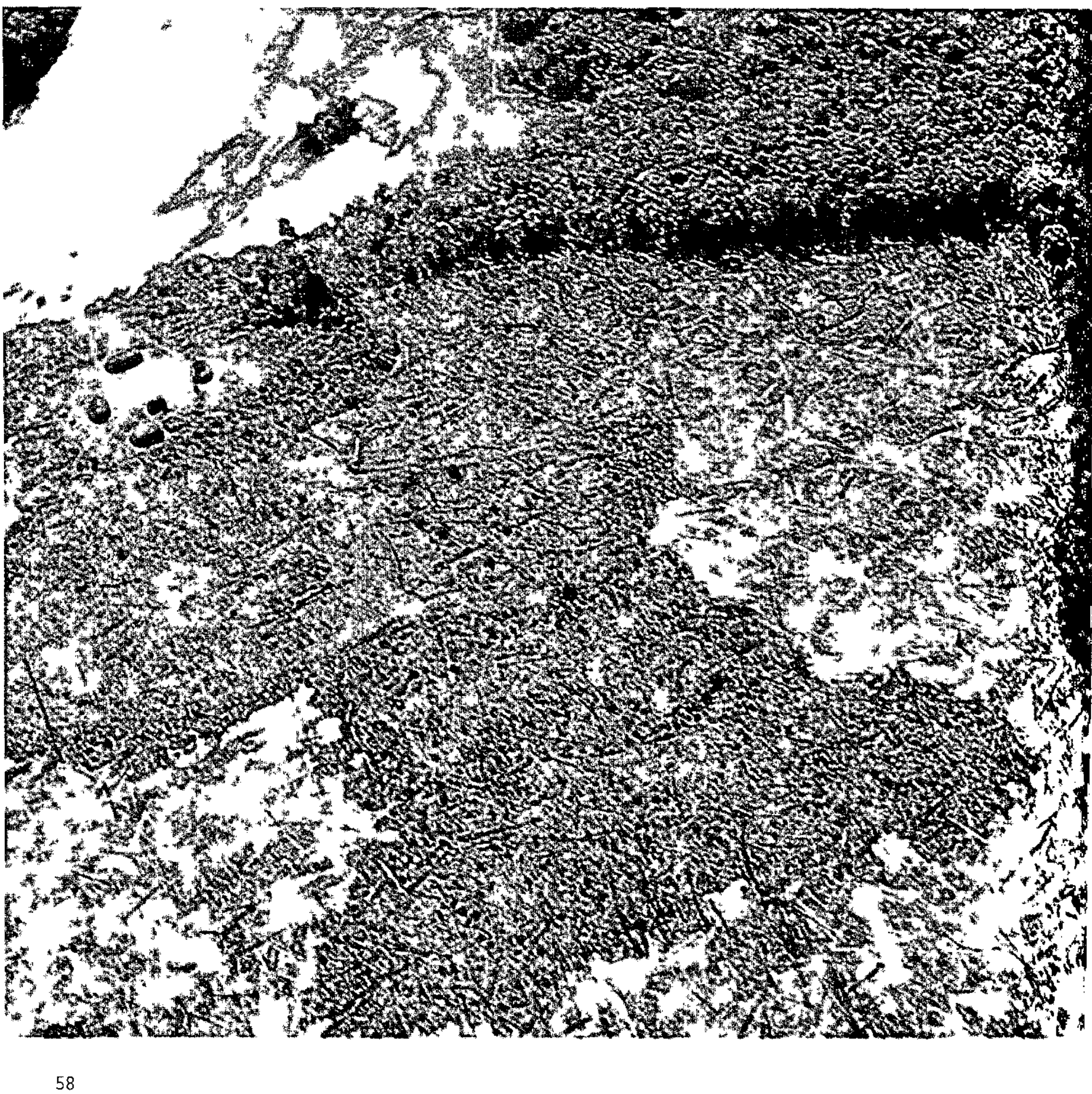
THE TROPICAL RAIN FOREST

One of the oldest ecosystems and a reservoir of genetic diversity, the wet evergreen tropical forest is threatened by the activities of man and may virtually disappear by the end of the 20th century

by Paul W. Richards



If it had been possible to photograph the earth from a satellite 150 or 200 years ago, one of the conspicuous features of the planet would have been a belt of green extending 10 degrees or more north and south of the Equator. This green zone was the wet evergreen tropical forest, more commonly known as the tropical rain forest. Two centuries ago it stretched almost unbroken over the lowlands of the humid Tropics of Central and South America, Africa, Southeast Asia and the islands of Indonesia.

If such photographs had been made 1,000 or even several million years earlier, this part of the world would probably have looked much the same, because the tropical rain forest is one of the most ancient ecosystems. Fossil evidence in Malaysia and elsewhere suggests that it has existed continuously since the Cretaceous period, which ended more than 60 million years ago. It has shrunk in some periods and expanded in others, and the plants and animals of which it consists have changed in the course of evolution, but even in the remote past its general appearance and characteristics may well have been much as they are now.

Today, however, the rain forest, like most other natural ecosystems, is rapidly changing. Satellite photographs made recently show that it is no longer a continuous belt but is fragmented and much reduced in area. In the past two decades huge expanses have been felled for timber or replaced by plantations of oil palms, bananas, rubber, cocoa and other crops. Still larger areas have been cleared for "slash and burn" farming, a system of agriculture that demands a perpetual supply of uncultivated land. Sizable areas of rain forest still stand in Amazonia, Africa, Borneo and New Guinea, but even in these regions, as everywhere else, the rain forest is retreating. It is likely that by the end of this century very little will remain.

The destruction in modern times of a forest that is millions of years old is a major event in the earth's history. It is larger in scale than the clearing of the forests of temperate Eurasia and America, and it will be accomplished in a much shorter time.

Should the destruction of the tropical rain forests be noted as merely another landmark in man's conquest of nature? Or could some of its consequences be unwelcome or even dangerous? I shall consider here what these consequences are likely to be, both for man and for the biosphere as a whole. First, however, it is necessary to describe some of the characteristics of the rain forest, the ways in which it resembles other ecosystems and the ways in which it differs from them.

The Rain Forest Ecosystem

The tropical rain forest has been described frequently, although not always correctly, in travel books and magazine articles. The features most often mentioned are the monotonous green of the foliage; the scarcity of large, brightly colored flowers; the vines and epiphytes in the forest canopy; the tall, straight, disproportionately slender tree trunks, often buttressed at the base; the apparent scarcity of animal life except for occasional birds and the omnipresent ants, termites and other insects. Often misrepresented is the density of the undergrowth; actually the vegetation near the ground is not very dense or difficult to penetrate, except where the forest has been disturbed and at the edges of rivers and roads where light is admitted below the canopy. It is also often stated that the forest floor is littered with dead leaves and "rotting vegetation"; actually, because of the high temperature and humidity, decomposition is rapid and there is less dead organic material on and in the soil than there is in a temperate forest.

The tropical rain forest is the most complex ecosystem on the earth. It can nevertheless be described in the same way as other self-supporting ecosystems: as an association of producing, consuming and decomposing organisms, all ultimately deriving their energy from sunlight. The producers are the trees and other green plants; the consumers are the animals, some of which (the carnivores) prey on other animals; the third class of organisms, the decomposers, consists of bacteria, fungi and certain small animals such as termites, worms and mites, which break down dead organic material so that the carbon, nitrogen and minerals it contains can be recycled.

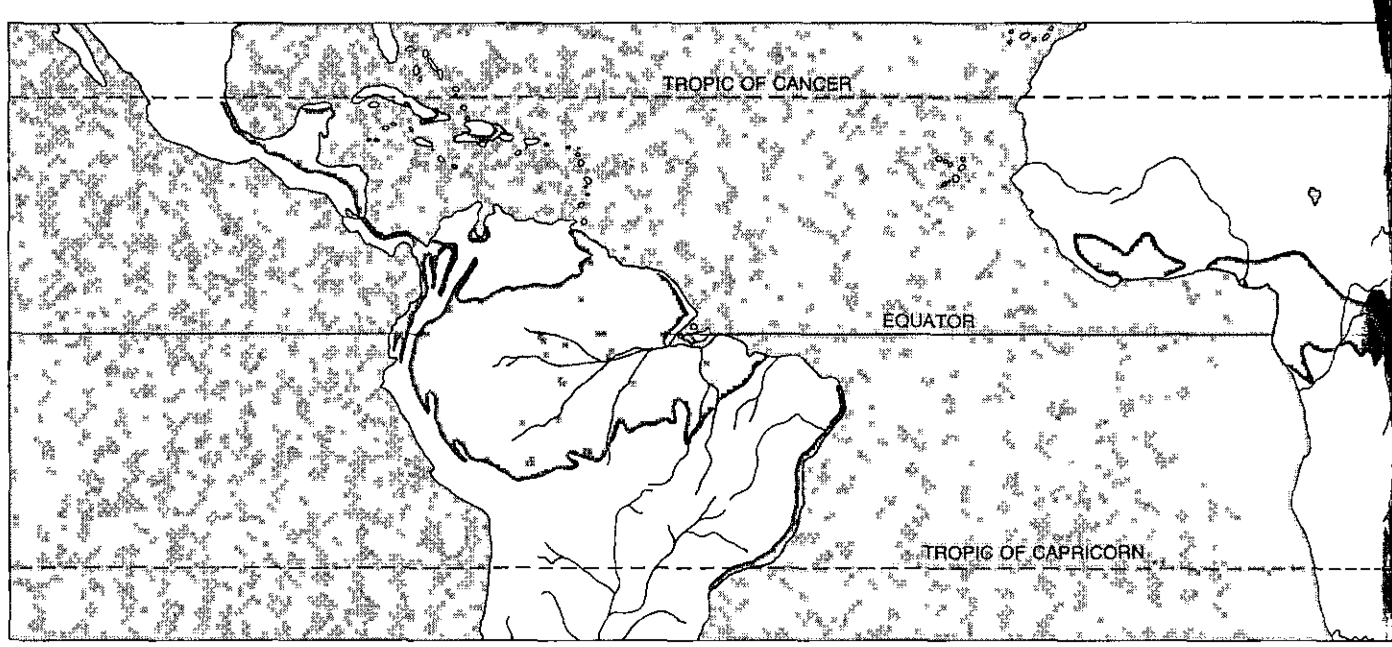
The most important of the producers are woody plants ranging in size from giant trees to miniature "treelets" no larger than shrubs but like trees in form. Also in this group are the woody-stemmed vines. In size the trees of the rain forest do not rival the redwoods or the Australian eucalypts, but the largest of them commonly grow to more than 150 feet, and sometimes (in Malaysia and occasionally in West Africa) they exceed 200 feet. The total leaf area of the trees, and hence the amount of chlorophyll available for photosynthesis, is roughly proportional to their height. Large trees are much less numerous than smaller ones, but no precise relation between the height of the trees and their numbers has been found.

The crowns and foliage of the rain forest trees form several strata, or stories [*see illustration on page 62*]. The stratification cannot be readily observed from the ground, and it is rarely well defined. In fact, it is often claimed that this structure does not actually exist, that it is imposed on the forest by the observer. Whether or not this is so, the presence of trees of many different heights subdivides the living space for animals and smaller plants. In the three or four horizontal layers that can be distinguished environmental conditions vary widely.

A major division is between the canopy, which is exposed to almost full sunlight, and the undergrowth, which is much less brightly illuminated, although flecks of sunlight penetrate even to the ground. The leaves, twigs and branches of the trees are barriers to the movement of air, to heat and to other forms of radiation as well as to visible light; there is therefore a strong contrast between the microclimate of the canopy and that of the strata closer to the ground, with intermediate microclimates at middle levels. In the canopy there is more air movement and a greater range of temperature and atmospheric humidity than there is in the undergrowth, which is one of the most constant of terrestrial environments. Insulated by the canopy from the effects of diurnal change, the forest floor rivals a cave or a laboratory growth room in uniformity of conditions.

The great vertical range of environ-

SLASH-AND-BURN FARMING, the prevailing system of subsistence agriculture in the humid Tropics, requires that tracts of rain forest be periodically cut down. In this aerial photograph of an Indian village near the Xingu River in Brazil, the bright area is recently burned forest (the gray material is wood ash); the central area was cut and burned a year or two earlier and bears a crop of manioc. The huts of the village are near the riverbank left of center. Two or three crops can be produced on the land before the nutrients of the soil are exhausted. The field will then lie fallow and a new section of forest will be cleared.



EXTENSIVE AREAS OF RAIN FOREST survive in three regions: the Amazon River basin in South America, the Congo River basin in equatorial Africa and the Malay Archipelago in Southeast Asia. Smaller forests are found in Central America, along the coast

ments in the rain forest is of fundamental importance to the organisms of which it is composed. Conditions for photosynthesis, transpiration and other plant functions in the crown of a large tree are quite unlike those for a treelet living in the shaded undergrowth. A large tree, during its development from seedling to maturity, must adapt successively to the entire range of light and other conditions.

For animals the variety of environments is equally important. In the various strata the available foods, the opportunities for concealment and the possible modes of locomotion are quite different. For example, animals living in the treetops can readily obtain large quantities of vegetable foods such as flowers, fruits and leaves but must have limbs adapted to climbing or running along branches and to swinging, jumping, gliding or flying from tree to tree. In contrast, the ground mammals (which include such large and ungainly creatures as the elephant and the rhinoceros) have little or no climbing ability and depend for food largely on fruits and other plant materials that drop from above, much as deep-sea animals depend on the rain of dead plankton that falls from the illuminated surface layers of the ocean.

For birds, reptiles and insects too, the opportunities for feeding and the other conditions of life are different in the various strata. Many of the butterflies, birds and frogs of the treetops rarely come down to ground level. The mosquitoes of the canopy are for the most part different from those of the undergrowth, and are normally limited to their upper-level habitat. The restriction of certain mosquito species to the treetops is of great importance to the epidemiology of malaria, yellow fever and other insect-borne diseases, which, it seems, did not develop on a catastrophic scale until tree-felling became extensive enough to bring the treetop mosquitoes into close contact with large human populations.

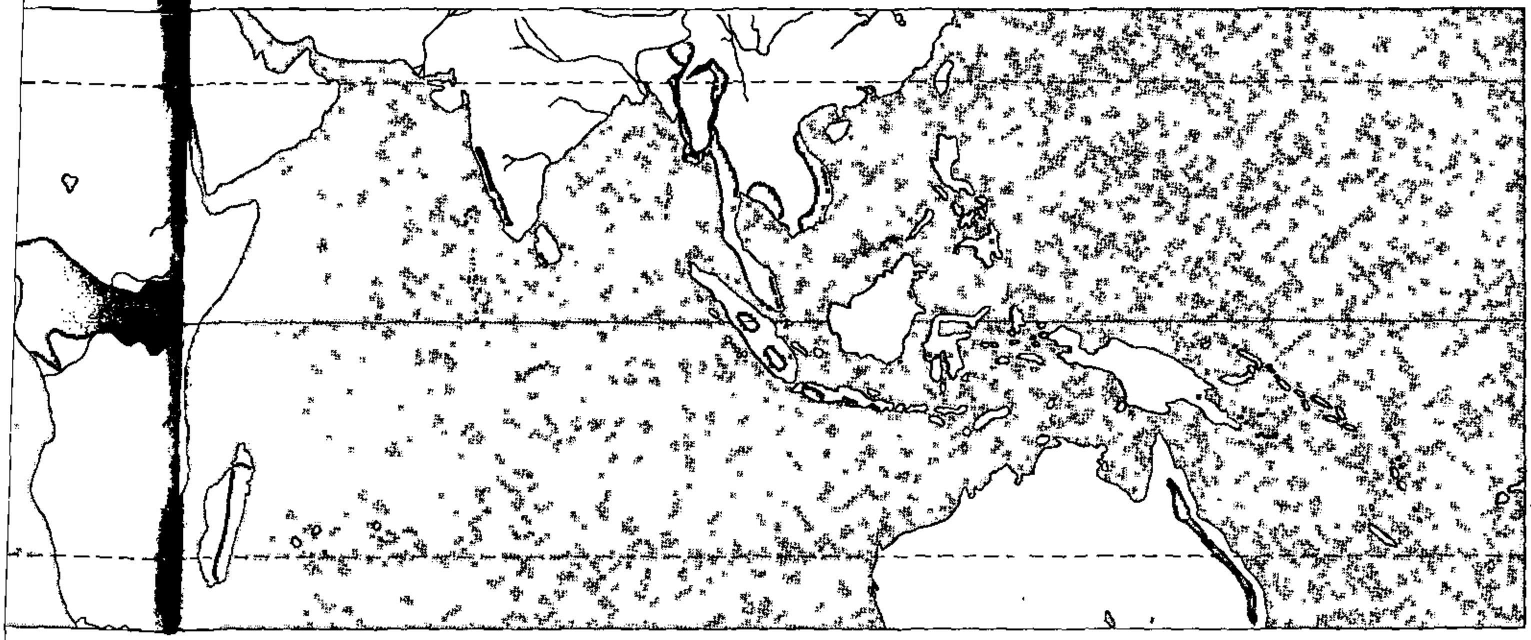
Species Richness

The most distinctive characteristic of the tropical rain forest is probably its great species richness; no other major ecological community has so many kinds of plants and animals. A two-hectare (about five-acre) sample of lowland rain forest often contains more than 100 species of trees a foot or more in diameter. In the richest areas, such as the (now almost vanished) lowland forest of the Malay Peninsula, more than 200 tree species have been recorded in a two-hectare plot. In a New England forest perhaps 10 species would be found in a comparable area, and even in the exceptionally species-rich "cove" forests of Tennessee and South Carolina there would be only about 25.

Large trees are of course only a part of the complement of plants. In the undergrowth there are (in addition to the smaller trees and treelets) herbaceous plants, including ferns; many vines, and often large numbers of orchids, bromeliads and other plants that grow epiphytically (nonparasitically) on the trunks and branches of trees. Less complex plants are also present, including mosses, liverworts, algae, fungi and lichens.

The composition of the animal population is more difficult to characterize because few groups of animals other than birds and mammals have been adequately studied and a vast number of species remain undescribed and unnamed. For those groups of animals that are well known, however, the number of species has been found to be very large. In Panama and Costa Rica, Edward O. Wilson and the late Robert H. MacArthur found that a 300-mile square of rain forest harbored from 500 to 600 resident species of birds, more than four times as many as are found in the broad-leaved temperate forests of eastern North America. Thomas W. Schoener and Daniel H. Janzen captured 500 species of insects in 2,000 sweeps of a net in the undergrowth of a Central American forest, and the number of insect species in the canopy and middle layers is certainly much higher. In the other animal groups too it is believed the number of species in the rain forest is large compared with the populations of other ecosystems.

Just as there is a great variety of plants and animals within a small sample area, there is diversity from hectare to hectare, from district to district and from continent to continent. The rain forests of the Old World and the New World are similar in general appearance and structure, yet they have almost no animal species and very few plant species in common. Entire groups of orga-



Southeast
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of the Gulf of Guinea in West Africa and in humid areas of India, Ceylon and Australia. In these latter regions much of the tropical rain forest has been cleared for agriculture, animal husbandry and habitation. Only isolated blocks and patches of forest remain.

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nisms common in one hemisphere are lacking or extremely rare in the other. For example, the hummingbirds of the Americas are absent in Asia and Africa, and the bromeliads, characteristic of the tropical forests of the New World, are represented in the Old by only one species. (Even this plant is rare and is found not in the forest but on rocky hills in one small region of West Africa.)

Within a particular forest it is common to find that some species are dispersed unevenly. MacArthur reported that patchy distributions that cannot easily be related to differences of climate or other environmental factors are apparently common among the ants and the birds of the rain forest. A comparable lack of uniformity has been found in the distribution of tree species in Borneo and parts of South America and probably exists elsewhere in the Tropics.

One result of the large number of species in the rain forest is that most species are widely scattered and have a very low population density. Alfred Russel Wallace wrote long ago (in *Tropical Nature*, 1878): "If the traveller notices a particular species [of tree] and wishes to find more like it, he may often turn his eyes in vain in every direction. Trees of varied forms, dimensions and colour are around him, but he rarely sees any one of them repeated. Time after time he goes towards a tree which looks like the one he seeks, but a closer examination proves it to be distinct. He may at length, perhaps, meet with a second specimen half a mile off, or may fail altogether, till on another occasion he stumbles on one by accident." In a sample plot of a few acres most tree species are usually represented by a single individual; only a very few species contribute large numbers of specimens to the population. Sparse distribution is also characteristic of many animal groups, although here there are important exceptions, notably among the social insects such as ants and termites, which live in nests that consist of enormous numbers of individuals.

This pattern of many species and few individuals is characteristic of tropical rain forests and to some extent of tropical biota generally. Several explanations for it have been proposed, but no one by itself seems sufficient.

One factor that is almost certainly important is the great age of the rain forest ecosystem. In the humid Tropics plant and animal species have evolved over an extremely long period. Although many have no doubt been eliminated by natural selection, many others have survived and thus the number of species has grown simply by accumulation. Another factor may be the constancy of the environment, the lack of seasonal changes. Because severe cold and drought are unknown, and because plant and animal reproduction can continue throughout the year, the various processes that contribute to speciation can proceed without interruption [*see illustration on page 66*].

The scattered distribution common to tropical trees may be imposed on them by the damage done by herbivores. The seeds, fruits and seedlings of tropical trees form the chief source of food for a horde of mammals, birds, insects and other animals, many of which seem to be "host specific," that is, they feed exclusively on a single tree species or on a small group of species. It is common for the entire seed crop of a large tree to be destroyed by these animals.

The pressure of herbivores is greatest close to the parent tree and the number of herbivores falls off roughly in proportion to distance. The number of seeds too decreases with distance from the parent tree, and Janzen has suggested that there must be an optimum distance at which the curve for the number of seeds available crosses that for the number of herbivores eating them. This distance will vary from species to species, but if the herbivores are host-specific, natural selection will always tend to produce diffuse rather than aggregated tree populations.

The relentless pressure of consumers of all kinds should favor the evolution of protective mechanisms in trees and other producer plants. In fact one of the most widespread and successful families of tropical trees, the Leguminosae, has seeds that often contain poisonous or intensely bitter substances that deter insect larvae and other animals. It is significant that in certain exceptional types of tropical rain forest in which a single species is dominant (as in the oak and beech forests of temperate climates) the dominant tree is usually a member of this family.

Recent research is showing that a number of features of rain forest vegetation that were previously difficult to understand can probably be interpreted as defenses against insects and other herbivores. Among these are the frequency of myrmecophytes, or "ant plants," in which colonies of ants occupy hollow stems or special organs, and the abundance in the leaves of plants of distasteful and toxic compounds such as alkaloids and polyphenols. The degree to which plants have succeeded in this competition is perhaps indicated by the surprisingly low total mass of animal life in the rain forest compared with the mass of vegetation. E. J. Fittkau and H. Klinge recently calculated that the mass of the living plants in a hectare of Amazon rain forest is more than 900 metric tons and that the animals in the same area weigh about .2 ton. Only about 7 percent of the animals (by weight) feed on living plant material such as leaves. About 19 percent eat living or dead wood, and about 50 percent feed mostly on litter and other decaying material. The low ratio of animal to plant life (when measured as weight) confirms a suspicion, derived from other observations, that there is a shortage of edible plants in the rain forest. For man too the rain forest is a poor place to live off the land. The scarcity of plant and animal food is the main reason that jungle peoples dependent on hunting have always had very low population densities.

Scarcity of Nutrients

It is one of the paradoxes of tropical ecology that however luxuriant rain forest vegetation may appear its presence is not an indication of great fertility in the soil. This is a fact of which politicians eager to "develop" the humid Tropics are insufficiently aware. The rain forest exists on a very small nutrient budget, and it survives only by maintaining an almost closed nutrient cycle. When the land is cleared and converted to agricultural use, the results are usually disappointing; profitable yields can be maintained only by heavy application of fertilizer (which often proves uneconomical). What fertility the land possesses often vanishes rapidly after the first harvest.

Native cultivators have learned to cope with the limitations of the soil by the seemingly inefficient system of slash-and-burn, shifting, or "swidden" agriculture. They fell the forest, burn the trees and gather a few harvests. Often after only two or three crops the land is left

VERTICAL STRUCTURE of the rain forest divides it into several stories or strata, each of which has a different microclimate. The diagram above is drawn from measurements of the size and position of trees in a strip of forest 25 feet wide in West Africa. The topmost stratum consists of very tall trees whose crowns are fully exposed to sunlight; neighboring crowns are not usually in contact, so that the trees do not form a continuous canopy. Below this stratum is a layer of trees with narrower crowns, more closely packed than those of the first story and often bound together by lianas growing from tree to tree. Still lower is a dense stratum of small trees, seldom more than 10 meters high, and, below this, the undergrowth of treelets, saplings and herbaceous plants. Near the ground there is less air movement and more sunlight, temperature is lower, humidity is higher and all conditions tend to be more constant than they are in the treetops or in a clearing. Because of these differences of environment each story of the forest has its own assemblage of insects and other animals. The stratification of the forest is not always distinct, and it varies from place to place.

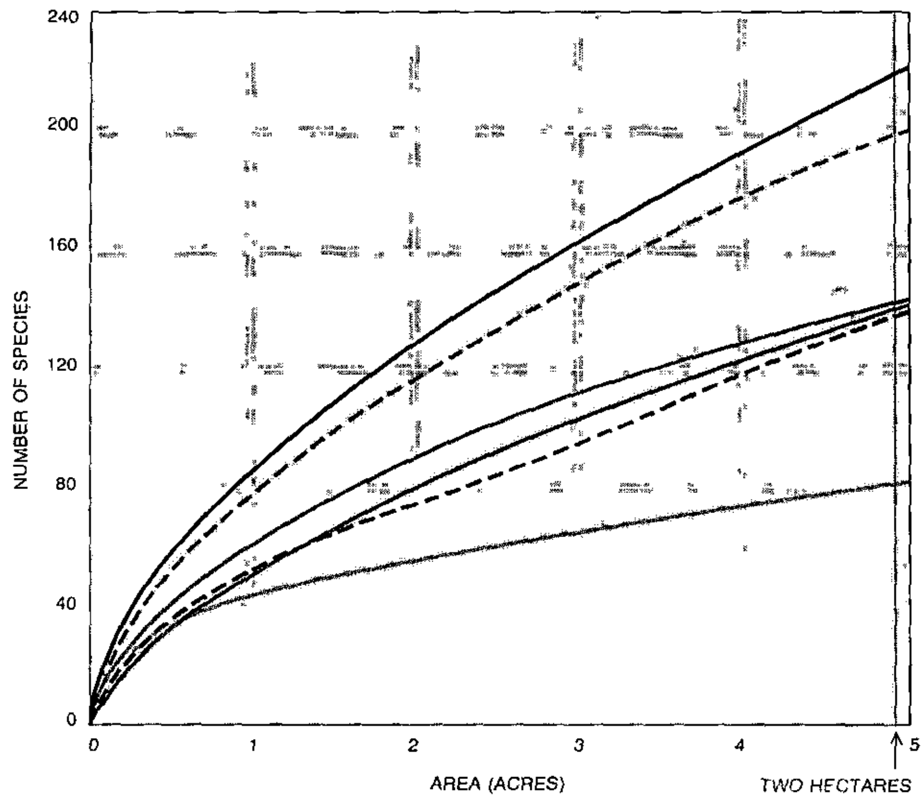
fallow and a new patch of forest is cleared as a "field." Where land is plentiful and the pressure of population is not great a fresh plot is cleared every year. If old fields are reused, it is not until they have lain fallow long enough for the fertility to have been at least partially restored.

For native farmers under existing economic conditions, cultivation systems that incorporate a long period of "forest fallow" are the only ones practicable for the growing of food crops. The most successful permanent crops in the Tropics are those, such as rubber and cocoa, that make relatively small demands on the soil because the amount of nutrients removed from the ecosystem in harvesting is not large.

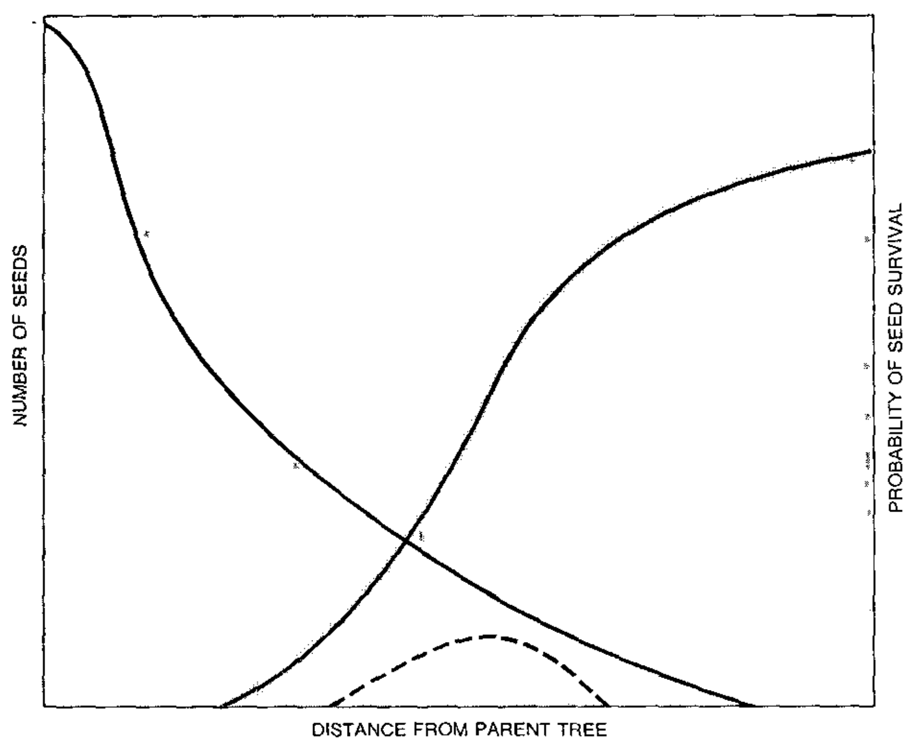
The factors that ordinarily limit growth in the temperate region—low temperatures, lack of water and a short growing season—are of little importance in the humid Tropics. Except on alluvial land and in areas where the soil is frequently enriched by volcanic dust, however, the stock of available mineral nutrients is quite small. The rain forest is able to flourish under these conditions because a large fraction of the available nitrogen, calcium, phosphorus, potassium and other minerals is held in the vegetation itself. The nutrients contained in dead wood and leaves and in the excretions and dead bodies of animals are quickly released by the activities of the decomposer organisms. Once the dead material has been broken down the minerals do not remain in the soil but are almost immediately taken up by the roots of the trees and other plants. Thus, although the total stock of nutrients is not large, recycling is rapid. It is also efficient; very little is lost from the system.

The roots of tropical trees are generally shallow; most are within the top three or four feet of soil and the greatest concentration of fine roots (which are the most active in the absorption of nutrients) are found in or just below the thin layer of litter at the soil surface. Fungal hyphae branch everywhere in the litter and surface soil and are in intimate contact with both the decomposing organic matter and the active plant roots. The fungi play an essential role in the process of decay. According to Frits W. Went and Nellie M. Stark, they carry the nutrients "door to door" from the decomposing material to the living root, so that almost nothing escapes.

Even if the mineral-transport system were slightly less efficient and small quantities of nutrients were carried away in drainage water, the losses could



SPECIES RICHNESS of the rain forest is indicated by counts of tree species at six sites in the trust territory of Brunei on the island of Borneo. The data were collected by P. S. Ashton and include all trees exceeding 12 inches in girth. The solid black line represents the species found in a valley bottom in the Andulau Forest Reserve; 220 species were recorded in the five-acre plot. The other graphs are for a ridge at Andulau (*broken colored line*), a forest near the town of Badas (*gray line*) and three plots in the Belalong forest: a lower hillside (*dark colored line*), a ridge 550 meters high (*broken black line*) and a ridge 700 meters high (*light colored line*). A sample of temperate forest might contain 10 species.



SPARSE DISTRIBUTION of most rain forest trees may be a result of the destruction of seeds and seedlings by herbivores. The number of seeds decreases with distance from the parent tree. Because herbivores are also concentrated near the parent, however, the chances of a seedling's surviving increase with distance, so that a new tree is most likely to grow where the two curves intersect. The product of the curves is shown as a broken line.

be compensated for by the decomposition of rock, although in the Tropics the weathering of rock usually occurs at a considerable depth below the soil surface, so that the products are often not readily available to the plants. Nutrients are added by rainwater in relatively large quantities, however. Near Manaus in the center of the Amazon basin Edmund Altherr has recently found that a year's rainfall contains an average of about .3 kilogram of phosphorus per hectare, two kilograms of iron, 10 kilograms of nitrogen (in the form of ammonia and nitrates) and 3.6 kilograms of calcium per hectare.

The great efficiency of the forest mineral cycle is indicated by the low concentration of mineral ions in the waters of the Amazon and other rivers that drain rain forest areas. Near Manaus the litter falling to the forest floor contains about 18.4 kilograms of calcium per hectare, yet in the streams of the same area the concentration of calcium is too small to be detected.

The modest nutrient budget of the rain forest is mainly a consequence of heavy precipitation. The annual rainfall is seldom less than 80 inches and in some areas, such as the Chocó of Colombia, it is more than 300 inches. The rain constantly leaches nutrients from the soil, removing all soluble materials. In its long history the rain forest has adapted to these conditions by evolving mechanisms that provide a rapid and almost leak-free mineral cycle.

Some special types of rain forest are able to survive on an even more restricted supply of nutrients. In the Río Negro region of Amazonia, in the Guianas, in parts of Borneo and elsewhere extensive forests grow on podzolic sand, an extremely infertile soil that is white because even the iron oxides have been leached out. ("Podzol" is derived from the Russian *zola,* ashes.) Yet on these nutrient-poor acidic soils there are dense forests of trees growing to a height of more than 100 feet. Such vegetation probably receives almost no nutrients from the weathering of the soil. Apart from the activities of microorganisms that fix atmospheric nitrogen, the only input is from rainfall.

Where the shortage of nutrients is so severe that the replacement of leaves destroyed by animals represents a burden on the organism, adaptations that appear to be defense mechanisms against herbivores are common. Many of these plants produce large quantities of tannins and other phenolic compounds. In the "white-sand forests" of Borneo some plants even eke out their meager ration of nitrogen and phosphorus by preying on animal life. In these forests the insect-eating pitcher plants (*Nepenthes*) are common. The tropical podzols are useless even for shifting agriculture; the Dayak peoples of Borneo call them *kerangas:* "land on which one cannot grow rice."

The rain forest is well adapted to existence in a hot, humid, unvarying environment and to growing in relatively infertile soils. Frost and drought are rare, and the ability to endure such hazards is less important to survival than success in the competition between species and between individuals.

As in all ecosystems relations of dependence between organisms are important. Alfred North Whitehead wrote in *Science and the Modern World* that "a forest is the triumph of the organization of mutually dependent species." This is true of any forest, but it applies most forcibly to the tropical rain forest, where the number of species is large and where many strange and subtle interrelations are found.

One expression of the rain forest's degree of organization and integration consists of homeostatic mechanisms that repel invaders and maintain the stability of the system. Weeds and other nonnative organisms are almost never found in the rain forest except in man-made clearings and along paths. Epidemics of fungal diseases, plagues of caterpillars and other pest infestations, which are a menace to most tropical crops, do not seem to occur in the undisturbed forest. (One apparent exception is a curious caterpillar, or *ulat bulu,* plague in the swamp forests of Borneo, which has

SECONDARY SUCCESSION, the process that leads from cleared land to a stable, or climax, community, is illustrated schematically. The first invaders are weeds, tall grasses, vines and seedling trees. All these form a dense ground cover but the trees soon begin to overtop the other vegetation. The first trees are species that colonize clearings quickly because their seeds are dispersed more efficiently than those of the permanent forest trees. They thrive in full sunlight and are intolerant of shade. Most of them reach maturity

killed off trees in patches of a few acres. The forest affected is not a typical rain forest, however, but a specialized type dominated by a single tree species.)

Substitute Forests

In its natural condition the rain forest is clearly a very stable system; through natural selection it has acquired the ability to survive all the risks it has encountered in its history of many millions of years. It could not have acquired resistance to risks it has never experienced, however, such as those that have arisen in the past two centuries. These modern hazards result from the impact of civilized man. He has entered the forest in numbers and at a technical and cultural level far higher than those of the small groups of hunters and food-gatherers who previously were the only human inhabitants. Confronted by modern man, with his armory of power saws, bulldozers and herbicides, the rain forest is for the first time retreating and is in danger of disappearing altogether.

To say that the rain forest is retreating, or that it may eventually vanish, does not mean that bare ground will be left in its place. Because of the infertility of the soil, however, it is unlikely that more than a small part of the former forest area will ever become permanently productive farmland.

A clearing in a tropical forest, unless kept under continuous cultivation, soon becomes covered with a dense mass of weeds, shrubs, vines and young trees. Even many of the most heavily defoliated forest areas of Vietnam have sprouted green, seemingly healthy, vegetation. The tangle that springs up where the forest has been felled is the first stage in the growth of a "substitute forest." In more formal terms it is an early stage in the development of a "secondary forest," which will replace the cleared "primary forest."

The growth of a secondary forest can be most readily studied on the sites of native shifting agriculture. When a field has been exhausted and is left fallow, it becomes covered with vegetation, growing partly from seeds carried by the wind, by birds or by other animals, partly from seeds that have lain dormant in the soil and partly from roots that were not killed when the field was cleared for cultivation.

The first phase of the succession is dominated by weeds, including grasses, herbaceous dicotyledons, vines and shrubs, that grow to a height of from five to 10 feet. Trees soon take over and in a short time become quite tall; after about three years they produce enough shade to suppress many of the light-demanding plants of the first phase. These trees differ in several ways from those that dominate the primary forest. They are soft-wooded, fast-growing and short-lived; probably they seldom reach an age of 20 years, whereas the trees of the primary forest have a life-span of several hundred years.

Most trees of the secondary forest have light seeds easily carried by the wind, or edible fruits attractive to birds or fruit bats. They are thus "opportunists," able to colonize gaps and clearings quickly. The seeds and fruits of primary forest trees are usually much heavier, have less efficient dispersal mechanisms and therefore have a smaller dispersal range. Most of the smaller plants and probably many of the animals are also different in the secondary forest.

When the first generation of secondary forest trees reaches the end of its life, another group, still different from those of the primary forest, takes its place. These are somewhat slower-growing and more long-lived than the pioneers. Successional changes continue, but at a lower rate, until eventually a climax community is established, similar to the forest that originally occupied the site. The time from the clearing of the field to the reestablishment of the primary forest is probably measured in centuries, but the period required is not accurately known because long-term records of tropical successions have not been kept and because the absence of annual growth rings makes it difficult to determine the age of rain forest trees.

Such a progressive succession, leading

and die in 15 to 20 years; often only a single generation grows because the trees are unable to regenerate in their own shade. Growing below the pioneer trees, and eventually replacing them, are more long-lived and more varied species (*color*), which establish a community that in time begins to resemble the primary forest. A disproportionate number of light-demanding trees remain for many years, however; these are replaced only very slowly by trees more tolerant of shade. The succession may take centuries to complete.

to the restoration of the climax forest, is possible only if enough primary forest remains to restock the cleared areas. One reason for disquiet about the clearing of the forests of Indonesia, Brazil and other regions is that almost no refuge for the flora and fauna of the primary forest may be left.

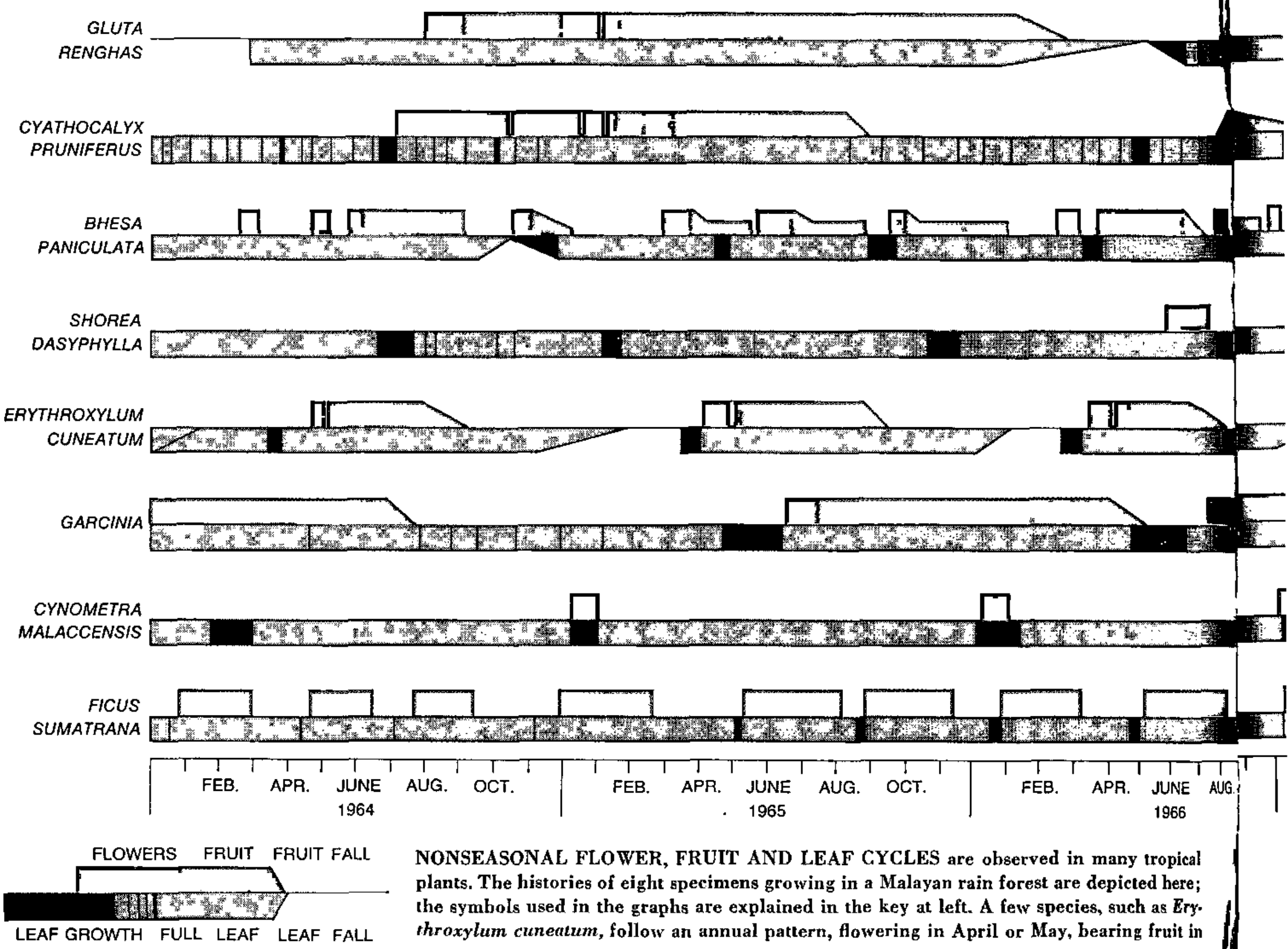
For a progressive succession it is also necessary that the secondary forest be allowed to develop undisturbed. Unfortunately with increasing population such land is often used as a source of firewood and timber and after a few years may be cleared again for cultivation. When that is done, the soil becomes increasingly impoverished and eventually becomes incapable of supporting even a secondary forest. It is then given over to savannas of coarse, nonnutritious grasses, bamboo thickets and stands of bracken and other ferns. Such vegetation tends to become inflammable in dry weather and is regularly burned, so that the reestablishment of the forest is indefinitely postponed.

It appears likely that all the world's tropical rain forests, with the exception of a few small, conserved relics, will be destroyed in the next 20 to 30 years. This destruction will inevitably have important consequences for life on the earth, although the nature and magnitude of these consequences cannot be foreseen with precision.

One effect that is certain, and probably already irreversible, is that man's impact on the tropical forest will permanently alter the course of plant and animal evolution. Biologists are generally agreed that much of the existing flora and fauna of the world, perhaps including man himself, originated in the humid Tropics. The rain forest has for millions of years served as a factory and storehouse of evolutionary diversity from which plants and animals able to adapt to more rigorous environments have migrated to populate the subtropical, temperate and colder regions. This role the tropical rain forest can play no longer; the destruction of forests and other ecosystems has already cut the lines of communication and made these migrations impossible. Even if the present, very reduced areas of rain forest were to be conserved, they could hardly play the same role as the much more extensive forest did earlier. Man has diverted the process of evolution permanently.

It is sometimes asserted that the clearance of large areas of tropical rain forest has had, or will have, important effects on the global environment, outside as well as in the Tropics. Although the existing data are not adequate to measure or predict such effects, it seems unlikely that they will be as important as is sometimes suggested.

For example, it has been claimed that the destruction of the Amazon forest might have a large effect on the world's supply of oxygen. Forest trees, like other green plants, absorb carbon dioxide and during daylight release large quantities of oxygen. Calculations based on measurements of the rate of organic production in forests indicate that the amount of oxygen produced by all the world's forests, tropical and temperate, is about $55,490 \times 10^6$ metric tons per year, or an average of about 16.9 tons per hectare. The contribution of the tropical rain forests is estimated to be about $15,300 \times 10^6$ tons, or 28 tons per hectare per year. These numbers seem very large, but actually they represent only a small frac-



NONSEASONAL FLOWER, FRUIT AND LEAF CYCLES are observed in many tropical plants. The histories of eight specimens growing in a Malayan rain forest are depicted here; the symbols used in the graphs are explained in the key at left. A few species, such as *Erythroxylum cuneatum*, follow an annual pattern, flowering in April or May, bearing fruit in tion of the oxygen in the earth's atmosphere. The oxygen produced by forests probably does not account for more than that consumed by the small organisms that decompose dead organic matter.

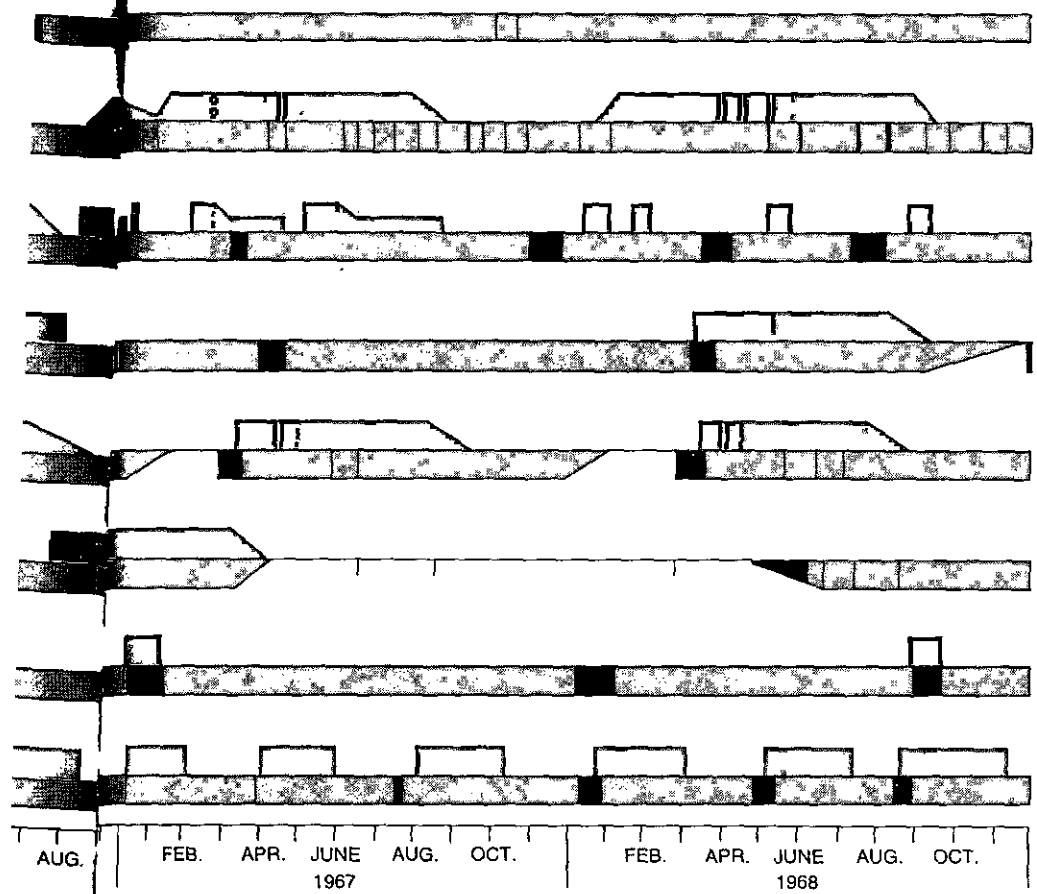
Possible effects on climate have also been mentioned. Forests obviously modify environmental conditions near the surface on which they are growing. Under a stand of trees the soil temperature is more constant, and in hot climates it is lower, than in the air above the trees. In a tropical rain forest the temperature of the soil surface is typically about 26 degrees Celsius, with a variation during the year of less than two degrees. At a depth of 60 centimeters the temperature hardly varies at all. On bare soil or under other types of plant covering, such as grassland, temperatures are higher and the fluctuations are much larger.

Forests also affect the water regime by regulating the runoff of excess rainfall and by maintaining layers of humid air near the ground. To what extent forests affect the amount of rain falling over any large area, however, is a matter on which climatologists are not agreed.

It is thus uncertain whether or not the removal of all the world's rain forests would have any significant consequences for the global climate, even if they were replaced by bare rock and soil. As we have seen, the primary forests will probably be replaced by systems of impermanent cultivation, by artificial forests of much simpler ecological structure, and by secondary forests, scrub and savanna. This vegetation will also contribute oxygen to the atmosphere and will modify the microclimates at and near the surface, although the effects produced may be somewhat smaller than those produced by the original forest.

Consequences of Destruction

The real causes for concern are quite different. The tropical rain forest is a unique and rich community of plant and animal species that includes many of the most beautiful and bizarre forms of life. Only here are found such insects as the brilliant blue morpho butterfly of tropical America, countless striking and lovely birds, mammals such as the orangutan, the sloths and the scaly anteater, as well as magnificent orchids and trees.



July and August and dropping the fruit later in the year. In others the cycle is regular but apparently not annual (e.g., *Ficus sumatrana*). In some cases no pattern is discernible (e.g., *Bhesa paniculata, Shorea dasyphylla*). Many of these cycles, although not following an annual rhythm, seem to be determined by climatic factors such as droughts and rainy periods.

Tropical biota are so diverse and abundant, and they have received such limited scientific attention, that even among those species that have been named and described we know virtually nothing about the biological characteristics of a large majority. Much of the plant and animal life of the Tropics may thus become extinct before we have even begun to explore it. If we believe that all living creatures should be a source of wonder, enjoyment and instruction to man, a vast realm of potential human experience may disappear before there is even a bare record of its existence.

The tropical rain forest can be regarded as one of the world's great outdoor laboratories. Not only does it contain enormous wealth and variety of organisms, but also in its long history intricate and subtle relations have developed between organism and organism and between the organisms and the physical environment. In the past the tropical forest has been an important source of knowledge about nature and the human environment; Charles Darwin, Alfred Russel Wallace, Henry Walter Bates and Alexander von Humboldt are only four of many great investigators whose contributions to science depended largely on their experience of the rain forest. Today the rain forests of Costa Rica, Brazil, Panama, New Guinea and West and Central Africa are contributing much of fundamental importance to biology; if it were not for frustrating political and financial obstacles, they could contribute much more.

There is good reason to believe the tropical rain forest could yield at least as much knowledge in the future as it has in the past. If it is to do so, however, nature reserves, national parks and other conservation areas must be provided on a much more generous scale than they have been up to now.

It is generally agreed that ancient buildings and other monuments of the human past should be preserved; the efforts made to save them are often a source of national pride. Although the cost of preservation is sometimes high, it is considered to be justified by the insight such monuments give into the life and thought of past civilizations. The tropical rain forest is also a monument, far older than the human species. It offers insight into the complex principles of ecological balance and into the processes at the heart of evolution. It will be sad if we cannot provide the comparatively small amount of effort and money required to safeguard at least a few samples for the instruction and wonder of future generations.