Monitoring Tropical Forests:
A Review with Special Reference to Africa

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PREFACE

Tropical forest is widely recognized as being one of the world's most critical biological resources. There is already a great deal of work at the detailed planning stage for the monitoring of tropical forest. The main emphasis of this is to map the geographical extent of forests around the world and to recognize different grades of tree cover based on the percentage of ground actually covered by the tree canopy in different places. Both can usefully be done by the application of remote sensing techniques which can provide a valuable picture of the forest situation at the present time. Moreover, attempts can be made to avoid producing a purely static picture by estimating rates of change in the forest boundaries in selected areas wherever old aerial photographs exist and can be compared with the contemporary survey. This will improve to some extent the capability of predicting future change.

An important feature of the present review is to assist this predictive monitoring by providing the basis for a sensitive form of ground-truth. This is based on an understanding of the ecological processes which influence the dynamic pattern of species-associations within the forest and hence eventually determine the type of forest — present and future. This is important because critical observations at the ground level may clearly indicate that events have already been set in train which will completely alter the nature and composition of the species canopy or even completely destroy it after the present mature trees have gone. Such information cannot necessarily be obtained from remote sensing surveys but will immeasurably sharpen their interpretation. Thus the monitoring criteria discussed in the present review based on the ecological patterns and processes occurring at ground level, if adopted, may well add a new interpretative sensitivity and predictive dimension to the current aerial surveys.

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1.0 Introduction

This report reviews the available published literature on monitoring techniques and procedures relevant to certain features of tropical forests. Discussion focuses on the range, applicability and shortcomings of techniques available for monitoring forest area, general ecology, timber resources, timber stocking, tree growth and regeneration.

2.0 Historical changes in tropical climates and rainforest extent

The extent of tropical rainforests has been affected by human and also by climatic and geographic influences. When examining the extent and intensity of human influence, it is necessary to put into perspective the changes in area and location of rainforest caused by other influences. Some progress has been made in identifying past vegetation composition and climates (particularly rainfall and temperature averages) by examining pollen deposits, lake shorelines, erosion and deposition features and correlations with modern vegetation.

The climatic changes encountered with increasing altitude in tropical mountains are reflected in the transition from lowland to highland vegetation types. Hedberg (64) and others have described the "vegetation belts" in East Africa, and it was later concluded, after pollen analyses, that they occurred at much lower altitudes during the Pleistocene glaciations than they do now (26). However, the climatic changes which have occurred in Africa probably caused different effects among individual species rather than simple shifts of the existing lowland and highland vegetation belts.

The tropical rainforest formation evolved during the early Tertiary. Some of the plant genera may have existed during the Upper Cretaceous but most evolved in the Eocene and Oligocene. This was long after the separation of Africa from America, hence the structural similarities but floral and faunal distinctions between the main rainforest areas. The maximum global extent of rainforest probably occurred in the Eocene or Oligocene (89, 155), but some periods of communication and exchange of the flora and fauna of African and Asian rainforests probably occurred in the late Oligocene or early Miocene (85). The early Tertiary was perhaps climatically fairly stable in Africa but major changes, with long dry periods, have occurred from the Miocene. Similarly in South America, much of the Amazon basin was arid in the Miocene-Pliocene, and then largely flooded under a lake in the Pliocene-Pleistocene, with effects on species-survival and distribution which still persist among mammals, birds, reptiles, butterflies, plants and other groups (89, 102).

Climatic change over a long period has been a primary factor in the evolution of modern floral diversity (126) although the continuity of rainforest in suitable areas, locally, for many millions of years, has enabled many species to survive alongside more modern forms (*cf.* the many primitive Angiosperms in S.E. Asia (9)).

Quaternary changes can be identified more certainly with the aid of ^{14}C dating. During at least the last glaciation in temperate regions, tropical climates tended to be drier and cooler (although still variable) resulting in the retreat of rainforests. At various times during the last glaciation (c. 60,000–12,500 yr b.p.), especially near the end, there were extensive tropical arid zones in Africa and south America. Areas of old dune sand were reworked in southern Zaire and West Africa (89, 94). Conditions were at their driest c. 21,000–12,500 yr b.p., and subsequently became wetter but with continuing fluctuations up to now (59, 60, 94, 126, 140, 148, 153, 155).

At these times, much of the rainforest in all tropical regions was replaced by woodland, allowing the wide distribution of certain plants and animals now found as disjunct savanna populations, while some montane species descended by 800–1000m (59). Tropical rainforest species became extinct locally and survived only in small forest refuges, resulting in some modern disjunctions at a generic level. These refuges have been distinguished in Africa (60, 85), Amazonia (56, 89, 107, 126) and S.E. Asia (3), where the effects of mountainous landmasses and island geography are confounded with those of past climates.

In Africa, forest refuges were identified from mammal distribution (85), consistent with the distribution of trees (60) and other forms of life. They have a high species-diversity with many rare and relict species. In these areas, substantial forest cover existed through the Pleistocene:

- Upper Guinea Refuge: Liberia, Ivory Coast, west Ghana
- Cameroun–Gabon Refuge, extending into Congo and east Nigeria
- Central Refuge, mainly north and east Zaire
- Mountain Refuges: Cameroun and East African mountains including the Southern Highlands of Tanzania.

In other areas, most forests have arisen from expansion of refuges and riverine relicts in the past 12,000 years. In recent times, rainforest was probably most extensive 4,000–8,000 yr b.p. (59, 94), perhaps with some forest connections from Zaire to the East African coast. This was followed by a decline under a rather drier climate, perhaps drier than today's, now shown by some disjunctions at a specific or subspecific level. Thus, outside the refuges, present tropical African forests have existed for no more than 4,000–12,000 years, and often less.

The study of changes over the past few tens of thousands of years is based on pollen analyses and species distributions. It is important to correlate modern pollen-rain and vegetation to interpret the significance of fossil pollen assemblages (58, 59). Important future contributions may also arise from the study of erosion, leaching and soil formation under different vegetation types and hence the possible correlation of modern soil with past vegetation and climatic history.

3.0 Monitoring recent changes in forest area

During the past several hundred years, the vegetation of Africa has been altered more by human influence than by climatic changes, although sometimes these influences may have supported each other.

Man has been affecting the vegetation for many thousands of years, but in the past the net effect on regional vegetation types and structures was slight. The relative areas of grassland, open forest and closed rainforest changed relatively slowly because, where the total population was low, areas of abandoned cultivation quickly reverted to forest or woodland (although with a changed structure). Ancient open forest communities were once very widespread and probably formed the main human habitat for hundreds of thousands of years. They are now rare in Africa (unlike modern Miombo or savanna), occurring in parts of Zaire with relict areas in north-west Uganda and elsewhere. Under the influence of low populations of hunting-gathering communities, they have been affected relatively slightly by a low incidence of fires, which do not spread far through the small patches of grass, and by changes in the pattern of browsing and grazing induced by hunting.

There have now been large increases in human populations, more intensive use of iron implements and fire for forest clearance and cultivation, widespread introduction of domestic animals, and increased access and mobility arising from transport systems and forest exploitation. Forests have been more widely cleared, and the resulting inflammable vegetation converted at greater speed to more or less open "savanna". Here, the ground vegetation is dominated by grass exposed to regular and complete (rather than periodic, "patchwork") fires. Savanna/woodland and closed forest previously merged together in vast areas of more or less closed, more or less deciduous woodland, but are now clearly separated in most of Africa. The chances of a cleared area escaping subsequent fires and reverting to woodland or forest have become progressively less; the young plants are repeatedly burned or browsed. The progressive net loss of forest to savanna has been documented by many observers (5, 6, 7, 8, 90, 132) and, in many regions, reversion to forests is now possible only in areas depopulated by wars, diseases or modern conservation laws. In addition, even in countries where rainforests are adequately protected, wooded grasslands are being cleared for agriculture or for utilization as timber, poles, charcoal and firewood at an increasing rate. The increased intensity of burning and grazing, and shorter cycles of agricultural rotations, prevent their regeneration.

In the past, information about vegetation changes has come from reports and maps of early explorers and administrators, and from ground photographs (*e.g.* 133). These are valuable for spot locations but are often contradictory and without the required regional and quantitative information.

Measurements of changes in tree cover or forest area may be made from sequential remote sensing imagery, including photographs and radar from aeroplanes and satellites. Imagery produced for other purposes (such as inventories and vegetation- and site-type mapping) with different powers of locational precision and discrimination, may be used (91, 92).

Photographs from satellites, such as ERTS (Earth Resources Technology Satellite) are on a scale which gives a broad synoptic view of vast areas, for regional cover and land use, a useful feature not available from ordinary aerial photographs. However, they are limited by low resolution and locational accuracy, and, like all photographs, by interference from clouds and haze (65). The 1975 LANDSAT with infra-red imagery and much finer resolution, is expected to provide a better solution to these problems. Radar imagery such as SLAR (Side-Looking Airborne Radar) is particularly valuable in tropical regions where an interpretation needs to be based on physiographical features such as topography and drainage. Radar imagery can be recorded through fog, rain and cloud, critically important in the humid tropics, although it can distinguish only rather broad categories of vegetation cover. SLAR has already been used for several regional surveys of forested land and other vegetation in Panama, Nicaragua, Brazil, Papua New Guinea (96), Colombia (134) and elsewhere. Complete or partial coverage by remote sensing imagery may be repeated and combined with ground checks in areas identified with certainty on the imagery.

Aerial photographs of savannas and woodlands have been used for counting the trees and comparing the numbers at different dates. The main species and vegetation types can be identified and tree-density and cover calculated for each occasion. In forest areas, vegetation types may be simply classified as closed forest, devastated forest and cultivated or grazed land, or they may be classified into the smallest site-types distinguishable; the changing area of each type is then calculated.

Monitoring in this way is called "continuous area estimation", meaning, "the estimation of areas of forest at different times using successive photographic coverages" (91). This method was used in Ivory Coast to monitor the extent of rainforest between 1956 and 1966 (90) (*cf.* Annex 1) and in Uganda to quantify the decrease of woodland and tree cover (23). Surveys carried out for general land classification (*e.g.* for the atlas of Uganda compiled from aerial photographs (114)) can subsequently form the basis for monitoring the forest areas.

Increasing attention is now being paid to monitoring the extent of rainforest cover, in addition to its volume and value. For biosphere conservation and land planning, disturbed secondary forest is as important as more valuable timber reserves, and attempts to determine and monitor areas accurately are now being made at a national level in many countries. A global rainforest monitoring project using LANDSAT, SLAR and aerial photographs was formulated for FAO (Food and Agriculture Organization, 96), and the techniques recommended are being used although the standardized methodology recommended has not been universally used.

In addition to broad monitoring of the extent and decline of forest and tree cover, the vegetation and land use may be mapped in fine detail from remote sensing imagery. Vegetation-type mapping of reserved rainforests is commonly an early stage of intensive management (*cf.* for Uganda, numerous type-maps of forests drawn from aerial photographs with some ground checks, c. 1955–65, and (88)). At a local level, conventional aerial photographs, sometimes with colour and/or infra-red film, have been used most. Imagery from satellite platforms has lower locational accuracy; small features such as small clearings and forest roads are not discernible but are needed for correlation with ground checks of type-boundaries.

Before planning an aerial survey, the features of photography in separate wavebands should be considered. These can make it easier to distinguish areas of open water, bare soil, diseased trees, different canopy structures and conifer/broad-leaved communities, each of different local importance. Batteries of cameras with different films may be mounted for simultaneous exposures, allowing maximum versatility for analysis.

Comprehensive information about technical aspects of aerial photography, the merits of different films, environmental monitoring by remote sensing, and about interpretation in ecological terms is given in many publications (*e.g.,* 66, 67, 116).

Maps and surveys at a local level (up to 1 : 1000), covering only a few thousand hectares, assist in monitoring changes due to natural or deflected succession, including forest expansion, particularly invasion of secondary or colonizing forest into another community, or forest retreat or transformation caused by disease centres, invasion by aggressive plants or damaging animals, or local human interference. This information may not be obtainable from either broad regional surveys or small permanent plots. Even if the survey is not repeated, it may be possible to determine the direction and magnitude of current trends in forests by interpreting a single survey, if the scale and details are suitable. For example, the size and maturity of patches of fallow vegetation, and the relative usage of young and old fallow for renewed cultivation, can reveal the intensity of shifting cultivation or rotation of crops, even without a repeated survey, just as the dynamics of an animal population can be assessed by examining the population structure at one time.

Until recently, the great majority of numerical data and scientific and descriptive information about rainforests was collected by civil servants, either field officers or scientists in government research stations.

An enormous quantity of measurements and information exists. However, little of the data, or of the practical conclusions (often drawn from inadequate data and analyses) are published in internationally available journals. The rest of the information is often said to be lost or locked away in government files. In fact, some of it is produced in small-circulation reports, working plans, legal gazetting notices, conference papers, technical notes, correspondence etc., available often in some libraries outside the country of origin, while much of the rest still exists at source. For example, the data for the oldest regularly-measured plot in any untreated rainforest (R.P. 7, Budongo, Uganda, started 1939 (42)) are not published, summarized or analysed, and their continued existence is not mentioned in publications; however, they are maintained, in duplicate, in Entebbe.

This situation is perhaps unfamiliar to many scientists. In some other fields, the bulk of new information is gathered by researchers, teachers or writers who are aware of the methods and importance of reaching a wider audience.

Similarly, while many books have been written, on a national or continental basis, about tropical botany, zoology or agriculture, and also some about forests and trees, extremely few are about tropical forestry; of these few, most have done little more than describe existing methods of tropical silviculture (16, 44, 144), while fewer still have attempted to develop a basis for future silviculture and research (*e.g.,* 34). However, many limited-distribution reports deal with these problems.

Several attempts have been made to monitor tropical forest resources (*e.g.,* 46, 123, 124), but it has been difficult to extract the information required. The attempt to revise the World Forest Inventory was abandoned in 1971 because of the small response to the FAO questionnaire which ". . . was sent to 56 countries and territories in 1970, but one year later, in spite of repeated reminders, only 20 replies had been received" (124). This approach is not recommended now. Persson (124) resorted to visits and personal contacts in Africa, and a detailed examination of records in centres at FAO, Nogent-sur-Marne, Oxford and Reinbek (*op. cit.,* p.16). This method can, in the end, provide a great deal of required information from existing documents. It is an extremely slow process, but it is an essential complement to new expensive field-monitoring programmes.

4.0 Extent of closed tropical forests in Africa

Table 1 shows an estimate of the area of closed forest in all the countries of Africa in which tropical rainforests occur. The estimate includes closed montane, swamp and riverine forests, even in small patches, but excludes mangrove and bamboo.

A separate estimate is included for Miombo Woodland or Forêts

Table 1 Estimates of areas of closed forests in all countries of Africa where rainforests occur

	Areas in thousands of hectares		
Country	Closed forest	"Miombo"	Plantations
Angola	1,500	30,000	150
Burundi	50		25
Cameroun	17,500		15
Central African Republic	3,000		1
Comoro Island	45		
Congo	17,000		14
Dahomey	100		18
Equatorial Guinea	>1,620		
Ethiopia	4,000		40
Gabon	20,385		27
Gambia			1
Ghana	1,950		40
Guinea	100		20
Guinea-Bissau	250		>1
Ivory Coast	7,000		45
Kenya	640		250
Liberia	2,500		2
Madagascar	10,000		250
Malawi	10	1,700	40
Mozambique	1,000 (riverine)	40,000	22
Nigeria	4,380		100
Reunion	100		9
Rhodesia	1	30,000	100
Rwanda	300		29
Senegal	250	14	
Seychelles	5		1
Sierra Leone	289		6
Sudan	600		90
Tanzania	1,330	30,000	70
Togo	400		6
Uganda	855		30
Zaire	100,000	9,500	60
Zambia		35,000	23
Total	197,260	176,200	1,599

Claires (including chipya and *Baikiaea* forests) south of the equator, but other areas of woodland and savanna are not estimated. An estimate is also made for plantations established for any wood-products within these countries but not necessarily in the rainforest regions.

The main source of these figures has been Persson (124), modified by numerous other sources including local reports, FAO (47) and the Reinbek Weltforstatlas. It is misleading to make a single estimate for each country with no error-margins or source-references, but a full assessment is beyond the scope of this report (see, however, the awaited Part 2 from Persson). The aim is to show the diversity of the forest coverage in different countries.

The closeness of these country-estimates to the true figure is undoubtedly very variable, depending on the quality of the available data and the various interpretations of what constitutes closed tropical forest. The total of 197,260,000 ha is similar to a number of other estimates (123, 124, 47).

It is impossible to make an accurate estimate of the rate at which closed forests are being cleared in Africa, but the following estimates are included because it is believed that they are of the right order and refer to depletion of closed forests rather than woodlands.

Ethiopia	:	200,000 ha per annum
Ghana	:	45,000 ha per annum
Ivory Coast	:	500,000 ha per annum
Madagascar	:	150,000 ha per annum

For these countries, the rate of forest destruction appears to be 1.5 to 5 per cent p.a., so the annual rate for tropical Africa may be of the order of four million hectares or more.

5.0 Ecological surveillance

Apart from enumerations and measurements of trees, little progress has been made in developing methods for long-term environmental and ecological surveillance in forests; long-term studies in African rainforests have been almost completely restricted to the trees.

There are descriptions in Forest Working Plans of the general changes in species composition which occur after exploitation or treatment of rainforests, but these usually refer only to the trees, sometimes only the commercially valuable species. However, there is much empirical information about the response of rainforests to protection, interference or clearance, and it is now generally possible to predict the approximate composition of the forest which will arise after the manipulation or clearance of rainforest in most areas of the tropics.

Some descriptions of the vegetation-changes following disturbance include information about herbaceous plants as well as trees, such as the invading shade-intolerant species or weeds of cultivation, or the increased vulnerability to fire and 'savannization'. Furthermore, many descriptions have been published of the characteristic sequences of vegetation change and invading species which occur in abandoned cultivation.

Such descriptions are usually very generalized, making it impossible to reconstruct the detailed vegetational history of any one spot, except in some permanent, repeatedly-measured plots. In such plots, a history of the tree-community may be available, allowing growth rates and succession to be examined. Often a good description of the ground flora in a permanent plot is made at establishment, with valuable information about locally dominant herbs and a species list including rarities. However, there are no rainforest plots in which the herbs, shrubs or climbers are described more than cursorily on subsequent occasions.

Thus, even in plots with well-documented tree communities, there are no quantitative records of the changes with time of the whole plant communities, still less of the animals or soils.

The monitoring of changes in the total plant community has been taken further in savanna and grasslands by pasture agronomists and wildlife biologists interested in the food-resource, principally herbs. In small plots, used for monitoring changes in herbaceous biomass and composition, it is simple to include the trees, whereas the converse is not true in the large plots needed for monitoring the rainforest trees. Rather few studies have been made of browsing and grazing in rainforests, although the results are important and show the high selectivity of mammals in forests as in savanna (101, 154) and some of the plant-animal adaptations for insect-browsing (138, 149).

Vegetation monitoring in African savanna and grassland has usually involved permananent plots or repeated linear sampling in specified areas (*e.g.,* 25, 61, 62, 137). Sometimes, plots have been treated with different intensities of burning and/or grazing, and difficulties have arisen with methods of applying the treatments and excluding fire and grazing animals from protected plots, as well as recording and analysis. Many plots have been unreplicated. Often the results of different treatments have been spectacular, and deficiencies in the data have mattered little. Sometimes, however, subtle changes in the vegetation have been visible or postulated but cannot be demonstrated from the data.

Permanent plots are established in many sizes for monitoring rainforest trees, but they are usually subdivided for recording purposes into subplots or quadrats of 0.01 to 0.04 ha. However, in sampling herbaceous communities, quadrats of 0.1 to 1m² are commonly used, sometimes subdivided, although the quadrats may be arranged in groups or transects.

Clearly, sampling at different intensities is needed to monitor all levels of a rainforest. A U.K. Natural Environment Research Council (NERC) project entitled 'Permanent Inventory of Polyspecific Woodland' has developed a sampling design, methods for establishment and measurement, and programmes for data analysis. The result is a system for permanent low-fraction sampling of mixed uneven woodland, for diagnosing and predicting changes of composition and growth primarily of the dominant plants but also, by habitat correlation, of the whole community. The method involves square plots of 0.01 ha in which trees are counted and partially measured, plus circular quadrats of 0.1m² in which all vascular plants are measured. The system suits temperate forests, but in rainforests with difficult access, it might be more economical to use transects or fewer, larger plots.

Permanent plots are required for two main aims of ecological monitoring; first, to detect and quantify environmental changes even before it is known what changes will occur, and secondly, to answer the question which is frequently asked by ecologists: "What was this site like in the past?"

Ecological surveillance of plots or communities sometimes includes the fungi, animals (cf. 18, 43, 63, 79), and soils, including micro-flora and -fauna. These present formidable difficulties. Some short-term studies have been carried out in tropical Africa particularly to demonstrate (usually by inference or after the event) changes among animals of all sizes, and soils, caused by major disturbance. Very detailed studies have been carried out in several disciplines in a project in the Sahel zone of Senegal (19).

No such detailed ecological characterization has been achieved in an African rainforest as a short-term survey (much less regularly repeated), although a more thorough survey will be attempted in Ivory Coast (Tai Forest). Sometimes, an approach to full descriptive lists can be compiled over time from different sources. Nevertheless, soil changes are so fundamentally important for the productivity of the site and the long-term human environment that a monitoring programme must attempt to characterize the soil and any changes.

There have been many soil surveys and studies of the changes in soil-nutrients in small-scale, short-term treatment experiments and under traditional agriculture or after forest clearance (20, 31, 32, 70, 87, 111, 121, 122, 129, 136, discussed in 142). However, long-term monitoring must involve the detection of small, or slow, changes under forests following treatment, exploitation, replanting or natural succession (146). To reduce sampling errors, recurrent measurements should be made at the identical spots each time. Traditional methods of soil description and sampling often involve considerable disturbance to the site, invalidating subsequent samples from that spot, and they may not be acceptable in a plot designed as a sample of the surrounding vegetation.

It is necessary to develop methods of obtaining adequate material for analysis without excessive disturbance, valid for long-term repeated sampling and still suitable for rapid collection of many samples. The method used in the NERC project on polyspecific woodland provides essential information without compromising future assessments: small samples were collected from 0-10, 10-20, 20-30 cm depth at four fixed points per plot, and analysed for pH, particle size and essential plant nutrients. The response of soil moisture regimes to changes in cover or weather may be monitored with minimum disturbance after implanting resistance-units, or with neutron moisture meters (10).

6.0 Quantifying timber resources

The first step towards monitoring changes in the numbers or sizes of forest trees is the inventory of existing volumes, species composition and size-distribution. This always involves sampling, except in small-scale research when total enumerations and measurements may be possible.

Sampling may be of two types, first, the distribution of sample measurement areas through the forest, and secondly the selection of individual sample trees or logs for accurate volume determination. Frequently, all trees within the sample-areas are determined for species and diameter, and a smaller sample of trees is selected for more precise volume estimation from several measurements (log length, diameters at various points). Measurements are also made of defect and decay in the timber, from easily observed external features, sometimes from sections and borings (*cf.* de Milde in 118, 119), and perhaps eventually with sonic or X-ray equipment now being developed. A regression equation is calculated for total utilizable log volume on some more easily measured indicators such as the diameter near the base (*e.g.,* at breast-height, 1.3 m).

Several books describe the principles and practice of tropical forest inventories. Nyyssönen (112) described methods used in the tropics up to 1960, while recent FAO manuals (71, 91) provide much of the background and methods of sampling, remote sensing, measurements and analysis, and include an outline of the topics to be considered when preparing inventory plans. Textbooks by Loetsch *et al.* (95) include sections on tropical forest inventory.

Experience has been gained mainly from exploration (pre-investment) types of inventory designed to answer the question: "How much industrial wood, specified by species, dimensions and grades, can be made available within given time periods, at tentative mill-sites within alternative cost limits per volume unit?" (110, 113, Lanly in 118). Information on the methods that have been used are given in Annex 1.

7.0 Monitoring changes in timber stocking

Many methods have been developed for measuring changes with time in standing timber volume, *i.e.,* net volume increment. In a simple situation, a standard inventory may be repeated with temporary, undemarcated sample transects, plots or points. On each occasion, the total estimated volume stocking is obtained by multiplying the average sample stocking by the total area. If the samples are selected independently on two occasions, the sampling intensities which give acceptable precision to the estimate of volume stocking are likely to give unacceptably low precision to the estimate of increment by difference.

Better estimates of successive volumes, with a calculated precision, may be obtained by the methods of continuous forest inventory (CFI) in which permanent sample plots (PSP) are established and measured at intervals of perhaps two to five years. These give compatible estimates of growth and current volume and a greater sampling efficiency than independent samples. In some cases, cost-benefit efficiency may be improved by remeasuring only a proportion of the plots measured on the previous occasion, plus a proportion of new temporary sample plots (TSPs; CFI with partial replacement). It may be possible to carry out re-assessments on aerial photographs: "the monitoring of forest cover through the use of permanent plots on remote sensing imagery represents a large field of application of continuous forest inventory which does not relate only to forest management but also to land-use policy and environmental concern" (91).

For the background and numerical basis of these methods, see references 29, 30, 37, 106, 152. They are suitable for monitoring the standing volumes, but they are little practised for that purpose in the tropics since they do not provide the required information about tree-growth rates: "two successive and identical stand tables may indicate anything from total stagnation to rapid growth with heavy mortality and recruitment" (37).

In many forests in temperate countries, even natural stands, it is usually sufficient to determine the stand tables, total volumes and net increment by CFI. In tropical rainforest, timber-use is critically dependent on adequate size, and few species are utilized. Silviculture, management, control of output and the timing of harvesting depend on knowing when the trees will reach a required size and conversely how many will reach that size after a given length of time. If this information is needed, individual tree increments, mortality and recruitment must be measured, necessitating the recording and measurement of individual permanently marked trees (*cf.* Annex 2). When interest is centred only on the volume available for exploitation, a non-recurrent inventory is usually carried out.

Many studies have also been made of primary productivity in tropical forests, measuring total production and the partitioning of biomass and stored energy within the ecosystem (86, 82). In Africa, the most important studies have been in Ivory Coast (74, 108). In a "stable" forest, net growth is in theory balanced by decay, but in fact fluctuations in standing biomass occur, resulting in annual net gains or losses, even if the mean over many years remains stable. In young forest, net gain may be very large even when gross photosynthetic productivity is not much different from that in old "stable" forest. Therefore, much doubt remains about some estimates of net primary production, since so much depends on the succession and stability in the plot and the chance effects of tree-mortality, leaf-fall and weather during the (usually short) period of measurement. Quantitative estimates of CO_2 fluxes to and from the atmosphere are of interest to WMO (World Meteorological Organization) and to modellers of climate change.

8.0 Monitoring tree growth

The most widespread use of CFI, especially in the USA, is for assessing the current stand table or timber volume in conifer forests and determining the net increment by difference. There, the net volume increment is the most important piece of information.

In rainforests, where only few species and large sizes are used, the net volume increment per hectare in the marketable categories is often very low; great accuracy in the estimate is therefore required in order to make a reliable extrapolation over large areas of forest. It is difficult to estimate accurately the total volume or increment of a standing tree. Detailed measurements on a tree-by-tree scale, and subsequent extrapolation to the scale of the forest are preferred to medium-scale inventory-monitoring of volume per unit area.

The increment must be classified by species and sizes. The aim is to determine the volume increment of individual species and species groups, which are highly variable (as discussed by Mervart (104)). Estimates of mean increment-per-tree, in each size class and species, require fewer PSPs than similarly precise estimates of the increment per unit area.

The calculated mean increment in each size may be applied to stand-data for each species to obtain the total current increment or to predict the rotation or length of felling cycle required to grow each species to a required size. However, the use of the mean involves ignoring all the variability of individual increments within each species and size class and must result in unreliable predictions. Reliable methods of statistical analysis are not at present widely used, although there is considerable agreement about the methods of layout, establishment and measurement in different countries.

PSPs were established early in several rainforests (41, 42, 81), and Dawkins (34) collated information and developed techniques for reassessment and analysis. Later, developments have been described for field use in rainforests in Ghana (11), Sabah (51), Malaya (27, 28), Uganda and elsewhere, and related PSP methods are used for plantation increment studies in several other countries such as Tanzania, Kenya and Zaire.

The recurrent measurements provide the diameter or girth (and other parameters) for trees in permanent plots divided internally into quadrats. In each quadrat many or only a few individuals (often one to four) may be measured, either of all species or of only a few commercially valuable species. Each measured tree is individually numbered, labelled and recorded, and the result is a record of the development, growth, recruitment and mortality of the whole stand of trees or of those likely to form the next crop (Annex 2).

Repeated PSP measurements have been analysed and projected in various ways to forecast the future stand development in tropical rainforest (50, 115, 151), but such methods generally use various averages without taking adequate account of the differences within each species and size class, and between dominant and suppressed individuals. Many forecasts have involved untested assumptions about mortality and survival, and straight projections of current or smoothed average growth rates (12, 156); no confidence limits can be attached to such forecasts. The work of Mervart (103, 104, 105) at Ibadan and Palmer (117) at Oxford has led to a sounder statistical basis for interpreting PSP data and for diagnosing treatment-effects.

Several stochastic methods of modelling and projecting stand development, taking account of tree-by-tree variability, have been developed for selection forests (all ages and sizes) and mixed north temperate forests (several species of all ages and sizes) (21, 99, 120, 139, 147). These models are less effective for the very large numbers of species in rainforest, where many classes of many species are represented by one tree or none. A new programme is being developed at Oxford for forecasting future stands in tropical forests, by projecting observed growth rates, mortality and ingrowth.

The data may be summarized to show the mean increment per tree (*e.g.* cm diam/tree or m^2 b.a.*/tree) or per unit area (*e.g.* m^2 b.a. or m^3/ha) of all measured trees and for each species and each predetermined size-class (*e.g.* 10 cm diam-classes). The increments may be compared between species and sizes, between treatments. If more details are recorded in the field, increments may be compared between categories of ecological dominance or competitive status. It may be possible to correlate individual-tree increment with crown form, crown position, climber infestation or local density of tree-

* basal area.

stocking, etc., although up to now only weak correlations have been demonstrated (84).

In temperate forest areas, the analysis of growth-rings and wood-remains sometimes allows a detailed analysis to be made of past individual-tree increments and species-composition, often from simple increment-cores. Tree-ring analysis can be applied to fallen trees and wood fragments, and, with matching sections from different trees combined with radio-carbon dating and climate-data, a chronology can be built up. Such techniques have not been much used in the tropics, partly because there have been few reliable weather records until recent years and partly because growth rings in tropical trees are harder to distinguish and to relate to annual or seasonal cycles of weather.

Techniques for growth-ring analyses are now being developed which are more suited to tropical trees. By the use of densitometers .anatomical studies and stains, growth-rings can be distinguished in many rainforest species particularly from relatively seasonal areas. The rings are sometimes detectable only in the sapwood, and are not *necessarily annual, but they may be correlated with long or short, wet* and dry seasons or parts of seasons. This makes it possible to measure, at one time, the response of a species (or stand) to past seasonal weather fluctuations and also successive annual diameter increments.

For physiological studies of tree response to weather, growth rings have been analysed in Nigeria and elsewhere (1, 2, 24, 97) and used for increment studies in several countries to supplement repeated diameter measurements (15, 17, 38, 70, 100, 145).

The methods developed by Centre Technique Forestière Tropicale (*cf.* several reports by Mariaux and Detienne) require careful marking and measurement of each tree for some years before felling and examination. With increasing experience it should be possible to define the age and growth-rings of uncalibrated trees.

9.0 Monitoring the regeneration of forests

The stocking and species composition of the young regeneration (or all trees from seedlings up to nearly exploitable sizes) have been assessed in many rainforest surveys. The regeneration has then been related to the composition of the tree canopy and the local tree-flora, the treatments and disturbance of the forest, its age and seral status, and then to the possible future composition of the forest.

Most of the regeneration studies have been carried out by foresters concerned with managing stands to ensure adequate numbers of established trees of the desired species. Many of the commercially desirable rainforest species, relatively frequent in the canopy, are infrequent as young individuals, so much so that some populations must be unable to maintain themselves at existing levels. This apparent population instability was particularly puzzling in forests which were believed to be primary, "virgin, climax" forests, many of which were in fact old secondary forests. This problem (*cf.* 128, p. 43) led to the mosaic theory of regeneration with the species-composition stable overall but not locally (4). This process would be very difficult to monitor.

The young plants provide the best indication of the future composition of the forest, and methods have been developed for sampling and sometimes monitoring the regeneration and interpreting the results. Sampling usually involves enumerations along random or systematic transects through the forest. Each transect is divided into record-units (milliacre (4 sq.m.) quadrats or larger) in which fixed numbers or all young trees are counted and classified by size, species and competitive status. There are many published methods which could be adapted for more general monitoring or descriptive purposes (14, 69, 109). The results are used for prediction and also for diagnosing the condition of the regeneration (hence "diagnostic sampling") and for prescribing silvicultural treatments (such as thinning of the canopy) to ensure that adequate regeneration will reach maturity.

Some of these studies have involved repeated assessments of young plants over several years, to determine the effects of different treatments (*e.g.* R.P. 273, Nigeria; R.P. 441, Uganda). Such monitoring programmes have typically had many objectives, and an inadequate design or excessive labour commitment (on the principle of measuring all possible parameters to answer all possible questions) and the results have been modest (*e.g.* 125).

A few studies have been fundamentally ecological, examining only one or few species to explain as well as describe the situation (*e.g.* 143 for the seeds and seedlings of one African mahogany). Similarly, Janzen and associates have monitored the effects of seed-eating parasites and predators on the regeneration of American rainforest trees (76, 77) and the effects of adult tree-host/parasite interactions for mutual protection and competitive advantage (75, 78). It is now clear that a monitoring programme for rainforest species-composition and regeneration must do more than identify ecological niches and competition between plants; the enormous variety of reproductive strategies and chemical and phenological defence mechanisms must be examined. Very few rainforest species have had their life cycles examined in detail, but existing studies show their great complexity and the kinds of approach required.

10.0 Deficiences: information required

This section describes items relating to rainforests where a shortage of information is particularly felt and more work is required, with brief suggestions of how this information is gathered. No priorities are implied among these items which need not be the highest priorities for environmental agencies or national Forest Departments; they are suggested as the main priorities in the field of rainforest monitoring.

10.1 The present extent of closed forest, woodland and other vegetation types, separately, for reserved and unreserved areas

The accuracy of existing estimates varies widely, sometimes with margins of error of millions of hectares, because of lack of data or uncertainties about their interpretation. More reliable area-estimates can be obtained from remote sensing analysis.

10.2 The changes in forest extent (rate of depletion) during the recent past

These changes should be calculated for any areas (individual forests, regions) for any periods for which appropriate information, usually remote sensing imagery, is available, and as an ongoing exercise for frequent intervals into the future. Usually, the assistance of outside agencies is required within individual tropical countries and this has presented difficulties in some cases.

10.3 Timber resources

Although inventories have covered great areas, there are serious gaps in available information. The extent of tropical timber resources is now a matter of global importance and techniques for inventory are widely available.

Investment decisions about exploitation of tropical forests require statistics on the marketable volume per hectare, with average species-composition and log size, and estimates of the proportions of defect and of special qualities such as veneer logs.

10.4 Timber increment

Rainforests have a reputation for rapid growth-rates and high productivity but low annual yields of large sizes of valuable species. However, volume growth-rates are highly variable and have rarely been accurately measured. Even less information is available about total wood increment for all sizes and species.

Vast areas of rainforest, partially exploited, disturbed or treated, are growing at unknown rates, but many countries have made no attempt to monitor growth-rates and many others do not process existing data from permanent sample plots. The information can be obtained in relatively few years by methods of CFI.

10.5 Depletion of genetic resources

The natural genetic and geographical range of many species is already depleted by forest destruction. Many forest species are, or will be, economically important for growth in plantations for which, as for all crops, suitable strains must be selected and bred for different areas. Information is urgently needed about the range, local abundance, genetic variation and threats to the survival of, initially, the species of current economic importance. So far, work in this field has concentrated on only a few species, mostly tropical pines, but an expansion is required.

10.6 Soil changes

Not enough is known about the changes in fertility (including all parameters affecting long-term productivity) of forest soils following logging, thinning, changes in the species composition and particularly the change from mixed forest to monoculture. So far, research has concentrated on the drastic change from rainforests to cultivated farms, and to a lesser extent the change to conifer plantations. Small changes over large areas may be equally important.

ANNEX 1

Methods of obtaining inventories of forest resources

Most inventories involve tree-measurement in the forests (plus any remote sensing interpretation), by total enumeration (*cf.* 93, Cameroun) or sampling in transect lines divided into quadrats of fixed size, in random, systematic or clustered plots of fixed shape and size, or in point samples (variable area plots, sampling with varying probabilities) using angle-gauge instruments.

Many optical instruments have been developed (some originally from military rangefinders) for measuring heights, diameters and basal areas (b.a.) with varying degrees of accuracy and convenience. In order to achieve the precision needed for research, and the speed and accuracy needed for practical inventory, an optical dendrometer must include a magnifier and coincident or superimposed alignment of images (55). The Spiegel Relascope has been widely used for inventories in temperate and tropical countries including Nigeria (127, 141); the Barr and Stroud Dendrometer is more precise but much more expensive.

Often the versatility of an optical dendrometer is not required, and many routine plot-measurements and inventories are carried out with tapes and callipers for diameters and girths, and poles or clinometers (Haga, Blume-Leiss, and, more precise in use Suunto) for tree- or log-heights. For measuring inaccessible diameters (*e.g.* above buttresses), calibrated sticks, derivations of the 'Biltmore Stick, are sometimes used (39, 48, 95).

Great care is needed in selecting the most suitable size, shape and frequency of sampling units required, in relation to the required precision and the great heterogeneity of the forests and the aggregated or clumped distribution of certain species (*cf.* 135). Usually, numerous small plots allow greater precision than large plots of equal total area (*cf.* 33, Uganda, and 93, Cameroun). For one-off inventories, all plot shapes have different advantages of convenience or statistical efficiency so that examples of inventories with different techniques may be drawn from all tropical regions.

Point-sampling with angle-gauge dendrometers (variable area plots) has so far been used less frequently in the tropics than fixed-area plots, although widely used in temperate forests, but there are many advantages which have led to its increasing use. A trained worker can obtain numerous measurements less laboriously than by conventional methods; the statistical advantages are critically demonstrated by Banyard (13) for tropical forest conditions. The method most widely used is called PPS sampling (probability proportional to size), whereby the probability of sampling an individual tree is proportional to its size, *i.e.,* it depends on the ratio of the diameter (or b.a.) of the tree to its distance from the observer. The trees around the sampling point are examined against the scales visible through the instrument; the diameters may be read directly, or the total b.a. per unit area may be calculated from the number of trees whose diameters exceed (*i.e.,* subtend an angle greater than) the appropriate scale width.

Other methods of sampling with varying probabilities include list sampling, when the probability of sampling an individual is decided from the results of a previous partial enumeration, and 3P sampling (probability proportional to prediction), developed by Grosenbaugh (54).

In 3P sampling, a pilot survey is carried out to determine approximate numbers or range of size or value classes. Individuals are selected for detailed measurements using random numbers such that the sampling intensity increases with increasing size or value (*cf.* bibliography (98)). Thus, as with PPS sampling, more trees are measured, and sampling intensity increases, in the more important, usually larger classes.

In temperate-forest inventories, remote sensing imagery is widely used, with conventional aerial photographs or orthophotographs, invisible or infra-red wavebands, or with radar, from aircraft, rockets or satellites (*cf.* 45, 68, 92, 150). They make it possible to stratify the forest into blocks of different stocking or vegetation types, resulting in a more efficient design for the ground enumerations with sampling intensities appropriate to each type.

The density (stocking) and crown diameters of individual trees may be determined from magnified stereoscopic images of suitable scale. The crown density of dominant trees is broadly correlated with the total volume of timber and has been used for volume-class stratification for FAO inventories in Malaysia and Amazonia. In deciduous forest in India, it was possible to make rough estimates of the standing volume from the general appearance on aerial photographs of the canopy in the inventory area and in plots of known standing volume (83).

More precise estimates may also be possible. Individual tree species exhibit a characteristic ratio between crown diameter and bole diameter, hence volume, and a regression equation can be calculated allowing timber volume to be estimated from crown diameter. This relationship exists also for tropical trees (35, 52), where the crown-diameter : bole-diameter ratio is frequently 19–22 for shade tolerant species and up to 25–27 for less tolerant species (*e.g. Maesopsis eminii).* Dawkins (35) has shown how these ratios set an upper limit to the stocking of trees of any particular size above which crown interference and declining increment occur. At present, application of this principle in aerial timber inventories is limited by lack of information about the characteristic ratios and their variance, and the difficulty of accurately measuring the crown diameters of trees in and below the canopy of rainforest. These methods may utilize large-scale aerial photographs (1 : 600 to 1 : 3000) of selected sample locations from low flying aircraft with foliage-penetrating altimeters (113, 131).

Many measurements have also been made of total biomass in tropical forests, including its structure and distribution vertically and horizontally. These studies require detailed work in small plots, stratified according to site conditions as discussed by Brunig (22), although much can also be derived from less detailed work in permanent sample plots or inventories (36). Some studies have concentrated particularly on structure (architecture, spatial arrangement) and its significance (*e.g.* 57, 130, including African material), while many studies have involved both biomass and structure (72, 74 (Ivory Coast), 49 (Amazonia)). Some African studies have paid particular attention to below-ground biomass, which is most difficult to measure accurately (73, 80).

ANNEX 2

Examples of monitoring methods used

1.0 Introduction

In this section three of the types of assessment or monitoring of rainforests are described. These are cases where methods can be partially standardized.

Monitoring of rainforest cover: the method used in Ivory Coast to quantify the retreat of rainforest in 1956–1966 as described by Lanly (90).

Diagnostic samplings: a shortened and modified version of the field-instructions issued in Uganda for regular sampling of regeneration, after exploitation but before prescribing silvicultural treatment (69).

Continuous Forest Inventory with Permanent Sample Plots (PSP): a shortened version of the Uganda Forest Department Standing Orders for Natural Forest Sample Plots of 1971.

The Diagnostic Sampling and PSP techniques have been applied in slightly different ways in different countries. In particular, there are some differences in the PSP systems in Uganda, Ghana, Nigeria and the Malaysian States, and a version intended to retain their best features is being compiled by this writer. The methods described here are intended only to show the kinds of methods which are or have been applied locally as routine measures.

2.0 Monitoring the change in forest cover

The whole of Ivory Coast was covered by aerial photographs by the Institut Géographique National (IGN) at *c.* 1:50,000 in 1954–1957. From the photos, accurate measurements were made of the exact percentage of closed rainforest and the total area of the 'forest zone' (the southern region which characteristically had almost continuous cover of rainforest).

An inventory of timber was carried out by the Centre Technique Forestière Tropicale (CTFT), in 1966, and several sample strips of the forest zone (excluding the south-west) were covered by aerial photographs (panchromatic and infra-red) at *c.* 1:40,000.

On both sets of photos, it was possible to distinguish the limits of individual blocks of closed forest, using stereoscopic instruments.

The total area of the forest zone is *c.* 16 M ha, all of which was covered by the 1954–1957 photos. The coverage in 1966 amounted to 1.15 M ha on 558 photos, as strip-samples of 13.1 M ha of the forest zone.

A sample of 170 of the 1966 photos was studied in detail. In a central rectangle, equivalent to 1,500 ha, all areas equivalent to forest blocks larger than 10 ha were demarcated on each photo, and the total area occupied by such blocks was totalled, using a dot-grid.

On the 1954–1957 photos, the areas corresponding to each of these rectangles was accurately located and marked, and the total area occupied by forests of >10 ha was again measured. The change in the percentage forest cover between the two dates was calculated for each of the areas examined.

The results showed that the mean cover was 75 per cent in 1954–1957, and 53.6 per cent in 1966. The forest cover in the region inventoried by CTFT was 9.8 M ha in 1954–1957, so the estimated loss amounted to 2.8 M ha ± 350,000 ha.

The calculations and results were described in detail by Lanly, with critical comments on features of the local environment and analytical method which may have reduced the accuracy of the results. Rates of forest-clearance were clearly different in different regions, and highest near the forest-savanna boundary; more sampling in the worst affected areas would be appropriate. The analysis involved, in effect, two-stage sampling; first, in the strips photographed and secondly, in the individual photos selected for detailed examination; an appropriate analysis could have given a better estimate of the confidence limits of the calculated depletion.

The photographs showed that agricultural clearings were increasing most rapidly along roads and along new tracks built during logging operations. It appeared that extensive destruction consistently followed the opening up of new regions by timber exploitation, and it was noted that timber extraction had increased by *c.* 500 per cent between 1956 and 1966 (and it has increased further up to now, especially in the previously unexploited south-west).

3.0 Instructions for diagnostic sampling

3.1 Layout

3.1.1 Forests shall normally be sampled by transects at intervals of 20 m or thereabouts, running at right angles to the principal contours of topography and forest type.

3.1.2 The position of base lines and transects shall be drawn on

1 : 10,000 maps, and their bearings and numbers noted on the map. Diagnostic sampling maps shall be kept as part of the permanent Working Plan Records (WPR).

3.1.3 On each transect a central access line shall be cut and staked with numbered stakes at 10 m intervals. When sampling, temporary plots of 10 × 10 m (= 0.01 ha, 1/40 acre) shall be marked off along the lines as required, by using four sticks each 5 m long set out from the stakes on each side of the centre line and at right angles to it. These plots *must* be marked out accurately. When recording stocking, any trees on the plot boundaries shall be recorded only in alternate plots.

3.2 Sampling technique for routine assessments

3.2.1 Form for recording. A standard form shall be used for recording the stocking and silvicultural conditions in each 0.01 ha plot. Normally only one assessment shall be done in each plot, using a standard list of desirable trees appropriate for each area.

3.2.2 Leading desirables. Within each plot the largest sound desirable shall be recorded as the "first leading desirable" (1st LD) and the second largest sound desirable as the "second leading desirable" (2nd LD). If the largest desirable is unsound it shall not be recorded, but the next biggest sound desirable shall be taken instead. The following criteria shall be used to define unsound trees which must not be counted.

Trees of 30 cm diam. girth and cover
- (a) crown broken off by wind or felling damage;
- (b) severe rot;
- (c) forking or branching such that the tree will not produce one 4 m sawlog;
- (d) heavily fluted, twisted, or misshapen tree that will not produce one 4 m sawlog.

Poles and saplings
- (a) leader destroyed, and pole or sapling not likely to recover.
- (b) top bent over (*e.g.* by climbers) or whole stem growing at an angle from the vertical (e.g., due to impedence by shrubs or trees), such that the pole or sapling is unlikely to produce one sawlog.

3.2.3 Diameter measurement class. In each plot the first and second leading desirables shall be recorded in the following size classes:
Seedling (SD) — under 2 m high;
Sapling (SAP) — over 2 m high and under 5 cm diam;

Pole (P) — 5 cm to 10 cm diam.
Tree — 10 cm diam. class: 10 to 20 cm diam. at breast height
20 cm diam. class: 20 to 30 cm diam. at breast height
30 cm diam. class: 30 to 40 cm diam. at breast height
40 cm diam. class: 40 to 50 cm diam. at breast height etc.
Buttressed trees shall be measured above the buttresses. The designation SD, SAP, P, or the actual diam. class (10, 20, 30 etc.) shall be recorded in the appropriate columns for both first and second leading desirables.

3.2.4 Crown position. Exposure of the crown of the first leading desirable shall be recorded by using the relevant score number in the appropriate column.

Score 1. Crown completely shaded from above and on all sides;
Score 2. Crown completely shaded from above, but receives some side light;
Score 3. Crown only partly shaded from above and part receives light from above;
Score 4. Crown completely exposed to light from above, but not emergent;
Score 5. Crown emergent with exposure at least 45° all round from the base.

3.2.5 Impeders. Leading desirables with a crown score of less than 4 are shaded by other trees or vegetation, and in some circumstances even crown 4 trees may be impeded. In each plot the trees or vegetation that are impeding the first leading desirable shall be carefully recorded as follows:

(a) Climbers. (in column marked C) — W for woody climbers, and H for herbaceous climbers;
(b) Understorey trees and shrubs. (in column marked U) — tree species under 10 cm diam. and woody shrubs;
(c) Trees. — D for desirable species if sound, and (D) if defective. (It is essential to record whether or not a desirable impeder is defective). Undesirable species shall be recorded by name if known, or if not known as — W.

It is advisable to record all types of impeders that are having an adverse effect on the leading desirable, because various types of impeders often have very different silvicultural significance, and these may have to be evaluated separately when treatments are being determined.

3.2.6 Basal area enumeration

(a) In each plot number of trees (desirable and weed), together with shrubs and climbers, in each diameter class, shall be recorded in the appropriate columns of the form.

(b) Particular care shall be taken to record only trees inside the 0.01 ha plot. Trees actually on the boundary shall be recorded in plots with even numbers, but shall not be recorded in plots with odd numbers.

(c) Buttressed trees shall be measured above the butresses.

3.3 Sampling technique for special assessments

3.3.1 Assessment of highly desirable species. If it is thought advisable to sample using a list of desirable species restricted to a few timbers of high value, this can be done at the same time as the standard sampling, with the assessment on the basis of highly desirable species recorded for each plot on the line below the standard entry.

3.3.2 It may be necessary, in some forests, to select the most valuable rather than the largest desirable in a particular class (for example where the object of management is to produce high quality timber).

3.3.3 Assessment of regeneration. In some forests, the standard assessment may indicate that the amount of regeneration or its silvicultural condition require more detailed study, or perhaps it may seem advisable to assess regeneration by species. For such assessments the existing sampling field layout shall be used whenever possible with an appropriate plot size (0.005 ha, etc.) and field booking system.

3.3.4 If it is necessary to record numbers of seedlings or saplings, the maximum count per plot shall be restricted to a reasonable figure to give the information required (*e.g.* 5+ saplings, 2+ poles per plot).

3.4 Field organisation

3.4.1 A diagnostic sampling team normally consists of a recorder and three markers. Two men are responsible for placing the plot marker sticks and a third measures the trees to be recorded.

3.4.2 When the assessment of one plot has been completed, the rear pair of marker sticks shall be moved forward to demarcate the next plot, and a stake shall be placed at each corner. The observer shall record the 1st and 2nd leading desirables, with their size classes, and then the crown score and impeders of the 1st leading desirable. After that the basal area shall be measured and recorded by working systematically along each half of the plot. During this operation both marker men shall stand at the corners of the plot to indicate which trees are to be included, and the measurer shall girth trees as directed by the recorder.

3.4.3 At every tenth plot the recorder shall check carefully to make sure that all entries have been completed.

3.5 Equipment

3.5.1 Standard forms are used for recording in the field with a clip board. On the reverse side of this board shall be pasted a summary of diagnostic sampling instructions and the list of desirable trees for the forest type to be sampled.

3.5.2 Diameters will be measured with diameter-tapes. Buttressed trees will be measured above buttresses by tape or angle-gauge instrument or a diameter-stick.

4.0 Permanent Sample Plots in tropical rainforest (based on Uganda Forest Department Standing Orders)

4.1 Object

The primary object of establishing these plots is to calculate the increment and predict the volume of the future crop in exploited and/or tended forest. A knowledge of the standard error of these estimates is desirable, so a layout of stratified random pairs of plots has been chosen, with a systematic layout of blocks. The plots are not intended to estimate directly the stocking or yield of individual compartments but their increment data may be applied to an individual compartment by taking additional temporary samples to ascertain the actual stocking of that compartment and applying the general increment figures to this. They are to be samples in the true sense of the word — small representative parts of a much larger whole — and must be given precisely the same treatments as the rest of the forest.

4.2 Plot size, shape and distribution

Plots must be square, and of 1 ha each. Two plots must be sited randomly (and independently of compartment boundaries) within every *c.* 250 ha of tended productive forest.

4.3 Location

4.3.1 After siting a plot on the map, bearing(s) and distance(s) from the nearest or most convenient starting point must be measured on the map; the starting point must be easily re-locatable, *e.g.* where it is on a roadside or boundary the distance from some permanent and mapped landmark or corner must be measured, and it should be permanently marked.

4.3.2 From the starting point the access line must be cut according to the measurements taken from the map, and must be marked by direction trenches.

4.4 Selection of random position for sample plots in natural forest

4.4.1 Two plots 100 m × 100 m are selected from each block 1600 × 1600 m gridded into squares 100 m × 100 m. Each block therefore contains 16 × 16 plot positions. Two random numbers (one for each co-ordinate) are therefore required for selecting each plot.

4.4.2 The position of plots must be plotted on all copies of the Working Plan Management Map.

4.5 Numbering

All plots must be referred to by the Forest Reserve name, but numbering may be done serially by Compartment or Reserve. It is very important that plots should be laid down and measured in pairs.

4.6 Equipment. The following equipment is needed:

4.6.1 Siting

Map, protractor, one ha grid and metre scale (at scale of map), table of random numbers.

4.6.2 Location and demarcation

30 m chain, slope correction table, Abney level, compass, cross staff or optical instrument for laying out plot and quadrats, two hoes, four pangas, one sign board with the plot number for starting point of access line, aluminium nails.

4.6.3 Description and measurement

Description and measurement forms, carbon paper, HB pencil, plastic bag, list of desirable species, at least two 2 m and 5 m or 10 m diameter-tapes, ladders for buttressed trees, 30 aluminium labels for each of the numbers 1, 2, 3, 4; also for numbers 5 to 8 in the case of re-measurement, a hammer, 120 aluminium nails, some thin copper wire, ½ litre yellow paint in a stock tin, and two bins with wire handles, paint brushes, two lengths of webbing about 1 m and 5 m long, one wire brush for removing moss and loose bark, four timber crayons (and two red pencils if bark is wet).

4.7 *Staff labour and time*
Initial plot establishment and measurement will require the following men for 2 to 3 days.
One ranger, one guard, three painters and tree spotters, two other men (first on line cutting, then trenching). Re-measurement after a short period takes one day; after a long period takes two days.

4.8 Demarcation
4.8.1 The sides of the plot must be 100 m long, laid out N.S., E.W. The corners of the plot must be marked by "L" trenches. Along each side, four "T" trenches must be dug at 20 m intervals. The quadrats must be numbered serially clockwise starting with the one in the N.W. corner.
4.8.2 The standard of survey must be the same as that for forest boundaries and a closing error of 1 : 200 is permissible, *i.e.* 2 m in the 400 m of the perimeter. During the survey the boundaries between the quadrats should be marked on the perimeter. The internal lines are cut across the whole width of the plot, to strike the corresponding mark along the perimeter of the plot on the far side.

4.9 Description
When the plot is established an intial description form will be completed so far as information is readily available, *e.g.* soil pits need not be dug specially, the corner trenches being used for this purpose. The locality map and plot chart must always be completed. At re-measurements, new information such as change in the ground flora will be noted on the measurement forms.

4.10 Measurement
4.10.1 Within each quadrat the four "leading desirables" must be selected, identified, measured and labelled. These are the four desirables likely to have the greatest saleable volumes at the next felling cycle. They are therefore normally the *largest sound desirables that will last the rotation.*
4.10.2 All selected trees must be measured to the completed cm of diameter at breast height. If the breast height point is buttressed,

diameter will also be measured at 3 m from the ground. A tree of less than 1 cm diam. is recorded as 0.

4.10.3 The measured trees in each plot must be labelled by the appropriate aluminium number nailed with an aluminium nail to the stem at 2 m from the ground. Saplings too small to take the nail will have the label tied or wired loosely to them at a convenient height.

4.10.4 All measured trees will be painted at the actual point of measurement in such a way that the upper edge of the paint ring marks the position of the upper edge of the tape.

4.10.5 If the plot is established two or more years after poisoning, an enumeration of total basal area will be done (see 4.11.4).

4.11 Re-measurement

4.11.1 The first re-measurement of plots, in pairs, must be done two years after establishment and subsequently at the time of tending or every five years, whichever is the sooner; point of measurement marks must be repainted as often as this, or more often.

4.11.2 At re-measurement if one or more of the previously selected leading desirables cannot be found, replacement must be chosen and numbered 5, 6 etc.

4.11.3 Care must be taken not to miss a previously unselected tree which has now become one of the best four trees. The new tree should be measured and given a new number (5+), and the worst of the old ones discarded. The important rules are:

(a) the measurements of only the four best trees must be recorded;

(b) the same number must never be given to two trees in one quadrat, even if one has died;

(c) reasons for changes must be noted briefly on the measurement form, *e.g.,* "lost", "dead", "broken", "SS" = (superseded);

(d) trees must always be repainted and remeasured on the old paint ring.

4.11.4 (a) An estimate of the total basal area per ha. of all stems, including weeds, may also be obtained by a separate enumeration.

(b) All stems of 10 cm diameter and over will be recorded in 10 cm diam. classes.

(c) Buttressed stems may be classified by their diameter at 3 m.

(d) Dead trees are not recorded, but trees which have been poisoned and are likely to die should be booked with a P.

4.12 Booking

4.12.1 Standard forms are used for Description, Total Enumeration and Measurement of leading desirables in duplicate.

4.12.2 The desirables list should be that current at the time of measurement of the plot.

4.12.3 When booking, the tree numbers in a quadrat must be listed in numerical order *e.g.,* 1, 2, 3, 4.

4.13 Checking

A senior officer must do the original siting of the plots on the map, the preparation of instructions for their location, and subsequent checking that they have been properly located, demarcated and recorded.

ANNEX 3

Social and Ecomomic Links with Rainforests

1.0 Introduction

In a model of the place of rainforests in a national economy, it is important to appreciate the complex interactions which occur between the size of the forest resource, the size and purchasing power of the population and the wealth and effectiveness of the government. These result in very different patterns of silviculture, exploitation, conservation and new plantation.

It is misleading to make generalizations about what is happening in rainforests in Africa unless it is appreciated that they probably do not apply to any one country. The fate of forests depends partly on government policies, which are often similar in general aims but very different in execution, but also on financial and administrative resources and on the political, social and economic pressures in the population.

2.0 Affected features

The following rainforest features are affected by social and economic factors:

- (a) the intensity of management and silviculture;
- (b) the rate of destruction or conversion to agriculture;
- (c) the intensity and efficiency of utilization;
- (d) the rate of establishment of plantations;
- (e) the effectiveness of protection and conservation.

3.0 Main factors

The main factors affecting the fate of the rainforests are:

- (a) total rainforest extent, in relation to the local demand for timber;
- (b) human population in relation to the need for new farm land;
- (c) government revenue enabling development projects to be carried out;
- (d) government infrastructure, especially the effectiveness of the Forest Department, enabling policies to be put into effect;
- (e) the level of individual wealth controlling internal demand for timber;

(f) the level of foreign exchange balance determining the need to exploit natural resources.

Different intensities of these influences occur in many combinations in different countries, or even within one country.

3.1 Rainforest extent

Countries with a small forest area may be expected to reserve a larger proportion of the total than those with very extensive forests, other things being equal. However, this applies only when an effective organization exists for reserving and protecting forests. In practice, the current emphasis on plantation establishment is influenced as much by the financial and administrative resources of the government as by the extent of rainforests.

3.2 Population

High populations are invariably associated with a great pressure for forest clearance for agriculture. However, in countries with a high level of prosperity, a high population is also associated with a great demand for timber. If there is also an effective administration, it can result in an infrastructure of reserves, with controlled exploitation, supplemented by plantations; in other circumstances, a high population may result in massive and uncontrolled depletion of timber resources and conversion to agriculture.

3.3 Private incomes

Increased incomes are correlated with very large increases in demand for wood products. Public appreciation of the importance of timber supplies from forests, and the concern of the government with providing for the demand, are stronger in regions of high incomes. Areas of low incomes frequently have a social structure geared to forest clearance for subsistence agriculture with little interest in conservation of timber supplies.

3.4 Government revenue

The great disparity in incomes of governments in different countries has affected their attitude to large investments or even labour-intensive projects such as plantations for timber or pulp and paper (now partially counterbalanced by externally financed development).

3.5 Government infrastructure

Most anglophone countries in Africa have well-dispersed Forest Departments, capable of effective local control and protection of forests and associated activities. This has resulted in the establishment of numerous forest reserves which still largely retain their integrity although local excisions and additions are often made. In most francophone countries, effectively protected Reserves are on a very minor scale, reflecting a different tradition; forestry staff are only locally effective for protection and management, concentrated on areas of more intensive silviculture, with limited possibilities for influencing the large-scale survival or development of the rainforests.

4.0 National comparisons

A few comparisons between countries illustrate some of these points:

Nigeria has a dense population with a very high GNP and rich natural resources; the existing forests although large, cannot supply the national needs if managed by earlier methods; the country can afford to limit exports and invest in large plantation projects. Nearby Ghana has far less wealth, but the forests are extensive in relation to the population; the exports of timber are at a high level and plantation projects are relatively small.

In both these countries, forest reserves are large and numerous and protected by the local units of the Forest Department. In Ivory Coast, there are reserves, and rapid destruction of the forests is occurring.

Gabon, like Nigeria, is relatively rich in natural resources, and like Ivory Coast has little effective forest administration in outlying areas. Unlike these countries, however, Gabon has a very low population and the forests are not being destroyed on a large scale.

Kenya and Uganda have some similarities in their infrastructure and in their national wealth. However, the closed forests of Kenya are quite inadequate for the present or future needs of the country while Uganda is almost self-sufficient in wood-products except pulp and paper. Thus, in Uganda, much effort has been devoted to the silviculture and management of the closed forests, while in Kenya attention has been concentrated on plantations of conifers, often involving the replacement of indigenous forests.

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