MIST PRECIPITATION ON VEGETATION

By

O. KERFOOT*

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3. DISCUSSION AND SUMMARY

1. INTRODUCTION

Many experiments to determine the relationship between fog and mist precipitation and vegetation have been conducted during the last 80 years. On foggy or misty days, or in zones where advective sea fog is prevalent, moisture is intercepted by vegetation and precipitation is collected in the form of drip and stemflow, even though no rainfall is measured during the same period on adjacent open ground. This deposition of fog droplets on foliage or on the ground beneath may be beneficial to the plant and to the local water economy.

The present review is a synthesis of published opinion, often controversial. Interception of rain or drizzle by vegetation has usually implied a loss to the water cycle through vaporization *in situ* of moisture that would otherwise have reached the ground. The distinction between a 'gain', due to removal of moisture from a fog-laden air flow, and a 'loss', due to interception and evaporation of meteoric water, is clearly defined. No attempt is made, however, to examine the possibility that some of this atmospheric moisture may be directly absorbed and translocated by the intercepting plant, however relevant the process may be to ecosystem dynamics. The formation of dew, although an important process in certain regions, is generally associated with clear atmospheric conditions and lies outside the scope of this review. Stone [133] and Monteith [95] have discussed in detail the importance of occult precipitation as a source of water†.

2. HISTORICAL REVIEW

(A) *Early Qualitative Observations*

The first published reference to fog precipitation occurs in the Book of Genesis, Chapter II, verse 6 '. . . But there went up a mist from the earth, and watered the whole face of the ground . . .' From Biblical times to the present day, most references have been similarly observational in character (see also Exodus XVI, 13).

One of the earliest occurs in George Glas's 'History of the Canary Islands' [50], published in 1764. 'In one of the Canary Islands grows a tree which furnishes water to the inhabitants and beasts of the whole place . . . its leaves constantly distill such a quantity of water as is sufficient to furnish drink to every creature in Hierro, nature having provided this remedy for the drought of the island . . . On the north side of the trunk are two tanks or cisterns. One of these contains water for the drinking of the inhabitants and the other that which they use for their cattle, washing and such like purposes. Every morning, near this part of the island, a cloud or mist arises from the sea, which the south and easterly winds force against the fore-mentioned steep cliff so that the cloud . . . advances slowly . . . and then rests upon the thick leaves and wide-spreading branches of the tree from whence it distils in drops . . . this tree yields most water in those years when the Levant or easterly winds have prevailed for a continuance, for by these winds only the clouds or mists are drawn thither by the sea . . .' Glas was an accurate observer—his description of the 'Fountain or Holy Tree' (as it was known on Hierro or Ferro) would match a species of the genus *Ocotea* (Lauraceae)—but he made no quantitative assessment of drip or local climatic variables. Pérez, in a more recent article [110], confirms the substance of Glas's account but reports that a violent storm uprooted the tree, to the great distress of the inhabitants of that otherwise parched island.

* *Forest Research Station, Jonkershoek.*

† Occult precipitation, i.e. the condensation of dew, rime or frost to yield liquid water, is distinct from the precipitation of fog and mist on or by vegetation, or by other means, e.g. electrically [125]. Normal precipitation includes rain, hail and snow.

The terms 'distil' and 'condense', as used in this account and other comparable studies, have been sharply criticized as misleading [43]. By analogy, they merely indicate the screening action of a tree, whose foliage or trunk provides a barrier on which diffusing droplets collect.

Gilbert White [150] notes that 'in heavy fogs at elevated situations particularly, trees are perfect alambics'. An 'amazing amount of water may be distilled by one tree in a night's time, by condensing the vapour which trickles down the twigs and boughs so as to make the ground below quite in a float. On a misty day in Newton [Berkshire, England], a particular oak in leaf dropped so much water that the cartway stood in puddles and the ruts ran with water, though the ground in general was dusty'. White stated that certain *types* of leaf were more efficient in influencing the amount of water supplied, and that the drip kept small ponds full upon the summits of chalk hills, even during drought periods when ponds in the vales were dried up [151, 84].

(B) *Californian Experience: The Coastal Redwoods*

The relationship between trees and fog is discussed in many papers dealing mainly with the effect of Californian coastal stratus fogs upon the distribution of vegetation, and particularly of the coastal Redwoods. Cannon [23] and Cooper [27] both gave descriptive accounts of the phenomenon, and de Forest [42] noted that interception from 'wet fog' (the 'Nebelreissen' of Engler *et al.* [40, 41] may be considerable under certain conditions of wind velocity. Means [92], in an account drawing extensively on earlier publications, stated that soil under these trees was up to three times moister than soil under adjacent herbaceous vegetation.

The climatic environment of the forests claimed the attention of meteorologists, and Blake [8] started preliminary investigations on temperature inversions over the sea which were followed up in greater detail by Byers [20, 21, 22]. Byers suggested that although Pacific-coast stratus frequently occurred over the ocean when Redwood valleys were atmospherically clear, the effect of the fog on the trees would be to reduce the hours of sunshine, the diurnal temperatures, and thus the rates of vaporization. 'In the coastal valleys, the cloud dissipates at 10.00 a.m. during the summer and forms or moves in after sunset. On nights when cloud does not reach into the valleys, dew is likely to condense out of the moist air to the radiation-cooled earth, a much more important phenomenon in summer than fog drip. . . . However, in the Santa Cruz mountains, Douglas Fir does receive the summer fog and this probably accounts for its distribution' [22]. Isaac [66] recorded appreciable catches of fog in the Redwood zone, but the greatest amounts were obtained only two miles from the coast. Fog was present up to 5 miles from the coast, but there were not such marked differences inland between catches under the canopy and on open ground. Despite Byers' view of the limited value of summer fog in this region, Prat [116] considers it to be a dominant ecological factor, but effective only during drought periods and when plants are physiologically active, i.e. in *summer* in the Northern Hemisphere. His opinion seems to have received confirmation from more recent work, despite shortcomings in technique.

Oberlander [105] recorded precipitation under six fog-exposed trees in the San Francisco peninsula during five weeks in summer. His catch ranged from 1·8 to 58·8 in., the latter under a tree only 20 ft. high. More recently, Parsons [107] placed *one* standard 8-in. rain gauge under and slightly to the lee of a 100-ft.-high Monterey Pine (*P. radiata*), a dense-foliaged, conical-shaped tree from which the lower branches had been pruned. For a complete summer, but using only *one* gauge, 9·84 in. of fog drip was recorded although no rainfall was observed beyond the canopy of the tree. Parsons estimated the annual average fog drip to be 10 in., or the equivalent of nearly half the annual average precipitation for the area. He postulated that the amount of water contributed to the ground from fog is a function of: (*a*) size, shape and nature of the trees intercepting the fog droplets; (*b*) wind velocity; (*c*) air temperature (almost invariably between 48° and 50° F.). Parsons suggests (like Byers) that ground fog, wind and fog drip are not particularly common in the Redwood valleys, and that reduction of insolation is probably more influential. The close relationship between fog drip and wind velocity explains why drip is peculiarly a hill-crest phenomenon, as was noted by Gilbert White [150]. However, under very stable air conditions with particularly wet and persistent winter fog, drip in sheltered valleys in California may also be considerable [111, 102, 108, 94].

(C) *The Quantitative Approach: Techniques and Rationalized Experience*

Considerable diversity of opinion elsewhere in the world was exposed as a result of early research in California [112, 113, 17, 43]. Phillips [114] stated, *inter alia*, that moisture loss due to interception of rainfall by trees may be up to 25%, but *at least* 15 in. of precipitation is added to the ordinary rainfall as a result of 'condensation' of hydrometeoric mists by the forest canopy. He maintained that the taller the vegetation, the greater the fog precipitation may be, *up to* 15 in. per annum.

Synthesizing the work of meteorologists [19, 18] and ecological observations, Nicholson [103] produced a report for the U.K. and East African Governments, on the value of forests in influencing climate and water supply, which went far beyond the accepted opinions at that time. He was under no doubt that forests condensed fog from the atmosphere and that, under favourable conditions, montane forests in East Africa can effectively increase precipitation by up to at least 25% of the total annual rainfall, the condensing capacity of the forests being enhanced by the dampness of the air within the canopy (and presumably also the lower temperature of leaf surfaces?). He also emphasized the mechanical action of the trees in intercepting cloud and sea fog and causing them to lose their moisture. In the monsoon rainfall region (orographic rain), the major climatic influence of forests consists in inducing such precipitation.

Estimations, using fog-catching gauges, were made in other continents at the beginning of this century. Marloth [85, 86, 87] in South Africa and Linke [80, 81] in Germany initiated experiments of this type. Marloth erected his gauges on Table Mountain, to ascertain the amount of moisture deposited from prevailing south-east (orographic) clouds. By placing a number of reeds over the orifice of a standard 5-in. gauge, he found that the amount of water caught in misty weather was greater than that caught by a similar gauge without reeds. Various criticisms of Marloth's work have been expressed but, as Rubner [120, 121] pointed out in a detailed study of fog precipitation, if there were extreme conditions prevailing on Table Mountain, this was certainly not so in Linke's investigations in the Taunus Mountains.

Linke [80, 81] set up an ordinary gauge underneath a dense forest canopy, not far from a comparable gauge in the open. On days with continuous fog, the former recorded higher precipitation than the latter. Observations were continued for a number of years, using gauges set within the forest at various distances from the margin; the results largely confirmed those of Marloth. Dieckmann [36] obtained a similar pattern of precipitation, using a prototype fog-catcher. It consisted of a gauze cylinder, with a diameter ⅗ that of the rain gauge funnel, inserted in the neck of a standard gauge so that it projected 35 cm. above the rim of the orifice [99]. Rubner has discussed the validity of Linke's work in some detail and compared his results with, e.g., those of Schubert [124] and Descombes [33]. Rubner himself used a highly ingenious fog meter for his observations at Kriegwald, and many of his conclusions are apt. The gauze-cylinder type of apparatus has been installed, with modifications, in many subsequent studies but is not free from sources of error, particularly when used within the forest canopy [120, 121, 43, 122, 74, 78, 4, 79].

Grunow [53–57] found that, on fog-free days, the amount of rain caught by the two types of gauge did not vary significantly when averaged over a long period, although single comparisons were often markedly distinct. He attributed this to the direction of inclination of the rain [120, 121, 43]. Unfortunately, Grunow did not differentiate between the catch from rain and mist on foggy days, being primarily concerned with interception, but considered that, over a period of a year, fog drip accounted for 10–20% of the total precipitation recorded within a stand and, on the margin, for 50% of the moisture reaching the floor. In a more recent paper [58], he advocates the use of large measuring baths for collecting precipitation on the forest floor where no correlation has to be made with gauges on open ground [74]. He found that 13% of the water collected in the summer months represents fog condensation; this figure rises to 52% at the stand margin, increasing the proportion collected to 95% of that in the open.

More intensive experiments were continued by Delfs [31], Friedrich [44] and Sauberer [123]—the last author using lead-bisulphide photo-electric cells to measure the infra-red permeability of fog, and hence its effect on plant growth.

Delfs [31], like Linke, Grunow and Geiger [46], found maximum precipitation of fog and mist at forest margins, particularly in montane areas (confirmation of this effect at lower altitudes has been reported from Japan [63]). In windy weather, the windward edge has the lowest rate of interception, although no distinction is made between interception of fog and mist and that of rain—a constant failing in these experiments where 'interception loss' rather than 'precipitation gain' has been the object of study. Delf's views on interception (but including fog drip) may be summarized as follows: (1) A forest canopy intercepts less moisture in winter than in summer in the N. Hemisphere, owing to higher atmospheric relative humidity, reduced solar radiation and, in deciduous trees, reduction of leaf surface area. (2) Interception has different values depending on locality, the weather preceding the period of interception (i.e. interception after wet periods may be lower than after dry periods), the crop involved, and duration and intensity of rainfall. (3) Interception may vary with topography, and an increase in steepness of slope frequently results in an increase in precipitation (the normal gradient due to altitude and, sometimes, aspect). However, since steep and vulnerable slopes, particularly in Europe, are often maintained or planted with a tree stocking at higher-than-average density, this must be allowed for in assessing this factor. These views were supported by Eidmann [38, 38*a*]. (4) There are difficulties in applying formulae to interception problems: this is possible only if storage potential and the amount and distribution of rainfall are known, and if an over-all assessment of needle and stem surface is available. In any event, formulae can be applied only to comparable forests and forest areas. (5) The effects of interception differ markedly in temperate and tropical lands.

Earlier work in France, inspired by Descombes [33], was hydrological rather than climatological in character, but some emphasis on the effect of fog and mist on streamflow behaviour was evident [33, 34, 35, 89, 154], without materially advancing the state of our knowledge. (For criticisms of Descombes' work, see [120].) In 1941, Wicht [153] in South Africa remarked on the unreliability of early interception experiments, and gave a comprehensive review of the problems, as well as suggesting improvements in their design.

Wicht established apparatus at Jonkershoek to gauge water precipitated from both rain and mist. Moisture intercepted by foliage and evaporated—or otherwise translocated—was not measured. His experiments were designed to estimate the total penetration derived from rain and mist condensation and to compare it with rainfall recorded in the open. Eight-inch Casella siphon recorders were used in the open and 5-in. Snowden-type gauges beneath the canopy. Stem run-off was collected through lead guttering [64, 152, 32]. Wicht was not entirely satisfied with his gauging techniques, but the data obtained indicated that some penetration in the form of drip and stem run-off may have been derived from mist condensing on the trees.

Like Marloth [85, 86], Nagel [98] initially measured fog precipitation on Table Mountain with two gauges, one of which was equipped with a fog catcher. The value of his results is restricted because of the failure to separate precipitation from this source during periods when rain and drizzle were also augmenting the catch. He found that during his year of study, fog precipitated 3294 mm. and rain 1940 mm. He agreed that at least two sets of instruments would be required for satisfactory results; one on the plateau and the other some 200 m. lower down. Although the intention was never fulfilled, Nagel considered the use of large gauze cylinders in conjunction with anemograph and drop-size recorder. Too fine a mesh for the gauge is not suitable, as the fog catcher then acts as a solid cylinder and deflects the air flow bearing some of the water droplets. Similarly, too large a mesh allows more fog droplets to pass through the catcher.

Since 1956, Nagel [99] has made a series of measurements at Swakopmund in the fog desert of S.W. Africa, using double gauze screens, 10 × 2 m. in size. He estimated that a catch of 4000 to 5000 litres of fog water can be collected annually by this means.

In Hawaii, Mordy and Hurdis [96] anticipated the suggestions put forward by Garcia-Prieto *et al.* on Tenerife [45]. They considered that appreciable amounts of water could be obtained either by tree-planting or from artificial barriers constructed to collect cloud water. As a result of their representations, The Pineapple Research Institute established a 'fog drip experiment' on Lanai which ran for three years and is, to date, the most efficient and successful of all research projects in this field [24, 39].

With mechanical fog-catchers of various designs (the 'harp' type as well as louvres) the following results were obtained: (1) Fog-drip intensities vary with droplet size, distribution of droplets within passing clouds, wind speed, etc. (2) The highest recorded rate of catch, intercepted by the Norfolk Island Pine (*Araucaria heterophylla*), was 44·65 gal./hr. (3) From horizontal 8-in. rain gauges set under a Pine plantation, 16·19 in. were measured, compared with 15·52 in. for the watershed and only 1·16 in. from open ground. (4) The 'harp' type of fog catcher, kept oriented to oncoming clouds, was found to be most effective during periods of light rainfall and, during the period of study, a harp 37 × 37·5 in. in external dimensions with vertical copper wires (0·01 in. diam.) spaced 0·25 in. apart, collected 1964 in. of water, whereas rain gauges in the open caught only 104 in. The catcher is more effective when placed high above the ground.

As far as the trees are concerned, Norfolk Island Pines precipitate an additional 30 in. of rain each year from orographic cloud. During periods of light rain, mechanical interceptors catch a volume of water three times that recorded in the standard gauges on open ground. Mechanical devices are expensive to build and maintain, whereas the Pine trees need little attention after establishment. Indications are that conifers are better adapted than broadleaved species to intercept fog moisture.

On the island of Hokkaido, research has been mainly directed towards interception and capture of sea fog by shelterbelts planted along the foggy north-east coast. Notable successes have been claimed for 'fog-prevention forests' which strain the moisture—or much of it—from advection fogs moving inshore during the summer months. A fog-water content of 0·5 g./cu.m. is reported to be reduced to nearly zero immediately behind the shelterbelt at a height of 10 m., and to 60% of the frontal value at 40 m. above the ground. Estimated fog-water capture on the ground at the windward margin of the shelterbelt is 1 mm./hr. with a fog-water content of 0·3 g./cu.m. and a wind speed of 3·4 m./sec. Factors in the fog-preventing action of the forest were ascribed to three major phenomena: (1) capture of the fog particles;

(2) modification of air temperature by the forest, and evaporation or condensation of the fog particles; and (3) enhancement of turbulent motion of the air by the forest.

The Japanese experienced difficulty with their measurements, and as late as 1961 the conclusions were '. . . that we are not yet in a position to formulate the fog-capturing power of the forest and of the open ground in any definite form . . .' [106, 69, 63, 68, 91].

Turbulence is a factor that seems to vary according to type of cover and situation. Nagel [101] found with his Table Mountain experiments that turbulence over the scrub cover adversely affected the catch. The Japanese suggested that turbulence promotes precipitation by diverting the fog flowing over the top of the canopy into the interior of the forest. According to Thompson [139], when conditions of calm or light winds exist in the free air, there is—under moderate woodland canopies—an almost continuous and slow transfer of air between the canopy and the ground. With stronger winds, eddying about the trees overcomes these gentle movements, and air motion becomes erratic and turbulent, *although such turbulence lessens with decreasing density of cover*. During the daytime there is noticeable horizontal movement of air towards clearings where convection is at a maximum [28]. Penman [109] points out that as the height of vegetation increases, new factors affect evaporation. Increased roughness at the surface (i.e. of the plant/air interface) will increase evaporation rates, while the swaying of the crop transfers damper air from inside the canopy to above it [103, 91].

Went [149] refuted many of the earlier conceptions of the nature of fog and said, *inter alia*, that fog and mists are really low-hanging clouds in which the water droplets are so small that they do not settle on horizontal surfaces and thus do not register in a rain gauge. He suggests how trees can remove moisture from the atmosphere. The water droplets (0·01–0·1 mm.), too light to settle, are suspended in saturated air and hence cannot evaporate. When they move past solid surfaces, deflection of the air flow prevents contact. If the surface is small and narrow enough, the air is hardly deflected and the inertia of the droplets is sufficient to carry them against the surface where they may settle. In effect, small or narrow surfaces will act as strainers for the fog droplets. This would appear to be confirmed by the work of Costin and Wimbush [29], which indicated that fine-leaved grassland and heath (sclerophyll) vegetation were more efficient in this respect than a community of broadleaved species.

Went's views [149] are somewhat radical, as there are many examples of effective drip in broadleaved woodland. Hursh and Pereira [65] observed the effect of dew and mist in the Shimba Hills of Kenya. Cooler temperatures accompanying the southern monsoon produced a heavy dew, mist and fog. The mist apparently collected on all parts of the plants with which it came in contact, the amount of water collected therefore depending on the sum total of *surface area*. The fog and mist tended to remain in the forest for several hours longer than in the open. No experimental evidence was adduced but similar observations are on record [104, 90].

Coastal fogs of this nature, formed by moisture-laden air rising against coastal ranges, or clouds forming against mountains by lateral air movement, are ideal for condensation and must cause considerable turbulence, so that more cloud and fog droplets are available for precipitation than with laminar air-flow [28]. In the Shimba Hills, as elsewhere in the tropics, vegetation may be more luxuriant than one would normally expect for the recorded rainfall and, in one case at least, is physiognomically akin to rain forest, although adjacent terrain at a lower altitude outside the fog zone has a mean rainfall of under 200 mm. [78].

Although many authorities consider that fog and its condensation is of importance only in restricted localities such as mountain regions and certain coastal areas [6], it is probably of wider significance in the tropics where, generally speaking, there is a much greater water content in the atmosphere [62, 52]. Values for cloud drip of up to 10 times the normal precipitation have been quoted in the past from more temperate lands, but many of these figures should be treated with reserve. Hursh and Pereira [65] cite an example from Oregon in which 11·25 in. of extra water were accounted for in this manner during a period of 142 foggy days [76]. Subsequent investigation revealed that the gauge was sited under a large tree, itself adjacent to several other large-crowned trees and thus in a position to receive an augmented supply of water. In many cases no distinction is made between interception of moisture from stable stratus and rain clouds, although it is now fairly clear from the examples quoted in this review that rainfall under trees sited on cloud-shrouded peaks, particularly in the tropics, is greater than that in the open [131, 132, 141]. There is, however, no unanimity of opinion for the phenomenon as a whole.

Beard [7], reviewing his own experience in South Africa, suggested that condensation from mist over forest canopies never led to a higher catch than that recorded in the open; and if it did occur during periods of light rain, its presence was invariably masked by normal interception. According to Costin and Wimbush [29], precipitation at temperatures above freezing, under windless conditions in the Australian Alps, was about the same under trees and in the open. In windy weather, it was greater under the trees, especially at higher altitudes. Most of the extra water collected was from mists and rain: apparently the sparse, large-leaved tree canopies were ineffective in straining out the smaller droplets making up cloud and fog. At freezing temperatures, the trees accumulated large amounts of ice and rime from fog and cloud. Other observations indicated that fine-leaved grassland and heath vegetation accumulated considerable amounts of cloud water.

(D) Fog Drip: Symbiotic Relationships

The Redwood studies in Claifornia stimulated research of a quasi-ecological nature in other continents. In Sweden and South Africa, Romell [119] and Phillips [113] investigated the possibility of atmospheric moisture being absorbed by epiphytes and translocated to the host tree. The trees concerned in their particular studies were species of *Picea* and *Podocarpus*, both coniferous genera. Prat [116] stressed that the California sea fog favours the development of the lichen *Ramalina* which grows epiphytically on *Cupressus macrocarpa*, and Dodge [37] has confirmed that species of lichen such as *Usnea articulata* may absorb up to 50 times their own weight in water. Glover [51] makes a similar observation with regard to the prevalence of *Usnea* in the mist belt of northern Somalia and its association with *Juniperus procera*. Penetration of the cortex of the supporting tree by the hyphae of such epiphytes has not yet been substantiated, although Boaler [10] mentions a case in the *Juniperus* forest of Somalia.

Allen [2], working on the fruticose lichen *Cladonia*, found that water was absorbed during rain to the extent that soil under the lichen mat does not receive nearly as much moisture as soil in the open, although *in dry periods* it may receive more. The lichen may absorb 4–5 times its own weight in water before releasing any to the soil, and small catches were entirely absorbed. These results were confirmed by Moul and Buell [97], working on bryophytes and lichens, who found that moss can intercept up to 6% of the throughfall. In the Great Smoky Mountains above 3500 ft., Sharp [126] showed that there was a correlation between the incidence of fog and the presence of vascular epiphytes, their germination and growth being enhanced by high rainfall and humidity. Similar but less detailed observations have been made in Peru [77], Ecuador [52], Ethopia [82, 48], and South Africa [88].

(E) Fog Drip: Ecological Relationships

In New Zealand, the ecological implications of atmospheric moisture were studied by Zotov [156]. He noted that the upper timberline on Tararua Mountain coincides *entirely* with the lower line of heavy fog, which occurs on average on some 200 days a year and is associated with the moisture-laden N.E. winds. Zotov claimed that the formation of fog depends on the absolute amount of water vapour in the air and on the atmospheric temperature and pressure, and is closely associated in New Zealand with vegetation of a scrub-climax type. He states that the fog, composed of fairly large droplets [149], deposits a large amount of water in a relatively short time. As the leaf-area index (i.e. ratio of total leaf area to ground area) is high, the benefits of adsorption are obvious. Although fog composed of fine droplets ('dry' fog) deposits little moisture on foliage, its effect on the aerial environment of the plant may be the same as that of 'wet' fog (*Nebelreissen*). Zotov [156] goes on to examine other aspects—reduction of solar radiation (by 100 times), reduction of assimilation (by 5 times) and annual increment. He admitted that different plants may not show fog-shading effects so obviously; but he attributes the close association of scrub vegetation with fog shading to the fact that the component species are very much more efficient in monopolizing and utilizing the recorded light intensities than high-forest genera such as *Nothofagus* [142, 143, 52].

Zotov's work, although observational in character, was primarily concerned with three major groups of climatic factors important to plants, viz. solar radiation, precipitation and evaporation. Thornthwaite [140] stressed that plant growth is related to actual mositure used rather than to the total rainfall. Only when measurements of evaporation and condensation from natural surfaces under different types of plant cover are available for a large number of localities will it be possible to evaluate the moisture factor in plant distribution.

Unfortunately, many otherwise valuable observations of this category from African centres lack quantitative data. Kennedy-Cooke [72] discussed the ecological implications of mist effects in the hills of the Sudan [130]. Airy Shaw [1] considers that the so-called 'Coffee forest' of Angola depends for its existence upon the constant 'condensation', in valleys and sheltered slopes of the sub-plateau area, of water vapour brought in by the moisture-laden westerly sea breeze. In contrast to Zotov [156], he discloses that Angolan montane brushwood communities can frequently develop with some luxuriance even when exposed to dry winds from the east, which bring no mist. The 'Coffee forest' shows similarities to the Redwood groves, and occurs in a narrow strip running parallel to the coast. The *Welwitschia* zone of Angola is also near the sea, and Airy Shaw suggests that the bulk of moisture required for current growth is derived from sea fogs [98, 147, 148, 5]. However, the wide distribution of the species, even in the eastern areas where this kind of precipitation is negligible or lacking, proves that fog is no entirely a limiting factor for the existence of *Welwitschia* [75].

In Europe, Zenari [155] considered that fog may be a limiting factor for plant formations in th Italian Tyrol, and his opinion was endorsed by Bouet [11] for Swiss alpine communities. Prat [11 pointed out that, on the Mediterranean coast, fogs are chiefly localized in mountain ranges, where the action is very important in protecting forests, while in California the luxuriance of the sand-dun vegetation is due to the incidence of fog in summer, when rain is deficient. Carr [25], howeve studying fog formation in Honduras, tends to support the negative viewpoint of Zenari [155] and Bou [11] (see [117]). Ceballos and Ortuño [26], continuing earlier investigations in the Canary Islands, cam to the conclusion that the annual rainfall on Tenerife does *not* account for the humid type of fore present there and, although the data are scanty, state that fog interception not only occurs but may b three times the amount of precipitation in open terrain. Garcia-Prieto, Ludlam and Saunders [45] not similar effects on the same island to those observed by Glas [50] and suggest that efforts should be mad to estimate the amount of cloud water by the erection of a simple device consisting of several nets o wires or fine cords suspended some 30 ft. from the ground.

(*F*) *Physiological Implications*

It is noteworthy that sea fogs off the S.W. African littoral are more prevalent in winter, when plan are physiologically active, and Nagel [99, 101] suggests that *Welwitschia*, for example, is capable o extracting water from fog and vapour. Went [149] pointed out that in many arid regions some charac teristic plants have developed very small leaf surfaces in the form of needle-like leaves, and regards the as an adaptation, not for reducing transpiration, as is often suggested, but for straining moisture fro the atmosphere.

hoar frost is not frozen fogged droplets

It is now generally accepted that, at high altitudes at least, the coniferous type of needle is an efficie condenser of fog droplets at the normal rate of fog movement; e.g. hoar frost, which consists of froze fog droplets, may *cover* coniferous needles but only adheres to the edges of broadleaved species.

From the climatological point of view, it may be true that desert plants such as *Welwitschia* sustai life by collecting water from this source; Nagel considers that they may also absorb salt particles fro fog droplets at night, when relative humidity is high [99, 118].

In practice, Waisel [144, 145] found that absorption by the aerial parts of plants took place only und very high saturation deficits and over a long period of continued spraying. In the Negev desert o Israel, he experimented with *Tamarix aphylla*, a salt-excreting species. Fog precipitation is evident more pronounced under this tree (and atmospheric humidity below the saturation level is greater) tha under any other species studied, providing an additional source of water, particularly in regions wit frequent humid nights.

Kassas [70] is of the opinion that certain flowering xerophytes in arid zones can absorb moistu directly from atmospheric humidity, and Deacon, Priestley and Swinbank [30] suggest that it is th sodium-chloride crystals on such plants that form the absorbing surface. For the physiologic implications of absorption by leaves under humid conditions reference may be made to a series of im portant papers [14, 15, 60, 61, 134–8, 127–9, 3, 93, 67, 49].

The experiments of Stone and his colleagues in the U.S.A. [134–8] seem to indicate that the need form of leaf is very much more effective as a condensing surface, and in an admirable review Ston indicates that absorption of fog and mist is a strong possibility wherever gradients exist, i.e. und conditions of high humidity and soil moisture stress [133]. In practice, it is therefore probably just fiable to take fog precipitation into account when calculating the water balance of *entire* catchment are [9, 146] even if, as Baumgartner [6] maintains, fog precipitation is important only on the summits an higher slopes in mountainous regions and plays a very minor role in the water régime as a whole.

3. DISCUSSION AND SUMMARY

The historical background and the salient features of fog precipitation have been reviewed at som length. It is clear that many of the earlier projects designed to investigate the process failed to differe tiate between water deposited from cloud and fog and that derived from rainfall. Fourcarde's criticis of Phillips' and Marloth's experiments and, by the same token, Nagel's, is valid in so far as it concern rainfall.

According to Fourcade [43], the influence of the inclination of rain, at altitudinal cloud levels in whic misty rains prevail, is considerable. On mountains, the inclination may be horizontal or even upwar resulting in extraordinary differences in equivalent rainfall. Rubner [120–1] has also stressed th importance of horizontal precipitation and its relationship to vertical precipitation over forest canopie but warns against generalizing from purely local experience. The neglect of the inclination factor has introduced errors into the interpretation of results and has attributed to vegetation a greater capacity for moisture capture than may exist in reality.

It is nevertheless accepted that since fog and mist are widespread, their deposition as water on vegetation may have a profound effect on its growth, development and distribution. Precipitation of fog seems to be largely dependent on the nature and velocity of the inflowing air: this may account for the prevalence of fog drip in hilly terrain. Because moisture-laden air moving laterally from the sea against coastal ranges provides the turbulent, saturated conditions ideal for deposition, the incidence of fog precipitation is most widely reported from tropical montane regions. Kerfoot [73] and Grubb and Whitmore [52] suggest that fog may be one of the most important environmental factors determining the distribution of forest types under these conditions.

Absolute values for water precipitated from mist are still conjectural, but with sufficient experience they can be estimated fairly well from the frequency of occurrence and density of the clouds and from the wind speed. The quantity is likely to be substantial, and on mountains that are *higher* than the bases of both fine-weather and rain clouds, fog precipitation appears to exceed the actual rainfall. It should be taken into consideration in all studies of the water balance of catchment areas and during compilation of climatic atlases [16, 100, 101]. Owing largely to the pattern of air flow and characteristics of the earth's surface, fog-laden air is more localized in temperate lands, and the more extravagant claims advanced for water income from this source should be treated with reserve.

Irrespective of any direct benefit, to both vegetation and water supplies, it has been suggested that intercepted moisture which remains on foliage may be considered quantitatively as a *net* gain, since the energy expended in its evaporation from the leaf surfaces during fog-free periods would have been used in transpiration of an equal amount of water from the soil [83, 73]. Grubb and Whitmore [52] stated that the whole aerial environment is altered by foggy conditions, and basic physiological processes of the plants are bound to be affected. These features have seldom been stressed in published research but undoubtedly require further study. In any event, they emphasize the importance of mist during periods when plants are physiologically active, i.e. in summer in the Northern Hemisphere.

There seems to be some doubt whether the type of leaf is more important than the sum total of leaf surface area. It has been stated that fine-leaved vegetation (e.g. the 'fynbos' of the Cape floral kingdom, or its macchia and chaparral counterparts in the N. Hemisphere) is a more effective screening surface for fog droplets than any other. Available data would seem to indicate also that a coniferous forest is superior in this respect to a deciduous or broadleaved canopy. The criteria, however, do not appear to be generally valid, and atmospheric humidity and temperature probably have considerable influence on the process. Doubtless other climatic phenomena, and even edaphic variables such as soil moisture, are involved as well. Grubb and Whitmore [52] state that the greater abundance of epiphytes in the montane forest is related to more frequent wetting with liquid water from fog rather than to a constantly higher humidity.

Published results from Japan seem to show that a coniferous canopy enhances turbulence, which in turn promotes a downward diffusion of fog that would otherwise have flowed inland and dispersed. Penman [109] and others maintain that increased turbulence over a high-forest canopy will increase evaporation rates by creating channels for vapour transport from inside the forest. In mountainous areas of the drier tropics, it is significant that coniferous species, e.g. *Juniperus procera* and *Podocarpus* spp. in north-east and east tropical Africa, are invariably found in zones where fog and mist are frequent but not necessarily persistent, and rainfall is comparatively scanty.

For absorption and translocation of fog water, the evidence is scanty and almost entirely derived from laboratory studies. It seems certain that epiphytes can absorb moisture directly from the atmosphere, but it is not yet proved that this moisture can be taken up by the host plants. In the laboratory, in a saturated atmosphere, both positive and negative transport of water, depending on the direction of the diffusion-pressure-deficit gradients, has been demonstrated in certain higher plants. Absorption of fog water is therefore a strong possibility because such gradients are seasonally present in all but the very wettest soils. A recent paper by Gindel [49] describes an investigation into the influence of mist and dew on the water economy of woody xerophytes growing under arid conditions. Preliminary results indicate the importance of atmospheric moisture in the establishment and development of natural woody vegetation in desert and subtropical regions, while chemical analysis shows that water from these sources contains ions that are important in the nutrition of the plant.

Many observers have remarked on the shortcomings in both measuring and sampling techniques for estimating the volume of water deposited from fog-laden air. These inadequacies have restricted our appreciation of the rôle of fog and mist in the ecosystem. As Miller [94] concluded, 'Whether the aim is to ameliorate the climate, to add moisture of the inflowing air to local water resources, or to arrive at a better understanding *of its influence on the distribution of species and the dynamics of vegetation* [the italics are mine], further research is essential'.

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