After storm damage
Flux (kg/ha)
15
10
5
0
a2
a3
a1
b2
b3
c3
c2
c1
d1
e3
e1
Rain
0
100
200
300
Distance from edge (M)

Figure 7.1

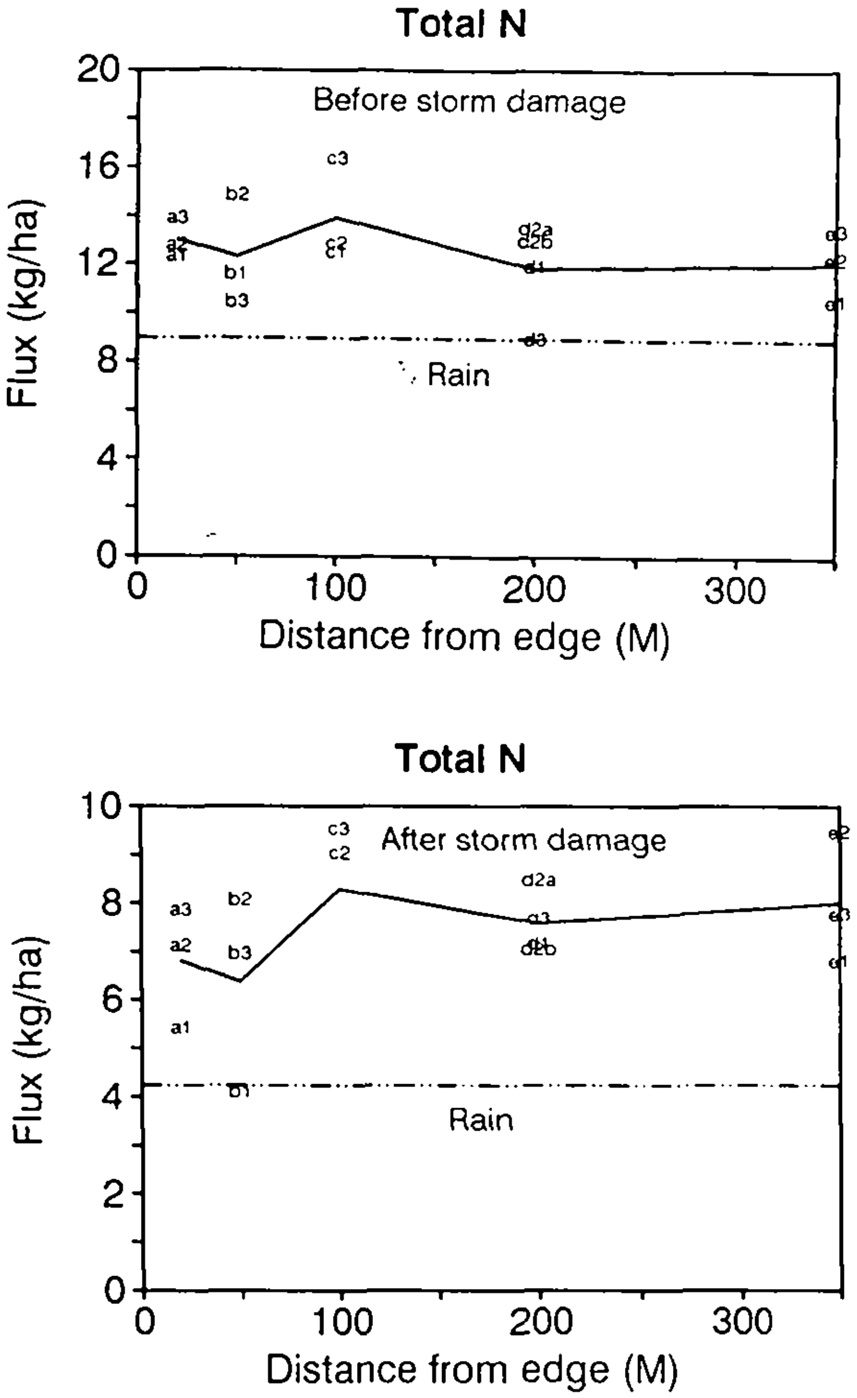
Total N
Before storm damage
Flux (kg/ha)
20
16
12
8
4
0
0
100
200
300
Distance from edge (M)
a1
a2
a3
b1
b2
b3
c1
c2
c3
d1
d2a
d2b
d3
e1
e2
e3
Rain
Total N
After storm damage
Flux (kg/ha)
10
8
6
4
2
0
0
100
200
300
Distance from edge (M)
a1
a2
a3
b1
b2
b3
c2
c3
d1
d2a
d2b
d3
e1
e2
e3
Rain

Figure 7.1

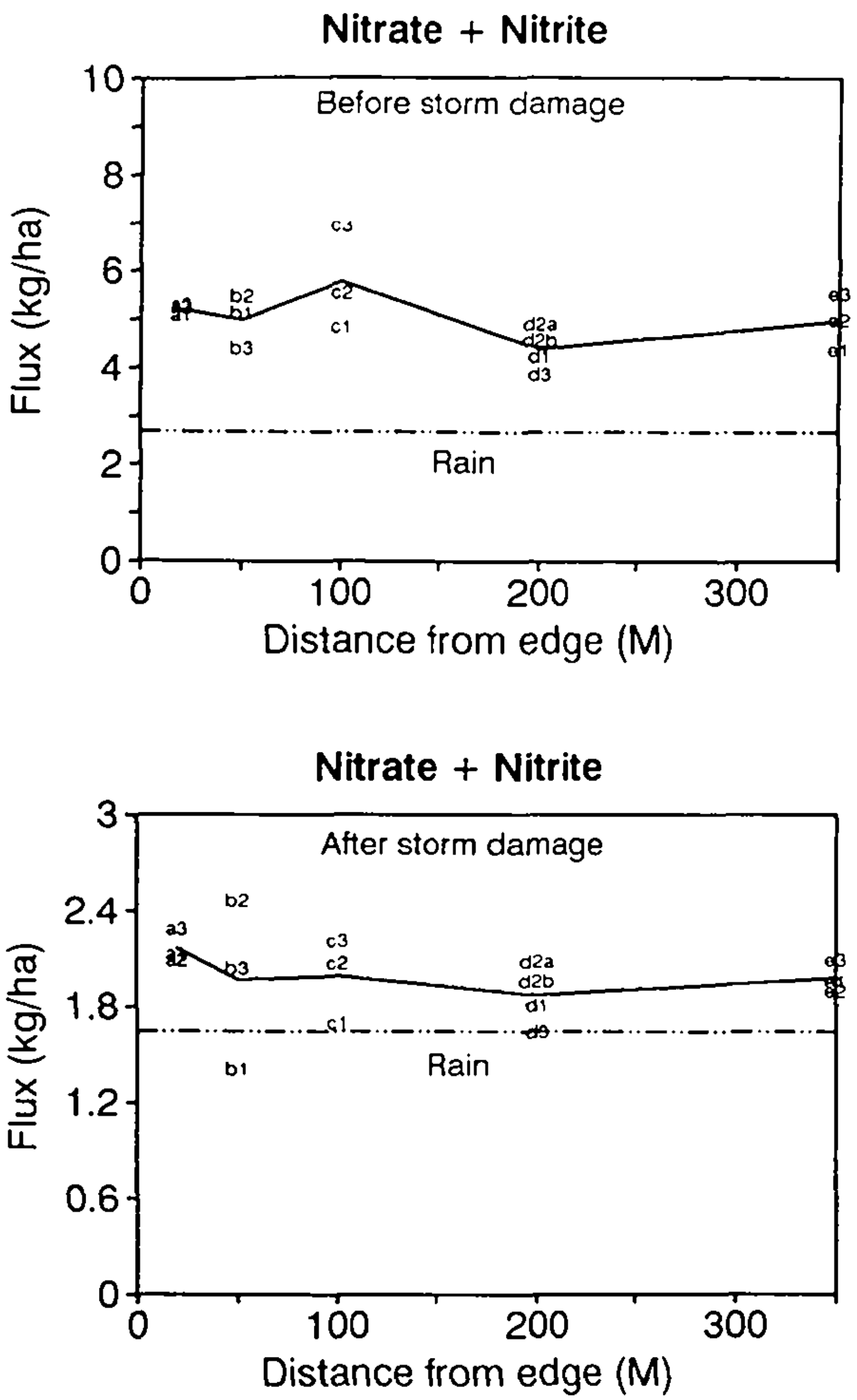
Nitrate + Nitrite
Before storm damage
Flux (kg/ha)
10
8
6
4
2
0
0
100
200
300
Distance from edge (M)
a1
a2
a3
b1
b2
b3
c1
c2
c3
d1
d2a
d2b
d3
e1
e2
e3
Rain
Nitrate + Nitrite
After storm damage
Flux (kg/ha)
3
2.4
1.8
1.2
0.6
0
0
100
200
300
Distance from edge (M)
a1
a2
a3
b1
b2
b3
c1
c2
c3
d1
d2a
d2b
d3
e1
e2
e3
Rain

Figure 7.1

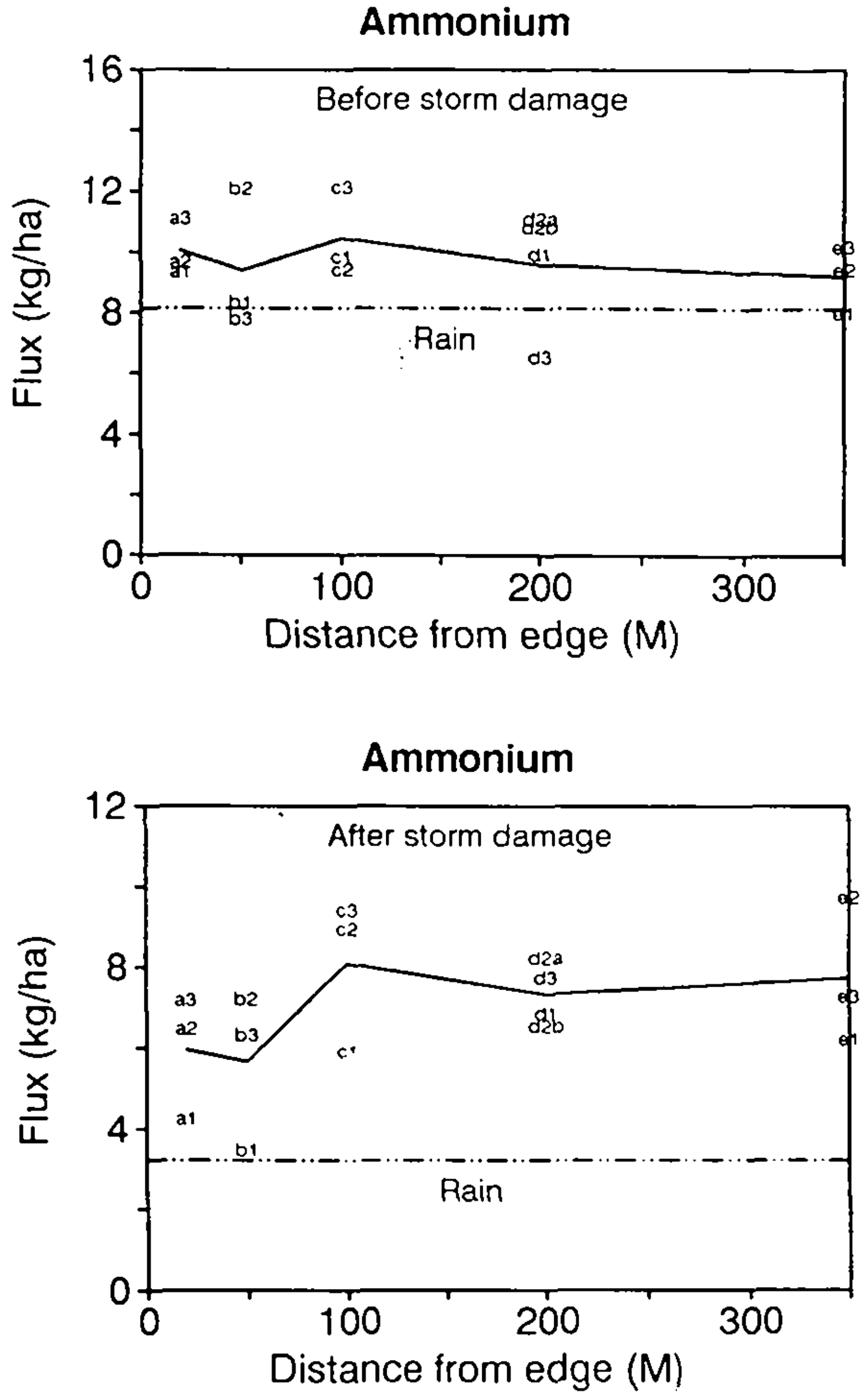
Ammonium
Before storm damage
Flux (kg/ha)
16
12
8
4
0
0
100
200
300
Distance from edge (M)
a3
a2
a1
b2
b1
b3
c3
c1
c2
d2a
d2b
d1
d3
e3
e2
e1
Rain
Ammonium
After storm damage
Flux (kg/ha)
12
8
4
0
0
100
200
300
Distance from edge (M)
a3
a2
a1
b2
b3
b1
c3
c2
c1
d2a
d3
d1
d2b
e2
e3
e1
Rain

Figure 7.1

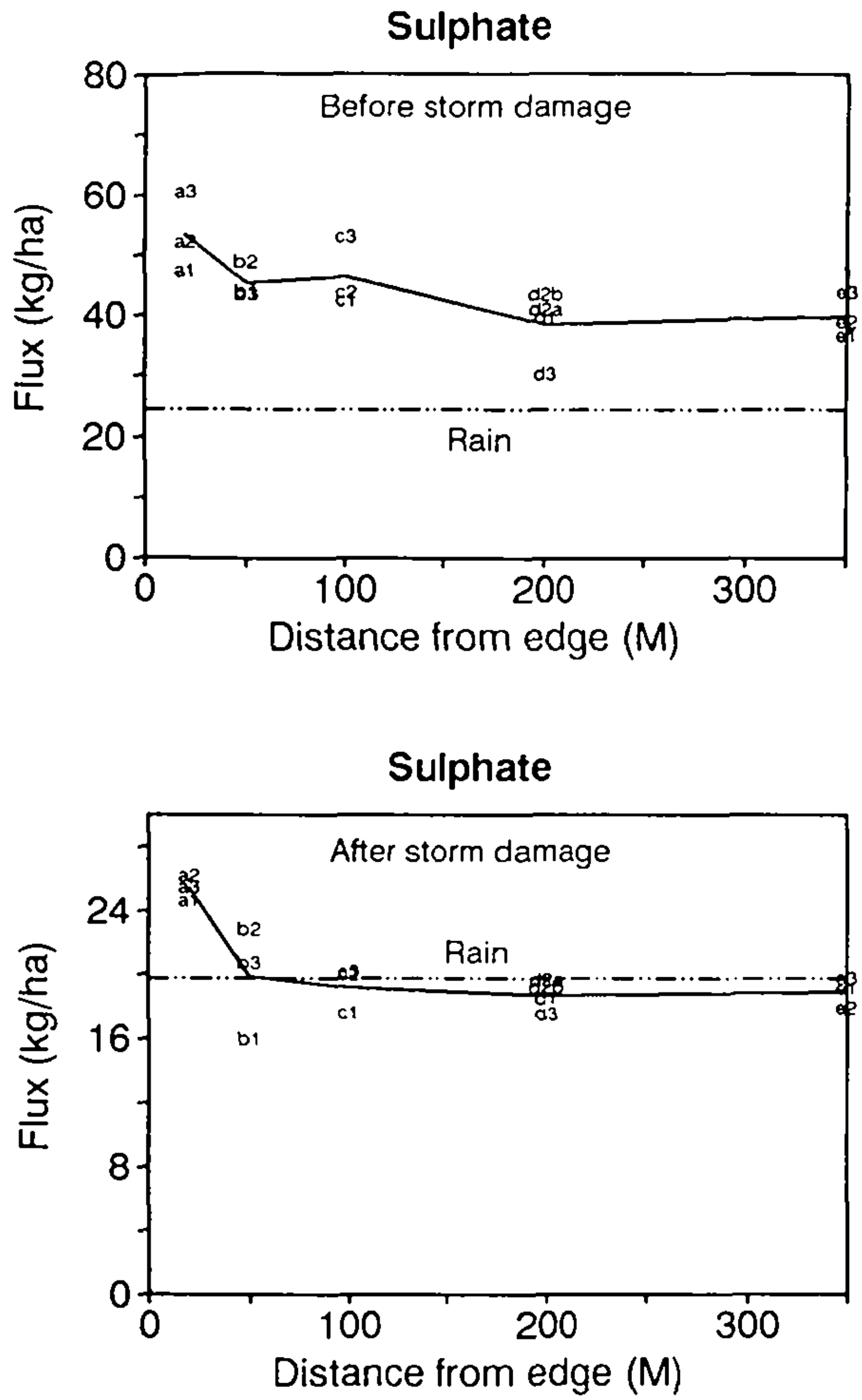
Sulphate
Before storm damage
Flux (kg/ha)
80
60
40
20
0
a3
a2
a1
b2
b3
c3
c2
c1
d2b
d2a
d1
d3
e3
e2
e1
Rain
0
100
200
300
Distance from edge (M)
Sulphate
After storm damage
Flux (kg/ha)
24
16
8
0
a2
a3
a1
b2
b3
b1
c3
c1
d2a
d2b
d1
d3
e3
e1
e2
Rain
0
100
200
300
Distance from edge (M)

Figure 7.1

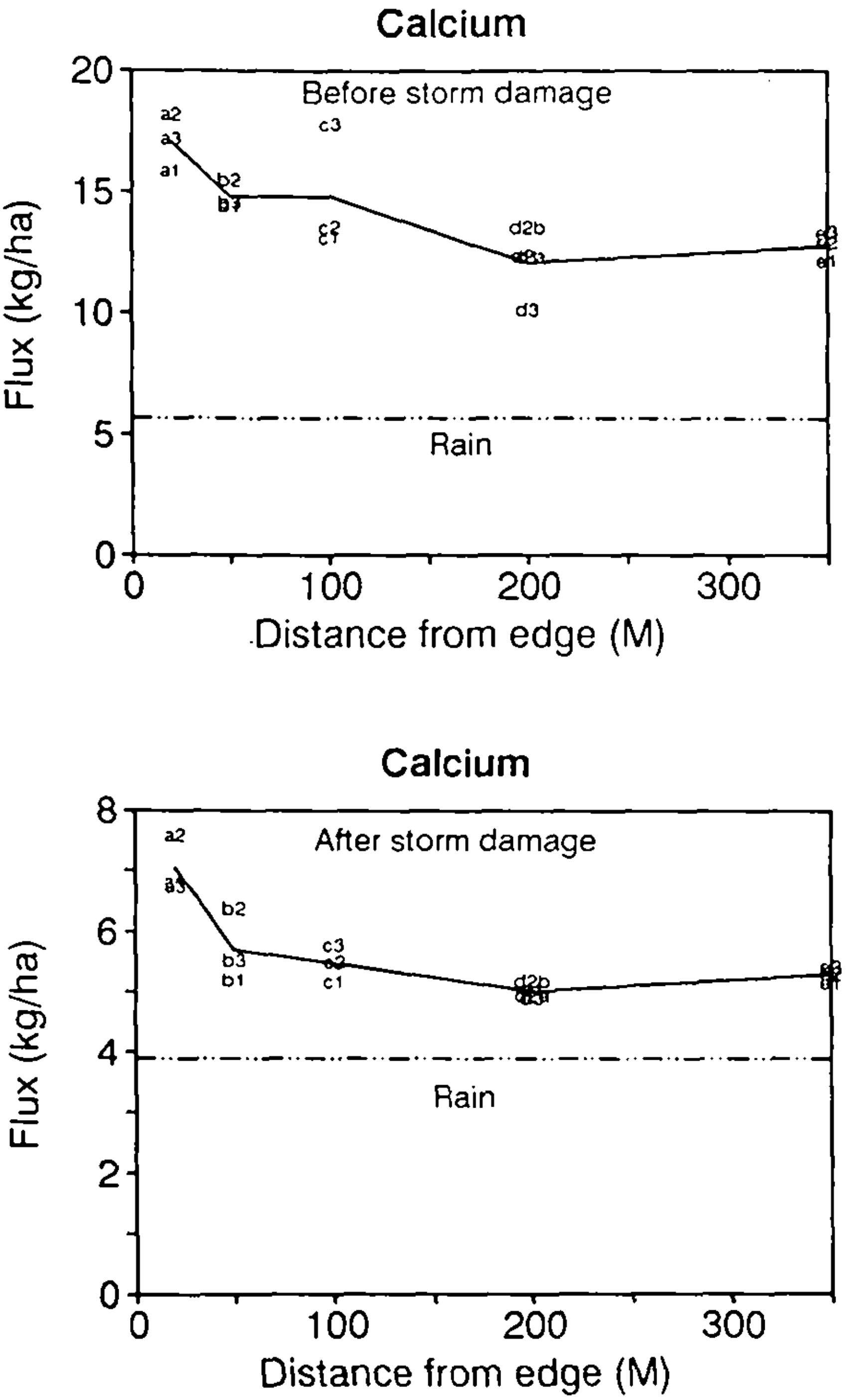Calcium
Before storm damage
Flux (kg/ha)
20
15
10
5
0
a2
a3
a1
b2
b1
c3
c2
c1
d2b
d3
e1
Rain
0
100
200
300
Distance from edge (M)
Calcium
After storm damage
Flux (kg/ha)
8
6
4
2
0
a2
a3
b2
b3
b1
c3
c2
c1
d2b
Rain
0
100
200
300
Distance from edge (M)

Figure 7.1

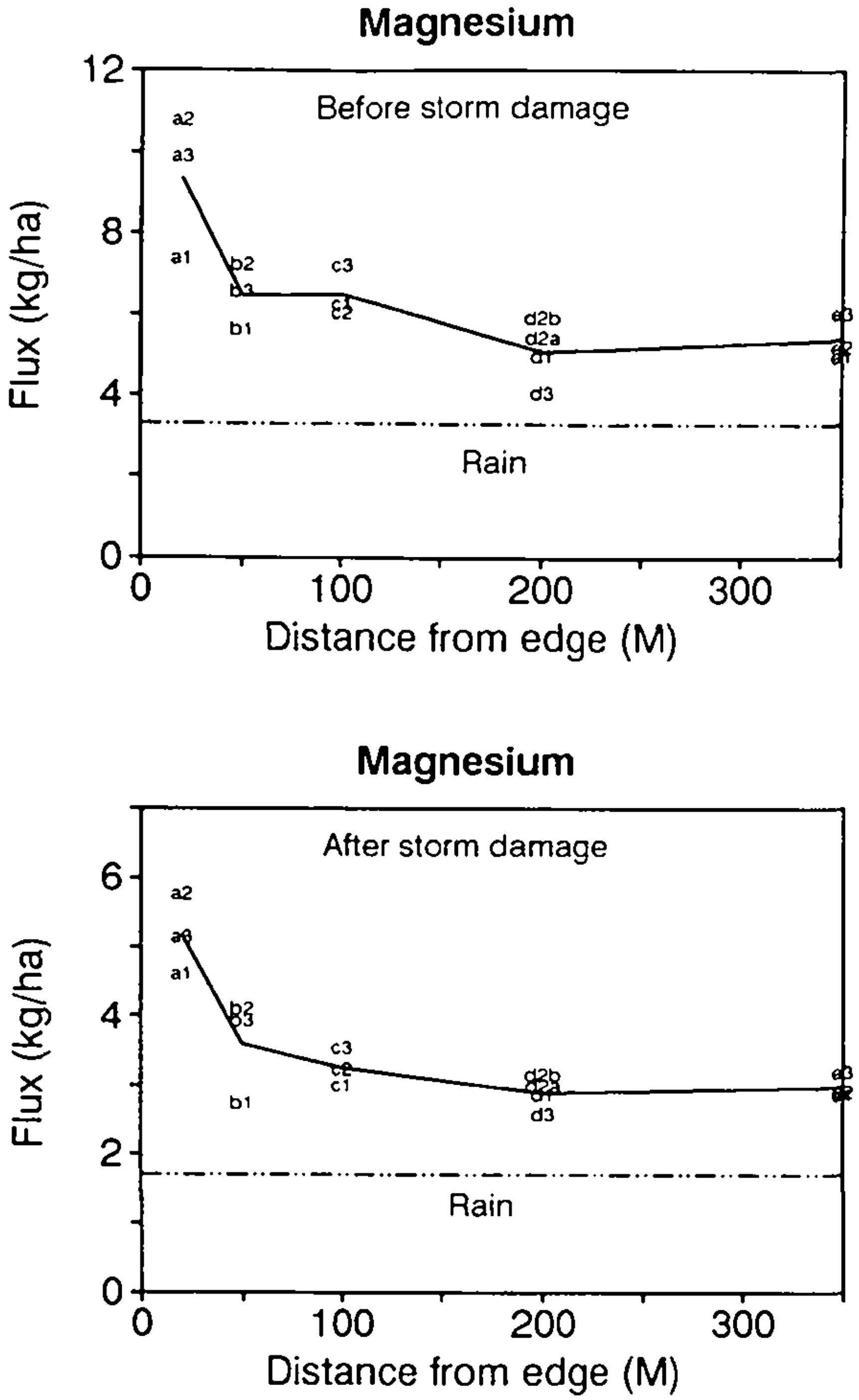
Magnesium
Before storm damage
Flux (kg/ha)
0
4
8
12
a2
a3
a1
b2
b3
b1
c3
c1
c2
d2b
d2a
d1
d3
e3
Rain
0
100
200
300
Distance from edge (M)
Magnesium
After storm damage
Flux (kg/ha)
0
2
4
6
a2
a3
a1
b2
b3
b1
c3
c2
c1
d2b
d2a
d1
d3
e3
Rain
0
100
200
300
Distance from edge (M)

Figure 7.1

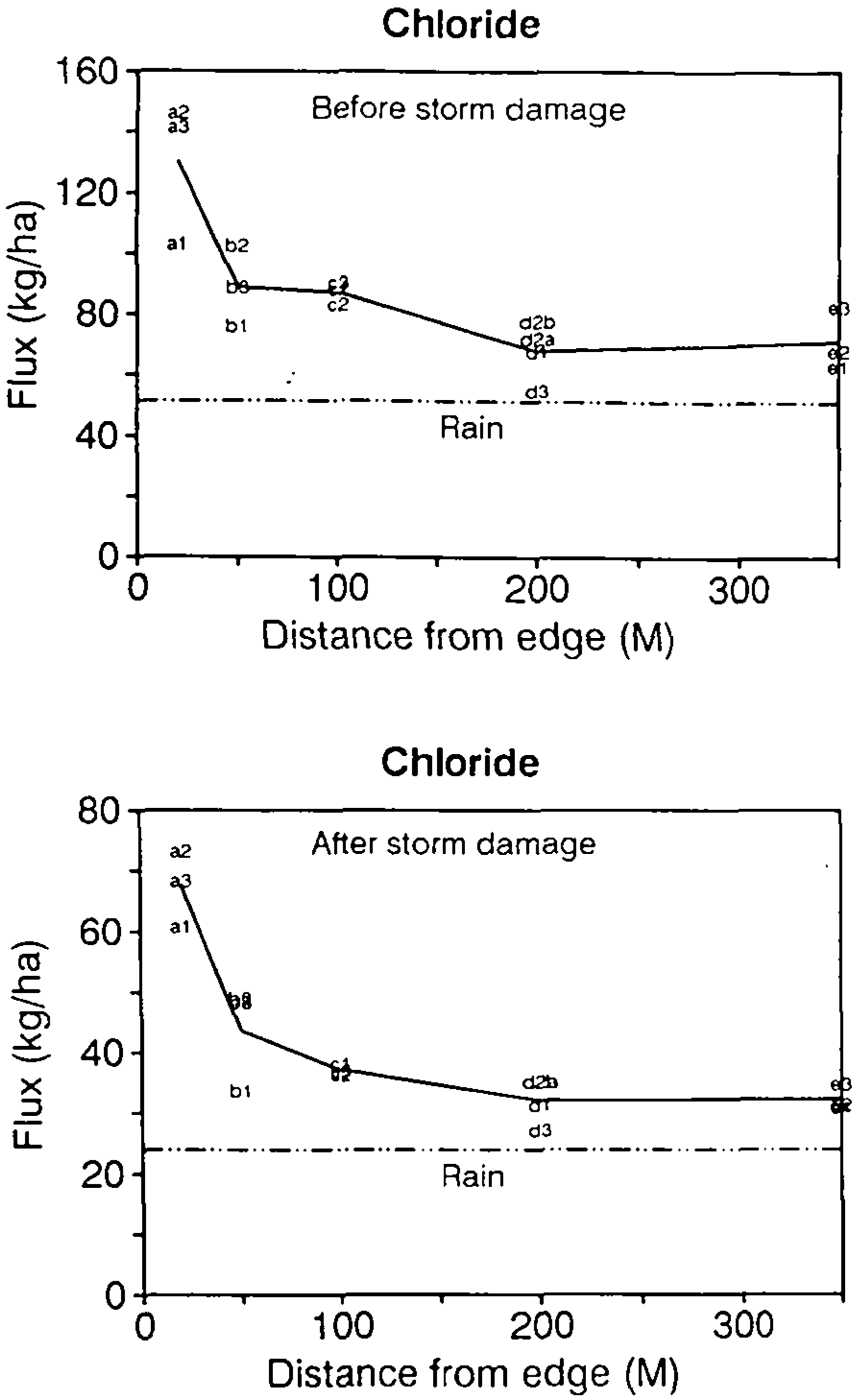Chloride
Before storm damage
Flux (kg/ha)
Distance from edge (M)
0
40
80
120
160
0
100
200
300
a2
a3
a1
b2
b3
b1
c3
c1
c2
d2b
d2a
d1
d3
e3
e2
e1
Rain
Chloride
After storm damage
Flux (kg/ha)
Distance from edge (M)
0
20
40
60
80
0
100
200
300
a2
a3
a1
b2
b3
b1
c1
c2
d2b
d1
d3
e3
e2
e1
Rain

Figure 7.1

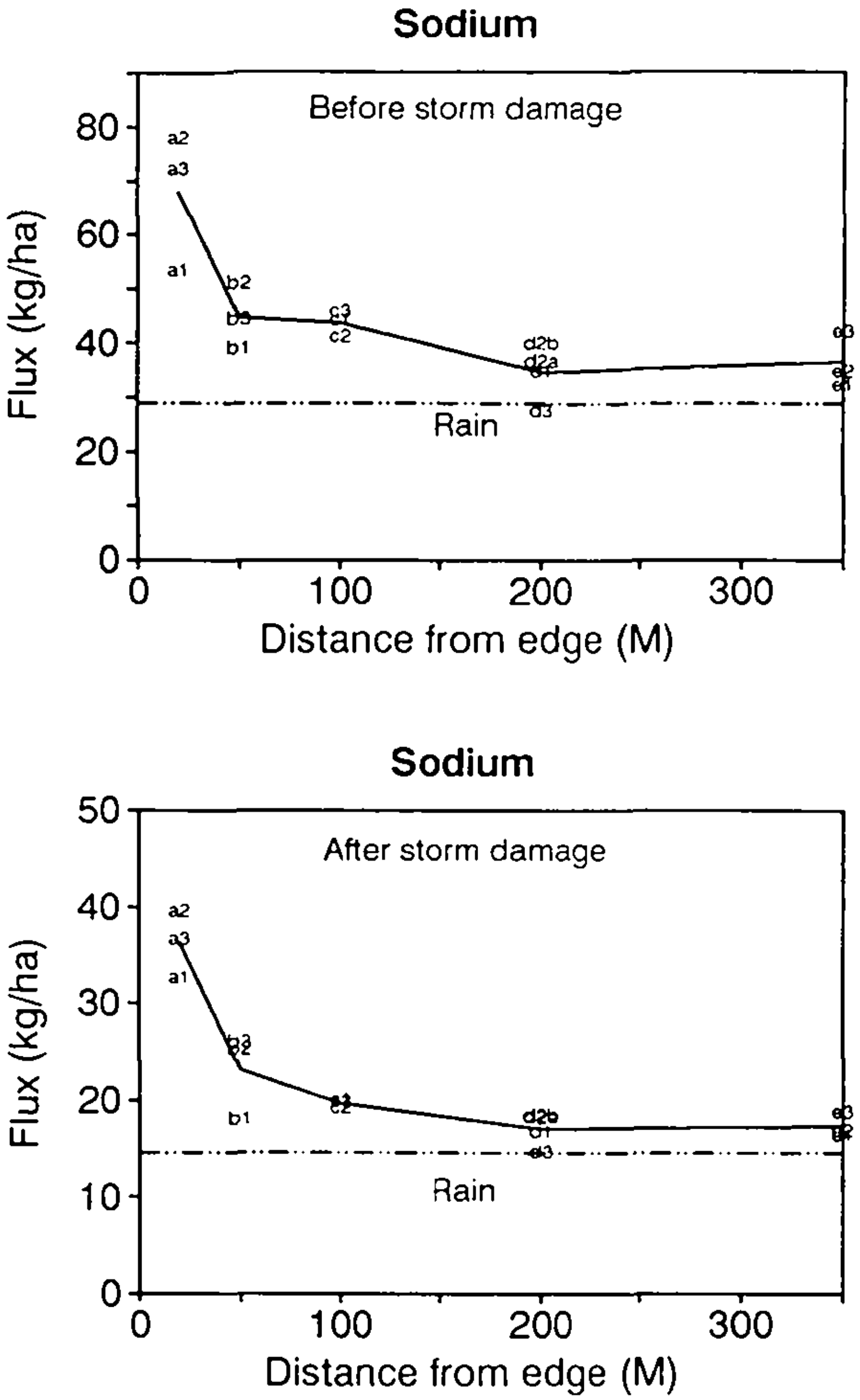
Sodium
Before storm damage
Flux (kg/ha)
80
60
40
20
0
a2
a3
a1
b2
b3
b1
c3
c1
c2
d2b
d2a
d1
d3
e3
e2
e1
Rain
0
100
200
300
Distance from edge (M)
Sodium
After storm damage
Flux (kg/ha)
50
40
30
20
10
0
a2
a3
a1
b3
b2
b1
c1
c2
d2b
d1
d3
e3
e2
e1
Rain
0
100
200
300
Distance from edge (M)

Figure 7.1

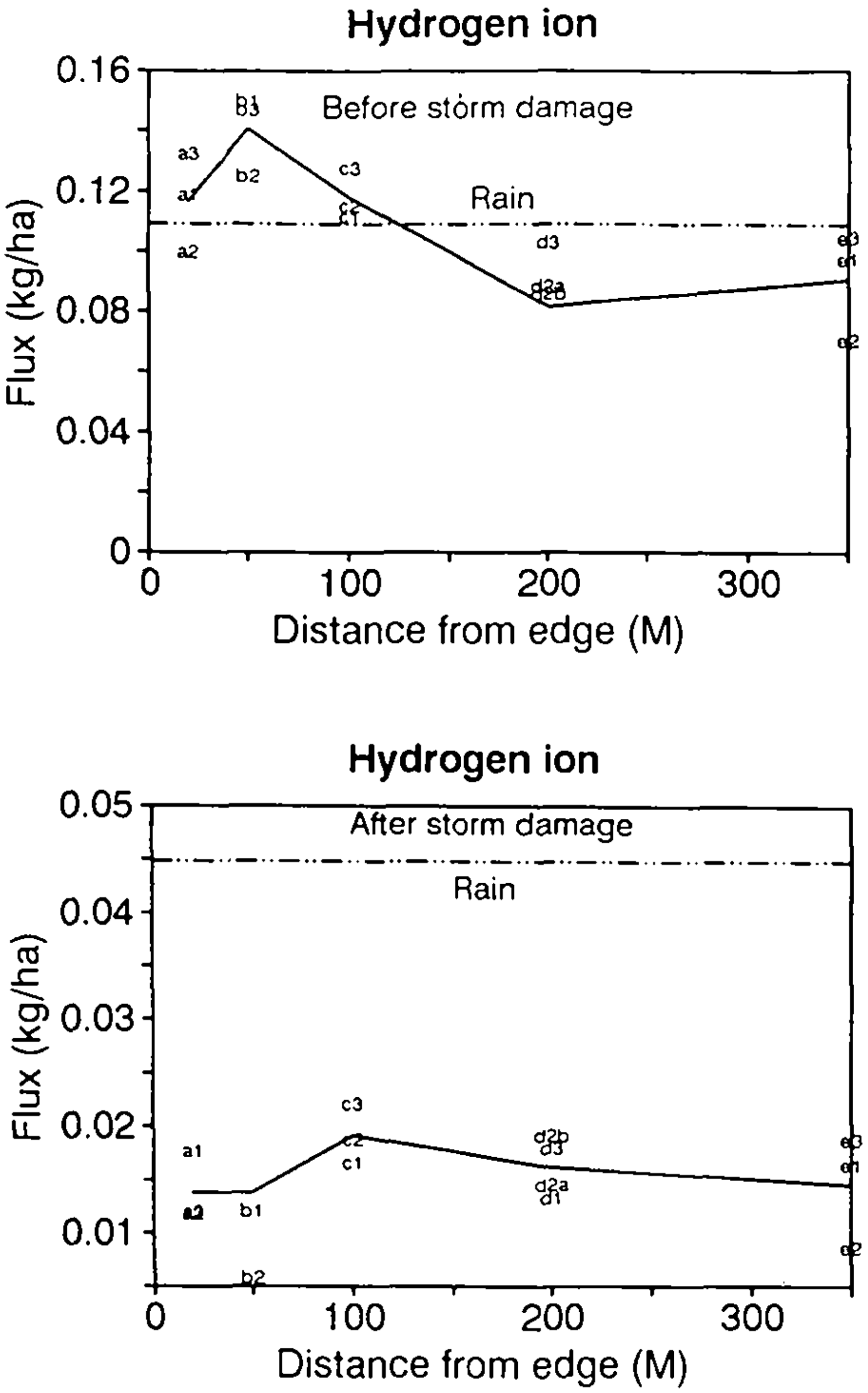
Hydrogen ion
Before storm damage
Rain
Flux (kg/ha)
0.16
0.12
0.08
0.04
0
0
100
200
300
Distance from edge (M)
a1
a2
a3
b1
b2
c1
c2
c3
d1
d2a
d2b
d3
e1
e2
e3
Hydrogen ion
After storm damage
Rain
Flux (kg/ha)
0.05
0.04
0.03
0.02
0.01
0
100
200
300
Distance from edge (M)
a1
a2
b1
b2
c1
c2
c3
d1
d2a
d2b
d3
e1
e2
e3

Figure 7.1

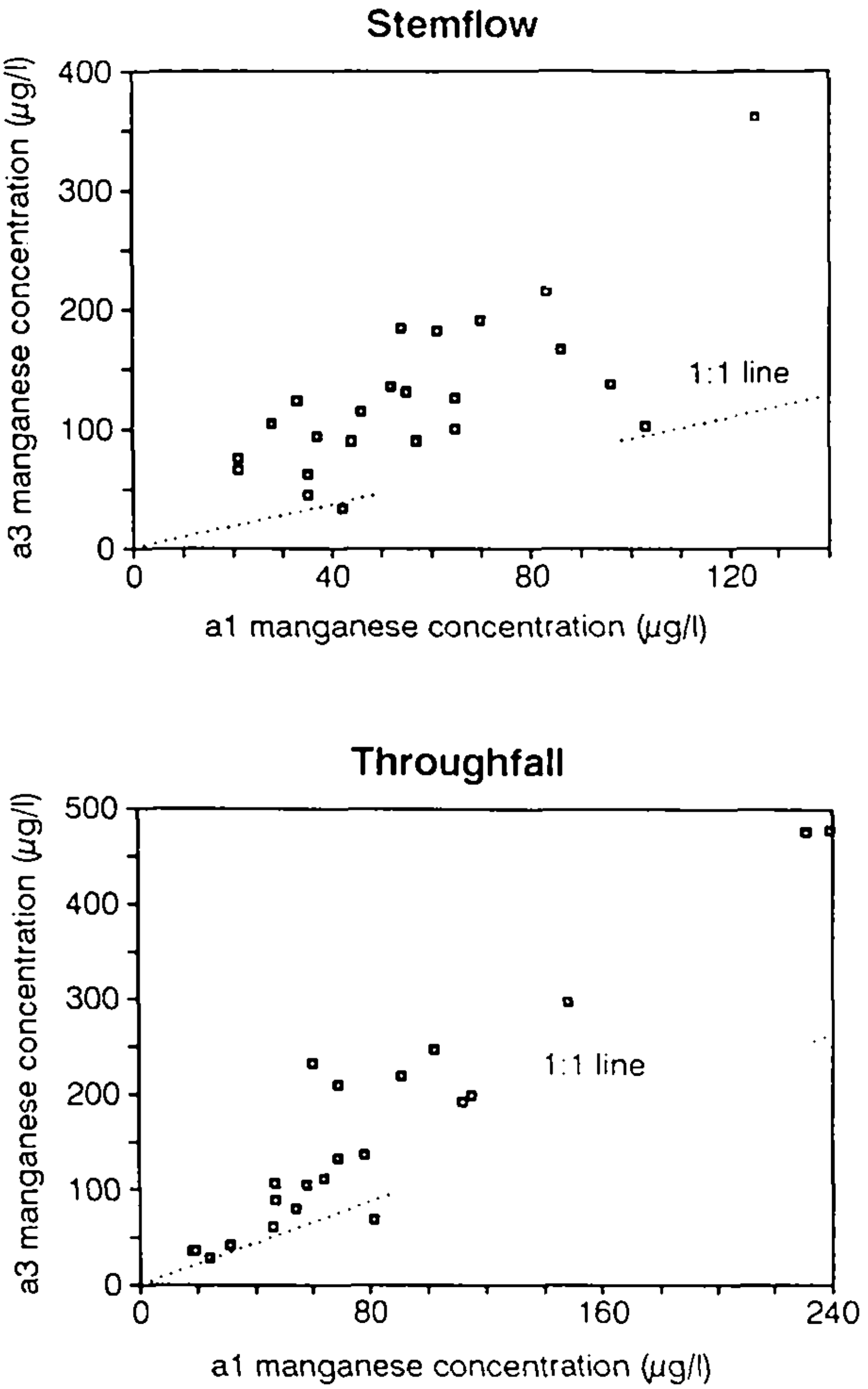

Figure 7.2 Manganese concentration covariations, in stemflow and throughfall, for plots a1 and a3. Data cover the period 1/5/1989 to 21/8/1990

Table 7.2 Rainfall, stemflow and throughfall concentrations for the major elements. All units are µg/l. Bracketed values indicate the range in concentration.

Element	Rainfall	Stemflow	Throughfall
B	2 (0-50)	21 (0-180)	15 (0-180)
Sr		10 (0-58)	10 (3-56)
Ba		4 (0-84)	10 (0-1042)
Mn	19 (0-89)	57 (5-362)	87 (3-633)
Fe	43 (0-1140)	26 (0-660)	31 (0-1840)
Cu	0.3 (0-30)	0.2 (0-30)	0.2 (0-30)
Al	63 (0-1800)	5 (0-400)	0.5 (0-140)
Zn		27 (0-350)	43 (0-970)
H^+	18.0 (0.1-115)	51.7 (0.03-407)	15.7 (0.01-123)

The rainfall flux is lower than the corresponding flux through the forest canopy for all the chemical determinands (Figure 7.1). Sodium, magnesium, chloride, and sulphate exhibit about a 5 to 30% increase away from the forest edge: near the forest edge larger differences are encountered. Potassium, calcium, manganese and boron show increases between 80 and 300% and, in these cases, there are small differences between the edge and the interior of the forest (Figure 7.1). The nitrogen species show increases between 20 and 100% with little enhancement near the forest edge (Figure 7.1).

Atmospheric ammonia, nitrogen oxide and sulphur oxide gas levels

During the past 12 months, average monthly ammonia concentrations have remained, for the main part, in the range 2 to 5 ppb. However during January and February of 1990, the average monthly concentrations were an order of magnitude higher (20 - 22 ppb). Data scatter also increased during these abnormal months, values ranging from less than 1 to 110 ppb. Ammonia concentrations above the canopy are roughly twice those in the forest. More detailed studies are required to see if this difference is significant since (1) for each assay only two above canopy assays are made (compared to 16 within the forest), (2) all the data shows large scatter and (3) the wind speeds will be far higher above the canopy than in the forest (this will affect the efficiency of the gas tubes).

Over the same period, monthly averaged nitrogen oxide concentrations have varied between 3 and 14 ppb, maximum values occurred in November 1989 and the lowest values were observed in January 1990. Nitrogen oxide concentrations were about the same above the canopy and inside the forest although, as with ammonia, it remains doubtful that reliable comparisons can be made at this stage.

Sulphur oxide determinations have been problematical owing to chemical contamination. The contamination has been identified following the rigorous field design: blank values show an excessively large range of values. This feature comes about due to poor sealing of the standard gas tubes used: modifications have been made and field trials are almost complete. Provisional results suggest sulphur oxide levels at Black Wood are in the range 0 to 11 ppb.

Discussion

For the chemical components such as sodium, chloride and sulphate, which are not cycled through the vegetation, there is only a small discrepancy between the wet rainfall input and the stemflow plus throughfall away from the forest edge. Since rainfall collectors are known to be inefficient in capturing small droplets and dry materials, an under-catch would be anticipated. This feature could easily account for most of the differences observed. The results strongly suggest that increased scavenging of chemicals occurs near the forest edge for those components essentially derived directly from the atmosphere. In the case of elements which are known to cycle through the vegetation (e.g. nitrate, calcium and potassium) the stemflow plus throughfall fluxes are higher, by factors of up to 2, than the rainfall flux. For this group of elements, the enhanced scavenging near the forest edge is small.

The network design used in this study seems to be of the correct scale to integrate the chemical and hydrological variability for localised (100 M2) regions. The results show remarkable consistency on a plot to plot scale. Whatever processes are determining water and chemical fluxes through the forest are uniform in their nature.

8. Old Pond Close

Site Selection

To complement the existing measurement programme at Black Wood an additional site was needed for two reasons:

1. To extend the range of environmental conditions, Black Wood is sited on chalk and although chalk is a common geological type in the UK it does

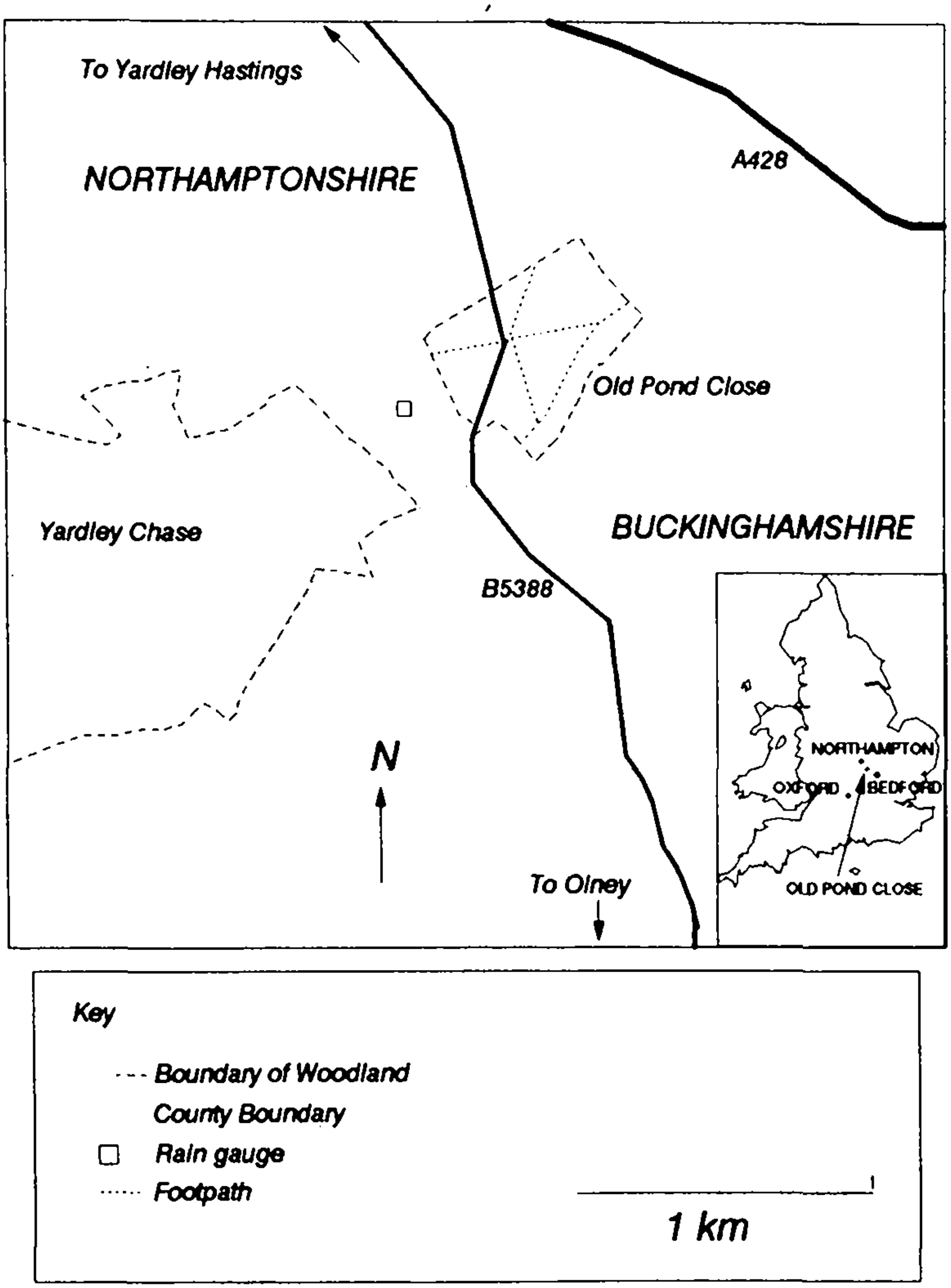

Figure 8.1 Location of Old Pond Close

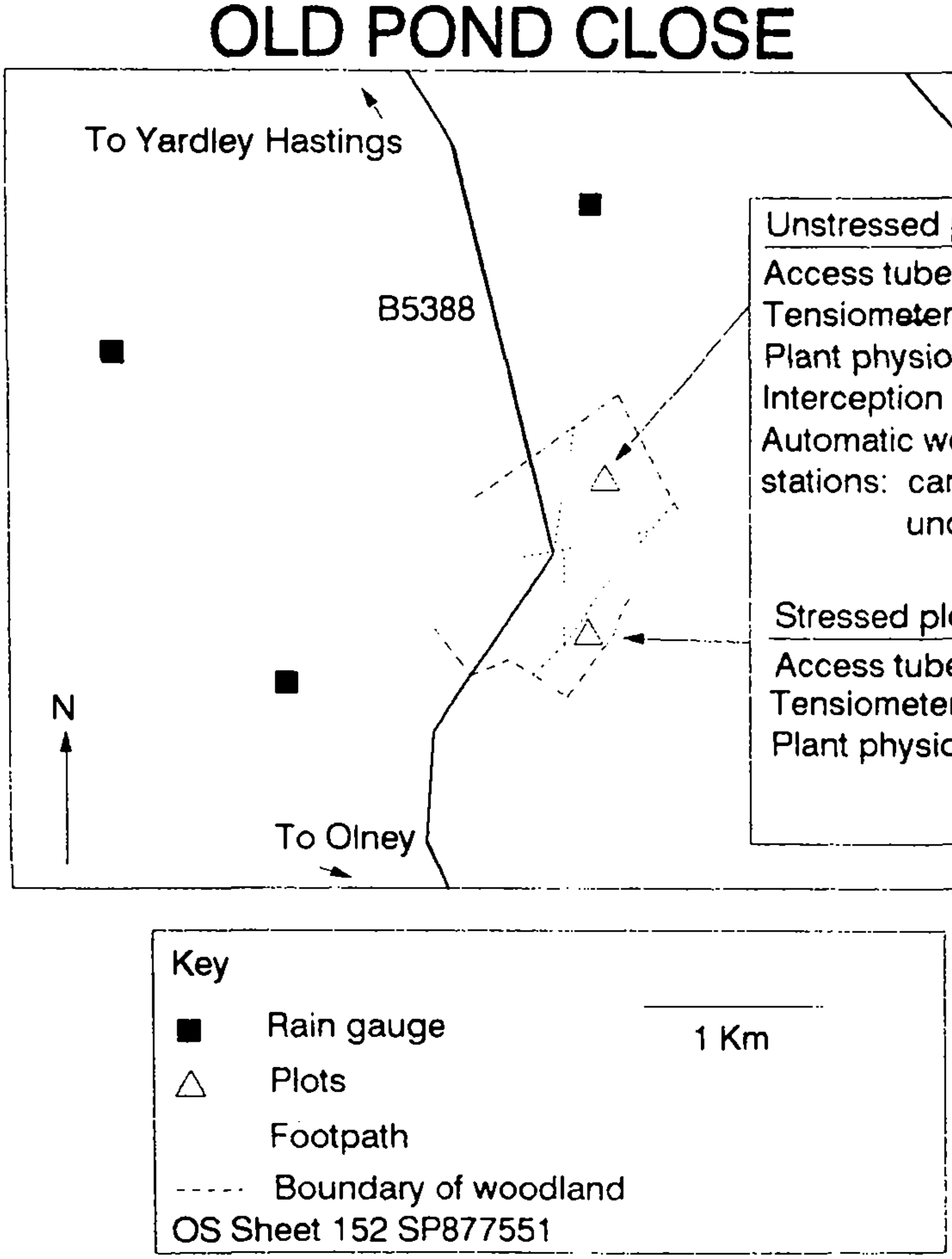

Figure 8.2 Location of unstressed (control) and stressed plots

have special water retention and transport facilities.

2. The ash site at Black Wood is small and may not be representative of larger ash plantations.

Old Pond Close near Olney, Figure 8.1 was selected as the second site. Old Pond Close (grid reference SP877551) is a small (25ha) Forestry Commission wood containing a variety of mature, mainly broadleaf species such as oak, poplar and large stands of ash on a clay soil. The land being managed by Compton Estates Management Services on behalf of the Marquess of Northampton, D.L.

The site has a flat topography making measurements of rainfall easy, is within one and a half hours drive from the Institute of Hydrology which allows frequent visits for data collection and has mature ash plantations within the mixed broadleaf woodland.

Experimental Plan

Soil moisture measurements from Black Wood for 1989 showed large deficits had built up beneath the ash and the beech plantations but that neither species had suffered as a result of this. To ensure that the effect of a soil moisture deficit would be experienced by the ash trees it was planned to physically isolate a group of trees from receiving any rainfall. Old Pond Close consists of two plots (200 m apart) one a control (unstressed) plot and the other a stressed plot. The stressed plot consists of a group of 4 trees isolated from the rest of the trees by a 1m deep ditch. A rope network with suspended black plastic covers the plot to stop all rainfall from entering. The two plots, Figure 8.2, were instrumented in April and May 1990 as follows:

Control (unstressed plot)

1. Hiway tower with above canopy mounted automatic weather station. The tower also allows access to the canopy for plant physiological measurements.

2. Five randomly located access tubes for soil moisture measurements.

3. Tensiometer profile for determining soil water potential measurements.

4. Large plastic-sheet net-rainfall gauge for interception measurements.

5. Automatic weather station mounted above the understorey.

Stressed Plot

1. Hiway tower to allow access to the canopy for plant physiological measurements.

2. Five randomly sited access tubes for soil moisture measurements.

3. Tensiometer profile for determining soil water potential measurements.

Immediately adjacent to the stressed plot is a 30m x 15m plot of 20 randomly located trays for litter collection, Figure 8.3.

9. Old Pond Close observations 1990

A good set of meteorological, interception, soil moisture and plant physiological measurements have been made through 1990. Table 9.1 gives details of the measurements, their start date and frequency of observation.

Table 9.1: Measurements made at Old Pond Close

Measurement	Start Date	Frequency	Start Date	Frequency
Rainfall (network)	3.5.90 and 5.6.90	1 minute during storms and storage gauge		
	UNSTRESSED		STRESSED	
Interception				
Net rainfall gauge	3.5.90 4.4.90	5 minute Storm	NA	NA
Canopy level rainfall	3.5.90	5 minute	NA	NA
Meteorology				
Above canopy	3.5.90	5 minute and hourly	NA	NA
Below canopy	3.5.90	5 minute and hourly	NA	NA
Soil Moisture				
Neutron Probe	23.5.90	Weekly	23.5.90	Weekly
Tensiometers	26.6.90	Weekly	5.6.90	Weekly
Plant Physiology				
Stomatal Conductance	20.6.90	Fortnight	23.5.90	Fortnight
Leaf Water Potential	20.6.90	Fortnight	23.5.90	Fortnight
Leaf Area Index			to be done in Oct 1990	Fortnight

The two automatic weather stations were installed on 3 May 1990. Figures 9.1 and 9.2 show the daily net radiation and air temperature from the canopy

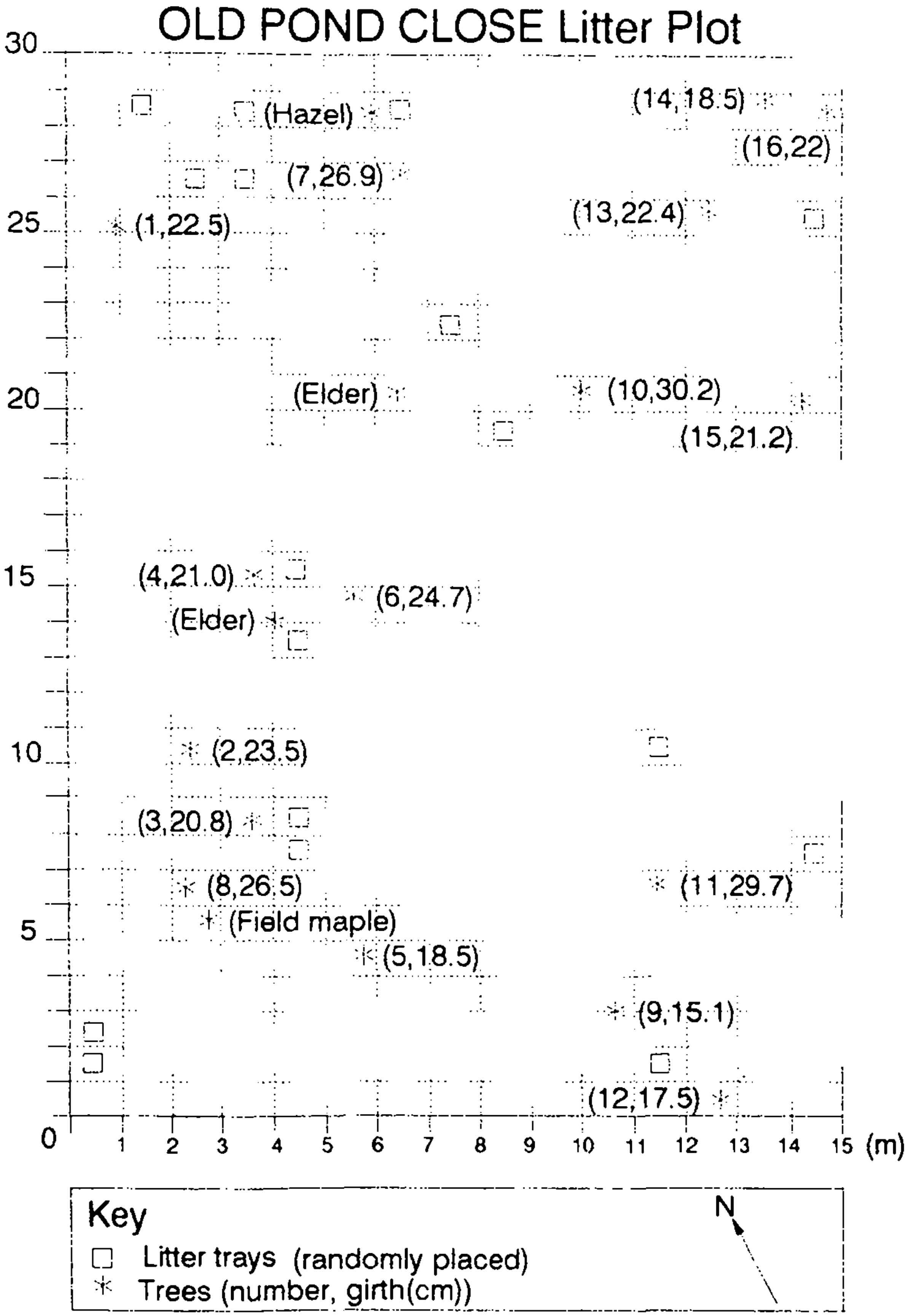

Figure 8.3 Map of litter plot

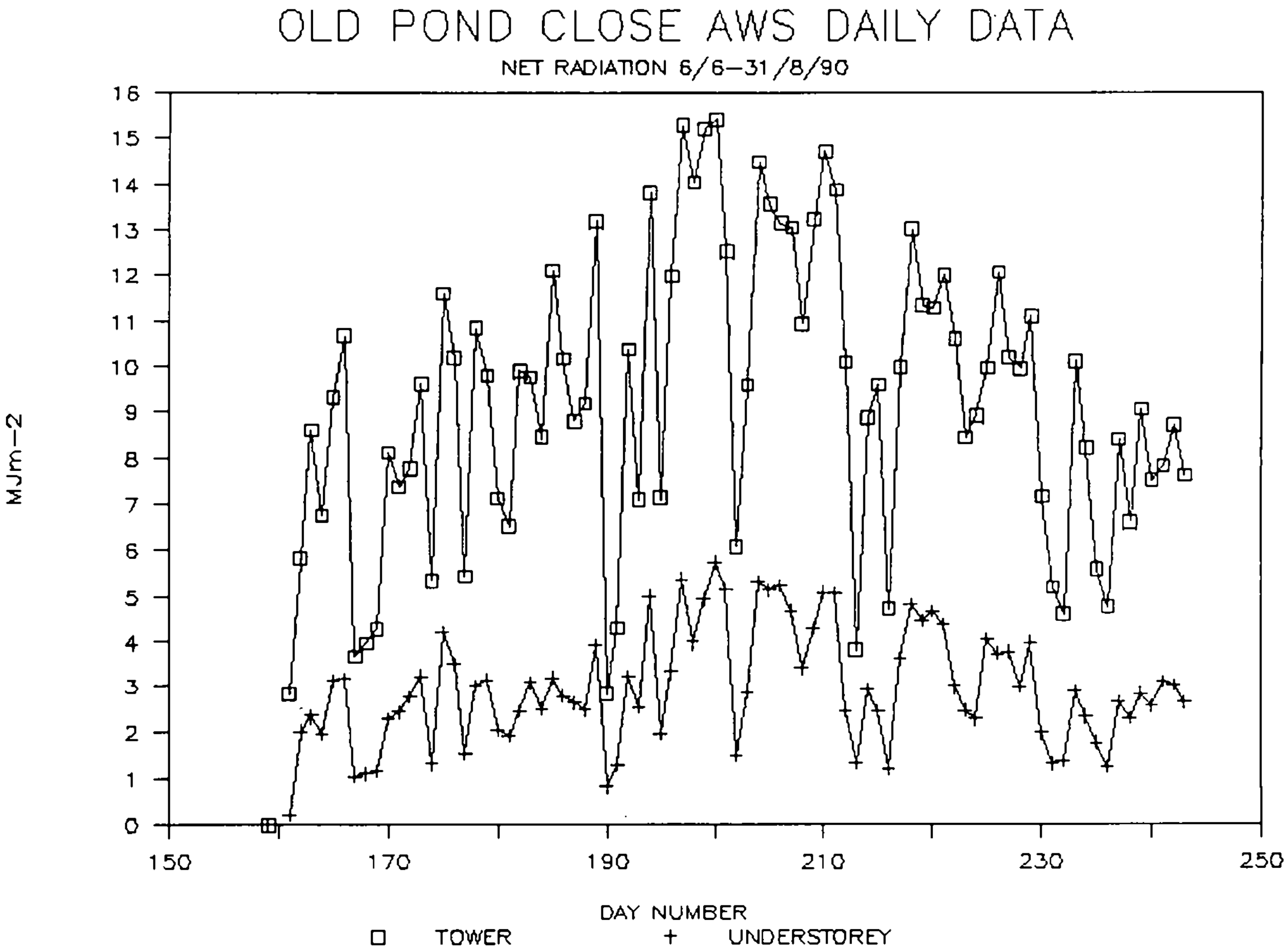

Figure 9.1 Daily total of net radiation from the canopy and understorey weather stations

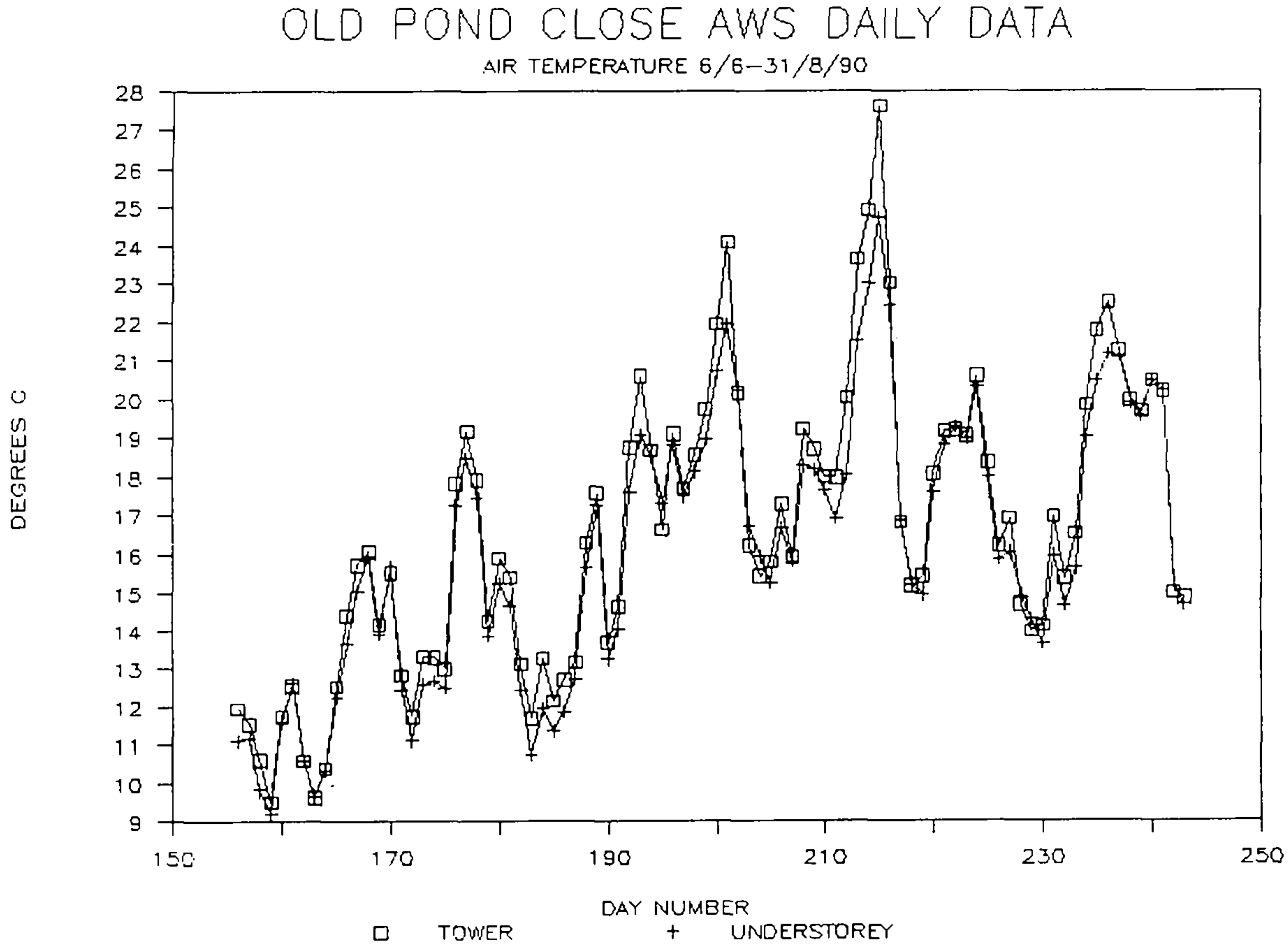

Figure 9.2 Daily air temperature from the canopy and understorey weather stations

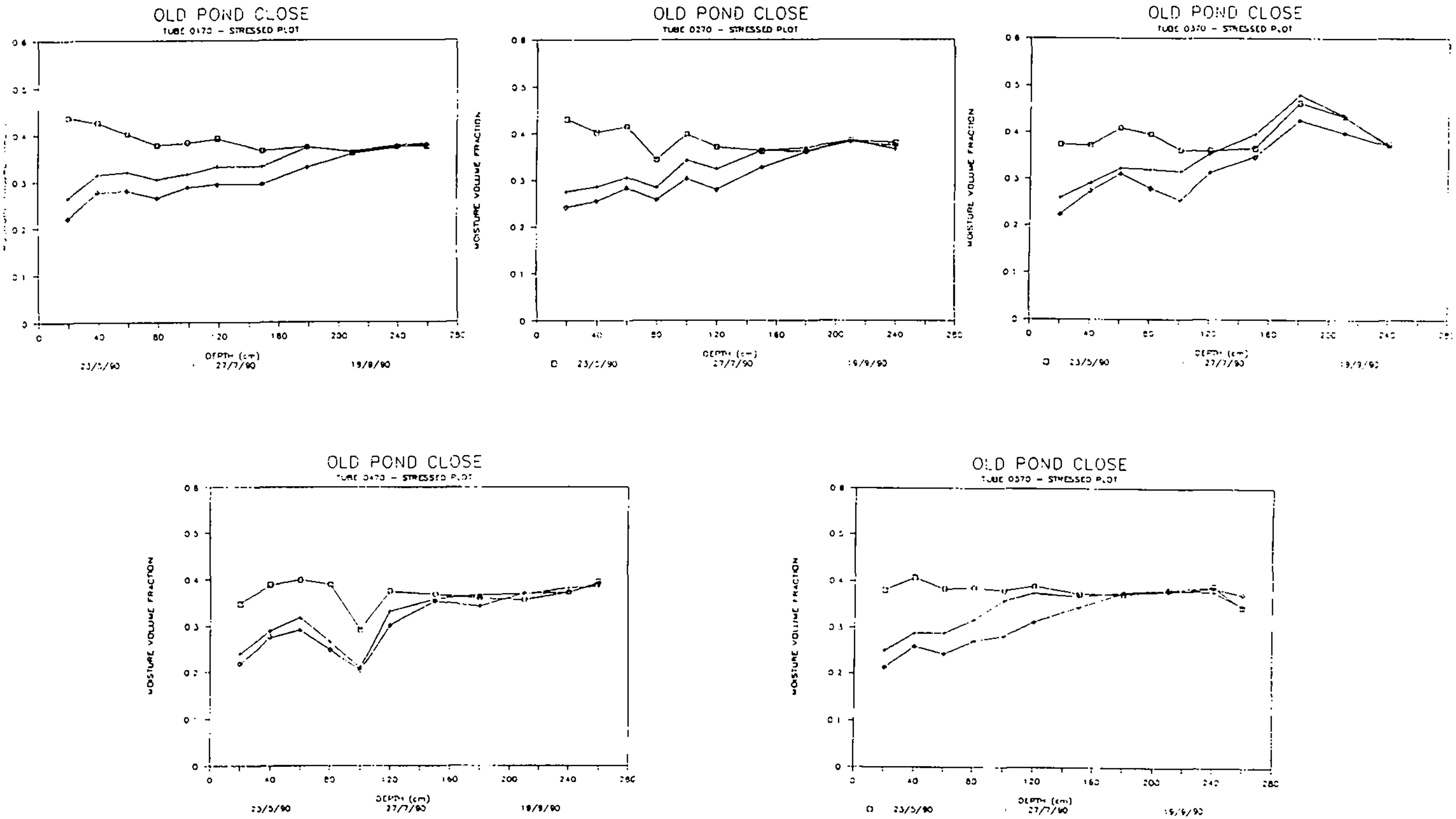

Figure 9.3 Soil moisture profiles from the stressed plot

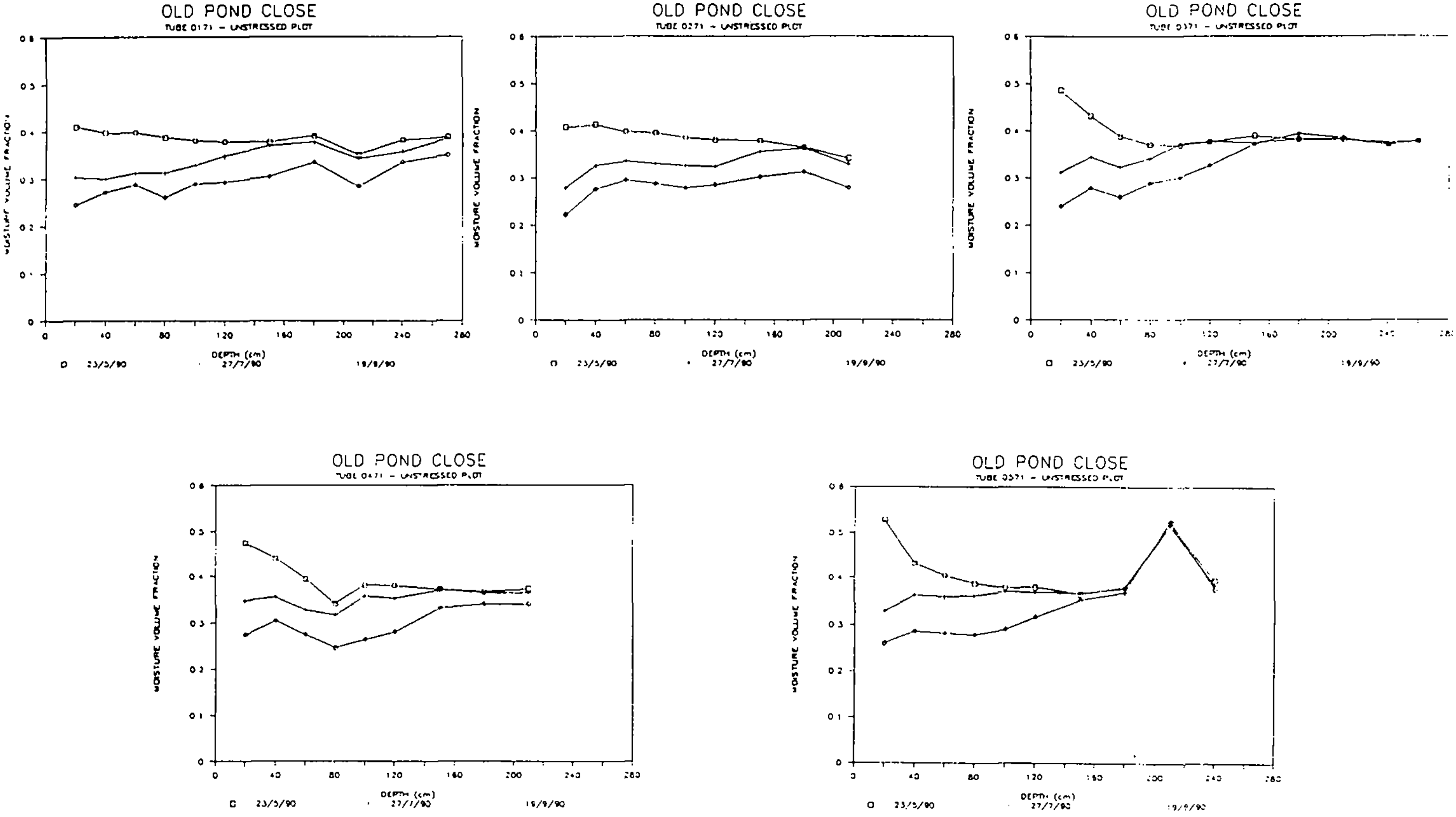

Figure 9.4 Soil moisture profiles for the unstressed plot

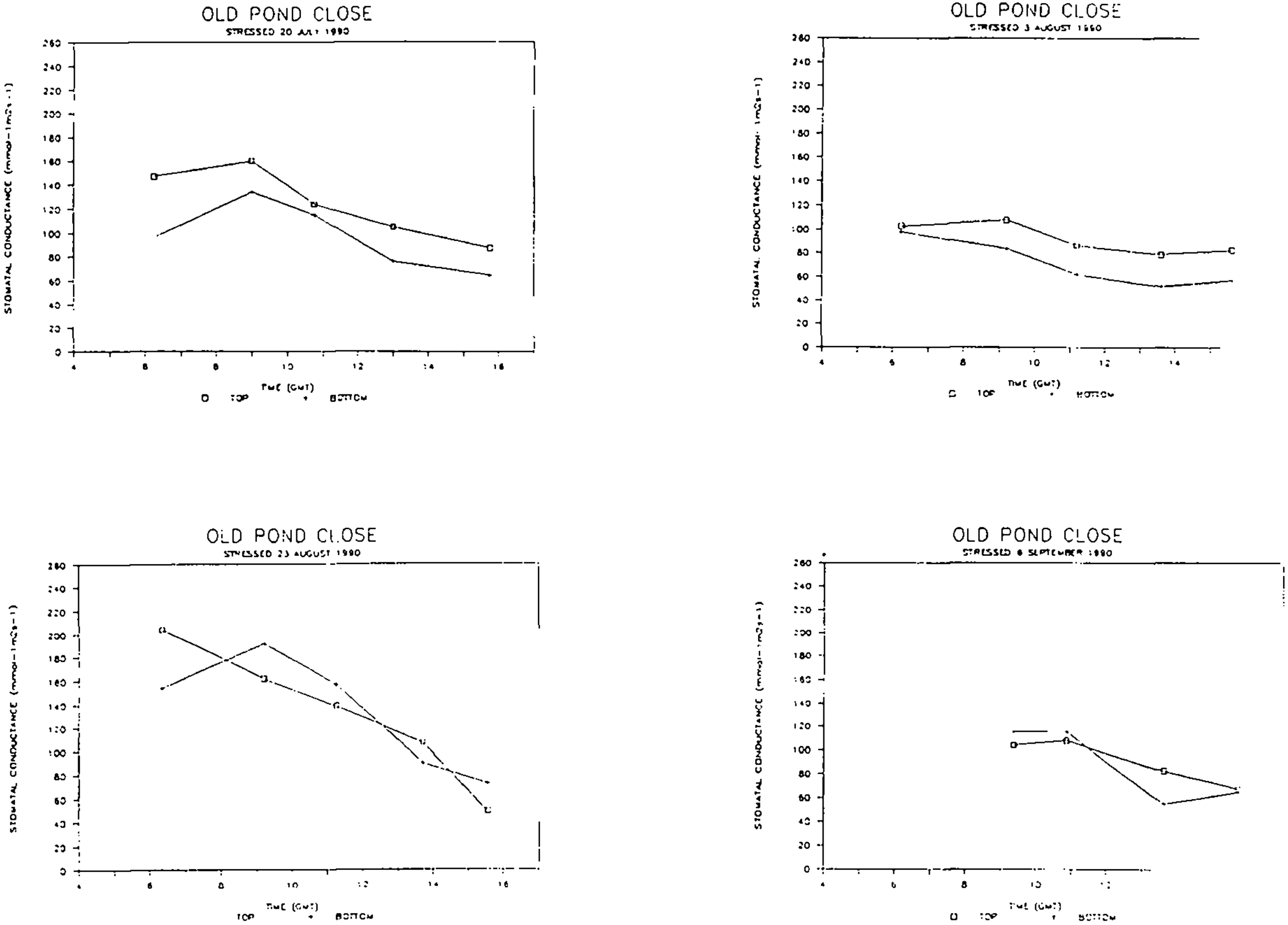

Figure 9.5 Stomatal conductance data from the stressed plot

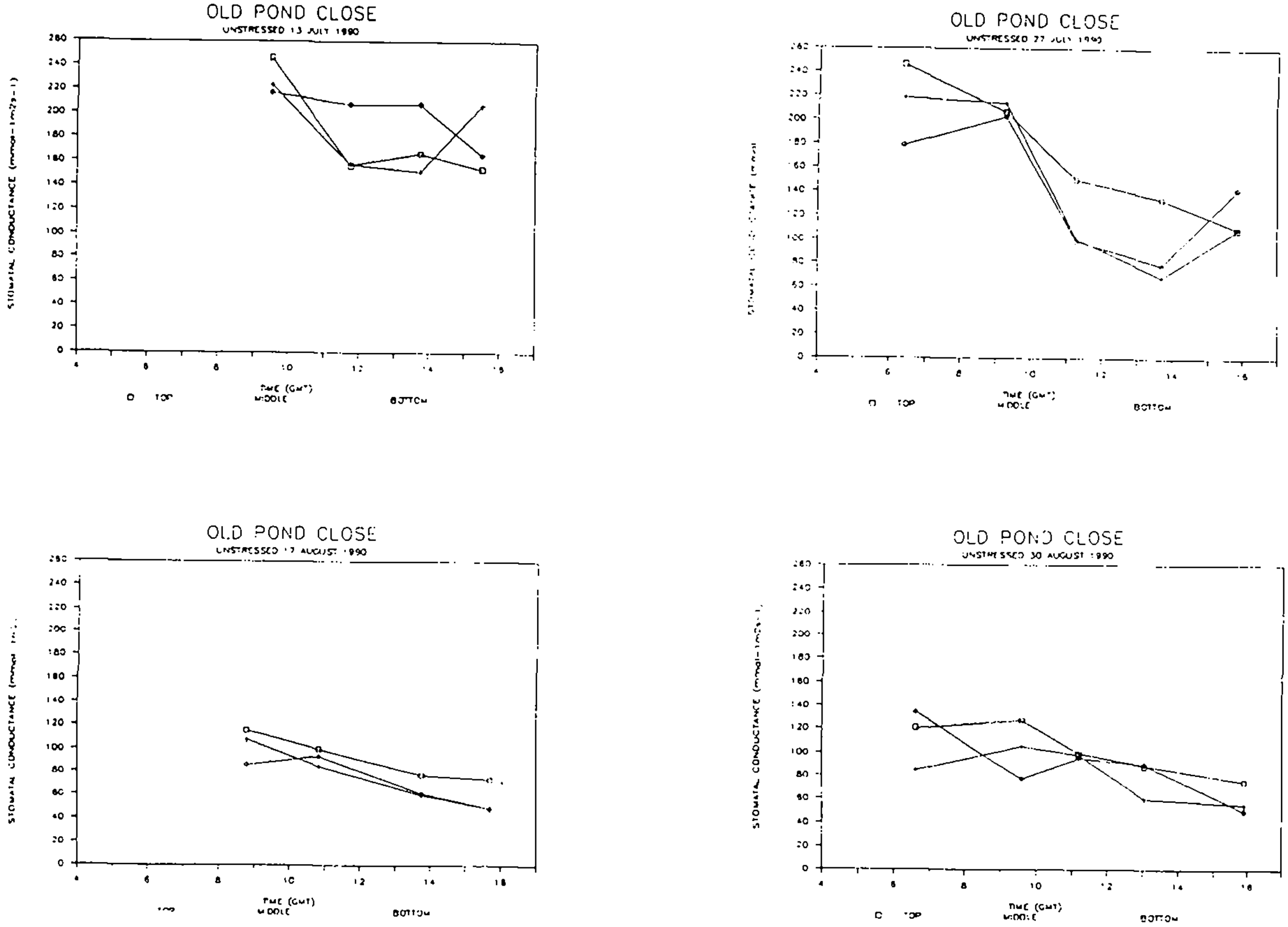

Figure 9.6 Stomatal conductance data from the unstressed plot

and understorey automatic weather stations from June - August. As expected the understorey weather station shows much lower radiation and slightly lower temperature.

The monthly rainfall figures from the two recording raingauges for June - August inclusive is shown in Table 9.2 and is compared to the four yearly average (1984-1987) from the raingauge at Olney Sewage Works.

The agreement between raingauges 1 and 2 is good, and is only 50% of the 1984-1987 average from the raingauge at Olney Sewage Works.

Table 9.2: Raingauge comparison

Month	Raingauge 1	Raingauge 2	Olney Sewage Works (1984-1987 average)
June	42.3	37.8	85.3
July	34.1	35.6	36.3
August	11.8	15.8	60.4
Total	88.2	89.2	182.0

Soil moisture observations from Old Pond Close started at the end of May and were taken on a weekly basis. Figures 9.3 and 9.4 show the profiles from the stressed and unstressed plots. The profiles from the stressed plots show soil water depletion in the top 180 cm with little change beneath this. The profiles from the unstressed plot are in two groups - those that show no change below 180 cm and those that show some change, albeit rather small. One difference between the two sites is that the unstressed plot has an understorey which, if deep rooted, would affect the soil moisture profiles. Measurements of leaf gas exchange (stomatal conductance and net photosynthesis) have been made from both the stressed and unstressed plots throughout July, August and early September. Data is available from 2 layers within the stressed canopy and 3 layers from the unstressed canopy. Stomatal conductance (g_s) of stressed and unstressed trees are shown in Figures 9.5 and 9.6 respectively. The maximum g_s is to be found in trees from the unstressed plot. However, both plots show a gradual fall in g_s throughout the day and a fall in g_s through the canopy. Much lower conductances were measured in trees from the stressed plot indicating that they were affected by the lowered soil moisture levels.

10. C. Lancelott project 1989

During 1989 (May to September inclusive) a sandwich course student from Coventry Polytechnic, Miss Cynthia Lancelott, based at the Institute of Hydrology for her placement year undertook a dissertation titled "Stomatal

Conductance and Water Relations of cherry (Prunus avium) and poplar (Populus tremula) in response to changing environmental conditions", on trees within the grounds of the Institute. The main conclusions of her dissertation were that:

Cherry was more responsive to changes in available soil moisture than poplar.

2. The stomatal conductances of both cherry and poplar are strongly correlated to solar radiation.

3. The leaf water potential of cherry was correlated to solar radiation while poplar was not.

The leaf water potential of cherry was strongly correlated to rainfall while poplar was not.

5. Overall, during the periods of observation, cherry was more stressed than the poplar indicating that the poplar was either planted in a much wetter soil than the cherry or, as is more likely, poplar was able to extract water from greater depth than cherry.

These observations support the conclusions of Dr P. G. Biddle in his report "Patterns of soil drying and moisture deficit in the vicinity of trees on clay soils, research results 1989", who found increased soil moisture depletion beneath individual poplar trees.

11. Recommendations and future work

Work planned for the coming year

On the water use, work will concentrate on filling gaps in the data and consolidating the water use modelling.

1. The routine measurements at both sites will continue, in particular it is hoped to acquire a complete set of interception dates.

2. Work is required on soil water movement to allow the separation of the effects of drainage from the profile and transpiration.

3. Knowledge on the role of the understorey vegetation is incomplete. Detailed measurements will be made through 1991.

4. The transpiration model is sensitive to the leaf area index measurement. Improved measurements of this, and its distribution through the canopy will be made.

Interception models will be developed and used in conjunction with the transpiration model to produce a total water use model which will be applied to all available data.

6. Simplified models of total water use will be developed for practical usage.

7. The chemical monitoring programme will continue until April 1991.

8. A detailed statistical evaluation of the chemical data will be carried out.

Long term research options

It was recognised at the outset that this was a multivariate problem: soil type, species type, age class, climate and silvicultural practices will all potentially affect the hydrological effects of plantation. An important start in the study of the water use and hydrochemical effects of broadleaf forest has been made. However, many aspects of basic understanding and practical application remain. Those which might be tackled in the next three years subject to funding include:

EDGE EFFECT. The data collected before the storm damage showed a small, not statistically significant effect. However, the data collected is not sufficient for a full assessment, especially in the leafed condition, when interception losses will be largest.

TRANSPORT MECHANISMS THROUGH THE CANOPY. We know very little about these fundamental processes which are of particular importance for understanding evaporation and chemical movement.

OTHER SPECIES. There are indications that other species, such as poplar and cherry, have very different transpiration characteristics and their hydrochemical properties are unknown.

YOUNG TREES. The hydrological effects of transpiration will depend upon the age of the plantation. Little is known about the water use of immature trees or their hydrochemical characteristics.

OTHER SOIL TYPES. Clays and chalk soils have been covered but soils on sandstones and sands may introduce additional stresses due to soil water deficits and may have a radically different hydrochemical behaviour.

MODELLING. Comparative modelling of forest, cereals and grassland is required for a complete picture of the hydrological impact of plantations.

CHEMICAL CYCLING. We are still a long way from understanding the processes involved.

HYDROLOGICAL ASPECTS OF NEW BROADLEAF PLANTATIONS

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INTRODUCTION

Over the next decade it is generally expected that there will be an increase in woodland in southern Britain as farmland is taken out of production to reduce food surpluses. Environmental advantages and economic incentives make it likely that the new woods and plantations will chiefly consist of hardwoods such as ash (Fraxinus excelsior), sycamore (Acer pseudoplatanus), sweet chestnut (Castanea sativa) and cherry (Prunus) and will be small and scattered in a mosaic over the countryside. Conventional broad-leaf plantation is also expected to increase.

An increase in the amount of broad-leaf plantation is expected to result in a decrease in runoff and aquifer recharge as has been found for large coniferous forests in the wet west of Britain. Although the plantations in southern Britain will be smaller their effect could be significant. Because of the relatively small difference between rainfall and evaporation and the large consumer demand in much of southern Britain, local sources of supply are sensitive to any increase in evaporative loss. Moreover the small size of the plantations may, through enhanced evaporation around their edges, result in a larger water use for a given area of woodland.

Before accurate predictions can be made of the hydrological consequences of the new broad-leaf plantations it is necessary to understand the mechanisms controlling evaporation from broad-leaf trees. The information available is briefly reviewed in this paper and speculative estimates of water use are made based on this information. The review shows that for the plantations of interest there is little relevant information and that new research work is needed. The type of measurements needed are given in the final part of this paper which describes a current project run by the Institute of Hydrology and primarily funded by the Department of the Environment.

To estimate evaporative loss from trees accurately it is necessary to consider it in its component parts of transpiration and interception loss. This division is also convenient and helpful for reviewing the work to date.

TRANSPIRATION CHARACTERISTICS OF BROAD-LEAF PLANTATIONS

Annual transpiration from different forest types

Annual transpiration totals from hardwood stands are not available from studies in the United Kingdom but a significant literature does exist for other parts of Europe. In Table 1 are presented the data available for broad-leaf forests in Europe and other temperate regions. In addition, values are listed from some transpiration studies in tropical rainforest and coniferous forest in Europe. Several features emerge from Table 1 especially the notable similarity in annual transpiration from the European studies. Data from these studies are characterized by annual transpiration totals substantially less than the potential transpiration for the region of observation. The similarity of annual transpiration for conifers and hardwoods in Europe suggests that with the shorter period of foliation in the broad-leaf stands a greater daily rate of transpiration would be expected for the broad-leaf species in their leafy period. Examination of Table 1 also leads to the conclusion that as well as the need to gain information on the transpiration rates and behaviour of all deciduous tree species under conditions in the United Kingdom, it is clear that information on a wider variety of deciduous species in Europe is required. No information on annual transpiration totals seems to be available for mature stands of common European broad-leaf trees such as ash, birch (Betula), cherry, poplar (Populus), sycamore and willow (Salix).

Transpiration totals from forest studies made in temperate regions outside Europe are higher than those from the European studies. These non-European studies were made at lower latitudes with generally higher mean temperatures and solar radiation in the seasons when the trees are in leaf. These meteorological variables reach a maximum in tropical regions where the highest annual transpiration totals are reported.

With the small amount of information available on annual transpiration of candidate species for the new plantations it may be necessary to examine data relating to these species for factors such as stomatal and boundary layer conductances and leaf area index. These variables have a fundamental control of transpiration levels and inspection of their values allows some insight into the likely transpiration of a species.

A physical description of the process of transpiration from vegetation has been given by Monteith (1965) in the following formula:

$$\lambda E_T = \frac{sA + \rho c_p D g_a}{s + (c_p/\lambda)\{1 + (g_a/g_c)\}}$$

Where A = the available radiative energy above the forest canopy, c_p = the specific heat of air at constant pressure, E_T = the transpiration rate, g_a = the aerodynamic conductance, g_c = the canopy conductance, D = the specific humidity deficit, s = the rate of change of saturated specific humidity with temperature, λ = the latent heat of evaporation of water and ρ = the density of air.

As well as the climatically determined variables in the Monteith formulation, transpiration will also be controlled by the principal plant based parameters: the aerodynamic and canopy conductances. So far very little information is available on the aerodynamic conductances of forests and little guidance can be given as to the effect of planting tree species with differing structures. More information is available on the surface conductance of forests and this is examined in the next section.

Surface characteristics of forests

The surface conductance of a forest is usually determined from meteorological measurements made above the forest. It is a bulk conductance and includes a component allowing for fluxes of water vapour from soil or litter or both. These fluxes are usually small and can for most purposes be ignored. Then the surface conductance can be equated to the canopy conductance. The canopy conductance is determined by measuring the stomatal conductance at different canopy layers with a porometer. These values are then multiplied by a Leaf Area index (LAI), the leaf area per unit ground area, for the equivalent canopy layer and summed to give a bulk stomatal (canopy) conductance.

Surface conductance has the advantage that no environmental variables are intrinsic in the value other than if they affect stomatal conductance responses directly. Comparison of surface conductances therefore makes a much more realistic assessment of the behaviour of vegetation surfaces than straight forward comparisons of transpiration which will also include the effects of the environment as a driving variable. Figure 1 compares the surface conductance of four woodland types measured micrometeorologically. It shows that coniferous forest is lower than all the other types and that a tropical forest in Brazil (Shuttleworth 1988) generally has the highest surface conductance which would go some way to explaining the high annual rates of transpiration for tropical forests (Table 1). Surface conductances of temperate woodlands and woody swamp are similar and intermediate between tropical forest and coniferous forest.

While the studies of surface conductance may give a valuable insight into the surface behaviour of different vegetation types

Fig. 1 Diurnal trends in surface conductance in four woody vegetation types.

for macrohydrological purposes or modelling global climates and circulation, insufficient studies are available to permit discrimination of the surface behaviour of different deciduous woodland types.

Stomatal characteristics of forest species

Canopy conductance of crop surfaces is usually assumed equal to the surface conductance but it is possible to calculate it by multiplying values of stomatal conductance, g_s, measured on individual leaves by the leaf area index (LAI). Unfortunately it is only rarely that intensive studies of stomatal conductance in combination with LAI have been made at forest sites e.g. Tan & Black (1976), Beadle et al., (1985). However, stomatal conductance and leaf area index determinations have been made separately for a very wide range of species although a large proportion of the conductance determinations have been made on young material in controlled environment or greenhouse conditions. Nevertheless these data are examined to investigate if particular species emerge as having stomatal characteristics significantly different from others. In Table 2 maximum stomatal conductances are presented for tree species which represent genera present amongst the broad-leaves present in the United Kingdom. It is important to realize that although the list of species is extensive it also gives a very clear indication of how little is known about the physiological performance and behaviour of broad-leaf trees found most frequently in the United Kingdom. It is only for beech (Fagus) and oak (Quercus) that data are available for conductance in mature forest canopies. There is no detailed information readily available on mature stands for some of the species considered as candidates for broad-leaf plantation particularly sycamore, cherry and ash.

The maximum stomatal conductances shown for species within the genera of particular interest (sycamore, beech, ash, poplar and cherry) are between 250-400 mmol $m^{-2}s^{-1}$. It should be noted that only data for one leaf surface are given for poplar but in fact stomata can occur on both surfaces. The maximum conductance for this species could then be substantially higher (~ 60% greater).

However, there should be some caution in using maximum g_s as an indicator of transpiration differences between species over a wide range of conditions. It is becoming clear (Morison, 1987) that species having leaves with an initially high g_s usually have a greater response to environmental factors which are thought to influence stomata. This is supported for tree species by data drawn from Federer (1977) replotted here as Fig 2. The rate of decline of g_s in association with increasing in vapour pressure deficit shows a direct relationship to the maximum g_s. The suggestion that different responses of g_s to vapour pressure deficit mightly largely offset differences in maximum g_s between species deserves further study. There is now considerable evidence that g_s declines in association with increasing vapour

Fig. 2 Changes in stomatal conductance with increasing vapour pressure deficit in several broad-leaf species.

pressure deficit in a wide variety of species with temperate broad-leaf and coniferous species well-represented. This negative association of g_s and vapour pressure deficit is a fundamental factor in limiting transpiration rates of forests as already referred to in discussion of Table 1. An additional factor which might influence these responses and changes in response to species, site and management differences is soil moisture.
The values of g_s determined throughout forest canopies multiplied by a leaf area index appropriate for the canopy layer in which g_s values have been determined will give the canopy conductance (g_c) which can be substituted into equation 1. Therefore, the surface behaviour of a forest depends additionally on the canopy quantities present in a profile in a forest. Table 3 presents LAI data available for broad-leaf species related to species used in forestry in the United Kingdom. The mean value of these data is 5.6 ± 1.4 if the studies of alder, southern beech and oak are excluded the mean value is 5.70 ± 1.0.

The determination of LAI in forest stands has been a tedious exercise in the past but development for a technique of determining light beam transmission with sensors below forest canopies (Norman & Campbell, 1989) shows a great deal of promise and deserves a full investigation particularly in relation to the uncertainty introduced by the presence of branches. Also well worthy of further investigation is the degree of association between average canopy g_s and LAI. G_s in C_3 species will be limited by irradiance below about 0.25 of maximum daylight irradiance. It is therefore, reasonable to assume that in stands with a high LAI, lower branches with be in lower irradiance with an associated lower g_s. This is a further factor which might limit the overal canopy conductance and also deserves a fuller investigation.

Another feature of forests which can compensate for different physiological performance in tree canopies of different species is the presence of absence of an understorey. The contribution made by forest understoreys to total transpiration should not be not in others. The contribution made by forest understoreys to the total forest transpiration underestimated (Roberts et al., 1980). Roberts et al (1982) have shown how the transpiration from a bracken understorey below an open pine canopy can compensate for the lower transpiration of that canopy when compared with that from a dense pine canopy without an understorey below.

INTERCEPTION

Introduction

Interception loss from trees is calculated as the difference between gross rainfall measured in the open, sometimes above the tree canopy, and net rainfall which is usually measured as the sum of throughfall, water which either falls straight through the canopy or drips from leaves and branches, and stemflow. Throughfall is measured using convenient collectors placed beneath the canopy and stemflow is invariably measured by collecting the water running down the tree trunks using pliable guttering spiralled around and suitably sealed to them. Sampling of both must be thorough to minimise the variability; especially for small storms.

Table 4 summarises the results of European interception studies on deciduous tree species made during the last 40 years. The annual percentage interception loss from these studies have been plotted against annual rainfall (Fig. 3). As would be expected for results from a range of species, ages, planting densities and climatic regimes there is much scatter. Errors of ± 8% can typically be associated with each point. Nevertheless, all of the points lie below the curve fitted to interception data for coniferous forest given by Calder (1982).

Figure 3. The annual interception loss expressed as a percentage of annual precipitation plotted against annual precipitation for European broad-leaved trees. The hatched line represents the annual interception percentage for conifers taken from Calder (1982) and the numbers assigned to the points are the reference numbers given in Table 4.

Further evidence that, on an annual basis, interception loss from conifers exceeds that from broadleaved species is given by various comparative studies made at the same locations e.g. Leyton et al (1967) and Rogerson and Byrnes (1968). This is reasonable given the deciduous nature of most broadleaved species since interception loss is, among other things, a function of the canopy capacity which is generally considered to reach a maximum when the trees are in full leaf. However as discussed below this may not be uniformly true. The high annual interception loss found by Noirfalise (1959) for a mixture of oak and birch was mainly the result of very high winter values which he attributed to the intricate nature of the exposed branches and twigs of the birch. Other workers too have reported larger canopy capacity for leafless rather than leafy trees (see Table 5).

Species differences

The careful measurements of White and Carlisle (1967) provided useful comparative values of interception loss for several broad-leaf species. They worked in an uneven-aged, multistoried and dense canopied (LAI = 8) woodland of coppice with standards covering about 22 ha in Cumbria where the annual rainfall was 1200 mm. Over two leafy and one leafless seasons they measured the annual interception loss for uneven-aged mixed broad-leaf woodland as 12.4% of the annual precipitation. Additionally they measured the interception loss for individual crowns of different species. However unlike some others e.g. Horton (1919) these individual crowns were not of isolated trees but were within the wood so that the evaporation rates measured would be reasonably representative of woodland specimens. The values they obtained are included in Table 4. The dense-canopied and large-leaved sycamore and lime (Tilia) evaporated significantly more intercepted water than either ash or oak which at 13.1% was identical to the figure for oak measured by Carlisle et al (1965) at a high rainfall (1714 mm) site also in Cumbria.

Seasonal effects: physiological and climatic

Studies of the effect of the deciduous nature of the northern broad-leaved species on interception loss was reviewed by Reynolds and Henderson (1967) who concluded that ..although sometimes there is a measurable reduction of interception losses in winter due to leaf fall, the effect is commonly surprisingly small' However, Helvey and Patric (1965) derived two significantly different interception regression equations for the dormant and growing seasons based on all the available results for hardwood forests in the eastern USA. It would probably be nearer the truth to say that the expected reduction in interception loss between winter and summrer due to leaf fall has on occasions been found to be surprisingly small.

As previously mentioned, one of the important factors controlling interception loss is the canopy capacity S of the trees. Table 5 summarises the best published values of canopy capacities of different species for leafy and leafless periods. Reynolds and Henderson (1967) found the canopy capacity of beech to be highest when the trees were leafless. However Brechtel (1976) found no seasonal difference in canopy capacity for beech or any other species he studied. These slightly surprising results may be the result of the different climatic conditions at their respective sites.

The effect of leaf fall on interception loss is confounded by seasonal climatic differences. Thompson (1972) used an arboricide to permanently defoliate a stand of oak coppice so that by comparison with an untreated control plot he could study the effect of foliage on interception loss under the same conditions. He found significant differences at the 5% level between the treated and untreated plots during the summer months and concluded that for southern England interception loss from foliated oak coppice is greater than from unfoliated. In addition he suggested that high interception losses in winter may sometimes be the result of a larger canopy capacity in the winter than in the summer because of the greater exposure of the woody parts of the tress and of any mosses and lichens growing on them.

As well as the canopy and trunk storage capacity, the interception loss from a tree canopy is also dependent upon the rate at which water is evaporated from it when it is wet. Where the majority of the annual precipitation falls in many short rain storms the canopy capacity will be the most important parameter. However, where the rain falls in long duration low intensity storms such as in the wet west of Britain, the rate of evaporation of water during rainfall becomes more important. According to Calder (1982) the majority of intercepted water is evaporated during rainfall from coniferous forest in central Wales.

The rate at which water evaporates from the surface of wet vegetation is dependent upon the prevailing weather and the ease with which water vapour can transfer from the wet surface into the atmosphere which is parameterised as r_a; the aerodynamic resistance to water vapour transport. Because trees are aerodynamically rough they produce efficient mixing of the air above them and r_a is relatively small: for conifers values are typically 3 to 10 sm^{-1} compared to typically 40-50 sm^{-1} for agricultural crops.

There are no values of r_a for broad-leaf trees in the literature. However, the displacement height d and roughness length z_o have been measured and the values are given in Table 6. From these values the bulk momentum transfer coefficient C_{am} and aerodynamic resistance to momentum transport r_m can be calculated from

$$C_{am} = \left[\frac{k}{\ell n \left(\frac{z - d}{z_o}\right)}\right]^2$$

and $r_m = (uC_{am})^{-1}$

where k is von Karman's constant (= 0.41) and z is the height at which the windspeed u was measured. From Table 3.3 it is evident that C_{am} for broad-leaf and coniferous trees are of the same order which implies that foliated broad-leaves are as efficient as conifers at generating turbulence. This in turn implies that in the turbulent layer of air above the trees the transport of water vapour from a wet broad-leaf canopy is as easy as from a wet conifer canopy. Although strictly r_m cannot be equated to r_a it is often taken as a good approximation to it. This being so the available data suggest that given the same weather rates of evaporation of intercepted water from deciduous trees in summer will be similar to those from conifers.

Thus the current knowledge of the relative canopy capacities (S = (1 ± 0.3) mm compared with S = (1.4 ± 0.6) mm for conifers from 20 studies of 8 species) and values of r_m for broadleaves and conifers suggest that interception loss during the foliated period from some broad-leaf species will equal that from some conifers. The results of Leyton et al (1967) and Rogerson and Byrnes (1968) support this showing very similar interception loss during summer from spruce (Picea) and hornbeam (Carpinus betulus) and red pine (Pinus resinosa) and oak respectively.

DISCUSSION AND CONCLUSIONS

The above review indicates that transpiration from broad-leaf and coniferous trees on an annual basis is conservative and is typically 320-350 mm (see also Roberts 1983). However, the annual interception loss is dependent upon rainfall regime, species and age of trees.

Using published data it is possible to make speculative estimates of annual water use for southern England. Table 7 shows the results of summing the transpiration loss, taken as 350 mm a year and the interception loss from conifers and broad-leaf woodland in Cambridgeshire (550 mm annual precipitation) and Devon (1100 mm annual precipitation). The interception loss was calculated using an annual interception percentage of 28% for Cambridgeshire and

20% for Devon these representing typical values (see Fig. 3.1) and reflecting the difference in annual rainfall. Likewise the interception loss from conifers was calculated using annual interception percentages of 39% and 33%. Water use by grass was assumed equal to the annual Penman potential evaporation. The figures in parentheses were calculated using likely minimum interception percentages of 13% and 10% for Cambridgeshire and Devon respectively and represent the minimum annual water use which would be expected from current knowledge.

Table 7 shows that in Devon broad-leaf plantation might be expected to use slightly more water as compared with grassland whereas coniferous plantation will result in a significant increase. In Cambridgeshire little change in water use is predicted within the uncertainties of the estimates. It must however be emphasised that these are annual estimates and are inadequate for the water manager. Although the annual transpiration loss for conifers and broad-leaves are very similar this transpiration occurs over only about five summer months for broadleaves and interception losses during this period are also at a maximum. Consequently the rate of water use will be highest when consumer demand is also largest

Although these estimates should only be taken as a very rough indication of what might be expected such calculations do highlight shortcomings in current knowledge. The main ones are

For some species values for annual or seasonal percentage interception loss are given in the literature. These are derived from ad hoc studies and the results cannot be extrapolated to areas of different climate particularly rainfall regime. Regression relationships between interception loss and rainfall also have the same limitations.

2. There has been very little work on the evaporative loss from understorey vegetation. The little that has been done indicates that on occasions evaporation from the understorey of conifers can be a significant fraction of the total evaporation. e.g. Tan et al. (1978), Roberts et al. (1980).

3. There have been no studies on the evaporation from the margins of woods and plantations. Indeed it is usual to make measurements as far from any 'edges' as possible.

4. Transpiration studies have not been done of all the species likely to form new plantation.

In the light of these shortcomings there is a need for studies of interception and transpiration processes in the relevant tree species and of the understoreys. Also, because in small woods a large proportion of the trees are subject to the environment at the edges, research is needed on the influence of the edges in enhancing evaporative loss.

The Institute of Hydrology is operating a major project funded by the National Rivers Authority, the Department of Rural Affairs and the Natural Environment Research Council to undertake such studies. Two wood sites are currently in use: one over a shallow water table and a larger one over a deep water table. With these it will be possible to gain useful insights into the effect of plantation size and the way that transpiration is affected by the position of the water table.

Black Wood, a large Forestry Commission wood (grid ref. SU534428) on the chalk downland between Basingstoke and Winchester, was chosen as the first location for intensive study. The wood comprises mainly beech but has an ash plantation near its centre which will allow a comparison of water use between species to be made. A second, smaller wood, Old Pond Close, near Olney was chosen as a second site for measurements where the species are predominantly ash and oak, with large stands fo pure ash, growing on a deep clay. Measurements are being made throughout the growth and dormant seasons on the beech and ash at Black Wood and on the ash at Old Pond Close.

At Black Wood interception loss is determined from weekly measurements of throughfall and stemflow at increasing distances from the edge of the beech plantation in conjunction with gross rainfall measurements made above and around the wood. Throughfall is collected in randomly relocated gauges under the canopy and stemflow collected using spiral stemflow gauges from a random sample of trees. Meteorological variables are measured above the canopy by automatic weather stations on towers. In addition storm-based interception data are collected from plastic-sheet net-rainfall gauges (Calder and Rosier, 1976) and flowmeters beneath the beech and the ash.

Transpiration loss from both species is being measured using complementary techniques, viz: measurement of the soil moisture depletion using a neutron probe meter in conjunction with tensiometers to determine the zero-flux plane and plant physiological measurements using porometers and pressure bombs.

Evaporation from the ground vegetation and litter will also be measured using plant physiological methods and a weighing lysimeter system together with measurements of the trunk-space weather using an automatic weather station.

At Old Pond Close a similar set of measurements are being made. However there is just a single interception gauge in the middle of the wood, no attempt is being made to investigate the edge effect here, and a study of comparative transpiration loss from stressed and unstressed trees is also being made. (A plot of trees is being stressed using plastic sheeting to prevent rainfall from entering the soil.)

These measurements will provide vital data necessary for a better understanding of the physical processes controlling evaporation from broad-leaf plantation and will make possible more accurate predictions of water use through physically based mathematical models.

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Table 1. Annual transpiration totals for a range of forest studies.

Species	Rainfall (mm)	Transpiration (mm)	Location	Authors
Oak,Ash,Lime	513	285	European, USSR	Molchanov (1971)
Scots pine	595	353	Thetford, UK	Gash & Stewart (1977)
Norway Spruce	2760	330	Wales	Calder (1976)
Red oak	663	304	Germany	Brechtel (1976)
Oak	663	327	?	Brechtel (1976)
Beech	663	301	?	Brechtel (1976)
Spruce	827	324	?	Ernstberger & Sokollek (1983)
Beech	896	319		Benecke & van der Ploeg (1975) van der Ploeg (1975)
Mixed oak	966	343		Schnock (1969)
Native hardwood	1380	430	New Zealand	O'Loughlin et al (1985)
Deciduous forest	1580	487	NC, USA	Hoover (1944)
Southern Beech	1480	340	New Zealand	Pearce et al (1982)
Douglas Fir (Pluvius)	1410	560	Canada	Riha & Campbell (1985)
Oak/Hickory	2135	602	NC, USA	Waring et al (1980)
Southern Beech	2600	340	New Zealand	Pearce et al (1982)
Tropical forest	2593	1030	Amazon	Shuttleworth (1988)
Tropical forest	2851	886	Java	Calder et al (1986)
Hard Beech (NZ)	1500	423	New Zealand	Benecke & Evans (1987)

Table 2 Maximum stomatal conductances of representatives of broad-lea genera growing in the United Kingdom

Genus/species	Conductance (mmol m^{-2}s^{-1})	Author
Acer		
campestre	80	Elias (1979)
saccharum	160	Federer & Gee (1976)
saccharum	[illegible]	Hinckley et al (1978)
glabrum	384	Cline & Campbell (1976)
platanoides	292	Scheel (unpublished)*
platanoides	52	Holgren et al (1965)
rubrum	88	Turner & Heichel (1977)
Alnus		
pinnata		Cline & Campbell (1976)
viridis		Korner et al (1979)
Betula		
B. alleghanensis	264	Federer & Gee (1976)
verrucosa	336	Holgren et al (1965)
Carpinus		
betulus		(1979)
Corylus		
C. americana		& Kuppers (1979)
Fagus		
F. sylvatica		Schulze (1970)
"		Scheel (unpublished)*
Fraxinus		
F. excelsior	284	Scheel & Levy (1980)
"	284	Aussenac & Levy (1980)
pennsylvanica	96	Sena Gomes & Koslowski (1980)
Juglans		
J. regia	248	Korner (unpublished)*
J. regia	232	Scheel (Unpublished)*
Malus		
M. domestica	360	Landsberg et al (1975)
M. domestica	272	Landsberg et al (1976)
M. domestica	340	Jones & Cumming (1984)
Poplus		
P. deltoides	300	Schulte et al (1987)$
P. trichocarpa	200	Schulte et al (1987)$
P. deltoides x trichocarpa	240	Schulte et al (1987)$
P. deltoides	212	Pereira & Koslowski (1977)
Prunus		
P. avium		unpublished*
avium		unpublished*
Quercus		
Q. petraea		(1979)
robur		unpublished
[illegible]		& van der Burg (1988)
		al ([illegible])
		(1977)
Tilia		
T. cordata		Scheel unpublished*
Ulmus		
americana	128	Federer (1977)
americana	144	Pereira & Koslowski (1977)

only one surface

* given in Korner, et al (1979)

Table 3. Leaf area index for broad-leaf stands

Species	LAI	Location	Authors
Acer platanoides	5.0	Russia	Rauner (1976)
Acer saccharum	6.0	USA	De Angelis et al (1981)*
Alnus glutinosa	3.6	UK	Hughes (1971)
Betula verrucosa & pubescens	6.5	UK	Ovington & Madgwick (1959
Betula verrucosa	5.3	Russia	Rauner (1976)
Carpinus betulus	5.2	Czechoslovakia	De Angelis et al (1981)
Castanea sativa	5.6	UK	Ford & Newbould (1971)
Fagus sylvatica	5.7	Germany	Schulze (1970)
Fagus sylvatica	5.9	Germany	De Angelis et al (1981)
Fagus sylvatica	6.7	Germany	De Angelis et al (1981)
Fagus sylvatica	6.5	Germany	De Angelis et al (1981)
Fagus sylvatica	6.6	France	Lemee (1978)
Fraxinus excelsior	5.4	Denmark	Boysen-Jensen (1932)
Nothofagus truncata	8.3	NZ	Benecke & Evans (1987)
Populus tremula	3.8	Russia	Rauner (1976)
Populus tremula	7.1	Russia	Rauner (1976)
Quercus robur	2.0	Holland	Dolman & Van den Burg$ (1988)
Quercus robur	4.6	Russia	Rauner (1976)
Quercus robur	5.0	Russia	Rauner (1976)
Quercus	6.8	Belgium	De Angelis et al (1981)
Quercus robur	4.6	Belgium	De Angelis et al (1981)
Quercus petraea	8.1	Hungary	Cannell (1982)*
Quercus petraea	5.3	UK	De Angelis et al (1981)
Tilia cordata	4.8	Russia	Rauner (1976)

$ Authors believe low values due to defoliation by *Tortrix viridana*

* De Angelis et al (1981) and Cannell (1982) have compiled data from many published reports on forest biomass. The original sources will be found in those reviews.

Table 4. Annual and seasonal interception loss as a percentage of gross rainfall for European broad-leaf trees

Species	Annual Precipitation (mm)	Percentage interception loss Annual	 Growing season	 Dormant season	Reference	Reference no used in Fig. 3
Alder	1333	11.5			Cape pers. comm.	
	1680	15.7			Cape pers. comm.	
Ash	1200	12			White & Carlisle (1967)	
Beech	425	15	[illegible]		Aussenac & Boulangeat (1980)	
Beech/hornbeam	724	17	18.6	15.1	Aussenac (1968)	
Birch	1099	21			Skeffington pers. comm.	
Hornbeam	447	36	45	29	Leyton et al (1967)	
Hornbeam/oak	966	16.5	22.3	10.5	Schnock (1969)	
Lime	1200	32			White & Carlisle (1967)	2
Oak	1714	13.1	16.9	9.9	Carlisle et al (1965)	8
Oak	895	37			*Ovington (1954)	9
Oak	1333	10.3			Cape pers. comm.	1
	1680	14.7			Cape pers. comm.	1
Oak	1099	22			Skeffington pers. comm.	5
Oak			31	11	Dolman (1987)	
Oak coppice	673	18.1	24	12	Thompson (1972)	10
Oak/birch	877	29.8	23	36	Noirfalise (1959)	11
Southern beech	895	31			*Ovington (1954)	9
Sycamore	1200	23.9			White & Carlisle (1967)	2
Mixed	1200	12.4	16.7	12.1	White & Carlisle (1967)	2

*The values given by Ovington were calculated for a three year period after he had established relationships between interception loss and rainfall intensity and total from measurements made over several days throughout a year.

Table 5. Canopy capacities in mm of european broad-leaf trees

Species	Canopy Capacity		Reference
	Leafy	Leafless	
Beech	1.5 ± 0.4	2.4 ± 0.3	Reynolds & Henderson (1967)
Beech	0.8	0.8	Brechtel (1976)
Hornbeam	0.7	0.7	Brechtel (1976)
Hornbeam		0.6	Leyton et al (1967)
Oak	0.8	0.3	Dolman (1987)
Oak	1.6		Romer Rasmussen & Rasmussen (1984)
German oak	0.8	0.9	Brechtel (1976)
Red oak	0.8	0.8	Brechtel (1976)
Oak coppice		0.4	Thompson (1972)
Mean value	1 ± 0.3	0.9 ± 0.6	

Table 6 Momentum transfer coefficient and associated values

Species	Zero-plane displacement (d) normalised by tree height (h) d/h	Roughness length (z_0) normalised by tree height (h) z_0/h	Momentum transfer coefficient	Reference
Oak/ hickory			[illegible]	Verma et al (1986)
Oak	0.75 (0.5	0.1 (0.09		Dolman (1986)
Beech/ Maple	0.83	0.07		Singh & Szeicz (1979)
Tropical	0.86	0.06	0.23	Shuttleworth (1988)
Conifers	0.78 ± 0	0.075 ± 0	0.04 0	Jarvis et al (1976)

*Parentheses enclose values measured when trees were leafless

Table 7. Speculative annual water use

Annual Rainfall	Water Use (mm)		
	Conifers	Grass	Deciduous
550 (Cambridge)	566	529	504 (421)
1100 (Devon)	710	527	570 (460)

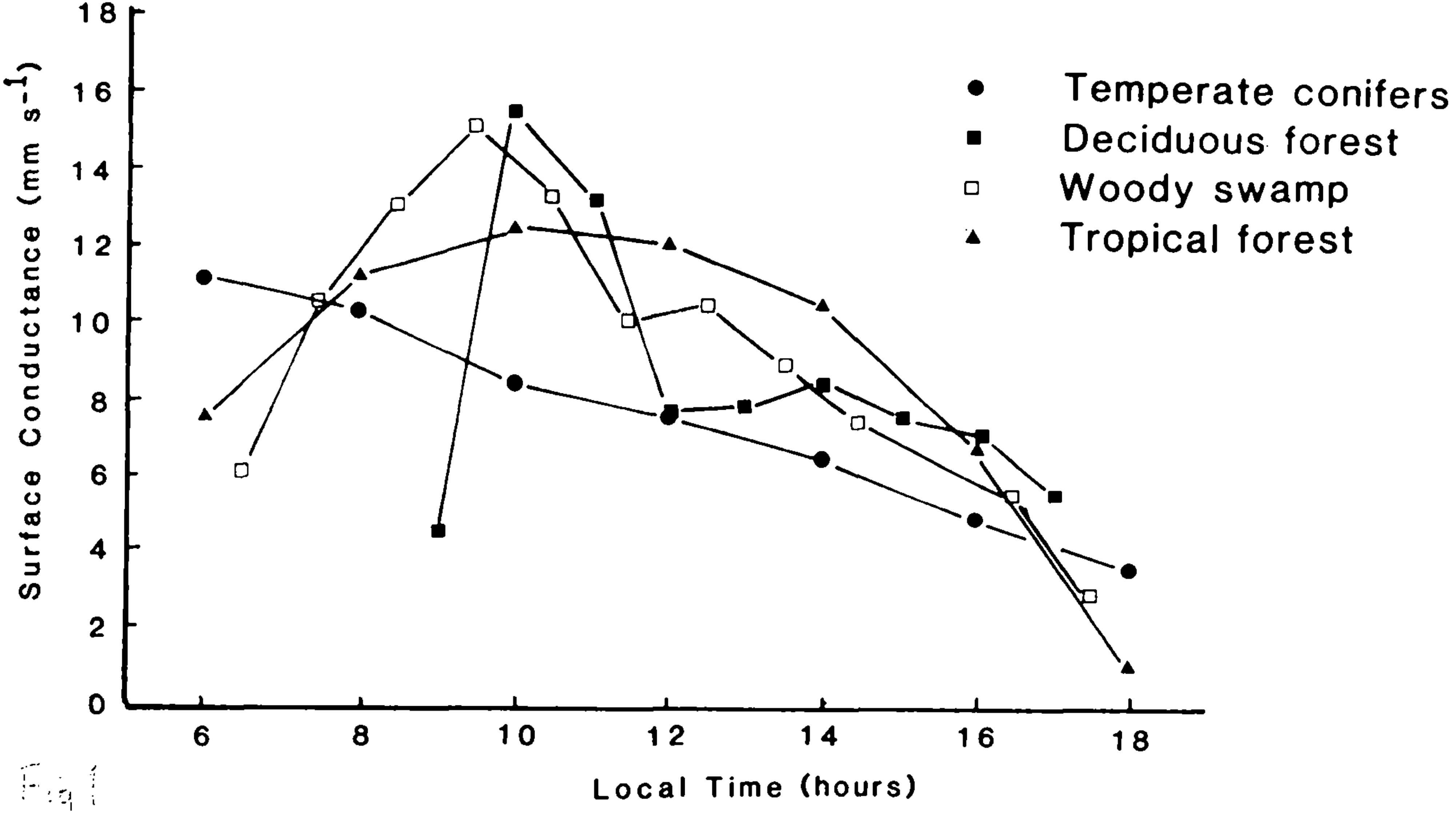

Surface Conductance (mm s^{-1})
18
16
14
12
10
8
6
4
2
0
6
8
10
12
14
16
18
Local Time (hours)
● Temperate conifers
■ Deciduous forest
□ Woody swamp
▲ Tropical forest

Fig 1

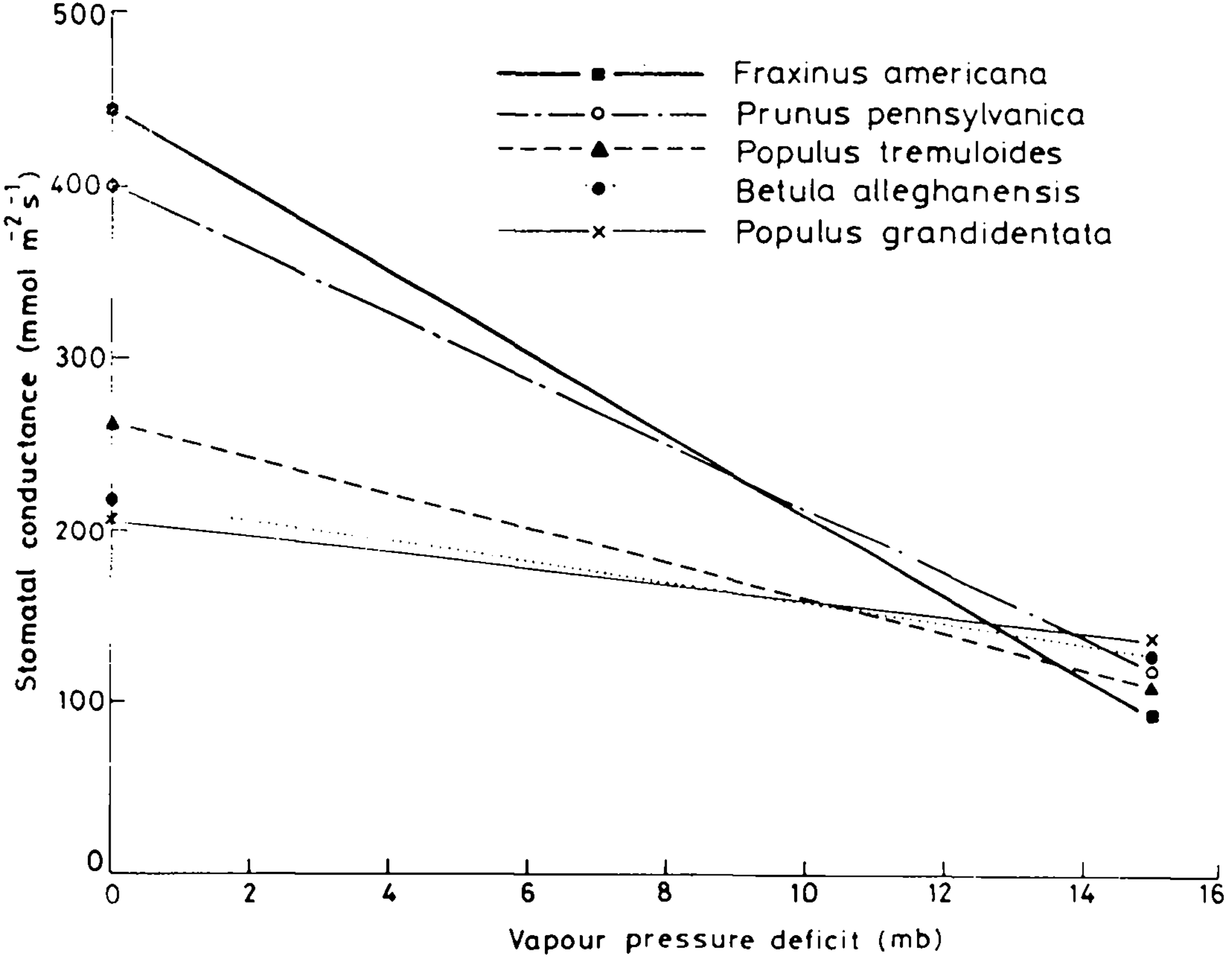
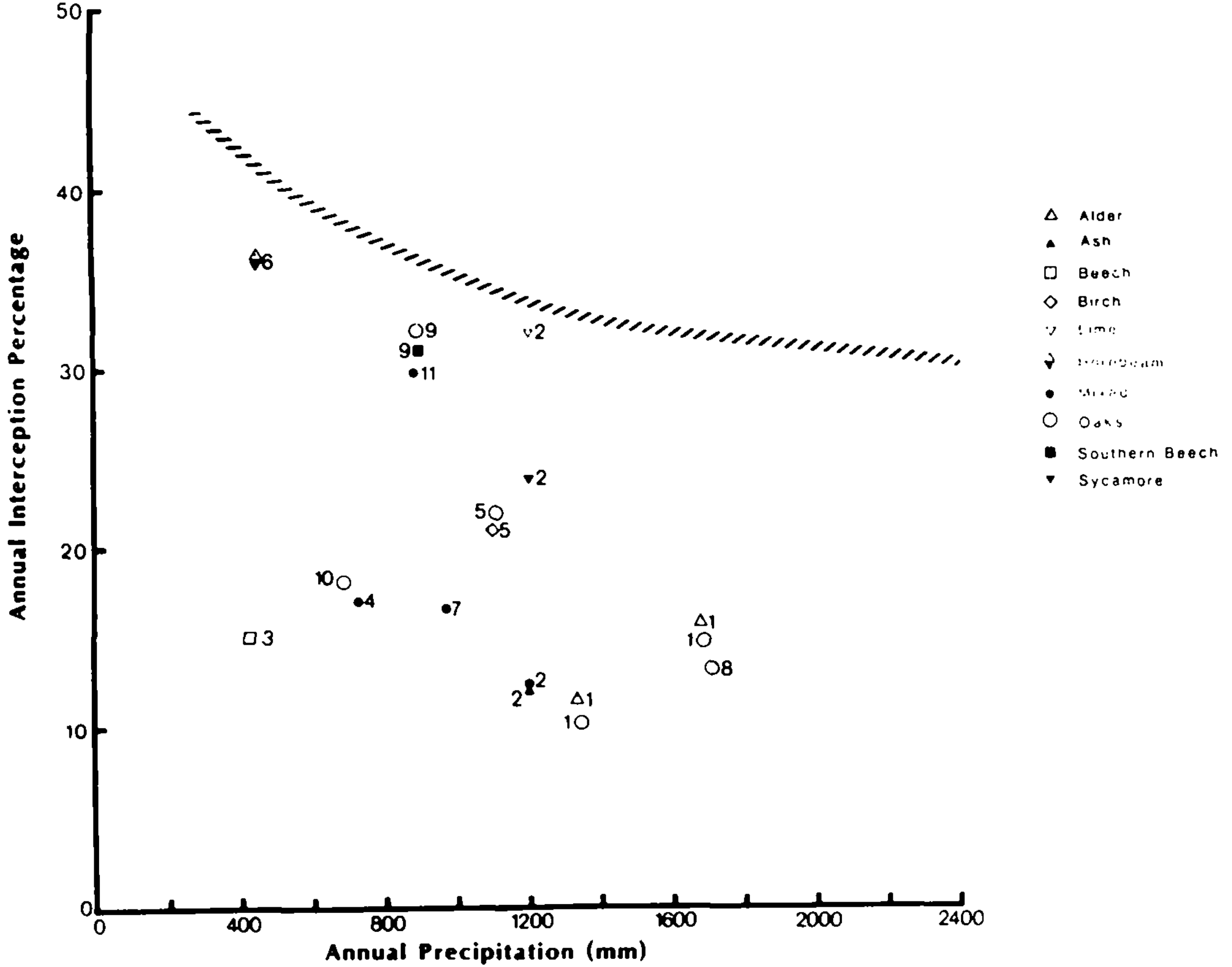

500
400
300
200
100
0
Stomatal conductance (mmol m^{-2} s^{-1})
0
2
4
6
8
10
12
14
16
Vapour pressure deficit (mb)
Fraxinus americana
Prunus pennsylvanica
Populus tremuloides
Betula alleghanensis
Populus grandidentata

Fig 2


Annual Interception Percentage
0
10
20
30
40
50
Annual Precipitation (mm)
0
400
800
1200
1600
2000
2400
6
3
10
4
9
9
11
7
5
5
2
2
2
2
1
1
1
1
8
△ Alder
▲ Ash
☐ Beech
◇ Birch
▽ Lime
▼ Hornbeam
● Mixed
○ Oaks
■ Southern Beech
▼ Sycamore

HYDROLOGICAL IMPACTS OF HARDWOOD PLANTATION IN LOWLAND BRITAIN: PRELIMINARY FINDINGS ON INTERCEPTION AT A FOREST EDGE, BLACKWOOD FOREST, HAMPSHIRE, SOUTHERN ENGLAND.

ABSTRACT.

Throughfall, stemflow and net rainfall data are presented for a network of collectors located in a beech plantation forest in Southern England. The results cover the period 2 May 1989 to 2 February 1990. The results, analyzed within a statistical framework, show;-

(a) average net rainfall is relatively constant with distance from the forest edge (20 to 350 metres; monitoring nearer than 20 metres from the edge proved impracticable);

(b) interception loss averages about 12% in the leafed and 11% in the unleafed periods;

(c) the stemflow increases as a proportion of the net rainfall from 2% in the leafed to 6% in the unleafed period;

(d) a network approach is important for assessing interception losses: localised rainfall inputs are observed; systematic differences are seen between similar localities.

INTRODUCTION.

Overproduction of cereal crops within the European Economic Community has resulted in a marked change in the collective agricultural policy. In the United Kingdom, reductions in cereal farming will be forthcoming. Impacts will centre in the low lying areas of Britain, particularly central and southern England. In response to the changing European Economic Community agricultural policy, there is strong pressure for the deployment of these areas for hardwood plantation forestry: the UK produces only about 10% of its timber requirements (Blyth et al, 1987); environmental factors such as amenity value and conservation of habitat also come into play (Blyth et al, 1987). Tree species considered, for the development of these areas, include ash (Fraxinus excelsior), sweet chestnut (Castanea sativa), sycamore (Acer pseudoplatanus), poplar (Poplus sp.), beech (Fagus sylvatica) and cherry (Prunus avium).

It is anticipated that water recharge will be reduced by forestry plantation because of comparatively higher evaporation losses (via interception and transpiration) from the trees relative to cereal crops. This may well result in water resource management problems: in lowland Britain, rainfall is relatively low compared with the rest of the UK; the water available for river flow and aquifer recharge is therefore highly sensitive to small changes in evaporation.

Being aerodynamically rougher than agricultural crops, trees will probably produce enhanced scavenging of atmospheric pollutants (Cape and Lightowlers, 1988; UKAWRG, 1988). After deposition onto the vegetation surface, the atmospheric pollutants are either absorbed by the vegetation or washed away, as stemflow and throughfall, to the soil. Lowland Britain experiences relatively high atmospheric acidic oxide (NO_x and SO_x)

and ammonia concentrations (UKRGAR, 1987) so there is the potential for significant pollutant scavenging. As rainfall can be highly acidic, in these regions (UKRGAR, 1987), this extra input would add to an already high burden (UKAWRG, 1988). In the case of nitrates, improvements may accrue due to cessation of agricultural fertilizer application.

The new plantations will probably be deciduous woodland in small irregular blocks (<5 ha) across the countryside. Because of this mosaic pattern there will be a large number of field-woodland boundaries at which enhanced pollutant scavenging and evaporation losses compared to larger forests are expected.

Because of these factors, the new plantation forestry may well have adverse quantity and quality effects on ground water and stream water. This is particularly important for ground water resources, the major supply of drinking water in the lowland regions. Previous published work have not addressed this water resource impact and data contained therein do not allow a full evaluation to be made.

A project "the hydrological impacts of hardwood plantation in lowland Britain" was initiated at the Institute of Hydrology in 1988 to address the problems outlined above. The project's objectives were initially two fold. First, to assess the hydrological effects of small-scale hardwood plantations in lowland Britain by studying the evaporative processes (interception and transpiration). Second, to assess the hydrochemical effects, both temporally and spatially, by determining the chemistry associated with rainfall, throughfall and stemflow. Subsequently, an opportunity has been taken to assess the hydrochemical effects of wind blow on a beech forest. This was prompted as a consequence of extreme gales in January and February 1990 in which 20% of the trees studied were blown down; damage was mainly confined to the forest edge.

In this paper, hydrological results are presented which centre around data collected from the monitoring network prior to storm damage. The results are presented to:-

i. assess the effects of forest edges in modifying the water interception losses;

ii. provide a baseline analysis to set against the new information being collected on storm damage;

iii. highlight the need for a network design for obtaining representative information on water interception by the forest.

STUDY AREA AND EXPERIMENTAL DESIGN.

Initially, an extensive survey of small broadleaf forest sites within reasonable distance from the Wallingford laboratories was undertaken to identify potential sites: it was hoped that the study area would be planted with the recommended tree species. In practice no ideal site was found which satisfied all the requirements. The Forestry Commission's Blackwood forest plantation was finally chosen for detailed study. Located near Micheldever, mid-way between Winchester and Basingstoke in Hampshire, southern England (Figure 1), this small plantation (2.4 km^2) is set in rural surroundings with agricultural farming of cereal, legume and pulse crops. The forest is bounded to the north and east by dual carriage and motorway roads (A303, A33, M3: Figure 1). The plantation is mainly confined to beech (Fagus sylvatica) forestry, planted 20 to 40 years ago onto agricultural, limed, land. Tree spacings are typically 20 metres apart and tree heights are about 35 metres. Bedrock geology is Cretaceous age chalk which produces well drained conditions in the overlying, shallow (<50 cm), organic-rich forest soils. Annual rainfall is typically 800 mm/year and wind direction is mainly from the west (Chandler and Gregory, 1976). Altitude range for the forest as a whole is 100-150 metres above sea level (OS, 1988) and mean monthly temperatures vary typically from 3° C in January to 17° C in August (Chandler and Gregory, 1976).

The monitoring programme began in spring 1989 with the installation of (a) neutron access tubes and tensiometers for soil moisture measurement, (b) automatic weather stations located above the tree canopy, (c) plastic sheet net rainfall gauges, (d) stemflow and throughfall collectors and (e) rainfall collectors located above the canopy and in a network around the forest. The results presented here relate to the above canopy rainfall collectors and the network of stemflow and throughfall collectors: these merit more detailed description.

The network of throughfall and stemflow collectors were located to the western and central part of the plantation. This part of the forest was chosen since (a) it and the surrounding land is flat lying (120 to 150 meters: OS, 1988; Figure 1) and (b) the forest has a north-south linear edge perpendicularly facing into the prevailing, westerly, winds (Figure 1). These conditions allow the ideal opportunity for studying the hydrological and hydrochemical effects of the forest edge: simple aerodynamic wind flow characteristics apply.

Since the experiment involved the assessment of interception gradients near and away from a forest edge a network design was introduced. A series of plots were used to provide information on the hydrological variability both parallel and perpendicular to the forest edge. The works of Wilm (1943), Helvey and Patric (1965) and Lloyd and de Marques (1988) were consulted to provide estimates of the number of throughfall collectors required. Their recommendation to utilise relocatable throughfall collectors was taken up to minimise the number of collectors needed. [n.b. this information could only be used as a guide for our experimental design. The extent to which random relocation of samplers will reduce the standard error of measurement cannot be judged at present in a precise manner as some type of weighting is required to allow for volumes of catch per interchange. For example, if collectors were relocated daily and rain only fell on only one of the days between collection dates, no benefit in relocating the collectors would have accrued.]

Collections were made at 5 distances in from the edge (20, 50, 100, 200, 350 metres). Sampling nearer to the edge proved impracticable because of the presence of anomalously large trees in the first row of the forest edge and a minor forest road within 4 metres of the edge. At each of these distances a row of three plots were established, each consisting of roughly circular areas bounding four trees (Figure 2). At each plot four stemflow and eight throughfall samplers were installed. Each plot covered an area of about 100 square meters. Adjacent plots in each row were typically separated by about 60 metres. Stemflow was collected for individual trees: a polypropylene collar was set around each tree and water transferred to a bin of 450 litre volume. The throughfall collectors consisted of circular gauges (7.6 mm radius, funnel rims about 500 mm above ground level). Small mesh filters were incorporated into the funnel bottoms to avoid chemical contamination. These filters were cleared of debris each sampling visit: flow restriction was minimal and hence overtopping and significant "splash off" did not occur. In addition to the 15 (3 times 5) plots a further one was established directly next to the central plot on row 4 to allow comparison between sheet and network estimates of net rainfall (Figure 2). Input rainfall was measured above the canopy using four circular rainfall funnel collectors installed at the top of two towers (Figure 1). Rainfall was collected in a bottle at the base of each tower, water being transferred between the funnels and bottle by long lengths of 7 mm diameter plastic tubing.

Monitoring from the network began 2 May 1989 and has continued with sampling visits determined by the frequency and intensity of each storm: typically one to two weekly intervals. After each collection, throughfall gauges were randomly moved within the plot to give reliable estimates. Stemflow volumes were determined by measuring the level of water in the bins and then by calculation using a calibration relationship derived by filling six bins with known volumes of water and measuring the water level. The calibration data was fitted to an equation linking volumes to height for a truncated conic section. A remarkably good calibration was obtained (correlation coefficient > 0.9999 for 6 times 5 data points). Throughfall and rainfall volumes were determined by a weighing procedure.

RESULTS AND DISCUSSION

Basic Hydrological findings.

Of the net rainfall (throughfall plus stemflow), throughfall constitutes on average 95.6 % of the volume for the site (Figure 3, Table 1). A seasonal effect is observed, the proportion of stemflow increasing from about 2% in the summer months to about 6% in the winter. For each sampling period scatter in the stemflow proportions is seen. This scatter is higher in the winter period. The main changes observed occur about the same time as autumn leaf loss (late October: day 150 on the diagrams): a causal link cannot however be inferred without further study.

The throughfall and stemflow catches are correlated with the rainfall (Figure 4). In the throughfall case the correlation is particularly high (correlation coefficient 0.985) and the intercept is not significantly different from zero. With stemflow much greater scatter is observed (correlation coefficient 0.89). About 8 mm of rainfall is required before stemflow occurs. This corresponds to the filling of the canopy and stem storage before flow commences.

The gross and net rainfall measured at the site between May 1989 and February 1990 is given in Table 1 and plotted in Figure 4. Rainfall collected over the canopy is expected to be systematically underestimated (Rodda, 1967) due to two factors: turbulence effects around the collector funnel in high wind-speed conditions; the amount of rain required to wet the gauges before collection occurs. Set against this, during convective storm events the above-canopy gauges will give the best estimate of the gross rainfall: the localised nature of such events may result in some gauges in the network being largely missed (as seen on a very localised scale for the storm event of 2 to 26 May 1989 described later in this paper). A comparison of the above-canopy rainfall with the mean value calculated from the network shows values of 451.7 and 461.2 mm respectively for the period of joint collection (11 July 1989 to 2 February 1990). This suggests that the above canopy catch has provided a sufficiently reliable rainfall estimate: the network and above canopy gauge collectors agree to within 2%.

Leaf fall began in the last 2 weeks of September and was complete by 26 October. Ignoring this transitional period gives an interception loss of 12% for the leafy period and 11% for the leafless period. Thus for this wood, over the period of study, there was no significant difference between the interception loss for the two seasons.

Rainfall, throughfall and stemflow collection variability.

As rainfall passes through the tree canopy, its flow becomes less homogeneous due to the occurrence of "drip points" and "shielded areas" at the canopy level and along the stems and branches. This phenomenon is well exhibited with the data presented here. The mean catch for each row and collection period is considered to illustrate this point. The catch ranges by a factor of 0.7 to 1.5, 0.3 to 2.8 and 0 to 4 times the mean for rainfall, throughfall and stemflow respectively. The widest variation occurs for stemflow where in some instances only one of the four trees within a plot has collected water for an individual event. In the throughfall case very occasionally high catches are observed and almost invariably the collectors are located under stem dislocations with associated drip points. The distributions of rainfall, stemflow and throughfall are illustrated in Figure 5. The data are presented as differences about the mean for each row and collection period.

Spatial effects

In order to evaluate the variations in net rainfall within the forest a statistical analysis of the network is required. For this, analysis of variance techniques were used (see appendix 1). The model was used to test whether spatial differences across the network were significant.

A slight variation in net rainfall with distance from the forest edge is visually apparent when average values are taken for each row (Figure 6). However, the data show large scatter when all the data for each plot are considered individually (Figure 7). To test for the significance of this, a row effect was used in the model. The row effect was not found to be significant even at an 80% confidence level when net rainfall and throughfall were considered. Indeed the differences between rows are so small as to be hydrologically negligible. In contrast, the stemflow showed a discernable effect (significance level was 99%) with the edge row, row a, having markedly higher stemflow than rows e, c and b: row d is not significantly different to any other row.

A test was also undertaken to see if any spatial differences occur in a direction perpendicular to the rows (ie a column effect; Figure 2). A significant effect was found (99% confidence level). The central column gave significantly lower yields than the other two. However as no North-South trend emerges this is probably due to random plot to plot variations (Figure 7). This begs the question as to whether the column differences occur due to "freak" storm conditions or whether they relate to a "consistent" phenomenon. To evaluate which condition appertained, the most marked plot to plot difference seen within a row (b1 and b2; Figure 7) was examined. Figure 8 shows that not only is there a high correlation between plots (correlation coefficient = 0.993) but also that the collection for b2 is consistently lower than that of b1 by about 18%. This suggests that the difference reflects homogeneous, physical, processes. It is unclear, from examination of the vegetation and topographic characteristics of each plot, why this difference occurs: the plots were all located in areas where the trees were evenly spaced and of similar size.

While one can observe systematic behaviour of the plots this does not exclude "freak" occurrences. In one instance, for a summer storm, a clear example of this abnormal behaviour was observed. Net rainfall values were significantly higher for two plots within the network (C2 and C3). Further, the estimated net rainfall for these two plots unrealistically exceeded the estimated rainfall. These differences reflect consistently high throughfall values for all the collectors within these two plots (Figure 9). On this basis it seems that a very localised additional rainfall input has been observed within the throughfall network which has not been monitored within the rainfall network (throughfall volumes being twice the corresponding rainfall value): remember that these two plots are only 20 to 50 metres away from their nearest neighbours and only 150 metres away from one of the rainfall collection sites. This conclusion is independently supported from the chemical assays; the throughfall chemistry is very different for these two plots compared with all the others in the network (e.g. pH over one unit different) on this one occasion.

Network evaluation.

The above analysis has shown that plot to plot differences can be statistically significant for throughfall, and stemflow. Given the large degree of scatter throughout the data there is clearly a need for extensive monitoring if accurate water balance answers are to be provided. From the data collected one can assess how successful the monitoring scheme has been in terms of the efficiency of the throughfall and stemflow network layout. This analysis is undertaken below.

There are three basic variables in the network design: number of collectors, collection periods and plots. A relationship between the expected error and these variables was estimated using statistical theory outlined in appendix 1. This was used to investigate how well alternative sampling arrangements would have performed. An example, the error associated with a row mean is considered here. As the number of sampled events increases the standard error about the mean decreases (Figure 10). The effect of varying the number of plots and throughfall collectors for 14 sampling events is shown in Figure 11. Increasing either the number of plots or the collectors clearly reduces the error. However the results also suggest that given a fixed number of collectors per row it is better to have a large number of plots and only a few collectors in each, rather than a few plots with a large number of collectors (Figure 12).

Considering throughfall measurement in the network, the analysis reveals that by 14 collection periods the errors are fairly constant. Little improvement would have resulted from increasing the number of throughfall collectors above 8 per plot. Also, given the practical constraints on the total number of collectors per row (24) an arrangement of 3 plots with 8 collectors was retrospectively a good choice. A slight reduction in the overall error (about 25%) should have occurred with 6 plots per row and 4 collectors per plot. It should however be bourne in mind that decreasing the number of collectors in each plot would reduce the precision by which plot to plot differences can be compared.

The conclusions hold for the net rainfall as well. The stemflow contribution (and its associated errors) is small relative to the throughfall: errors in the stemflow estimates will have only a small effect on the total deposition error.
If one was specifically interested in stemflow then a much more extensive monitoring scheme, than the one described here, would be required given the large variability in catch and the impracticality of random relocation.

WIDER DISCUSSION

For the pertaining conditions, the mean interception loss amounted to 11% These results are similar to previous observations on beech (6, 15, 21%; Aussenac and Boulangeat, 1980) and beech-hornbeam (15, 17, 19%; Aussenac, 1968). The period of study is short relative to climatic and seasonal variations. Measurements do not extend to a full hydrological year and, within the sampling time, the summer period was abnormally dry. It would therefore be premature to generalise results.

Although relatively little rainfall was collected during the leafy period when interception loss would be expected to be greatest, no seasonal volumetric effect was discernable for interception loss (12% during the leafy and 11% during the leafless periods): previous results show similar behaviour for more representative periods (Hall and Roberts, 1990). None the less, a seasonal pattern is discernable for stemflow-throughfall relationships.

Despite the limitations, our results suggest that any volumetric enhancement is limited to the first 20 metres of the leading edge of the forest. Thus for woodland arranged in 4 ha square blocks the maximum area affected will be about 10%. So, given a typical hydrological year with 800 mm of rainfall, even if the average enhancement in this edge region was as much as 50% higher (132 mm as opposed to 88 mm), this would only give an overall increased loss of 4.4 mm for the block. Correspondingly, for a 1 ha forest block the maximum area affected would be about 20% and the increased loss in interception would only be 8.8 mm. This difference is within experimental error (cf the above canopy and network rainfall collector comparison: 10.5 mm discrepancy for a 6 month period). For larger plantations the edge effect becomes negligible.

The results show the importance of careful network design. Given a fixed number of collectors it is better to spread the collectors more thinly across a large number of plots if accurate average net rainfall, stemflow and throughfall values are required. When increasing the number of plots their size and spacing should be maintained; sampling is thereby extended to cover a larger, more representative, forest area. If one is also interested in the spacial variability there is a need for a balance between increasing the number of plots (increasing accuracy for the overall accuracy) and increasing the number of collectors per plot (reducing the precision on data for each plot).

Sub-division of the rows into plots has also proved worthwhile. Plot to plot differences have been identified and improved estimation of row and edge effect results. Spatial differences can also be seen more clearly (as in the summer storm where throughfall catches for c2 and c3 were very different from the remaining plots). The plot to plot variation can be quite substantial:- even though Blackwood forest is relatively flat and uniformly dense with trees of similar height. The variation is likely to be greater for other woodland sites (topography, forest edge geometry, tree size and tree spacing being more irregular):- so a large area must be sampled to get accurate results. The plot to plot differences have important repercussions for sheet interception devices. The results obtained from such devices are precise but only apply to a very localised area and should not be generalised to provide accurate interception losses for an entire forest.

Although a reasonably detailed network has been established for stemflow and throughfall, the same cannot be guaranteed for rainfall measurement: the freak storm event for the 2 to 26 of May 1989 illustrating this. For the present study, only 2 towers were available to support above canopy collectors. For future interception studies, using network designs, our results point to the need for a more extensive above-canopy rainfall sampling scheme.

APPENDIX 1

Statistical methodology for error analysis.

The following form of model was fitted to throughfall data.

$$\text{volume}(i,j,k) = \text{plot}(i) + \text{collection}(j) + e_1(i,j) + e_2(i,j,k)$$

where i denotes the plot $(1<=i<=14)$
j denotes the collection period $(1<=j<=14)$
k denotes the throughfall collectors in each plot $(1<=k<=8)$

plot(i) is an effect for each plot. The sum of an effect for distance into the forest and a random component is considered in the model:-

$$\text{plot}(i) = \text{row}(r(i)) + e_0(i)$$

where e_0 has a normal distribution $N(0,\sigma_0^2)$. For throughfall the row effect was not significant and, to simplify matters, was set to zero.

The term collection(j) is used to describe an effect due to differences in hydrometereological conditions (rainfall, wind direction etc) between collection periods.

e_1 represents the variation in the plot response for a collection period due to spatial storm variations for the period. It is assumed to have a normal distribution $N(0,\sigma_1^2)$.

e_2 represents the variation in the individual throughfall collector values. It is assumed to have normal distribution $N(0,\sigma_2^2)$.

Given these assumptions, the following hold,

i. variation of the individual throughfall collector values about the plot mean for each collection period

$$= \sigma_2^2 \qquad (1)$$

(this was estimated using the residual variation for an anova model in which a plot*collection effect is fitted. This is the 'within-plot' error);

ii. variation of the mean value of each plot for each period relative to the expected mean for that plot and period (estimated by the residual variation when a plot and collection period effect are modelled to these means)

$$= \sigma_1^2 + \sigma_2^2/(nc) \qquad (2)$$

where nc is the number of collectors per plot;

iii. variation of the overall plot means about the overall site mean

$$= \sigma_0^2 + \sigma_1^2/np + \sigma_2^2/nc*np \qquad (3)$$

where np is the number of collection periods: equation 3 is estimated by the residual error when an ANOVA model is fitted to the plot means (this is the 'between-plot' error);

iv. the variation of the mean of p plots (for example p = 3 for a row as there are three plots in a row)

$$= \sigma_0^2/p + \sigma_1^2/np*p + \sigma_2^2/nc*np*p \qquad (4).$$

Equations 1-3 are used to estimate σ_0, σ_1 and σ_2. The variances given in 1-3 being found from the residual error estimates of their respective ANOVA models. They give the following results.

$\sigma_0=$	2.6
$\sigma_1=$	1.9
$\sigma_2=$	12.7

These estimates were substituted into equations 1 to 4 and the parameters np, nc, p varied to determine the best allocation of collectors and plots to achieve minimum errors on the estimates.

For the stemflow a similar type of analysis was conducted. Slight differences arise because the stemflow collectors are not relocated between collections. The form of the model was

$$\text{volume}(i,j,l) = \text{plot}(i) + \text{collection}(j) + \text{tree}(l) + e_1(i,j) + e_2(i,j,l)$$

where,

l denotes the tree ($1 <= l <= 60$);

plot(i), collection(j), $e_1(i,j)$ and $e_2(i,j)$ are defined as for throughfall;

tree(l) is a random effect with normal distribution $N(0,\sigma_t^2)$ representing differences between the trees.

The term $e_1(i,j)$ was found not to be significant. Thus the variation of the mean of p plots (for example p = 3 corresponds to the experimental design used in this paper as there are three plots in a row)

$$=\sigma_0^2/p + \sigma_t^2/t*p + \sigma_2^2/nc*np*p \qquad (4)$$

where t is the number of trees with stemflow collectors per plot.

The resultant error estimates were as follows

σ_0	0.027
σ_t	0.019
σ_2	0.098

FIGURES

Figure 1. Location map for Blackwood forest.

Figure 2. Network layout.

Figure 3. Percentage of Stemflow and Throughfall making up Net Rainfall, for all the plots, with time: sampling period 2 May 1989 to 2 February 1990.

Figure 4. Throughfall, Stemflow and Net Rainfall relations with Rainfall: sampling period 2 May 1989 to 2 February 1990. Row means for each collection period are shown.

Figure 5. Frequency distributions for rainfall, throughfall and stemflow differences about the mean for each row (number of sample points 64, 1920, 960 respectively).

Figure 6. Stemflow, Throughfall and Net Rainfall variations with

distance from the forest edge, totalled for the period 2 May 1989 to 2 February 1990.

Figure 7. Throughfall variation with distance from the forest edge for the period 2 May 1989 to 2 February 1990: averaged values for individual plot data are presented.

Figure 8. Inter-plot Net Rainfall comparisons for B1 and B2 sites: sampling period 2 May 1989 to 2 February 1990.

Figure 9. Throughfall collector data for the period 2 to 26 May 1989.

Figure 10. The Standard error for the mean throughfall for a row of three plots with 8 collectors per plots is graphed against the number of collection periods.

Figure 11. The standard error for the throughfall row mean (averaged over 14 collection periods) is plotted as a function of the number of plots per row. Parallel lines show the effect of varying the number of throughfall collectors per plot.

Figure 12. The standard error for the throughfall row mean (averaged over 14 collection periods) is plotted for different arrangements of collectors within a row. The total number of throughfall collectors in the row is constant for a single line. Different lines show the effect of varying the total number of collectors.

TABLES.

Table 1. Rainfall, Throughfall, Stemflow and Net Rainfall summary

data*.

Date	Rain	Stem	Through	Net Dep.	% Evap.	% Stem
	mm	mm	mm	mm	mm	mm
26/5/89	15.6	0.2	14.4	14.7	5.6	1.6
2/6/89	11.5	0.1	9.3	9.4	18.6	1.0
8/6 89	15.4	0.3	12.8	13.0	15.6	1.7
4/7 89	18.4	0.2	13.0	13.3	27.8	1.2
11/7/89	23.6	0.5	20.7	21.2	10.1	2.1
15/8/89	22.8	0.7	22.3	23.0	-1.1	3.0
12/9/89	6.5	0.0	5.6	5.6	13.6	0.4
26/9/89	42.9	1.7	42.3	44.0	-2.6	3.9
26/10/89	54.5	2.0	40.9	42.8	21.4	3.6
6/11/89	50.5	2.3	44.4	46.7	7.6	4.6
20/11/89	18.3	0.7	14.2	15.0	18.3	3.9
22/12/89	117.0	6.0	102.7	108.6	7.2	5.1
4/1/90	24.1	1.6	20.1	21.7	10.0	6.6
18/1/90	24.7	2.2	23.8	26.0	-5.6	9.1
2/2/90	90.5	5.2	67.5	72.6	19.7	5.7
	Sum	Sum	Sum	Sum	%	o
Summary	536.2	23.8	453.9	477.7	10.9	4.4

* average for all plots: start date 2 May 1989.

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Fig 1

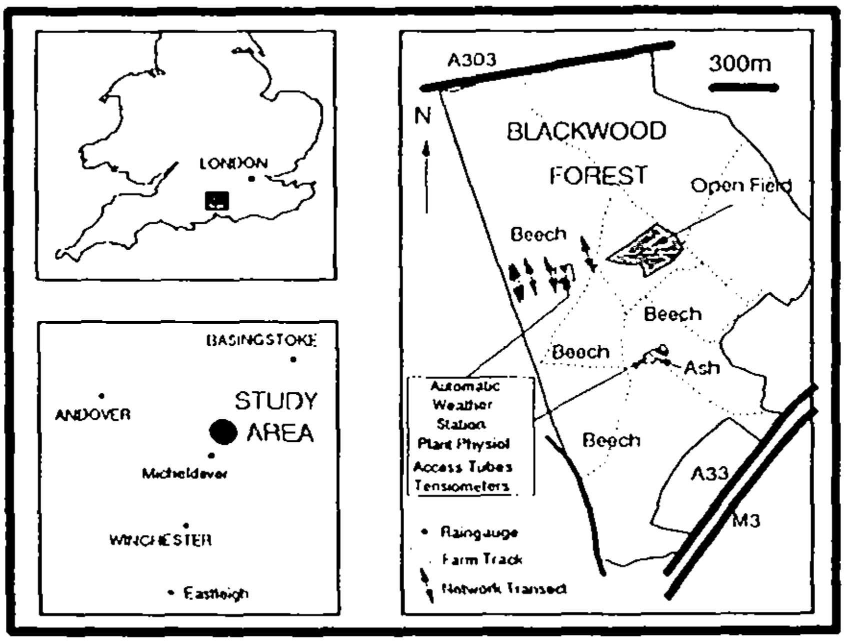

LONDON
BASINGSTOKE
ANDOVER
STUDY
AREA
Micheldever
WINCHESTER
Eastleigh
A303
300m
N
BLACKWOOD
FOREST
Open Field
Beech
Beech
Beech
Ash
Beech
A33
M3
Automatic
Weather
Station
Plant Physiol
Access Tubes
Tensiometers
Raingauge
Farm Track
Network Transect

Fig 1

Fig 2

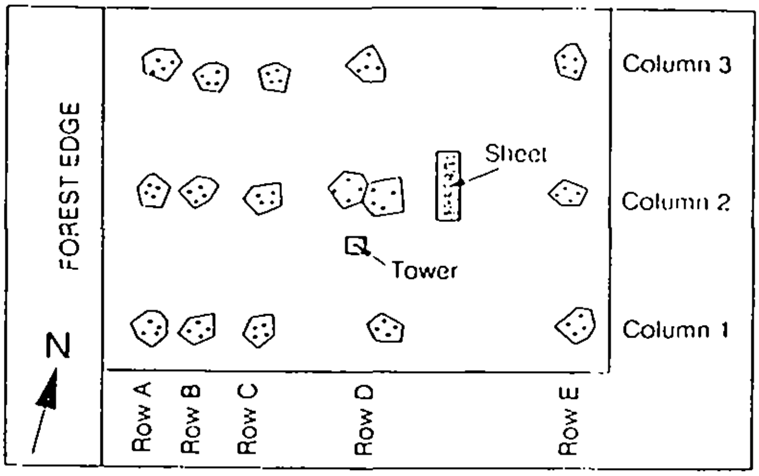
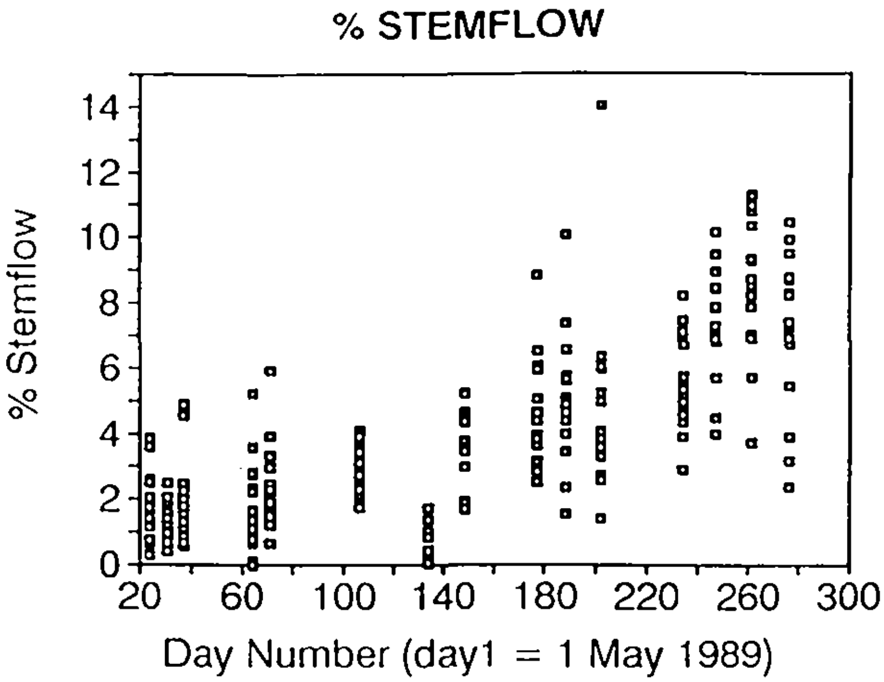

FOREST EDGE
N
Column 3
Sheet
Column 2
Tower
Column 1
Row A
Row B
Row C
Row D
Row E

Fig 2

Fig 3


% STEMFLOW
% Stemflow
0
2
4
6
8
10
12
14
20
60
100
140
180
220
260
300
Day Number (day1 = 1 May 1989)

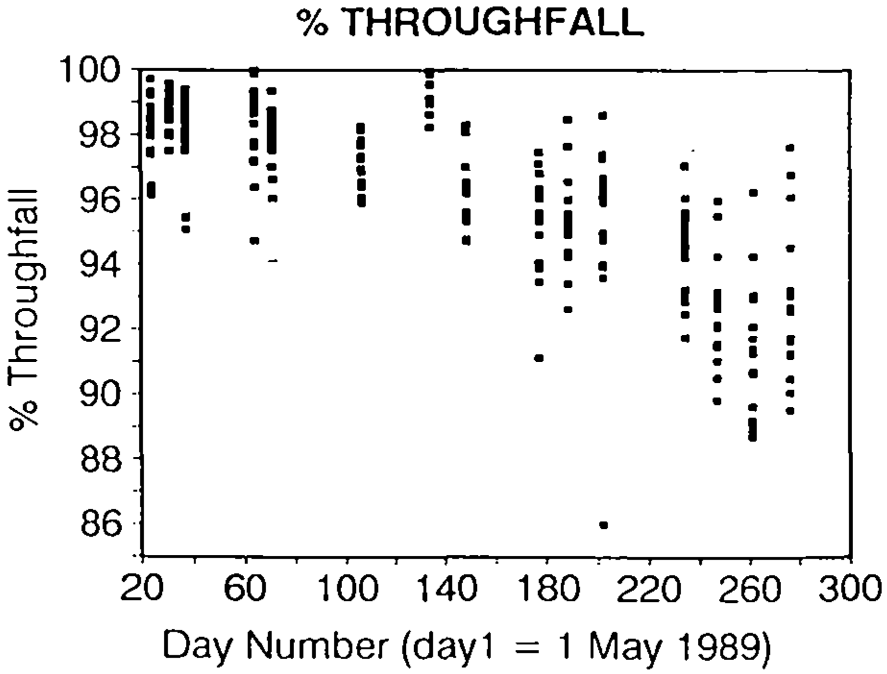

% THROUGHFALL
% Throughfall
86
88
90
92
94
96
98
100
20
60
100
140
180
220
260
300
Day Number (day1 = 1 May 1989)

Fig 3

Fig 4

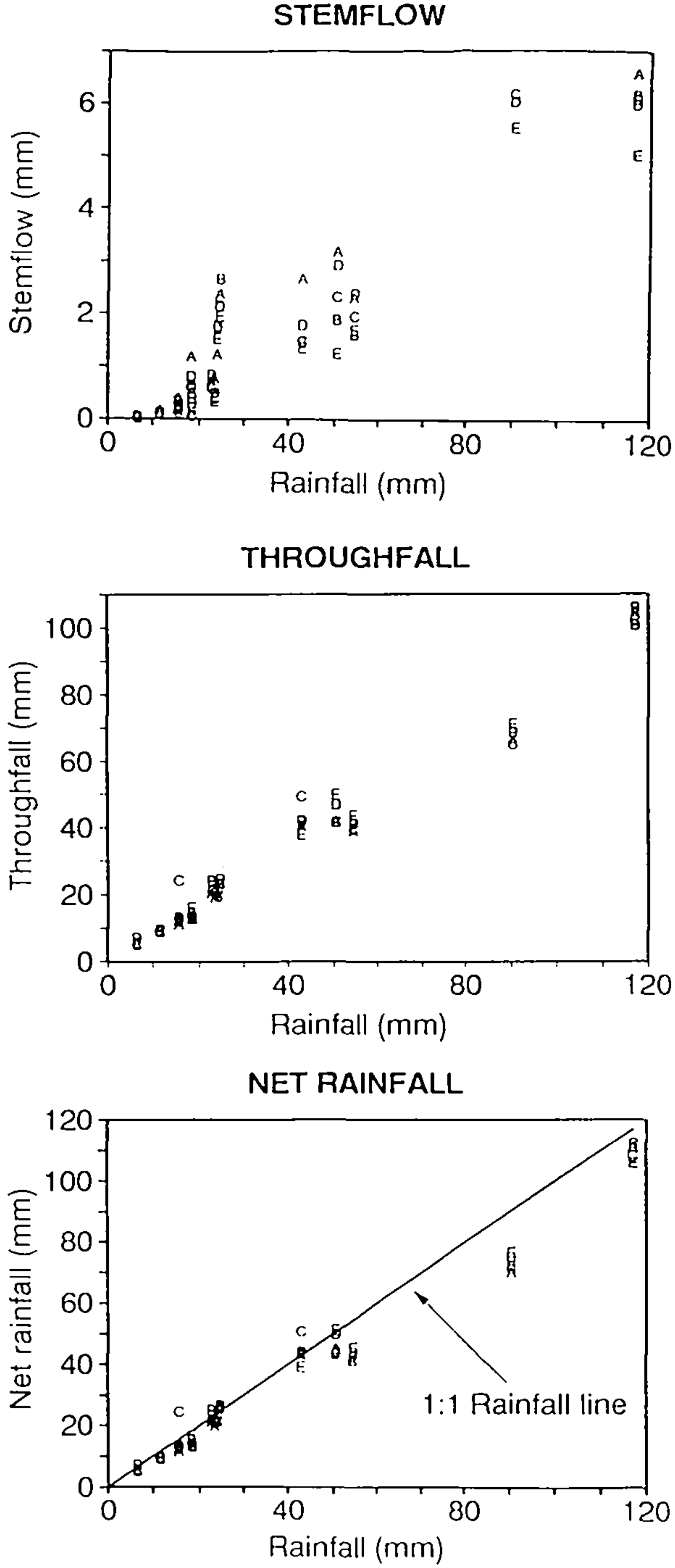

STEMFLOW
Stemflow (mm)
0
2
4
6
Rainfall (mm)
0
40
80
120
A
B
C
D
E
THROUGHFALL
Throughfall (mm)
0
20
40
60
80
100
Rainfall (mm)
0
40
80
120
NET RAINFALL
Net rainfall (mm)
0
20
40
60
80
100
120
Rainfall (mm)
0
40
80
120
1:1 Rainfall line

Fig 5

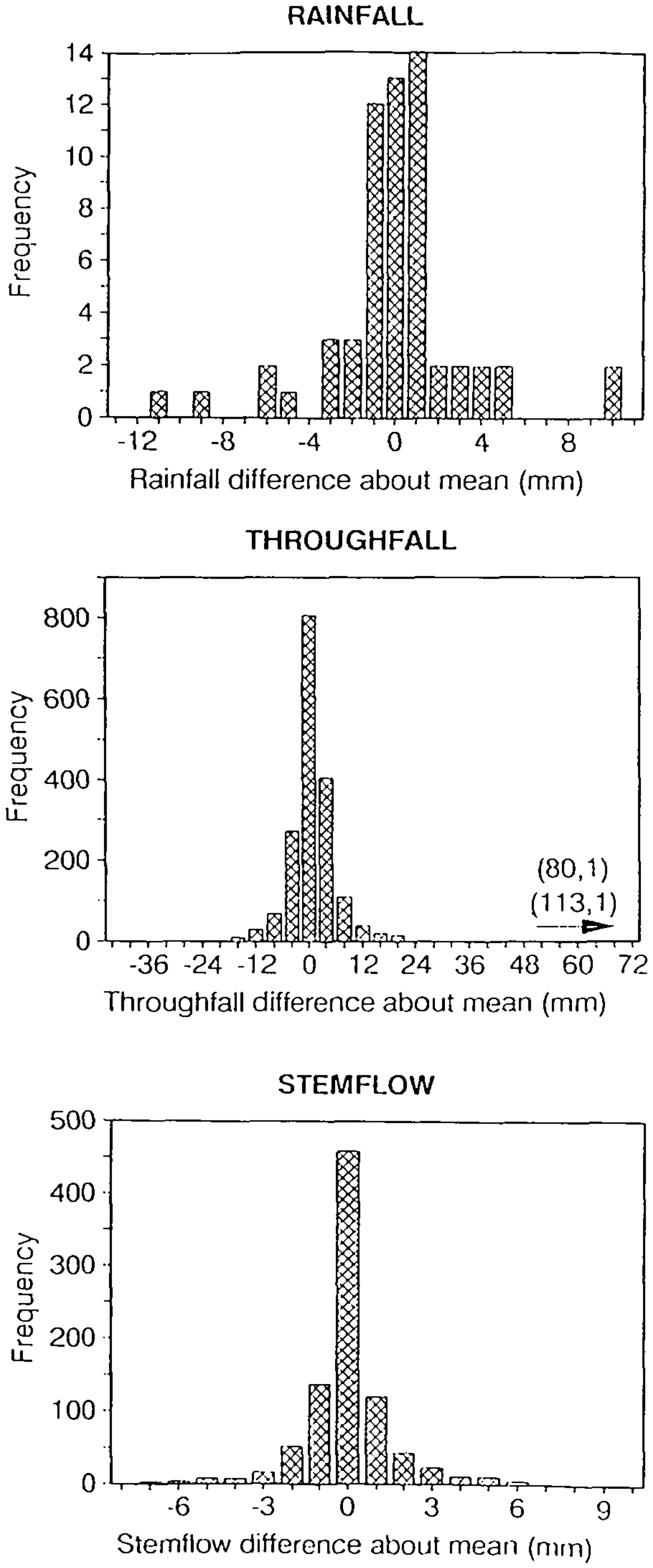

RAINFALL
Frequency
0
2
4
6
8
10
12
14
-12
-8
-4
0
4
8
Rainfall difference about mean (mm)
THROUGHFALL
Frequency
0
200
400
600
800
-36
-24
-12
0
12
24
36
48
60
72
(80,1)
(113,1)
Throughfall difference about mean (mm)
STEMFLOW
Frequency
0
100
200
300
400
500
-6
-3
0
3
6
9
Stemflow difference about mean (mm)

Fig 6

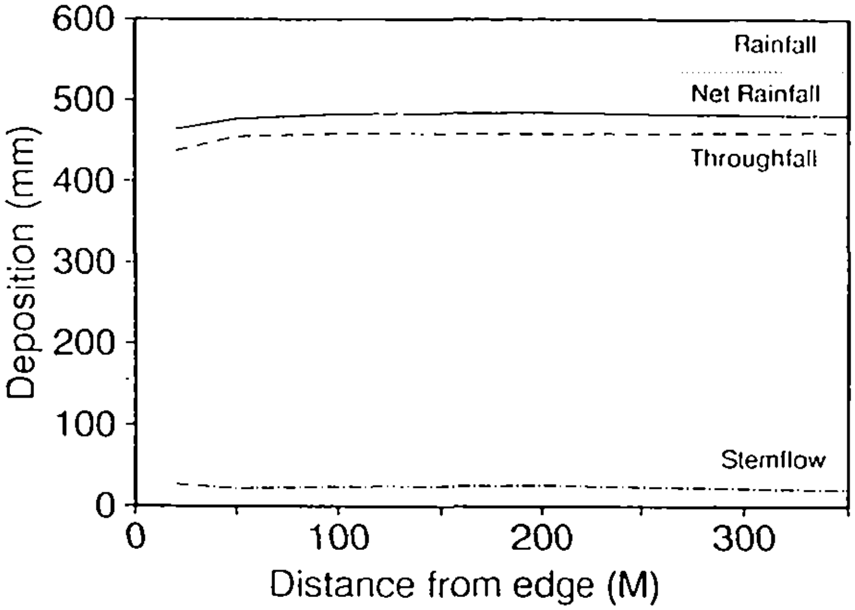
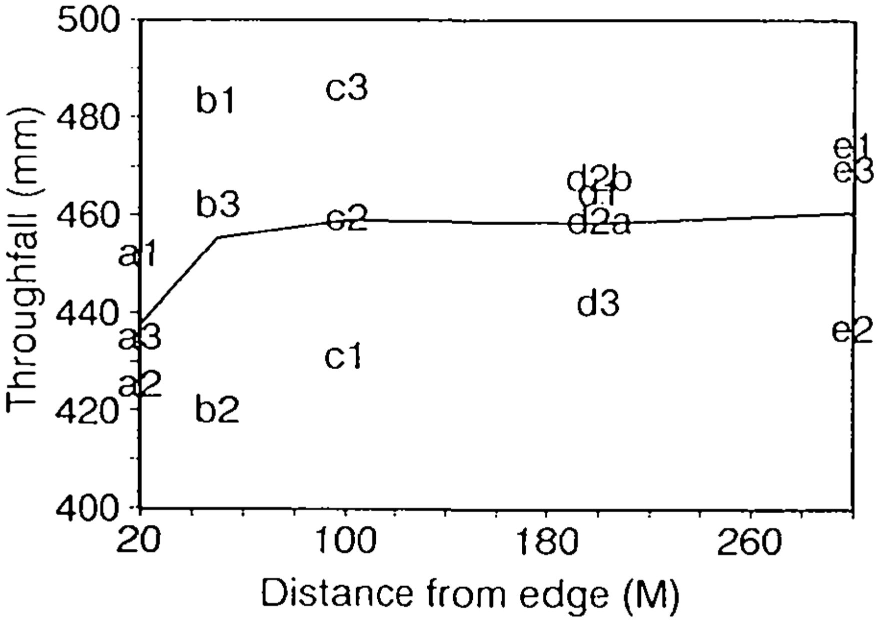
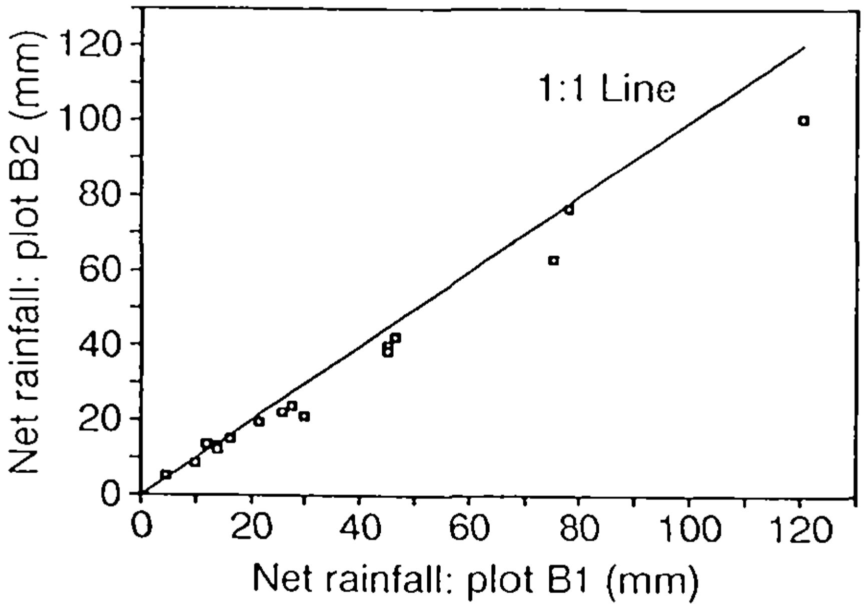

600
500
400
300
200
100
0
Deposition (mm)
Rainfall
Net Rainfall
Throughfall
Stemflow
0
100
200
300
Distance from edge (M)

Fig 7



500
480
460
440
420
400
Throughfall (mm)
b1
c3
b3
c2
a1
a3
a2
b2
c1
d2b
d1
d2a
d3
e1
e3
e2
20
100
180
260
Distance from edge (M)

Fig 8



1:1 Line
Net rainfall: plot B2 (mm)
0
20
40
60
80
100
120
Net rainfall: plot B1 (mm)
0
20
40
60
80
100
120

Fig 9

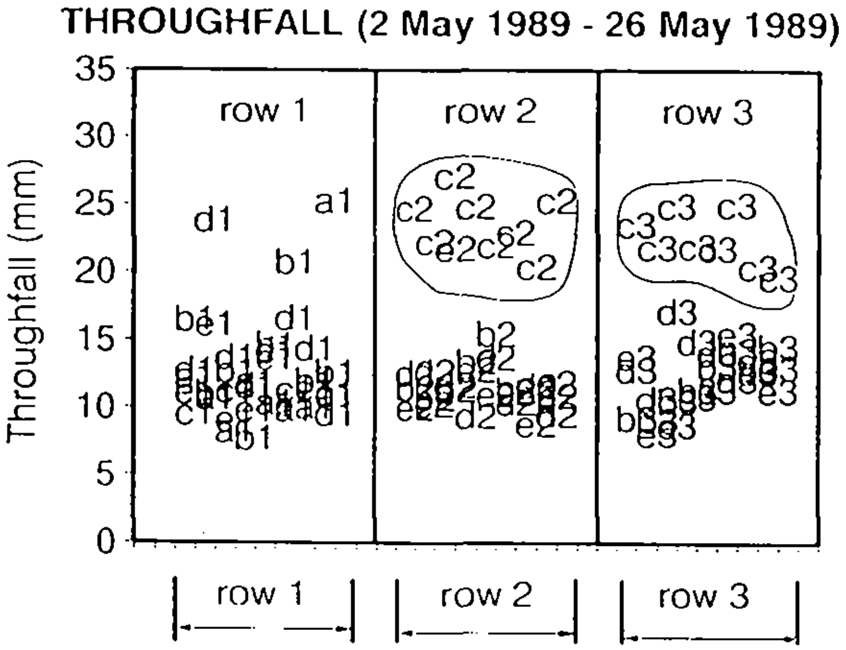
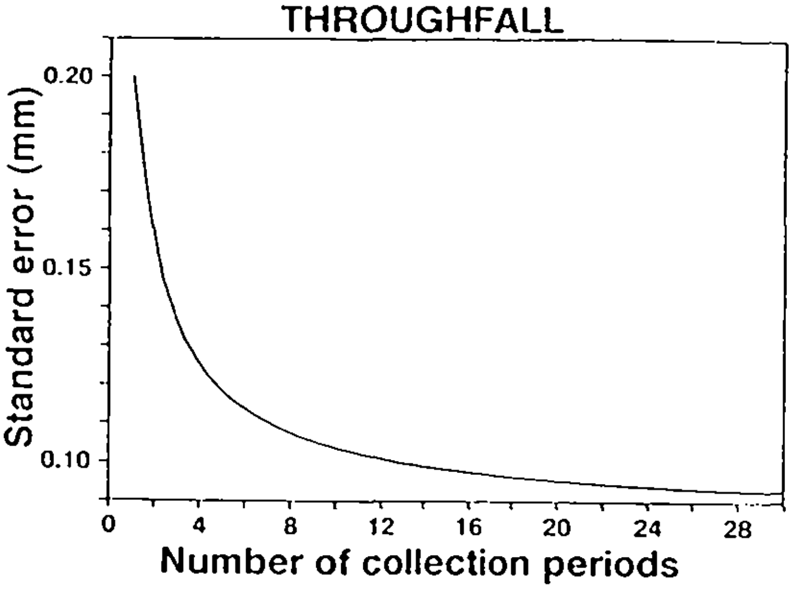

THROUGHFALL (2 May 1989 - 26 May 1989)

Fig 10



THROUGHFALL
Standard error (mm)
0.20
0.15
0.10
0
4
8
12
16
20
24
28
Number of collection periods

Fig 11

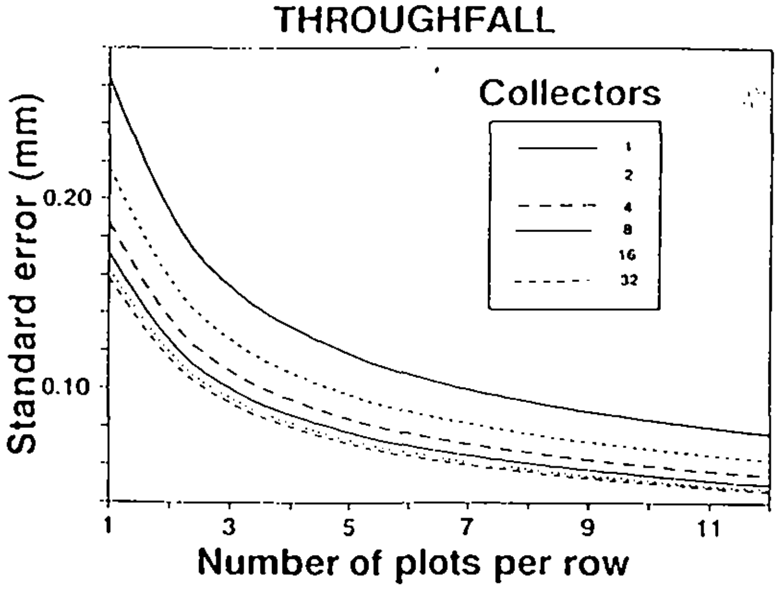
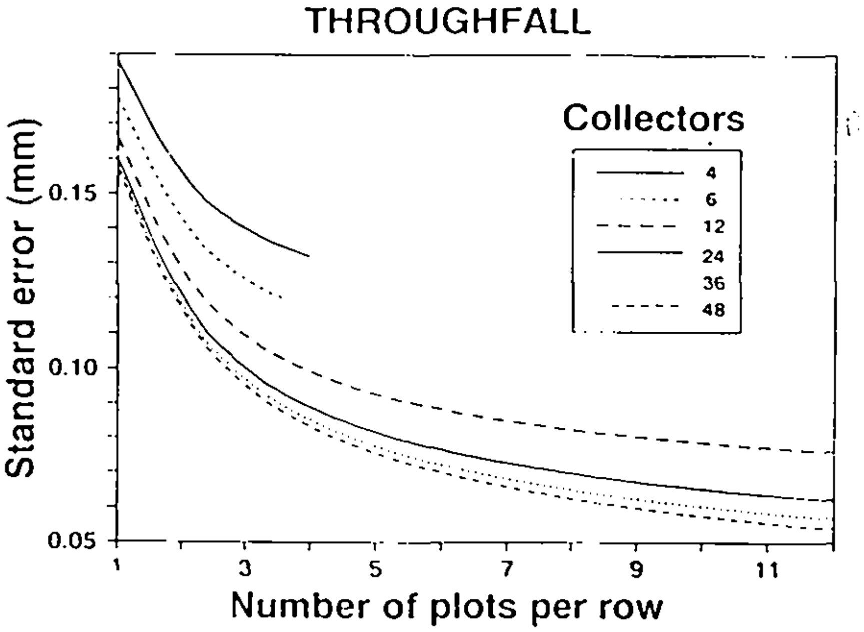

THROUGHFALL
Collectors
1
2
4
8
16
32
Standard error (mm)
0.20
0.10
1
3
5
7
9
11
Number of plots per row

Fig 12


THROUGHFALL
Collectors
4
6
12
24
36
48
Standard error (mm)
0.15
0.10
0.05
1
3
5
7
9
11
Number of plots per row

The demand for long-term scientific capabilities concerning the resources of the land and its freshwaters is rising sharply as the power of man to change his environment is growing, and with it the scale of his impact. Comprehensive research facilities (laboratories, field studies, computer modelling, instrumentation, remote sensing) are needed to provide solutions to the challenging problems of the modern world in its concern for appropriate and sympathetic management of the fragile systems of the land's surface.

The **Terrestrial and Freshwater Sciences** Directorate of the Natural Environment Research Council brings together an exceptionally wide range of appropriate disciplines (chemistry, biology, engineering, physics, geology, geography, mathematics and computer sciences) comprising one of the world's largest bodies of established environmental expertise. A staff of 550, largely graduate and professional, from four Institutes at eleven laboratories and field stations and two University units provide the specialised knowledge and experience to meet national and international needs in three major areas:

★

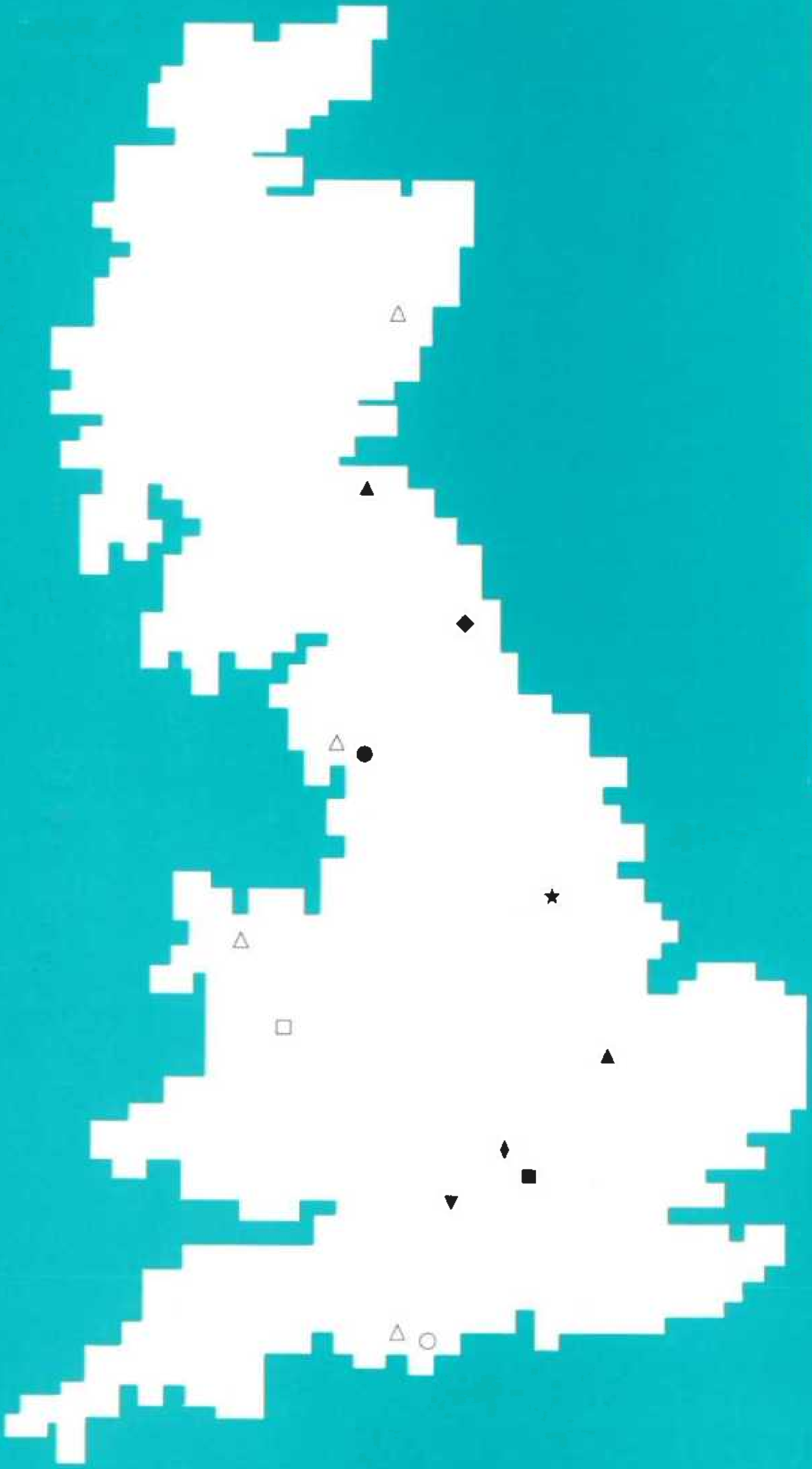
Land Use and Natural Resources

★

Environmental Quality and Pollution

★

Ecology and Conservation



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