In 1965 I prepared a vegetation map for the Park after Dr. Fosberg had drawn tentative boundaries on a set of 1954 air photos. Ground work for this took about four months and following that, I had two graduate students working in 1966 and 1967 on vegetation samples (i.e., 64 relevés) that were distributed throughout the major vegetation units. These were established for deriving more detailed information on the plant composition, tree growth and soil substrate of each unit.

The map was first presented together with the Atlas for Bioecology Studies (Doty and Mueller-Dombois 1966) on 55 individual 70 cm x 70 cm air photos as transparent overlays at a scale of 1:12,000. In this form it was available only in two sets (one located at Hawaii Volcanoes National Park Headquarters, the other at the University of Hawaii Botany Department). In this bulky format, the map has been used by a few researchers as a tool for orientation, but it was a time-consuming job for them to obtain the needed information. For the same reason little use had been made of the mapped information by management.

Because of a general request, the air photo map was later transcribed to the 1:24,000 topographic map sheets covering the Park. Then it was further reduced to a scale of 1:52,000 and made generally available in a CPSU technical report (Mueller-Dombois and Fosberg 1974). In this format, in which the map appeared on 25 topographic half-sheets of each 8 1/2 x 11 inches, the map became useful as a field reference guide in notebook form.

Several people disassembled this report and glued the individual map sheets together into a single sheet for providing a general overview.

Apart from the technical difficulty of reading the map symbols from a distance, the mosaic of vegetation units of the whole Park presents further problems of interpretation which are inherent in any two-dimensional map projection of single ecosystem components.

For overcoming this problem or for bringing the mapped information "to life," I would like to briefly discuss three tools for interpreting such a map.
Tools for Map Interpretation

(1) Environmental Data: Plant communities, which can be defined spatially as recurring similar plant assemblages, form in response to environmental forces acting in certain patterns upon the flora of an area. One of the outstanding environmental forces is the climate, another the substrate on which the communities occur. The latter is a very obvious control on community development in this Park where lava flows of differing dates and ash deposits determine the vegetation boundaries in many cases. Therefore, a geological map drawn to the same scale and used as a transparent overlay could serve as a useful interpretive tool for the vegetation map. This aspect has not yet been utilized.

However, here I would like to draw particular attention to the use of climatic data. The Park Management has accumulated rainfall data over the years in various places and this has not yet been fully exploited for interpretive purposes. I had begun to do that for the Atlas of Bioecology, and the outcome was the climate diagram map for the Island of Hawaii (Figure 1).

Generally, the most important climatic parameters for plant and community distribution are rainfall and temperature. With respect to rainfall, perennial plants are controlled not only by the normal (or mean) annual amounts of precipitation occurring at a given site, but especially also by the variation of rainfall throughout the year. Therefore, mean rainfall isohyets explain vegetation distribution only in a very general sense. Month-to-month variations are more critical, particularly in the tropics. Temperature may control certain plant distributions more or less directly in the form of heat, but temperature is more important indirectly as it determines largely the effectiveness of rainfall for plant growth. For example, 1000 mm of rain falling in the mountain parkland on Mauna Loa provides more effective moisture for plant growth than 1000 mm falling in the coastal lowland of the Park, where the mean air temperature is about 10°C higher. These ecological aspects are incorporated in the climate diagrams, which were prepared after the method of Walter (1957): The months of the year are shown on the abscissa of each diagram (from January to January with July in the center). The left ordinate has a temperature scale in °C and the right ordinate a precipitation scale in mm. Each diagram shows two curves, an almost horizontal or slightly one-modal, smooth curve, which gives the mean monthly temperatures of the station, and an uneven or zig-zag curve, which shows the month-to-month rainfall variation. An index of rainfall efficiency is built into the diagrams by making 20 mm rainfall correspond to 10°C in the scaling of the two ordinates.
This has the advantage that one can recognize with one glance whether a place has a seasonal or a continuously moist or humid climate. Wherever a rainfall curve undercuts a temperature curve a drought season is indicated. An example is Hale-ma'uma'u Crater at the north end of the Ka'ū Desert. In the tropics such severe seasonality is similar for the vegetation to a winter season in the temperate zone, i.e. the perennial vegetation can be expected to be dormant at that time. A dry season is indicated where the rainfall curve drops below 100 mm or 4 inches per month, and a wet season is indicated where the monthly rainfall remains above 100 mm. A typical rain forest climate shows month-to-month precipitation in excess of 100 mm. Such climates are indicated at Park Headquarters, Hilo, Ka-poho and other places, where rainfall in excess of 100 mm is shown as black fields on the diagrams. For maintaining the diagrams within practical sizes, the scale above 100 mm was reduced by 10%. This is indicated by blackening the area under the curve. Each diagram shows also the station name, its altitude (here by map location) and the mean annual rainfall. Mean annual temperature is shown only for stations with on-site records. For the others the temperatures were interpolated by using the adiabatic lapse rate and elevation of the nearest recording station.

Although there are diagrams for only five stations in the Park and four nearby, this information is extremely useful for explaining the major vegetation types in the Park. Another useful tool is the following.

(2) Profile Diagrams: Figures 2 and 3 are two diagrams out of the five that I prepared originally for interpreting the vegetation map. Their locations are indicated on the climate diagram map.

The profiles give first of all a third dimension, which is missing on the vegetation map. This third dimension, indicated by the topographic variation along each profile, removes some of the abstractness that is inherent in any flat map projection. In addition, the profile allows one to further abstract and indicate climatic and substrate relationships as well as the major vegetation-structural features which cannot be shown on the vegetation map. By displaying the four components, climate, vegetation, soil substrate and topography together, one can now speak of having established ecosystems in the structural sense. Twelve such structural ecosystems are shown for the east-flank of Mauna Loa (Profile 1) in the Park, and eleven are shown for Profile 2, which extends from the Kī-lau-ea Forest through the Ka'ū Desert via Hilina Pali to the coast. By establishing samples in all of these units and by comparing them with one another, one can then establish ecosystem types, i.e. they can be
identified systematically. For example, ecosystem nine on Profile 1 and ecosystem eight on Profile 2 are the same (the closed mixed forest of Kipuka-pua-ulu), also unit ten on Profile 1 and unit seven on Profile 2 are the same ecosystems, the open 'ohi'a (Metrosideros) scrub-forest with native shrubs and lichens, which extends from the Tree Molds to Kipuka-pua-ulu), and south to around the Volcano Observatory. On this basis of comparison, the Park's vegetation was classified into 31 major vegetation or structural ecosystem types (Mueller-Dombois and Fosberg 1974).

(3) Ecological Zones: Such a large number of major vegetation types is still not easy to comprehend. Their relationships, however, are more easily understood when they are grouped into ecological zones. In this way, the number of vegetation types is reduced to less than 10 for each zone, a number more manageable for Park policy considerations. When based on vegetation research, knowledge of animal home ranges and environmental data, such ecological zoning is not entirely an arbitrary divisioning. An important criterion for ecological zones are macroclimatic boundaries. In a terrain with pronounced topographic variations (as existing here in Hawaii Volcanoes National Park), topography is a major integrator of climate. Therefore, ecological zones can be defined in part by topographic boundaries for mapping. Where certain types of substrate prevail over large areas, the soil-substrate may help in defining ecological zones. In Hawaii Volcanoes National Park, which in its entirety occurs on recent volcanic substrates, the finer substrate boundaries occur mostly on too small a scale for ecological zoning or they extend, like some lava flows do, through a range of macroclimates. Therefore, soil substrate was of more limited value in defining ecological zones for the Park. A fourth important component is the vegetation itself. For example, the rain forest in the Park cuts across a considerable range of altitude (from about 5000 to 1500 feet), where it reflects the boundary (approximately along the Chain-of-Craters Road) of the moist windward and drier leeward orographically controlled air movements.

Ecological Zones as Major Ecosystems

By integrating climate, topography, substrate, and vegetation, the six ecological zones (here superimposed on the Park's vegetation map) were derived. An important functional element can now be added that renders each zone to be considered as a major ecosystem in the Park, which deserves to be treated as having some individuality of its own.
(1) Alpine Zone: This zone contains only two major vegetation types, a *Rhacomitrium* moss desert [map symbol r(R)] and a *Vaccinium-Styphelia* lowscrub desert [symbol r(ns)]. This sparsely vegetated area, which extends from the summit of Mauna Loa to 8500 feet (2590 m) altitude has a dry, cool climate. The peculiarity of this area is that ground frost occurs nightly throughout the year. This night-frost climate limits development and activity of many biota. Even horse droppings on trails remain undecomposed for years, it seems.

(2) Subalpine Zone: Three major vegetation types were mapped in this zone: an open to closed globose scrub (without trees) [symbol ns; the shrubs *Vaccinium plecanum*, *Styphelia douglasii* and *Dodonaea viscosa* form clusters of dominants], a globose scrub with scattered *Metrosideros* trees [symbol ns(M), the treeline ecosystem], and an open *Metrosideros* scrub-forest with scattered *Sophora* trees [symbol oM(So...ns)]. This zone extends in the Park from 8,500 down to 6,700 feet (2590-2042 m) altitude.

The most interesting vegetation type here is perhaps the treeline ecosystem, which experiences night frosts at least through the winter months of the year. Here also we find the upper limit and well-established habitat of the Nene (Hawaiian goose) and an environment favorable for growth of the silversword (*Argyroxyphium* sp.). The climate is summer-dry with about 1000 mm annual rainfall and cool with 9.5° to 12°C mean air temperatures. Daily temperature ranges are pronounced and may be 10° to 12°C. The substrate is mostly lava rock outcrop of both pahoehoe and a'a with little soil overlay. This results in the sparseness of grasses. The subalpine zone thus appears less of a fire hazard zone. Also, pigs are largely absent because of the lack of soil for grubbing. In contrast, goats have been seen to browse in this zone.

(3) Montane Seasonal Zone: This zone is characterized by frequent clouds near ground. It has also a summer-dry climate but with more rainfall (from 1100-1600 mm/yr) and warmer mean air temperatures (of 12°-17°C). Five major vegetation types were recognized and mapped in this zone. The three more important ones are: the mountain parkland [symbol mx-ns(ACSoM)] the savannah [symbol mx-AcSaM] and the forested Kipukas [symbol AcSaM(ad)]. The other two types are *Metrosideros* communities on more recent lava flows and or ash deposits [symbols oM(ns-L) and scM(ns)].

The zone extends from the upper limit of the mountain parkland (from the Mauna Loa Rainshelter) at 6700 feet (2042 m) to 3800 feet (1160) around and south of Volcano Observatory. The two grassland vegetations (parkland and savannah) had periodic fires in the past (Mueller-Dombois
and Lamoureux 1967). A few native grasses are present (Eragrostis grandis, Panicum tenuifolium, Deschampsia australis and Trisetum glomeratum). Acacia koa sprouts vegetatively from root suckers. Fire in these habitats, if not too frequent and extensive, does not seem to form a serious threat to the integrity of these communities. Activity of introduced ungulates is high in this zone. It is a favored environment for cattle grazing outside the Park, and an area where feral goats and pigs overlap in the Park. After the more effective goat control now, feral pigs are still a major cause of damage (Spatz and Mueller-Dombois 1975).

(4) Montane Rain Forest Zone: Six major forest types are mapped for this zone. Four of them have Metrosideros collina ('ōhi'a) as the sole dominant tree, one is a tree fern (Cibotium spp.) forest and the other a mixed koa-'ōhi'a rain forest. The four pure 'ōhi'a forest types are differentiated by structure (open vs. closed) and by the differing dominance of undergrowing ferns (Dicranopteris vs. Cibotium).

The climate is humid throughout the year (i.e. 100 mm monthly rainfall or more). A short dry season in June may occur as a normal event, however, for example, around the Park Headquarters area. Mean annual rainfall is generally above 2000 mm, and in the Park may go up to 4000 mm ('Ola'a Tract).

The major perturbations in this zone are the feral pigs and the 'ōhi'a dieback phenomenon. Both of these merit attention by Park Management as they may threaten the integrity by precipitating the invasion of exotics and destruction of endangered endemic species. Fire has never been a problem here, neither have feral goats.

The substrates in this zone vary from lava rock outcrop to deep ash. Most of the destructive pig activity is restricted to the rain forest types with ash substrates.

(5) Submontane Seasonal Zone: This includes a large area in the Park from south of Hālema'uma'u and south of the Chain-of-Craters Road, including 'Aina-hou Ranch and Nā'ālū Forest downslope to the palis (Hōlei and Hilina Pali). Six major vegetation types were mapped in this zone. These are the broomsedge (Andropogon) savannah above Hilina Pali [symbol An(ns-M) and An(ns-i)], a large area covered with an open 'ōhi'a-broomsedge (Metrosideros-Andropogon)-native shrub forest [symbol oM(ns-An)], a native closed shrub vegetation with scattered 'ōhi'a trees [symbol ns(i-An-M)] (which occurs mostly east of the 'Aina-hou Ranch in an area now poorly accessible because of lava flows), and an open and a very open 'ōhi'a-łama (Metrosideros-Diospyros) forest [symbol MD(ns-i-An-r) and MD(r), respectively] mostly along the major palis on 'a'a rubble.
The sixth important vegetation type in this zone is the Ka'ū Desert with extremely sparse xerophytic vegetation (symbol r-ash(poik)). Apart from its substrate peculiarity (shifting ash dunes) and its sulfur steaming influence from Halema'uma'u Crater, the Ka'ū Desert also is influenced by a more severe dry season (i.e., drought) in the summer and thus can be recognized as a separate subzone of the submontane seasonal zone. Also with regard to management considerations it may be a separate entity. Fire in the other vegetation types of the submontane seasonal zone is a real threat, both from the viewpoint of easily combustible material (particularly the presence of broomsedge) and the destructiveness to endemic species. *Metrosideros* (in contrast to koa) does not resprout well after fires and none of the native shrubs in these vegetation (except perhaps *Dodonaea viscosa*) appear to be fire adapted. Fire apparently has never been an evolutionary stress factor in this zone as it was in the montane seasonal zone. Fire has only become a real problem lately with the invasion of broomsedge. Thus, fire prevention techniques will need to be perfected particularly for this major ecosystem of the Park.

(6) Coastal-Lowland Zone: This Park ecosystem is defined as the area below approximately 1000 feet (330 m) elevation extending along the coast from Kalapana to below Kū-ka-lau-ula Pali. Seven major vegetation types were mapped. Two were grasslands, an annual *Eragrostis tenella* (love grass) grassland and a perennial *Heteropogon contortus* (pili) grassland. One was a lowshrub savannah, i.e. *Heteropogon* grassland with low shrubs [symbol H(ls-i)] and three were predominantly woody vegetations, a widely scattered old *Metrosideros* tree vegetation without appreciable undergrowth mostly on old 'a'ā lava flows [symbol r(M)], a mixed (native and introduced species) lowland scrub [symbols ls(i) and ls(E-H), including the native *Canthium odoratum*, *Wikstroemia phillyreaefolia*, *Diospyros ferrea* and *Erythrina sandwicensis* and the exotic *Schinus terebinthifolius*, *Pluchea odorata*, *Psidium guajava* and *Eugenia cumini*] and an open mixed lowland forest of mostly exotic trees (*Mangifera indica*, *Samanea saman*, *Aleurites moluccana*, *Thespesia*, *Pandanus* and *Cocos*). The latter vegetation types occur near Kalapana and the change from woody vegetations to annual grassland from east to west along to the coast is related to a decreasing mean annual rainfall gradient from about 1700 mm to 700 mm (south of the Ka'ū Desert). The seventh major vegetation type mapped includes the salt spray and other strand communities found in a narrow (about 50 m wide belt) directly along the coast.

The coastal lowland zone has a warm-tropical climate (mean air temperature 23°C) with an increasingly severe summer-dry season from east to west and frequent, strong and desiccating winds.
This is the Park ecosystem that has suffered the strongest alteration under the feral goats that were very abundant for probably more than a century here up to 1972 (Mueller-Dombois and Spatz 1975). With the fencing and goat eradication program nearing completion the vegetation is undergoing considerable changes and should be remapped soon.

Two exotic, taller-growing woody plants (*Leucaena latisiliqua* and *Ricinus communis*), both with an enormous seed-producing potential, are now invading the chamaephyte stage in a few locations. If this process is not closely checked, this area will convert rapidly into an undesirable thicket with very low species diversity. At the present time, these two weed-tree species form only a few small colonies in the vast area of this coastal lowland.

As step 2 in the ecosystem restoration program of this formerly goat-infested territory, these two exotic tree-pests should be monitored for elimination at very frequent (preferably monthly) intervals. As step 3, a few strategically located seed source centers should be established by planting (in aggregation) native dry-zone tree species (such as *Canthium odoratum*, *Dispyros ferrea*, *Erythrina sandwicensis*). The seed source for these centers should be obtained from within an approximate three-mile limit of the formerly goat-infested territory.

Conclusions

In a recent article in the Journal "Parks," R. M. Linn (1976) (formerly NPS Chief Scientist) declared vegetation mapping and park zoning the basic tool for masterplanning in the U. S. National Parks.

Mapping can be done for different purposes. For masterplanning a map should in my opinion accomplish three major objectives. It should form a useful frame of reference for:

(1) **Research**: One of its functions here is to form a basis for sample stratification and for determining the spatial extent to which results from biological field studies can be extrapolated. Another, and perhaps even more important function of a vegetation map is to encourage research with more specific questions in mind. For example, the Mauna Loa Transect analysis of our IBP research was generated through this map.
(2) Management: Here it is particularly the more generalized level of ecological zones that appears useful when superimposed on a vegetation map. As I have tried to emphasize in the foregoing discussion, the different nature of each zone merits individual treatment and the establishment of different management objectives for each zone. On a functional level the zones can be recognized as the six major Park ecosystems, while the vegetation types may be regarded as forming important modifications in each ecosystem.

(3) Interpretation: My special concern in this paper was to convert the more abstract information presented in the vegetation map into a more concrete form for Park interpretation. This I did by emphasizing three tools for map interpretation: environmental data, profile diagrams, and ecological zoning. The latter was given particular emphasis as a tool for summarizing the mapped vegetation types and as a key to interpreting the nature and distribution of the major dynamic events occurring as periodic or erratic perturbations in the Park, i.e. fires, goats, pigs, frost, volcanic activity, 'ōhi'a dieback and encroachment of exotic plant species. These perturbations should further be interpreted for each ecosystem as to whether they represent long-standing evolutionary stress factors or are recent and therefore artificial stresses which form a threat to the integrity of the system in question.
Figure 1. Climate diagram map of the island of Hawaii with location of five ecosystem profiles in Hawaii Volcanoes National Park.
Figure 2. Profile 1: East flank of Mauna Loa in the Park.
Figure 3. Profile 2: South slope on Kilauea via Hilina Pali (segment 3) to the Pacific Ocean.
Literature Cited


