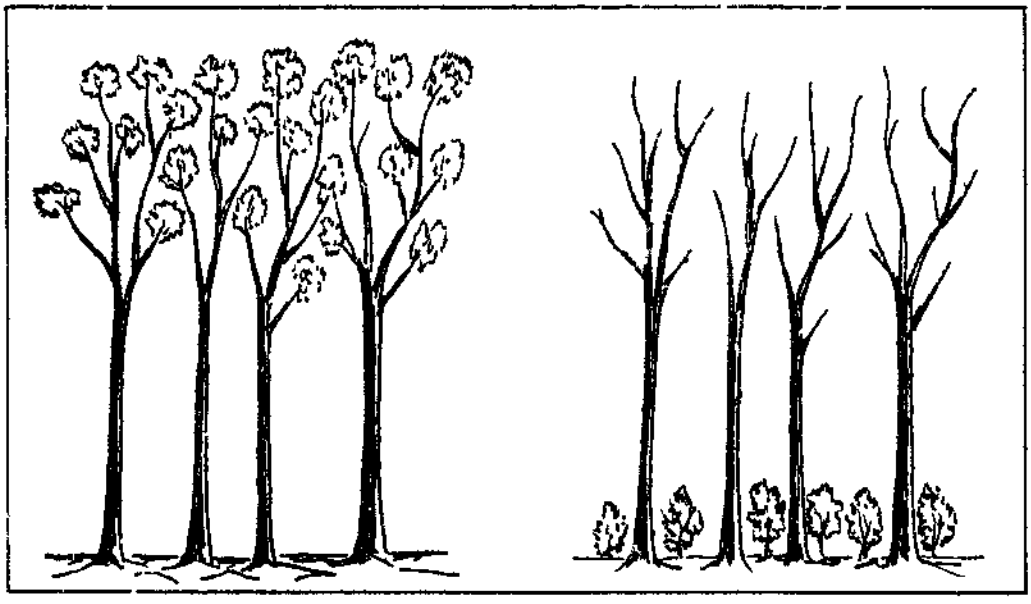
THE MAUI FOREST TROUBLE: A LITERATURE REVIEW AND PROPOSAL FOR RESEARCH

ROBERT ALAN HOLT



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The Maui Forest Trouble: A Literature Review and Proposal for Research [1]

R. Alan Holt [2]

ABSTRACT: This paper reviews and discusses the literature pertaining to a proposed ecological study of a catastrophic dying of native Metrosideros (Myrtaceae) forest which occurred on windward East Maui in the Hawaiian Islands during the first decade of this century. This dieback event was documented by several workers, most notably H.L. Lyon, and became known as the Maui Forest Trouble. The geology, climate, soils, and vegetation of the proposed study area are described. The historic dieback event is reconstructed in detail from all available information sources. Next, canopy dieback in other Hawaiian forests is described, with emphasis on the island of Hawaii, research methods used there and pertinent findings. Then, a review of canopy dieback in areas outside Hawaii leads to a discussion of dieback concepts and theory. Aspects of bog formation or paludification processes which relate to the Maui Forest Trouble are reviewed. Finally, research on the present-day floristic, structural and edaphic characteristics of the Maui Forest Trouble is proposed.

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INTRODUCTION

The sight of large numbers of dead trees in a forest canopy usually arouses uneasy feelings and thoughts of epidemic disease. This paper is part of one of a growing number of studies which consider the possibility that, in some forests, widespread canopy death may be a natural successional phenomenon.

During the last ten years intensive research by a number of workers has been focused on dieback of native Metrosideros polymorpha Gaud. ('ohi'a) forests on the island of Hawaii (Papp et al. 1979, Mueller-Dombois et al. 1980, Mueller-Dombois 1981, Adee and Wood, unpublished). Dieback of canopy dominants in other tropical Pacific regions (Ash 1981) as well as in temperate forests (Manion 1981, Mueller-Dombois et al. 1983) has shown that dieback is not unique to Hawaii. This has lent support to the hypothesis that dieback is an evolved successional phenomenon (Mueller-Dombois 1974).

In Hawaii and most other dieback areas research has been carried out either in forests which died back only recently or in older dieback stands of unknown age. Historical accounts of widespread canopy death are not abundant, and those that exist do not provide sufficient detail to serve as comparative bases for present-day work on the same sites. The exception to this is the account by Dr. Harold L. Lyon (1909) of widespread canopy death which occurred on the windward slopes of East Maui in the first decade of this century. The writings and photographs by Lyon and a few of his contemporaries provide what may be the first detailed account of forest dieback in the world, and certainly the first good account of

Hawaiian 'ohi'a dieback. Only on East Maui is it possible to find stands in which dieback and habitat were described in detail some 75 years ago. The present study was undertaken to take advantage of this historical data to assess the changes in a dieback stand 75 years after canopy death and to compare the East Maui dieback with that described on Hawaii and in other regions.

The literature review below follows an investigative path designed to lead to a thorough understanding of the phenomenon of canopy dieback as it relates to the East Maui forest. First, the study area and the region which encompasses it are described, with sections on geology, climate, soils, and the dominant plant species, Metrosideros polymorpha. Second, the historic East Maui dieback incident, known as the Maui Forest Trouble, is reconstructed in detail from all available information sources. Third, canopy dieback in other Hawaiian forests is described, with emphasis on the island of Hawaii, the methods of study and pertinent findings. Fourth, a review of canopy dieback in areas outside Hawaii leads to a discussion of dieback concepts and theory. Fifth, aspects of bog formation or paludification processes which relate to the Maui Forest Trouble are reviewed.

A proposal of research follows the literature review. Hypotheses drawn from the literature review are stated, as are several secondary study objectives. Proposed methods of study are briefly outlined.

DESCRIPTION OF THE AREA

The Maui Forest Trouble area is part of the windward slope of Haleakala volcano on the Hawaiian Island of Maui (Fig. 1, p.52). The Haleakala portion of this island is referred to as East Maui and the windward slope of East Maui is known as Ko'olau (literally, "windward" in Hawaiian) (Pukui et al. 1974). The geology, topography, soils, climate and vegetation of Ko'olau are described below, with particular reference to the Maui Forest Trouble area.

Geology

Lavas from two of the three major volcanic series which formed Haleakala compose the surface of the Ko'olau region (Fig 1, p. 52). Kula lavas are the older series. They form the substrate in the Maui Forest Trouble area west of Kopiliula stream, (approximate boundary), except where younger Hana lavas have filled Keanae Valley and two lesser stream gulches east of Keanae (Stearns and Macdonald 1942). East of Kopiliula stream, lavas of the Hana series predominate. The majority of the Maui Forest Trouble area lies on Kula lavas, but a considerable section near Nahiku is well within the Hana lava region.

Hana and Kula lavas are both composed mostly of 'a'a flows, with pahoehoe only near the summit vents. Kula flows are from 50 to 200 feet thick in the region of the study area, while the more fluid Hana flows are thinner. The chronological differences between Kula and Hana lavas are only roughly known. Kula lavas flowed in the Early and Middle Pleistocene (i.e., 1.5-2 million years ago). After an erosional lag phase, volcanic activity renewed in the Late Pleistocene to produce the Hana series, with the most recent flow (on

leeward East Maui) occurring in the late eighteenth century. Hana series activity along the volcano's east rift veneered the lands in and out of Nahiku with new lava, and laid down 1 to 20 feet of ash over large areas. Presumably, this thick ash deposit was restricted to the lands east of Kuhiwa valley, and, so, did not reach the study area (Stearns and Macdonald 1942: Pl. 1).

Kula and Hana lavas differ greatly in their water-bearing properties. Hana lavas are "so permeable that they act like a great sponge absorbing immense quantities of rain" (Stearns and Macdonald 1942). This permeability accounts for the dearth of perennial streams between the town of Hana and Nahiku. Kula lavas near the surface, however, were laid down as volcanic activity was waning. Long time-lags between eruptions allowed weathering and soil development. As Stearns and Macdonald (1942) explain:

> The Kula volcanic series must be visualized as an assemblage of interstratified soils, vitric tuff beds, weathered clinker zones, and wide bands of rock to understand its influence on the movement of groundwater. Most of the individual beds are permeable and unable to perch water. But when the whole formation is considered as a unit, it contains enough more or less impermeable layers, even though discontinous, to retard greatly the downward percolation of water in areas where 100 to 400 inches of rain fall annually.

Major permeability differences might suggest that the boundaries between Hana and Kula lavas should be made distinct by vegetational patterns. This is only true where Hana lavas filled stream valleys to considerable depths, as at Keanae, Waiokamilo, and Wailuanui. The forests in these valleys are tall and vigorous, with closed canopy and no evidence of canopy death despite abundant dieback on adjacent

broad ridges. Otherwise, the boundaries between Hana and Kula Lavas are indistinct. Stearns and Macdonald (1942) demark the two lavas at Kopiliula stream, but the reason for this choice is not evidenced by any vegetational unconformity. Masking of boundaries between lavas on Mauna Kea on the island of Hawaii is attributed to overlying ash deposits (Adee and Wood, unpublished, Jacobi, personal communication). This may be true for Ko'olau also, although surface ash deposits of sufficient depth are not reported in the boundary region by Stearns and Macdonald (1942).

Topography

From the northern rim of Haleakala, the Ko'olau slope drops steeply toward the sea, with slopes between 50 and 60 per cent from the rim down to about 5000 feet elevation. At middle elevations (3000-5000 feet) slopes average around 20 per cent, and below 2800 feet elevation the general slope of the land nears 10 per cent. Ridges become broader as streams coalesce downslope, adding to the relative flatness of the terrain below 3000 feet elevation. Below 1000 feet elevation, streams have carved deep valleys, leaving flat, intervening ridges in a highly dissected landscape.

Soils

The Soil Survey of the state of Hawaii (USDA 1972) maps the major soil types for the Ko'olau region. These are based on low-intensity ground surveys and extrapolation by aerial photo vegetation analysis (Fig. 2, p.53).

West of Keanae Valley the majority of the lands between 1000 and 3000 feet elevation are mapped as belonging to the "Honomanu-Amalu Association" of soils. Honomanu soils are typified as well-drained and ash-derived, occupying the steeper slopes of gulches. Permeability is moderately rapid, and runoff is slow. Honomanu soils make up about 60 per cent of the association, and Amalu soils about 40 per cent. Amalu soils are poorly drained, having developed from organic matter and material weathered from basic igneous rock. They occur on the flatter ridge tops and interfluvial areas. The stream gulches throughout the study area are mapped as "rough mountainous land" with thin soil and good drainage.

East of Keanae and well beyond the eastern boundary of the dieback area at Hanawi stream, virtually the entire Ko'olau slope above about 1400 feet elevation is mapped as "Hydrandepts - Tropaquods Association." Once again, gulch lands are "rough mountainous land." Hydrandepts occupy about 60 per cent of this association and are well-drained to moderately well-drained, much like the Honomanu series. They are associated with steeper slopes. Tropaquods are poorly drained soils similar to those of the Amalu series, occurring on less sloping terrain. Tropaquods and Hydrandepts are developed in volcanic ash and in material weathered from cinder and basic igneous rock.

"Honomanu silty clays" on 5 to 25 per cent slopes occupy the lands east of Keanae between the Hana road and about 1400 feet elevation. These soils are well-drained and developed in volcanic ash. They are described as providing relatively deep root penetration.

Climate

The climate of Ko'olau is depicted for three stations in the climate diagrams (Fig. 3. p.53). These were constructed according to the method of Walter (1971), from data provided by the State of Hawaii Division of Water and Land Development. The isohyetal rainfall map upon which the climate diagrams are mounted is the most recent produced by that Division. Northeast tradewinds (Fig. 3, p.53) are the primary climatic influence on this windward slope, bringing abundant rainfall most of the year but especially in winter (Leopold 1949, Blumenstock 1961). The heaviest rainfall (6000-9000 mm per year) occurs in an altitudinal belt centering on about 3000 feet elevation. Kuhiwa valley, with 9000 mm of rain annually, is among the wettest spots in the state. Rainfall falls off quickly west of Kailua stream and east of the Ko'olau-Hana district boundary.

Winter storms are sometimes accompanied by high winds which may cause significant windthrow and foliage loss in native forest and timber plantations (Blumenstock 1961, Gerrish 1981). (One such storm struck Maui in January, 1980.) Cloud cover is normally present over all but the coastal areas for the better part of most days, although clear, sunny periods are not rare.

Temperature varies only slightly with season, around an annual mean of about 20 degrees C at 300 m elevation.

Vegetation

Tropical montane and submontane rain forest covers all but the highest and lowest fringes of Ko'olau. Subalpine shrubland and alpine grasslands occur above about 7000 feet elevation. Native

forest has been converted to pasture or forestry plantations or replaced by secondary forest of introduced weedy species below about 1500 feet elevation, especially west of Nahiku. Much of what has been converted fits Knapp's (1975) classification of "submontane rain forest". Most of the remaining native forest in Ko'olau is what Knapp calls "montane rain forest." Of the Hawaiian vegetation zones described by Krajina (1963), the Maui dieback forest fits Zone 7 most closely with Cheirodendron, Cibotium, and several epiphytic ferns as indicator species.

Throughout the Ko'olau forest, the canopy is dominated by the myrtaceous tree 'ohi'a (Metrosideros polymorpha). Higher elevation 'ohi'a forests are generally tall (10-20 m) and vigorous. Canopy height and density tend to lessen downslope. This trend may relate to reduction in slope and increase in rainfall as one travels downslope into middle elevations. The least vigorous and most open 'ohi'a formations occur on the wet, nearly flat ridge tops of the Maui Forest Trouble area.

Metrosideros polymorpha

This tree species is the most common of the Hawaiian members of this genus, occurring over large areas of the six major islands. Five other relatively distinct species are recognized, all of much more restricted range than M. polymorpha. None occur on the island of Maui. (For a thorough treatment of Hawaiian Metrosideros see Rock (1917) and St. John (1979).) In 1917, Rock reduced M. polymorpha to a subspecies of M. collina, the species described by Gray from the

Society Islands and Fuji. Most recently, Skottsberg (1944), Dawson (1970), and St. John (1979) have returned M. polymorpha to the status of an endemic Hawaiian species as originally determined by Gaudichaud. However, the name M. collina is retained as a synonym (St. John 1973).

The specific epithet polymorpha is indicative of the incredible variability of this 'ohi'a. St. John (1973) lists M. polymorpha as a complex of some 17 subspecies, varieties and forms. Corn and Hiesey (1973) believe this species has evolved into genetically differentiated climatic races or ecotypes. Mueller-Dombois et al. (1980) suggest the existence of successional ecotypes of 'ohi'a adapted to survival in a broad spectrum of seral and climax communities in the Hawaiian Islands. 'Ohi'a occurs from sea level to 8500 feet elevation and over a rainfall gradient from 30 to 450 inches per year (Corn and Hiesey 1973, Knapp 1975). This species can be found in virtually any topographic situation and in poorly drained to excessively drained habitats from the oldest soils to the newest lava. 'Ohi'a is relatively shade-intolerant (Burton 1980) and typically forms even-sized stands (Adee and Wood, unpublished, Mueller-Dombois et al. 1980). In form it may vary from a nearly prostrate shrub to a towering, straight-boled tree of 70 feet or more in height. Variations in leaf shape, texture and pubescence as well as certain floral characteristics are the basis for taxonomic differentiation. Research on the physiological characteristics of supposed ecotypes or successional types is currently underway (Stemmermann 1983).

THE MAUI FOREST TROUBLE

Introduction

The following history and description of the Maui Forest Trouble is intended to serve two purposes. First, it is an effort to construct from all available information the most detailed account of the Ko'olau forest both before and after the widespread tree death described in 1909. This purpose is primarily suited to the present study, to facilitate comparison of the historical informa- tion with the forest today. Second, this history is intended to depict, as much as possible, a crucial episode in the development of forest management in Hawaii. For this reason, information is included which may not be directly applicable to quantitative vegetation ecology. Considerable attention is given to the concepts which guided the actions of Lyon and others. Also, certain descrip- tive information is included which may not be discussed in the remainder of this paper (eg, soil bacteria, soil chemistry) but which, in the writer's opinion, should be made available to other workers interested in the Maui Forest Trouble.

The information for this section was derived from many sources. These include readily available journal publications, company correspondence and internal report, original field notes, archival photographs, and personal communication. The correspondence and reports files of the Hawaiian Sugar Planters' Association (HSPA) provided a great many details formerly unavailable, and were especially valuable in depicting the thinking of the day.

The HSPA library also allowed the writer to use Dr. Lyon's original field notes from his 1908-1909 survey of the Maui Forest Trouble. Several of Dr. Lyon's colleagues provided important information. All of these sources are combined in the following.

Lyon's description

In 1906, the HSPA began to receive reports of widespread dying of the native forest in the Ko'olau region of East Maui. The potential loss of watershed in this region was particularly alarming. Alexander and Baldwin Company, the major Maui sugar interest and member of the association, had only recently completed a very costly system of ditches designed to capture Ko'olau water for irrigation of cane fields in the dry central isthmus of Maui (Clarke 1878).

The phenomenon was soon dubbed the Maui Forest Trouble or Forest Disease due to the suddenness with which it appeared to spread (Lewton-Brain 1909). Amidst the crossfire of opinion and hypotheses, scientists of HSPA's Division of Pathology and Physiology set out to study the problem. Dr. Harold Lyon first visited Ko'olau briefly in October, 1907. His director, Dr. L. Lewton-Brain, visited the area in August, 1908. Finally, Lyon spent November, 1908 through January, 1909 completing an extensive survey of the affected Forest. Observations from these three visits form the bulk of the early descriptive material on Ko'olau forests in general and the Maui Forest Trouble in particular. Although earlier botanists and naturalists visited the Ko'olau region, none left any detailed record (St. John, personal communication).

By the end of January, 1909, Lyon had traversed--on foot or horseback--most of the "ditch country" of Ko'olau accessible by trails, spending the better part of his 45-day stay actually in the field. The following is a summary of his observations and hypotheses, with those of other workers interjected where appropriate.

Extent of the affected area

Lyon (1909) described the area of the dead forest in 1908-1909 as extending "from about 5 miles west of Kailua, east to Nahiku; or in other words, it is co-extensive with the ditch system in the forest (Fig. 1, p. 52). In breadth it extends from the lower edge of the forest to an elevation of from one to three thousand feet". He estimated the affected area as 3000 acres in 1909. It was believed that the forest had been dying for quite some time, certainly before the first reports in 1906 (Lewton-Brain 1909). The dying of the forest was reported to have proceeded from seaward to mountainward, mostly on the broad, nearly flat ridge tops while the steep sides of gulches hosted healthy trees. Lyon noted a clear relationship between tree health and slope of the substrate, "...the rapidity of (the trees') destruction being directly determined by the inclination of the ground in which they are growing, the steeper the slope the longer they will survive" (Lyon 1909).

Symptoms of the dying trees

Lyon (1909) noted that, prior to widespread dying, a large part of the forest had the appearance that the trees could "barely maintain themselves." Although 'ohi'a was by far the dominant tree in the

the affected forest and comprised the bulk of the dying and dead forest canopy, Lyon and others clearly state that practically all tree species were equally affected. In fact, early reports (Lewton-Brain 1909) indicated that all species, including herbaceous plants, died simultaneously, but this was later cited as misinformation (Lewton-Brain, unpublished report). Among the trees only the araliaceous species appeared to be relatively immune to the "disease" (Lyon 1909).

Typically, the "disease" first became apparent with the death of the native liana Freycinetia arborea ('ie'ie) and 'ohi'a. One early report (unpublished) describes the phenomenon as "the disease of the 'ie'ie vine." Symptoms of dying trees may be derived from early photographs (Fig 4, p.55& 5, p.56). Foliage and twig death and abscission eventually left numerous bare, standing snags. Trunk sprouting also occurred. Lyon and Lewton-Brain focused on the root systems of dying trees, which were found to be largely dead and blue-black in color wherever they penetrated to depths greater than a few inches in poorly-drained soil.

Stature of the forest

Typical forest of the Maui Forest Trouble area in 1908 was apparently of small stature. Lewton-Brain (1909) noted the "small size of all the trees found in the region, compared with that which they reach in other localities..." Photographs accompanying Lewton-Brain's 1909 report clearly depict trees 2 to 5 meters tall comprising the bulk of the dead canopy (Fig. 4). Lyon gives the following description in his 1908-1909 field notes:

> On some of the sharp ridges between Honomanu and Waikamoi the healthy forest runs clear down to the pali (ocean cliffs). The entire forest on this side of the mountain is composed mostly of small trees, large trees occurring only on the sharp ridges and slopes of gulches. On some of the flat, gentle, sloping ridge tops there will be acres of forest in which a tree six inches in diameter or more cannot be found...In many parts of the forest what appear to be large trees are really composite trees (ie., an original tree has been embraced by several 'ohi'a trees in succession) the whole forming a trunk of considerable diameter...
>
> ...In Nahiku the forest appears to be quite different from the forest west of Honomanu gulch. In the first place there are a great many more large trees to be met with on the flat tops of the ridges...

Species composition of the affected forest

Lyon also lists the most common tree species of the region. These included Metrosideros polymorpha ('ohi'a), Psychotria sp. (kopiko), Eugenia sandwicensis ('ohi'a paihi), Ilex anomala (ka'awau), and Pisonia umbellifera (papala kepau). The liana Freycinetia arborea ('ie'ie), once a common forest component, was usually found dead in the affected forest. Although he never explicitly describes the species composition west of Honomanu, we can derive some information from this comparative description of the Nahiku forests:

> At Nahiku...the species composing the forest are more numerous and the ohia lehua occupies a much less conspicuous place (than it does west of Honomanu.) Ohia paihi is to be found on most of the ridges in considerable numbers and in large trees. Byronia (Ilex) is also more numerous in this region and is represented by trees of considerable size. Their trunks are often 9 to 12 inches in diameter and they reach 40 to 50 feet in height. The Araliaceous trees are also numerous and conspicuous...A Pelea is also common and grows into a tree of considerable size (6-inch diameter, 40-foot height).

Lyon occassionally makes note of species west of Honomanu. Cheirodendron was common above 2000 feet elevation near Honomanu. Tetraplasandra sp. was locally common along the upper ditch. The

good health of these trees led Lyon to hypothesize that the araliaceous trees may have been more resistant to the conditions which were killing most trees. He notes, however, that araliaceous trees were "very rare in the affected region" (Lyon 1909). Large groves of bananas were also a prominent vegetation component (Lyon, unpublished).

Of the understory Lyon noted that the introduced grass Paspalum conjugatum and the native matted fern Dicranopteris linearis were covering the ground where exposed to light under dead canopy trees. Lyon describes the understory as having consisted of "ie'ie vines, tree ferns, and innumerable tender ferns which covered the trunks of the trees and the forest floor" (Lyon, unpublished) before the death of the canopy trees. It is not clear, however, that Lyon ever saw such an understory under living trees which later died as part of the Maui Forest Trouble. He may have gotten this information from Maui informants or may have extrapolated from his observations of understory in similar forests.

Causal agents

Throughout his survey Lyon compiled information which allowed him to get at the causal possibilities for the widespread tree death. His findings are summarized here.

FUNGI: "A carefully conducted field and laboratory study enables me to say with absolute certainty that the death of the trees is not due to parasitic fungi" (Lyon 1909). Thus, Lyon lay to rest one of the

most widely suspected possibilities for the cause of the "disease". The limitation of the dying forest to certain topographical features (ie., broad ridge tops) and the involvement of a number of unrelated plant taxa were evidence cited against the hypothetical involvement of parasitic fungi.

INSECTS: Lyon quickly dispensed with insects as a primary cause of forest death in Ko'olau, stating that "as in the case of fungi there are not a sufficient number of insects in the district to make collecting interesting" (Lyon 1909). Except for an incomplete report by entomologist C.J. Austin to Territorial Foester R.S. Hosmer in 1907 implying beetle infestation of Ilex anomala, Lyon's assessment of insects as causal agents was not contested.

SOIL CONDITIONS: In his search for root parasites Lyon noticed that the soil in affected areas was peculiar in several respects. "It is light gray in the first four to six inches and iron gray below this depth. The upper portion has the consistency of a fine sticky clay, while the deeper portion is much stiffer" (Lyon 1909). He noted that the deeper soil, when exposed.

> liberates free hydrogen sulphide to such an extent that its odor is very noticeable and the gas is easily detected chemically. This gas is, in itself, a virulent plant poison and its presence alone would be sufficient to kill such roots as it comes in contact with. Furthermore, in addition to its own poisonous properties, it changes some of the harmless compounds of the original soil into others of a more poisonous nature. To be explicit, it changes the harmless ferric (iron) compounds into poisonous ferrous (iron) compounds. (Lyon 1909)

Lyon had earlier performed an elegantly simple experiment on this chemical activity of the soil using a rust-encrusted pick-axe head:

> The head of this pick was...buried in the soil among the roots of dying trees on the top of a ridge and allowed to remain there twenty-one days. When removed and examined it was found that the incrustations of rust on its surface had been so altered that it could be washed off like so much mud, leaving clean steel exposed.

Lyon later concluded that "the hydrogen sulphide in the soil reduced the rust (ferric hydrate) to ferroso-ferric hydrate and possibly iron sulphide" (Lyon 1909). Later laboratory analysis of the soil revealed that 20 percent of the soluble matter was in the form of ferrous iron. Lyon commented that "the relatively enormous quantities in which this plant poison occurs in the soil should absolutely prohibit the growth of any ordinary upland tree" (Lyon 1909).

Lyon's hypotheses

By the end of his 1909 field work, Lyon had formed an impression of the forest in the Ko'olau ditch country which remained the basis of his thinking on Hawaiian forests throughout his career. From his observations he formulated a set of hypotheses regarding causal agent, the future of the forest, and management alternatives.

Investigation of soil drainage and chemistry focused Lyon's thinking on soil bacteria. He regarded the naturally poor soil drainage as an important predisposing factor to bacterial activity:

> If, by stagnant water or other causes, the air is excluded from a soil rich in ferric hydrate and containing sulphates and organic matter, fermentation may be set up by bacteria which result in the liberation of hydrogen sulphide and the formation of ferrous iron compounds.

He goes on to offer, first, his hypothesis regarding the primary cause of the Maui Forest Trouble:

> The sudden and simultaneous dying of the forest throughout the length of the ditch system is, without doubt, due primarily to the activities of bacteria in the soil. It is quite possible that these are exceptionally active forms of recent introduction. The ditches have been a certain means for the distribution of this bacteria throughout the forest which they traverse.

A second hypothesis explains the acute and synchronous nature of tree death in Ko'olau:

> The ultimate death of the trees has been greatly hastened by the exposure of the deeper forest formation to the weather through the breaking of the natural windward (forest) formation.

Dr. Lyon does not specifically identify the deleterious effects of the weather on the "deeper forest", noting only that the "stature and habit" of these trees is ill-adapted to such exposure.

As for the future of the forest in the Forest Trouble area, Lyon writes:

> It is not to be expected that the native trees, unaided, will again cover the affected area; at least not for many years to come.

According to Lyon, the dominant native tree, Metrosideros polymorpha, was not making a comeback:

> Such young ohia trees as now appear to be springing up in the dead forest are sprouts from old trees or young trees perched on plant debris and not rooted in the soil.

He did not think these small vegetative and epiphytic trees capable of acquiring normal tree stature. Meanwhile, exotic grasses and a native matted fern were covering the ground, reducing the reproductive potential of the native trees.

Regarding management of the forest as watershed, Lyon saw two possibilities. If native trees were to have any hope of re-establishing and maintaining over the long term, the entire area of the broad ridges--all the poorly-drained country--would have to be drained artificially. As this was quite infeasible, the only option available was to "build upon these (areas) a formation of plants adapted to swamp life and immune to its ills" (Lyon 1909). These plants would have to be gathered from swamp forests throughout the tropical world and tested for suitability to Maui conditions. Lyon emphasized the need for planting of plant associations, including trees, shrubs, vines, ferns and mosses. Also, native trees and shrubs which persisted on steep gulch slopes and other better-drained areas were to be protected.

Lyon continued to visit the Maui Forest Trouble area during the next twenty years of his career. He had become committed to the idea of reforestation with swamp-adapted species of all life-forms and pushed for such a program in his reports and other official

correspondence. The results of this effort are discussed below.Although his basic thinking remained unchanged after the 1908-1909 survey, Lyon's later field notes and reports add details to the impression of the forest after the widespread tree death. In 1917, he reported that most places lacked sufficient seedlings of "large-growing species" to form "the nucleus of a reasonably good forest cover." Hilo grass (Paspalum conjugatum) continued to cover the ground, hindering growth of all young trees and germination of seed.

In 1923 he issued this report:

> Now, the aspect of the entire country is that of an open scrub or bush-barren. The native rain forest has disappeared from most of the gulches as well as from the flattopped ridges: even the tree ferns and bananas have succumbed in most places, while the tender shrubs and ferns that covered the trunks of trees and clothed the forest floor are no longer in evidence. The entire region is dominated by staghorn fern (uluhi) (Dicranopteris linearis) which has transformed the landscape into a dreary, endless fern brake which is dotted with struggling bushes of ohia. These are in most part branches or offshoots from former trees which have sent out roots and established themselves as independent plants. In many cases, they are still perched upon the old tree trunks or stumps, but have extended their roots into the soil. Ohia starting in this way do not, as a rule, develop into large trees with a single trunk, but persist as bushes and never attain any considerable height.
>
> ...the native rain forest...will never be able to dislodge the staghorn fern which now has the entire area most effectually under its control. In some places the ohia bushes are so numerous as to constitute a reasonable ground cover but they do not promise to attain the height or assume the shape of trees and consequently will never form the necessary canopy to protect and encourage the development of the proper undergrowth which is an essential part of a rain forest. (Lyon, unpublished).

Dr. Lyon's commitment to reforestation with introduced species

was strengthened by his understanding of the origin of the Hawaiian flora. He adhered to the view that the colonization of the Islands had occurred when Hawaii was attached to the Asian mainland (Lyon 1918). In this theory, the Islands were then quite newly developed, and only those species adapted to bare or recent volcanic substrates were successful colonists. Today, this ancient flora, composed almost entirely of pioneer species and long ago cut off from further plant arrivals, must survive on old soils except where new lavas are produced. To this situation, said Lyon, Hawaiian plants are not adapted, so that there was no hope that native forest could survive much longer. Native forests were, he stated, "dying out gradually in some places and very rapidly in others." Further, the factors causing their destruction--ie., soil conditions--were beyond human control. Finally, their destruction had been irrevocably hastened by the encroachments of man and his livestock, exposing the once-protected interior forest to the calamities of wind and storm. In short, Lyon said "our native forests are doomed," and he meant virtually all native forests (Lyon 1918, 1919). For this reason, he steadfastly supported a gradual and carefully executed replacement of the Hawaiian rain forests with introduced hydrophytic species of low timber and fuel value (he did not want the planted forests destroyed for profit). In this endeavor he had the support of several reknown students of the Hawaiian biota, including Joseph Rock (Lyon 1918) and R.C.L. Perkins (HSPA unpublished correspondence files).

Forbes' observations

Dr. Charles N. Forbes, botanist for the B.P. Bishop Museum of

Honolulu, collected extensively in the Ko'olau region of East Maui from June 11 through July 5, 1920. Forbes is one of the few earlier collectors to keep detailed field notes regarding the general aspect of the vegetation, local geography, and relative abundances of species. His Ko'olau work was done along the ditch trails as well as in the forest inland. He entered several areas not seen by Lyon, adding further to our picture of the forest. From his notes it is clear that, in general, the native forest of the ditch country between Keanae Valley and Kopiliula Stream was much like that west of Honomanu. Also, Forbes' notes confirm that Lyon's description of the forest west of Honomanu was generally accurate.

The forest near Kopiliula Stream may have died considerably earlier than that to the west, judging by Forbes' observations that very few trees were standing, their trunks having already decomposed in many cases. (Both Lyon and Forbes describe other areas as hosting large numbers of standing dead trees in 1920. Early photos also support this.) Forbes' appraisal of Metrosideros regeneration differs strikingly from Lyon, however. Between Kailua and Keanae, Forbes says, the "trees 25 to 30 feet" tall were "all dead and even the bark gone" or they at least had dead upper crowns, but "many young trees" were coming up beneath these snags. He makes similar observations of "abundant regrowth of 'ohi'a" at other points in the field notes and in captions of photographs of the area (see photos, Fig. 5, p.56).

Other parties regarded 'ohi'a regeneration as abundant in the "disease" area, judging by an editorial which appeared in the

Honolulu Advertiser on September 9, 1923, entitled "Undue Haste in Reforestation". The editorial describes the debate between Ma i sugar growers and HSPA forestry experts over the continued planting of introduced Ficus trees on Maui Forest Trouble terrain. The growers are reported to have believed that "throughout the whole of the Nahiku rain forests the mountain slopes are being covered anew with a luxuriant growth of ohia, koa, young 'ie'ie vines and native ferns..." Further, the planters are said to have believed "that an open ohia forest interspersed with staghorn fern and 'ie'ie vines makes absolutely the best cover" (Honolulu Advertiser 1923).

Curran's viewpoint

In 1911, at the invitation of Territorial foresters, H.M. Curran of the Phillipine Bureau of Forestry spent a few days along the Ko'olau ditch system in order to formulate a "second opinion" regarding the present status and future management of the Maui Forest Trouble area. As reported to the Territorial Board of Agriculture and Forestry (Curran 1911) his brief description of the area is in line with the more detailed work by Lyon. Curran's conception of the causal agent or mechanism of widespread tree death differs from Lyon's only in that he places primary importance on the "wind storms of exceptional violence" (Curran 1911) reported to have hit the area just prior to widespread tree death. In doing so, Curran reduces the soil conditions--including soil bacteria-- to predisposing secondary factors.

Both men agreed that the dying forest had reached a point prior to widespread death at which "it was unable to withstand any further increase of unfavorable conditions" (Curran 1911).

Curran differs markedly with Lyon in his assessment of, a) recovery of the native forest after catastrophic tree death, and, b) the place of the catastrophe in the long-term dynamics of the Hawaiian rain forest. Curran reports:

> A close examination of the affected areas shows a return of all elements of the original cover. Herbaceous and shrubby plants are coming in rapidly and the trees very slowly. In the virgin forest beyond the principal tract of dead timber are older areas where the trees have been killed, probably by a similar combination of adverse conditions. These older areas are in various stages of return to normal forest cover.
>
> It is believed that the dying of the forest in this region is not a new and dangerous condition liable to spread rapidly, and cause a complete destruction of the water-bearing forest, but that since the first establishment of forests on the bare volcanic slopes they have been subject to injury by wind and that certain areas where conditions were least favorable to tree growth have been periodically denuded.
>
> Abnormal conditions, due to the interference by men and grazing animals with the normal forest cover, have accentuated the already extremely unfavorable conditions and made it possible for the winds to devastate larger areas than formerly (Curran 1911).

In accordance with this understanding, Curran recommended only that further artificial opening of the forest be prevented and that windbreak trees be planted. With adequate protection against damage to foliage, he claimed, "the forest, even if shallow rooted, may be expected to re-establish itself."

Mr. Curran proceeded to recommend increased forest management and planting of timber species, not to guard against the loss of watershed due to dying native forest but to create an improved source of revenue for the Territory.

MANAGEMENT OF THE MAUI FOREST TROUBLE AREA SINCE 1909

The work of Harold Lyon--H.M. Curran notwithstanding--spurred the HSPA to develop a large-scale reforestation effort for the Maui Forest Trouble area. This effort received broad support, even from such notable students of the native Hawaiian biota as Dr. R.C.L. Perkins. (Perkins recommended Melaleuca spp. as good candidates for reforestation.) The planning took on greater significance as reports were made of widespread tree death in West Maui rain forests, again on broad poorly drained ridge tops (HSPA correspondence files), and on Kauai (Larsen 1910). In 1910 the Territorial Division of Forestry offered to take over the reforestation effort from HSPA, which by then had planned nurseries in the Ko'olau region and begun propagation studies on a few hundred tropical woody species.

Establishment of major plantations of introduced tree species began in earnest in 1928 under the Division of Forestry (Skolman 1980). Hundreds of species were tried, including a number of Hawaiian species (Skolman 1980). Planting operations were all by hand labor, with no large scale clearing of exisiting cover. According to Mr. Wesley Wong (personal communication), District Forester for Maui County, seedlings were planted in rough rows, a few feet apart, in small holes with minimal clearing. There was no broadcasting of propagules, and the reforestation area was limited to the terrain accessible on foot or muleback. Planting programs were designed for forest reserve areas according to the following priority schedule: 1) fire-damaged areas, 2) areas of heavy feral mammal (usually cattle) damage, and 3) areas where the native cover showed poor vigor.

Any planted species which failed to show good growth with minimal care was planted over with a proven species, either Eucalyptus robusta or Melaleuca quinquenervia in nearly all cases.

Today, about 5100 acres (2064 ha) within the area of the Maui Forest Trouble described by Lyon have been planted with introduced tree species. The remaining area in which severe dieback of native forest is apparent on aerial photos is about 3200 acres (1295 ha). (Area determinations from computer planimetry by the writer.) The majority of the plantation area occurs on broad ridges which most likely once hosted affected native forests. At least half of the former Maui Forest Trouble area has been covered in forestry plantations (Fig. 6, p. 56).

WIDESPREAD CANOPY DEATH IN OTHER HAWAIIAN RAIN FORESTS

Ohia dieback trouble on Hawaii

The Maui Forest Trouble of 1907 was the first documented case of widespread native forest collapse in the Islands (other than reports of forest destruction by men or livestock). The second such incident began to emerge over 60 years later on the island of Hawaii. Mueller-Dombois and Krajina (1968) first reported a large band of forest on the eastern flank of Mauna Kea "...from 4500 ft. (1360 m) down to near 2900 ft (880m) (in which) large patches (from one to several acres in size) of the Metrosideros stand are currently dead or dying." Various workers coined the terms "'ohi'a dieback" and "'ohi'a decline" to describe the phenomenon. Foresters and

pathologists of the U.S. Forest Service and the University of Hawaii began a study of the area of dying forest, focusing on the search for causal agents of what they termed a "severe epidemic" (Petteys et al. 1975). Burgan et al. (1972) presented a preliminary estimate of the extent of forest killed and suggested fungal pathogens as causal agents (see also Laemlen and Bega 1972). Petteys et al. (1975) completed a survey of aerial photos of a 197,000 acre (80,000 ha) study area of the windward slopes of Hawaii. Comparison of photos from 1954, 1965 and 1972 indicated that the area of forest affected by the "epidemic" had increased from 120 ha to 34,500 ha in this 18 year period. Forests on widely different sites and trees of all ages were reported to be affected. Further, it was suggested that even if the "epidemic" should stop, regeneration of the native forest "is not a certainty" in the face of potential invasion of decline areas by aggressive adventive plants. These authors concluded that if the decline continued at the indicated rate the remaining 'ohi'a forest of windward Hawaii would be virtually eliminated in 15 to 25 years.

Research by the U.S. Forest Service between 1972 and 1979 was focused on suspected fungal and insect pathogenic agents. Chief among these were the root-rot fungi Armillaria mellea and, especially, Phytophthora cinnamomi, and the native 'ohi'a borer, Plagithmysus bilineatus (Cerambycidae) (Kliejunas and Ko 1973, Hwang 1977, Laemlen and Bega 1974). After intensive research, these organisms were shown to play secondary rather than primary roles in effecting 'ohi'a dieback, perhaps serving to hasten the death of dying trees (Papp et al. 1979). Meanwhile, Kliejunas and Ko (1974) showed that the vigor of certain dieback stands can be increased by

application of NPK fertilizer, suggesting nutrient starvation as a decline factor and reducing the significance of biotic factors. However, the U.S. Forest Service hesitates to relegate Phytophthora and Plagithmysus to secondary status, preferring to describe them as important parts of a complex of factors --including substrate aging, flooding, drought, and other--which, together, cause 'ohi'a dieback (Forest Pest Management 1981).

Ecological dieback research

Simultaneous with this largely pathological research in 1974, Mueller-Dombois et al. (1980) began to study the dieback phenomenon under the hypothesis that the dieback may be a recurring natural event in primary succession. This hypothesis was based on three observations: that the dieback observed on Mauna Kea occurred mostly on poorly-drained sites; that Lyon (1909) reported a similar phenomenon that occurred on Maui (as described in this paper); that despite claims by Petteys et al. (1979) that trees of all ages were dying, Mueller-Dombois found appreciable death only in upper-story 'ohi'a (Mueller-Dombois 1980).

Between 1974 and 1981, Mueller-Dombois and his co-workers completed extensive descriptive research in an 80,000 ha study area on the windward slopes of Mauna Loa and Mauna Kea on the island of Hawaii (roughly the same area studied by Petteys et al. 1975). A detailed vegetation map was completed from aerial photos and ground checking at the scale of 1:24,000 in cooperation with the U.S. Fish and Wildlife Service. Sixty-two releves (Mueller-Dombois and

Ellenberg 1974) were established to collect detailed floristic and structural data for the major vegetation types defined during the mapping work. Additional information was gathered along a 2 km belt transect through adjacent "healthy" and dieback stands (Jacobi 1983). Substrate, soils, drainage and physiographic information was compiled for each sampling area. Analysis of 'ohi'a population structures was carried out at 60 of the releve sites.

Classification of Dieback Types

From this large body of descriptive information Mueller-Dombois generated classification schemes for forest structure and for habitat types of the "dieback terrain" of windward Hawaii (Mueller-Dombois *et al.* 1980; Mueller-Dombois 1981). Forest structure was classified into types based on 1) tree canopy cover, 2) vegetation stature, and 3) associated dominant species or life forms. Of the 127 types recognized, the majority of the rain forest dieback terrain was included in 18 types (Mueller-Dombois 1981). Habitat types were classified according to soil depth, substrate type, and habitat parameters relating to drainage such as texture of substrate or topographic position. Ten habitat types were recognized for the dieback area (Mueller-Dombois 1981).

These mapping and classification efforts coupled with floristic and population structure data added several important points to the study of dieback, as outlined by Mueller-Dombois in 1981. First, a descriptive "definition of dieback" useful in fieldwork was stated: 'ohi'a dieback or decline is typically manifested as a collapse of

canopy trees and by the presence of large groups of 'ohi'a snags. Second, it appeared that the rapid progression of the decline on Hawaii--which had aroused so much attention in 1975--had stopped. Third, it was reaffirmed that, in the view of this team of workers, 'ohi'a dieback cannot be explained by any simple causative relationship of root flooding, disease, insect pest, or any combination thereof. Fourth, canopy collapse is disuniform in time and space--ie., a dieback stand may be immediately adjacent to a healthy stand-- and this disuniformity seems to correlate with variation in habitat types. Fifth, in some habitats canopy collapse is associated with vigorous 'ohi'a reproduction while in others collapse is associated with the successional displacement of 'ohi'a.

These fourth and fifth conclusions led to the classification of types of 'ohi'a dieback which correlate with the previously classified habitat types (Mueller-Dombois et al. 1980). Four major types of dieback were recognized, two occurring on lava rock substrates and two on ash or ash-derived soils:

1) Wetland dieback: This type occurs over relatively large areas (several ha or larger), and is typified by poor drainage of impermeable lava substrates. Abundant 'ohi'a reproduction occurs upon death of the canopy trees.

2) Dryland dieback: Dryland dieback occurs in patches of small extent (usually less than 1 ha). Substrates are very well drained permeable lavas. Abundant 'ohi'a reproduction occurs upon death of the canopy.

3) Displacement dieback: This type occurs on nutritionally rich (eutrophic) ash. As the canopy 'ohi'a die, reproduction of this

species is crowded out by tree ferns (Cibotium spp.) which reach their ecological optimum in such habitats.

4) Bog-Formation dieback: This type occurs on nutritionally poor (oligotrophic) ash soils. Closed-canopy, tall-statured 'ohi'a stands degenerate into open, more stunted tree formations on poorly-drained substrate. In permanently swampy areas shrub bogs may develop and, in the most extreme cases, these may become treeless sedge bogs. Intervening low ridges or knolls are forested with taller 'ohi'a and exhibit small patches of dieback accompanied by abundant regeneration. This ridge or knoll subtype has been called "Gap Formation dieback" (Mueller-Dombois 1981).

The work of Adee and Wood

Adee and Wood (unpublished) carried out extensive ecological research on the structural and compositional consequences of dieback in the 'ohi'a rain forest. Their study area was largely the same as that sampled by Mueller-Dombois et al. (1980) on the windward slopes of Mauna Kea and Mauna Loa. Their work involved detailed description of forest structure and composition, including structural data for all tree and shrub species.

Plots 0.1 ha in size were selected in healthy and dieback stands located by aerial photo and ground survey. Classification and ordination delineated three healthy and five dieback 'ohi'a forest types. Only the dieback types are outlined here.

1) Stunted 'ohi'a wetland: Treed bogs with dense gleicheniaceous fern patches. 'Ohi'a are generally stunted, unhealthy, and mostly of

vegetative origin from larger fallen 'ohi'a. Intervening ridges and hummocks host more abundant 'ohi'a with less severe dieback. Found on shallow or deep very poorly drained soils.

2) 'Ohi'a wetland: 'Ohi'a trees and treeferns are more abundant and larger than in the stunted 'ohi'a wetland. Well-drained microsites are abundant and boggy patches smaller in extent. Gleicheniaceous ferns do not form large dense mats. 'Ohi'a occurs in two strata, large dieback trees (mostly dead), and abundant, healthy, smaller trees. Primarily on moderately shallow organic soils underlain by recent pahoehoe lava.

3) 'Ohi'a-koa: 'Ohi'a occur as scattered individuals of variable size and vigor, with Acacia koa (koa) the basal area dominant in many areas and co-dominant with 'ohi'a in others. Occurs on deep, moderately well drained to somewhat poorly drained Inceptisols at lower elevations.

4) 'Ohi'a-treefern: Small number of large-diameter, dieback 'ohi'a and a moderate number of smaller vigorous 'ohi'a reach above a closed treefern canopy. Occurs on moderately deep to deep Inceptisols, or occassionally, Histosols.

5) Pubescent 'ohi'a: 'Ohi'a trees with densely pubescent abaxial leaf surfaces dominate very well drained sites (shallow Histosols over 'a'a) at higher elevations. Many of the relatively small canopy trees are dead, and smaller vigorous 'ohi'a are abundant.

The primary focus on stand structure and composition, with secondary focus on site characteristics, led to a single classification system for this 'ohi'a forest. This is somewhat analogous to

the development of 'ohi'a dieback types by Mueller-Dombois from his previous classifications of forest structural types and habitat types. The analogy is not complete, however, especially in that Adee's system focuses on vegetation structure and composition, while Mueller-Dombois' dieback type system focuses on substrate conditions which seem to relate to vegetation structure and composition. The beauty of this apparent conflict is that each researcher's work has reinforced the validity of the other's. For the most part each dieback type in one system has its counterpart--virtually identical in range, structure, composition, and substrate--in the other, despite the difference in approach by the two teams. The only exception to this is Adee and Wood's "'Ohi'a-koa" structural type. Mueller-Dombois' system includes no type in which koa is a major competitor with 'ohi'a, the only instance of 'ohi'a displacement by arborescent species occurring where tree ferns thrive on rich ash substrates. Mueller-Dombois' group found "no significant 'ohi'a dieback" in forests where koa is a second dominant (Mueller-Dombois et al. 1980).

Another point of contrast is that Adee does not emphasize differences in nutrient levels on ash substrates as Mueller-Dombois does (Adee, personal communication). For complete comparison of these two classification systems one must read the detailed descriptions by their authors (Adee and Wood, unpublished, Mueller-Dombois et al. 1980).

Adee and Wood add considerable detail to the conceptual model of succession in the Hawaiian rain forest and the place of dieback in

that model. In addition, their work further substantiates several hypotheses put forth by earlier workers. Adee and Wood agree with Mueller-Dombois and with Papp et al. (1979) that the structure and composition of forest stands (including dieback stands) cannot be traced to any simple causal mechanism; rather, a complex set of geologic, edaphic, floristic, and other environmental factors interact to determine the make-up of a particular stand. Soil drainage again emerges as an especially important element. Further, Adee and Wood substantiate Mueller-Dombois' hypothesis that on sites with extremely poor drainage 'ohi'a is being displaced by herbaceous species, especially graminoids and gleicheniaceous ferns. However, these authors agree that 'ohi'a is the best-adapted among native woody species for poorly-drained sites.

Mueller-Dombois et al (1980, Mueller-Dombois 1980, 1981) have stated that in dieback on lava rock substrates (his Wetland and Dryland types, Adee's 'Ohi'a Wetland and Pubescent 'Ohi'a types) 'ohi'a reproduction is abundant after canopy opening via dieback. Adee and Wood add that an increase in the abundance of small 'ohi'a takes place in all dieback stands after canopy openings, regardless of structural type. This increase, then, also occurs in the very poorly drained habitats. Inverse-J-shaped diameter distributions of 'ohi'a shorter than 10m are characteristic of all dieback stands regardless of structural type (Adee and Wood, unpublished). Only seedlings are under represented in any structural type. Further, in poorly-drained areas 'ohi'a maintains itself primarily through vegetative reproduction, with sexual reproduction only on available well-drained miscrosites.

Both Mueller-Dombois et al (1980) and Adee and Wood (unpublished) provide evidence that on poorly-drained sites 'ohi'a reproduction after dieback may be inhibited by dense growth of invasive herbaceous plants. Gleicheniaceous fern mats (especially of Dicranopteris spp.) may shade out 'ohi'a seedlings, and dense rooting of grasses, sedges, and rushes may prevent adequate root development by 'ohi'a seedlings. Alternatively, Gerrish and Mueller-Dombois (1980) suggest that Dicranopteris spp. may benefit 'ohi'a after dieback by eliminating regeneration which is not epiphytically established above the fern mat. Adee and Wood (unpublished) see no reason why 'ohi'a should be favored by this, in that many other native woody species are capable of epiphytic establishment.

DIEBACK OF DOMINANT CANOPY SPECIES OUTSIDE HAWAII

Dieback in other Pacific forests

A literature search reveals several examples of dieback of canopy-dominant tree species outside the Hawaiian Islands. These are described below, followed by a discussion of common elements and relationship to Hawaiian Metrosideros dieback. Excluded are those examples of widespread tree death which are clearly due to invasive pathogens (ie., American chestnut blight, Dutch elm disease).

Ash (1981) describes dieback in portions of montane rain forest in Papua New Guinea dominated by even-aged stands of Nothofagus spp. (Fagacae). Three dieback structural types are described. In two of these, canopy death is followed by vigorous Nothofagus regeneration.

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In the third dieback type, Nothofagus is gradually displaced by a multi-genera forest as senescent tree groups die. Ash (1981) points out that, as Nothofagus is shade-intolerant, regeneration is typically within local or extensive canopy gaps.

In New Guinea these openings occur as the result of large-scale perturbations such as landslides, wind, snow, fire, or insect damage or, usually on a smaller scale, due to death of senescent tree groups. Pure stands of N. pullei appear to be successionally displaced when undergoing dieback by N. rubra on poorly-drained sites. Where drainage is very poor, Nothofagus regrowth may be largely vegetative and stunted (Mueller-Dombois 1982a, Ash 1981). The symptoms of dieback trees in New Guinea are very similar to those found in Hawaiian Metrosideros. In addition, pathological research in New Guinea has focused on a cerambycid wood-borer and the root-rot fungus Phytophthora cinnamomi, just as in Hawaii. The same conclusions were reached -- these species are secondary agents of tree death. Ash (1981) states that New Guinea Nothofagus dieback is "usually associated with a combination of weather, substrate, pathogens, and hosts at a suitable stage of development."

Dieback of Nothofagus spp. has been reported in other southern-hemisphere forests where members of this genus form dominant stands. In New Caledonia, New Zealand, and Australia Nothofagus dieback fits, for the most part, the descriptions given by Ash for New Guinea (Ash 1981, Brown, in Ash 1981, Veblen et al. 1980, Mueller- Dombois 1982a). In all cases, regeneration is dependent on canopy opening. Even-agedness or even size of stands is related to abundant

regeneration on new or newly exposed substrates. In the Valdivian Andes of southern Chile, two- or three-age-class stands may develop when the canopy is partially opened and the understory killed by light volcanic ash-fall which does not kill canopy Nothofagus (Veblen et al. 1980). In Chile, these mid-elevation Nothofagus forests are maintained primarily by recurring mass movements (landslides) due to tectonic activity. Stands which reach senescence without being destroyed by ash fall or landslides tend to be overtaken by shade-tolerant genera upon death of canopy Nothofagus.

Wood-boring insects and root-rot fungi are suspected pathogens in Australian Nothofagus dieback (Brown, in Ash 1981).

Members of the genus Metrosideros exhibit dieback in parts of New Zealand proper (Stewart and Veblen 1982, 1983) as well as on Bench and Stewart Islands (Veblen and Stewart 1980). In these forests, Metrosideros (primarily M. umbellata) is frequently co-dominant with Weinmannia racemosa (Cunoniaceae) which is reported to die also. Tree death occurs in relatively small patches and is thought by many to be the result of defoliation by an introduced Australian possum (Trichosurus vulpecula). Stewart and Veblen (1982, 1983), however, feel that the effects of possums have been over-emphasized and that an understanding of the natural population dynamics of the canopy trees is basic to a study of the mortality. They point out that Metrosideros and Weinmannia are pioneer species, forming even-aged stands on the frequent landslides in the habitat region. After several hundred years many of the trees on a former slide may reach a stage of senescence at the same time, predisposing them to suffer

irreversible damage and perhaps death as a consequence of detrimental influences. The possum may provide this detrimental influence in some areas. Although Metrosideros/Weinmannia dieback has been reported in the absence of the possums (Stewart and Veblen 1983) it is unclear what other perturbations operate. Also, there is no report regarding the nature of regeneration under canopies opened by Metrosideros/Weinmannia dieback. In other words, it is unclear whether these species regenerate in the canopy gaps or are displaced by other taxa. There is no report of stunted regrowth on poorly-drained sites.

Dieback in forests of the continental U.S.

In the pathological literature, the topic of "decline diseases" includes several examples which share many properties with the diebacks or declines discussed so far (Manion 1981, Mueller-Dombois et al. 1983). Widespread death of dominant canopy species has attracted much attention in several temperate ecosystems. The term "decline" has been applied to those instances which can only be explained by a "complex of factors" or causes (Manion 1981). By this definition, the diebacks in Hawaii, New Guinea, New Zealand and Australia may be called declines.

In several declines of temperate trees, a pioneer canopy dominant is successionally displaced following decline. The "Littleleaf disease" of Pinus echinata in the Piedmont region of the southeastern U.S. is one such example (Campbell 1961, Campbell and Copeland 1954). Pinus echinata pioneers abandoned fields and

burnt-over sites. Where drainage is poor, old, even-aged stands may die synchronously and suddenly, allowing shade-tolerant hardwoods to emerge as canopy trees. Stand death is hastened by the rootpathogen Phytophthora cinnamomi (Campbell and Copeland 1954). On better-drained sites, P. echinata dies out more gradually (too gradually to merit the label "decline") and, again, is displaced by mixed hardwoods (Oosting 1942).

Pole blight of western white pine (Pinus monticola) is an important decline in the northern Rocky Mountains and British Columbia where this tree forms even-aged stands after fire or logging (Manion 1981). Dense, vigorous stands at the peak of maturity become highly susceptible to water stress on certain sites, perhaps due to limited root development in this species. Roots and trunks of water-stressed trees are attacked by fungi and large stands may collapse within a few years of the onset of symptoms. Following decline white pine is present but greatly reduced in a stand of mixed conifers (Hodges, personal communication).

In other temperate forests declines may operate to maintain the dominance of seral species. The spruce budworm "epidemics" of North America have received considerable scientific attention since 1950 (Morris 1963, McLeod 1980). Abies balsamea (balsam fir) and Picea glauca (white spruce) are seral species restricted to well- developed forest soils. They are shade-intolerant. The floral and vegetative buds of these species are the preferred foods of the spruce budworm (Choristoneura spp.), the larva of a moth which occurs at very low frequency in these forests under normal conditions. However, in

stands composed of mature and overmature trees spring budworm populations can reach tremendous proportions in synchrony with bud bursting of fir and spruce. This is typically coincident with unusually warm spring and autumn weather, which recurs every few decades. In severe outbreaks, the area of affected fir-spruce forest may exceed 1 million acres. Immature stands are also affected, but these are thinned rather than cleared by this infestation.

Upon opening of the forest canopy following budworm infestation regeneration of balsam fir and white spruce is abundant, with balsam fir dominant. A new stand is regenerated without major disturbance of soil. Without such widespread canopy opening, balsam fir and white spruce are restricted to wind-throws and similar small canopy gaps. Fire alters the soil conditions necessary for maintenance of these species.

Similarities among forests with dieback

All of the diebacks or declines discussed share certain common attributes. By definition they occur in forest trees which form monodominant or very low-diversity canopies. All of the species subject to dieback are also shade-intolerant and form even-aged or few-age-class stands. With the exception of Abies balsamea and Picea glauca (spruce budworm epidemic) all dieback species are pioneer or early seral species. Dieback may serve either to restore habitat conditions suitable to stand rejuvenation by the dominant species (whether those conditions be pioneer or mid-seral) or may result in the displacement of the canopy dominant(s) by more shade-tolerant

genera. Among the pioneer and early seral species (Metrosideros spp., Weinmannia racemosa , Nothofagus spp., Pinus echinata, Pinus monticola) stand rejuvenation (replacement) usually occurs on more extreme sites (e.g., waterlogged, nutrient-poor, or bare substrates) while stand displacement prevails on better sites (such as the Valdivian Andes and New Zealand landslide slopes, or Hawaiian eutrophic ash soils). Where stand rejuvenation occurs, the dieback is often hastened by fungal and insect pathogens; in the case of Nothofagus spp. and Metrosideros spp. the Cerambycid wood-borers and the root-rot fungi Phytophthora cinnamomi and Armillaria mellea are frequently involved. Also, in many cases dieback occurs primarily or exclusively in overmature or senescent stands. Stewart and Veblen (1982, 1983) and Mueller-Dombois (1981, 1982a) have stressed the central place of senescence in even-aged stands in the understanding of widespread tree mortality. Mueller- Dombois (1981, 1982a) has refined this point to formulate a theory of dieback based on the facts generated in Hawaiian and Pacific islands studies. His theory states that "dieback is primarily a function of cohort senescing which can be further synchronized by certain secondary and tertiary environmental perturbations. "He adds that "the pattern of dieback is largely a function of the distribution of the cohort." The term "cohort" refers to all members of a population derived from the same regeneration wave.

It is apparent that widespread canopy dieback is not a phenomenon unique to Maui, the Hawaiian Islands, or the species Metrosideros polymorpha. Also, the details of a particular dieback

vary with habitat region, and species characteristics. Although dieback or decline is somewhat common, it is still poorly understood in most cases and is not yet widely accepted as a normal, healthy forest process.

BOG-FORMATION DIEBACK

Observations and hypotheses

It was Mueller-Dombois (1974) who first compared the Maui Forest Trouble to 'ohi'a dieback on the island of Hawaii. In his 1981 report he refined this comparison, describing the Maui Forest Trouble as similar to the Bog-Formation dieback on the east flank of Mauna Kea. Adee and Wood (unpublished) drew the same parallel between the Maui Forest Trouble area and their Stunted 'Ohi'a Wetland structural type of Mauna Kea. (As noted earlier, Bog-Formation and Stunted 'Ohi'a Wetland are names applied by these authors to the same regional forest type on Mauna Kea.) These observations permit a more discriminating view of the vast 'ohi'a dieback situation on Hawaii relative to Maui dieback studies. Bog-Formation or Stunted 'Ohi'a Wetland dieback may well provide a detailed comparative basis for analysis of findings from a new study of the Maui Forest Trouble. Gerrish (1980) also visited the Maui Forest Trouble area briefly in order to compare it with his study area at Pupukea on O'ahu. He found many structural and compositional similarities between the broad, flat ridge top forests of Maui and the smaller flat ridge top or gulch bottom dieback areas at Pupukea. His study may provide

additional comparable material.

The Bog-Formation dieback of Mauna Kea (as it will be called hereafter) appears to result in the reduction of Metrosideros biomass on very poorly-drained sites, with a concomitant increase in cover of hydrophytic graminoids and gleicheniaceous ferns. Mueller-Dombois et al. (1980), in describing and naming this dieback type, have hypothesized a successional trend toward bogs on such sites. They were not the first to do so. Mueller-Dombois cites Fosberg (1961) who first hypothesized the connection between dieback and bog formation, based on his observations of dieback on soils with well-developed basal clay layers in montane rain forests on Kauai:

> It is suggested that these decadent (dieback) forests are stages in the process leading to the formation of bogs. Weathering of the basalt under cool, very wet, conditions that permit an accumulation of humus and thus percolation of humic acid solutions yields clay (Wentworth et al. 1939). Formation of clay on level or gently sloping ground gradually impedes drainage, and brings about the accumulation of perched water on top of the clay. This drowns the rootsystems of the large trees, causing them to die slowly, as is seen in the decadent forests. They are replaced by smaller trees, more shallowly rooted. As the clay layer becomes more impervious and perhaps more extensive, the accumulation of water may become greater and may even drown the shallow root systems of the small trees. This process repeats itself, until the low forest, the shrub bog, and finally the very low sedge bog vegetation, are formed.
>
> This theory would account for the present distribution of bogs in the Hawaiian Islands, for the correlation of decadent forest with flat, very wet terrain, and for the correlation of clay layers on the basalt with decadent forest and bogs. It would also account for the decadence of the forest on flat ground immediately adjacent to healthy forest of tall stature on steeper slopes. This gradual dwarfing process might also have brought about the evolution of dwarf races of such forest trees as Metrosideros that are in full flower when only a few centimeters tall.

Fosberg's hypothesis describes a steady reduction of soil drainage as impermeable clays develop and become more extensive, and a concomitant stepwise reduction of 'ohi'a biomass as successive generations are drowned by a rising water table. On East Maui, Lyon's early descriptions state that a vigorous closed canopy forest

died suddenly and was replaced by a stunted, open 'ohi'a wetland. In other words, the reduction of 'ohi'a biomass and paludification of the East Maui site appear to have been more drastic than the model suggested by Fosberg (1961) and Mueller-Dombois et al. (1980). This has led Mueller-Dombois (1981) to hypothesize that in very wet, poorly-drained areas loss of 'ohi'a canopy via dieback can of itself cause an increase in soil moisture through reduction in soil drainage by evapotranspiration and interception. In other words, the stand dynamics of 'ohi'a are at least in part responsible for paludification of these wet sites, together with pan formation (Mueller-Dombois, personal communication).

Anticipating the discussion of this hypothesis as it relates to the Maui Forest Trouble, the literature review was expanded to include processes and theories of paludification. Of particular interest were references dealing with the effects of forest removal on soil moisture and the processes of bog formation in the tropics and subtropics.

Effects of forest removal on soil moisture

The basic influences of vegetation on soil moisture have long

been established (Bay 1967). Some precipitation is intercepted by the aboveground portion of plants before it can reach the soil surface. Soil water is taken up by the root systems of plants and returned to the air via evapotranspiration. Species vary in their rates of evapotranspiration and in their adaptations to soil moisture extremes (Bay 1967). Further, the influences of vegetation on soil moisture vary with vegetation type. Several studies have illustrated the variations in soil moisture on a given soil type under different vegetation types (Mueller-Dombois 1973, Wood 1977, Daubenmire 1972).

Influences of forest cover on soil moisture also vary with stand age. For Russian spruce and birch stands on peatlands Molchanov (1960) has shown that rate of soil water loss increases with stand age up to 50 or 60 years and then decreases as the stand grows older.

It is also well known that removal of forest cover in wet areas causes an increase in soil moisture. Most of the literature deals with temperate forestry plantations although work has been done in tropical forestry (Balek 1977, Daniel 1974). While forest hydrology studies typically focus on interception, evapotran- spiration and runoff, several studies have directly monitored watertable variations before and after forest clearing. Rise in water table is directly proportional to the degree of tree clearing in Scandinavian forests on wet sites (Heikurainen 1967). In Denmark, both clearcutting and sheltercutting of planted beech on heavy moraine soils resulted in a higher water table during the growing season (Holstener-Jorgensen 1967). Clearcutting resulted in a 2m rise in the water table

followed by establishment on the site of a dense growth of grasses, sedges, and rushes. Where a 160 year old stand was sheltercut, the remaining shelter trees were frequently observed to wilt, they developed stagheadedness, and were attacked by wood-boring insects and root-rot fungi much as in Metrosideros dieback trees. Thinning of the plot had resulted in a 1m water-table rise which was sufficient to drown the root systems of the remaining old trees. This plot was also invaded by hydro- phytic graminoids. When replanted with more hydrophytic spruce, these plots again showed a lowering of the water-table during the growing season. Although this study took place in the temperate zone on glacial substrates it shows that a very wet soil environment, by drowning the roots of just a few trees in an overmature stand, could trigger a steady rise in soil moisture and, hence, tree death--as more trees die, soil drainage is further decreased so that more trees die and so on.

It is currently hypothesized that Iron Age man may have triggered such a chain-reaction paludification process over large areas. Forest clearing, thinning and grazing by Iron Age man have been closely correlated with the origin of peatlands in the British Isles and Scandinavia (Merryfield and Moore 1974, Moore 1975) and in Poland (Moore 1975). These are cases where the soil hydrology and, consequently, the vegetation of entire regions may have been shifted toward that of bogs by the removal or partial removal of forest from otherwise poorly-drained sites. No tropical or subtropical counterparts to this human impact have been reported.

Bog-formation processes

The ability of mankind to bring about paludification by removing forest cover has been made clear enough. However, there is little literary record of bog formation as a result of natural succession from forest except where forest is flooded by a river. This may say ore about the status of the literature than it does about nature. By far the majority of bog literature concerns temperate and subarctic peatlands. Two common paludification mechanisms are recognized (Gorham 1957). Bog areas develop either where lakes are filled with soil or where vegetation develops over impermeable parent material. A cold, wet climate is essential for peat development in either case. A third mechanism is not widely acknowledged, in which the development of hardpan during soil maturation leads to restricted drainage and bog formation (Ugolini and Mann 1979). This hardpan formation mechanism corresponds to Fosberg's (1961) thinking of Hawaiian bog formation and, of the three reported processes, is the only one which is compatible with the East Maui dieback terrain. Selling (1948) represents the most commonly held theory for Hawaiian bog formation. He focuses on climatic change as the mechanism by which bog peats were allowed to develop. Paludification after tree death as part of a natural succession toward bog has not been reported. This may, in part, be due to the very recent acknowledgement of forest dieback as a successional phenomenon.

PROPOSAL FOR VEGETATION RESEARCH

Questions and hypotheses

Probably the most common and most difficult question asked about dieback or decline incidents is "Will the forest come back?". The Maui Forest Trouble is no exception in this regard. Lyon (1909) was convinced that the 'ohi'a regeneration which was occurring in dieback areas was mostly vegetative or epiphytic, and was insufficient to reproduce a closed-canopy 'ohi'a forest. Forbes (unpublished notes) and Curran (1911) claimed that in many areas 'ohi'a regeneration was abundant and the forest on its way toward re-establishment. It would be very difficult to set a limit which would clearly demark "adequate" or "canopy-producing" from "inadequate" or "non-canopy-producing" 'ohi'a regeneration. However, the answer to this conflict is essential to discussion of succession in East Maui's submontane rain forest. It is also an important test of the bog formation hypothesis of Mueller-Dombois et. al. (1980). Finally, it is of value as a test of the pattern of dieback phenomena in forests in general: i.e., does the Maui Forest Trouble represent a replacement or a displacement of 'ohi'a, or some other pattern? With these ulterior objectives in mind, the first hypothesis for testing in this proposed new study is stated as follows:

1) There are proportionately large areas within that forested region of Ko'olau which died in the first decade of this century in which small size-class Metrosideros are under-represented relative to

vigorous, closed-canopy stands on the island of Hawaii, and in which Metrosideros has been displaced by herbaceous cover.

Another informational conflict concerns the pattern and range of dieback in the Maui Forest Trouble area. Lyon noted considerable floristic and structural differences between the Nahiku forests and those west of Honomanu. Forbes described the Kopiliula region between Keanae and Nahiku in which advanced decomposition of snags indicated that these forests had died somewhat earlier than those west of Honomanu. Meanwhile, the geologic and soils literature describe fairly distinct regional differences in substrate and drainage properties within the dieback area described by Lyon. However, aerial photos of the area reveal no obvious vegetational non-conformity between regions. It is apparent that thorough ground checking is needed. The second hypothesis for testing is stated as follows:

2) There exist regional differences in species composition and vegetation structure within the dieback area which can be related to regional differences in parent material and soils.

Comparison of the Maui Forest Trouble area with dieback elsewhere is included, in part, in the first hypothesis. It is expected after preliminary reconnaissance that the Maui dieback is very similar to the dieback in mid-elevation forests on Mauna Kea on Hawaii. This Mauna Kea dieback has been studied by Mueller-Domobis et al. (1980) and by Adee and Wood (unpublished). Also, similar dieback on O'ahu has been described in some detail (Gerrish and Mueller-Dombois 1980). These provide adequate comparative material

on population structure, habitat parameters and floristics. This comparison will provide further insight on all three diebacks and will be a test of applicability for the dieback classification schemes developed. The third hypothesis may be stated as follows:
3) The historic dieback on East Maui was closely comparable to the more recent diebacks described on Mauna Kea as Bog Formation or Stunted 'Ohi'a Wetland dieback by previous authors.

The Mauna Kea dieback discussed above is considered by Mueller-Dombois and others as a successional phase in bog formation. Implicit in the formation of bogs in this terrain are a) a reduction in woody ('ohi'a) biomass with a concomitant rise in hydrophytic herbaceous cover, b) the formation of impervious hardpans which restrict drainage, and c) paludification due to loss of drainage via evapotranspiration and interception upon dieback of the forest canopy. It is desirable to test this thinking where possible in the study of East Maui dieback. Reduction of 'ohi'a biomass and dominance of herbaceous cover is among the subjects included in the first hypothesis. The idea of paludification due to loss of forest canopy could be tested by monitoring soil moisture and evapotranspiration in healthy and dieback stands on similar substrates. This is infeasible at present due to limitations of time and manpower. However, hardpan formation can be tested, at least in terms of presence or absence in dieback terrain. The fourth hypothesis is as follows:
4) Dieback in the Maui Forest Trouble area is positively correlated

with the presence of an impermeable hardpan in the soil.

Along with these four hypotheses, it is the general purpose of this study to provide an accurate description and information base for the Maui Forest Trouble aea which will aid future ecological forest research.

Research approach suggested

For purposes of standardization and to facilitate the comparisons discussed in the first and third hypotheses, the Maui Forest Trouble terrain will be described by the same methods used by Mueller-Dombois et al. (1980). Dieback areas and internal entities will be located by aerial reconnaissance and aerial photo survey followed by ground checking. Releve samples ($400m^2$ each) will be placed in each entity, with attention to representative and unbiased sampling of the entire dieback region (Hypothesis 2). Floristic and structural components will be described according to the releve and Braun-Blanquet techniques in Mueller-Dombois and Ellenberg (1974). Population structure of 'ohi'a will be described using height and diameter classes established by Mueller-Dombois et al. (1980). Soil profiles will be described in each releve according to USDA (1951) conventions (Hypothesis 4).

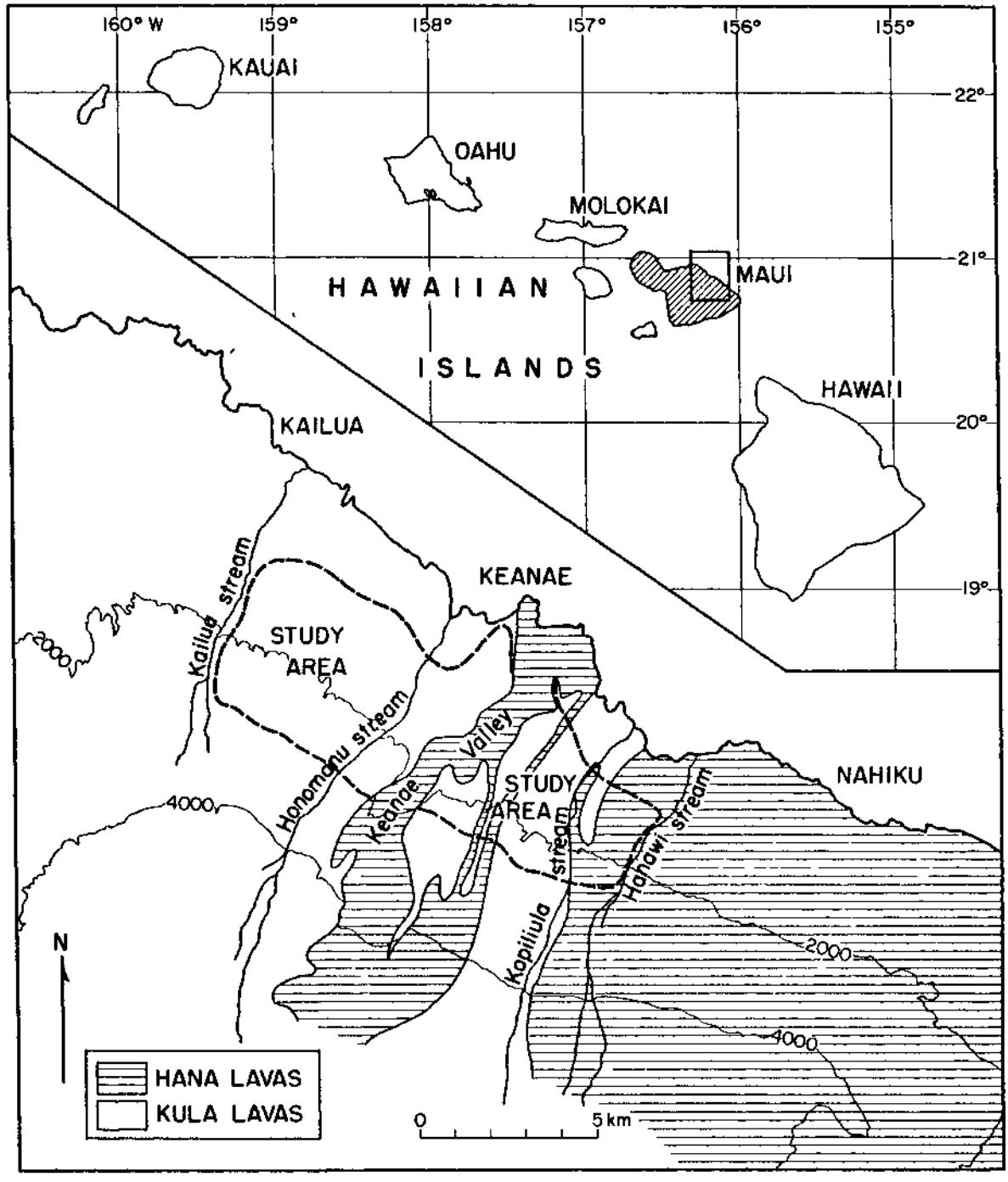

Fig. 1. Study area and geology of windward East Maui.

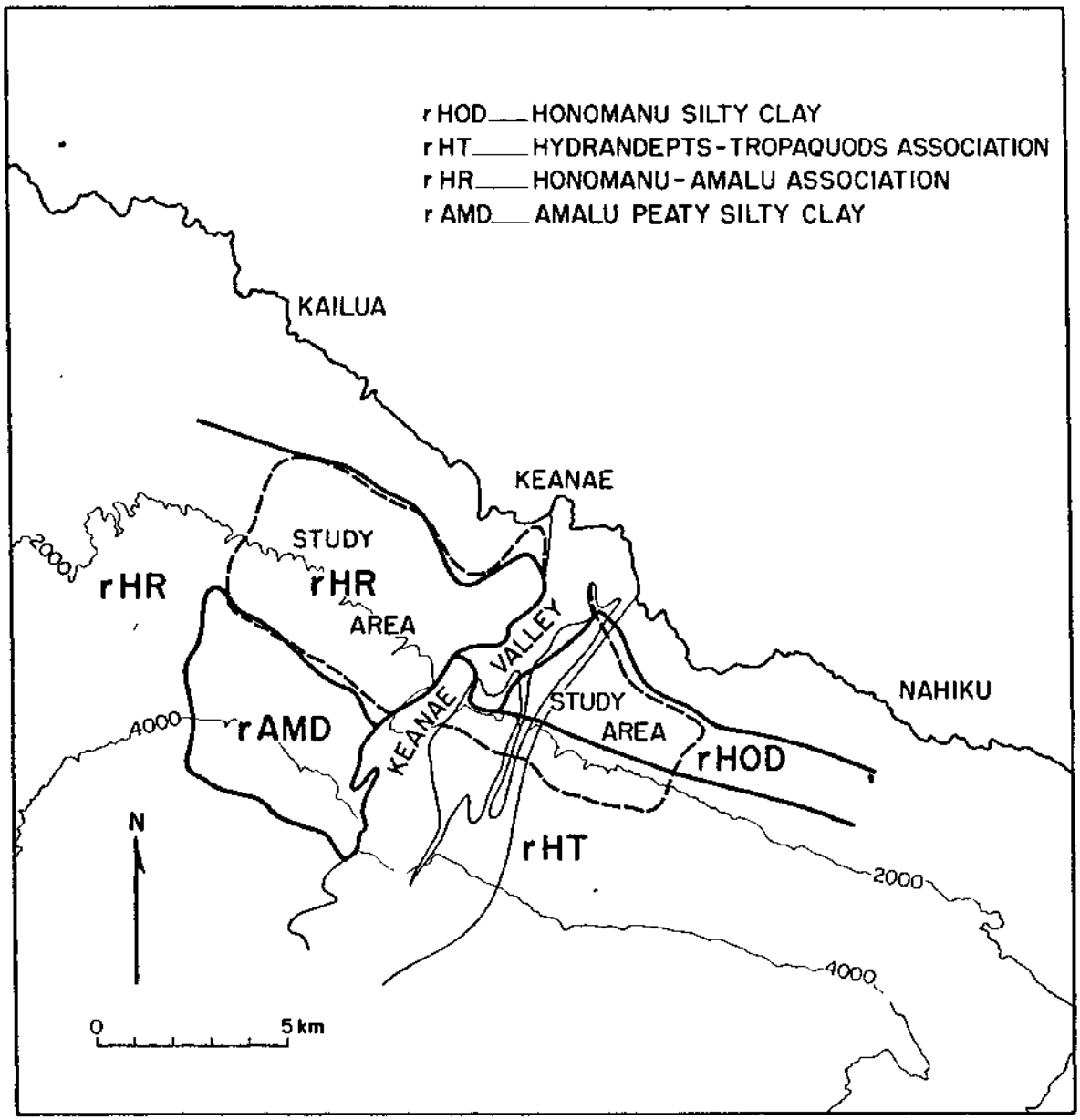

Fig. 2. Soil types in and around the study area.

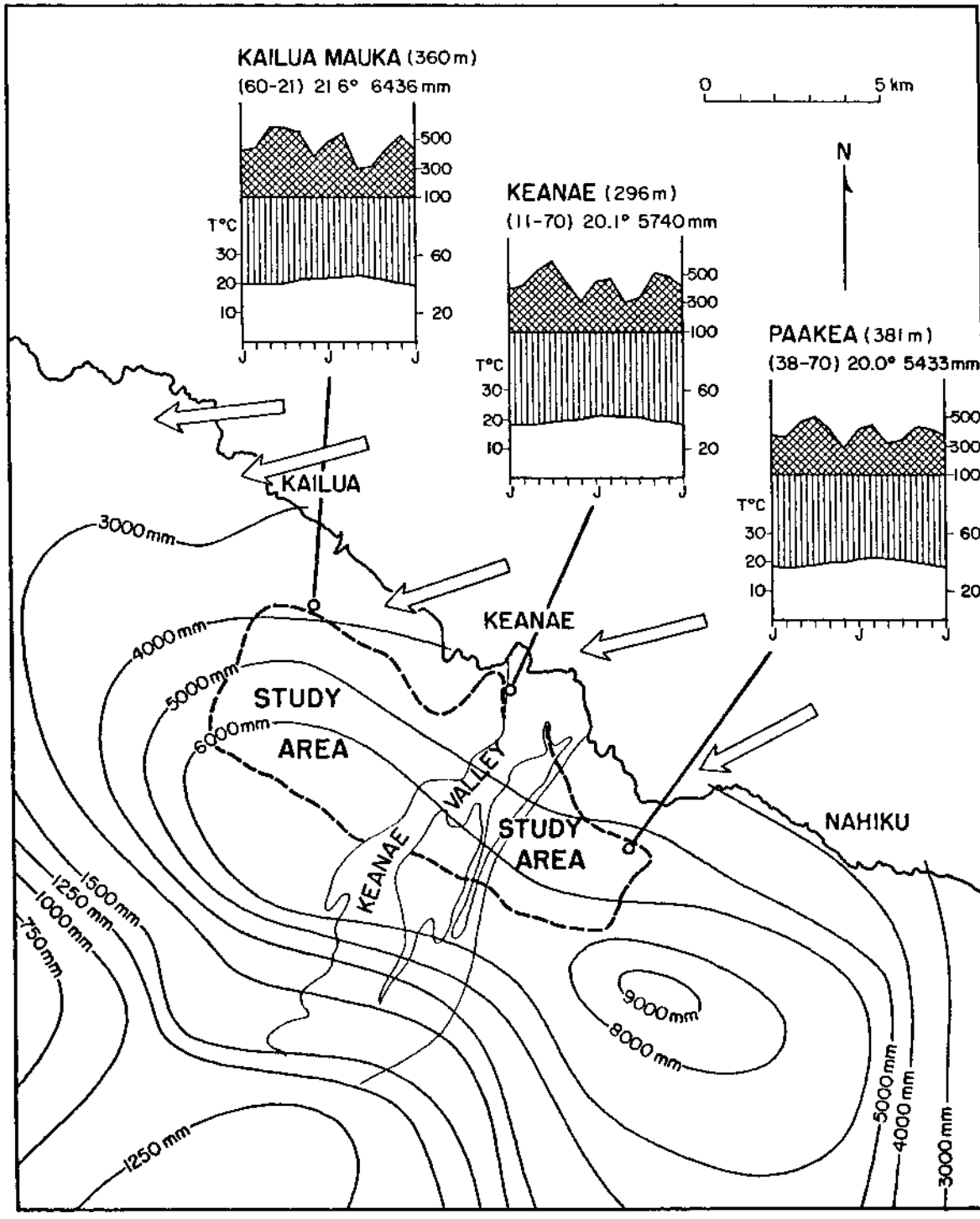

Fig. 3. Climate map of windward East Maui. Climate diagrams after Walter et al. 1975.

Fig. 4. Maui Forest Trouble in the Kailua region circa 1909. See Fig. 1 for location. Photo from Lyon (1909).

Fig. 5. Dieback in Honomanu watershed near 2500 feet elevation. For location see Fig. 1. Photo by Forbes, 1920.

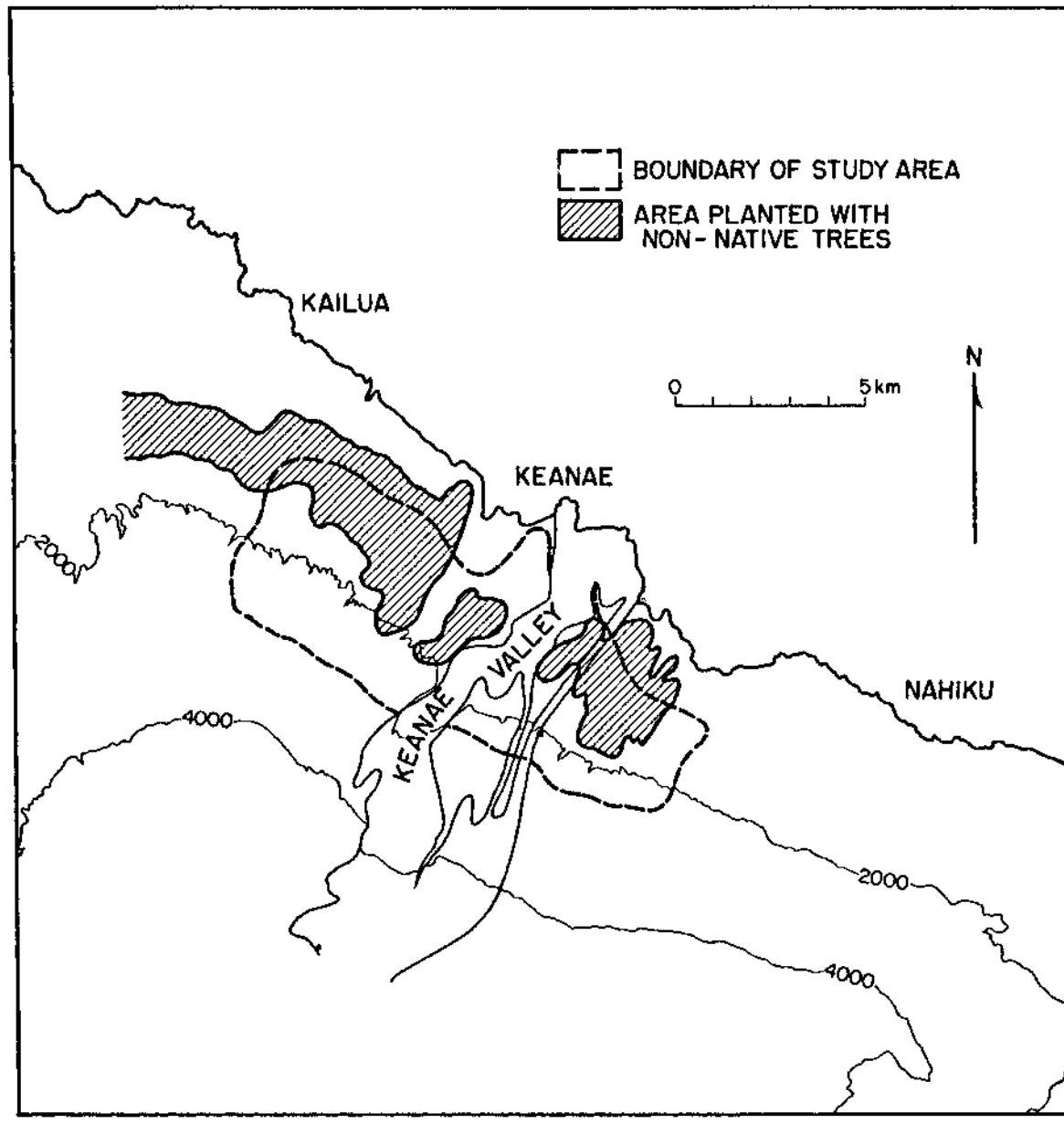

Fig. 6. Non-native tree plantations in the study area.

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