14. WET DEPOSITION AND THE MOVEMENT OF POLLUTANTS THROUGH FORESTS

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With a greater or lesser degree of certainty, it has been suggested that sulphur dioxide and other sulphur-derived pollutants can directly and indirectly affect the productivity of terrestrial and aquatic ecosystems. Although SO_2 and acid precipitation, resulting from the hydration and oxidation of SO_2, may separately affect the different ecosystems, it is often difficult to distinguish their influences one from the other, or from the combined effects of mixtures including other types of pollutant, eg NO_X and ozone. Our knowledge is still surprisingly deficient.

Research within ITE is concentrated on the fate and effects of sulphur pollutants, measured above and within a stand of Scots pine *(Pinus sylvestris)* in the Devilla section of the Forestry Commission's Ochil forest in central Scotland. Observations are being made of dry deposition, the direct transfer of gaseous and particulate material from the atmosphere to surfaces, and wet deposition, the transfer of an element or substance from the atmosphere in aqueous solution or suspension, whether rain, snow or fog, wet deposition being the subject of this chapter.

1. Wet deposition and precipitation acidity

1.1 Wet deposition

At distances from emission sources, amounts of atmospheric SO_2 are depleted as a result of (i) its dry deposition and (ii) its oxidation to sulphate, SO_4^{2-}/SO_2 ratios tending to increase with distances from sources.

Sulphur dioxide is absorbed by water droplets in the cloud-producing layers, but, although it is very soluble, solubility is nevertheless strongly pH-dependent, the amounts absorbed decreasing as the pH of water droplets decreases. This removal of SO_2 is known as rainout, whereas the collection (scavenging) of gaseous and particulate sulphur by falling raindrops is known as washout. Small drops are more efficient scavengers than large drops and therefore remove more SO_2 per mm of precipitation.

Raindrops, drizzle and other relatively large drops > 0.5 mm are deposited by sedimentation. In contrast, the much smaller fog droplets ($< 100\ \mu$, characteristically $10\ \mu$) reach surfaces by physical processes similar to those responsible for dry deposition of small particles (turbulent impaction); their deposition is therefore significantly affected by the nature of the different surfaces, eg the size and distribution of leaves.

1.2 Changing precipitation chemistry

The formation of sulphuric acid is mainly responsible for acidifying precipitation. Rain samples from North America, for example, showed that sulphate accounted for *c* 62% of the anions present (Likens & Bormann, 1974). Major changes in precipitation acidity, similarly largely attributable to the presence of sulphate, have been recorded in western and northern Europe including Norway and Sweden, where amounts of deposited sulphate, of non-marine origin, increased appreciably between 1955 and 1970 (Malmer, 1974): in Britain, Martin (1978) concluded from a limited amount of data that the largest increase in rain acidity occurred before 1957.

Although Gorham (1957) presented evidence, as far back as the mid-1950s, suggesting that industrial pollution was increasing the acidity of rain in the English Lake District, his observations had surprisingly little impact, at that time, on ecological research. Evidence of increasing acidity and its effects in Scandinavia was first documented in a Swedish government report in 1967.

To add to the analysis made of rain collected at a few locations scattered over the length of Britain, ITE established, in 1977, a relatively intensive network covering much of northern Britain. Compared with the very polluted areas in southern Norway, most sites in Britain appear to receive proportionately less rain of low pH, and the sulphate content of rain is less (Figure 35); nonetheless rain in northern Britain is usually considerably more acid than pH 5.7 (the so-called "neutral" point for rain) and on some occasions, at some stations, very acid rain containing large concentrations of sulphur have been recorded.

2. Effects of forests on wet deposition

Setting aside the possibility that forests on a regional scale may influence the occurrence of precipitation, their structures also (i) alter the ways in which incident precipitation is partitioned into stemflow, throughfall and interception and (ii) affect the deposition of fog.

2.1 Deposition of rain and snow within forests

Most forests, natural and man-made, are structured with dominant, sub-dominant and suppressed trees, shrub and ground floras which act as a

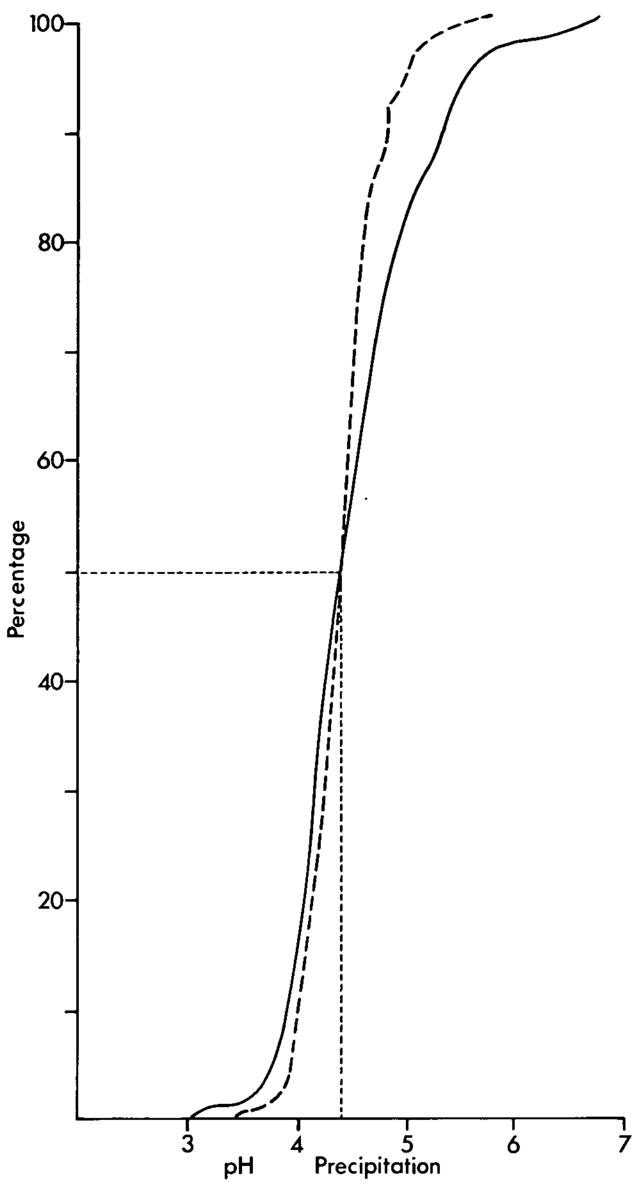

Fig. 35 *Cumulative distributions showing percentage of total precipitation with pH lower than given values. 1978/79 means for Banchory (—) are compared with those for 1972/75 at Birkenes, Norway (– – –) (Dovland* et al., *1976). Mean annual precipitation at Banchory and Birkenes amounted to 780 and 3,900 mm respectively.*

series of 'baffles' ensuring that very little precipitation falls directly on to soil. Passage through forests will be influenced by the density of each layer of the canopy, with amounts of wet deposition being greater on some layers, or parts of layers, than on others. Snow penetrates vegetation less readily than rainfall and therefore amounts deposited tend to be spatially disparate, usually with large accumulations, attributable to drifting, in clearings and at the forest edge.

2.2 Fog deposition

Whereas fog blown inland from the sea sometimes contains appreciable quantities of solutes (Azevedo & Morgan, 1974), inversion fogs in polluted atmospheres tend to have large concentrations of pollutants. Fog deposition from advection fogs, which are caused by cooling resulting from advection of warmer air over a colder surface, has been studied in coastal areas of Japan and on the Pacific coast of North America where such fogs are commonplace. It has been found that 6 - 10 times as much fog drip was trapped by forests as was collected on the ground in nearby open fields, this filtering effect being attributed to the transport of fog particles to foliage and branches by turbulent diffusion. Additionally, large quantities of precipitation have been recorded at the edges of the forests where fog was driven by strong winds, so-called horizontal deposition. (Imahori, 1953; Oura, 1953 *a, b*; Yosida, 1953).

In foggy conditions, plant surfaces are moist. These moisture films are important because they:

(i) provide an efficient sink for gaseous atmospheric pollutants (Fowler, 1978; Brimblecombe, 1978);

(ii) possibly enhance leaf leaching;

and (iii) increase the possibilities of interactions between pollutants occurring by wet and dry deposition.

3. Precipitation input: 'pathways' and changes in chemical composition

3.1 Effects of foliage on precipitation chemistry

'Sulphur' can be deposited on the surfaces of leaves and bark and absorbed in the gas phase through leaf stomata when it may be metabolised without necessarily causing damage. Many studies have shown that the composition of rainwater changes as it passes over plant surfaces and that different tree species have different effects on throughfall (eg Madgwick & Ovington, 1959; Henderson *et al.*, 1977) and stemflow, the largest concentrations of solutes and suspended matter usually being found in this fraction (Voigt, 1960; Abrahamsen *et al.*, 1975). Bjor and his colleagues (1974) working in Norway found that throughfall beneath Norway spruce and Scots pine was more acid and contained larger concentrations of sulphate than precipitation collected in open terrain, whereas that of birch contained smaller amounts of strong acid (Table 17).

The composition of water draining from leaves and stems is usually augmented by the addition of surface deposits and foliar leachates and depleted by the removal of substances, including moisture, by leaf absorption.

TABLE 17 Relative effects of canopies of different tree species on amounts and chemical composition of throughfall, comparisons being made with precipitation collected on nearby open terrain whose amounts, and composition, were taken as 100 (Bjor *et al.,* 1974).

Species of tree	Position of rain gauges+	Volume of throughfall as % of incident precipitation†	Relative concentrations of different chemical constituents		
			Strong Acid	Mg^{2+}	SO_4^{2-}
Norway spruce	Inner	35	138	102	131
	Outer	99	181	187	211
Scots pine	Inner	82	297	259	215
	Outer	83	248	230	202
Birch	Inner	92	92	158	101
	Outer	71	62	161	89
Open terrain		100	100	100	100

+ Positions relative to canopy—inner, near trunk; outer, at perimeter.

† The deficits in relation to open terrain are attributed to 'interception' losses and amounts of stemflow which were not measured.

TABLE 18 Data illustrating effects of antecedent weather on amounts of sulphate-sulphur removed from surfaces by washing leaves of holly, and bark of ash, birch and holly taken from trees growing around Manchester. Data from Parr's Fold, a site known to have received prolonged heavy rain (>30 mm in 24 h) immediately before sampling in December, are compared with data from 5 other sites (in the same 'zone' of atmospheric pollution: winter mean conc. >150 $\mu g\ SO_2\ m^{-3}$) sampled subsequently during the same winter. Values are also shown for samples taken from the same sites sampled in summer after a long period without rainfall (Kinnaird *et al.,* Unpubl.).

	Leaves (Holly)			Bark (Means of ash, birch, and holly)		
	Parr's Fold (a)	Other sites (b)	a/b (%)	Parr's Fold (c)	Other sites (d)	c/d (%)
	Amounts of SO_4 - S mg m^{-2}					
I The sample at Parr's Fold, unlike those at other sites, was taken immediately after prolonged heavy rain: observations made in winter	0.1	1.1	9	<0.2	1.9	<10
II The sample at Parr's Fold, like those at other sites, was taken after a prolonged dry spell: observations made in summer	1.6	3.1	52	2.4	5.7	42

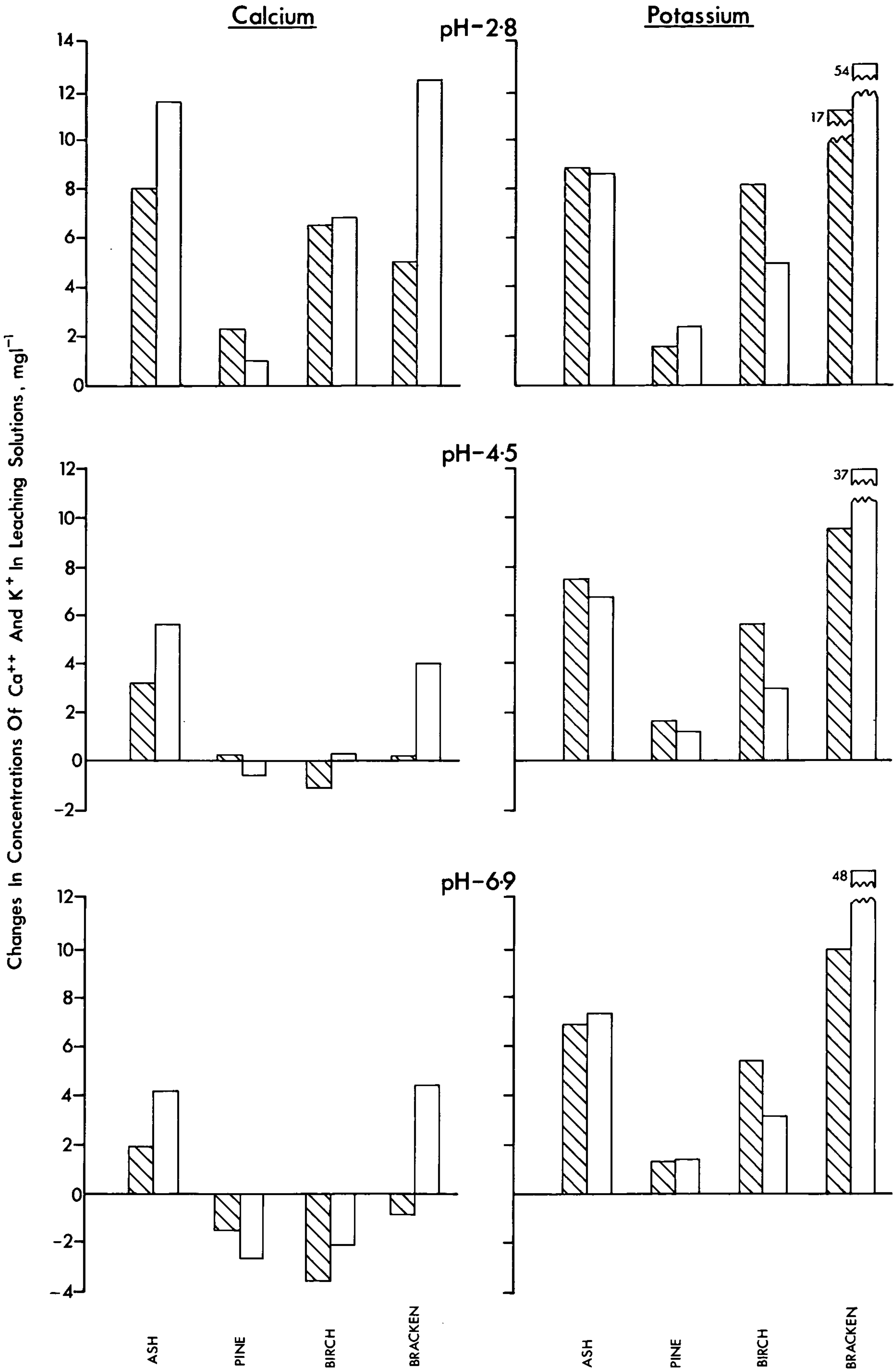

Fig. 36 *Effects of increasing the acidity of leaching solutions from pH 6.9 to 2.8 on the release of Ca++ and K+ from detached leaves of ash, Scots pine, birch and bracken. Experiments done in August* [hatched box] *and October* [open box] *.*

Surface deposits

In and around urban areas, bark and leaves of deciduous and evergreen species accumulate, on their surfaces, relatively large amounts of sulphate which can be readily depleted by rain. (Table 18).

Leachates

It has been known for a long time that amounts of leachates are affected by internal and external factors but the effect of strongly acid rain, which increases cation leaching, was only recently reported (Wood & Bormann, 1975). Experiments done with detached leaves of ash, Scots pine, birch and bracken have shown that increasing amounts of Ca^{2+} were leached when washed with increasingly acidic simulated rain, the effect on K^+ leaching being much less marked (Kinnaird & Nicholson, unpubl.) (Figure 36).

Substances absorbed

Whereas surface deposits and leachates may augment the concentrations of solutes and suspended matter in throughfall and stemflow, some solutes and water may be lost by absorption (Voigt & Swolinski, 1964). Many substances can be absorbed (Tukey *et al.,* 1956; Franke, 1967) including nitrate and ammonium ions by foliage of Norway spruce, Scots pine and birch (Abrahamsen *et al.,* 1976); foliage of Norway spruce was found to absorb phosphorus and potassium (Kilian, 1977). Even in the dormant season, the bark of fruit trees has been found to accumulate phosphorus and potassium by absorption.

3.2 Woodland structure and re-distribution of precipitation

In forests with many tree species providing a complex series of "baffles", the route by which precipitation reaches the ground is likely to be more complex than in a single-species plantation forest, as exists at the ITE study area in Devilla forest. Here precipitation may reach the soil (i) after passage through the canopy without contact with any plant parts (representing true wet deposition to the soil), (ii) by dripping from the foliage or (iii) by stemflow. Of these 'pathways' stemflow is of special interest. The absolute amounts of water involved may be relatively unimportant when considering the water budget of the forest system, for example stemflow may only account for 1-5% of the total precipitation (Zinke, 1967); but the input of water and dissolved substances to the soil is disproportionately large when calculated as a depth of water falling on a surface equal to the ground area occupied by the tree stem. In some studies, amounts of water reaching the soil in these localised areas have been many times the amounts deposited on equivalent areas elsewhere in a forest (Reynolds & Leyton, 1963).

Interestingly, the large amounts of sulphate found on the bark of pine in urban areas of the UK are paralleled by results from southern Norway where stemflow from Scots pine, compared with that of Norway spruce and birch, contained particularly large concentrations of sulphate. With some exceptions (eg Zinke, 1962; Adriano & Pinder, 1977), few studies, since the early work of Müller (1887), have considered the ways in which soil properties beneath forest canopies are patterned. But does the addition of pollutants increase the podsolizing effects of stemflow noted by Mina (1967)?

4. Development of research on wet deposition

At the risk of giving a distorted picture (by omitting problems of dry deposition), 2 areas of research need particular attention: (i) the atmosphere/leaf surface interface where reactions occur that may influence the deposition and transformation of substances which interfere with exchange reactions, internal and external, with photosynthesis, transpiration and other leaf functions and with leaf surface microbes, and (ii) the impact of stemflow on soil processes and properties.

References

Abrahamsen, G., Horntvedt, R. & Tveite, B. 1975. *Impacts of acid precipitation on coniferous forest ecosystems.* Oslo-Ås: SNSF. (Research report, SNSF project no. 2).

Abrahamsen, G., Bjor, K., Horntvedt, R. & Tveite, B. 1976. Effects of acid precipitation on coniferous forest. In: *Impact of acid precipitation on forest and freshwater ecosystems in Norway,* edited by F.H. Braekke, 37-64. Oslo-Ås: SNSF. (Research report, SNSF project no. 6).

Adriano, D.C. & Pinder, J.E. 1977. Aerial deposition of plutonium in mixed forest stands from nuclear fuel processing. *J. environ. Qual.,* **6,** 303-307.

Azevedo, J. & Morgan, D.L. 1974. Fog precipitation in coastal California forests. *Ecology,* **55,** 1135-1141.

Bjor, K., Horntvedt, R. & Joranger, E. 1974. The distribution and chemical composition of precipitation in a forest stand in southern Norway (July-December 1972). Oslo-As: SNSF. (Research report, SNSF project no. 1).

Brimblecombe, P. 1978. "Dew" as a sink for sulphur dioxide. *Tellus,* **30,** 151-157.

Dovland, H., Joranger, E. & Semb, A. 1976. Deposition of air pollutants in Norway. In: *Impact of acid precipitation on forest and freshwater ecosystems in Norway,* edited by F.H. Braekke, 15-35. Oslo-As: SNSF. (Research report, SNSF project no. 6).

Fowler, D. 1978. Dry deposition of SO_2 on agricultural crops. *Atmos. Environ.,* **12,** 369-373.

Franke, W. 1967. Mechanisms of foliar penetration of solutions. *A. Rev. Pl. Physiol.,* **18,** 281-299.

Gorham, E. 1957. The chemical composition of rain from Rosscahill in County Galway. *Ir. Nat. J.,* **12,** 122-126.

Henderson, G.S., Harris, W.F., Todd, D.E. jr & Grizzard, T. 1977. Quantity and chemistry of throughfall as influenced by forest-type and season. *J. Ecol.* **65**, 365-374.

Imahori, K. 1953. On the vanishing mechanism of advection fog and the role of turbulence. In: *Studies on fogs in relation to fog-preventing forests,* edited by T. Hori, 35-67. Sapporo: Tanne Trading Co. Ltd.

Kilian, W. 1977. Zur Nahrstoffaufnahme der Fichte (*Picea abies* (L.) Karst) uber die Nadeln. I. Die Aufnahme von Kalium und Phosphor. *Zentbl. ges. Forstw.,* **94**, 32-49.

Likens, G.E. & Bormann, F.H. 1974. Acid rain: a serious regional environmental problem. *Science, N.Y.,* **184**, 1176-1179.

Madgwick, H.A.I. & Ovington, J.D. 1959. The chemical composition of precipitation in adjacent forest and open plots. *Forestry,* **32**, 14-22.

Malmer, N. 1974. *On the effects on water, soil and vegetation of an increasing atmospheric supply of sulphur.* Stockholm: National Swedish Environmental Protection Board. (SNV-PM-402E).

Martin, A. 1978. *A survey of the acidity of rainwater over large areas of Great Britain.* Central Electricity Generating Board, Report SSD/MID/N3/78.

Mina, V.N. 1967. Influence of stemflow on soil. *Soviet Soil Sci.,* **10**, 1321-1328.

Müller, P.E. 1887. *Studien über die naturlichen Humusformen und deren Einwirkungen auf Vegetation und Boden.* Berlin: Springer.

Oura, H. 1953*a*. On the capture of fog particles by a forest. 1. In: *Studies on fogs in relation to fog-preventing forests,* edited by T. Hori, 239-252. Sapporo: Tanne Trading Co. Ltd.

Oura, H. 1953*b*. On the capture of fog particles by a forest. 2. In: *Studies on fogs in relation to fog-preventing forests,* edited by T. Hori, 253-259. Sapporo: Tanne Trading Co. Ltd.

Reynolds, E.R.C. & Leyton, L. 1963. Measurement and significance of throughfall in forest stands. In: *The water relation of plants,* edited by A.J. Rutter and F.H. Whitehead, 127-141. Oxford: Blackwell.

Tukey, H.B., Wittwer, S.H., Teubner, F.G. & Long, W.G. 1956. Utilisation of radioactive isotopes in resolving the effectiveness of foliar absorption of plant nutrients. *Proc. int. Conf. on the Peaceful Uses of Atomic Energy,* **12**, 1135-1141.

Voigt, G.K. 1960. Alteration of the composition of rainwater by trees. *Am. Midl. Nat.,* **63**, 321-326.

Voigt, G.K. & Swolinski, M.J. 1964. Absorption of stemflow by bark of young red and white pines. *Forest Sci.,* **10**, 277-282.

Wood, T. & Bormann, F.H. 1975. Increases in foliar leaching caused by acidification of an artificial mist. *Ambio,* **4**, 169-171.

Yosida, Z. 1953. General survey of the studies on fog-preventing forest. In: *Studies on fogs in relation to fog-preventing forests,* edited by T. Hori, 1-24. Sapporo: Tanne Trading Co. Ltd.

Zinke, P.J. 1962. The pattern of influence of individual forest trees on soil properties. *Ecology,* **43**, 130-133.

Zinke, P.J. 1967. Forest interception studies in the United States. In: *Forest hydrology,* edited by W.E. Sopper and H.W. Lull, 137-160. Oxford: Pergamon.