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AN ASSESSMENT OF ECOLOGICAL CONSEQUENCES OF THE DEFOLIATION PROGRAM IN VIETNAM[1]

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INTRODUCTION

An assessment of ecologic consequences of the defoliation program in Vietnam was undertaken at the request of the U.S. Department of State. This paper is based on a report made as a part of an overall review of the defoliation and crop destruction programs in Vietnam.

The timetable for completion of the [policy] review required submittal of a report one month after my arrival in Vietnam on March 15, 1968. The period from mid-March to mid-April was the end of the dry season when many tree species are naturally defoliated. This added to the difficulty of determining the effects of herbicides on vegetation.

The dry season, the short time available, and the difficulty of making on-the-ground observations were restrictive for an ecologic evaluation. Thus, this report is not a detailed analysis, but an assessment based on the observations that were possible and discussions with foresters and others knowledgeable about the local situation. The observations were supported by published literature and personal

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1/ The assessment and report on which this paper is based were prepared by the author when he served as an advisor to the U.S. Department of State. That report was released in September by the U.S. Embassy in Saigon.

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research experience in ecology and the effect of herbicides on vegetation in temperate and tropical America.

There were no constraints placed on what I was permitted to see in Vietnam or on what I reported. Some areas and vegetative types could not be visited because there was not adequate time, or because safety could not be assured in areas of military activity. In other areas, inspections were limited to aerial observations because the sites were not sufficiently secure to permit ground assessments. Civilian and military elements of the U.S. Mission in Vietnam gave me all the help and cooperation that was possible. The military provided aircraft for aerial surveys of defoliated and non-defoliated forests, arranged transport to Special Forces Camps and a security force for observations from the ground, arranged briefings on all aspects of the defoliation program, and made available whatever records I wished to see on where and when forests were sprayed with defoliants. Civilian elements of the U.S. Mission provided background information based on their experience in Vietnam, aircraft for additional aerial surveys, introductions to Vietnamese foresters, and literature needed for writing my report. Probably the best indication of the lack of constraints on my activities was that the report I prepared was released by the U.S. Mission in Saigon without a word having been changed.

This manuscript is essentially the same as the report I prepared in Vietnam. Some material has been deleted because of space limitations in Science, but my observations and the conclusions I reached do not differ from the original report.

DEFOLIATED AREAS SURVEYED

Time did not permit a survey of all the defoliated areas in Vietnam. Therefore, my observations were limited to those areas where large blocks of forest had been sprayed with herbicides. The ecologic consequences of the defoliation program would be expected to be most evident and most readily definable in such areas.

The most intensive defoliation treatments in the mangrove vegetational complex have been applied in the Rung Sat Special Zone, an area that surrounds the shipping channel into Saigon. Defoliation of the mangrove was started in 1966, but most of the defoliation flights were made after June 1967. A block of about 460 km^2 had been treated by the end of January 1968. The Rung Sat Special Zone was surveyed from a helicopter ranging in height from treetop level to about 1,000 feet. Mangrove on the Ca Mau peninsula was surveyed from a C-123 flying at about 2,000 feet. This flight also permitted a survey of a 1962 herbicidal treatment of mangrove on both sides of the Ong Doc River.

The most intensive defoliation treatments on upland semideciduous forest have been applied in War Zones C and D and in the Demilitarized Zone. My efforts were limited to War Zones C and D. The general location of War Zone C is NW of Saigon between the Song Be River and the Cambodian Border; that of War Zone D is NE of Saigon between the Son Be and Song Dong Nai Rivers. Blocks of about 920 km^2 and 1920 km^2 have been sprayed in War Zones C and D, respectively. Some areas within those blocks have received two to four treatments. Defoliation in the semideciduous forest was observed from two relatively high-level flights in fixed-wing aircraft, six high- and low-level flights in helicopters, and observations from the ground in forests surrounding the four Special Forces Camps of Thien Ngon, Katum, Tong Le Chon, and Bo Dop. Several hours were spent in the forest at each location to assess defoliation, refoliation, successional patterns, and to get an idea of the possible effects of the defoliation on wildlife. In addition to personal observations, men at the camps were questioned regarding the effect of defoliation on their operation, their impressions about the relative difficulty of human movement in the forest (a rough measure of the density and composition of the ground story vegetation), and sightings they had made of wildlife.

EFFECT OF DEFOLIATION ON CLIMATE

Not uncommonly one hears that large-scale modification of vegetation (forest to savanna or grassland, for example) or the vegetative denudation of an area will cause a change of climate, particularly the amount of rainfall. The theory behind this statement is that as forest is converted to grassland or the soil is bared of vegetation, the evapo-transpirational surface is reduced and thus there is less moisture released to the atmosphere for subsequent precipitation. The fallacy of the theory is readily apparent when one considers the vast scale of atmospheric air flow, with the moisture it contains, and the relatively insignificant reduction in moisture that might be caused by reduced evapo-transpiration from a small area. It is instructive to make some simple calculations that point out the fallacy of the theory more explicitly.

By applying the reasoning used for an arid area (1), let us apply some simple calculations to a forested area that is 100 km on a side.

If we assume, conservatively I think, that the total moisture in a vertical column of the atmosphere above the area has a depth of 3 cm and the air mass is moving over the area at a rate of 5 km per hr, we can calculate that moisture is passing over the area at a rate of 4.17×10^9 gm per second. Now let us further assume that our hypothetical forest has been entirely denuded of vegetation and we reasoned that it may have been contributing 10 percent to the total atmospheric moisture. In other words, we expect a 10 percent decrease of rainfall after the vegetation is removed. Ten percent of the total atmospheric moisture would be 4.17×10^8 gm per second. In other words, our hypothetical forest would have to be contributing moisture to the atmosphere at a rate of 1.1×10^5 gallons per second. Clearly, such a figure is unreasonable. If we carry this calculation further and consider one tree with its branches in the upper or middle canopy for each 10 m^2, then evapo-transpiration from each 10 m^2 area would have to be 417 ml per second. That is far beyond the measurements that have been made for salt cedar (Tamarix pentandra), one of the heaviest users of water (2).

The work of Ohman and Pratt (3) also lends itself to this discussion. They measured dew point over and downwind from a desert irrigation project covering some 100,000 acres near Yuma, Arizona (annual precipitation about 3 in). Despite application of annual totals of from 5 to 10 ft of irrigation water on this area extending some 20 miles parallel to prevailing winds for the summer months studied, all influence of the irrigated fields upon crop-level dew points became immeasurably small only 100 ft to the lee of the downwind edge of the entire area. And at 12 ft above the crop level, dew points were not measurably increased even at points inside the irrigated acreage. These measurements were made under midday conditions in July and August when monthly totals of irrigation varied between about 0.7 and 1.5 ft of applied water. These measurements show impressively the small effect that artificial measures have on atmospheric moisture content.

My conclusion is that defoliation in Vietnam has no significant measurable effect on atmospheric moisture and thus would have no effect on precipitation.

Another point that refutes the evapo-transpiration:precipitation theory is that water molecules are not motionless in the atmosphere. Sutcliffe (4) estimated that the average time between a water molecule's evaporation into and its precipitation from the atmosphere to be about 10 days. Thus, from mean wind speed considerations, the average water molecule must drift many hundreds of miles before it is precipitated.

Extensive defoliation would be expected to change temperature patterns through a forest profile simply because there would be less shielding of direct solar radiation. In addition, the average wind speed would be greater in a defoliated than in an undefoliated forest. These two factors probably would not have a great effect on higher plants and animals, but might temporarily affect lower life forms that are more dependant on specific micro-climatic niches for growth and survival.

EFFECT OF DEFOLIATION ON SOILS

One of the principal fears about exposing soil in the tropics is the possibility of increased laterization. The term laterite generally refers to an indurated concretionary deposit, high in iron or aluminum oxide content, which has formed in place by the weathering of rocks. True laterite hardens irreversibly. Laterite has been found to be best developed when the following conditions exist (5):

1. The climate must have high rainfall and uniformly high temperatures.
2. The topography must have been fairly gentle, peneplain in nature.
3. A well drained soil must have been present. This is usually an alluvial soil, but soils high in iron content may be an exception.
4. There must have been a uniformly fluctuating water table which had a definite low level during the dry season.
5. Stable geological conditions must have existed for a long time.

About 30 percent of the soils of Vietnam have a potential for laterization (5). Many of the red soils of Vietnam (often confused with laterite) dry out and become hard but soften again upon wetting. The soft doughy laterite, which hardens to a rocklike material upon exposure to alternate wetting and drying is not found in significant amounts in Vietnam.

Two kinds of laterite are found in Vietnam. Worm-hole laterite is generally consolidated and occurs as massive beds, commonly at the bottom of a 1 to 30 ft layer of well drained soil. It is red to brown in color, and has a slaggy appearance due to numerous holes that are often interconnecting and thus facilitate the passage of ground water. Worm-hole laterite occurs throughout most of the Mekong Terrace region, in soils of both forested and cultivated areas.

Pellet laterite is unconsolidated and occurs as small pellet-like concretions in an iron- or aluminum-rich soil. The hard concretions are usually surrounded by fine grained material that is generally clayey when moist. The coarser particles in this fine grained material are commonly iron stained quartz sand. Pellet laterite occurs on the iron-rich basalt plateau soils of the Mekong Terrace, the basalt plateau of Ban Me Thuot, the extreme western edge of the high plateau west of Pleiku, and in a small area around Quang Ngai. Pellet laterite has been observed forming on the metamorphic rocks near Bong Son and on some of the rocks near Qui Nhon. It is likely that worm-hole and pellet laterite could occur in the Northeastern Coastlands, but this has not been substantiated by field studies.

Laterization under natural conditions is a long term process. The process is accelerated when soil is exposed to direct solar radiation and wind. I do not find it reasonable to conclude that the defoliation program in Vietnam would hasten the laterization process significantly because bare soil does not result from defoliation. It is possible, however, that laterization will be accelerated around Base and Special Forces Camps where the soil is maintained free of vegetation.

Erosion as a consequence of defoliation must also be discussed briefly. The degree of erosion that will occur depends on soil type, topography, relative degree of vegetative cover, and rainfall amount and intensity. In general, erosion will be greatest on steep slopes of bare soil, decreasing as slope decreases and vegetation becomes more dense. It was not possible to examine defoliated forest in mountainous terrain critically for evidence of accelerated erosion. I did not detect such evidence during aerial overflights of defoliated areas. Gully and sheet erosion were noted around camps where there was little or no vegetation, regardless of whether or not those areas were sprayed.

The possibility of flooding or of changes in the water table as a result of defoliation are subjects that need careful consideration. The replacement of woody vegetation with grass in the Southwestern U.S. has resulted in perennial flow of streams that were only intermittent before and also in the flow of springs that had been dry for many years. There are cases where harvesting trees increased stream flow (6) and where a marshy condition unsuitable for desirable timber species followed clearcutting (7). I mention these points because they have occurred elsewhere and could conceivably occur in Vietnam. But I do not know the local situation well enough to make a reasonable assessment of that probability.

Micro-organisms are an essential feature of the soil system. A herbicide that killed the micro-organisms would have a severe effect on soil ecology. What are the possibilities of destroying the microbial population in the soil with the chemicals being used for defoliation in Vietnam?

The code names for the defoliants used in Vietnam are Orange and White. The constituents of Orange are *n*-butyl esters of (2,4-dichlorophenoxy)acetic acid [2,4-D] and (2,4,5-trichlorophenoxy)acetic acid [2,4,5-T] in a 1:1 ratio. The constituents of White are tri-isopropanolamine salts of 2,4-D and 4-amino-3,5,6-trichloropicolinic acid [picloram] in a 4:1 ratio. There seems to be no danger that any of the three chemicals will kill micro-organisms. Actually, numbers of soil micro-organisms capable of inactivating 2,4-D apparently increase when 2,4-D is present in the soil. Thus, repeat applications of 2,4-D were less persistent in soil than the initial application (8). There is no published literature suggesting that the effect of 2,4,5-T on micro-organisms is significantly different from 2,4-D. Picloram does not destroy soil micro-organisms, but neither is the microbial population enriched as a result of picloram application. Thus, picloram cannot be considered a good energy source for micro-organisms. The decomposition of picloram is an incidental process in the breakdown of soil organic matter, requiring the loss of approximately 10,000 to 100,000 lbs of organic matter per lb of herbicide (9).

EFFECT OF DEFOLIATION ON PLANT AND ANIMAL POPULATIONS

The chemicals 2,4-D and 2,4,5-T are highly selective herbicides, picloram is somewhat less selective. Not all plant species react similarly to them. The differential susceptibility may be a function of such factors as time of treatment, nature of the leaf surface, variable capacity for absorption and translocation of the herbicide, biochemistry of the plant, or the nature of the herbicide itself. Some established annual and perennial grasses are tolerant to rates of application used in the Republic of Vietnam(RVN). Thus, in any vegetative type, one would expect that some species would not be killed; some would be killed easily; others with difficulty. Most species in the mangrove association are highly susceptible to the herbicides being used for defoliation in Vietnam, and thus represent an exception to the general rule. For that reason, and because the mangrove association presents a different set of ecological considerations than does the semi-deciduous forest, each will be discussed separately.

MANGROVE FOREST

Botanical considerations - The mangrove association is relatively simple floristically. The principal species include:

Avicennia marina	*Phoenix* spp.
Avicennia intermedia	*Lumnitzera coccinea*
Rhizophora conjugata	*Sonneratia acida*
Bruguiera parviflora	*Melaleuca leucadendron*
Bruguiera gymnorhiza	*Excoecaria agallocha*
Ceriops candolleana	*Carapa obovata*
Nipa fruticans	*Acronychia laurifolia*

Other plant species are represented in the mangrove type, but they are of lesser importance. Bamboo was not observed in the mangrove association.

Susceptibility to herbicides - The mangrove species seem to be almost uniformly susceptible to Orange and White, the herbicides used for their control in Vietnam. An exception is *Nipa fruticans*, which is reported to be resistant to White. Strips of mangrove on both sides of the Ong Doc River, sprayed with Orange in 1962, were of particular interest. The treated strips were still plainly visible. Thus, one must assume that the trees were not simply defoliated, but were killed.

Successional aspects - The mangrove type in RVN occurs on about 2,800 km^2 (10). Avicennia marina is the pioneer species of the mangrove type, colonizing on the clay accretion areas at the sea face. At the 5th and 6th year Rhizophora conjugata, Bruguiera parviflora, and Ceriops candolleana will develop where there has been partial stabilization of the soil. About the 20th year Rhizophora and Bruguiera will dominate the site. From that point on, further succession depends on the degree of silting and the consequent decrease of water circulation. As organic matter accumulates, conditions are created for the advent of other species into the mangrove complex. The final stage in the mangrove type is the cajeput (Melaleuca leucadendron), found on the highest, most stable soil above high tide.

Seed production of mangrove species is annual and abundant to prolific, with seeds viviparous or otherwise, of high germinability and capable of remaining viable for long periods (11). Germination and rooting are usually rapid and successful. In some locations, when the seeds are able to settle as a result of favorable water conditions, natural regeneration may become successfully established in less than a year. The movement of the water, however, may not only bring in seeds but may also carry them away before they can take root.

The most serious animal pest is the crab, which may entirely prevent regeneration by attacks on seedlings (12). In Malaya two species of Acrostichum (a fern) may hinder the establishment of water-borne seedlings. The fern grows and spreads rapidly when the tree cover is removed. McKinley (10) mentions two ferns (Choai, a creeping form; Don, an erect form) as occurring in the climax mangrove, but does not comment on their possible interference with regeneration.

Ecologic considerations - According to the timetable discussed by McKinley, about 20 years are required for the establishment of a dominant Rhizophora-Bruguiera association. That timetable was established for a situation in which newly silted areas were colonized by Avicennia and then replaced by Rhizophora-Bruguiera. It is not unreasonable to suspect that the same timetable might apply to areas in which the trees had been killed by herbicides. Dead trees do not hold soil as well as do living trees. The amount of soil removed would depend on the rapidity of tidal recession, which is unknown to me. The greater the amount of soil removed, the greater would be the time required for regeneration of a mangrove stand similar to the original.

The regeneration of mangrove since the 1962 treatments along the Ong Doc River was observed from an aircraft flying at 2,000 feet. Regeneration was apparent as fingers extending into the treated strip, but I could not determine if regeneration had occurred across the entire breadth of the treated strip.

In the mangrove areas treated in 1962 trees of the colonizing species were not yet discernible from 2,000 ft on all the treated area. Thus, extrapolating the information provided by McKinley, 20 years may be a reasonable estimate of the time needed for this forest to return to its original condition.

Little information is available regarding the effect of killing mangrove on animal populations. In that regard, I considered the food chain among aquatic organisms. Although it was not possible to obtain information on the many links in the food chain, phytophagous and carnivorous fish would be near the top of the food chain. Disruption of lower links in the chain might be expected to reduce fish populations.

Information on fish populations is based on fish catch statistics provided by the Fisheries Branch of USAID. The total catch, in metric tons, for the past three years is as follows:

Year	Fresh Water	Marine	Cuttlefish, mollusca, shrimp, crabs, etc.	Total
1965	57,000	289,000	29,000	375,000
1966	64,710	287,450	28,340	380,500
1967	54,300	324,700	31,700	379,700

Fish catch appears to have been increasing. The drop for fresh water fish in 1967 was at first a cause for concern. But the Assistant Chief of Inland Fisheries explained that the reduction was due to an absence of flooding in the Mekong Delta in 1967. When flooding does occur, fish are trapped in rice paddies and fishermen have no trouble catching them.

The fish catch statistics give a strong indication that the aquatic food chain has not been seriously disturbed. Data comparable to fish were not available for birds and other animals.

The application of herbicide in strips or in a checkerboard pattern rather than large-area treatment would be a tremendous ecologic advantage. The trees remaining in untreated strips would provide a seed source for reforestation as well as habitat for animals and lower plant forms. The ecological effects in large treated areas would be greater and recovery would probably be slower.

SEMI-DECIDUOUS FOREST

RVN has a total area of 172,540 km^2, of which about 30 percent is forested (10). The types of forest, their area of coverage, and the approximate area treated for defoliation are:

Vegetation Type	Area of Coverage, Km^2	Approximate Area Treated, Km^2
Open Forest (Semi-deciduous forest)	50,150	8,140
Flooded Area		
Mangrove	2,800	960
Other aquatic plants	2,000	0
Coniferous Forest		
3-leaved pine	900	0
2-leaved pine	350	0
	56,200	9,100

Some coniferous forest may have been treated in strips along roads, but I have no specific information on that point. I am sure that no large areas of coniferous forest have been treated.

Botanical considerations - I will not attempt to characterize all of the vegetation types of RVN. There are different forest types, but except for the pine forest, the differences are ones of degree rather than substance. My discussion of the forests in III Corps can be extrapolated to other semi-deciduous forests of RVN. It can not be extrapolated to the pine forests or to the small area of rain forest that probably exists (based on literature reviews and weather records) in a small area of Northwestern RVN along the Laotian border.

The forests of War Zone C are, for the most part, what has been described as secondary forests with an admixture of bamboo, and semi-deciduous forest of Lagerstroemia and legumes (General Forest Map of RVN, Phan Thuong Tuu, 1966). The forests of War Zone D are moist forest over most of the area, and semi-deciduous forest of Lagerstroemia and legumes over the remainder.

There are obvious differences among the three forest types. The differences are taxonomic for the most part. Physiognomically, they are similar. In terms of ecologic considerations, therefore, they will be discussed collectively.

The three forests are similarly characterized by having members of the family Dipterocarpaceae as dominant trees in the upper canopy. This does not mean necessarily that Dipterocarps are numerically superior. Other well represented families include the Leguminosae, Meliaceae, Lythraceae, Guttiferae, and Sterculiaceae (personal observation, 10,13,14). Botanical composition, taxonomically and numerically, will vary from one location to another.

The difficulty of a botanic description of the forest may be appreciated with the knowledge that about 1500 woody species occur in RVN (10). Moreover, I saw the forests at a time when identification was most difficult. Many species are normally deciduous during the dry season; many that are normally evergreen had been defoliated by herbicides or by fire.

The period from mid-March to mid-April was not an ideal time to assess the ecologic impact of the defoliation program on the semi-deciduous forests of RVN. The combination of natural defoliation,

defoliation by herbicides, and defoliation by many, many fires (civilian and military caused) made the determination of the causes of defoliation difficult. A careful delineation of the causative factors within a one-month period was not possible. An ecologic assessment during the middle or latter part of the rainy season would not have to contend with the confounding influences of natural defoliation and fire.

Susceptibility to herbicides - Trees in the semi-deciduous forests of Vietnam are almost uniformly susceptible in terms of initial defoliation. But when refoliation and the percentage of plants killed is considered, the average susceptibility of the vegetative type is unknown. The best estimate I can obtain is an extrapolation of data developed in Thailand by Darrow, et al, (15) and in Puerto Rico by Tschirley, et al, (16).

Darrow's tests in Thailand were conducted in a semi-evergreen monsoon forest having an annual precipitation of about 40 inches. Two hundred twenty plant species were identified from two test sites totaling 3,400 acres, so species diversity was high. Darrow found that two or more gallons of Purple (same as Orange except that 20 percent of the 2,4,5,-T is an isobutyl ester rather than n-butyl) caused defoliation greater than 60 to 65 percent for a period of 6 to 8 or 9 months. Percentages of kill were not given, but they would have been considerably lower than for defoliation.

Tschirley, et al, worked in a semi-evergreen forest in Puerto Rico having an annual precipitation of about 85 inches. Species diversity was high; 106 woody species were recorded on 2.4 acres in an area adjacent to the aerial test plots. Tschirley, et al, also worked in a tropical rain forest in Puerto Rico having an annual precipitation of about 120 inches. About 88 woody species were recorded for the rain forest site. Defoliation of the semi-evergreen forest treated with 3 gallons of Purple was 61 percent 6 months after treatment. In the rain forest, an equivalent rate of Orange provided 66 percent defoliation 6 months after treatment and 55 percent one year after treatment.

Thus, the defoliation obtained in taxonomically distinct forests in opposite parts of the world was similar. It is justifiable, then, to expect that average defoliation in the semi-deciduous forests of Vietnam would be about the same. Actually, I would expect defoliation in Vietnam to be somewhat lower because applications are made from greater height than was the case for the experimental work in Thailand and Puerto Rico.

Multiple treatments were not made in Thailand or Puerto Rico so the effects of two and three treatments in War Zones C and D can only be inferred from extensive experience in woody plant control in temperate zones and my experience in tropical America, instead of being extrapolated from actual research data. But the inference is necessary because the ecologic impact becomes greater with each succeeding treatment.

A single treatment with 3 gallons of Orange or White would not be expected to have a great or lasting effect on a semi-deciduous forest in Vietnam. Some trees would be killed and the canopy would be less dense temporarily. But within several years the canopy would again be closed and even a careful observer would be hard pressed to circumscribe the treated area. A second application during the period of recovery would have a wholly different effect.

Research on a two-storied oak-yaupon forest in Texas showed that the top canopy intercepted about 72 percent of the spray droplets and the understory intercepted an additional 22 percent. Only 6 percent of the droplets reached the ground (16). Thus, one would expect that the principal effect from an initial treatment would be on trees of the top canopy. As the density of the top canopy is reduced, subsequent treatments will kill more trees in the top canopy and have a far greater effect on the understory, regenerating vegetation.

The theoretical response to multiple herbicide applications developed in the previous paragraph was supported by observations on the ground. The area visited at Thien Ngon was sprayed with Orange on December 19, 1966; the area at Katum was treated with White on November 9, 1966 and with Orange on October 28, 1967. Two areas were visited at Tong Le Chon; one treated with Orange on September 23, 1967 and the other with White on November 7, 1966. There were more dead trees and a higher percentage of defoliation at Katum than at any other site. Granting the inadequacy of the sample at each location, the difference between Katum and the other sites was obvious. Despite more defoliation and more dead trees at Katum, the ground was not bare. Many established grasses are tolerant to the herbicides used. In addition, grasses, sedges, and vines quickly occupy areas that have been defoliated. Grasses were abundant in all defoliated areas observed on the ground.

Successional aspects - I can think of no better introduction to this section than a quotation from Richards (17). "The process of natural regeneration in tropical forests is no doubt exceedingly complex, and though its practical importance to the forester is obvious, surprisingly little is known about it. Much of what has been written about the so-called 'natural regeneration' of rain forest refers to the reproduction of a few economic species under conditions rendered more or less unnatural by the exploitation of timber. Before regeneration under these artifical conditions can be understood or controlled scientifically, we need to know what happens under undisturbed conditions, and information about this is extremely scanty."

I must emphasize the last sentence of the quotation. Data on regeneration of tropical forests is indeed scanty--and particularly scanty for Vietnam!

There is general agreement that the usual successional series in a terrestrial tropical forest is grass----- shrub----- secondary forest----- primary forest (14,17,18). The same successional series could be applied equally well to deciduous forests in temperate zones.

Because of the inadequacy of data about forest regeneration in Vietnam, perhaps an example in a different situation would be instructive. The island of Krakatau represents a classic example of ecologic succession. According to Richards (17), "Krakatau is one of a group of small volcanic islands situated between Java and Sumatra. Early in 1883 it was about 9 km long and 5 km broad, rising to a peak 2,728 ft (822 m) above sea level. At this date the whole island was covered with luxuriant vegetation. About the nature and composition of this vegetation next to nothing is known, but there is every reason for supposing that it was mostly tropical rain forest similar to that now existing in the neighboring parts of Sumatra. In May 1883, the volcano which had long been regarded as extinct began to be active and the activity gradually increased until it reached a climax on August 26 and 27. On these two days occurred the famous eruption, the sound of which was heard as far away as Ceylon and Australia. More than half the island sank beneath the sea, the peak being split in two, though its highest point still remained. The surviving parts of Krakatau were covered with pumice stone and ash to an average depth of about 30 m and a new marginal belt 4.6 km^2 in area was added to the southern coast. During the period of volcanic activity the bulk of the vegetation was certainly destroyed." For a while the island remained without any vegetation. The only living thing a visitor saw in May 1884 was one spider. In 1886 there was already a considerable amount of vegetation on the island and the succeeding seral stages have developed quite rapidly. A diagram of the succession is shown in Fig. 1.

In 1964 Richards wrote, "The development of vegetation on Krakatau has not yet reached a stable climax stage, but the general course of future changes can be predicted with some confidence, at least for the middle and upper regions of the island. In the former it may be expected that the Macaranga-Ficus woodland will develop by a series of changes into a stable climax rain forest to some extent similar to the mixed primary rain forest of the neighboring parts of Sumatra and Java. How long this development will take is difficult to guess, but the study of secondary successions suggests that it will be much longer than from the great eruption to the present day."

The example of Krakatau cannot, and should not be applied to the semi-deciduous forests of Vietnam for at least three reasons: (a) defoliation does not destroy all vegetation; (b) it does not cover the soil with pumice stone and ash; and (c) RVN is not an island. *Krakatau is merely an example of the relative time* needed for the development of a mature forest when it must start from nothing. That is not the case in Vietnam.

There are a few published records of tree ages in tropical forests that give an indication of the time required for regeneration of a mature forest. An average individual of Parashorea malaanonan in the Philippine Dipterocarp forest reaches a diameter of 80 cm in 197 years (19). The average maximum age of Shorea leprosula in Malaya is 250 years (20). Both are primary forest species. The fast-growing trees characteristic of secondary forest have a shorter life than do primary forest species.

The principal ecologic danger imposed by repeated treatments with herbicide is that saplings and poles present in the lower story, and then seedlings, may be killed. If that happens in large areas, natural reseeding may be a problem. Dipterocarp seeds are wind-disseminated and thus would be expected among the first tree species to repopulate an area. Seeds of other species, dependent on dissemination by small mammals and rodents and by birds, would probably not spread as rapidly. Seeds of some species would undoubtedly remain viable in the soil and would germinate after the last in a series of multiple treatments.

Many species in the family Leguminosae have that capability. Less is known about seed characteristics in other families. Turrill (21) reported it has been proved at Rothamstead that seeds of arable weeds remained viable in soil under pasture after 300 years in one area and 30 to 40 years in others.

"Little is known of the time scale of secondary successions in the tropics. Chevalier (1948) states that the forest on the site of the ancient town of Angkor Vat in Cambodia, destroyed probably some five or six centuries ago, now resembles the virgin tropical forest of the district, but still shows certain differences. In general, it seems clear that the longer the period between the destruction of the primary forest and the onset of the secondary succession and the greater the modification of the soil and the environment in general during this period, the longer the time needed for the re-establishment of the climax" (17).

The paragraph quoted does not apply to the forests being defoliated in Vietnam because the Vietnamese forests were not primary, but secondary at the time of treatment. The time required for the establishment of a secondary forest is much less than for a primary forest.

The greatest danger resulting from repeated defoliation treatments in Vietnam is that such areas will be invaded by bamboo. The presence of bamboo is the most constant feature of the semi-deciduous forests I saw in Vietnam. Species of large bamboo (the most common being *Dendrocalamus strictus* and *Bambusa arundinacea* according to a local RVN forester) are particularly apparent in areas where the "rai" (slash and burn) system of agriculture has been practiced. But bamboo is not limited to areas that were previously cleared of trees. A small-stemmed bamboo is present as an understory in many forested areas and can be seen frequently where trees have been defoliated. In addition, the small bamboo _Schisostachyum sollingeri_, 10 to 15 ft high, was present in the forest at all of the camps I visited. The presence of bamboo in Asian forests is well documented (17,22,23,24). Aerial observations in RVN suggest that it first invades new areas along routes of more favorable moisture supply. From there it can spread throughout the forest.

While making ground observations at the four Special Forces Camps, I attempted to evaluate the relative density of seedling and sapling tree species in bamboo-infested sites. Although I have no quantitative data, seedlings were rare in dense bamboo, but frequent to numerous where there was no bamboo. Probably of more importance is the fact that saplings were rare in dense bamboo.

The length of time that bamboo might retard the natural successional progression is unknown, but I am certain it would cause a retardation. The following statement by Ahmed (25) may be cause for concern: "A bamboo will be the first member to colonize on a new site in a seed year and will be the last to leave it. Once established on a soil it is difficult to eradicate it."

The life history of different bamboo species varies, but usually culms die after flowering. The germination to flowering cycle may be from 30 to 50 years (17,26). Flowering is gregarious (whole populations flowering in one year) in some species and sporadic in others. Most bamboo species have very efficient vegetative reproduction from buds on creeping rhizomes.

Seedling mortality of tree species is naturally high in tropical forests. A study of Euterpe globosa, a palm found in the American tropics, showed that the mortality of seedlings was 95 percent, of established seedlings 12 percent, and of shrubs 64 percent. Thus, only 1.6 percent of the seedlings survived to the tree stage (27). Another study (27) showed the average half life of all seedlings in test plots to be 6 months.

If it were not for the probable invasion by bamboo of severely defoliated areas in the forests of Vietnam, I am reasonably certain that the successional progression to a secondary forest would proceed without undue retardation. A reason for feeling so is based on data I obtained from plots in Puerto Rico that were treated with 3, 9, and 27 lb/acre rates of picloram, 5-bromo-3-sec-butyl-6-methyluracil [bromacil], 3,6-dichloro-o-anisic acid [dicamba], 3-(3,4-dichlorophenyl)-1,1-dimethylurea [diuron], (2,3,6-trichlorophenyl)acetic acid [fenac], and 2,4-bis(isopropylamino)-6-(methylthio)-s-triazine [prometone] applied to the soil. The plots were examined 2 years after treatment for seedling presence. Many of the secondary forest species and several primary forest species were present as seedlings. In addition, there was no apparent differential effect of the six herbicides.

The presence of seedlings on plots treated with such high rates of herbicides is an important point. Several of the herbicides, particularly fenac and picloram, are known to be persistent in soil. There is no doubt that highly susceptible plant species would be affected by herbicide residues in the soil. But experience has shown that species commonly present in forests are not so susceptible that regeneration would be prevented. The small experimental plots in Puerto Rico were treated with 27 lb/acre of picloram; one treatment with White in Vietnam would apply only 1.5 lb of picloram per acre.

In conclusion, the time scale for succession in a semi-deciduous forest in RVN is unknown. Single treatments with defoliants should not cause severe successional problems, but multiple treatments probably will because of site dominance by bamboo.

Ecologic considerations - The ecologic considerations as they apply to plant populations were discussed in the previous section of this report. The effect of defoliation on animal populations is truly unknown.

Men stationed at Special Forces Camps have told me of seeing deer (two reports), birds (many reports), tiger (one sighting, several sound identifications), elephant (two reports), monkey (numerous reports), and cold blooded vertebrates (numerous reports). I saw a tiger track in the road at Katum. There were no reports of bovines. It is possible that such bovines as the kouprey, gaur, and banteng, reported to be rare (28), are no longer present in the defoliated areas in War Zones C and D. But I suspect that bombing, artillery, fire, human presence, and hunting have had a far greater effect than has defoliation.

TOXICITY OF HERBICIDES

A discussion of ecologic effects would hardly be complete without mentioning the relative toxicity of the herbicides being used for defoliation and crop destruction. The herbicides used in Vietnam are only moderately toxic to warm blooded animals. None deserves a lengthy discussion except for Agent Blue (cacodylic acid), which contains arsenic.

Inorganic arsenicals such as arsenic trioxide, sodium arsenite, lead arsenate, calcium arsenate, and Paris Green are extremely toxic. Organic arsenicals, such as Blue, have a low mammalian toxicity. Two series of organic arsenicals are used as herbicides. The arsonic acid series is formed by a single organic group combined directly to arsenic; the arsinic acid series has two organic groups. By varying the organic group in either series, a wide range of phytotoxicities can be obtained in products with a relatively low level of mammalian toxicity. The LD_{50} (mg/kg of body weight needed to kill 50 percent of test animals) for the herbicides used in RVN and for several other chemical compounds are as follows (29):

Chemical	LD_{50}
Sodium arsenite	10-50
Paraquat (1,1'-dimethyl-4,4'-bipyridinium salt)	150
2,4,5-T	100-300
2,4-D	300-1000
Cacodylic acid (active ingredient of Agent Blue)	830
Aspirin	1775
Picloram	8200

Toxicity studies for White have shown the acute oral LD_{50} to be 3,080 mg/kg for rats, 2,000 for sheep, and more than 3,163 for cattle (30,31). The acute oral LD_{50} for Blue is 2,600 mg/kg for rats (32). There is no evidence to suggest that the herbicides used in Vietnam will cause toxicity problems for man or animals.

SUMMARY AND CONCLUSIONS

If my assignment had been simply to determine if the defoliation program had an ecologic effect, the answer would have been a simple "yes", and a trip to the country would not have been necessary. But to assess the magnitude of the ecologic effect is an entirely different matter.

One must realize that biologic populations, even those remote from man, are dynamic. Seasonal changes, violent weather events, fire, birth, maturation, senescence, and death cause a continuing ecologic flux. Normally, the ecologic flux operates within narrow limits in a climax community. It is only catastrophic events that cause an extreme ecologic shift and reduce the community to a lower seral stage.

The defoliation program has caused ecologic changes. I do not feel the changes are irreversible, but complete recovery may take a long time. The mangrove type is killed with a single treatment. Regeneration of the mangrove forest to its original condition is estimated to require about 20 years.

A single treatment on semi-deciduous forest would cause an inconsequential ecologic change. Repeated treatments will result in invasion of many sites by bamboo. Presence of dense bamboo will then retard regeneration of the forest. The time scale for regeneration of semi-deciduous forest is unknown. Available information is so scanty that a prediction would have no validity and certainly no real meaning. Most of the defoliation treatments in the semi-deciduous forests have been made in strips along lines of communication. The ecologic effect of defoliation in those areas would not be as severe as in areas where large blocks have been treated.

The effect of defoliation on animals is not known, but it does not appear to have been extreme. I hasten to add that I know far less about animals than about plants. Fish catch has increased during a period of intensive treatment for defoliation, which surprised and pleased me. Actual data were not available for population trends of other forms of animal life. Large mammals have been seen recently in War Zones C and D, the areas of greatest defoliation activity. Included were tiger, monkey, elephant, and deer.

RECOMMENDATIONS

1. The desirability of ecologic research in Vietnam after the war ends cannot be over-emphasized. The research should be administered through an institution that will provide continuity and breadth for the research program. The opportunity of establishing ecologic research under the International Biological Program should be explored.

2. Continuing assessment of the defoliation program as it affects forestry and watershed values should be made. Ground observations are most desirable, but aerial surveys during various seasons of the year will contribute much good information.

3. From an ecologic point of view, the concept of defoliating in strips or in a checkerboard pattern has great merit. Undefoliated areas would serve as a seed source for regeneration and as habitat for wildlife.

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Fig. 1. Diagram of successions on Krakatau since the eruption of 1883 (15).