資料 3.

MALAYAN FOREST RECORDS, No. 23

PART III.—NATURAL REGENERATION

SILVICULTURE AND FOREST MANAGEMENT

OBJECTIVES OF MANAGEMENT

Part III of this manual deals with the renewal of the existing natural forest crop by means of natural regeneration as opposed to artificial regeneration, which is dealt with in Part IV. A chapter, however, is enclosed in Part III on enrichment planting, which, as the name suggests, is defined as the *supplementation* of existing natural regeneration of desirable species when this is considered to be deficient.

A further major difference between the contents of Part III and Part IV lies in the desired end product. In the former this is considered to be a saw log of six feet girth at breast height, and the forests are actually being managed to this end. In the latter the consideration is that of research into the performance both of species with a future use as high class cabinet timber and of high yielding species suitable for paper pulp and for timber; and which are capable of establishment, if necessary, on sites unsuited to indigenous high forest species.

MALAYAN FOREST RECORDS, No. 23

PART III.—NATURAL REGENERATION

Chapter 1

SILVICULTURAL SYSTEMS

by

J. WYATT-SMITH

CONTENTS

CLASSIFICATION

A *silvicultural system* is defined by Troup (1928) as "the process by which the crops constituting a forest are tended, removed, and replaced by new crops, resulting in the production of forests of a distinctive form".

The following classification of the main system is based on that in British Commonwealth Forest Terminology, Part I, Appendix I, 1953, which was itself adapted from that by Troup.

I. HIGH FOREST SYSTEMS. Crops normally of seedling origin, either natural or artificial or a combination of both. Rotation usually long.

   A. Felling and regeneration for the time being concentrated on part of the forest area only:

      1. CLEARCUTTING SYSTEM. Old crop cleared by one single felling; usually artificial but natural regeneration sometimes possible by seeding from adjoining areas or from seed or advance growth already on the ground; resulting crop even-aged.

      2. SHELTERWOOD SYSTEMS. Systems of successive regeneration fellings. Old crop cleared by two or more successive fellings: resulting crop more or less even-aged or somewhat uneven-aged:

(a) Regeneration fellings distributed over whole compartments or sub-compartments:

i. *Uniform System.* Opening of canopy fairly even: regeneration interval fairly short and young crop more or less even-aged and uniform.

(*N.B.* A local adaptation of the Uniform System in many tropical forests is commonly known as the *Tropical Shelterwood System.*)

ii. *Group System.* Opening of canopy by scattered groups: young crop more or less even-aged.

iii. *Irregular Shelter-wood System.* Opening of canopy irregular and gradual: young crop somewhat uneven-aged.

(b) Regeneration fellings confined to certain portions of compartments or sub-compartments at a time:

i. *Strip System* (various). Felling in strips.

ii. *Wedge System.* Felling in internal lines and advancing outwards in wedge formation.

B. Felling and regeneration distributed continuously over the whole area: crop wholly uneven-aged with adequate representation of all age classes:

1. SELECTION SYSTEM. Trees removed individually over whole area; regeneration mainly natural and crop ideally all-aged.

2. GROUP SELECTION SYSTEM. Like the selection system but trees removed in small groups at a time.

C. Accessory systems, arising out of other systems:

1. TWO-STORIED HIGH FOREST SYSTEM. Form of forest produced by introducing a young crop beneath an existing immature one.

2. HIGH FOREST WITH STANDARDS SYSTEM. Form of forest produced by retaining certain trees of the old crop after regeneration is completed.

II. COPPICE SYSTEMS. Crops, in part at least, originating from stool-shoots (coppice) or by other vegetative means:

A. Simple Coppice Systems. Crop consisting entirely of stool shoots:

1. COPPICE SYSTEM. Crop removed by clear felling, even-aged.

2. COPPICE SELECTION SYSTEMS (various). Only a portion of the shoots cut at each felling: crop uneven-aged.

B. **Coppice with Standard System.** Crop consisting partly of vegetative shoots and partly of trees generally of seedling origin.

C. **Pollard System.** Crop consisting entirely of shoots from stems cut well above the ground.

MALAYAN SILVICULTURAL SYSTEMS

The above are the main classical and in general European systems but the classification and definitions as given do not necessarily fit tropical rain-forest. They certainly do not fit the system, the Malayan Uniform System, as applied today to the Malayan forests and to forests in Borneo where the Malayan system has been adopted, though the former Malayan Regeneration Improvement System is a tropical shelterwood system and a local adaption of the standard Uniform System.

The reasons for this divergence are many. Firstly there is in natural inland Malayan forests, as in most tropical rain-forests, a great diversity of species, many uneconomic, with different growth rates, so that even apparent even-aged converted forest is rarely even-sized or single-storeyed. Secondly, for the reason above, the removal of the economic timber crop in a single operation in mixed tropical rain forest, as in Malaya today, in no way leaves the ground in the same comparatively bare state as that found and universally expected and recognised to be the case in the Clear-cutting System. Thirdly the High Forest Systems defined above usually rely on seedfall subsequent to opening of the canopy to provide regeneration, whereas in Malaya today it is seedlings already on the ground, when the canopy is opened, which provide all or by far the most of the regeneration, although as indicated in Part I, Chapter 3 and Part III, Chapter 4 this most important and fundamental point was not fully accepted until after World War II.

Using the categories given in the classification above, the Malayan silvicultural systems, both pre-war and post-war, may thus be defined as:—

I. HIGH FOREST SYSTEM. Crops normally of seedling origin.

A. Felling and regeneration for the time being concentrated on part of the forest area only:

2. SHELTERWOOD SYSTEMS. Systems of successive regeneration fellings. Old crop cleared by two or more successive fellings: resulting crop more or less even-aged or somewhat uneven-aged:

(a) Regeneration fellings distributed over whole compartments or sub-compartments:

iv. (new). *Malayan Regeneration Improvement System.* Opening of canopy in successive stages; regeneration interval usually less than ten years; regeneration natural and from both advance growth and subsequent seeding; young crop of varying age but in general more or less uniform in size (*see* Part III, Chapter 3).

3. (new). MALAYAN UNIFORM SYSTEM. Old crop in virgin tropical rain-forest cleared by one single commercial felling followed immediately by systematic poisoning of unwanted species to release natural regeneration obtained from advance growth. Resulting crop more or less even-sized. A system for converting mixed tropical rainforest to more or less even-aged forest containing a greater proportion of economic species; managed under the Uniform System. (*see* Part III, Chapter 4).

The Selection System and accessory systems have been practised to a very small extent, but then only in a modified manner, and they really form part of the Malayan Regeneration Improvement System. The Coppice System is practised in some of the small experimental plantations. The Strip System was tried experimentally over a single compartment.

In addition to the above two silvicultural systems there were what were termed "Departmental Improvement Fellings" but these as explained in Part III, Chapter 2 were mainly concerned with improving the timber crop for future exploitation and were in fact treatment or tending and not regeneration operations.

Successful natural regeneration has been established by both Malayan Systems but a basic difference in financing the two systems was concisely stated in 1954 by E. J. Shrubshall (then Director) in a memorandum advocating the formation of a 'Forest Fund' to overcome the difficulties of financing long-term silvicultural operations from annually recurrent votes. The following paragraphs are quoted from this memorandum (No. 41 in D.F. 327/53A).

"5. Before the war, the silvicultural system in use in Malaya demanded the gradual establishment and growth of the young crop to sapling size, before the final removal of the old crop: from this it followed that:—

(a) Most of the expenditure for establishing the new crop was incurred *before* the revenue arising from the old crop was realised, and

(b) If funds were withheld or labour not available at any point, or if for any reason the young crop failed at any time before the removal of the old crop, there was always hope of the area being again naturally regenerated by seed from the remaining parent trees. This supplied a measure of silvicultural insurance against failure to establish regeneration.

"6. Modern methods of mechanised exploitation necessitate the removal of the whole of the old crop in one operation, and it has been established experimentally that this can safely be done provided that:—

(a) There exists on the ground a reasonably full stocking of seedling regeneration, well distributed throughout the compartment, and

(b) Adequate funds and labour can be provided for the subsequent tending of the young crop up to pole size.

"7. It will be seen that the present method of management has led to the unavoidable loss of the "silvicultural insurance" mentioned in 5 (b) above, and a financial guarantee is necessary against the failure of labour and funds for subsequent tending operations; for, if the young crop fails, there are no selected seed bearers left to seed up the area again, and in the last resort the area might have to be artificially regenerated by planting at greatly increased cost, or abandoned for timber production altogether."

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PART III.—NATURAL REGENERATION

Chapter 2

MALAYAN IMPROVEMENT FELLINGS. SALVAGE FELLINGS. SELECTION SYSTEM. STRIP SYSTEM

by

J. WYATT-SMITH

CONTENTS

MALAYAN IMPROVEMENT FELLINGS

Introduction. The early operations in the Malayan forests, and which took place primarily in Malacca, Negri Sembilan and Selangor, were primarily concerned with improving the existing timber crop for future exploitation. These were really treatment or tending and not regeneration operations, although the cutting of the undergrowth and in particular of bertam (*Eugeissona triste*) to assist taban (*Palaquium gutta*), Heavy Hardwood producing species, kapur (*Dryobalanops aromatica*) and red-meranti (many *Shorea* species) was also undoubtedly aimed at enriching the forest with these species by assisting their regeneration. The objects of the operations, as far as can be determined, were nowhere laid down but at the second Malayan Forest Conference in 1926 (Proceedings, p.57, para. 13) it was stated that "it seems that they are to bring the forest into such a state of stocking that some form of selection felling could be allowed."

System of Improvement Fellings in Selangor, 1910 onwards

Improvement fellings in Selangor are described by J. P. Mead (then Ag. Dy. Conservator of Forests, Selangor) in a paper submitted for discussion at the First Malayan Forest Conference, 1915 (Appendix V, p.35, of the printed Proceedings; 1916). He records that up to 1910 so-called improvement fellings had been made solely in favour of *tahan*, and that all undergrowth was cut over rectangular blocks except for *tahan*. This undergrowth cutting was abandoned in 1913 as it often gave insufficient assistance to the *tahan*, it was expensive and wasteful and areas which contained no *tahan* were frequently treated.

The system in force in Selangor in 1915 followed arbitrary rules as follows:

(i) For the *first improvement fellings*:—

(a) All inferior species, whose crowns come within 6 ft. of the crowns of any tree comprised in Class I of the Forest Rules 1909, to be felled or girdled unless the top of the inferior tree is below the lowest portion of the crown of the Class I tree;

(b) *Bertam* palms within a radius of 8 ft. of the crowns of any Class I tree to be cut;

(c) All creepers to be cut (except rattans) whether growing on Class I trees or not;

(d) Rattans to be left, even though growing on Class I trees;

(e) In all reserves a record of Class I trees 6 feet in height and over, freed or met with, to be kept (in two classes, 6 ft. tall to 3 ft. girth and 3 ft. in girth and over).

(ii) For *the second improvement felling* which usually took place after an interval of about 2 years, the same rules obtained but the distance in (a) was increased to 8 ft. and in (b) to 10 ft.

The advantage claimed was only that the rules were easy to carry out, though without constant supervision it was found that subordinates would "always clear undergrowth when there is no sylvicultural necessity for it, find it hard to understand that it is the crowns of the trees that must be looked to, and on several occasions have been found girdling an enormous tree for the sake of a little Class I seedling at its base." The main disadvantages were:—the expense of "going slowly through" the forest where Class I trees were scarce; no differentiation between Class I trees of different value, so trees like kapur (*Dryobalanops aromatica*) and chengal (*Balanocarpus heimii*) were left suppressed by kelat (*Eugenia* spp.), petaling (*Ochanostachys amentacea*) and medang (*Lauraceae*); partial cutting of *bertam* under the radius rule was ineffective; many girdled trees did not die; shade-bearers were assisted equally with light demanders and it was recognised that *merbau*, *chengal* and *meranti* are light demanding. The cost was about $3.50 per acre for the two treatments.

Mead considered that "improvement fellings were inadvisable along the tops of ridges, when *bertam* predominates, and in semi-swampy ground where usually only a few Class I trees are met." He stated that "Dipterocarpaceae seem to be most responsive to treatment."

System of Improvement Fellings in Negri Sembilan, 1911 onwards

A paper read at the 1926 Second Malayan Forest Conference (Proceedings, Appendix XII, p.73) describes the Kinsey and Clerk 'N.S.' (Negri Sembilan) improvement operations started in 1911 over 75 acres of compartment 1 Senaling Inas Forest Reserve where the undergrowth was mainly bertam (*Eugeissona triste*), palas (*Licuala* spp.) and other palms. The sequence of operations was as follows and, theoretically, treatments were to be carried out at five yearly intervals.

First treatment (1911). All *bertam* and other palms cut as nearly flush with the ground as possible and all climbers except rotans cut. A very little girdling is done to free and give light to existing Class I poles. These operations are carried out to secure natural regeneration of which there is little or none owing to the *bertam*.

Second treatment (1917). Similar to the first but Class II trees are felled or girdled where casting too heavy shade over Class I seedlings and saplings which have come in since the first treatment.

Third treatment (1924). All undergrowth is cut back again and all Class II trees are now either felled or deeply ringed, the girdle sometimes being treated with Atlas Preservative to hasten death.

There were heavy seed years in 1911 and 1915, and, in 1917/18, 83 overmature Class I trees were exploited which destroyed a number of Class I seedlings and saplings. The condition in 1926 was described as consisting of a fairly evenly distributed crop of Class I seedlings, saplings and poles (the predominating species being chengal (*Balanocarpus heimii*), balau kumus (*Shorea laevis*), seraya (*S. curtisii*) and meranti (many Light Hardwood *Shorea* spp.)), *bertam* almost completely disappeared and the regeneration best where *bertam* was thickest. Countings showed a substantial increase for *meranti* and *seraya* under 3 ft. girth from 1911-1925. The cost of the three operations was $11.93 per acre, the revenue from the overmature trees was $9.00 per acre and 2.7 trees per acre over 6 ft. girth of the above-mentioned four timber species remained.

Developments from Negri Sembilan and Selangor Systems of Improvement Fellings, 1915

The Selangor system was intended to improve the forest, not regenerate it and there was no mention up to the date (1915) of Mead's paper of any exploitation of the mature or overmature timber trees. In the Negri Sembilan system, however, the original object of the first operation was to secure an adequate supply of seedlings, the saplings and poles being dealt with in more detail at a later stage. The latter was considered inadvisable by the 1926 Conference as it "would be necessary to return to the area after a very short interval", whereas the intention of these improvement fellings appeared to be to increase the present timber crop for future exploitation and "as much as possible should be accomplished in a single operation". Another major difference between the two systems was that the Negri Sembilan system had no arbitrary rules as to the distance to which suppressed trees should be freed.

The conclusions reached at the 1915 First Malayan Forest Conference were that:

(a) Improvement fellings should, for the present, be in the nature of large scale experiments over definite areas which should be carefully described before work is started.

(b) The trees for whose benefit the fellings were made, should be one or more of the predominant valuable species to be chosen after a careful examination of the area to be treated.

(c) Before undertaking work on new areas, improvement fellings should be repeated in any area in which they have been started until the desired results had been attained or found impracticable. It was pointed out at the 1926 Conference (Proceedings, p. 57, para. 13) that the desired results were nowhere laid down "but it seems probable that they are to bring the forest into such a state of stocking that some form of selection felling could be allowed."

(d) Work should be carried out on silvicultural principles and not according to arbitrary rules.

(e) Planting in improvement fellings should not as a rule be carried out but experiments should be made to induce natural regeneration.

(f) Efforts should be made to exploit over-mature Class I and Class II trees of all sizes prior to carrying out improvement fellings. If this failed, over-mature Class I trees might be girdled.

(g) Climbers, with the exception of the more valuable rattans, should be cut.

(h) Damaged and unsound seedlings, saplings and poles of selected species should be coppiced.

It was, also, agreed that information should be collected on the light requirements and coppicing powers of the different species and the effect of girdling these; experiments should be made on eradication of bertam (*Eugeissona triste*); training given to subordinates; detailed costs kept of work done; and timber traders encouraged to experiment with more species.

Departmental Improvement Fellings, 1926

A. E. Rambaut in his review of the years between 1915 and 1926 at the 1926 Second Malay Forest Conference doubted whether any improvement fellings of this nature had been carried out in Perak and Selangor since 1916 and considered that in view of the demand for Class II trees in these States for firewood no more should be undertaken. He also doubted whether improvement fellings would be justifiable in other States since he considered that regeneration fellings would probably be more profitable. Nevertheless the conclusions of the 1915 Conference (see opposite page) were amended or confirmed as follows:

(a) No improvement fellings shall be made in any forests in which there is a possibility of a market for Class II trees within the next ten years nor in forests in which it would be impossible or inexpedient to exploit Class I trees if success is attained.

(b) Unchanged.

(c) In a given forest the result desired from the operations shall be laid down before the work starts; and, until this is attained, fellings shall be repeated at appropriate intervals. No new work shall be undertaken until all re-treatments laid down by the plan for the year have been carried out.

(d) Unchanged except for the addition of "as far as possible".

(e) Planting in improvement fellings should not as a rule be carried out if natural regeneration can be successfully secured.

(f) Deleted, as it was reported that in every case, felling over-mature trees had been abused.

(g) Unchanged.

(h) Omitted as it was considered that the staff were not sufficiently trained to decide what were damaged and unsound stems.

(i) New rule: no economical method of eradicating *bertam* had yet been discovered and for the time being improvement fellings should not be made in areas heavily infested with *bertam*.

Improvement of existing growing Stock, post World War II

The improvement fellings of *circa* 1915 (see pages III--2/2-4) were considered ineffective largely because they did not result in the establishment of masses of young regeneration, but Watson (1930) contended that these operations did cause a considerable improvement to the growing stock by releasing the larger advanced regeneration (poles of timber species and immature timber trees) from the competition of less valuable trees. Enumerations such as those described by Arnot (1932), and studies of virgin jungle (Wyatt-Smith; 1949) have shown that economic species in the 4 to 16 inches diameter classes are well represented, being about five times as numerous as economic species of 16 inches d.b.h. and larger. It has been suggested by Setten (1953) that improvement poison-girdling in forests not likely to be exploited for 10 to 20 years or more might be a highly desirable and economic treatment. The annual girth increment of the released poles and immature trees would undoubtedly be increased, so that trees in the 3 to 5 ft. girth class would be enabled to grow to commercial size (5 to 7 ft. girth) by the time fellings take place, thus developing a larger exploitable stand per acre. A pole crop of desirable species growing at a high increment rate would be established by the time felling took place and this, if not seriously damaged by the felling, would provide a further yield some 20 to 30 years later. It is hoped that an experimental area treated on these lines will be set up as soon as possible because it appears quite probable that forest which is likely to become accessible during the next 40-50 years may have been exploited before the timber demands can be met from mature areas of regenerated Forest Reserve carrying an enhanced economic volume (Policy; 1959). If forest can be cheaply improved now to give a considerably larger yield per acre in 20 to 30 years time, it may not only be profitable but may prevent an excessive future increase in timber prices, before the new crops are ready for exploitation.

SALVAGE FELLINGS

Timber fellings or 'salvage fellings' as they are often called have frequently been carried out in the past in abnormal partly-worked forest on the grounds of cleaning up the compartment and removing all economic timber. Unfortunately this has often been extended to include forest areas —usually very accessible—which were officially completely worked (and often passed as regenerated) but which owing to an incomplete subsequent poison-girdling still contained a number of large trees of species which in the course of the years and a change in market conditions have become economic, *e.g.* kempas (*Koompassia malaccensis*), mersawa (*Anisoptera* spp.), White meranti (species belonging to *Anthoshorea* section of genus *Shorea*). The realization of some extra revenue is attractive but silviculturally such fellings are most undesirable. In re-logging such areas not only is considerable damage done to the new crop through the construction of extraction tracks and the felling of the trees but much of the larger trees of the new crop are often marked for felling in error or illegally felled. Adequate control is always difficult and even poles of economic species have been known to be illegally removed or felled for extraction purposes. Further the natural succession is often set back considerably and development of such weeds as resam (*Gleichenia linearis*) and climbers encouraged.

Consequently it has now been laid down that no timber fellings between successive final fellings are now permitted with the exception of silvicultural thinnings and silvicultural canopy manipulation for regeneration purposes (*see* Part III, Chapter 5).

SELECTION SYSTEM

The Selection System has been advocated as the ideal Silvicultural System for tropical rain forest and has been discussed by Arnot and Landon (1937) and by R. C. Barnard, J. E. Cousens, G. G. K. Setten, J. S. Smith, J. Wyatt-Smith in Headquarters Bulletin 1951-52. From the ecological aspect, true selection forest (not forest managed under minimum girth or selective fellings) has a resemblance to natural forest but in practice and, as an original conversion operation, it is doubtful if the Selection System would be economic or practicable for the following reasons. The management of selection forest calls for a higher degree of expert supervision than uniform forest; extraction routes in tropical rain-forest quickly become overgrown or eroded unless continually maintained, making the frequent removal of small quantities of timber from large areas expensive; the absence of annual growth-rings in tropical rain-forest trees makes it impossible to estimate the current growth rate of any individual trees, so that the removal of the slower growing trees while retaining the faster growing ones, which is the basis of the selection system, cannot be done without regular measurement and records of every tree in the forest; damage to regeneration by crowns of felled trees is extensive (Wyatt-Smith *et al;* 1962); and improvement operations to assist the more valuable stems and regeneration would need to be repeated over the whole area at frequent intervals because any opening in the canopy is rapidly closed by adjacent trees of one storey or another. However, an investigation scheme to compare yields and costs of uniform with selection forest has been prepared and the study will be started when staff and funds permit. When the richer new crop matures at the end of the first (conversion) rotation, management by the selection system with some modifications may become a practicable proposition.

STRIP SYSTEM

A trial was also begun in 1927 of the Strip System (*see* Part I, Chapter 2). This was carried out in compartment 20, Parit Reserve, Perak. It had as its main object the determination of a system which would concentrate firewood working, reduce windfall and reduce the number of quick growing 'weed species' so prevalent in canopy gaps formed under the system of Commercial Regeneration Fellings. The regeneration improvement system then in force was considered responsible by the author of the trial for much of the wind damage and the consequent deleterious effect on the microclimate of having over-large gaps in the canopy after the first seeding felling; it was also hoped that the number of quick growing 'weed species' would be reduced by having a ready source of seed of high forest undergrowth and main storey species from trees of such species in the unfelled strips. An interesting secondary objection to the existing system was that it was likely to lead to a too high a proportion of meranti (*Shorea* spp. producing a light red grade of Light Hardwood timber) and that the timber of *meranti* species grown quickly in youth developed 'brittle heart'. A width of one chain for the cleared strip and one chain (richer forest) and two chains (poorer forest) for the unfelled forest was laid down. It was also decided that cleanings in the felled strips should consist of pulling up *all* seedlings and saplings less than 10 feet tall of the 'weed species' and of cutting the taller ones, and of cutting individuals of other Class II species only if within 6 feet (later reduced to 3 feet) of an individual of a Class I species. However the system proved a complete failure as regards the original objects since wind damage proved perhaps even greater and growth of *meranti* saplings was found to be faster. On the other hand the latter observation on *meranti* growth was a most important one and was possibly another factor in pointing out to the more cautious foresters that a uniform system was feasible and that the regrowth tangle in felled areas was largely ephemeral provided it was left alone. C. C. L. Durant, later to become the department's silviculturist, wrote in his diary for 19th July, 1934: —

> "Compt. 20 (The Wilkinson Strip Trial) is very interesting. It is now entering the *belukar tua* (old secondary growth) stage. There is a complete canopy some 30 ft. high and the soil is in good condition. The canopy consists principally of telinga gajah (*Macaranga gigantea*) but there is a surprisingly nice crop of *meranti* poles scattered fairly evenly over the area. These give the impression of having come up beneath the *telinga gajah* and now that the latter have slackened their height growth to be pushing through them. There is a very little seedling regeneration about but such as I did find—some meranti (*Shorea* spp.), rengas (many Anacardiaceae) and chengal (*Balanocarpus heimii*) appeared to be growing quite happily under a close canopy of *telinga gajah*. All this suggests that perhaps we are wrong in eliminating so vigorously these so called weeds in our cleanings Their function as nurses may be more effective than we have believed. This compartment is so interesting that it would be well worth while to have a silvicultural observation plot in it."

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MALAYAN FOREST RECORDS, No. 23

PART III.—NATURAL REGENERATION

Chapter 3

MALAYAN REGENERATION IMPROVEMENT SYSTEM

by

J. WYATT-SMITH

CONTENTS

INTRODUCTION

The pre- and immediate post-World War II system in force was, whatever the actual technique used, a conversion of the natural high forest by means of a shelterwood system. This was the foundation of the Tropical Shelterwood System which has been adopted by many other countries.

The actual technique depended on a number of considerations, chief among which were (a) the possibility of predisposal of the less valuable constituents of the crop in the form of poles or firewood, (b) the presence or absence of valuable Heavy Hardwood species in the overwood, (c) the amount of wanted regeneration already on the ground and (d) the marketing prospects of the main crop.

The methods employed could be broadly divided into two as follows: —

1. *Commercial Regeneration Fellings* (or *Scheme Fellings*) in which the regeneration operations—canopy breaking—was carried out by contractors or permit holders and at a profit to Government, and

2. *Departmental Regeneration Fellings* (or *Regeneration Improvement Fellings, R.I.F.*) in which the regeneration operations—canopy breaking—was carried out by the Forest Department and at a cost to Government.

There were various modifications of the above methods which have been described under such names as "Selection Fellings", "Selective Fellings", "Preliminary Timber Fellings" or more unkindly "Improvement Fellings in Favour of the Contractor", and "Key Tree Poisoning."

The rotation of the new crop was never emphatically stated until 1938 when an intensive management scheme was drawn up on the basis of a rotation of 130 years for areas under management for Heavy Hardwoods and of 70 years for areas under management for Medium and Light Hardwoods (see Part I, Chapter 3, Productive Forest Estate 1935-61). The latter rotation was largely based on a yield table for *Shorea leprosula* in which it was postulated that under early and repeated thinnings a final crop of ten stems per acre with a mean girth at breast height or above buttresses of eight feet could be attained in sixty-four years (Sanger-Davies; 1937), though Noakes (1937) suggested that it would probably pay to reduce the rotation for *Shorea leprosula* since the main crop volume appeared to culminate at fifty-two years and fall off sharply after sixty years.

Similarly no thinning schedule was established nor any serious attempt made to carry out thinnings on a large scale—the regenerated crops were, in general, still too young on the outbreak of the Second World War. Sanger-Davies, however, in his suggestion of a rotation for *Shorea leprosula*, the commonest economic Light Hardwood species in regenerated forest, recommended a thinning during the second cleaning operation *before* final felling, *i.e.* during the period of regeneration fellings. He recommended further thinnings during the cleaning immediately after final felling, and at ten, sixteen, twenty-five, forty, fifty and fifty-five years after final felling; and he postulated that the smallest dominant trees would reach 4 feet girth breast height at forty years, when they would become saleable as thinnings.

Details on the regeneration establishment period using the two methods of Commercial and of Departmental Fellings are given in full in the subsequent sections.

COMMERCIAL REGENERATION FELLINGS*

Introduction. The early development or history of these fellings or operations is described in full in Part I, Chapter 2. The method has also been given the name of "Scheme Fellings" in deference to the need for a working plan or scheme for any forest or working circle subject to such a comparatively fixed sequence of operations as indicated in the table below.

Sequence of Operations, Commercial Regeneration Fellings.

Symbol	OPERATION	Prior to 1926	Adopted at 1926 Conference	Normal sequence as stated in 1937 by Durant
		Year	Year	Year
P	Unmarked Class II poles (under 2 ft. girth)	n — 1	n — 1	n — x
S_1	First marked seeding felling of Class II trees	n	n	n
C_1 or CG_1 (Durant)	First cleaning and girdling	n + 1 or 2	n + 2 or + 3 (if necessary)	n + 1
S_2	Second marked seeding felling of Class II trees	n + 2 or 3 or omit (Selangor)	n + 4	n + 3
C_2 or CG_2 (Durant)	Second cleaning and girdling	—	n + 5 (always)	n + 4
F	Marked final felling of Class I trees	n + 3 or 4	n + 6 (if established regeneration verified in C_2)	n + 5
C or CG_3	Cleaning after final felling	n + 4 or 5	n + 7 (if necessary)	n + 6 or 7
Th_1	First thinning, etc.	?	?	? n + 10

The theoretical sequence of operations may be summarized as follows:—

Poles (P) felling according to the demand of the market.

First Seeding (S_1) felling starting in the year n.

First Cleaning (C_1) in the year n + 1 or n + 2.

Second seeding (S_2) felling in the year n + 4 }
Second cleaning (C_2) in the year n + 5 or n + 6 } These two operations may, in favourable circumstances be omitted.

Final (F) felling the year n + 8.

Third cleaning (C_3) n + 11.

In practice the second seeding felling can usually be omitted.

* The majority of this section has been taken *in toto* from the 1941 draft "Manual of Malayan Silviculture" by A. B. Walton.

Pole Felling (P). In this operation, unmarked poles (small trees up to a maximum girth of 3 feet) of inferior species are removed by contractors under permit. They are quite independent of Seeding Fellings and can be repeated as the demand arises.

The opening of the canopy thus achieved is usually slight, but probably helps a certain amount of regeneration to survive. The main object, however, is to obtain revenue from silviculturally valueless material, which would otherwise be destroyed in the process of felling the larger trees. Its practicability in Malaya is largely dependent upon the presence of gravel pump mines in the vicinity. Supervision by the forest staff is limited to insuring that no poles of valuable species are cut and that exploitation is not confined to the most accessible portion of the compartment. The former danger was originally not as great as might be thought, since the bulk of the pole growth in virgin forest consists of permanent constituents of the middle storeys that were of no significance as timber producers (*i.e.* they are not candidates for the top storey), and also because poles of the *meranti* type are neither strong nor durable enough for mining purposes. It was only in areas rich in Heavy Hardwoods that any very great vigilance was needed, and here it was necessary to insist on marking by the staff.

However with the introduction of sawmill conversion with a more catholic taste of what constitutes an economic species and of improved methods of extraction which required poles for crib-work in *panglongs** and as sleepers in light railways the danger and disadvantage of pole felling came to the fore. Still further the removal of most of the light crowned saplings of uneconomic timber species meant often the loss of the best fillers for the new crop. Great vigilance is essential. It is almost certainly not without significance that the stocking is poorest in the new crop in Selangor, one of the main mining States in the Federation (Wyatt-Smith and Abdul Majid; 1958).

No pole felling should be allowed in regenerated forest.

Seeding Fellings (S_1 and S_2). These are described together because they are similar operations and the second is frequently omitted. The object of the first seeding felling is to break the canopy sufficiently to allow existing regeneration to develop and is best attained by creating in the canopy evenly spaced gaps of from 25 to 40 feet diameter. It was originally claimed that this operation also prepared the ground for the germination of seed, but it is now generally recognised that virgin forest provides more suitable conditions and that when regeneration is scanty, it is desirable to delay opening of the canopy until a seed year has occurred. The volume to be removed in a seeding felling should therefore, be governed chiefly by the presence or otherwise of the desired regeneration. Should it be plentiful, a comparatively drastic opening of the canopy is indicated (see below) and the two seeding fellings may profitably be combined in a single operation.

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* Greased pole-constructed extraction track.

The permit holder is first required to lay out his extraction tracks to the satisfaction of the District Forest Officer. The trees to be felled are then selected and hammer-marked by the forest staff, the general principle being to create in the canopy at the end of the operations gaps of from forty to sixty feet in diameter by the removal of first the smaller and then the larger, stems of inferior species, followed, if silviculturally desirable and if the remaining timber crop is not thereby reduced to below an economic limit, by a proportion of the timber trees. Careful attention should be given to the regular opening of the canopy in preference to the elimination of trees merely because they are of low utility. Where regeneration is abundant or advanced, a large proportion of trees may be removed; if it be deficient the canopy should be kept correspondingly closer. If regeneration be plentiful, it is probable that so many trees will be removed in the first seeding felling that a second operation will be neither desirable nor commercially feasible. In any case it is always preferable, if the demands of the market permit, to delay the first felling until a seeding occurs, rather than be compelled to postpone the final felling in the hope of belatedly obtaining the necessary regeneration under adverse conditions.

In certain circumstances, notably in hill forest and other accessible areas where there is a selective demand for timber but where firewood working would be uneconomical, the treatment described may be modified by allowing the removal of a certain amount of timber in advance; in other words, the first seeding felling is achieved partly or wholly (according to the possibilities of disposal of inferior species) by removing some of the preferred species together with, or instead of, the unwanted ones. This method has the obvious advantage of bringing immediate revenue and has been variously described under the names "Selection Fellings", "Selective Fellings", "Preliminary Timber Fellings" or, rather unkindly, "Improvement Fellings in Favour of the Contractor", though actually it is nothing more or less than a seeding felling, for a gap is a gap, whether it is brought about by the removal of a worthless or valuable tree. Moreover the progeny of some of the more valuable Heavy Hardwoods, notably merbau (*Intsia palembanica*) and chengal (*Balanocarpus heimii*), which have heavy wingless seeds that fall directly to the ground) can profit only by the felling of the parent trees or of their immediate neighbours, so that the mere removal of the unwanted constituents of the crop is likely to do no more than give an impetus to the fast-growing Medium and Light Hardwoods, without helping the regeneration of the Heavy Hardwoods. Provided, therefore, that such initial timber fellings are properly controlled, are confined either (1) to areas on which regeneration either exists already or can confidently be expected from adjacent trees or (2) to forest from which the economic crop is rich enough to be financially attractive for removal in more than one operation, and that the fellings are followed up by cleanings and girdlings, there is no reason why they should not be completely successful.

Forests in which selective fellings can be instituted are especially those in which kapur (*Dryobalanops aromatica*), chengal, merbau, balau kumus (*Shorea laevis*) and balau laut (*S. glauca*) are common, and also especially in hilly forests.

In these timber fellings the most important rule to be observed by the marking officer is that no trees should be selected unless it has either (1) a plentiful supply of regeneration in its vicinity or (2) is one of a group of other timber trees of equivalent or greater value as seed bearers. After the felling is complete, the whole *productive* area should be given a cleaning in the undergrowth (*see* Part I, Chapter 3), but poison-girdling of the larger trees should be done only in the vicinity of regenerated felling gaps for a minimum distance of one chain and a maximum distance of five chains' radius from the stumps, or where there is young regeneration or advance growth requiring assistance. The disadvantages of 'patch' cleanings are discussed elsewhere (*see* Part I, Chapter 3) and in this operation they should normally be avoided. Several cleanings may be necessary before a crop is properly established and in any case the whole area should be treated a second time to insure that no regeneration has been missed, but, since the effective part of the operation is largely confined to the regenerated gaps and the groups of advance growth the average expenditure should be low.

This system is suitable for the small contractor, particularly those extracting logs by buffalo, and, if all goes well, the regeneration period may be allowed to extend over several years, cleanings being made when necessary, until all available trees have been marked. Strict forest control must, however, be assured. Fresh regeneration should permit the removal of additional stems after an interval of a year or two and, although complete conversion can hardly be expected after a single rotation, the method when properly applied is far safer and more economical than Departmental Regeneration Fellings (see page III--3/9) followed by half-hearted final fellings, particularly in hill forests and where intensive management appears unlikely or complete exploitation undesirable on account of the broken nature of the ground and the steepness of the hills. Recurrent selective fellings over the same area with only a short cycle should never however be permitted as it will quickly lead to degradation of the growing stock (see also Salvage Fellings, Part III, Chapter 2). A minimum felling cycle of thirty years is advised. Selective fellings should not be permitted in Forest Reserve if State Land forest is available, since it is extremely unlikely if productivity of the forest will be increased by such fellings, though on the other hand if properly controlled there should be no danger of the timber crop being impaired.

A modification of this system might be considered in localities, as in the eastern States, where only Heavy Hardwood species and a limited number of the normally commercial species are marketable. The fellings, marked as already described, would be followed by a survey of the extraction tracks, from which it should be possible to ascertain the extent of the felling areas and to demarcate them in compact blocks. These blocks, or sub-compartments, would then receive treatment, the remainder of the forest being left untouched.

First and Second Cleanings (C_1 and C_2). The seeding fellings are completed by cleanings (*see* Part I, Chapter 3) in which undergrowth, climbers and superfluous trees are eliminated. The object of these operations, the first cleaning is essential, is to provide the existing regeneration of desired species with the optimum condition for vigorous growth, and the following rules are suggested:

1. Cut all climbers, palms, wild ginger, bananas, *Eupatorium odoratum* and other weeds.

2. Where there is regeneration, cut all saplings of unclassified species up to a diameter of 2 inches. In the absence of regeneration a proportion of these, spaced about ten feet apart, may be left.

3. Poison-girdle all poles of inferior species up to 3 feet in girth, except where their retention is desirable for silvicultural or other reasons. The majority of these will be badly shaped poles for which there is no market.

4. Poison-girdle any trees which should have been removed in the seeding felling just completed but which were left owing to incomplete exploitation or lack of demand.

Final Felling (F). Some two or three years after the seeding felling and when regeneration is judged to be sufficient, the remainder of the timber crop should be removed. All trees to be felled should be hammer-marked to ensure the orderly exploitation of the area and to prevent the contractor from cutting only the most valuable species. The retention of exploitable trees because there is insufficient regeneration in their immediate vicinity is to be deprecated. Even if they should produce seed, the location and cleaning of the resulting regeneration would be expensive in such isolated areas and it would be unlikely to develop satisfactorily without assistance.

Cleanings after Final Felling (C_3). The first two cleanings are part of the seeding felling operation and should follow it without undue delay, but after the final felling, there should be established regeneration of, perhaps, two to four inches diameter and this should require no immediate assistance. It is preferable, therefore, to delay the C_3 operation for at least two or three years, by which time the felling gaps should have filled in and fresh growth, grass, herbaceous weeds and climbers will have been largely superseded by woody types and a dense young pole crop of mixed species. In this a *tebas* is neither necessary nor desirable and the cleaning is mainly a thinning, including commercial species and on the basis of a 6 feet stick thinning, and climber cutting coupled with the poison girdling of all the unwanted trees left after the final felling. It is at this stage that the claims of advance growth will have to be considered. Trees that were too small to be taken in the final fellings have frequently been left with the object of providing an intermediate yield, but it is doubtful whether the revenue so obtained is not more than offset by the damage done to the regeneration, which by that time should consist mainly of poles. It is, therefore, considered undesirable to leave such advance growth unless it can stand until the end of the rotation and is not hampering the development of more valuable regeneration. Speaking generally, advance growth of Heavy Hardwoods will be retained but advance growth of Medium and Light Hardwoods will only be kept if it in itself is sufficient to constitute full stocking at maturity. In Medium and Light Hardwood forest it is quite possible that no treatment apart from the girdling of the overwood, is necessary at this stage, experience having shown that established regeneration of *meranti* (Light Hardwood species of *Shorea*) can compete successfully with secondary growth. In Heavy Hardwood areas, however, this cleaning (aimed particularly at assisting the Heavy Hardwood regeneration), and perhaps a fourth, are required. The cost of C_3 should not exceed four man days an acre.

Special Treatment of Heavy Hardwood* Forests. Some modification of the usual commercial felling technique is necessary for the regeneration of Heavy Hardwood species, mainly because, being slower growing, they require a longer regeneration period and more assistance before the new crop is established. The following suggestions may help in the solution of this problem.

1. Preparatory treatment. After a general fruiting of Heavy Hardwoods, a preparatory cleaning in the vicinity of the mother trees may preserve regeneration that would otherwise die. This is perhaps worth considering only in lowland *chengal* forest where freshly germinated seedlings die off very rapidly, possibly owing to the dense undergrowth.

2. Early removal of mother trees. Abundant stunted seedlings often occur round mother trees which, in such cases, should be felled as soon as practicable, thus enabling the regeneration to develop in favourable conditions and to benefit to the full from the subsequent cleanings. Obviously if the seedlings cannot develop (and they do not develop under the parent tree) the routine cleanings do little good. The dormant seeds of *merbau* require sunlight for successful germination.

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* This refers principally to the balau group of the genus *Shorea*, Chengal (*Balanocarpus heimii*) and merbau (*Intsia palembanica*).

3. ATTENTION DURING CLEANINGS. Heavy Hardwoods should be favoured during cleanings and, although the light shade from most *meranti* probably does no harm, competing regeneration of dense-crowned species, even those of economic species, such as nyatoh (Sapotaceae), penaga (*Mesua ferrea*), meranti melantai (*Shorea macroptera*) and meranti sengkawang (*S. singkawang*) should be removed.

4. ASSISTANCE AFTER CLEANINGS. If, after the normal conversion operations have finished, the Heavy Hardwood regeneration is still not fully established and dominant in its size class, further help must be given. This may take the form of a C_3 repeated (in which only the Heavy Hardwood areas are treated) combined with such thinning as is desirable.

Marking Plans. In order to ensure full exploitation and prevent "frontage scratching", the progress of markings in seeding and final fellings must be shown in a plan of the compartment being worked. This is particularly important in the so called "Selective Fellings" described on page III—3/5. If topography allows, marking should proceed in a series of strips at right angles to the main line of extraction but, in any case, exploitation should reach the least accessible parts of the area by the time the operation is half finished.

REGENERATION IMPROVEMENT FELLINGS*
(Departmental Regeneration Fellings)

Introduction. Credit for the development of these operations, as well as for their abbreviated title—R.I.F.—must be given to Mr. A. E. Sanger-Davies, though the technique has been considerably modified since he first introduced them in 1927 in Negri Sembilan. The use of the word "felling", however, is really a misnomer, for the effect of seeding fellings is actually achieved by poison-girdling the unwanted constituents of the crop, which subsequently die and disintegrate with the minimum of damage to the underwood. The term R.I.F. was subsequently applied to the whole system of departmental (as opposed to commercial—see page III—3/3) regeneration, which is accomplished by combined cleanings and girdlings designated individually by the initials CG followed by a number indicating how often they have been repeated. The full sequence of operations is given in the table below, though it may be summarized as follows:—

CG_1 in the year n

CG_2 in the year n + 3 or n + 4 if necessary

F in the year n + 6 or n + 7

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* The majority of this section has been taken *in toto* from the 1941 draft "Manual of Malayan Silviculture" by A. B. Walton.

Sequence of Operations, Regeneration Improvement Fellings.

Symbol Hodgson	Symbol Durant	Operation	Normal sequence as stated in 1932 by Hodgson	Normal sequence as stated in 1937 by Durant
CG_1	RIF_1	First regeneration improvement felling (removal by poison-girdling of Class 2 species, combined with cleanings to assist Class 1 regeneration)	n	n
CG_2	RIF_2	Second regeneration improvement felling (mainly a retreatment of trees surviving first treatment, combined with cleanings to assist Class 1 regeneration)	n + 3 or 4	n + 2
C		Intermediate cleaning	if necessary	
F		Marked final felling of Class 1 trees	n + 5 to 8	n + 3 or 4
C	CG_3	Cleaning after final felling	as necessary	n + 5
	Th.	First thinning, etc.	?	? n + 10

First Cleaning and Girdling (CG_1). In principle the operation is similar to a commercial felling and consists of the gradual removal of the inferior species combined with cleanings to assist the desired regeneration, with the difference, however, that the low-grade material must be eliminated by Government agency in the absence of a market for it.

Assuming that regeneration or seedfall is present, and it generally is, the first step is a combined cleaning and girdling which disposes of all climbers, palms and miscellaneous unwanted undergrowth regeneration. The middle storey poles and small trees are poisoned and the canopy is opened by the selective girdling of trees unsuitable for timber production. The effect of the poison in the usual strengths (½-1 lb. sodium arsenite per gallon up to 1941, 1 lb. up to 1956, now 2 lbs.) being slow, the larger trees survive from six months to two or more years; where adequate regeneration is present, more trees may therefore be girdled than could safely be felled in a commercial operation. The slow death of the poisoned trees is, however, a source of danger, for the full effects are not immediately apparent and mistakes can easily pass notice.

The subordinate in charge must be capable of exercising discretion, for if rule of thumb methods are attempted they may easily result in the virtual elimination of the overwood in those portions that are deficient in seed-bearers of desired species and the replacement of high forest by useless secondary growth. It was because of this that Oliphant (1934) advanced his system of 'Key Tree Poisoning', which in essence was a *skilled selection* of the *minimum* number of trees to be removed in order to secure the light intensity desired as opposed to a rigid ruling of the elimination of *all* Class II trees. He further hoped that the traditional *tebas* or cleaning in the undergrowth could be eliminated and considerable economy made thereby.

The intensity of girdling in a CG_1 operation depends on the composition of the forest, the abundance of regeneration, and whether sawmill exploitation and mechanical or *panglong** method of extraction is likely to be employed. In rich forest, the removal of all inferior species will often not constitute an excessive opening and, if regeneration is plentiful, this may safely be allowed. Such instructions, however, should not apply over large areas in which islands of poorer forest are certain to be found and where trees of low utility must be retained to prevent excessive opening of the canopy. The principal timber species are normally the dominants, but it is unusual for them to form a closed upper canopy. Girdling should aim at retaining the slender crowned poles and a shelter wood of main crop trees with, ideally, gaps of from 20 feet to 40 feet between their crowns. The object of the opetration being to establish abundant regeneration while retaining the canopy in such a condition that the lower storey is under control and secondary growth conditions cannot become established (Walton; 1933).

Second Cleaning and Girdling (CG_2). The necessity for and intensity of this operation will depend on the results of the CG_1 and the prospects of disposal of the final crops. Since most of the unwanted constituents will normally have been eliminated in the former operation, the CG_2 will usually be in the nature of a cleaning only for the purpose of assisting established regeneration. If this is present in sufficient quantity and an immediate purchaser can be found for the final fellings, the cleaning may well be deferred until extraction has been completed, in which case it beomes a C_3. Similarly it may be possible to carry out a Seeding Felling (see page III—3/4) followed by a Cleaning (C_2) to remove part of the commercial crop, provided the amount for a final crop is not unduly depleted to make it financially unattractive.

Final Felling (F). When regeneration is sufficient both in size and quantity, the exploitable timber trees are felled and removed by contractors, as already described in the case of commercial regeneration fellings on page III—3/7, but the inaccessibility of departmentally regenerated areas is often

* Extraction by manually hauled sledge over a greased pole-constructed track and crib work.

the cause of selective exploitation on the part of the contractors, who take only the best and soundest trees of a limited number of species. In such cases it is frequently impossible to enforce complete exploitation and the silvicultural effect of the final felling may be very slight. Complete opening of the canopy could then be effected only by girdling the remaining stems at the sacrifice of much potentially valuable timber. This state of affairs was most prevalent in forests that are rich in Heavy Hardwoods (*e.g.* some of the reserves in Negri Sembilan) where silvicultural operations have been carried out, mainly to assist the regeneration of the valuable Heavy Hardwoods and where the Medium and Light Hardwoods in the final fellings are at a discount owing to the availability of more accessible supplies from State land.

In such circumstances the alternatives are either to poison the unsaleable timber trees or to allow them to stand in the hope that they will be marketable later. The decision must depend on the nature of the regeneration achieved and the possible interference of the overwood with its future development, but, generally speaking, the former alternative is preferable and false sentiment should not be allowed to upset the cycle of operations.

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PART III.—NATURAL REGENERATION

Chapter 4

MALAYAN UNIFORM SYSTEM

by

J. WYATT-SMITH

CONTENTS

Introduction. The Malayan Uniform System was first formulated into an approved system at the 1949 Conference of Malayan State Forest Officers and first appeared in print together with its important Linear Regeneration Sampling techniques in the July 1950 issue of the Malayan Forester (Barnard; 1950 (a) and 1950 (b)).

The important essentials of the Malayan Uniform System[1] in its correct form can be briefly described as the felling (and removal) in *natural* forest, in a short single operation over an adequate number of selected natural seedling regeneration determined by systematic linear sampling, of that part of the upper canopy which consists of the economic crop; to be followed immediately by the poison-girdling of the uneconomic balance of the canopy of commercial sized trees and of all the smaller trees and saplings down to a minimum girth over bark of 6 to 18 inches, other than those of economic species of sound form. A systematic sampling of all the trees of exploitable size is also frequently carried out at the time of the seedling regeneration sampling.

The above upper canopy removal is followed after 4 to 5 years (not later) by a systematic linear sampling of the stocking of young sapling regeneration of economic species and noting its stage of development, and after 10 years by a similar sampling of the sapling and advance growth of economic species. In both cases treatment is prescribed on the basis of the sampling *and a field inspection.* This ten year period is regarded as the *establishment stage* of the new crop, and the latter sampling forms the basis of of whether an area can be classed as having been successfully regenerated or not. The former sampling (LS½) is not necessarily considered essential in *meranti*-rich regeneration but any decision not to carry out the sampling must be based both on a known high percentage seedling stocking prior to timber exploitation and on a confirmatory field inspection by the District Forest Officer along a pilot line.

Tending aims at the development of several-storeyed, 'even-aged' forest with a balance stocking of emergent and main storey timber species. The thinning regime after establishment is very unlikely at present on economic grounds alone, other than in Kapur forest, to exceed three operations at a crop 'age' of approximately 20, 35 and 55 years. It will probably consist of two operations at about 20 and 55 years and may be only one at about 50 years. The rotation (period between successive final fellings) is estimated to be seventy years, though the ages of the crop trees will be variable owing (i) to the unknown age of natural regeneration on the ground at the time of final felling and (ii) to the retention of advance growth of economic species of whatever size *that is of sound form and shape and that can be expected to last the coming rotation of seventy years.* The crop is not expected to exceed twenty commercial trees per acre and the yield at the end of the conversion rotation is estimated to average at about forty tons of logs per acre.

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[1] It has been suggested that it should be defined in the revised book on "British Commonwealth Forest Terminology" as "A system for converting virgin tropical rainforest to more or less even-aged forest containing a greater proportion of economic species managed under the Uniform System. Achieved by a clear felling release of selected natural regeneration of varying age, aided by systematic poisoning of unwanted species".

The present management policy is one of definitely favouring the quicker growing lighter timbers; and the rotation of 70 years is based on the estimated time taken for the crop trees of economic Medium Hardwood and Light Hardwood species to attain a mean girth of six feet at breast height or above buttresses. (A *Shorea* individual of six feet girth has a log volume of about 120 cubic feet.) It is considered that trees of Heavy Hardwood species will in general require about one hundred and thirty years to reach crop size; and it is intended that individuals of these species will be left to take their chance amongst a favoured crop of Medium and Light Hardwood species on a double rotation of about 140 years. The exceptions to this will be the rare instances where an area is especially designed to the growing of Heavy Hardwoods.

Temperate zone forests may envisage the whole forest being laid bare as a result of the Malayan Uniform System. This is definitely not the case. The dying uneconomic trees that have been poison girdled, the advance growth of all sizes, the dense vegetative growth below the minimum poison-girdling girth and the tropical conditions which encourage very fast growth given full light provide an entirely different picture; the vegetation very quickly becomes denser than under natural forest.

History and Evolution of System. As has been stated in Part I, Chapter 2 the evolution of the Malayan Uniform System was due to the economic necessity of exploiting the forest in one operation owing to the introduction of mechanical extraction, to the cost of making roads and their high cost of maintenance under tropical conditions—all of which necessitated a high average financial yield per acre to recover the costs—and to the lack of demand for inland firewood. The demand for firewood had previously enabled pre-treatment of the forest to be carried out at a profit and had ensured establishment of regeneration through the opening of the canopy under a Tropical Shelterwood System or 'Commercial Regeneration Felling' or 'Scheme Felling'—as it was called. With the decline of the firewood demand a Tropical Shelterwood System had continued by Departmental canopy manipulation through girdling and poison-girdling of the unwanted trees; the system was called 'Regeneration Improvement Fellings'—*see* Part III, Chapter 3 for definitions. The reason for pre-treatment was largely due to the greater interest that was shown pre-World War II in the naturally durable Heavy Hardwoods which are not only shade tolerant but slower growing and are apt to succumb to intensive competition from other woody regrowth. The development of the sawmill industry and a corresponding greater utilisation of the tree species in the forest, the increasing use of preservatives and both field observations and research results that indicated the regeneration of the common Light Hardwoods was normally present in natural forest and could withstand competition from the intense comparatively ephemeral regrowth resulting from heavy canopy opening, all played their part in the post-war shift of silvicultural operations from pre-treatment and a series of fellings--Tropical Shelter Wood System--to one of a single felling and *post*-treatment--Malayan Uniform System--which had previously only been advocated for kapur (*Dryobalanops aromatica*) forest. This has to a certain extent spelled the doom of the formerly preferred Heavy Hardwood species with naturally durable timber, but it is expected that some of them will survive in open competition; further it is laid down that more frequent cleaning must be carried out in the early stages in areas containing very rich regeneration of such species and which management has laid down should be developed as Heavy Hardwood areas. The Malayan Uniform System is elastic enough to cater for this. The system is also sufficiently elastic to cater for any desired variation in intensity of canopy manipulation for any particular type of forest by means of either raising or lowering the minimum poison-girdling girth in the departmental operation or second half of the canopy manipulation, which is carried out immediately after exploitation has been completed, or even by delaying this departmental operation for a few years.

Importance of Seedling Regeneration. The key to the whole system is the *presence of seedling regeneration of the economic species on the ground at the time of exploitation,* though the complete and early removal of the canopy of unwanted species, the delay of any tending for a few years until the dense climber stage is passed and the maintenance of conditions to prevent a return to such a tangle are all important. However, the first and most important requisite above is an axiom, which although it would be thought would be natural enough, is unfortunately so often very conveniently forgotten or disregarded by forest officers on management grounds. In this respect the *standard* Malayan Uniform System is not as elastic as the former Tropical Shelterwood Systems. The latter very definitely followed the fruit or at least the seedlings of the better economic species, and this not only specifically enabled pre-treatment or the beginning of the series of regenerations to take place at the right time and over a sufficiently big enough area to cater for management demands during the anticipated period between successive good fruit years, but prevented final felling or the removal of the mature economic mother trees taking place before assessment and establishment of regeneration.

Treatment prior to exploitation. There is little reason other than slight conservatism, though economics are undoubtedly also a factor, to prevent the carrying out of canopy manipulation (including bertam (*Eugeissona triste*) control) *prior to the exploitation of the crop* to ensure the establishment of regeneration. This is particularly the case whenever a good fruit year of the more valuable species, such as meranti (Light Hardwood species of *Shorea*) and keruing (*Dipterocarpus* spp.), occurs.

After a good year seedling mortality is very high for the first two years; and seedlings of most of the common economic Medium and Light

Hardwood species do not survive longer than about seven years under dense shade. The conservatism is born from a mistaken belief that the change over from the earlier Malayan Regeneration Improvement System, with its successive canopy openings, to the present Malayan Uniform System was due to the needlessness of pre-treatment rather than to the necessity of removing the economic timber crop in a single operation. With the introduction of Working Plans, annual coupes are known well in advance and it should be possible to treat a sufficiently large area to cover the necessary coupes for a period of five to seven years. These coupes should of necessity exclude the intended coupes of the immediate forthcoming two years to ensure that all poison-girdled trees are not only dead but fallen and disintegrated before exploitation starts; felling in the jungle is hazardous enough without adding any further risk. Pre-treatment of this nature had been suggested by Watson (1938) pre-World War II in his proposals for the evolution of a suitable silvicultural system in forests exploited by sawmills. This is now recommended and will, it is hoped, become an integral part of the Malayan Uniform System (*see* Part III, Chapter 5).

Pole Fellings. The exploitation of stems of species that do not grow to timber size or are unacceptable as saw-logs if they do can be permitted before or during exploitation, *but never in regenerated forest.* Careful supervision must, however, always be given to the work since it is unfortunately true to say that in general it is the economic species that make the best poles. Pole fellings should certainly not be allowed under any circumstances to take place in forest under regeneration operations or in regenerated forest, since the saplings of even the uneconomic species are required as 'fillers' to ensure the best growth and form to the economic species.

Sequence of Operations. The following is a table showing the full sequence of operations in virgin or scarcely disturbed forest: —

SYMBOL	OPERATION	SEQUENCE
GCL (pre-F)	Poison girdling of dense-crowned trees of middle or lower storeys and if necessary of occasional uneconomic upper storey trees and cutting and poisoning of climbers	n−7 to n−2 (following good seed year only)
B	Bertam eradication (where necessary)	not less than n−3
LSM	Milliacre sampling of regeneration and location of Heavy Hardwood areas	n−1½ to n−½
EN	Enumeration of big trees	
F	Final felling (not to continue for more than two years)	n to n+1
GCL	Poison girdling of unwanted trees and cutting and poisoning of climbers	immediately after F

CG (HHW)$_1$	Heavy Hardwood designated area only: 3 ft. leaf-to-leaf cleaning and climber cutting in favour of HHW regeneration and poisoning of climbers	n + 2 to n + 3
CG (HHW)$_2$	Heavy Hardwood designated area only: Repeat of n + 2 to n + 3 operation plus thinning of 5-10 ft. tall HHW saplings with 4 ft. stick and 10 ft. tall with 6 ft. stick	n + 4 to n + 5
LS¼	Non-Heavy Hardwood areas: Quarter chain square sampling of saplings. (Not a vital sampling in known rich forest.)	n + 4 to n + 5
	No treatment (very unlikely) or treatment consisting of any of following:	immediately after LS¼
C	(i) Cleaning in the undergrowth and climber cutting and poisoning	
CL	(ii) Climber cutting and poisoning only	
G	(iii) Poison-girdling of unwanted trees (relics and commercial trees of bad form)	
PL	(iv) Planting of gaps including direct sowing	
GCL (HHW)	Heavy Hardwood designated area only: Treatment if necessary to maintain supremacy of HHW canopy. No cleaning in undergrowth.	n + 6 to n + 7
GCL (HHW)	Heavy Hardwood designated area only: Poison-girdling of undesirable competition and climber cutting and poisoning	n + 10
LS½	Non-Heavy Hardwood areas: Half-chain square sampling of saplings and advance growth. (An essential sampling.)	n + 10
Treatment	No treatment (very unlikely); alternatively treatment of any of (i-iv) under LS¼ above and limited selective improvement	immediately after LS½
R	Passed as regenerated if percentage stock at half chain square sampling > 60%	immediately after treatment
LSR (20) LSR (35) etc.	Half-chain square sampling of new crop.	n + 20 and at approximate intervals of 10—15 years. Thinning schedule not yet decided on.
Treatment	No treatment; alternatively thinning, or climber cutting and poisoning, or poison-girdling of undesirable competition.	immediately after sampling

Malayan Uniform System in practice 1950-1960. The above sequence of events, other than the suggestion of pre-treatment, has not changed since 1959 though in practice the sequence has extremely rarely been followed *in toto*. In 1960/61 some changes in the linear sampling technique were introduced.

The major reason for the former state of affairs is due to the inheritance of (a) the large acreage of incompletely worked pre-World War II areas managed under the former Tropical Shelterwood Systems (Malayan Regeneration Improvement System), and (b) the very extensive uncontrolled and selective timber felling which took place during the years from 1942-46. Exploitation and regeneration of these areas had to be completed first. Unfortunately the acreage of abnormal lowland forest then proceeded actually to increase. The ever-changing security situation from 1948 until 1959 during the Emergency resulted in sudden closures and equally sudden and unprepared openings---and therefore without milliacre sampling of seedling regeneration or timber enumeration--to absorb the displaced loggers and maintain the necessary timber supplies. Further the work in the forest frequently went completely unsupervised due to the shortage of senior staff, a high percentage of whom were seconded to other duties, and this resulted at times in highly selective logging. Staff naturally were also often reluctant, even if the security situation appeared to permit it, to carry out planned silvicultural treatment in the forest.

Changes in technique 1961. The recent changes in the linear sampling technique are as follows. These were brought into force with effect from the 1st July, 1961.

(a) A major change. The number of species' classes in Linear Sampling has been increased from three to four. List A comprises all the economic Heavy Hardwoods and expected slower growers. Lists B, C and D comprise the economic Medium and Light Hardwoods arranged in classes of preference — 'Preferred', 'Desirable' and 'Acceptable'.

(b) The overall number of species has been greatly expended though some of the poorer species, *e.g.* bayur (*Pterospermum* spp.), perah (*Elateriospermum tapos*) or ones with which uneconomic species are liable to be confused, *e.g.* kelat jambu (*Eugenia* spp.), penarahan arang (*Myristica* spp.), rengas (many Anacardiaceae), have been pruned. The list follows in general the revised edition of 'Ilmu Pokok-Pokok', which is taught at the Kepong Forest School, and includes the recently revised vernacular names.

(c) To cater for the increased size of the list and the inclusion of many species which the field staff may not yet recognise specifically, but which it is hoped they will in due course, symbols for vernacular groups of species have also been provided, *e.g.* nyatoh (Sapotaceae), bintangor (*Calophyllum* spp.), sepetir (*Sindora* spp.), ramin (*Gonystylus* spp.), kedondong (Burseraceae).

(d) Some vernacular name changes and symbols have perforce been made, *e.g.* the symbol for *meranti batu* is now MBU (formerly MBT), *kerantai* species have changed to KDKL and KDKB from KRT, *kelat samak* to SKP from KTS.

(e) Another major change is that the sampling of Heavy Hardwoods (Class A) and Medium- and Light-Hardwoods (Classes B-D) are being done completely independently for each quadrat whether milliacre, quarter-chain or half-chain square.

(f) Another important change is the splitting of the smallest size class* (seedlings less than 5 feet tall) into two, Class H0 (seedlings less than 1 foot tall) and Class H1 (seedlings of 1 foot and less than 5 feet tall). The size class was found to be too large to indicate growth of the regeneration, particularly that of Heavy Hardwoods.

(g) Size Class H10 will always be sampled for Heavy Hardwoods in a standard LS½, *i.e.* 10 years after final felling and Size Class H1 for Heavy Hardwoods in a standard LS½, *i.e.* 4-5 years after final felling commenced.

(h) No secondary tree will be chosen for HHWs, nor of course for Class B trees with the exception of kapur (*Dryobalanops aromatica*).

(i) The crown classification has been modified slightly in order to differentiate between the true Dominant chosen trees and those which are dominated by another Linear Sampling species. It is also now stated that relics of the old crop are to be ignored in recording crown classification, since the effect of relics is already being assessed and, if significant, will normally be dealt with anyway

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*The symbols of the size classes were changed at the end of 1962 from 1A, 1B, 2, 3, 4, 5, 6, 7, 8 and 9 to H0 ('H' represents height), H1, H5, H10, G½ ('G' represents girth), G1, G2, G3, G4, G5, and so on. This has been done to assist in memorising the size limits of the classes, *e.g.* Size Class H0 (formerly 1A) represents seedlings less than one foot tall, Size Class H1 (formerly 1B) seedlings of a height of one foot but less than five feet tall, G½ (formerly 4) saplings of 6 inches but less than one foot girth breast height, G1 (formerly 5) poles of one foot girth but less than two feet girth breast height, and so on. Size Class G5, however, represents trees of 5 feet but less than 6 feet girth breast height, G6 trees of 6 feet but less than 7 feet girth breast height and soon, whereas the former Size Class 9 represented all trees of 5 feet girth breast height and greater. The new system also has the merit of easily permitting future changes that might be required both in the range covered by any particular size class and in the introduction of new intermediate classes.

in any treatment prescribed. The purpose of recording crown classification is to determine the status of the regeneration *vis-a-vis* the other woody regrowth.

(j) Additional data on the effect of relics on the new crop are now obtained by recording the domination of a sampling square by a relic with a single cross (+) and of a chosen tree with two crosses (++).

(k) The preparation of summaries is a tiresome business and much of the necessary historical detail that they should contain has often in the past been unfortunately left out. Further, typing of three copies is still required after the field staff member's fair draft. To eliminate the typing required, and to reduce the chance of leaving out vital data, blank forms have been printed on sufficiently thin paper and in book form so that members of the field staff with the aid of single sided carbon paper and a ballpoint pen can produce free-hand the three copies necessary.

(l) The new forms provide for stocking analysis by Species' Classes and also into emergent and main storey categories for (a) the Heavy Hardwoods and (b) for Medium Hardwoods and Light Hardwoods. Provision is also made on the milliacre forms for Size Class HS regeneration which it may be profitable to enumerate in abnormal forest (former fellings), in balau laut (*Shorea glauca*) forest and in *kapur* forest; both these species are shade tolerant and in consequence there is usually abundant sapling advance growth present.

The new instructions and examples of completed sample forms, both field sheets and summaries, are included in Part III, Chapter 5.

Linear Sampling of Regeneration and Big Trees

The most important tool in the Malayan Uniform System is the linear sampling technique. This consists of a systematic sampling of the seedling regeneration (LSM) of the classified species that are present at the time of felling, and subsequently of the sapling regeneration (LS¼ and LS½) and its development status during the regeneration period (*see* Part III, Chapter 5). In addition, it is laid down that a sampling of the commercial size trees should be undertaken prior to allowing timber felling (*see* Part III, Chapter 5). And recently a sampling method based on the half-chain square quadrat has been developed for diagnosing the necessary silvicultural treatment required in crops passed as regenerated (LSR).

Owing to the lack of information on forest and soil types and since sampling is carried out essentially for *management purposes*, over comparatively small blocks of forest—Forest Reserves are, in general, divided into compartments or units not larger than 400 acres—and often in broken hilly country, systematic sampling has been retained for the present in preference to stratified random sampling (Vincent; 1961). The technique is simple, cheap and effective and provides the necessary quantitative data, plus an adequate coverage of the whole compartment from which a map can conveniently be produced, to aid the District Forest Officer *in the field* in his management decisions.

It has not been sufficiently realised how elastic is the sampling technique for regeneration, that its success depends entirely upon sampling the correct size classes and that in abnormal forest, which as has been pointed out earlier has to-date been the type of forest most treated, it is not only the number of years that have lapsed since canopy opening that determines sapling size but the intensity of the canopy opening. In consequence not only has LS¼ often been carried out when LS¼ would have been preferable and *vice versa*, but advantage has not been taken of using a wider range of size classes than that laid down for standard sampling in normal forest. The absolute necessity in abnormal forest of a preliminary *field inspection* to decide on the type of sampling has not always been adequately realised or at least executed.

(a) **Milliacre Regeneration Sampling (LSM) and Big Tree Enumeration (EN) Stocking and opening to exploitation.** Forty per cent or four hundred per acre well distributed samples (milliacres) stocked with seedling regeneration in LSM has been arbitrarily taken up to the present as adequate, until research proves otherwise, to regenerate an area. If present, timber felling is invariably permitted according to the limits set out in Working Plans. (In practice, however, few areas opened to felling have had until recently a milliacre sampling except in Kedah (Wyatt-Smith *et al.*; 1958) and, even if carried out, have had the timber felling postponed when the percentage was found to be less than forty. And even fewer areas have had an enumeration of the large trees, though the omission of this is not vital (see Part III, Chapter 5).) A dividing line of forty per cent. is naturally by itself not a particularly satisfactory method to refuse or permit opening to timber felling, especially on the very lengthy and comprehensive linear sampling list of classified species. This list includes many species which are barely commercial and also some vernacular names incorporating groups of botanical species some members of which do not or rarely reach timber size. A low percentage with a very high percentage of the more valuable species is undoubtedly preferable to a high one swollen by the less valuable species. The species represented in the stocking must, therefore, be closely studied.

On the basis of the few examples to date where LSM and LS¼ have been carried out over the same compartment and where the forest has been managed under the Malayan Uniform System, Wyatt-Smith (1960) suggests that, until further information is available the arbitrary percentage stocking standards of 'adequate' regeneration could be changed to 30% for LSM when using the revised 1961 Linear Sampling list of species, coupled with a minimum overall percentage stocking of 20% for Class B and C species of the total number of quadrats sampled.

It is sometimes impossible to delay timber felling on management grounds whatever the percentage stocking. On the other hand it is reprehensible to open an area to felling, but regrettably occasionally the case, if regeneration of the better timber species is scarce but an enumeration or field inspection has shown that seed-bearers of such species are present in fair quantity. The Malayan Uniform System is not only dependent on natural regeneration but forest management is planning to obtain from regenerated forest an average yield more than 2 to 3 times greater than that from natural forest. This cannot be obtained if natural regeneration is absent unless a costly and extensive enrichment planting programme is carried out, and this for many reasons appears unlikely to occur, at least for some years.

(b) Milliacre Regeneration Sampling (LSM) and Heavy Hardwood Areas. It was laid down in the 1954 Silvicultural Manual that where milliacre sampling had shown that there was a sufficient acreage of regeneration of Heavy Hardwood species to justify intensive treatment such treatment must start within two years of felling. In practice no area has been so designated, although over many forest areas regeneration of Heavy-Hardwood species are common and undoubtedly in several cases such designation and subsequent treatment should probably have been given. In the 1961 revised version of Linear Sampling with dual sampling along the same line the comparative richness of an area with Heavy Hardwoods *vis-a-vis* Medium and Light Hardwoods can be easily determined and the relative merit of future management decided on.

The present policy is one of favouring the quicker growing lighter timbers and letting the slower growing and somewhat shade tolerant Heavy Hardwoods take their chance.

(c) Quarter-chain Square Sampling (LS¼) (see also under LS½ below). The quarter-chain square sampling is designed to determine the stocking and status of the young sapling regeneration taller than five feet and of a girth less than twelve inches and which it is estimated will have reached this size in normal forest some four to five years after timber felling was initiated. It has only been very infrequently carried out and then generally in former selectively felled or incompletely worked forest, where it can prove extremely useful in assisting a decision on treatment. LS¼ is not considered to be a vital sampling in normal forest, in particular Red Meranti-Keruing forest, and can in most of these cases be conveniently omitted. Sixty per cent. or 96 per acre well distributed samples (quarter-chain squares) stocked with sapling regeneration has arbitrarily been taken up to the present as being adequate, until research proves otherwise, to regenerate an area. On the basis of the very few examples to date where LSM and LS½ have been carried out over the same compartment and where the forest has been managed under the Malayan Uniform System, it has been suggested (Wyatt-Smith; 1960) that until more data are available a figure of 55% when using the old Linear Sampling list and 50% when using the revised list can be accepted, though in the latter case it must be coupled with a minimum overall percentage stocking of 40% for Class B and Class C species of the total number of quadrats sampled.

(d) **Half-chain Square Sampling (LS½).** The half-chain square sampling was designed to sample the stocking and status of the sapling regeneration greater than six inches girth some eight to ten years after felling had ceased in normal forest. Its use to date has been confined to very abnormal forest and to forest worked under the former shelterwood system to determine whether the area can be regarded as regenerated and to assist in the prescription of silvicultural treatment. Regeneration of the requisite age derived from normal forest managed under the Malayan Uniform System is not yet available. Seventy-five per cent. or 30 per acre well distributed samples (half chain square) stocked with regeneration has been arbitrarily taken as being adequate, until research proves otherwise, to regenerate an area. On the other hand it has more recently been suggested (Wyatt-Smith *et.al.*; 1958) that a stocking of 24 per acre (60%) well distributed samples would probably be a more realistic *minimum* figure, and *provided half of this stocking comprised Class B or Preferred species;* and this is the *minimum* figure advised today on the present list of Linear Sampling species and treating Class A and Classes B—D species independently; but the aim still remains very much higher.

(e) **Choice of Sampling.** In forest not passed as regenerated and where the forest or regeneration is irregular or abnormal, a preliminary field inspection is necessary to decide whether milliacre, quarter-chain square or half-chain square sampling is most suitable for the size of the regeneration, and what size classes are to be recorded.

The size range described above under LSM, LS¼ and LS½ are those suggested for forest managed under the Malayan Uniform System in its entirety. In abnormal forest there are invariably a large number of relics of all sizes and economic species, many of very poor form, apart from regeneration of all sizes due to different canopy densities and periods that the canopy has been opened up. In normal forest this should not occur, though in practice it has often been difficult to persuade the field staff to girdle a classified timber species of poor form; similarly it is equally difficult to persuade them not to select such individuals as the chosen trees. The use of LS½, with no upper size limit for the chosen tree, can within abnormal forest give a very false impression of the value and composition of the regeneration (Cousens; 1958), therefore the upper size limit is now restricted to less than five feet girth at breast height (Class G4) for all samplings at ten years after completion of final felling. It is also recommended that LS½ with a higher size limit than is customary for normal forest is preferable in abnormal forest and that it should, if possible, be combined with an enumeration of the commercial size trees.

(f) **Linear Sampling of Regenerated Forest (LSR).** The existing half-chain square sampling technique (LS½), which was designed to determine whether an area could be regarded as regenerated and to assist in the prescription of silvicultural treatment, proved inadequate for regenerated forest, and a new technique for diagnosing treatment in such forest has very recently been developed. It is based on the half-chain square sampling technique, but (i) no separate sampling of Heavy Hardwoods and of Medium and Light Hardwoods is undertaken, (ii) the stand density by species and species' groups (LS, non-LS, relic and weed) is recorded, and (iii) the degree of treatment necessary in the crop is assessed (*see* Part III, Chapter 5, Linear Regeneration Sampling).

(g) **Prescription of Treatment.** A detailed inspection of the compartment by the District Forest Officer with the sampling results in hand, is essential before prescribing what treatment, if any, is to be done and when (*see* Part III; Chapter 5). If the District Forest Officer is inexperienced he should be accompanied by the State Forest Officer.

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MALAYAN FOREST RECORDS, No. 23

PART III.—NATURAL REGENERATION

Chapter 6

ENRICHMENT PLANTING

by

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CONTENTS

Introduction

Compared with other tropical regions of the world the rain forests of South East Asia are generally endowed, fortunately for the forester, with a large amount of natural regeneration of the economic timber-producing species. Malayan forests are no exception to this generalisation; and it is the accepted policy *today* that the new crop will be attained, as far as possible, by natural regeneration under a Uniform silvicultural system. There are occasions, however, when the natural regeneration of desirable species present is considered to be inadequate and alternative means of obtaining an economic crop by artificial regeneration must be considered.

The intensity of artificial regeneration can be divided into two broad categories:

(i) The establishment of regular plantations, often by means of exotic species, which is described in Part IV, Artificial Regeneration, of this manual, and

(ii) The enrichment of areas naturally poor in desirable species, which is described in this chapter.

Definition

Enrichment planting, as the name suggests, is defined in Malaya as the *supplementing* of existing natural regeneration of desirable species when this is considered to be deficient. It does not normally entail the planting of completely deforested areas nor areas formerly cleared of forest cover and revegetated with secondary vegetation or scrub (for these see Part IV, Artificial Regeneration). It entails the enrichment of high forest, though forest from which the currently commercial timber has been removed or that which is considered too poor to be economic to exploit, apart from commercial thinnings, within the rotation of the planted species.

Conditions meriting enrichment planting

Economics permitting, the present conditions under which enrichment planting should be considered are:

(i) Where at the end of the ten year establishment stage of the new crop under the Malayan Uniform System, sampling by means of LS½ has shown an inadequate stocking of regeneration. It is impossible to give an overall definition of what is meant by 'inadequate'; it all depends upon the amount of regeneration and its composition, the forest type and the District (*see* Part III, Chapter 5, Interpretation of Linear Sampling Summaries).

(ii) In all, small, clear felled or deforested areas such as log yards, *kongsi* sites and abandoned small cultivation areas. Areas should not be greater than five to ten acres. Planting should not take place until some woody regrowth has begun to cover the area.

(iii) Where sampling, prior to timber felling, has shown a grave deficiency in seedling regeneration of economic timber species, but timber felling has perforce not been delayed on account of management considerations.

(iv) Where sampling, prior to timber felling, has shown a grave deficiency in seedling regeneration of economic timber species *and* in potential seedbearers to the extent that either timber felling was not worth delaying or no commercial exploitation was worthwhile.

It must be fully realised at the outset that enrichment planting is only really feasible under a Uniform System and *then only after the economic timber crop has been removed* or where, apart from commercial thinnings, no exploitation will be carried out within the rotation of the planted species.

Problems confronting enrichment planting

The problems confronting enrichment planting are:

(i) Seedling stock supply. The absence of any real definite seasonal change in the wet tropics militates against any regular flowering and fruiting; and the emergent trees, which comprise the majority of the economic timber species, are probably even more irregular and more sporadic in flowering and fruiting than trees of the lower storeys. Moreover the period of viability of the seed of most of the economic species, and certainly the Dipterocarps, is short. In consequence a regular supply of seed for a nursery cannot be depended on, nor is it possible to predict when seed will be available (*see* Part IV, Chapter I, Objectives of Planting and Chapter 2, Choice of Species). Planning an enrichment planting programme is therefore not possible, though fortunately local variations within Malaya as a whole do often result most years in some flowering and fruiting of a species, even of Dipterocarps.

A short and fairly consistent dry season occurs in the extreme north-west of Malaya and flowering and fruiting is more regular, but apart from *Dipterocarpus kerrii* and *Schima noronhae* none of the favoured species occur in this area. It is possible that cold and/or gas storage might prove suitable in prolonging the viability of seed, and research into this is being considered.

(ii) Wildings. Large wildings have not been tried on an experimental scale in Malaya, but the few individuals tried have not been a success. Seedling wildings of about twelve to eighteen inches in height have been tried in several instances for a few species, and in particular with kapur (*Dryobalanops aromatica*) on an extension scale and keladan (*D. oblongifolia*) on an experimental scale (Barnard and Setten; 1955), but not with a great deal of success. Moreover the success has been achieved with young seedlings comparable in size and probable age to nursery raised stock. Thus it was found with *keladan* that the period between seed fall and transplanting should not exceed eighteen months and the best height growth was obtained from wildings transplanted between six and twelve months after seed fall (Barnard and Setten; 1955). Since seedlings in the jungle suffer a great mortality rate during the first two years, the forest floor cannot serve as a continuous annual source of supplies of stock. A planting programme can therefore depend no more on wildings than it can on nursery raised stock.

(iii) Vegetation density and height. Normally enrichment planting is not decided upon until the end of the ten year establishment stage of the rotation and as a result of half-chain square sampling. Exceptions to this are those occasions described in sub-section (ii) of the preceding section, and when milliacre sampling prior to felling showed the area to be extremely poor but for management reasons felling could not be postponed. In consequence there will generally be present a dense twenty to thirty feet tall thicket, which is overtopped here and there by retained advance growth of economic species. The latter, however, will undoubtedly be very sparse, if the area is so poor as to merit enrichment planting. And it is in this dense mat of regrowth, often including many climbers, that the seedlings will have to be planted, conditions which are definitely not favourable to seedling development.

(iv) Size difference between newly planted seedlings and ten years or more old natural regeneration. Any planting in ten years old secondary growth brings out the problem of the relative difference in size between the seedlings planted and the larger natural regeneration present, and that both groups require different and conflicting treatment (*see* section on 'Planting' in this chapter).

(v) Costs. Costs are high in all artificial regeneration that is carried out, and the object should always be to achieve the most valuable crop feasible as cheaply as possible.

Raising nursery seedlings and planting them out under suitable conditions is expensive, c.f. natural regeneration, and the cost within small limits remains the same for all species. In consequence it is naturally essential to choose species with a known high economic potential, in addition to such qualities as low potential costs for beating up, establishment and tending.

Silvical characters of ideal enrichment planting species

The following are the silvical characters which go to make an ideal enrichment planting species. The characters listed are not in any order of preference, but those starred with an asterisk are considered to be the most important.

*(i) Frequent flowering and fruiting, and hence a ready seed supply.

(ii) Easy seed collection.

(iii) Reasonable period of seed viability, *i.e.* not less than one week.

(iv) Good percentage germination.

*(v) Easy handling in the nursery.

(vi) High percentage survival on planting out.

*(vii) Fast height growth in the early stages.

*(viii) Tolerant of reasonable amount of shade and side competition.

(ix) Either indigenous to the country and to the type of site, or a proven exotic species with many of the desirable characters and in particular that of exhibiting successful natural regeneration in Malaya.

(x) Good natural bole form.

(xi) Naturally self-pruning.

(xii) Naturally gregarious.

(xiii) Low crown diameter/girth breast height ratio.

*(xiv) Rapid growth in girth or fast volume producer.

(xv) Normally free from insect and fungal attack of all kinds.

*(xvi) Producer of valuable poles in thinnings.

*(xvii) Producer of timber of high or above average economic value.

Methods

The methods employed for enrichment planting are by Line or Group planting. Of these two methods the former is the simpler to carry out and to control subsequently; the latter, however, offers more protection to the plants if browsing game are a problem, which is very rarely the case in Malaya, and in addition plants require less individual attention (Ironside; 1954).

(i) **Line planting.** This consists of clearing, from a convenient base line (or base lines), about four feet wide parallel lines in the undergrowth at predetermined regular horizontal intervals. It has been suggested that the cleared lines should, as far as is possible, be orientated in an east-west direction to obtain the maximum number of hours of sunshine (Foury; 1956). In undulating and steep country it is undoubtedly easier to cut lines across the contours, though cleaning operations are obviously more convenient along the contours; access will probably decide the final lay-out. It is not essential that the pattern of line direction should be uniform throughout a forest block. A plan of the layout of the cut-lines must be prepared for record purposes. A rough stake should be inserted by the cutting gang at each proposed planting site.

(ii) **Group planting.** This method requires a similar initial lay-out and clearing as with line planting though lines need be no wider than two to three feet. Extra clearing will, however, be required at the group site and its extent will depend upon the number of trees in the group. A rough stake should be inserted by the cutting gang at the centre of each proposed group. The arrangement of the plants within a group is immaterial as long as it is compact. The distance between plants within a group should be about three feet, and the number of plants within each group should be sufficient to ensure the eventual survival of one individual. The arrangement of groups should be square.

Suggested species

No species in Malaya fulfils all the desirable silvical requirements listed earlier in this Chapter, but some species fulfil several of them (Unpublished data at the Forest Research Institute, Kepong; Edwards; 1930 and Vincent; 1961a, b, and c). These species in order of importance (and including four possible unranked exotic species) are given below; full details are provided in Part IV, Chapter 2, Choice of Species. Unless specified the species are recommended for flat, undulating and hilly terrain. Today, on productivity grounds, no Heavy Hardwoods should be planted, though in the past, and as early as pre-World War I, chengal (*Balanocarpus heimii*) and to a minor extent merbau (*Intsia palembanica*) were successfully line planted, *e.g.* Baloh F.R. (chengal, 1906-09), Kepis F.R. (chengal, 1906-12) and Senaling Inas F.R. (merbau, 1907-09).

(i) Indigenous species (in order of importance)

Dryobalanops aromatica
Agathis alba
Dipterocarpus spp. (except *D. apterus*, *D. crinitus* and *D. oblongifolius*) and especially *D. baudii*, *D. costulatus*, *D. grandiflorus*, *D. kerrii* and *D. verrucosus*
Shorea pauciflora
,, *leprosula*
,, *ovalis*
,, *parvifolia*
,, *acuminata*
,, *platyclados*—hills
,, *curtisii*—hills
Schima noronhae
Pentaspadon officinalis
Dyera costulata
Tarrietia spp.

(ii) Exotic species (not in order of importance)

Araucaria cunninghamii
,, *hunsteinii* (syn. *A. klinkii*)
Maesopsis eminii—well drained light soil and alluvial wash
Shorea gysbertsiana—alluvial flats and riverine areas

Seed

The availability of seed supply and the short viability of most of the desirable species, as has already been mentioned, are two of the major problems confronting enrichment planting with indigenous trees. In addition seed of *Dipterocarpus* species, an important group for enrichment planting from every other angle, is normally of very low viability. Full details of collection, despatch and handling of seed on arrival are given in Part IV, Chapter 3, Seed.

Nursery

In any large scale enrichment planting programme a proper established permanent nursery is necessary, but in all other circumstances a small temporary forest nursery is probably adequate.

(i) **Permanent nursery.** Full details for the establishment and maintenance of a permanent nursery are given in Part IV, Chapter 4, Nursery Requirements.

(ii) **Forest nursery.** (*See* also Part IV, Chapter 4). By a forest nursery is meant a temporary convenient site in the forest—relatively accessible, near water, not too distant from the mother trees and yet moderately close to staff quarters—where a few temporary beds are made and recent jungle seedlings or germinating seed are tubed (*see* Part IV, Chapter 4, Nursery Requirements and Chapter 5, Plant Raising) to take advantage of any local fruiting of the more valuable economic species, and thereby provide planting stock for any local areas deficient in natural regeneration. Such nurseries could cater in particular for log yards and *kongsi* sites as soon as exploitation and extraction has ceased in the area.

Intensity of Planting

The intensity of planting depends upon several factors:

(i) The species:—its expected percentage survival during establishment, the required number of established saplings from which to choose the final crop trees, and the number of final crop trees, which itself depends upon the crown diameter/girth breast height ratio of the species;

(ii) The cost of raising seedlings and planting them out; and

(iii) The density of existing advance growth of desirable species.

Line and Group Planting

In both line and group planting it is very much cheaper (initially less clearing and subsequently easier treatment) to have the lines or groups at approximately final crop spacing and to allow for the expected wastage

TABLE 1. LINE PLANTING

Location	Year of planting	Species	Distance between lines	Seedling spacing along lines	Stock	Treatment to date	No. plants	Survival per cent Total	Survival per cent Successful*	Average height of successful* saplings in feet	Average b.h. girth of successful* saplings in inches	Silvicultural Notes
Ayer Panas F.R. Compt. 6A	1952	*Shorea acuminata* " *maxwelliana* *Swietenia macrophylla*	1 chain 1 chain 1 chain	16½ ft. 16½ ft. 16½ ft.	Bare rooted, nursery	Normal site preparation; annual treatment at 1-5 and 7-10 years (1.7.62)	284 71 142	30 30 17	40 14 13	19 ± 1 14 ± 2 24 ± 4	4.7 ± 0.4 2.6 ± 0.7 6.9 ± 1.3	In 40 feet tall secondary growth and cleaning has been far too intensive at and around ground level and not nearly enough overhead. Cut line or 'ride' appearance still remains with even tallest saplings lower than surrounding matrix. Costs are exorbitant and success still very doubtful (1962)
Kanching F.R. Compt. 14A	1949	*Dryobalanops aromatica*	12 ft.	6 ft.	Bare rooted, wildings	Normal site preparation; annual treatment at 4-11 years (1.12.61)	23,651	9	8	—	—	
Kanching F.R. Compt. 16A	1949	*Dryobalanops aromatica*	12 ft.	6 ft.	Bare rooted, wildings	Normal site preparation; annual treatment at 4-11 years (1.12.61)	15,220	12	12	—	—	In 30-40 feet tall secondary growth. Saplings tall, many with poor crown. Heavy side canopy removal necessary (1961)
Kanching F.R. Compt. 14B	1955	*Dryobalanops aromatica*	20 ft.	10 ft.	Half tubed nursery; half bare rooted wildings	Normal site preparation; annual treatment at 1-5 years (1.12.61)	5,831	33	18	—	—	
Kanching F.R. Compt. 16B	1955	*Dryobalanops aromatica*	20 ft.	10 ft.	Tubed nursery	Normal site preparation; annual treatment at 1-5 years (1.12.61)	2,603	51	32	—	—	
Kanching F.R. Compt. 11	1956	*Dryobalanops aromatica*	20 ft.	10 ft.	Tubed nursery	Normal site preparation; annual treatment at 1-4 years (1.12.61)	4,131	68	34	—	—	In 30 feet tall secondary growth with abundant bamboo. Saplings tall but whippy and heavy side canopy removal necessary (1961)

* A successful plant has been arbitrarily taken as one in which the sapling is 10 feet in height or taller.

TABLE 2. GROUP PLANTING

Location	Year of planting	Species	Group spacing	No. seedlings in group	Seedling spacing	Stock	Treatment to date (1.7.62)	No. groups	Assessment period in years	Average No. survivors per group	Percentage success of groups**	Average height of the tallest sapling from each successful group, in feet**	Average girth of the tallest sapling from each successful group, in ins.**	Silvicultural Notes
Ayer Panas F.R. Compt. 6A	1952	**Shorea acuminata*	1 ch. x 1 ch.	1, 3, 5, 3, 1 (13)	3' x 3'	Nursery seedlings	Normal site preparation; treatment at 1, 2, 3, 4, 5, 7, 8, 9 and 10 years	120	10	5.6 ± 0.5	92	23 ± 1	5.9 ± 0.5	In 40 feet tall secondary growth and cleaning has been far too intensive at and around ground level and not nearly enough overhead. Cut line or 'ride' appearance still remains with even tallest saplings lower than surrounding matrix. Costs are therefore exorbitant and success after ten and eleven years still very doubtful.
		* ,, *leprosula*						18	10	4.6 ± 0.9	94	23 ± 3	6.6 ± 1.0	
		,, *maxwelliana*						37	10	7.8 ± 0.8	89	17 ± 1	3.2 ± 0.3	
		* ,, *pauciflora*						18	10	7.5 ± 1.3	94	22 ± 2	6.5 ± 0.9	
		Swietenia macrophylla						50	10	6.2 ± 1.1	82	31 ± 4	9.7 ± 1.5	
Bukit Sedanan F.R. Compt. 6c	1951	*Swietenia macrophylla*	1 ch. x 1 ch.	1, 3, 5, 3, 1 (13)	3' x 3'	Nursery seedlings	Normal site preparation; treatment at 4, 6, 8, 9, 10 and 11 years	143	11	7.0 ± 0.3	77	29 ± 2	8.2 ± 0.7	
		**Shorea acuminata*						228	11	4.2 ± 0.5	36	14 ± 1	3.6 ± 0.2	
		* ,, *pauciflora*						250	11	4.1 ± 0.4	44	15 ± 1	4.2 ± 0.3	
F.R.I., Field 10F	1952	**Shorea hemsleyana*	1 ch. x ½ ch.	3, 2, 3 (8)	4' x 4'	Nursery seedlings	Normal site preparation; treatment at 2 months and 6 and 8½ years	18	10	4.0 ± 0.9	100	27 ± 4	10.9 ± 1.5	Appears to have been very successful but this is probably due to the poorer competing regrowth and better than usual side light conditions (roads).
,, ,, 10K	1952	**Shorea hemsleyana*	1 ch. x ½ ch.	3, 2, 3 (8)	4' x 4'	Nursery seedlings	Normal site preparation at 2 and 4 mths. and 6, 7½ and 8½ years	15	10	2.5 ± 0.7	100	27 ± 3	12.1 ± 1.7	
,, ,, 29	1959	**Shorea leprosula*	0.7ch.x0.7ch.	2, 3, 2 (7)	3' x 3'	Tubed seedlings	Normal site preparation except that overhead canopy in *Schima* sites was treated at time of planting. In *Shorea* sites after 3 weeks and in *Dryobalanops* sites after 2½ months	73	3	4.6 ± 0.3	94	11 ± 1	—	Likely to be successful and not costly. In 20—30 feet tall, secondary growth with fairly thick *Eugeissona* palm and small open area with *Gleichenia* fern. Heavy canopy opening probably the reason. Casualties mainly in *Gleichenia*.
,, ,, 29	1959	*Schima noronhae*						138	3	6.4 ± 0.2	99	11 ± 1	—	
,, ,, 29	1959	*Dryobalanops aromatica*						62	3	3.7 ± 0.5	79	9 ± 1	—	
Senaling Inas F.R.	1952	*Balanocarpus heimii*	1 ch. x 1 ch.	1, 3, 5, 3, 1 (13)	3' x 3'	Nursery seedlings	Normal site preparation; treatment at 3, 4, 6 and 12 months and 9 years	18	10	9.9 ± 0.9	100	19 ± 2	4.4 ± 0.5	In secondary growth in which *Mikania scandens* was common. The lack of treatment resulting in a dense overhead cover appears to have been most satisfactory for *Balanocarpus* but very unsatisfactory for *Intsia*.
		Intsia palembanica						33	10	2.0 ± 0.5	59	9½ ± 1½	2.2 ± 0.5	

* Red Meranti group of genus *Shorea*.

** A successful group has been arbitrarily taken as one in which the tallest sapling is 10 feet in height or taller, except in the case of the 1959 F.R.I. plantings and the 1952 Senaling Inas *Intsia palembanica* plantings where 5 feet or taller has been taken.

from the number of plants along the lines or within the groups, rather than have additional or intermediate lines or groups. According to Dawkins (1958), West African experience has shown that at least ten trees must be planted for every one retained as the final crop trees; this appears to be slightly high on Malayan standards and it is considered that about seven or eight will suffice.

It is not anticipated that a full stocking of final crop trees will amount to more than 40 trees or be less than 20 trees per acre, and this will require an average spacing of between half a chain (33 feet) and three quarters of a chain (50 feet) between trees.

In Malaya line planting has in recent years been carried out mainly at line intervals of 20 feet and at 10 feet spacing along the line, though in Malacca there has been extensive planting with lines spaced at intervals of one (66 feet) or occasionally half a chain (33 feet) and at intervals of 12½ or more frequently 16½ feet (5 or 4 plants per chain) along the lines. The former (20 ft. x 10 ft.) is obviously too close on economic grounds and the latter (66 ft. x 12½ ft. or 33 ft. x 16½ ft.) is far too widely spaced along the lines. Details of some of the line planting are given in Table 1.

Group planting has been carried out on an experimental basis at the Forest Research Institute, Kepong, in Senaling Inas Forest Reserve, Negri Sembilan and in Ayer Panas and Bukit Sedanan Forest Reserves, Malacca. Details of these trials are given in Table 2.

It is recommended for the present that for all future enrichment planting the following intensity be adopted and that line planting be used in preference to group planting Table 3. Expected losses caused by falling debris of poisoned trees and from other reasons have been taken into account.

TABLE 3. INTENSITY OF PLANTING

Species	Estimated no. final crop per acre	Line planting Interval between/along* lines in feet		Line planting No. seedlings per acre	Group planting Interval between*/within groups in feet		Group planting No. seedlings per group
Agathis alba	35	40	6	180	40	3	6
Dipterocarpus spp.	35	40	5	220	40	3	7
Dryobalanops aromatica	30	45	4	240	45	3	9
Pentaspadon officinalis	35	35	6	210	35	3	7
Schima noronhae	50	30	7	210	30	3	5
Shorea spp.	20	50	5	175	50	3	8

* but depending upon advance growth present.

Site Preparation

This entails the preparation of the actual planting site and opening of the overhead cover.

(i) Planting site. The site of the planting hole should be clean weeded (including roots) to a horizontal radius of 6 inches and a depth of 9 inches, and all growth up to a girth of 6 inches within a horizontal radius of three feet cut at ground level (for details of this and digging holes *see* Part IV, Chapter 7, Planting Site). The actual position of the planting site should not be rigid and it should be moved a few yards in any direction to obtain a favourable or to avoid an unfavourable situation.

(ii) Overhead cover. All overhead cover of economic stems that will not last the rotation and of uneconomic stems down to a minimum girth of 6 inches in the block undergoing enrichment planting should be poison girdled (*see* Part III, Chapter 5, Frill Girdling and Poisoning), and all smaller growth with foliage extending to within a vertical cylinder of a radius of three feet around each planting site should be cut at the time of and in no case later than three months after planting. If the overhead canopy is particularly dense and many refractory species or large trees are present, it is recommended that a strength of three pounds of sodium arsenite to one gallon of aqueous solution be used. It is imperative that the overhead canopy be opened up early and completely removed after 3 to 4 years. It should be remembered that even stems and large branches of dead trees provide a considerable amount of shade. Treatment of clumps of bertam palm (*Eugeissona triste*) should be considered whenever present and should always be carried out if in any doubt (*see* Part III, Chapter 5, Bertam Control).

(iii) Miscellaneous weeds. Treatment of such weeds as resam (*Gleichenia linearis*), woody climbers, bamboo, *Imperata* grass and palms other than *bertam* should be carried out if considered necessary.

Planting

Full details of planting are given in Part IV, Chapter 8. Two of the most important details are that bare rooted seedlings, if used, should be collected on the morning of planting and that no planting should be undertaken after about 11.00 a.m. It is further recommended that tubed seedlings are always used in preference to bare rooted or earth balled nursery seedlings or wildings.

It is essential in enrichment planting to remember that full use should be made of existing natural regeneration of desirable species of good form, and which it is intended should constitute part of the new crop. It is a complete waste of money and effort to underplant *desirable* stems with seedling stock. Therefore the officer in charge of the planting must inspect the forest after the lines have been cut and either remove or change the location of the stakes marking the planting sites wherever existing natural regeneration, of the better desirable species (Class B only of the Linear Sampling list) and of good form and size and in adequate numbers, is found to be present within 'competing distance'. The words "size", "in adequate numbers" and "competing distance" are deliberately used since a solitary small seedling within twenty feet can be discounted, but twenty small seedlings or a single twenty to thirty foot sapling within twenty feet should certainly be credited, the author considers, as probably being adequate to form a final crop tree. In certain cases a whole part of a compartment or block of forest can possibly be classed as not warranting enrichment planting, even though half-chain square linear sampling had shown it to be poorly stocked. This would be due to such sampling not taking into account the regeneration smaller than six inches girth at breast height. In such cases silvicultural treatment, which may consist of that described in the immediately preceding sub-section, Overhead Cover, should be carried out.

Beating up

No beating up is required in group planting, and in line planting it should only be done within the first eighteen months after planting (*see* Part IV, Chapter 9, Initial care and maintenance).

Tending during normal establishment stage under Malayan Uniform System

(i) **Group planting.** No tending should be carried out other than at 3 to 5 years and at 8 to 10 years after planting. Such tending should consist of the standard operations carried out in crops of this age (*see* Part III, Chapter 5, Cleaning operations after LS½ and LS½ in crops up to 10 years after final felling), with the exception that at 8 to 10 years a definite thinning operation should be carried out to remove all but two of any strongly competing stems. It should be remembered that the groups are at final crop spacing and it is too early to remove all reserve saplings.

(ii) **Line planting.** Cleanings, coupled with enumeration of survivors in standard linear sampling size classes and recorded separately for each line, should, if possible, be carried out at 3, 6, 12, 18 and 24 months along the lines. Particular attention should be paid to cutting back and poisoning climbers and to cutting back and poisoning woody growth to provide *full overhead* light (90° inverted cone). The ground should not be clean weeded again after the initial preparation of the planting site, nor should cleaning result in a tunnel effect. At 12, 18 and 24 months all tall poisoned overwood not yet dead should be repoisoned with sodium arsenite solution of a strength of 3 lbs. per gallon. Further treatment should be given at 3 to 5 years and at 8 to 10 years as normally carried out in crops of this age (*see* Part III, Chapter 5, Cleaning operations after LS½ and LS½ in crops up to 10 years after final felling) with the exception that at 8 to 10 years a definite thinning operation should be carried out to remove one of any two strongly competing stems.

Tending of established crops

Tending should follow the procedure laid down for crops established by natural regeneration (*see* Part III, Chapter 5, Thinnings and improvement operations in regenerated forest). However, the standard systematic sampling along sampling lines 5 or 10 chains apart should not be carried out. Instead the standard data recorded in such a sampling should be carried out along every fifth planting line and in group planting along every fifth 'line' of groups (*see* Part III, Chapter 5, Treatment diagnosis in regenerated forest).

Costs

It is extremely difficult to give even an approximate estimate of costs, other than it is considered that it should not exceed a maximum of $150 or about 45 man/days per acre at establishment stage, and that this should be achieved in 10 years. A figure of $100 or about 30 man/days per acre is considered to be a reasonable average cost.

Some idea of breakdown of costs can be obtained from the following data. Additional data can be found in the respective chapters of Part IV, Artificial Regeneration.

Cost of raising tubed seedlings in nursery: 17 cts. per plant (based on a production of 100,000 plants during 1961 at the Forest Research Institute using modified John Innes compost and polythene tubes (80 per cent.) and veneer tubes (20 per cent.); lowest daily wage for a labourer was $2.40)

Cost of raising bare rooted seedlings in nursery: 7 cts. per plant (Nisbet; 1953); 4·8 cts. (unpublished 1962 data from Bentong)

Cost of raising tubed seedlings in nursery: 6-10 cts. per plant (unpublished 1962 data from Bentong)

Site preparation (lines; 4 plants per chain): 32 man/days per 100 chains (Nisbet; 1953)

Site preparation (groups: 1 group, 15 ft. diameter, per chain with 13 plants): 33 man/days per 100 groups (Nisbet; 1953)

Site preparation (groups; 7 tubed seedlings per group): 25 man/days per 100 groups (Ja'afar Hassan; 1959)

Planting (lines: 4 bare rooted seedlings per chain): 10½ man/days per 100 chains (Nisbet; 1953)

Planting (lines; tubed seedlings): 30 to 40 tubed seedlings per man/day (unpublished 1962 data from Bentong)

Planting (groups; 13 bare rooted seedlings per group): 16 man/days per 100 groups (Nisbet; 1953)

Opening canopy (lines): 20 man/days per 100 chains (Nisbet; 1953)

Opening canopy (groups): 8 man/days per 100 groups (Nisbet: 1953)

Tending for first 3 years (no tending after 3½ months): 9 man/days per 100 groups (Ja'afar Hassan; 1959)

Tending for first 6 years (no tending after 6 months): 9 man/days per 100 groups (Ja'afar Hassan; 1959)

Tending for first 10 years (Heavy Hardwoods: heavy tending for first year and then no tending till ninth year): 18 man/days per 100 groups (unpublished 1962 data for Senaling Inas F.R. from Kuala Pilah)

Tending for first 11 years (Light Hardwoods: insufficient canopy opening in early years and excess of low line cleaning): 70 man/days per 100 groups (unpublished 1962 data from Malacca)

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資料 4.

MANUAL OF FOREST INVENTORY

with special reference to mixed tropical forests

FOOD AND AGRICULTURE ORGANIZATION OF THE UNITED NATIONS
ROME, 1973

FOREWORD

The Forestry Department (formerly Forestry and Forest Products Division) of the Food and Agriculture Organization of the United Nations has been involved since this Organization's inception in the definition and implementation of forest resource evaluation programmes, at all levels, from world and regional forest appraisals to local management inventories. It has performed a number of forest resource surveys in many countries of the world, has carried out a series of world and regional studies - such as the World Forest Inventory and the regional timber trends and prospects studies - and has produced a few publications on the methodology side such as "Planning a Forest Inventory" by Dr. B. Husch, and the "Manual for forest inventory operations executed by FAO" (1967).

To take the experience gained by FAO in the last few years into account and to fulfil in this field FAO's role concerning dissemination of knowledge, Mr. J.P. Lanly, Forest Resource Surveys Officer, was asked to write a new manual of forest inventory. This manual is intended to be of use mainly to professionals dealing with the evaluation and management of mixed tropical forests, since it is restricted to inventory methods and practices which have been found feasible in these areas.

At the beginning of 1972 about thirty specialists all over the world were asked to give their comments on a draft of the outline and of the main contents. Most of their suggestions have been taken into consideration. They must all be thanked here, with a particular mention of Dr. P.G. de Vries from Wageningen University in the Netherlands who made the most substantial proposals. The sections of Chapter V devoted to measurement and volume estimation techniques formed the basis of lectures delivered by Mr. J.P. Lanly at the training course on forest inventory organized in August and September 1973 by the Royal College of Forestry in Stockholm in cooperation with FAO, and include information on recovery studies and accessibility problems, two topics which need to be given more consideration in future inventory work. The section on accessibility problems was reviewed by Prof. U. Sundberg, Chief of the Forest Logging and Transport Branch of the Forest Resources Division, and Chapter VI on data recording and processing was drafted by Dr. H.E. Marsch of the Forest Management Branch. Thanks are due also to Messrs. R. Bolton, J.W. Eastwood, J. Jackson and D.A. Harcharik for their contribution to the editing of the English version and to Mrs. R.S. Borelli for her secretarial help.

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CHAPTER II

PURPOSE AND PLANNING OF A FOREST INVENTORY

The main components of a forest inventory and the programming depend upon the size of the operation. Purpose and planning are closely related; purpose must be clearly defined and planning designed to achieve that purpose. For this reason they are put together in this chapter. Further comments regarding these matters will be found in "Planning a Forest Inventory", by B. Husch (FAO Forestry and Forest Products Studies No. 17).

1 Purpose of the inventory

11 Introduction

It is very important to define clearly the various objectives of the proposed inventory. The relative importance of each must be considered, in order to design and implement an operation which best solves the problem. Account must also be taken of the unavoidable constraints and limitations such as available time and funds and ability of the staff.

A usual criticism made to the people responsible for designing and executing inventory operations is that they undertake such work without a clear idea of the objectives to be met and thus provide forestry officers, economists, loggers and industrialists with inadequate or even useless information.

Sometimes a thorough study of the problem may indicate that inventory will not provide the correct answer. A cost benefit analysis may also conclude that a forest inventory is not the most efficient tool for providing the information required due to existing constraints and limitations. Compilation of information already available, comparison with other similar stands already inventoried and use of research results, may meet the required degree of precision at less expense.

There may be, at the same time and in the same country, a need for different kinds of inventory, for instance inventory at a country-wide level ("national forest inventory"), inventories of big units of forest area (for instance 100,000 ha of forest) or inventories of stands for the preparation of working plans. But, as an example, it cannot be expected that information obtained from a national forest inventory will be adequate to form the basis of a detailed local management plan. This has to be pointed out to the decision-makers who sometimes believe that a single type of forest inventory will provide them with all the information they need at different levels. Generally, for lack of resources, priority has to be given to that type of inventory which will solve the more urgent problems.

Sometimes a careful study may demonstrate that the most useful operation to be carried out is a combination of partial inventories at the various levels. Recently a request to UNDP/SF for a national forest inventory was converted into a combination of the following operations:

- reconnaissance by photointerpretation and some field plots of the forested area of the country, for an estimation of the areas covered by each vegetation and forest type;

- vegetation mapping of a selection of forest reserves, with complementary field plots for rough estimation of the growing stock of each forest type;

- intensive inventory, with vegetation mapping, of the most valuable forest area.

This example shows that a forest inventory programme may include different types of inventory in order to meet different objectives.

12 Definition of the objectives

121 The objectives must be defined jointly by the people who will make use of the inventory results (e.g. decision-makers, forest managers) and by the inventory specialist, not by the latter alone. The inventory specialist should design an inventory which will provide the users with the information they need in a suitable form and with the required precision. This cooperation with the potential users is necessary from the time that the inventory is prepared until the delivery of the final results.

Regarding this cooperation two difficulties may be encountered:

a) In certain cases the inventory specialist has to prepare the inventory at a time when the users are either not present or do not have a clear and definitive idea of the information needed. For instance, in a forestry development project, management, logging and economics advisers may arrive only after the inventory has started or has even been completed, because they cannot function effectively until the information provided by the inventory is available. Usually they do not participate in the preparation of the inventory, and this may explain why the information given by the inventory is inadequate in some cases. Possibilities of avoiding this drawback are to seek advice from the greatest possible number of eventual users, to compare with other similar inventories already completed and if necessary to request consultancies from forest management, logging, or forest economics specialists at the time when the inventory is being designed.

b) Another difficulty comes from the evolution of the purpose of the inventory. The aims defined during the preparation of the inventory may change during the course of the operation. This occurs, for instance, when the unit size of the blocks, for which the results are to be provided with a given precision, changes. This is also true for long programmes of forest inventory at a national level. There is no general course of action to overcome this difficulty; the only observation to be made is that the more flexible the initial design, the easier the transformation thereof. Moreover, every effort should be made to foresee some of these eventual modifications when designing the inventory.

122 Priority of objectives. Not all the objectives have the same importance. Some are very fundamental and can in themselves justify the whole inventory. The corresponding information has to be given in the required form or the operation will fail. The degree of precision of the information provided is also a most important requirement. On the other hand, it may be acceptable to fulfill a secondary objective only approximately (for instance, by accepting a lower precision in the corresponding information).

The priority of the objectives to be met has to be clearly assessed before designing an inventory. For instance, if the estimation of the area of a forest is more important than the estimation of its volume, the inventory design will strengthen the work of interpretation of remote sensing imagery and mapping and give less importance to tree measurements on imagery or in the field. Likewise, priority can be assessed among the zones or the blocks of the region inventoried. As far as volume estimation is concerned, species do not have the same economic value, so the inventory will be designed in order to provide the results with a specific precision for the most important species: volumes of individual secondary species may be estimated less precisely, especially if they have a very low stocking density and are unevenly distributed.

123 Additional requirements. Forest inventories generally include a substantial amount of field work, which implies high expenditure and more or less difficult logistics. In particular the ratio:cost of accessibility to the sampling plots/cost of data recording is sometimes very high. The additional cost incurred by measuring and recording other parameters, not directly related to the purpose of the inventory, may prove insignificant. Under such conditions it may be desirable to take the opportunity offered by the inventory logistics to collect data of value to specialists not concerned with the primary purpose of the inventory (soil scientists, dendrologists, phytosociologists, etc.). This is all the more justified as a forest inventory often provides the most objective and exhaustive way of penetrating unknown and remote areas.

There is no general answer to this question, and each inventory operation is a special case. Many things have to be considered, among which we can quote (a) the cost of the collection of these additional data, and (b) the qualifications and training of the field staff for this additional work and the corresponding reliability and precision of the data collected.

Even if not explicitly required for the purpose of the inventory, some data have to be systematically collected, because they are known to be useful in any case. In tropical forest inventories these data are:

- logging parameters, i.e. slopes, soil bearing capacity, terrain obstacles, undergrowth, occurrence of swampy areas, etc.;
- complete enumeration of trees by species and diameter classes above a given minimum diameter (say 10 cm) in a sub-sample of the sampling plots, if only certain commercial species are to be inventoried in the main sample;
- enumeration of seedlings, saplings and poles of the most important species in a sub-sample of the sampling plots, for further regeneration and management studies.

Other data, although not of direct relevance to the purpose of a forest inventory, can easily be recorded either in the office (such as climatic data) or in the field (such as seed collection aspects for individual species, degree of dominance of the crowns, dates and periodicity of seed crops, etc.).

In any case the attitude of the inventory officer, when he is faced with requests concerning additional data, should be positive. Probably the most advantageous solution is to ask the respective specialists and researchers or some of their trained staff to use the inventory infrastructure and join the inventory staff in order to collect their own data. This solution would also be the most efficient as the data collected would be more reliable and the cost of the infrastructure shared between the two parties.

124 Most important specifications for the purpose of a forest inventory

i) Exact limits and size of the area to be inventoried (the existence of good recent topographic and land-use maps and/or remote sensing imagery will facilitate decisions at this stage);

ii) Divisions to be made within the area: this question is important as the intensity of the inventory depends on the size of the ultimate forest subdivision for which results are requested with a specific precision (these classifications exclude the stratification(s) performed to improve the precision of the results for the above units); these classifications may be:

- based on bioclimatic relationships (as for instance land capability classification);
- related to existing land-use and vegetation;
- related to forest management criteria such as:

  ownership and tenure
  administration
  physiography and accessibility
  protection (watershed catchment area)
  other management critera, e.g. logging compartments

- combination of two or several of the above classifications.

iii) Nature of the information required: Information may be pictorial (maps, mosaics, graphs and charts, etc.), descriptive (qualitative description of the forest types, for instance), or quantitative.

Regarding pictorial information some characteristics have to be defined such as scale and resolution (what the dimensions of the smallest patch of forest type to be shown on the map will be). This last characteristic pertains also to the precision of the required information.

As for quantitative results one may consider the following questions:

- do they correspond to a static and/or dynamic appraisal ? (i.e. at the time of the inventory only, or also concerning the evolution of the forest);
- are they means per unit area, e.g. per hectare (or, for some stands, per tree) or totals ?
- are the final results areas, numbers of trees, volumes, weights (for instance, in forest inventories for pulp production), prices (taking into account the unit prices of the products) ?

iv) Presentation of the information required: Once the type of information to be provided is know, as well as the desired precision, the method of eventual presentation of the results can be decided. The format of the final tables, for instance, will be drafted and shown to the users in order to get their agreement. This must be considered as an important item because clarity and reduction of the "access time" to the results are two important qualities of an inventory report. Moreover a dialogue between the users and the makers of the inventory at this stage, regarding the eventual presentation of the results, sometimes facilitates a clearer definition of the objectives by the users.

A set of table outlines for quantitative results concerning areas and volumes, considered as the basic minimum information to be presented by all FAO forest inventories, was designed during the meeting of forest inventory experts attached to UNDP/SF projects held in 1967 in Rome. The purpose of this exercise was to harmonize the presentation of the results of FAO operations (and thus facilitate in particular the periodic assessment of forest resources at national, regional or world-wide levels). These tables are presented in Chapter 6 of this Manual which deals with data recording and processing problems in forest inventory.

Complete standardization of the tables of results given by all forest inventories is probably not foreseeable in the near future. However, it would help considerably if the table outlines in Chapter 6 could be used as far as possible, with additional tables produced whenever necessary.

v) Precision of the information required: the precision of the results corresponding to the most important parameters must be determined prior to the inventory. For some other parameters, the precision required may not be determined exactly, but must not exceed a certain order of magnitude. Regarding precision, three important considerations have to be taken into account:

a) the total error of a sampling estimate has two components:

- one is the sampling error calculated from the values measured in the sampling units, which is related to "precision" in its statistically restricted sense;
- the second is the bias which may originate either from the sampling procedure, from the estimation procedure or from the measurement errors (for analysis of bias in sampling, see paragraph 24 of Chapter 3). Sometimes the bias may far exceed the sampling error[1] which is, often and wrongly, the only one taken into account. When we speak about precision of an estimate in general, we must refer to the total error and not only to the sampling error. One must try to estimate the total error using in particular objective checking procedures, and must design the inventory to ensure that this total error is no more than the admissible error. This point is one of the most tricky problems and, unfortunately, one of the least studied in textbooks and inventory reports.

b) Required precision in all sampling designs must be given at a certain probability level. The meaning and the choice of a probability level is not always well conceived by the potential users of inventory results, although this has a considerable impact on the intensity of the inventory work. Whenever necessary, this point will have to be well clarified before designing the inventory.

c) Required precision must be referred to a given population, which may be the whole area inventoried or only subdivisions of it (administrative units, vegetation types, compartments, watershed catchments, logging blocks). The mean size of these divisions greatly influences the intensity of the inventory work.

It is desirable that each figure be given at least with its corresponding sampling error. Precision for many secondary results is frequently not estimated in order to reduce the cost of data processing. However, precision of certain figures may be very low, due to the high variability of the corresponding parameter. It is necessary to point out the expected low precision of these figures or to omit them altogether (for instance if the result is related to the volume of a species of very rare occurrence, it may be combined with the corresponding figure for other species so that the combined figure is reasonaly precise).

1/ Especially in complete (100% sample) inventories in which, by definition, sampling error is zero.

2 Outline for preparing inventory plans

The following outline is presented as an example of a format which can be used in preparing plans for a forest inventory. This example is given with the knowledge that there is no single outline which should be used at all times, since the outline will necessarily vary to fit the inventory under consideration. The important point is that a written plan should be prepared and all the topics shown below should be considered. Items mentioned in the previous sub-chapter are summarized under the heading "Purpose of the inventory".

I. Purpose of the inventory

a) General definition of the objectives in collaboration with the potential users of the results of the inventory.

b) Priority of objectives.

c) Additional requirements (to be discussed with interested specialists: soil scientists, ecologists, botanists, etc.).

d) Detailed specifications of the objectives:
- exact limits and size of the area to be inventoried
- divisions to be made within the area
- nature of the information required
- presentation of the information required
- precision of the information required

II. General information

a) Authority responsible for the inventory and other agencies collaborating.

b) Available information and data on the area to be inventoried from past surveys, reports, maps or remote sensing imagery on:
- general description of forest
- variability of parameters to be measured
- condition of terrain, accessibility, transport facilities

c) Resources available for carrying out the inventory.

III. Inventory design

a) Outline of inventory design to be used.

b) General description of the various phases.

i) aerial surveys, interpretation of remote sensing imagery
ii) mapping and area estimation procedures
iii) complete tally or sampling methods for recording of forest characteristics
iv) relationships to be used for expressing estimated quantitative data of stands, e.g. volume tables

IV. Measurement procedures

a) Description of design for both office and field work; in particular, size, shape, number and distribution of sampling units to meet required precision.

b) Procedures of interpretation of remote sensing imagery:

i) detailed instructions on all techniques;
ii) staffing and description of duties;
iii) instruments;
iv) forms and recording of observations

c) Field organization:

i) crew organization and description of duties;
ii) transportation procedures and directives;
iii) camping instructions;
iv) provisions for logistical support

d) Field procedures including detailed procedures on:

i) sampling unit location;
ii) establishment of sampling unit;
iii) measurements on sample unit;
iv) instruments and directives for use;
v) tree and other plot measurements;
vi) other field measurements such as growth, insect damage, mortality, soil and topographic conditions, seed collection aspects and information on non-productive roles of the forests;
vii) design of forms and recording of observations

V. Compilation procedures

a) Detailed instructions on processing of data from imagery interpretation and field measurements:

i) formulae for estimates of means totals and their sampling errors;
ii) relationships to be used for converting imagery or field measurements to desired expressions of quantity; e.g. photo-volume tables, individual tree volume tables, etc.

b) Calculation and compilation methods:

i) description of procedure, e.g. desk calculation, electronic computers, etc.;
ii) detailed description of all phases of calculation from raw data on original forms to final results (for electronic computation, description of inputs, programmes, and outputs).

VI. Final Report

a) Outline (note that the inventory plan, with some modifications, can serve as a basis for the final report).
b) Estimated time for preparation.
c) Responsibilities for preparation.
d) Method of reproduction.
e) Number of copies
f) Distribution.

CHAPTER VII

CONSIDERATIONS ON INVENTORY DESIGNS

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CONSIDERATIONS ON INVENTORY DESIGNS

1 Introduction

The former chapters have been devoted to the study of the principal techniques that are useful in forest inventory, namely sampling techniques, remote sensing techniques, forest mensuration techniques and data processing. Planning and designing a forest inventory consist mainly in developing the most efficient combination of these various techniques to fulfil the objectives of the operation, taking into account the prevailing human and environmental conditions. In this respect even data processing problems have to be contemplated from the very beginning since available means in manpower and computing facilities also have a bearing on the type of inventory methodology used, as has already been mentioned in chapter VI.

There is no point trying to cover all the situations and objectives assigned to forest resource surveys and the corresponding combinations of techniques which are likely to be the most appropriate in each case. This would be an endless and illusory task. A more modest and also more realistic approach is used in this chapter where some problems arising from the combination of these techniques will be dealt with and some recommendations will be made on the suitability of these techniques to actual working conditions.

Techniques of volume estimation and quality assessment have already been compared in chapter V. Their effects on the precision and on the usefulness of the inventory results are far from negligible; but, especially in mixed tropical forests, the largest part of the total cost involved comes from the field enumeration work. The most important questions to be considered are therefore related to the latter part of the inventory work and are mainly the following:

- to what extent interpretation of remote sensing imagery can be combined with the field enumeration work so as to decrease the effort spent on the latter, and thus reduce the total cost of the inventory (for a given precision of the final estimates of the parameters over the whole inventoried area) ?

- the importance of interpretation of remote sensing imagery being decided upon, what are the most suitable characteristics of the field sampling design ?

Some indications useful in solving these problems are given in the two main following sections of this chapter. The formulas corresponding to some classical combinations of photointerpretation and field sampling procedures are indicated, together with the cases to which they apply (section 2). General formulas corresponding to the most classical field sampling designs have already been given in chapter III and the contents of section 3 are restricted to some guidelines on the selection of the most appropriate field sampling design with special reference to mixed tropical forests.

Most forest inventories aim at estimating the characteristics of forest stands at a given time. There exist, however, some permanent inventory designs which consist in the combination of different samples selected on successive occasions, which can be grouped under the generic denomination of "Continuous Forest Inventory", and which are briefly commented on in section 4. Another type of sampling designs follows a stepwise procedure, in which the decision whether or not to undertake further sampling depends on the results already obtained from the sample; this is called sequential sampling and is dealt with in section 5.

2 Combinations of photointerpretation and field sampling procedures

21 Preliminary remarks

It is assumed in this section that some basic conditions which are those already indicated in the introduction of Chapter IV are fulfilled: the total area of the inventoried zone is supposed to be exactly known and mapped at a suitable scale (which allows for the definition of frames for sampling designs), and the stand characteristics are estimated through field sampling (the case of photogrammetric measurements of stand characteristics being excluded as it is generally not applicable to inventories of mixed tropical forests).

The main use of interpretation of remote sensing imagery in forest inventory is to stratify the area to be inventoried into more homogeneous parts or strata which are sampled separately in the field, in order to get more precise estimates of the total values of the forest characteristics over the whole area. For reasons mentioned in the following paragraph it is relatively rare that areas of the strata are known exactly or almost exactly, and generally they have to be estimated through a sound sampling design.

22 Areas of the strata exactly or almost exactly known

Stratum areas can be said to be exactly or almost exactly known when the actual and present limits of the strata are drawn on a reliable and stable planimetric map and their areas carefully planimetered or estimated very precisely by use of very dense dot grids (see section 5 of chapter IV). The actual and present limits of the strata can be located on the photographs if:

- very recent aerial photographs at a suitable scale are available, or, if they are not very recent (say if they are two or three years old, but not more) if no significant changes are likely to have occurred between the date of the aerial coverage and the date of the field inventory (significant, that is, in relation to the accepted accuracy of the area figures);

- no systematic photointerpretation error is expected, and consequently none - or a negligible part - of the sampling units of the field inventory will have to be transferred from the strata to which, through misinterpretation, they have been assigned by photointerpretation to different strata to which they actually belong.

It can be easily understood from the above considerations that such cases very seldom happen. Even if the aerial coverage has been taken in the same year as the field work, inconsistencies and errors in the photointerinterpretation work can always be expected since conventional interpretation of remote sensing imagery is not a purely objective exercise. Inconsistencies and errors over time by the same interpreter or between interpreters can be avoided only if the stratification is simple and easy and if there are sharp limits between strata (as has already been mentioned in paragraph 334.1 of chapter IV it is generally difficult to draw objectively a limit between strata as there may be more or less wide transition zones).

In the rare cases when an exact (or almost exact) evaluation of the areas of the strata can be secured, i.e. when it is assumed that there is no misinterpretation in the photointerpretation, the sampling frame for each stratum is well defined and an independent selection of the field sample can be made within each stratum. The mean values and estimated variances of the forest characteristics per ultimate unit over the whole population estimated from the field sample can be derived from the corresponding formulas given in chapter III for sampling designs with stratification prior to sampling (formulas 5, 6 of 11, 12 in case of one-stage sampling designs), in which the total sizes N_h (or X_h) of the strata and N (or X) of the whole population can be replaced by the total areas S_h and S respectively.

The total values of the forest characteristics for the whole inventoried area is obtained by multiplying the mean value per ultimate unit by the total number (which is exactly known) of ultimate units in the whole area. The percentage standard error is the same as that of the mean value.

It may happen that an unstratified sample is first selected for the whole area and that stratification is made by photointerpretation after the sampling on the basis of criteria recognized in the field and identifiable on the photographs. If it is possible to assume that this stratification is fully valid, then the exact sizes of these strata can be known and the estimated means and their estimated variances are derived from formulas (7) and (8) of chapter III (in the case of one-stage sampling with equal units), which are somewhat different from those corresponding to stratification prior to sampling. Total values are obtained in the same way as in the case of stratification prior to sampling and the estimated relative standard errors are the same as for the corresponding mean values.

23 Areas of the strata estimated through sampling

In this case the estimation of the strata through a sampling design increases the sampling error of the estimates of the total values of stand characteristics over the whole inventoried area or over individual strata.

In forest inventory there are various ways of estimating the areas of the strata using sampling. The main alternatives are:

(a) sampling on the photographs (or on the maps), the photointerpretation being supposed to be unbiased (same case as in the above paragraph, planimetering being replaced by sampling);

(b) sampling in the field from the same (or a larger) sample used for the estimation of the stand characteristics: in this method the area estimates are supposed to be unbiased and do not need to be corrected since identification of the strata is made on the spot;

(c) sampling from the photographs (or even possibly planimetering on the maps), the area estimates obtained being afterwards corrected through a sampling in the field, using the sample used for estimation of the stand characteristics or a larger sample.

When estimating areas through sampling it is important also to distinguish the case when the sampling units are points or plots (the associated parameter having the values 1 or 0 according to whether the plot belongs to the relevant stratum or not) from the case when the sampling units are lines or strips (in which case the associated parameter is a length or a ratio of lengths, both continuous variates).

231 Area estimates from one sample only.[1] Stratification and estimation of the areas of the strata can be made by sampling on photographs or in the field, if photographs are considered unsuitable (too old or too bad to allow for a useful stratification). The sample used for estimation of the areas of the strata may be the same as the one used in the field for estimation of the stand characteristics or may be a larger one (including the sampling units used for the estimation of the stand characteristics).

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(1) Sample is used here as in the rest of this manual to designate the whole set of sampling units selected according to a given sampling design.

231.1 Area estimation using plots as sampling units

In this case the associated parameter can take the values 1 or 0 according to whether the plot belongs to the particular stratum considered or not. The area of a stratum is obtained by multiplying the total area of the inventoried zone (which is supposed to be known exactly) by the proportion (estimate) of plots falling in this stratum.

231.11 Area and stand characteristics estimation from the same sample

If area estimation is made by photointerpretation, the sampling units in the field used for the estimation of the stand characteristics are centred on the plots interpreted on the photographs (see paragraph 334.2 of chapter IV). They may be single plots or clusters of plots, a bit smaller or larger than the photoplots but each of them is supposed to belong entirely to the stratum of the corresponding plot on the photographs (no correction of the photointerpretation is supposed to be necessary).

If the plots are randomly distributed the proportions P_h of the strata and their variances are estimated by formulas (3) and (4) of chapter III if it is a one-stage sampling design, or by formulas (13')and 14')of the same chapter if a two-stage design has been used, in which the primary units are the effective areas of the photographs (supposed equal) and are selected at random, the same number of plots (secondary units) being sampled on each selected photograph. Other sampling designs can be contemplated as has already been mentioned in paragraph 532 of chapter IV. The percentage standard errors of the estimates of the areas of the strata are equal to those of the corresponding proportions since the total area is supposed to be known exactly.

If the plots are systematically distributed in a one-stage design, it is recommended to use the formula given in paragraph 531 of chapter IV for the estimation of the variances, in which the constant k is given a value according to the shape of the corresponding stratum.

The estimates of the mean values per ultimate sampling unit of the stand characteristics and their variances are obtained by the formulas of the corresponding unstratified sampling design. The corresponding estimates of the total values over the whole population are obtained by multiplying the estimated means by the total number of plots in the whole inventoried zone (or by its total area if they are means per area unit) and their percentage standard errors are the same as those of the respective means.

Estimates of the means per ultimate unit in each stratum and of their variances are obtained from the individual values in the sampling units belonging to the corresponding stratum. However care must be exercised since the sampling is done within the population as a whole and the same formulas as for the whole population do not apply necessarily to each stratum. Estimates of the totals per stratum are obtained by multiplying the corresponding estimated means by the estimated area of the respective stratum.

If $\bar{y}_h$ is the estimated mean per area unit of a stand characteristic y in stratum h,

$\hat{P}_h$ is the estimated proportion of stratum h

S is the total area of the inventoried zone,

an estimate $\hat{Y}_h$ of the total value of this characteristic in stratum h is: $\hat{Y}_h = S\hat{P}_h\bar{y}_h$

and an estimate of its variance is:

$$v(\hat{Y}_h) = S^2 [\hat{P}_h^2 v(\bar{y}_h) + \bar{y}_h^2 v(\hat{P}_h)]$$

where $v(\bar{y}_h)$ and $v(\hat{P}_h)$ stand respectively for the estimated variances of $\bar{y}_h$ and $\hat{P}_h$. This formula is acceptable if $v(\bar{y}_h)$ and $v(\hat{P}_h)$ are small relative to $\bar{y}_h^2$ and $\hat{P}_h^2$ respectively.

Attention is drawn to the fact that these designs are definitely different from designs using stratification after sampling. In these latter it is assumed that the sizes of the strata are known exactly or almost exactly, which is not the case with the designs studied in this paragraph where only an estimate of the sizes of the strata is obtained.

In the above paragraphs, as well as in the rest of section 23, we do not consider the case of correction or weighting of the values found in the individual plots interpreted on the photographs which are necessary for taking into account the variation in scale and in overlaps of the photographic coverage used (see paragraph 334.2 of chapter IV). This correction corresponds to coefficients which appear in the formulas of the estimated means and totals and adds some complication to the estimation of the corresponding variances. In order to avoid it, it is recommended that the sample to be used for area estimation by photointerpretation is laid out on an existing map or on the corresponding uncontrolled mosaic provided this can be accepted as a reasonable approximation to a map. In case correction is deemed preferable, the reader will study with profit the examples given in paragraph 25.32 of "Forest Inventory" (Volume 1, pages 235-244) by F. Loetsch and K. Haller.

231.12 Area estimation from a larger sample than the field sample used for estimation of stand characteristics

The field sample for the estimation of the stand characteristics is a subsample of the sample used in photointerpretation or in the field for the estimation of the areas of the strata. If area estimation is made by photointerpretation the field sampling units of the subsample are centred on the plots interpreted on the photographs and each of them is supposed to belong entirely to the stratum of the corresponding plot. We will assume that the selection of the large sample and of the subsample from the large sample are both random one-stage samples. This type of combined sampling is called two-phase sampling or double sampling.

Areas are estimated from the large sample of plots, in the same way as described in the preceding paragraph.

If $\hat{S}_h$, $\hat{P}_h$ and S stand respectively for the estimated area of the stratum h (L strata in total), the estimated proportion from the large sample and the total area (exactly known) of the whole inventoried zone, we have:

$$\hat{S}_h = \hat{P}_h \cdot S \qquad \left(\sum_{h=1}^{L} \hat{P}_h = 1\right) \tag{1}$$

The estimated means $\bar{y}_{st}$ of the stand characteristics over the whole inventoried zone per sampling unit are given by:

$$\bar{y}_{st} = \sum_{h=1}^{L} \hat{P}_h \bar{y}_h \tag{2}$$

where the $\bar{y}_h$ are the estimated mean of the stand characteristic per sampling unit in each stratum obtained from the field subsample, the summation being extended to all the strata.

The calculation of the variances of the estimates $\bar{y}_{st}$ depends on the way the subsample has been selected from the sample.

(a) If the numbers of sampling units per stratum in the subsample n_h do not depend on the estimated proportion $\hat{P}_h$ of the corresponding stratum, then an estimate of the variance of $\bar{y}_{st}$ is:

$$v(\bar{y}_{st}) = \sum_{h=1}^{L} \left[(\hat{P}_h^2 - \frac{\hat{P}_h}{n'}) \frac{s_h^2}{n_h} + \frac{\hat{P}_h(\bar{y}_h - \bar{y}_{st})^2}{n'} \right] \qquad (3)$$

which can also be written as:

$$v(\bar{y}_{st}) = \sum_{h=1}^{L} (\hat{P}_h^2 - \frac{\hat{P}_h}{n'}) \frac{s_h^2}{n_h} + \frac{1}{n'} \left[\sum_h \hat{P}_h \bar{y}_h^2 - (\sum_h \hat{P}_h \bar{y}_h)^2 \right] \qquad (3')$$

where: n' is the number of sampling units of the large sample

s_h^2 is the estimated variance of the stand characteristic y in stratum h:

$$s_h^2 = \frac{\sum_{i=1}^{n_h} (y_{hi} - \bar{y}_h)^2}{n_h - 1}$$

(i being the index of a sampling unit in stratum h of the field subsample)

(b) If the n_h depend on the $\hat{P}_h$, the formula giving the estimated variance of $\bar{y}_{st}$ is somewhat different. In case of a proportional allocation of the sampling units in the field subsample, i.e. if $n_h = n\hat{P}_h$ where $n = \sum_{h=1}^{L} n_h$ is the size of the subsample, an estimate of the variance is:

$$v(\bar{y}_{st}) = \sum_{h=1}^{L} \hat{P}_h \cdot \frac{s_h^2}{n_h} + \frac{1}{n'} \left[\sum_{h=1}^{L} \hat{P}_h \bar{y}_h^2 - (\sum_h \hat{P}_h \bar{y}_h)^2 \right] \qquad (4)$$

Formulas (2), (3), (3') and (4) are known as formulas of double sampling with stratification. Totals over the whole inventoried area are obtained by multiplying the estimated means by the total area exactly known and their relative standard error is the same as those of the corresponding means. Estimates of the totals per strata are:

$$\hat{Y}_h = \hat{S}_h \cdot \bar{y}_h = (\hat{P}_h \cdot S) \bar{y}_h \qquad (5)$$

231.2 Area estimation using parallel lines as sampling units

In this case the line will be considered as the sampling unit and the associated parameter for a given stratum is a continuous variable since the length of the portion of a line which is found (on the photographs or maps or possibly in the field) within a given stratum can take in principle all values between 0 and the total length of the line. The case applies also to strips and to lines of plots, the occurrence of the stratum being checked only at the plots in the latter case, and even also to clusters of plots, provided that the number of plots per line or per cluster is large enough.

We will confine ourselves to the cases when the same sample is used for estimating the areas of the strata and the stand characteristics.

If all the lines have the same total length l within the whole inventoried zone (e.g. if the inventoried zone is square or rectangular and the lines parallel to one side of the area) the areas of the strata are estimated (in a one-stage design) by:

$$\hat{S}_h = S . \frac{\sum_i l_{hi}}{nl} = \frac{S}{l} . \bar{l}_h \qquad (6)$$

where S is the total area of the inventoried zone

$\bar{l}_h$ is the estimated mean length of a line (sampling unit) in the stratum h: $\bar{l}_h = \frac{\sum_i l_{hi}}{n}$ (i being the index of a line)

If the parallel lines are randomly distributed formula (2) of chapter III is applicable to the estimation of the variance of $\bar{l}_h$, the percentage standard error of $\hat{S}_h$ being equal to that of $\bar{l}_h$. If they are systematically distributed formulas suggested in section 423 of chapter III have to be adapted.

In most cases the lines have unequal total lengths and then ratio estimation is necessary. If we assume a one-stage random design of n parallel lines, and if l_i and l_{ih} stand respectively for the total length of line i and the length of the portion(s) of line i within stratum h, an estimate of the area of stratum h will be:

$$\hat{S}_h = S \frac{\sum_{i=1}^{n} l_{ih}}{\sum_{i=1}^{n} l_i} = S \frac{\bar{l}_h}{\bar{l}} \qquad (7)$$

$\bar{l}_h$ and $\bar{l}$ being respectively the means per line of lengths within stratum h and of total length.

The standard error of $\hat{S}_h$ can be estimated by using formulas (10) or (10') of chapter III related to the variance of a ratio estimate.

The estimates of the means per area unit of the stand characteristics over the whole population are ratio estimates in the case when the lines have different total lengths, with total length of a line as the auxiliary parameter. Means for each stratum can be estimated also and will be ratio estimates. But, as has already been said in paragraph 231.11, the sampling design must be considered as unstratified, since the exact size of each stratum is not known. Indications given in the above mentioned paragraph concerning the estimation of the means and totals per stratum are valid also in this case.

The case of continuous lines can be extended to the case of continuous strips, of lines of plots and of clusters.

232 Area estimates with correction in the field. In many cases there are unavoidable mistakes and biases in the photointerpretation work due to the interpreters, to the stratification adopted which may be too refined, to the bad characteristics of the photographs and, most often, to changes in vegetation which have occurred between the aerial survey and the field inventory. Estimation of the areas made by photointerpretation need then to be corrected by field checks made in a subsample of the photointerpretation sample.

We will confine ourselves to the design described below which is very much used in forest inventory in temperate zones and which needs to be adapted in an efficient way in mixed tropical forests, which consists of:

(a) selection of an unstratified sample of plots to be interpreted on the photographs for an assessment of the strata h as identified by photointerpretation, e.g. by a systematic grid put on the effective area of each photograph, or by a systematic grid put on a mosaic of these photographs, or by a random selection on a map of points transferred afterwards onto the corresponding photographs, etc.);

(b) selection (in one stage) of a subsample of plots among the interpreted plots, the number of these plots in each stratum h (as interpreted on the photographs) being dependent or independent of the proportion of this stratum (as found by photointerpretation);

(c) identification in the field of the actual strata k to which the plots of the subsample belong and measurements for estimation of the stand characteristics y in these plots.

If $\hat{P}_h$ is the proportion of plots of the large sample found in stratum h by photointerpretation

$\hat{P}_{hk}$ is the proportion of plots of the subsample found to be in stratum h by photointerpretation and in stratum k in the field (whenever $k \neq h$ there is misinterpretation)

an estimate $\hat{P}_k$ of the actual proportion of stratum k in the whole inventoried zone is given by:

$$\hat{P}_k = \sum_{h=1}^{L} \hat{P}_h \cdot \hat{P}_{hk} \qquad (8)$$

An estimate $\bar{y}_{st}$ of the mean value per unit (or per area unit) over the whole inventoried zone of the stand characteristic y is given by:

$$\bar{y}_{st} = \sum_{k=1}^{L} \sum_{h=1}^{L} \hat{P}_h \cdot \hat{P}_{hk} \bar{y}_{hk} \qquad (9)$$

where $\bar{y}_{hk}$ is the estimate of the mean value per sampling unit (or per area unit) of the stand characteristic y in the part of actual stratum k belonging to the photointerpretation stratum h.

The estimate of the mean value per unit (or per area unit) in stratum k of y is equal to:

$$\bar{y}_k = \frac{\sum_{h=1}^{L} \hat{P}_h \cdot \hat{P}_{hk} \bar{y}_{hk}}{\sum_{h=1}^{L} \hat{P}_h \cdot \hat{P}_{hk}} \qquad (10)$$

The estimated totals $\hat{Y}$ over the whole inventoried zone and $\hat{Y}_k$ over the stratum k are obtained by multiplying the expressions in (9) and (10) respective by S and $S(\sum_{h=1}^{L} \hat{P}_h \cdot \hat{P}_{hk})$, ($S$ being the area of the inventoried zone), $\bar{y}_{hk}$ in formulas (9) and (10) being the mean value per area unit.

An estimation of the variance of $\hat{p}_k$ is given by applying the formula of double sampling with stratification to the variable (1,0) indicating whether a plot interpreted in stratum h on the photographs belongs to actual stratum k or not. Transformation of formula (3') gives thus (in case the n_h are independent of the $\hat{P}_h$):

$$v(\hat{p}_k) = \sum_{h=1}^{L} (\hat{P}_h^2 - \frac{\hat{P}_h}{n'}) \frac{\hat{p}_{hk}(1-\hat{p}_{hk})}{n_h} + \frac{1}{n'} \left[\sum_{h=1}^{L} \hat{P}_h \hat{p}_{hk}^2 - (\sum_h \hat{P}_h \hat{p}_{hk})^2 \right] \quad (11)$$

n' and n_h standing as in formula (3) for the size of the large photointerpretation sample and the number of units of the subsample selected in stratum h. In most cases the term $\frac{\hat{P}_h}{n'}$ can be neglected.

If a proportional allocation of the subsample among the photointerpretation strata h is made, (i.e. if $n_h = n\hat{P}_h$, with $n = \sum_h n_h$), then the formula (11) becomes:

$$v(\hat{p}_k) = \sum_{h=1}^{L} \hat{P}_h \frac{\hat{p}_{hk}(1 - \hat{p}_{hk})}{n_h} + \frac{1}{n'} \left[\sum_{h=1}^{L} \hat{P}_h \hat{p}_{hk}^2 - (\sum_h \hat{P}_h \hat{p}_{hk})^2 \right] \quad (12)$$

Although the estimates of the variances of the means and totals of the stand characteristics per stratum and for the whole inventoried zone are somewhat complicated, such a design is very useful as it permits a reduction of the error by use of photo-interpretation, even when the photographs are not completely recent as is often the case. (Assistance of a statistician will be looked for to determine an estimate of the variances of the means and totals of the stand characteristics.) However it must be realized that if the discrepancies between photointerpretation and ground checks are likely to be large and if the size of the subsample is relatively small, the areas of the strata will be estimated with a very low accuracy.

24 Other uses of double sampling designs

The double sampling designs indicated above are used to improve the precision of the estimates of the stand characteristics through a better estimation of the size (area) of the strata. They are called double sampling methods for stratification.

However, double sampling designs can be used in forest inventory for other purposes. Double sampling for regression is also used in some cases, for instance when photogrammetric measurements of a stand characteristic (e.g. gross volume of all species) are made on a large sample of plots on the photographs and are corrected by regression on the field subsample of these plots. Assuming that each sample is an unstratified random sample, the corrected mean $\bar{y}_{Re}$ per sampling unit is estimated by:

$$\bar{y}_{Re} = \bar{y} + b\,(\bar{x}' - \bar{x}) \quad (13)$$

where: $\bar{y}$ is the estimate of the mean per sampling unit of the characteristic y obtained from the field subsample

$$\bar{y} = \frac{\sum_{i=1}^{n} y_i}{n}$$

$\bar{x}$ is the estimate of the mean per sampling unit of the photogrammetric measurements of this characteristic on the plots of the field subsample

$$\bar{x} = \frac{\sum_{i=1}^{n} x_i}{n}$$

$\bar{x}'$ is the estimate of the mean per sampling unit of the photogrammetric measurements of this characteristic on the plots of the large sample

$$\bar{x}' = \frac{\sum_{i=1}^{n'} x_i}{n'}$$

and b is estimated by:

$$b = \frac{\sum_{i=1}^{n}(x_i-\bar{x})(y_i-\bar{y})}{\sum_{i=1}^{n}(x_i-\bar{x})^2}$$

where x_i and y_i stand for the value of x (photogrammetric measurement) and y (characteristic measured in the field) in the plot i of the field subsample.

An estimate of the variance of $\bar{y}_{Re}$ when the size n of the subsample is not too small is:

$$v(\bar{y}_{Re}) = \frac{s^2_{y.x}}{n} + \frac{s^2_y - s^2_{y.x}}{n'} \qquad (14)$$

with: n' being the size of the large sample

$$s^2_y = \frac{\sum_{i=1}^{n}(y_i-\bar{y})^2}{n-1}$$

and $$s^2_{y.x} = \frac{1}{n-2}\left[\sum_{i=1}^{n}(y_i-\bar{y})^2 - b^2\sum_{i=1}^{n}(x_i-\bar{x})^2\right]$$

Double sampling for regression can be imagined for the estimation of a stand characteristic y with any other auxiliary variate x estimated from a larger sample on photographs or in the field and which is linearily correlated with y.

Double sampling for regression is also useful with estimates of areas of strata obtained by reconnaissance flights along parallel transects used, for instance, to correct estimates obtained by photointerpretation. However such methods must be used carefully since it is generally difficult to locate precisely on a map a point overflown because of the irregular speed and orientation of the plane.

When the straight line representing the relation between y and the auxiliary parameter x goes through the origin - i.e. when y tends to zero with x - double sampling is used for ratio estimation. In this case the corrected ratio estimate $\bar{y}_R$ will be equal to:

$$\bar{y}_R = \frac{\bar{y}}{\bar{x}} \bar{x}' = \hat{R}\bar{x}' \qquad (15)$$

where $\bar{y}$ is the estimate of the mean per sampling unit of the characteristic y obtained from the subsample

$\bar{x}$ is the estimate of the mean per sampling unit of the auxiliary parameter obtained from the field subsample

$$\bar{x} = \frac{\sum_{i=1}^{n} x_i}{n} \qquad \bar{y} = \frac{\sum_{i=1}^{n} y_i}{n}$$

$\bar{x}'$ is the estimate of the mean per sampling unit of the auxiliary parameter obtained from the large sample

$$\bar{x}' = \frac{\sum_{i=1}^{n'} x_i}{n'}$$

An estimate of the variance of $\bar{y}_R$ - the smaller sample (size n) being a subsample of the larger one (size n') - is equal to:

$$v(\bar{y}_R) = \frac{s_y^2 - 2\hat{R}\, s_{xy} + \hat{R}^2 s_x^2}{n} + \frac{2\hat{R}\, s_{xy} - \hat{R}^2 s_x^2}{n'} \qquad (16)$$

with n, n', $\hat{R}$ and s_y^2 having the same meaning as above and

$$s_x^2 = \frac{\sum_{i=1}^{n} (x_i - \bar{x})^2}{n-1}$$

$$s_{xy} = \frac{\sum_{i=1}^{n} (x_i - \bar{x})(y_i - \bar{y})}{n-1} \quad \text{(estimate of the covariance of x and y)}$$

An example of double sampling with ratio estimation is the one where an estimate of timber volume is performed in a quick way on a field sample (this quick estimate being the auxiliary parameter x) and a more accurate assessment of the volume (y) being made from detailed tree measurements on a subsample.

Double sampling designs are a very powerful tool in forest inventory either for stratification or with the use of an auxiliary parameter (regression or ratio estimation) but leads in many cases to difficult and rather complicated estimation of the variances of the results. In case of double sampling with ratio or regression estimation the relationship between the parameter to be estimated and the auxiliary parameter has to be assessed and the design must be conceived in order to reduce the unavoidable biases of the estimates. Assistance of a statistician proves to be particularly useful in this case.

3 Considerations on field sampling designs

The former section dealt with some aspects of the combination of information obtained from remote sensing imagery and information collected in the field. It is important indeed when designing a forest inventory to reduce the field work as much as possible by making the greatest possible use of interpretation of remote sensing imagery since this involves less manpower, equipment and operating expenses than field work. However, field work cannot be avoided in most forest inventories, especially when stand characteristics including gross and extractable volumes have to be estimated precisely. Even in the case of surveys of homogeneous stands using large-scale aerial photography and photo volume tables, ground checks are necessary to correct, through a double sampling procedure, the estimates obtained from the photographs. In mixed tropical forests field sampling is generally the most important and expensive part of forest inventory operations, due to the limitations of interpretation of aerial photographs in these areas. As has already been mentioned in chapter IV the first constraint on the use of aerial photographs for estimation of stand characteristics in mixed tropical forests is the difficulty of identifying tree species. But even if species could be identified satisfactorily, other difficulties in the estimation of stand characteristics from remote sensing imagery remain, such as the relatively loose correlation between crown characteristics and stem dimensions in these natural forests. Furthermore there is no way to assess, from remote sensing imagery, characteristics of regeneration, of quality and of occurrence of decay or of accessibility such as soil bearing capacity or ground roughness.

Therefore the choice of the field sampling design is particularly important. Some indications are given below of the suitability and relative advantages of various types of distribution of the sample (sampling design strictly speaking) and of the possible nature, size and shape of the sampling units. These two topics are considered separately although they are in fact very closely linked: for instance the decision whether to use a one-stage or two-stage sampling design depends partly on the size of the sampling units; if the latter are relatively large a two-stage sampling design may not bring a significant increase in efficiency even in an inventory of a vast forested area.

31 Distribution of the sample

311 Unrestricted versus stratified sampling. As said in Cochran's "Sampling techniques" (2nd edition, page 99), stratification "if intelligently used nearly always results in a smaller variance for the estimated mean or total than is given by a comparable simple random sample". Stratification in forest inventory is generally performed through interpretation of remote sensing imagery prior to the field sampling (or after sampling if stratification criteria are assessed after the field sampling). It must be emphasized again that the field sampling is actually stratified only if the size of the strata can be exactly (or almost exactly) known or if, as in the case of double sampling for stratification, their size is estimated from a larger sample. Thus formulas giving the estimated variances obtained from stratified samples (such as formulas (6) or (8) of chapter III) should not be applied when limits of "strata" are drawn around a set of sampling units, and there is no further interpretation to ascertain whether all the units of these "strata" correspond to the criteria defined for this stratification (e.g. slope greater than 50%, height of the dominant trees larger than 15 metres, etc...).

The criteria for stratification must be defined in a clear and understandable form. Very refined stratification by photointerpretation is generally illusory since the possible gain in precision by comparison with a more simple classification may be more than counter-balanced by subjective biases, misinterpretations and discrepancies between photointerpreters and over time. Even in the case of a simple and easy classification, misinterpretations are possible due to low quality and the age of the remote sensing imagery; it is therefore necessary to correct the areas of the strata by a sampling procedure such as the one described in paragraph 232 of this chapter: the precision of the estimated means of the stand characteristics over the whole inventoried area decreases as the proportion of misinterpretations increases and the gain by stratification may become insignificant compared with the total cost of the stratification work. It must be realized also that when stratification has to be corrected by a sampling procedure an exact assessment of the actual location of the strata is not possible, the estimates of their real areas becoming less precise as the intensity of the field sample is lower.

312 Random versus systematic sampling. In the case of one-stage sampling designs there is no doubt that the practical advantages of the systematic distribution of the sampling units greatly exceed its main theoretical shortcoming, that is the difficulty of estimating the variances of the results. Most of the practical advantages of systematic sampling in temperate forests are still more evident in tropical mixed forests where environmental conditions hamper field work. Among these advantages may be quoted reduction of access cost for an area unit of sample, greater certainty of objectivity in the selection of the sample (the systematic distribution of the sample leaves less room for possible modification of the location of the sampling units by the field crews) and more uniform distribution of the sample (and consequently of information) over the inventoried area (this latter advantage being more significant in areas which are surveyed for the first time). Moreover research is being pursued on the estimation of statistical error in systematic sampling and it is expected that methods based on the theory of stochastic processes will soon become available in practice. For all these reasons it is highly recommended that a systematic distribution of the sampling units should be adopted whenever one stage sampling is feasible.

In multi-stage sampling designs, the choice between a systematic and a random distribution of the sampling units has to be made at each stage of the sampling procedure. The advantages of a systematic distribution are not equally important in the various stages. Regular distribution of information within the penultimate units (within the primary units in a two-stage design) is generally not essential, while the systematic layout of the sampling units of the first stages may be particularly useful. For instance, in a two-stage sampling design where the primary units are squares of 2 kilometre sides, and secondary units strips of 2 kilometres in length and, say, 10 metres in width, the random allocation of the strips within each primary unit will not bring a significant increase in access cost but, on the contrary, the systematic distribution of the squares over the whole inventoried area may be of great value, especially if the area is surveyed for the first time.

313 One-stage versus multi-stage sampling. The main advantage of a multi-stage design in comparison with a one-stage design of the same overall sampling intensity and with the same size and shape of the (ultimate) sampling units, is that the component of the cost allocated to the access of the (ultimate) sampling units is greatly reduced. This is particularly true in mixed tropical forests where penetration is difficult. Against this the concentration of the sample resulting from a multi-stage procedure increases the variance of the estimates, and the greater the variability is between the units of the first stage, the larger is this increase in variance.

These considerations can be illustrated in a very simple and sketchy way in the case of two-stage designs (see Desabie - 1966):

(a) the variance of the estimate can very often be expressed as:

$$V = \frac{A}{n} + \frac{B}{n\bar{m}}$$

where: n is the number of primary sampling units

$\bar{m}$ is the mean number of secondary sampling units per primary sampling unit

A is a measure of the variability between primary units

B is a measure of the average variability between secondary units within a given primary unit.

(b) the cost of the sampling can often be expressed approximately as:

$$C = nC_1 + n\bar{m}C_2$$

where: C_1 is the cost of access to and reconnaissance of one primary unit

C_2 is the cost of access to a secondary unit (when the primary unit has been reached) and of recording inventory data in this unit.

It can be understood from these two formulas that v depends very much on A and $\bar{n}$ and is likely to be larger than the variance corresponding to a one-stage design with $\bar{m}$ sampling units. On the other hand the second formula explains why C will be smaller than the cost of reaching and recording $\bar{m}$ secondary units distributed in a one-stage design.

If acceptable estimates of A, B, C_1 and C_2 are available the two-stage design can be optimized under certain constraints using the procedure indicated in paragraph 341 of chapter III.

This simple formulation should be kept in mind when deciding between a one-stage or two-stage design. As already said the size of the ultimate sampling units is an important factor and some one-stage cluster sampling designs do not differ much in cost although they are fundamentally different as far as variance estimation is concerned. The larger and the more inaccessible the inventoried area, the more suitable a multi-stage design, but other factors are important such as the need for information uniformly distributed over the whole inventoried area and also the size of inventory units for which estimates have to be provided.

314 <u>Equal or unequal probability in sampling.</u> Most field sampling designs used in forest inventory consist of sampling units selected with equal probabilities (and without replacement). But there exist some efficient designs for which the probability of selection of the sampling units are proportional to their size as the one indicated in paragraph 422.122 of chapter III. When selecting such a design one has to remember that the sizes of all the units of the population considered (population of the primary units in the above-mentioned example) have to be known and listed: in certain cases the cost of the corresponding work may be too high compared with the expected gain in precision.

315 <u>Use of an auxiliary parameter.</u> Whenever an auxiliary parameter which is linearily correlated with the parameters to be estimated by the field sampling can be known exactly or estimated cheaply from a large sample, its use is recommended. Examples of ratio and regression estimates in double sampling have already been given in section 2 of this chapter. A classical example in forest inventory is also the use of the <u>size of the sampling units as an auxiliary parameter for ratio estimation</u> of the stand characteristics. It is very common in inventories of mixed tropical forests to have ultimate units of different size; for instance, if parallel strips are used as sampling units their area may vary due to the irregular shape of the inventoried area and of the relevant stratum or both, and also with the steepness of the terrain (if the dimensions of the strips are measured along the terrain and not horizontally). However when using this type of estimation, it must not be forgotten that the "ratio of the means" estimates are biased and that this bias has to be reduced to a minimum (see footnote, page 49).

32 Characteristics of the sampling units

321 <u>Plot sampling versus polyareal sampling.</u> Plot sampling consists of designs using area elements as sampling units or record units (with the same sampling or record unit possibly composed of two or three plots of different size for the recording of different parameters - see for an example paragraph 23 of chapter V), while polyareal sampling corresponds to point (or line) sampling designs in which the size of the recording area in each unit is a continuous function of a characteristic of the tree (e.g. its basal area in horizontal point sampling).

In this latter case there is no sampling or record unit in the physical sense and the whole population to be inventoried cannot be considered, strictly speaking, as the collection of the points or lines used as sampling "units". The practicality of polyareal sampling designs in mixed tropical forests has already been briefly discussed in paragraph 422.2 of chapter III. Cost precision studies in temperate forests have shown that horizontal point sampling is generally more efficient but there is no evidence for the time being that it is the same in the tropics. Furthermore a mere efficiency study is not sufficient and other factors have to be considered such as the reliability of the data recorded - selection of the trees to be recorded is more difficult in point sampling than in plot sampling - and the advantages of obtaining in each unit a representative picture of the forest, which is not provided by point sampling. There exist some combined point sampling designs where all trees below a given diameter (say 30 cm) are recorded provided they fall within the circular plot the radius of which is determined by this diameter and the basal area factor used in the sampling, the larger trees being of course recorded in the normal manner used in point sampling.

322 Size of the sampling units. It is commonly accepted that the coefficient of variation C_v of a given stand characteristic (parameter), (say number of trees more than a given diameter per sampling unit) is linked with the area of the sampling unit by the following empirical relation:

$$C_v = \frac{\sigma_y}{\bar{y}} = ka^{-c} \qquad (17)$$

where: σ_y is the standard deviation of the individual values of the stand characteristic y in the units of the population

$\bar{y}$ is the mean of the stand characteristic per sampling unit

a is the individual area of the sampling units

k and c are positive constants independent of a.

This relation can also be written in logarithmic form:

$$\log C_v = \log k - c \log a = K - c \log a$$

c is equal to 0.5 when the distribution of the values per unit of the stand characteristic is a random distribution, such as the Poisson distribution. This is approximately true of parameters related to the occurrence of trees of species with a very low density in mixed tropical forests (e.g. numbers of stems and corresponding gross volumes of the "mahoganies" in West Africa forests). For many other parameters in tropical forests c is found to be rather lower than 0.5.

It is interesting to compare different sizes of sampling unit in unstratified random sampling design for the same sampling intensity. In this case we have:

$$na = \text{constant}$$

where n and a are respectively the number of the sampling units and the area of one sampling unit. The percentage standard error of y (mean value per unit of a stand characteristic y) is equal to:

$$e = \frac{\sqrt{v(\bar{y})}}{\bar{y}} = \frac{C_v}{\sqrt{n}} = k' (C_v \sqrt{a}) = k'' a^{0.5-c} \qquad (18)$$

the latter expression being obtained from the empirical formula (17)

For most of the parameters in mixed tropical forests we have $C < 0.5$. It can be concluded from (16) that, *for a given sampling intensity, the smaller the sampling units the better the precision.* However it is useful to have in each sampling unit a fairly representative image of the forest and this can only be obtained if the sampling units have a reasonable size: a sampling unit of 0.01 ha in a mixed tropical forest for estimation of the volume of exploitable size would not be useful in this respect. In addition the total number of borderline trees in the whole sample (all sampling units) is higher for a sample consisting of a large number of small sampling units than for an equivalent sample (same total area) consisting of a smaller number of larger sampling units of the same shape. The selected size of the sampling units is thus a compromise between the conflicting requirements of the sampling precision and of the important practical aspects of representativeness of the sampling units and reliability of the basic data. An area of the sampling unit equal *to 1 acre (0.4 ha) or to 0.5 ha* is often considered as a suitable compromise in inventories of mixed tropical forests.

323 *Shape of the sampling units*

323.1 *Circular versus square or rectangular plots*

The main advantages of circular plots are:

- the minimum perimeter for a given area of the circle compared to other simple geometric shapes, which in turn implies the minimum number of borderline trees;

- the isotropic image of the forest around the centre given by a circular sampling unit.

Its use in temperate areas is increasing although it must be realized that, for practical reasons, the form of these plots is in fact elliptic whenever there is a slope. (Interesting devices using a range-finder and a stadia rod with adjustable sighting marks for assessment of this type of plot are mentioned in "Forest Inventory" by Loetsch-Zöhrer-Haller, Volume II, pages 324-325 and in "Dendrometrie" by Pardé, pages 190-199.)

However the difficult environmental conditions and the need for a larger size of the sampling units prevent the use of circular sampling units in mixed tropical forests (but not that of circular recording units: see below, paragraph 324.3). Square or rectangular sampling units (and also record units) are often preferred in mixed tropical forests. They may be strips of a given width (generally from 10 metres to 25 metres) along parallel lines of penetration, cut through the undergrowth, and going through all the inventoried area or through a part or a stratum of it. The width should not be larger than 30 metres - i.e. 15 metres on each side of the transect line - in order to allow for a good control of the recording operation, and the width can be measured either horizontally or along the terrain; in the first case no correction has to be made for the determination of the area of the strip, but the recording is more time-consuming and possibly less reliable because of the borderline trees; the second method may be more reliable but involves measurement of the transverse slopes and more computations. The sampling units can also be either *rectangular plots*, or *lines of rectangular plots*, the plots being, in the second case, the record units and *not* the sampling units. The plots cannot be used as the sampling units as the distance between two consecutive plots along the line is not sufficient to secure statistical independence with regard to the parameters to be estimated (see paragraph 322.2 of chapter III).

323.2 *Form of the rectangular plots*

In a study made in Cameroon it has been found that *the more elongated the shape of a rectangular sampling plot of a given size, the better the precision,* although this effect on the precision of the shape of the sampling units was found to be less important and less significant than the effect of their size. However this was not true for very long strips (unit areas of more than 5 hectares) and very wide strips (100 metres and more in width) were found to give better precision. Of course the use of such very wide plots would not be possible in practice in the inventory of mixed tropical forest.

323.3 Clusters

In inventories of mixed tropical forests, sampling units are often groups or clusters of circular plots, in order to profit from the advantages of circular plots while having at the same time sufficiently large sampling units. In this case the circular plots are the recording units, and are often arranged along a straight line or a squared or rectangular line ("tracts" of some European national forest inventories). However for the same size of sampling unit, a cluster of circular plots may have a longer total perimeter (and consequently more borderline trees) than the equivalent rectangular sampling unit: for instance a cluster of five circular plots of 0.1 ha has a longer total perimeter than a rectangle of 200 metres long on 25 metres width (roughly 560 metres against 450 metres).

Once a given size of circular plot (recording unit) is chosen the unit size of a sampling unit must be ascertained, i.e. what number M of plots each sampling unit must contain. This is an optimization problem with M as one of the characteristics of the sampling design to be determined. The following paragraph gives an example of such an optimization procedure and is partly extracted from "Sampling Techniques" by Cochran (2nd edition, pages 244-247).

Let us consider an unrestricted random sampling with n equal clusters (sampling units) of M circular plots each. The variance of the mean $\bar{\bar{y}}$ per circular plot (record unit) of a given stand characteristic is equal to:

$$v(\bar{\bar{y}}) = \frac{S_b^2}{nM} \qquad (19)$$

where S_b^2 is the variance between clusters (variance among the total values of y in the clusters on a circular plot basis)

The first problem is to estimate S_b^2 from the variances among the values of y in the circular plots, i.e. S_w^2 variance among the values of y in the M plots within a cluster and S^2 variance among the values of y in the circular plots in the whole inventoried area. We have approximately:

$$S_b^2 \approx MS^2 - (M-1)\, S_w^2 \qquad (20)$$

(this result being obtained by an analysis of the variance of y for the whole population).

It has been found that, in many surveys S_w^2 can be expressed by the following empirical formula:

$$S_w^2 = AM^g$$

with A and g positive constants independent of M.

If we have a cost function of the same type as indicated in paragraph 313 of this chapter for two-stage sampling designs, i.e.:

$$C = nC_1 + nMC_2$$

(where C_1 and C_2 have the same meaning as in paragraph 313, the cluster standing for the primary unit and the circular plot for the secondary unit) then the optimization problem amounts finally to find out the values of M (and also n) which minimizes

$$v(\bar{\bar{y}}) = \frac{S^2 - (M-1)AM^{g-1}}{n} \qquad (21)$$

for a given total cost: $C = nC_1 + nMC_2 = Co$ (22)

Applying the procedure indicated in paragraph 341 of chapter III, it can be easily found that the optimal value Mo of M is given by the following equation:

$$AM_o^{g-2}\,(C_2M_o^3 + C_1M_o^2 - C_1M_o^2 + C_1) - C_2S^2 = 0$$

The corresponding value n_o of the number of clusters is determined by replacing M by M_o in the equation (22).

4 Continuous forest inventory

41 Definition and utilization

Continuous forest inventory comprises all forest inventory designs in which sampling is used on successive occasions. This definition is much broader in scope than the one of the north American CFI in which all the successive inventories use the same sample (all the sampling units are said to be "permanent" units).

Sampling on successive occasions should be considered in designing a forest inventory when, in addition to an estimate of present forest conditions, accurate determination of past growth is required and the users of this information are willing to wait the necessary and often lengthy period of time for its accumulation.

Assembling growth information in this manner presupposes that forest management will be carried out on a continuing basis. Although forest management on a continuing basis is at a very early stage in many tropical countries, and has not even been started in some cases, inventory officers should always keep in mind the need of such inventories for forest management purposes and should initiate continuous forest inventory programmes whenever the concern for forest management and the probability of making use of the results of such inventories are deemed sufficiently high. In this respect the concept of forest management must be understood in a broad sense; the monitoring of the 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.

42 Description of design

421 Different types of continuous forest inventory. The objectives of repeated sampling in forest inventory are threefold:

1. to estimate characteristics of the forest present at the first inventory;
2. to do the same on the occasion of the second inventory;
3. to estimate the changes in the forest during the period between inventories.

(Note that the repetitive process can be continued and on the occasion of all subsequent inventories the previous inventory is referred to as the "first inventory".)

There are four basic ways in which the above information can be obtained:

1. A completely new sample can be drawn from the forest at the time of each inventory. The sampling units on occasion 2 are different from those taken on occasion 1.

2. The sampling points taken at the first inventory are remeasured at the second and all succeeding inventories. This is the concept of permanent sample plots and the basis of the Continuous Forest Inventory (CFI) developed in North America.

3. At the second inventory a portion of the initial sampling units are remeasured and new ones are taken. This is often called successive sampling with partial replacement (SPR).

4. At the second inventory a portion of the sampling units taken at the first inventory are remeasured.

422 Sampling with partial replacement (SPR). Of the four approaches the most efficient is the third, successive sampling with partial replacement. If repeated inventories are planned, inventory officers should design their procedures on this basis.

Only a concise summary of the design and analysis of this one method is attempted here and for more details reference should be made to Ware and Cunia (1962) as shown in the list of references. A good description of this and the other three kinds of repeated sampling are also covered in F. Loetsch and K. Haller "Forest Inventory" (volume 1, pages 259 to 277).

At the initial inventory there are two kinds of sampling units; plots measured only on the first occasion (unmatched) and plots measured at the first inventory and to be remeasured at the second (matched). At the second inventory there will be the plots taken at the first inventory and now to be remeasured (matched). In addition there will be new plots to be taken which did not appear at the first inventory (new). The following symbols for the number of sampling units and the observations are needed:

First inventory

u = number of unmatched sampling units taken at the first inventory

x_{ui} = parameter (stand characteristic) measured on unmatched sampling units at first inventory

m = number of matched sampling units taken at the first inventory

x_{mj} = parameter measured on matched sampling units at first inventory

$u + m = n_1$ = total number of sampling units at the first inventory

Second inventory

m = number of matched sampling units taken at the second inventory (same as m of first inventory)

y_{mj} = parameter (same as x) measured on matched sampling units at second inventory

n = new sampling units taken at second inventory

y_{nk} = parameter (same as x) measured on new sampling units at second inventory

$m + n = n_2$ = total number of sampling units at the second inventory.

Then: $\bar{x}_u = \frac{\sum_{i=1}^{u} x_{ui}}{u}$ mean of values of the parameter per sampling unit measured on first occasion from unmatched units

$\bar{x}_m = \frac{\sum_{j=1}^{m} x_{mj}}{m}$ mean of values of the parameter per sampling unit on first occasion from matched units

$\bar{y}_m = \frac{\sum_{j=1}^{m} y_{mj}}{m}$ mean of values of the parameter per sampling unit on second occasion from matched units

$\bar{y}_n = \frac{\sum_{k=1}^{n} y_{nk}}{n}$ mean of values of the parameter per sampling unit on second occasion from unmatched units

(a) Estimation of the means per sampling unit at first and second inventories.

1. The estimate $\bar{x}$ of the mean per sampling unit of the parameter at the first inventory is:

$$\bar{x} = \frac{m\bar{x}_m + u\bar{x}_u}{n_1} = \frac{\sum_{j=1}^{m} x_{mj} + \sum_{i=1}^{u} x_{ui}}{n_1}$$

2. The best estimate $\bar{y}$ of the mean per sampling unit of the parameter at the second inventory is given by:

$$\bar{y} = a(\bar{x}_u - \bar{x}_m) + c\bar{y}_m + (1-c)\bar{y}_n$$

where:

$$a = \frac{m\left(\frac{u}{n_1}\right)r \ \frac{s_y}{s_x}}{n_2 - \left(\frac{u}{n_1}\right)mr^2}$$

$$c = \frac{m}{n_2 - \left(\frac{u}{n_1}\right)mr^2}$$

with:

$$s_x^2 = \frac{\sum^{n_1} x^2 - \frac{\left(\sum^{n_1} x\right)^2}{n_1}}{n_1 - 1} \qquad \left(\sum^{n_1} x = \sum_{i=1}^{u} x_{ui} + \sum_{j=1}^{m} x_{mj} \qquad \sum^{n_1} x^2 = \sum_{i=1}^{u} x_{ui}^2 + \sum_{j=1}^{m} x_{mj}^2 \right)$$

$$s_y^2 = \frac{\sum^{n_2} y^2 - \frac{\left(\sum^{n_2} y\right)^2}{n_2}}{n_2 - 1}$$

($\sum^{n_2} y$ and $\sum^{n_2} y^2$ being obtained similarly to $\sum^{n_1} x$ and $\sum^{n_1} x^2$)

and
$$r = \frac{\sum_{j=1}^{m}(x_{mj}-\bar{x}_m)(y_{mj}-\bar{y}_m)}{\sqrt{\sum_{j=1}^{m}(x_{mj}-\bar{x}_m)^2 \sum_{j=1}^{m}(y_{mj}-\bar{y}_m)^2}}$$

An estimate of the variance of $\bar{y}$, $v(\bar{y})$, is given by:

$$v(\bar{y}) = a^2 \left(\frac{1}{u} + \frac{1}{m}\right)s_x^2 + \left[\frac{c^2}{m} + \frac{(1-c)^2}{n}\right]s_y^2 - 2\,\frac{ac}{m}\,r s_x s_y$$

which can be expressed more simply as:

$$v(\bar{y}) = \frac{1-\frac{u}{n_1}r^2}{n_2-\left(\frac{u}{n_1}\right)nr^2}\; s_y^2 = \frac{c}{m}\left(1-\frac{u}{n_1}r^2\right)s_y^2$$

(b) **Estimation of difference between the mean values per sampling unit of the parameter at first and second inventories.**

In the case when the parameter indicated by x and y is a volume, this difference will express the <u>growth</u> of the stand corresponding to this volume over the period between the two inventories.

The best estimate of this mean growth per sampling unit is given by the formula:

$$g = A\bar{y}_m + (1-A)\bar{y}_n - B\bar{x}_m - (1-B)\bar{x}_u$$

where:
$$A = \frac{m+n\left(\frac{m}{n_1}\right)r\,\frac{s_x}{s_y}}{n_2-\left(\frac{u}{n_1}\right)nr^2}$$

$$B = \frac{m\left(\frac{u}{n_1}\right)r\,\frac{s_y}{s_x} + n_2\left(\frac{m}{n_1}\right)}{n_2-\left(\frac{u}{n_1}\right)nr^2}$$

An estimate of the variance of g is given by:

$$v(g) = \frac{A^2 s_y^2 + B^2 s_x^2 - 2ABr s_x . s_y}{m} + \frac{(1-A)^2 s_y^2}{n} + \frac{(1-B)^2 s_x^2}{u}$$

which can also be written as:

$$v(g) = \frac{1}{n_2 - (\frac{u}{n_1}) nr^2} \left[(1 - \frac{u}{n_1} r^2) s_y^2 + (\frac{n_2}{n_1} - \frac{nr^2}{n_1}) s_x^2 - 2 \frac{nr}{n_1} s_x s_y \right]$$

5 Sequential sampling

Sequential sampling, like continuous forest inventory, also involves a series of samples but each of these samples includes all the sampling units of the former sample (u = o whatever the sample) and in addition the time span between two successive samples is negligible so that from a forestry viewpoint all the samples can be considered as simultaneous.

The purpose of sequential sampling is to permit the taking of a relatively secure decision about a population (forest stand) from a limited number of units of this population. Let us consider the example of a planted area where it has to be decided whether a cleaning of the plants is necessary to free them from weed vegetation. Let us suppose also that this planted area can be divided into equal lines (units) of twenty plants. Lines will be selected at random to constitute the successive samples and in each sample the total number of freed plants is recorded. Each sample drawn (the second sample including all the lines of the first and some new ones, the third including all the lines of the second and new ones, and so on) will be represented by a point on a chart, the x-coordinate of this point being the size (number of lines) of the sample, the y-coordinate being the total number of freed plants of this sample. Moreover on this "sequential sampling chart" two parallel lines are drawn which divide the chart into three regions: "no cleaning", "continue sampling" and "cleaning necessary".

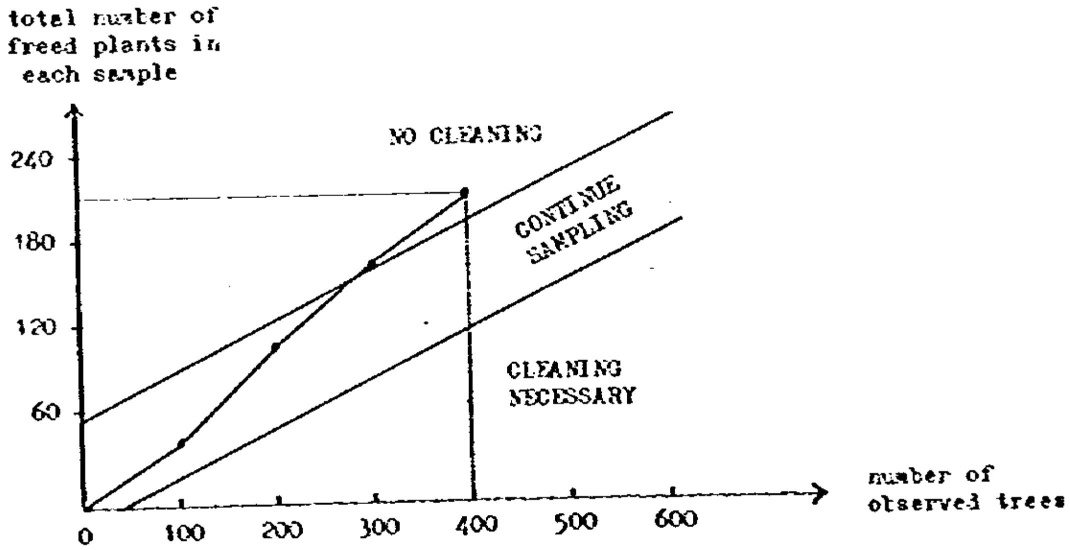

Fig.1

If the representative points of the last samples remain in the region "no cleaning" (as in figure 1) the sampling procedure can be stopped and the decision is taken not to carry out any cleaning operation. If the points stay in the region "cleaning necessary" further sampling is unnecessary and the decision is taken to begin cleaning. If the representative points are in the region "continue sampling", no decision can be taken with sufficient security and the sampling has to be pursued.

The slopes and zero ordinates of the two parallel lines which are the basic elements of this sampling procedure are a function of:

- the distribution of the "decision parameter" in the studied population (in the above example number of freed trees per line), which is to be assimilated for the sake of simplicity to a classic distribution such as binomial or Poisson distribution;

- the minimum proportion of freed trees in a line for considering that this line does not need any cleaning treatment (say 60% or 12 trees); ("acceptable" proportion of freed trees);

- the maximum proportion of freed trees in a line for considering that this line does not need a cleaning treatment (say 50% or 10 trees); ("unacceptable" proportion of freed trees);

- the two accepted risks expressed in percentages of probability:

  - of cleaning the planted area although it has in fact a sufficient number of freed trees ("rejection" risk or "producer's risk");

  - of making no cleaning at all in the planted area although it has in fact an insufficient proportion of freed trees ("acceptance" risk or "consumer's risk").

The distribution being known and the four quantities above being decided upon, it is possible to draw the lines of the chart which will help in taking the decision. A detailed description of the design and the corresponding formulas is given in "Forest Inventory" by F. Loetsch and K. Haller (Volume I, pages 278 to 289).

Although this procedure is very attractive, it has found relatively little application in forestry, mainly for the reason that little is known on the distribution of forest parameters. In mixed tropical forests there is another drawback which results from the fact that all sampling units must be selected at random, which increases the total access cost of the sampling procedure. It has been applied in forestry for regeneration surveys and for disease and insect surveys.