Chapter 9
Forestry Research

Research will probably always be an important need in tropical forestry. Not only are the forests and their environment complex but responses to interactions are not all readily visible or immediate. Research should not be looked upon by the forest manager as purely something for advanced specialists. The solution to many of the problems of forest management has resulted from the acute observations and resourceful interpretations of employees not considered "scientists." Supplementary to this, however, the manager must recognize that the greater the impact of forest operations on the forest the more profound should be concurrent study of the consequences as a guide to future improvement.

Research may be defined as systematic investigation of phenomena to determine facts. Knowledge critical to tropical forestry is elusive because of the complex and invisible nature of many of the forces involved. Also, in many tropical areas, forestry research has barely begun because only recently has the need to do more than merely reap the bounties of already existing forests become compellingly evident.

History of Tropical Forestry Research

In the broad sense, forestry research in the Tropics began with the practice of forestry itself, because observed trials of any new practices constitute rudimentary research. Some of the earliest work was essentially botanical and descriptive. Broad classes of forests were recognized, and tropical tree species were identified and classified according to traditional uses. An early stage of such collected knowledge is reflected in the monumental descriptive work of Schimper (1903) on plant geography, referred to throughout Chapter 2.

Studies of tropical woods were reported as early as 1901 in the Malay Peninsula (Ridley 1901) and were followed by other detailed reports (Foxworthy 1909, 1921). The timbers of India were first described extensively in 1902 (Gamble 1902).

Formalized institutional research did not develop until later. The Forest Research Institute at Dehra Dun, India, was established in 1906 (Hart 1922). Four years later, a program of sample-plot measurement was begun that by 1956 totaled 1,762 plots covering observations of more than 100 tree species (Mathauda 1956). By 1931, an "Experimental Manual" for India had been produced (Nair 1952). And by 1960, broad research programs were underway in several of the states of India. In Mysore, lines of investigation included nursery practice, planting, taungya, teak *(Tectona grandis)* seed origin comparisons, the application of manure, and termite controls (Krishnaswamy 1960). In Madhya Pradesh, research was dealing with rehabilitation of former proprietary forests, natural regeneration of teak, thinning, and rates of tree growth within the forests (Mujumdar 1960b).

In what is now Malaysia, formalized forest research began in 1918, 17 years after the appointment of its first forest officer (Menon 1976). The Forest Research Institute of Malaysia at Kepong has been in existence since 1929. The source of much of the advanced dipterocarp forest silviculture, this institution has become one of the largest of its kind in the world (Anon. 1988a). In 1987, the Institute had a professional and subprofessional staff of more than 100, the world's best dipterocarp arboretum, and an herbarium of more than 100,000 sheets. Branches of the Institute are concerned with natural forest silviculture, plantations, biology, forest protection, and forest products.

In the Philippines, evidence of early research can be found in a study of *Leucaena leucocephala* management published in 1914 that is still remarkably valid (Matthews 1914). In Nigeria, planting was first tested in 1907, and a Research Branch of the Forest Department was established in 1943 (Rosevear and Lancaster 1952). In what is now Sri Lanka, phenological records in the diaries of forest officers marked the beginning of research in 1937 (Holmes 1956). These records were later systematized to cover 2,000 trees of 125 species in 40 plots visited monthly for 5 years.

In the Western Hemisphere, systematic forestry research appears to have begun in southern Brazil with *Eucalyptus* introductions, dating from about 1906 (Navarro de Andrade 1941a). Interest in indigenous forest trees of Brazil was formalized by studies of nine species beginning in 1953 (Gurgel Filho 1975). A formal forestry research program began in the Amazon with the work of Pitt in 1960 (Pitt 1961a), which included studies of natural regeneration, post logging coppice, enrichment, and close plantings.

Research has accompanied forestry development in all countries of tropical America, although the intensity of the research effort varies widely. Research institutions with independent programs now at least exist in Argentina, Brazil, Colombia, Costa Rica, Mexico, Peru, Puerto Rico, and Venezuela (fig. 9–1). Research in tropical Mexico, more recent than research on the Temperate

Figure 9–1.—*Headquarters of the USDA Forest Service, International Institute of Tropical Forestry, in Puerto Rico, one of the most venerable research institutions.*

Zone forests in that country, has for some time included extensive studies of natural forests, plantations, and agroforestry (Cedeno Sanchez 1976, Chavelas Polito 1976).

A need for international collaboration among forestry research institutions and scientists was recognized by the Food and Agriculture Organization (FAO) Regional Office for Latin America in supporting the Instituto Forestal Latinoamericano de Investigacion y Capacitacion at Merida, Venezuela, in 1956. The FAO Latin American Forestry Commission established a Regional Committee on Forestry Research in 1958. A product of that committee's work was an analysis of 16 research institutions, showing a high degree of similarity in the goals of their respective research programs and administrative problems (Wadsworth 1969).

Actually, international collaboration on forestry research in the Tropics began among the countries of the various colonial empires. More recently, broader based collaboration was fostered by the Commonwealth Forestry Institute (now Oxford Forestry Institute) through the collection and distribution of seeds of popular plantation species from a variety of provenances. By 1990, the Institute had collected and distributed more than 22,000 separate seedlots of 108 tree species to 122 countries, including most of those of tropical America (Barnes and Burley 1990).

Tropical America must do more of its own research. The solution to the area's problems will be found within the area and must be integrated with the changes being brought about by development.

Regional Research Needs

Before research needs are listed, a fundamental condition in most of the Tropics needs to be emphasized. What is termed "modern" research is almost totally a product of wealthy societies (Mlinsek 1982). These countries have tended toward expensive methods that substitute elaborate instrumentation for cruder techniques of approximation. Such methods have their place in raising the precision and conclusiveness of results. Yet, under common conditions in the Tropics, where approximations may initially be adequate in the absence of any prior work, the very cost of such methods may be excessive if not prohibitive. The selection of technology that is appropriate to the Tropics is thus as important to research as it is to the practice of forestry.

Tropical America needs more information on myriad forestry topics. The first (and still incomplete) task of those responsible for tropical forestry research is identifying the most urgent problems. A number of efforts to that end have been reported. Those summarized here indicate the conclusions reached by many experts. Three broad stages of timber management research have been recognized as follows (Dawkins 1949):

1. Compositional—How to recognize, measure, and use forest constituents

2. Ecological—How desirable trees behave in relation to site

3. Silvicultural—Effects of cultural practices on forest behavior and productivity.

A broad view of research needs by the FAO (King 1979b) was prefaced by the comment that developing countries are aware of the significant role that forests, forestry, and forest industries can play in economic development. They know that forests can help save and earn foreign exchange, can stimulate many other economic activities both at the raw-material source and in the fabrication of products, and can create significant employment opportunities, particularly in rural areas. Factors viewed as needing attention are:

- Tree species in moist tropical forests
- Standing wood volumes by species
- Tree species distribution and growth rates
- Forest reactions to silviculture and management systems
- Techniques for regenerating commercial species
- Economically feasible techniques for pulping mixtures
- Long-term effects of intensive tree plantation culture on soil productivity
- Superior seed sources
- Genotypes adapted to difficult sites
- Vegetative propagation techniques for tree improvement

Research needs of the Amazon region have been outlined in general terms (Fearnside 1979b, Prance 1982):

- The biota (at least 20 percent of the plant species are as yet unnamed as are more than half of the insects)
- The carrying capacity of sites in terms of number of people that can be supported and how much timber can be extracted under sustained yields
- The extent, causes, effects, and methods of controlling deforestation
- The rational, planned use of the forests
- The role of mycorrhizae
- Germplasm breeding systems.

The Center for International Forestry Research under the auspices of the Consultative Group for International Agricultural Research has drafted a medium-term program (1993–98) with the following components:

Policy development
- Policies and incentives to achieve sustainability of forests
- Systems for equitable distribution of benefits and costs of forest goods and services
- Adoption of policy change
- Policies to increase employment and income from forests
- Location and types of global forest resources to satisfy future demands for goods and services

Management and conservation of natural forests
- Low-impact harvesting and management
- Management for biodiversity and diverse products
- Growth-and-yield prediction systems
- Sustainable management of dry-zone woodlands
- Reproductive biology and genetics

Reforestation of degraded lands
- Nonindustrial techniques
- Matching tree species and genotype to biophysical site conditions and management systems
- Techniques for characterizing genetic variations and relating them to physiological and morphological adaptations
- Physiology and biochemistry of plant material for improved vegetative propagation
- Plantations of mixed tree species for multiple products
- Yields in second and subsequent rotations of tree plantations

Products and markets
- Management by local communities and user groups of resources for nonwood forest products
- Market requirements and possibilities for underused, nonwood forest products
- Expansion and harmonization of data bases on properties and uses of tropical timbers and nonwood forest products
- Social and economic effects of new technology for adding value to products in or near the forests

Research support and information
- Human resource development
- Publication and information services
- Data base harmonization, integration, and dissemination.

Bamboo (Gramineae) is one of the tropical plant groups of greatest present and potential use. Thus, a broad range of basic research priorities (many of which apply equally to many other forest species) has been recommended for this plant group (Lessard and Chouinard 1980) including: taxonomy, field identification, propagation, anatomical structure, mechanical strength, and preservative treatment.

It is not enough, however, to merely list subjects for study when the means for undertaking the research are inadequate everywhere. A review of 16 forestry research institutions in the region (Wadsworth 1969) led to the following conclusions:

- The most critical deficiency was in training of scientists.
- There was a danger of excessive duplication of effort, because technical problems are common to much of the area.
- Coordination of efforts should begin through regional problem analysis and priority setting.
- Meetings of institution leaders and scientists were either too infrequent or nonexistent, yet they are necessary to an effective regional research effort.
- Particularly neglected were the generally important technical fields of soils; hydrology; wildlife management; agroforestry; waste utilization; fire control; and the processing, grading, and marketing of products.

In 1970, the FAO Latin American Forestry Commission's Committee on Forest Research issued a comprehensive list of recommendations to national governments and international technical assistance agencies to strengthen forestry research in the region (Anon. 1970). Most observations detailed in that list are still valid, including the following:

- Forestry research must no longer be looked upon as merely a troubleshooting adjunct to forestry agencies or as an exercise in graduate teaching but rather as a technical spearhead for future forestry development.
- Forestry research responsibilities need to be clearly assigned and continuously supported within government organizations first, as a primary activity in a single national forestry authority, and second, as a supplementary activity at existing forestry colleges.
- Forestry scientists need salaries at least commensurate with those in other research fields and adequate to encourage career-oriented dedication.
- Research institutions concerned with forestry, agriculture, and wood technology need coordination, team effort, and frequent direct communication among scientific personnel.
- Forestry scientists need continuing training opportunities in special subjects, such as experimental design and techniques, research administration, and technical report writing.
- A centralized documentation service is of vital importance to the forestry scientists of the region.
- To ensure comparability, regionally standardized techniques are needed for the collection, analysis, and interpretation of forestry statistics and field data involving the measurement of forest trees and stands.
- An almost total lack of information concerning the economics of timber harvesting in the region calls for studies on the value of standing timber and the costs of logging and transportation to wood-processing facilities and consumption centers.
- There is a growing regional need for basic information on the role of forests in soil and water conservation and in flood control, calling for relevant investigations and a regional network of demonstration watersheds.
- There is need for a regionwide, up-to-date listing of centers of tropical forestry research able to supply or exchange quality forest tree seeds.
- There is a need to reserve natural areas in the unmodified forest ecosystems of the region for basic ecological research useful to forest management.

Worldwide concern with tropical forests has intensified the attention to research needs. Starting from a paper on forestry research needs in developing countries (Anon. 1981a), the second "Bellagio" meeting in 1988, working through a task force, led to a proposal for the following research thrusts (Anon. 1990a):

- The role of forests, woodlands, and on-farm trees in contributing to agricultural productivity and suitable land use (including soil fertility, microbiology, mycorrhizal organisms, the role of nitrogen (N)-fixing trees, pests, and diseases) tree-management systems, both intercropping and monoculture
- Conservation, selection, breeding, and improvement of multiple-purpose tree species, particularly N-fixing species for agroforestry, wasteland reclamation, fuelwood, fodder, cash crop-tree farming, and industrial planting
- Natural forest ecology, management, and conservation of biodiversity
- Utilization and forest products research: timber testing, forest products engineering, causes of deforestation, agricultural settlement, land tenure policies, economic linkages, incentives for reforestation, and equity and gender issues.

Research within tropical forests requires safeguards against outside interference. Representative forests (both primary and secondary stands) must be conserved until foreseen (or unforeseen) studies can be undertaken. Such preservation is vulnerable to pressures to modify or use the land for other purposes and may eventually fail unless an active forestry research program is undertaken and its findings publicized and utilized.

Research Components

Research must be approached with an open mind. One can neither complacently accept traditional knowledge nor summarily discard it. The scientist must constantly question, knowing full well that his or her questions may not always have simple answers. New studies will not always eliminate uncertainties, but they may provide a better basis for informed human judgment.

Orientation. Research is concerned with the nature, direction, and control of changes leading to a better future and with outcomes that represent long-term efforts. For these reasons, it is vital that scientists look far beyond current activities. For national research programs, this long-range view calls for analyzing forestry problems and setting priorities so that study selection may reflect the most critical needs, now and in the future.

One proven approach to research orientation is problem analysis, a detailed plan for problem solving in use in the United States (Anon. 1940–90). It contains pertinent literature and expert scientific thinking. Important points usually covered include the following:

- Precise problem definition
- Environmental considerations
- Problem components
- Predicted benefits of the solution of each component
- A proposed approach
- Indicated studies and priorities
- Plan for diffusion and implementation of results
- Personnel, facilities, and needed cooperation
- A time schedule for study initiation
- Anticipated completion time for each component
- Estimated cost of each component.

The development of clear questions to be answered is primary to research planning. The process of deriving research priorities for forestry oriented toward producing commodities is illustrated in figure 9–2.

Much has been written about how to conduct an experiment. Yet, most experiments do not accomplish all that is expected of them because they are imperfect in concept, execution, or interpretation. Some points to keep in mind about investigations are presented here.

Any serious study should begin with the preparation of a written plan, presenting sufficient detail so that it could

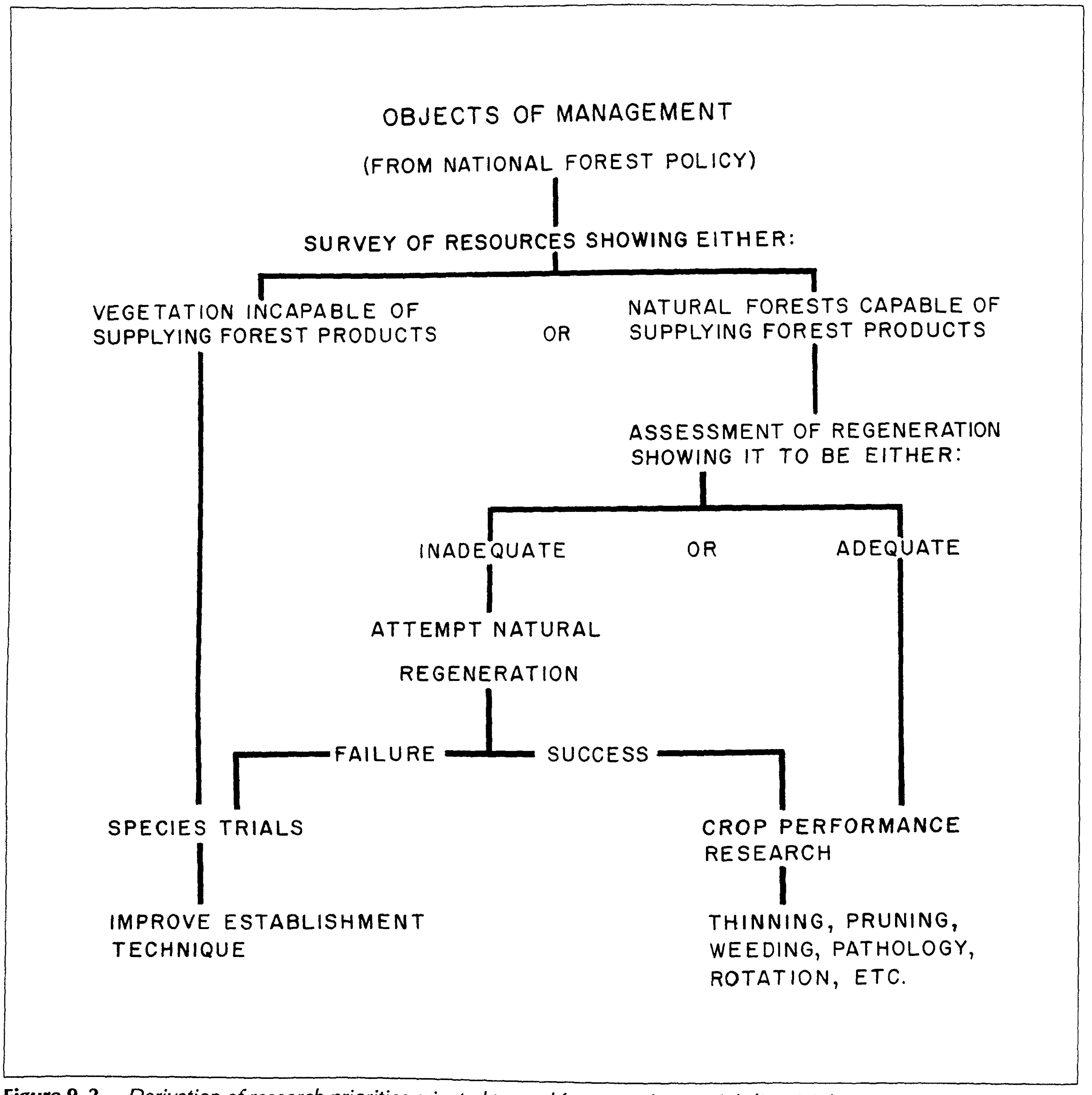

Figure 9–2.—*Derivation of research priorities oriented toward forest production (Philip 1964).*

continue if it were taken over by different scientists before being finished. Such a plan might include the following:

Title
The title should be brief yet distinct from other studies, and generally the plan is given a number.

Literature
The status of knowledge concerning the subject, techniques, related studies in progress, and literature sources should be described. Where literature is not readily available, it is still important to complete this step to the extent possible to avoid duplicating or overlooking recently developed methodology.

Objectives
The hypothesis and the specific question to be answered should be stated clearly, its importance and urgency explained, and potential applications and benefits of results described.

At the outset, the importance of the entire line of investigation must be assessed. This is a critical and often overlooked step. Not only must this investigative approach lead toward important conclusions or decisions, but it should be superior to alternative approaches.

Most research is undertaken to shed light on broad questions, such as, "Which is the best tree for site X?" Because of the multiplicity of interacting factors, seldom can a single experiment definitively answer such a question. Generally, a broad question must be reduced to a subset of more specific questions, such as, "Which of four promising tree species grows fastest in 3 years, untended, on site Q?" A single test may be designed to answer this question. Then, results from this and other tests concerned with ease of establishment, local site effects, wood quality, social acceptability, and so forth, can be synthesized into a hypothesis about species selection that can then be tested more comprehensively. An example could be that on the basis of a series of tests, species Y appears superior to W, X, and Z throughout the extent of site Q.

Forethought in selecting the question to be answered is of overriding importance. The question must be framed so that a clear response, either affirmative or negative, may be obtained, or if the answer raises the question "how much?," the amount must be decided in terms precise enough to distinguish important from unimportant differences.

Methods
The design of the experiment (size, replications, plot arrangement, derivation, and data to be collected) and corresponding analyses should be described. As appropriate, location should be assigned, time scheduled, and materials and equipment specified.

Use of Results
Methods of presentation to audiences, the review process, publications, and other means of using the results should be described.

Design and Analysis
The study objective should be stated in statistical terms, and an acceptable design (size, sites, replications, plot or sampling arrangement, data to be collected, and scheduling) should be derived. The proposed analytical use of the data should be described. As appropriate, locations, materials, and equipment should be prescribed.

Requirements
Human resources, scheduling, transportation, other facility needs, and funding should be taken into consideration.

Appendix
Location maps, plot arrangement, and recording instructions should be provided in appendices to the written study plan. An abstract should be prepared and placed at the beginning of the plan to attract the reader and summarize the problem, objectives, scope, design, and analysis.

Representativeness. Experiments are worthwhile only if they have predictive value. What has been observed on a small scale must be applicable to a larger area, or the study is of limited utility. It would seem obvious, therefore, that experiments must be done under conditions representing a large area of interest. However, this basic requirement is commonly either overlooked or given so little thought that many experiments are not truly representative. Results are then applied improperly to conditions that may in fact be very different from those of the study area. This discrepancy is commonly caused by bias toward locating experiments in areas that are accessible or convenient, a practice usually permissible only for exploratory tests to obtain crude information for more definitive, subsequent experiments.

The prospect that conditions in the area of application may not be uniform is also frequently overlooked. Wherever there is reason to suspect significant variation, this must be represented in the study design or in a series of trials to determine which of any recognizable "subconditions" may be significantly different. In testing new tree species, for example, trials should be carried out throughout the range of climates and soil conditions that characterizes the entire area for which results are needed. Should results differ significantly from place to place, independent conclusions will be needed for each, and the distinct sites must be studied separately.

Replication. Most conclusions in forest research are not finite but rather are based on probabilities, that is, the percentage of a total number of instances in which an observed phenomenon can be expected. These probabilities can be determined only by replicated (or repeated) observations. True replication occurs only when repeated tests are carried out in a similar manner and under conditions representing the full breadth of the question to be answered.

The number *(n)* of replicates (or samples) required for a desired degree of accuracy may be approximated in advance by the following steps (Burley and Wood 1976):

1. Determine from preliminary observations (or estimate) the mean value *(m)* to be expected.

2. Determine the standard deviation *(s)*. If preliminary observations are available, the square root of the sum of their individual departures from the mean is divided by their number less 1. If preliminary observations are not available, take one-quarter of the range from the predicted smallest and largest values to be expected.

3. Determine the coefficient of variation *(CV)* by dividing 100 times the standard deviation by the mean.

4. Select a degree of precision *(e)*, the number of units that constitutes an important difference.

5. Select a level of probability that is considered reliable, commonly 95 times out of 100.

6. Determine a proper value for "Students' t." As seen in tables (Wenger 1983), the "t" value depends on the number of replicates, which is what is being determined. So, the t value may have to be determined by trial and error. However, for all practical purposes, for any number of replicates over 30, the value t is 2 for 95 percent probability (table 9–1).

7. Determine the approximate sample size by squaring the product of t and *CV* divided by e^2.

For example, assume that the mean ratio of tree-crown diameters to stem diameters at breast height is to be determined. Measuring a few typical trees has indicated that the mean may be about 20 and the range may be from 10 to 30. The approximate standard deviation is then 30 minus 10 divided by 4. This means that the coefficient of variation is 100 times 5 divided by 25, or 20 percent. If the degree of precision desired for the ratio is within 2 points of the mean (20), then *e* equals 10 percent. The predicted value of t for a probability of 95 percent and an estimated number of replicates of 40 is 2.02. The first trial for the true number of replicates is then the square of 2.02 times 20, or 1,632.16, divided by the square of 10, giving the result of 16.3 replicates. Recalculation then with the t value corresponding to 16.3 replicates (2.12) gives the number of replicates as 18.0, or $(2.12 \times 20)^2/100$. Because of the approximations involved, a safe number of replicates apparently would be 20 or more.

Much of the guesswork in selecting sample sizes for research plots can be eliminated by using tables that give sample sizes as a function of an estimated coefficient of

Table 9–1.—Values of "Students' t" (95-percent probability level) for various numbers of replicates in research studies

Replicates	t	Replicates	t
2	12.71	10	2.23
3	4.30	15	2.13
4	3.18	20	2.09
5	2.78	30	2.04
6	2.57	40	2.02
7	2.45	60	2.00
8	2.36	120	1.98
9	2.31		

Source: Wenger 1983.

variation and a prescribed sampling error using various levels of confidence. A set of such tables has been published by Stauffer (1983). Many additional and more precise details on experimental design for various research inquiries are to be found in Burley and Wood (1976). Table 9–2 approximates numbers of replicates based on the coefficients of variation and the precision required.

Precision. Experimental differences that may have been slight on a small scale will be of similar proportion on the grander scale of application. The above process also tends to multiply any errors of experimentation and, thus, can easily lead to unacceptable results on a large scale.

The best safeguard against this problem is to ensure the precision with which observations are made and responses measured (fig. 9–3). At least three measurement levels merit attention. First, to the degree possible, the effects measured must be related directly and solely to causes. Eliminating extraneous influences or indirect responses is necessary to clarify true causes and effects.

Second, the instruments used in measuring responses should be selected for their reliability at the level of precision required. The fact that an instrument is new, complex, or sophisticated does not necessarily mean that it is appropriate to a particular study. Instruments may need prior testing or calibration under the precise conditions of the experiment.

Appropriate care must be used in obtaining measurements. The more precise are the readings required, the closer the supervision must be. Those who take readings not only must be trained for the task but also must be

Table 9–2.—Approximate number of observations required for a specified precision in experiments based on coefficients of variation

Coefficient of variation (%)	No. of observations for desired precision (95-percent probability)		
	±5 percent	±10 percent	±20 percent
10	16	4	1
30	144	36	9
50	400	100	25

Source: Burley and Wood 1976.

Figure 9–3.—*Accurate and repeated assessments of the forests are fundamental to the acquisition of new knowledge through research.*

fully convinced of the need for the stated level of precision and of the determination of the supervisor to accept nothing less.

Third, the data, once collected, should be interpreted only to the degree that their precision warrants. Measurements geared to centimeters tell nothing about unit precision in millimeters. Even where readings may be taken to the millimeter there may be no validity in generalizing from them. An example is annual rainfall, summed for a year or averaged for several years and presented to the nearest millimeter. Individual storm readings or daily totals may be measured to the nearest millimeter for the gauge used at its precise location and for the precise period measured. However, anyone measuring annual rainfall knows that for different years, totals differ, not by millimeters, but usually by many centimeters. Likewise, a second rain gauge, even if placed near the first, will show differences over a year measured in centimeters. Accordingly, summed rainfall data expressed in centimeters are, for most purposes, as meaningful as those in millimeters.

Results of summaries of observations or comparisons commonly are expressed in terms of sample means with some measure of dispersion, such as the standard error (standard deviation/n). For some practical purposes, a more meaningful figure than the sample mean is the "reliable minimum estimate," a figure derived by subtracting from the sample mean the standard error multiplied by the value of t for a probability of 0.95 (Dawkins

1958d). The reliable minimum estimate so determined is to be expected with a probability of 97.5 percent.

Comparing research results throughout a region as large as tropical America calls for similar reliability in the studies undertaken. This should not limit ingenuity in designing studies for specific local conditions. However, a goal of similarity could provide a guide to plot sizes and definitions of tree height and diameter groups for summarizing tree performance, and so forth.

Interpretation of Results. The foundation of interpretation is observation. Mlinsek (1982) points to the tendency to use expensive research equipment in place of direct observation. He states that forestry research used to lean on observation and clever interpretation, yet good qualitative results appeared. He concludes that, even with sophisticated instruments, it is still essential that scientists maintain a permanent contact with the nature of forests. This may be intellectually demanding but is modest in terms of equipment needs and may produce results equal to those of laboratory research.

The interpretation of research results calls for a broad understanding of all values involved. Plantation productivity, for example, is usually expressed in terms of volume (or aboveground phytomass) per unit of area and time. However, under some circumstances, the maximum volume yield per unit of investment or per unit of employment may be most meaningful (Wood 1974).

Investigations are commonly undertaken more to prove something already suspected or believed than to search for a completely unsuspected truth. The motivation is often to demonstrate the benefits of applying some new finding to management. Even where this is not the case, the investigator, either at the outset or as the study progresses, may be tempted to prejudge and interpret what has not yet been shown conclusively. This impulse can lead to bias in the design, conduct, and interpretation of investigations. Any satisfaction thus derived may be short lived, because decisions based on biased conclusions will sooner or later prove deficient and will be exposed by costly mistakes or by other more objective investigators. Interpretation should be limited to the strength or scope of the observations, even if the results fall short of study objectives. Such limitations, openly recognized and reported, can stimulate an improved second attempt by the same or other investigators.

Another aspect of interpretation concerns "indications" not fully supported by measurements (such as differences less than probable at the 95-percent level of confidence) but nevertheless part of the investigator's impressions during the study. These may lead to hypotheses to explain phenomena observed and, thus, to new profitable lines of investigation. Descriptions of such impressions are an important by-product of research expertise and have a place in scientific reporting, the only proviso being that they be described only for what they are and not as scientifically established fact.

Presentation. The purpose of research is to provide new information. But to whom? The audience is a critical consideration in selecting research priorities and presenting research results. The most obvious audience for research in forest production is the practitioner: the forest manager, agroforester, or landowner who may apply new information in policy formulation and in the treatment of forests and forest lands. A second distinct audience is the general public, whose support underlies much research and yet is interested only casually in the details. A third audience is the scientific community that is interested in learning of study techniques and technical results as a foundation for further research.

Good research should have something to offer each of these audiences, but seldom are all three addressed at the same time. Scientists tend to address other scientists in terms that are not familiar to either practitioners or the general public. Much research is, therefore, undersold where it might be applied or could win further support. It is incumbent on the scientist to reach all of these audiences with the results of his or her work. This calls for clarity, simplicity, and purposeful presentations acceptable in a variety of media.

Research Focuses

A balanced research program is generally composed of several studies that collectively are focused on critical problems. This balance normally is between long-term, fundamental investigations and short-term studies for prompt solutions to immediate problems. Long-term studies may concern underlying causes for observed phenomena, such as variations in the productivity of different sites. Balance also is enhanced by recognizing the priority of research to determine the physical, biological, and technical possibilities over the priority to determine the limits or degree of economic feasibility.

Forest Classification and Inventories. Climatic and ecological classifications of tropical forests have been described in earlier chapters. They are useful in that they emphasize key characteristics that (1) may be common to forests separated by long distances or superficially different, or (2) may distinguish forests otherwise apparently similar. But such classifications are imperfect and are a continuing subject for research in the region. One of their limitations arises directly from their tendency to group forests solely on the basis of a few readily measurable parameters. Attempts to achieve universal forest classification systems have been challenged for obscuring as many differences as they reveal similarities (Grubb and others 1963). Whereas broad similarities should be recognized, attention must also be paid to changes in associations and individual species with differentiation of site factors such as elevation, slope, aspect, and physical soil properties. Better understanding of these relationships through research should bring to light both limitations and possibilities for wiser forest management in tropical countries.

Forest inventories in tropical America promise to be an ongoing focus of research attention. Much of the region has never been inventoried, and yet rational protection and productive management must be based on forest assessments that only some form of inventory can provide. At the very least, inventories must provide reliable information on the location and extent of existing forests, information now derived almost universally by remote sensing.

Valuable as this basic information may be, it suffices only for cursory forest policies, suggesting the overall importance of forests as a national form of land use and possibly indicating where to concentrate forestry efforts. To rationalize harvesting rates, identify the most productive sites, and determine sustainable yields, tropical forests must be inventoried in much more detail and repeatedly over time. Continuous inventories, showing changes over time, are generally based on repeated measurements of representative samples of the forests.

In planning for the conversion of Uganda's forests to a 70-year, monocyclic management program, foresters found it essential to have reliable inventories based on well-planned, comprehensive ground sampling of the forest composition, the silvicultural condition, and the productive potential of each area (Hughes and Brown 1962).

The percentage of the forest to be included in the sample, the parameters to be measured, and the nature of the analysis all depend on how much information is required and how precise it must be. For overall estimates of total standing timber volume, sampling of 2 to 5 percent may suffice, but a much larger sample will generally be required in mixed forests when the goal is to estimate the volume of trees of harvestable size or of only one (or a few) species. Gathering these data could require an almost complete inventory because of the irregular occurrence of each species in mixed forests. Where possible, grouping of species in inventories may greatly reduce such irregularity and, consequently, the sampling intensity required for any specified level of precision. The sampling intensity required can be based on the coefficient of variation, as previously described (table 9–3; Meyer and others 1961).

The sampling intensity needed for a given reliability can be reduced by subdividing a heterogeneous forest into more homogeneous subunits. The heterogeneity of mixed forests can be reduced for sampling purposes by stratifying according to environmental factors such as elevation, soil type, or past forest treatment. Such stand variants may be discernible through remote sensing. In general, any variation that can be so mapped is a promising source of potential savings in field sampling intensity, because each forest type (or class) tends to be more homogeneous than the aggregate mixture, and thus, each

Table 9–3.—Probable error from ground sampling in forest inventories (%)

Size of forest (ha)	Probable error for different samples: 1 percent	5 percent	10 percent
	Coefficient of variation of 15 percent		
40	14.9	6.5	4.5
400	4.7	2.0	1.4
4,000	1.5	0.7	0.4
	Coefficient of variation of 60 percent		
40	59.8	26.2	18.0
400	18.9	8.3	5.7
4,000	6.0	2.6	1.8

Source: Meyer and others 1961.

might be sampled less intensively for a given level of probable error.

In any forest inventory, no matter how routine and repetitive, there is a continuous need to assess techniques as well as their results in a search for better and less expensive methods. For detailed information on forest inventories, their purposes, designs, sampling techniques, remote sensing, measurements, data recording and processing, and interpretation, the reader is referred to the FAO's manual on this subject (Lanly 1973). For tests of tree species, a good reference is that of Briscoe (1990).

Forest Ecosystems. Before rational decisions can be made about whether or how to modify tropical forests to stimulate production, one must be aware of how the natural functions of unmodified ecosystems operate (Assman 1970). For example, regeneration under undisturbed conditions must be understood as a guide for regeneration under conditions rendered unnatural by removal of timber (Richards 1957). Similarly, in secondary forests, the study of the natural succession of species can guide silviculture (Hall and Okali 1979).

Given the heterogeneity of tropical forest ecosystems, research may be less fruitful in the discovery of universals than in the search for causes of differences (Levins 1968). The challenge is to discover ways of treating natural systems for human benefit without losing the rich source of biological information they contain (Farnworth and Golley 1973). Research must be directed toward a sustainable yield of useful benefits or products, meaning that our actions must not diminish productivity, richness, or long-term stability.

An Institute of Ecology task force concluded that the following ecological research needs in tropical forests are of high priority (Farnworth and Golley 1973):

- Studies of the morphology, physiology, behavior, and population structure of forests
- Time and energy budgets of individual organisms and of populations, and rates and strategies of energy acquisition and expenditure
- Life histories of flora
- Potential organic yields, productivity, decomposition, and cycling
- Relation of diversity to stability
- Stress limits tolerable without loss of recovery potential
- Nutrient dynamics in forest treatment, destruction, and recovery
- Systems approach to pest management
- Research techniques

Other recommendations for strengthening ecological research on tropical forests (Brunig and others 1975) focused on: (1) the nature and quantity of flows and fluxes; (2) the structure, functions, and interactions of flora and fauna; (3) nutrient cycling and decomposition, and the role of mycorrhizae; (4) species-site relationships; (5) terrestrial and aquatic systems interrelationships; (6) reactions of the natural ecosystem structure and functions to environmental variation and human interference; and (7) the development of predictive models.

Basic data on forest structure and composition are considered essential to an understanding of the management of mixed Malaysian forests because of a tendency to increase the representation of commercial tree species and shift toward more even-aged crops (Wyatt-Smith 1966).

Tree Life Histories. Despite the need for studies of ecosystems as a whole, there is much to be gained by studying the life histories of individual component species. This is true partly because the culture of mixed forests for different management objectives usually favors some species at the expense of others. The selection process itself should be based partly on the relative performance of alternative species. Then, as a result of such selection, the performance of the system or stand as a whole tends to reflect the performance of the selected species that are gradually becoming more prominent within it.

For each species, various types of information are needed. The first to be considered is the species' "identity," including any racial variants, distinguishing taxonomic features, and species nomenclature, both scientific and vernacular. Second, the environmental factors that appear critical to its occurrence and welfare should be investigated. Among these are climate, including frost occurrence and drought severity; soils, particularly physical factors such as depth and porosity; and the supply of nutrients (Richards and others 1939).

Third, the nature of the forests where a species occurs (or is apparently well adapted) should also be determined. Information should be included on elements such as canopy closure, gap size, shade intensity, and any layer that may constitute the primary habitat of the species. Associated species are also significant, as is the species' relative occurrence in primary forests or forests in various successional stages.

Fourth, the habit of the species itself is also important, including form, size at maturity, bark peculiarities, buttresses, leaf type and size, deciduousness, flowering, pollination, fruiting, seed transport mechanisms, the mechanics of establishment and growth through life, and the relation of all these to the environment.

Under the category of "silvical information" would come the response of trees to silvicultural practice, data that may be derived in part from the behavior of the species in nature. Types of related information include adaptability to artificial regeneration, external dangers (such as pests and breakage), response to different silvicultural treatments, and rates of volume growth (Fanshawe 1947a, 1947b, 1948; Kadambi 1954; Soerianegara 1973). A compendium of silvical details on the trees of Trinidad and Tobago presented the following information categories (Marshall 1939): distribution and habitat, botanical description, germination, seedling development, silvicultural characteristics, and utilization. A presentation of tree information for Ghana (Taylor 1960) includes scientific, vernacular, and trade names, botanical description, uses, distribution, phenology, seeds and the seedling, and the abundance of and conditions for natural regeneration.

The Silvicultural Study Group of the North American Forestry Commission has developed from other sources a comprehensive outline for silvical information that should serve as a guide in the region and is presented in appendix M. Very nearly the same outline is being used by the Silvics Manual of Tropical American Trees, in preparation at the International Institute of Tropical Forestry in Puerto Rico (Francis 1984–present).

Field identification is generally based on more characters than are used for taxonomic classification. The identifying characters must be visible throughout the year. Some common examples (Allen 1956, Rosayro 1954) include crown form, bole form, buttresses, stilt roots, spines, dehiscence of bark, scaling bark, bark color, bark exudations (latex) of different colors, color change of inner bark on exposure, distinctive color of middle layer of bark, streaked inner bark, distinctive odor or taste of bark or wood, and presence of stinging ants. Such information for the preparation of field keys is basic to research in the region (Dubois 1971).

The study of natural regeneration of tropical trees is still in its infancy; generally, we know neither how most species reproduce in the absence of human intervention nor how the process might be stimulated. In India and what is now Malawi, natural regeneration became the accepted silvicultural practice decades before foresters recognized that little or nothing was really known about the reproductive process and that more research was needed (Hursh 1960, Nair 1960).

A case has been made for research on regeneration under undisturbed conditions as a source of basic information (Stern and Roche 1974), yet the study of regeneration (or the lack of it) under the modified conditions that typify exploited or secondary tropical forests may prove more useful. Furthermore, because the problems of natural regeneration are not solely those of recruitment, there is a need for concurrent developments of technology for regeneration inventories and for tending (Dubois 1971).

An understanding of the natural reproduction of key forest species is fundamental to silviculture and management of natural forests. An FAO Asia-Pacific Forestry Commission meeting in 1960 recommended that research first determine the ecology of the younger stages of economically significant tree species (Anon. 1960a). A need was seen for techniques to assess the abundance of regeneration present relative to what was deemed necessary for sound forest management.

Studies of natural regeneration logically begin with phenology—the timing of tree maturity and the season of flowering and fruiting. Because most tropical plants depend on animals for at least one phase of their reproductive cycle, it is particularly important that studies of pollination and seed dispersal be undertaken in natural environments, if possible before modifications (including those caused by invading honeybees) take place (Frankie and others 1974b).

Although the heterogeneous character of most tropical forests results from mechanisms that inhibit development of concentrated groups of the same species, the fact remains that many species successfully survive in pure or nearly pure stands. Some of these are fast-growing, long-lived pioneers, suggesting that they should be especially well adapted for intensive production (Whitmore 1981). Questions for research are how such species avoid diseases and epidemics, and what mechanisms are responsible for rapid growth.

The consolidation of information about a tree species necessary for its management is generally lacking. The components of such a life history have been outlined by Garcia Gutierrez (1976). Against a background of the description of the adult and its natural geographical range is presented information on the floral biology (including the period and duration of flowering), the flowering mechanism, the mechanisms and agents of pollination, the period of fruit maturation, the nature of the fruit, fruits per tree, and seeds per fruit. A natural sequence then includes details on seed durability and dispersion, the germination requirements, the germination process, the fate of seedlings, and the development of the tree to maturity.

Life histories have been published for few tropical tree species, including *Pentaclethra macroloba* and *Stryphnodendron excelsum* in Costa Rica (Hartshorn 1972), *Cecropia peltata* (Silander 1979), *Schefflera morototoni* (Nieves 1979), *Buchenavia capitata* (Sastre de Jesus 1979), and *Inga vera* (Muñiz-Melendez 1978) in Puerto Rico. All of these studies were made over a brief period and lack significant data on mortality rates and causes. The study of *P. macroloba,* based on 4 ha of forest, determined the rate of diminution of tree numbers per unit of forest area with increases in the tree height or diameter. From this was deduced the mortality rate relative to the time of passage from one tree size class to the next larger one.

Tree Growth. The assessment of forest ecosystems is not limited to determining current conditions. More elusive and yet more valuable in the long term is information on the character and rate of changes that may be taking place, particularly the volume growth of the potentially economic component of stands. Some of the earliest monitoring of tropical forests was undertaken in what is now Malaysia. Tree-growth data were derived from repeated measurements of selected specimens located along permanent transect lines (Watson 1934).

By 1958, measurement techniques had been developed in what is now Malaysia for determining the following (Wyatt-Smith 1958b):

- Volume of commercial-size timber for management purposes (commercial enumeration surveys)
- Composition and size-class distribution of trees and seedlings (research enumeration surveys and large botanical plots)
- Structure of the forest (profile transects)
- Frequency and distribution of the best seedling regeneration of economic species per unit of area (sampling for pre- and postexploitation seedling regeneration)
- Development (recurrent measurement in permanently marked botanical plots).

In harvested forests, linear sampling may be used to decide on a preliminary silvicultural treatment; sampling intensity generally varies from 2.5 to 10.0 percent, depending on tree size. When the treatment has been decided on, treatment plots are established to assess the effects. Units are 20 by 200 m in size, and within them, trees less than 10 cm in d.b.h. are subsampled. Units are grouped in a randomized block design in areas selected subjectively by any criterion independent of the treatment. Square arrangements are generally precluded by topography (Wyatt-Smith 1958b). In Malaysian rain forests, long, narrow samples are more efficient than square samples for obtaining a normal distribution of the basal area (Cousens 1958). Strips 20 m wide and 100 to 400 m long have proved satisfactory.

In Suriname, sampling for tree size and distribution of species has been done on quadrats 10 by 10 m, either located along lines or grouped in 1-ha squares (Schulz 1960). It was found that the 10 leading species could be assessed adequately on 50 to 100 quadrats. The most decisive parameter is the number of trees that reach 25 cm in d.b.h.

Uganda has had long experience in developing techniques for measuring high forest. It was concluded there that the only sound method of estimating growth is recurrent measurement of the whole stand (Dawkins 1958d). The second-best method is the use of permanent sample plots. Even within these plots, measuring all trees is difficult. Everything must be marked, including weeds, and both paint and nails have presented problems of durability. Ingrowth and mortality must be recorded currently, a task made less arduous by concentrating only on chosen trees. If the final crop of mature trees is to have no more than 50 stems per hectare, only two stems need be recorded per plot of 20 by 20 m. In practice in Uganda, yield plots are typically 100 m square and sited in random pairs, two per 250 ha. Each plot is subdivided into 25 quadrats within each of which the 4 best trees are measured. Each measured tree is tagged, even if no larger than a sapling or seedling. This system yields an adequate stand table.

A logical sequence of sampling techniques was developed in Uganda from a physical survey to a biological survey to a production survey (Dawkins 1958d). The physical survey, which was considered exploratory, estimates the tree population. This was followed by dynamic sampling, concerned with recruitment, growth, and mortality.

The simplest monitoring procedure in Uganda has focused on the tree-growth plot, designed to estimate the significance of the passage of time for desirable species. No more than 10 trees of any diameter class are needed on each site. The trees are selected for their potential soundness for sawtimber. A ring is painted at the point of measurement, and measurements to 0.1 cm in d.b.h. are repeated at 1- to 5-year intervals. Individual trees may then be classified as to crown position and form (Dawkins 1958d).

Production surveys in Uganda have called for classifying trees according to utilization (Dawkins 1958d). Those considered "desirables" include prime timbers, secondary timbers, and unknowns that are of potential value (considered harmless). "Undesirables" include proscripts (no known value), weeds, defectives, and impeders.

The absence of reliable growth rings in the wood of most tropical trees has left managers with a long-term task of determining growth rates. Efforts have been made to accelerate the development of this information, but the processes are complex and of uncertain reliability. Repeat measurements of the same areas or trees still produce the best results.

New, more precise methods for measuring diameter growth appeared with the introduction of the vernier d.b.h. tape and the use of fixed dendrometer (an instrument for measuring tree dimensions) bands. The latter, however, must be installed and reach stable tension a year before growth measurements are reliable (Bower and Blocker 1966). For special studies, the xylem of selected trees can be pricked through the bark with a needle, leaving a permanent mark against which later growth can be measured (Wolter 1968).

An attempt in Cuba to determine the age of planted trees by growth rings indicated that for at least a few species, the error need not be large (Gonzalez Rondon and Eremeev 1976). The mean number of years per growth ring (age coefficient) was found to be 0.8 for *Pinus caribaea,* 0.9 for *P. tropicalis,* 0.9 for *Cedrela odorata,* and 1.0 for *Eucalyptus saligna, Hibiscus elatus,* and *Swietenia* spp. Other studies have produced less certainty as to the number of clearly visible rings.

In the sharply seasonal climate of northern Australia, three species of *Eucalyptus* form clear annual rings (Mucha 1979). However, to determine tree ages, carefully selected material is needed. With increasing tree age, the width and distinctiveness of the outer rings diminish. These findings suggest a need for evaluating rings in other eucalypts in dry climates.

A sensitive indicator of forest condition and change is diversity, one measure of which is the number of tree species per unit of forest area. In unmodified forests, the more species there are, the more favorable conditions are presumed to be. The degree to which the species present are equally represented (rather than some common and some rare) is also recognized as a mark of diversity. A measure of this tendency is the Shannon-Weiner function, derived by multiplying the percentage of all trees that each species represents by the natural logarithm of the same percentage, changing the sign from minus to plus and summing for all species (Boyce and Cost 1978). The larger the result, the greater the number of species and the more uniform their respective degrees of representation, which is considered to be greater diversity.

Monitoring is especially useful in secondary forests as a guide to management during the early stages of recovery from disturbances (Richards 1955). The successional stages should indicate the stage of soil restoration.

An extension of the monitoring of past or current changes is the prediction of what to expect in the future. Inventory methods must not only measure the current composition and quantity of the growing stock but also indicate the prospective growth rate under alternative stand treatments (Bunn 1968).

Predictions of the consequences of human interventions in moist tropical forests are limited by the fact that tropical forest systems are imperfectly understood. Observational approaches may be based on assumed but unproved analogies with other ecosystems. Experimental predictive approaches are time consuming and costly. The preferred approach is computer simulation, which uses current measurements to compare the potentials of different strategies (Goodall 1975). The use of multiple regressions enables quantification of the relative effects on dependent variables of several levels of different independent variables, at least during periods of no extraneous interference (Dawkins 1964b). There is clearly a need to search for a stronger correlation between external tree measurements and product yields.

The effect of competition on individual trees would appear to be closely related to prospective growth rates. One expression of such competition is zone counting, a mathematical measurement of crown overlapping based on a basal area of about 10 m^2/ha (Opie 1968). Assuming that the zone of influence of each tree corresponds to a circle of a size that is a function of d.b.h., the theoretical areas of crown overlap can be determined. These techniques appear to be useful largely in research at present, but practical applications in the field may be developed later.

Another index of the competitive status has been tested in the Temperate Zone. The "area potentially available," as it is called, is the area of a polygon around each tree derived from points along lines to each of its neighbors, the location of the points being at a distance from each in proportion to their respective d.b.h. (Moore and others 1973). In one test, this index explained between 61 and 71 percent of growth variability.

It might seem most logical to monitor changes in forests by concentrating on individual components as indicators of constancy or change. However, the significance of such findings may be difficult to interpret. Extrapolating information about individual trees to a group effect for the ecosystem as a whole is a complex leap in logic that may be misleading. In fact, with vegetation of great diversity, the autecological or physiological approach may not be the best starting point for an investigation (Webb 1968). The physiological parameters of any community may not result from merely adding together those of its individual elements. It may well prove impossible to select significant indicators without wasting much time on unfruitful attempts. A more promising approach may be the study of plant communities, their succession and dynamic relationships (Webb 1968).

The difficulties of characterizing tropical forest stands through individual trees are further complicated by apparently irreducible differences in individual tree behavior due to the great variation in local environments and the stratification of complex forests (Mervart 1969). Each tree is subject to different probabilities of growth acceleration, deceleration, and death. To take all these factors into consideration, long-term observations of many trees are needed. Even then, the process of synthesizing to represent the stand as a whole may be problematic.

Difficulties in isolating cause and effect in complex ecosystems should come as no surprise. There is much evidence that the survival and welfare of the system as a whole are determined by subtle interactions among components. A corollary would seem to be that no single behavior is likely to be a response solely to one or maybe even a few causes.

Silviculture. So little is known about the effects of silvicultural treatments on mixed natural forests in the Tropics that the results of extensive silvicultural programs cannot be predicted. Three lines of research promise a broader scope for tropical silviculture (Synnott 1979). These are as follows:

- Markets for lesser used timber species and smaller products other than timber
- Felling and extraction practices that better conserve the productive potential of cutover forests
- Climber cutting, both before and after logging, to reduce logging damage and increase subsequent productivity.

Another assessment of silvicultural research needs for natural forests referred specifically to dipterocarp forests but is of general interest (Ashton 1978b). It was concluded that the research needed to ensure sustained yields from mixed dipterocarps has not yet been undertaken. Re-exploitation of natural forests in times of favorable markets is likely to preclude natural regeneration. Yet, plantations may prove profitable only on good sites where agriculture is a competitor. Research is needed to prove the dependence of rural communities on forests. Reserves must be set aside before modifications obscure ecological relationships that should guide management.

In the dipterocarp forests of Sabah, the following four lines of research have been considered most important (Fox 1967b):

- Study of the virgin forest to guide reservation of representative examples as controls and to locate and assess the volume available for removal
- Assessment of old regeneration in cutover forests
- Determination of seedling performance for a few of the more problematic species
- Management of competitive vegetative growth as a potential source of industrial cellulose.

Studies of natural regeneration and its response to silvicultural treatments can be relevant to much of the region. Of interest is the technique developed in Uganda to follow the fate of seeds and seedlings around seedtrees (Dawkins 1955a). Bands 2 m wide are cleared out from each tree in four directions just before seedfall. Quadrats are laid out to measure the quantity, time, and direction of seedfall, germination, and eventual survival. Hundreds of seeds per square meter may be monitored in this way.

Silvicultural research in the high forests of Uganda led to classifying studies by stand component and a corresponding set of plot sizes (Dawkins 1957). Studies of seedlings and small saplings record trees from 15 cm to 2 m tall by height class: the first class is 15 to 33 cm and subsequent classes increase by 33-cm increments to 2 m. In studies of shrub and lower understory species, saplings from 2 m tall to 5 cm in d.b.h. are counted, and poles from 5 to 20 cm in d.b.h are recorded in 2.5-cm d.b.h. classes. Studies of the overstory or canopy record trees larger than 20 cm in d.b.h. and measure their girth to the nearest 0.25 cm with a steel tape. The measured trees are permanently ringed with paint at the point of measurement to ensure precisely comparable remeasurements. The trees are classified by crown condition and quality.

The minimum plot size in Uganda has been the 20- by 20-m quadrat (Dawkins 1957). For studies of regeneration and survival of trees up to 20 cm in d.b.h., single quadrats are used. For studies of silvicultural effects on the understory or shrub layer, plots of 10 by 100 m or 60 by 80 m are used, and two quadrats are located randomly within each plot. For more extensive understory treatment, four quadrats may be located within an 80- by 80-m square. For studies of the overstory with no clear felling, nine quadrats are centrally located within a square hectare. For drastic canopy treatments, an area of 400 by 400 m is assessed along two transects 20 m wide, each with 20 quadrats.

For experiments that measure growth response following treatments, plot size should be based on the number of trees that are to remain at the end of the experiment, possibly after repeated thinnings or other treatments. In Europe, the recommended practice is to use replicate plots with not less than 100 measured trees in each (Assman 1970). In mixed tropical forests where a few species are being studied, such a requirement could dictate very large plots or long transects.

Priority research needs for bamboo recommended at a symposium in India in 1965 (Anon. 1965g) were as follows:

- Growth behavior and clump development, age of culm of maximum cellulose content, solidity and longevity of culms, root development and competition relative to trees, flowering and measures to delay or induce it
- Nutrient requirements, uptake, and recycling
- Ecology of gregarious flowering
- Analytical identification of bamboos
- Strength properties as related to age and locality
- Tree species suitable for mixtures with bamboos
- Inventory techniques
- Growth statistics and yields
- Genetic improvement
- Optimum felling cycles and cutting intensity

- Techniques for reducing clump congestion
- Effects of fertilizers.

Species Adaptability
The large number of tree species (both native and exotic) that grow well in tropical climates and the great variety of site conditions in the Tropics have led to widespread trial-and-error testing, producing conflicting results. Seeds have been exchanged with too little information about the species; as a result, plantings on unlikely sites have led to rejections of species based on inconclusive evidence. The results of large-scale planting based on such testing are apparent in Puerto Rico where, after 65 million trees were planted over a period of 37 years, only 3 percent were still alive in 1958 (Marrero and Wadsworth 1958).

A more systematic approach to species testing was used in a 1962 species trial in what is now Zambia (Cooling 1962b), involving the following steps: (1) screening of species on the basis of published information, (2) introduction and preliminary testing, (3) determination of growth and yield, and (4) response to edaphic variations.

Preliminary testing in this case was done in 0.4-ha plots, then replicated in two contiguous plots except where site variation was pronounced. Elsewhere, greater replication may be required. Replication in time was needed where seasonal changes were great. Spacing was usually 1.8 by 1.8 m or 1.8 by 2.7 m where mechanized weeding was practical. Plots of 35 to 64 trees were assessed for survival, vigor, health, and form; d.b.h. and tree height were measured annually for the first 5 years, at which time species could usually be selected. In some instances, it was necessary to continue observations to the 10th or even the 15th year (Cooling 1962b).

Growth-and-yield plots in this study, which were used only for the species selected from initial trials, were about 1 square hectare, with a 0.2-ha inner plot subject to measurement. These plots were not replicated but were sited as representatively as possible. Height, d.b.h., form, and vigor were measured. Thinning volume was measured to enable determination of yield. This information aided final species selection and shed light on the benefits and costs of thinning and pruning as well as on probable rotations (Cooling 1962b). Finally, uniformity trials were conducted over a range of site conditions to compare performances.

Experience with species testing in Kenya led to a different approach (Edwards and Howell 1962). The first step was to develop an "arboretum" where a few trees of each promising species were established to determine their suitability for further trials. Next, the promising species were established in "forest gardens" under favorable conditions where tree habit and performance could be observed further. Then, experiments with trees in randomly located plots in pairs or larger numbers were carried out. The final step was forest-scale plantations.

Kenya's experience showed the importance of clarifying planting objectives at the outset, classifying climates and soils, and obtaining all available information about new species. Where possible, seeds from at least three widely separated provenances were obtained. Seeds and nursery practices were not perfected until the species had proved satisfactory in the first trials (Edwards and Howell 1962).

In east Africa, the initial "arboretum stage" was thought to involve too many species for any helpful results and, thus, was not generally used (Leuchars 1962). The second step, using 0.04-ha plots, was thought to be simple and to avoid "high-flown statistical virtuosity for its own sake." Randomized blocks, either complete or incomplete, may be used. Thus, if the number of seedlings available is limiting, not all species need to be tested on all sites. Generally, more than one site was tested, and there may be several replications per site or in time. If the number of species is four to seven, the use of Latin squares is more precise than randomized blocks, because the numbers of species, rows, and columns may all be equal. Otherwise, an incomplete Latin square of lattice design may be appropriate. The use of split plots may provide for several years of planting in each square of a Latin square or block pattern. The final phase, concerned with spacing, pruning, and thinning, is on a larger scale and may require less replication (Leuchars 1962).

Practice in Uganda has included arboretum plots of 10 by 10 m, with 25 trees of each species. Height measurements are limited to two dominant trees per plot (Kriek 1967a through 1967h). For species trials, a series of 0.04-ha square plots was used, with 64 trees planted at a spacing of 2.4 by 2.4 m. The inner 16 trees of the sample were measured for d.b.h and height, beginning at 7.5 cm in d.b.h and repeated every 2 years. Mean annual increments are determined periodically.

In India, species elimination trials have been composed of two to four trees with six replications. Complete or incomplete blocks no larger than 0.5 ha (to avoid local site variation) were used (Ganguli 1967). In testing pines, the importance of provenance and the presence of mycorrhizal fungi have been recognized.

Others have tested species in three stages (Morandini 1968). The first stage, elimination trials, might involve many species with numerous repetitions on various sites. This phase is followed by establishment of a network of experimental plots of the most promising species on a scale that is sufficient to indicate their volume production. Finally, each chosen species is tested to find the best provenances.

The design of species trials has evolved independently in several tropical countries over the past 20 years. Five precepts appear to be universally applicable (Briscoe 1990): (1) define a range of conditions for testing, (2) restrict each study to no more than a few simple treatments, (3) randomize treatments located so as to minimize variation within blocks, (4) replicate each treatment (preferably four times), and (5) record everything planned and done.

Species trials with eucalypts have led to four generally recommended principles (Anon. 1963c): (1) the stands from which seeds are obtained should be carefully described, (2) nursery practices for each species should be comparable, (3) standards of rejection should be uniform for all species, and (4) species elimination trials should cover the widest possible range of sites. Fulfilling this last requirement may entail a detailed land survey, including climate, soil type, topography, and history of land use. Subsequent growth trials may be conducted on a more limited number of sites yet with as wide a range as possible.

With eucalypts, elimination trial plots of four, six, or nine trees have in some areas proved sufficient, and no guard rows have been required (Anon. 1963c). Blank rows have been left between plots. In contrast, subsequent growth trials have required plots of 16 to 100 trees, depending on the rotation of the study. Square plots have usually been acceptable, and they minimize intraplot competition for a given length of edge. Guard rows have been necessary. More than one plot of each species must occur on each site. The number of replicates needed has depended on the size of the differences regarded as important and the precision likely to be achieved.

The number of replicates needed to detect different degrees of precision in experiments in terms of percentage of the mean is indicated in table 9–4 (Anon. 1963c). For example, in an experiment with an expected precision of 10 percent in which a difference of 12 percent is important, six replicates would be needed. This might be six blocks with eight species in each.

The precision likely to be attained may be estimated where experience has been adequate. If this experience is not available, it may be advisable to confine early work to pilot trials designed to assess precision for more formal subsequent work.

Randomization of species plots in each experiment is essential if valid estimates of experimental errors are to be obtained (Anon. 1963c). Randomization must be strict, not haphazard, or other objective devices should be used to assign location. Moreover, conditions on the ground may affect the experimental layout. Within the randomized plots, the design should minimize variations resulting from vegetation, soil, or past use. Plots should be grouped within blocks so that each block contains a complete set of comparisons (or species); these groups

Table 9–4.—Differences for significance (expressed as a percentage of the mean) that will be obtained in experiments for given precision and number of replications (%)

No. of replications	Estimated precision of the experiment (percentage of mean)				
	5	10	15	20	25
2	10[a]	20	30	40	50
3	8	16	24	33	41
4	7	14	21	28	35
5	6	13	19	25	32
6	6	12	17	23	29
8	5	10	15	20	25
10	4	9	13	18	22
15	4	7	11	15	18
20	3	6	9	13	16
25	3	6	8	11	14

Source: Anon. 1963c.

Note: Numbers are the percentage difference for significance.

are termed "randomized blocks." Where site variations are in two directions (slope and aspect), Latin-square arrangements with each species in each row and column may be indicated if there are equal numbers of species and treatments. Otherwise, incomplete Latin-square or lattice designs are indicated. Complete standardization of experimental designs, however, is considered neither necessary nor desirable.

During a meeting of the Latin American Forestry Commission in Trinidad in 1967, a technical subcommittee called for coordination and standardization of species trials in tropical America (Anon. 1968a). The following recommendations are still valid. The aim of selection is to choose species that: (1) are suited to the site and will remain healthy throughout the anticipated rotation; (2) will produce an acceptable growth rate and yield; and (3) will produce raw materials suitable for the objectives defined by the policymaker, with flexibility for changing market demands.

The administrative steps in developing a program of species trials are typically as follows:

- Precisely define the research objective so that it is well understood by the research staff.
- Prepare a written plan for the research.
- Review the plan to ensure that it reflects a clear grasp of the objective, specifies adequate resources, schedules operations according to urgency and resources, provides adequate background information for choosing sites and species, makes adequate provision for statistical design, provides for meticulous standards of cultural practice, and provides for subsidiary experiments on cultural techniques.
- Obtain official approval for the plan along with a commitment to support it.
- Regularly report progress with continuing reference to the original plan or to needed modifications.

The document cited earlier (Anon. 1968a) cites Leuchars (1965) to the effect that three general requirements are necessary for study layout. The design must be: (1) robust, meaning that the loss of some plots will not jeopardize the remainder of the experiment; (2) flexible, so that it can be fit to any irregularities of the site; and (3) simple, so that it can be carried out by untrained field staff. Except under unusual circumstances, completely randomized blocks are recommended.

The initial step for species trials is to collect basic information on the sites to be planted, including climate (especially total and seasonal rainfall), soil (especially physical conditions), topography, vegetation, and past use or abuse. The choice of species is then based on the extrapolation of data from one locality to another.

Intraspecific variation may qualify the results of species trials. One sample from a species cannot be said to represent that species as a whole until the range of variation between its populations has been established (Harper 1977).

Even where all needed comparative data may be at hand (which is extremely rare), it may be unwise to proceed immediately with large-scale planting. Small experimental plots can provide better information than a 1,000-ha block and at a fraction of the cost. There is a sound argument for continually testing additional species that may prove superior or for at least providing alternatives for diversity.

While providing increasing data on sites and species, species trials progress from many species to few and from small plots to large. Three sequential phases are: elimination, testing, and proving (Anon. 1968a).

The elimination phase deals with possible species, often 20 to 40 in tropical America. The object is to reduce the number of species for more critical testing. Survival and early growth rates are the principal criteria. The number of possible species selected will depend on the site quality, the breadth of prospective market demand, and the availability of seeds, staff, and funds. The trials consist of small plots with 1 to 25 trees per plot. With the single-tree plots, there is no isolation between species, a circumstance that economizes on area but may penalize a species that is not precocious if it is located adjacent to others that are. In the 25-tree plot, if only the 9 (3 x 3) central trees are measured, outside interference may be eliminated.

Land and fund constraints for research have led to the use of single-tree plots (Shiue and Pauley 1961). In Puerto Rico, a lattice design has been used with 16 rows and 1 tree of each species in each row, replicated on each site. Mortality in such experiments constitutes a loss of plots, making the analysis more complicated here than in plots with more trees, where the effect of mortality is only partial (Wollons 1980).

In the testing phase, only the promising species are used. The object is to relate performance closely to site differences. Plots of 25 to 144 trees range in size from 0.02 to 0.10 ha. A generally recommended plot contains 121 trees (11 × 11) with a 2-row isolation strip, leaving 49 trees (7 × 7) in the middle for measurement. Growth in diameter, height, and basal area is measured to the time of a first thinning.

In the proving phase, the object is to confirm (for normal planting conditions) the results shown by one to three superior probable species. The intent is to determine how to manage the species for timber production. Plot size will depend on the range of thinning treatments to be evaluated and may range from 0.4 to 5.0 ha with isolation strips of up to five rows.

For single-tree plot elimination trials, only one location should be used in each major climatic (not edaphic) province, such as a life zone. Within each location, there should be 12 replicates, or trees, per species. Each replicate can be a single row of trees with one of each species laid out on the contour. With 25-tree plots, the only difference is that the number of replicates (plots) within each zone need not be more than 4.

In the testing phase, different sites and types within each life zone are compared in two or more groups of plots. At each location, at least three replicate plots are recommended. For the final proving phase, locational comparisons have already been made, and because large plots are used, no further geographical replication is generally necessary.

Tree-measurement practices vary with the nature of the test. For single-tree elimination plots, the height of every tree is measured at 6 months, at 1 year, and annually thereafter until the mean d.b.h. reaches 5 cm, at which time annual d.b.h. measurements begin. For the 25-tree plots, heights of only 2 of the dominants in the inner 3- by 3-tree plot are measured annually before a mean d.b.h. of 5 cm is reached. Thereafter, heights of these two trees and diameters of all nine trees are measured annually.

Measurements in the testing phase (121-tree plots) are confined to the inner 7 by 7 rows. Heights of the 250 tallest trees per hectare (8 per plot) are measured annually until at least age 5. Diameters of all trees are measured annually after a mean of 5 cm has been reached. A similar scheme is also suitable for proving trials, with provisions for permanent tree numbering, pre- and post-thinning measurements, and the felling and complete measurement of sample trees for volume determinations.

The usefulness of these studies decreases after their chief purpose has been served. Elimination trials may have served their purpose in 3 to 5 years; testing trials, in 5 to 10 years; and proving trials, by the end of a practical rotation. Measurements taken after these ages may be of some value but usually not in the context of the original test objectives.

The FAO guide (Anon. 1968a) makes a further point in discussing the use of standard species for comparison. Most species trials are conducted to find new species superior to those already recognized. Thus, it is necessary to include the species already considered best in each test of new species.

Species trials inevitably require a long time. Repeat trials may be necessary to compare seasons and weather, particularly in relation to the dry season. Absolute certainty regarding the adaptability of a species may not be established until after one or more rotations. Even later, insect or disease problems may appear.

Experience in Australia has shown the need to adhere strictly to the statistical requirements of replication and randomization and to plot establishment and maintenance (Wollons 1980). Without replications, it is not possible to test hypotheses or obtain precision estimates. Unreplicated treatments are always liable to be biased by a single result that could lead to erroneous management decisions. With limited replications, large phenotypic variations between trees may limit the value of experiments. Where background data is not at hand, one approach is to establish a series of uniformity plots for 2 to 5 years to compare variations within species on a site. These data can then be used to predict further variations.

In the Tropics, many treatments are greatly affected by season and site, meaning that only with a series of trials can general responses be evaluated (Wollons 1980). Block comparisons, where the variations between blocks can be kept small, give a higher sensitivity to variations than may be obtained in a generally randomized arrangement. The need for careful plot maintenance over whole rotations is also emphasized (Wollons 1980). Unanticipated problems may include disease and insect attacks, grazing, fire, wildlife damage, weed competition, and management errors. Because of these problems, it is prudent to search for early indicators that may predict future performance. For example, for some Mexican pines, height growth at 1 year may be strongly correlated with that at 5 years (Barrett 1970). Such indicators are important for managers who are reluctant to wait for full results of species testing.

When a species has been tentatively selected, further research may be needed to develop the best establishment techniques. This may be done by a series of short-term studies. In east Africa, uniform spacing of 1 by 1 m has been used, with up to 100 trees per treatment (Stuart 1955). Good nursery stock is planted in well-prepared and fertilized soil (Griffith and Howland 1962). Roots are pruned both vertically and horizontally every 2 weeks. Planting is done as early in the wet season as is safe and at a depth somewhat greater than in the nursery. Root exposure is avoided, and weeding is intensive, removing deep-rooted grasses.

A comprehensive manual on tropical species and provenance research (Burley and Wood 1976, 1977) is available as a general guide for most work. This manual calls for trials of provenances contemporary with trials for species because intraspecific variation may prove significant to comparisons with other species. The manual emphasizes a need for thorough study of the base population; genetic variation; site assessments, both for seed sources and for test sites; experimental design; care in propagation; and assessment of results.

Tree Propagation, Artificial Regeneration

Much research is needed on tree propagation and artificial regeneration; many problems are universal, although different solutions may be better in different areas. A logical (but generally underestimated) first step is a thorough review of the performance of any existing plantations under conditions similar to those where regeneration is proposed (Hinds 1952).

With a wide array of problems in need of study, it is crucial to assign local priorities and schedule studies in sequence, beginning with the most urgent. Public research institutions may be guided by the process of problem analysis, in which all factors contributing to the relative importance of the different problems and the relative benefits to be gained from their solution are assessed.

The complexity of some of the research required in tropical forestry should not be underestimated. This can be illustrated by the nearly 40 years of research on the adaptability of *C. odorata* in Trinidad (Beard 1942). *Cedrela odorata* is abundant in Trinidad's semi-evergreen forest. Research on its regeneration began in 1905. Attempts to establish the species with wildings and direct seeding were abandoned after repeated losses to fire. Then, the species was planted with food crops and in gaps under shelterwood. By 1923, these efforts were also considered failures. The species started well but could not be maintained because of insect and disease problems. Beginning in 1924, tests were made with different light intensities, soil supplements, and mixtures with other species, but again, all failed. Transplanting during the dry season, when the trees are out of leaf, gave good results initially, but later, the trees all died. By 1929, clean weeding was discontinued because it was thought that *C. odorata* needed cover. The results were disappointing. By 1933, it was concluded that *C. odorata* grew vigorously in evergreen forests for 18 months and in semi-evergreen forests for 3 years. Soil investigations were inconclusive. Soil deterioration resulting from prior exposure during cultivation was found not to be responsible. Nutrient studies applying N, phosphorus (P), potassium (K), calcium (Ca), and magnesium (Mg) showed that *C. odorata* grew no better with fertilizers than with tap water. It was concluded that the problem was chiefly one of soil moisture, because the trees frequently dropped their leaves during the rainy season. In 1945, it was further concluded that successful establishment of *C. odorata* may require several years of research by plant physiologists and soil chemists, yet the species is so valuable that success could repay such efforts (Cater 1945). Thus, the problems of production of *C. odorata,* an American species that is highly successful in parts of Africa, still remain unsolved in most of tropical America.

Fertilizer Use

The use of fertilizers in tropical nurseries and plantations has been generally accepted as desirable (Qureshi and Yadar 1967). In many areas, however, fertilizer applications have outrun any scientific basis for them. Frequently neglected is prior analysis of the fertility of the soil. Standard agricultural soil tests may be of some use, but they do not help in concerns important to forestry, such as growth period, rooting depth, and physiological requirements. Fertilizer tests generally needed (Qureshi and Yadar 1967) include: (1) dosage of NPK singly or in combination; (2) utility of inorganic fertilizers versus manure; (3) timing of applications and age of crop at which fertilizer applications should be discontinued; and (4) frequency and method of application.

The complexities of fertilizer research are illustrated by studies of *Pinus elliottii* in the Southern United States (Mead and Pritchett 1971). Studies on six soils showed a weak correlation between field and plot performance. No single measure of seedling response to treatment (height, diameter, or dry weight) consistently correlated with the average tree height in the field. The correlation of pot-experiment tree heights with those in the field was poor after 3 years and only slightly better after 7 years. Thus, although greenhouse experiments are useful for studying deficiency symptoms and for determining limiting nutrients, the results must be used cautiously for predicting fertilizer response in the field

Future research on fertilizers should involve studies of mycorrhizae because of their effect on nutrient assimilation. Deterioration of mycorrhizae in second-rotation plantations of *P. patula* in Swaziland (Robinson 1973) suggests the importance of these organisms.

Growing Space

Much silviculture is concerned with providing individual trees with adequate growing space. Experimental techniques for studying responses to spacing have been tested widely in the Tropics. Poor experimental design is common. Studies of natural stands require clearly understood objectives at the outset and a fixed number of surviving, measured trees over a wide range of spacings (Smith 1959). In plantations, the use of a constant number of trees for each spacing is more efficient than a uniform plot area with the number of trees variable. There should be an equal number of residuals after the final thinning for each treatment. A common final number has been 49 (7 x 7) with a 2-row buffer (Smith 1959).

The complications of thinning research have been pointed out by Vuokila (1965). Permanent plots, including extras, are necessary to determine responses to thinning. The precision of long-term studies suffers because of the subjective judgment of successive personnel. Field and calculation procedures change before studies terminate. Successive tree-volume estimates during short periods that are may be subject to too large an error to accurately measure growth. Thinning treatments that best show biological responses may be impractical for wider application. Different thinning intervals require growth comparisons between periods that are dissimilar in time and weather. Replicated plots greatly increase costs.

Two ingenious developments in thinning research techniques are O'Conner's correlated-curve-trend methods (1935) and the Pudden clinal-plot design of treatments (Borota and Procter 1967, Dawkins 1960, Vuokila 1965). O'Conner's correlated curve trend is based on the concept that the growth rates of different trees exposed to an array of spacings can be related before competition affects any of them; then, as competition starts to constrain the growth of those that are most closely spaced, the degree of constraint can be determined by comparing a tree's performance with that of widely spaced, unconstrained trees. Such spacing studies make it possible to develop regressions (1) predicting mean growth rates of any size trees at any spacing and (2) defining the spacings necessary to attain mature size within any period from any present tree size.

The Pudden clinal-plot design uses either narrow, rectangular plots or concentric circles in a sequence of spacings with differences between adjacent treatments that are so small that no isolation strips are needed (Dawkins 1960). A single row of trees is planted around the outside of the plot. The technique has been rightly criticized as nonrandom, but if it is replicated, the plot design should still be a reliable source of preliminary information on optimum spacings for different tree sizes. The Pudden rectangular layout may also be used for thinning, with progressively heavier treatments adjacent to one another. The heaviest thinning, which must leave 5 to 10 trees per plot, dictates minimum plot size (Dawkins 1960).

A layout for a clinal thinning study is illustrated in figure 9–4 (Borota and Procter 1967). The thinning schedule might then be set as in table 9–5.

Briscoe (1990), in an excellent research field manual, illustrated the circular-spacing study design of Nelder (1962) as shown in figure 9–5. As he describes it, the wheel is laid out with a fixed angle between the spokes, with distances between the trees increasing with distances from the hub.

Experience in Suriname led to systematic thinning and yield plots in plantations (Voorhoeve and Schulz 1968). These provide mean and periodic annual increments in diameter, height, and volume. They indicate site classes

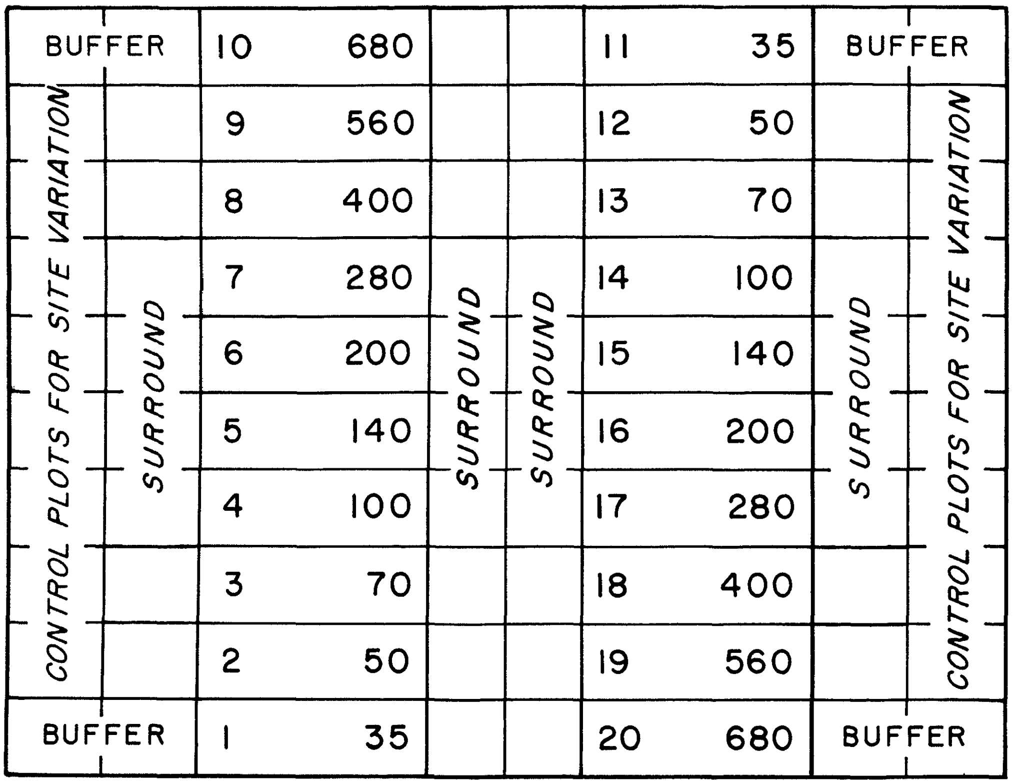

Figure 9–4.—*Clinal thinning study layout (Borota and Proctor 1967).*

Table 9–5.—Prescribed thinning schedule for the design in figure 9–2 (yr).

Final stocking (trees per ha)	Stems per hectare 1,380	990	690	490	345	245	170	125	85
1,680	Not thinned								
1,380	3[a]								
990		3							
690		3	4						
490		3	4	5					
345		3	4	5	6				
245		3	4	5	6	7			
170		3	4	5	6	7	8		
125		3	4	5	6	7	8	9	
85		3	4	5	6	7	8	9	10

Source: Borota and Procter 1967.
[a]Numbers are thinning age in years.

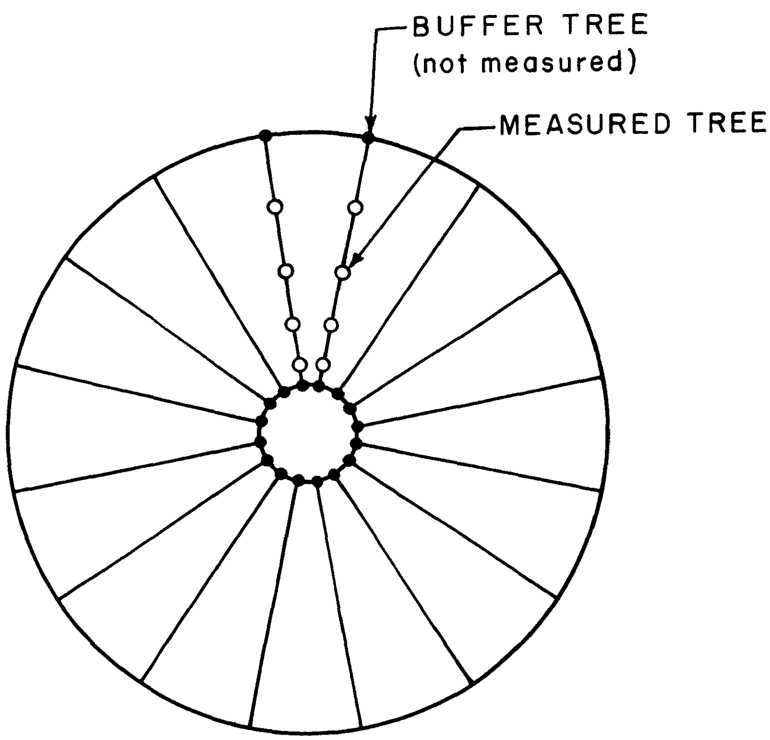

Figure 9–5.—*Nelder's (1962) design for spacing studies (Briscoe 1990).*

and are a source of volume and yield tables and thinning prescriptions. The data are collected from plots 10 by 10 m isolated by 10 m or eight rows of trees. Spacing is expressed in terms of the spacing index (S%), already described.

Tests in what is now Malaysia with widely spaced *Ochroma lagopus* (4.3 by 4.3 m) showed that a single boundary row was adequate to isolate the core planting (Wycherley and Mitchell 1962).

Pruning is much less common in the Tropics than is thinning, although it may be important in coniferous plantations. With many angiosperms, pruning may be done merely by control of spacing. Nevertheless, far too little is known about the effects, benefits, and economic returns of pruning. Research is needed to define the need for and response to pruning for different species, its effects on tree form, the timing of the first pruning, the best season for pruning, rapidity of healing, insect and decay problems, the effects of pruning on growth, and epicormic branching (Laurie 1941e).

Tree Improvement

Generally, timber harvesting in moist tropical forests is highly selective, removing only the best trees. Although the quality of trees in natural ecosystems is much more a reflection of environment than heredity, this could deteriorate the genetic quality of subsequent seed crops, an effect termed "dysgenic." Thus, genetic tree improvement is important, if only to counteract such deterioration (Jasso 1970).

General recommendations for tree-improvement research in the Tropics to counteract the negative impact of current forest treatment include the following (Jasso 1970):

- Explore and evaluate genera and species of worldwide economic importance.
- Evaluate the variability of species that have gone unnoticed and that may have economic importance.
- Increase research on vegetative propagation, with emphasis on species threatened with extinction of genotypes.
- Establish forest "gene banks" in countries where each important species is native to preserve trees of superior qualities.

A primary objective of tree-improvement research in tropical countries should be the conservation of germplasm in both natural populations and gene banks (Brune and Melchior 1976). To accomplish this, conservation of gene resources must become an integral part of forest-management planning and practice (Roche 1975). Conservation "in situ" is ideal, with protection extended to all distinct tropical ecosystems. Conserved gene sources should be used for research and for demonstration of their values.

Because the potential areas in the Tropics to be dedicated to forest production are large, even small genetic improvements may significantly increase social benefits, land values, and raw material production (fig. 9–6; Namkoong and others 1980).

A key feature of breeding is the recurrent and cumulative nature of genetic improvement (Namkoong and others 1980). Many generations of gain can be achieved and yields increased beyond the extremes of the present population. Gains in value as great as 30 percent have been made in the first generation of selection.

Genetic improvement of forest trees begins with the study of the external appearance of each individual (its phenotype) and seeks to enhance this appearance

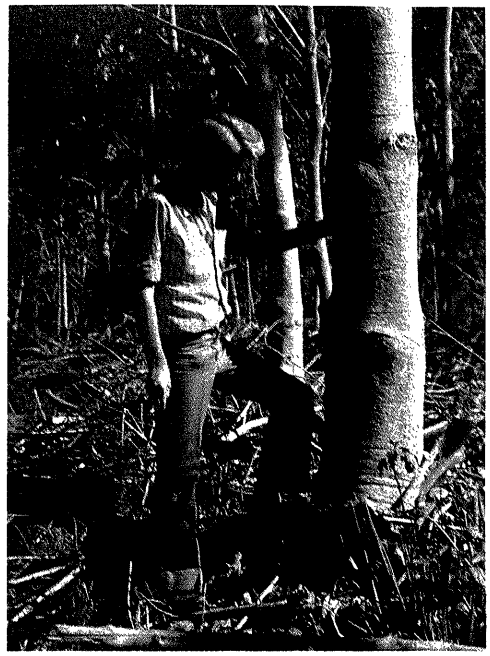

Figure 9–6.—*The exceptional growth of the 4-year-old* Gmelina arborea *at Jari, Brazil, is an example of the prospective sources of genetic improvement of tropical trees through modern research.*

through manipulation of inherent (or genotypic) qualities. Because of the long life of trees and their repeated seed crops or regrowth of vegetative material, opportunities for multiplication of desirable characters are greater than for shorter lived plants. Also, genetic tree improvements, once achieved, are inexpensive to maintain (Larsen 1956).

The natural variation displayed by most tropical species over their geographic ranges indicates the genetic variation that can be released by breeding (Namkoong and others 1980). The problems lie in the limited ability to observe variation, difficulties in recognizing gene combinations that may become useful only as requirements change, and the dangers of loss of variation through forest destruction.

Expected genetic improvement depends on the "selection differential," or the difference between the mean of a trait in the selected individuals and the population mean. If more than one trait is selected, the differential is reduced greatly for each trait that may be added (Shelbourne 1973).

Ideally, tree improvement should be limited to species that have been evaluated over a full rotation, at least in trial plots with not less than 100 ha of stands of good provenance (Shelbourne 1973). Wherever possible, the selection index should combine information on the economic importance of each trait and the expected prospects for changing each trait by genetic selection. Usually, an educated guess must be made at the outset.

Provenance variations in *P. taeda* and *P. elliottii* have both adaptive and nonadaptive significance (Burley 1966). Some are random, but most are clinal, relative to latitude and longitude. However, conclusions based on early observations may be contradicted later; so, long-term observations are needed.

By itself, higher yield is not an adequate tree-improvement objective. Wood quality must be accepted as a criterion for selection as are form and branching (Hughes 1973). Selection must also be related to performance on specified sites. On soils of marginal or better suitability for agriculture, only high tree productivity can succeed. Elsewhere, tolerance of soil poverty is important. Genotypes must be developed that have acceptable productivity with minimum fertilizer and yet do not lead to soil deterioration (Bevege 1976). A wide genetic base must also be maintained for continuing selection.

Cost increases for petroleum have suggested that genetics research should be directed toward low-input, multiuse, extensive agroecosystems to supplant high-input, intensive agriculture (Duke 1981). This would call for a pooling of genes best adapted to marginal environments. The goal of such efforts would not be single-product yields in monocultural situations but multiple yields in multitiered, intercropped agroecosystems. Prospective practices include the use of tolerant germplasm, intercropping, return of residues, biological pest control, and full utilization of yields (Duke 1981).

Cost is critical in tree-improvement research. Despite the promise of higher yields and quality, the necessary research calls for highly specialized scientists and long-term experimentation. Efforts must be made to keep costs moderate and to produce early results. Some possible ways to save include the following (Carlisle and Teich 1975):

- Determining the minimum level of sampling needed to represent natural genetic variation
- Determining the minimum period that tests must be exposed to climatic variation
- Rationally weighting yield and timber quality
- Predicting adult performance from early observations
- Exploiting the full potential of vegetative propagation.

In the Tropics, most of the fundamental information about differentials is not available and must be presumed from experience with similar species in the Temperate Zone. Nevertheless, scientists must proceed with tree improvement on many important tropical species. A tally by a panel of FAO experts on forest gene resources indicated that, for tropical America, 43 tree species merited tree-improvement research, and of these, 14 species urgently needed work (Kemp 1974).

Research on tropical tree improvement cannot be expected to prosper purely on an individual or local basis. It can best proceed regionally, with international cooperation. Most tropical tree species occur naturally and are potentially significant in more than one country. Few countries have the resources to support the highly specialized research necessary for tree improvement. International efforts can provide the following (Burley and Kemp 1973):

- Information on the distribution, phenotype variation, and genotype variation throughout the natural range of each tropical species
- Sufficient seeds for all interested countries to establish adequately designed and replicated provenance trials
- Representative gene pools for preservation
- Regionally centralized breeding orchards

Despite the need for regional tree-improvement efforts, final performance assessments are strictly a local responsibility. A test of six teak provenances in India showed after 16 years that local seeds usually produced good results but not necessarily the best; therefore, each provenance had to be tried on each site (Mathauda 1954a). Seeds from moist-site provenances proved superior to seeds from dry areas.

The impact of the local site on tree performance is seen in tests of *P. caribaea hondurensis* from the same provenance but grown in seven countries (Palmer and Tabb 1973). Variation in pulping characteristics of the wood species was so great that quality could be reliably forecast only on the basis of samples from the actual site.

The development of a genetics program for tropical forests typically begins by assessing genetic variations within the most important commercial tree species (Stern and Roche 1974). In countries not well endowed with commercial species, provenances of exotics may be introduced and tested under a variety of conditions. As these trees mature, single-tree selection for desirable characteristics is begun, and progeny are produced either from seeds or vegetatively. However, before selecting from exotic populations, it is highly advantageous to know about the performance of stands approaching rotation age (Goddard 1973). Superior test material is then mass produced. Short-term objectives may be achieved through seed orchards. For longer term objectives, research orchards are needed to conserve a broad genetic base of genotypes that may eventually prove useful. The next phase is a breeding program, which requires a knowledge of reproductive biology of the species based on phenological observations (Bawa 1976).

In the early stages of tree improvement, it is desirable to plant blocks of about 2 ha with each likely candidate species and provenance as a potential early source of seeds (Shelbourne 1973). Once local seed-bearing stands of a good provenance are available, superior seeds may be collected, either from the best individuals throughout the plantations or from a smaller area of exceptional quality thinned to about one-tenth of its original stocking and managed as a seed-production area.

In an analysis of the status of genetics research on tropical pines, Burley (1976) outlined a required orderly sequence of research. The first step is to study variations throughout the natural range and assess provenances in exotic as well as native environments. This phase, for tropical pines as with many other species, calls for international cooperation and coordination. Next, the nature of the breeding systems of each species must be determined. Then, further information must be collected on gene distribution and population structure, usually through studies of pollen and seed dispersal and resultant geographical distributions of genotypes. Methods of evaluating gene pools include provenance and progeny comparisons, analyses of chemical properties, and analyses of genotype interactions with the environment.

Provenance trials go through the same phases as species trials (Burley 1969). The first elimination phase may deal with 50 or more provenances. It is a simple comparison completed at one-fourth to one-half rotation age. Square plots of 1 to 25 trees may be used. The chief criteria are survival and height growth. In the second phase, involving 5 to 10 provenances, plots of 49 to 169 trees are utilized with a 1- to 2-row isolation strip. The proving phase involves replicated plots of 0.5 to 1.0 ha on the major sites in each country. For all stages, the most favored design is the randomized complete block with one plot of each provenance in each replication. Evaluation may be done at 6 months, after each of the first 3 years, and at 3- to 5-year intervals thereafter. Recorded are survival, height, d.b.h., crown width and depth, branch number and angle, uniformity, straightness of stem, and bark thickness.

A major contribution to tropical tree improvement is the "Manual on Species and Provenance Research" compiled by Burley and Wood (1976) from contributions by various scientists. The description that follows is adapted from this source.

Three natural types of variations result in differences among individuals of the same species. One is genetic and heritable, such as the number of stamens. Another is environmentally induced and commonly includes local variations in leaf size. The third may be termed developmental and is illustrated by the differences between juvenile tree leaves and those of mature specimens.

Seeds are frequently collected to improve the population or compare provenances. Careful choice of select phenotypes can greatly benefit population improvement. For representative samples of provenances, however, intensive selection is not appropriate. Likewise, collections to conserve a broad representation of genes must come from a large number of trees.

Selecting stands for provenance testing calls for at least five or six collection sites so that both the limits and the center of the geographical range can be sampled. When the approximate location of collection sites has been determined, specific stands must be selected that are representative and large enough to provide good samples. Within each, collections should be made from not less than 25 trees. Taking additional trees is a small added cost after site selection, access, and all other costs are considered. Tree selection might well be random, except that this is usually inconvenient and does not exclude diseased or deformed individuals; therefore, some subjectivity is desirable. With widely scattered tree species, it may be possible to collect from most of the trees and even then have a small number of samples. To the degree possible, the same number of seeds should be collected from each tree. Absolute certainty as to the seeds' origins is essential; so, each lot must be tagged as to site and possibly also as to tree number.

In the design of experiments to compare provenances, five possible sources of variation must be recognized. These are as follows:

1. Controlled genetic differences between the populations being compared

2. Controlled environmental differences within a site or between two or more experimental sites

3. Uncontrolled genetic variation among the experimental plants and between those plants and the population they represent

4. Uncontrolled environmental variations from plot to plot or tree to tree as a result of differences in soil, microclimate, aspect, etc., including some differences that cannot be assessed

5. Experimental error resulting from random variations within plants, errors in locating provenances within the plots, and inaccuracies in assessing and recording data.

Some pros and cons of common provenance test designs are summarized in table 9–6 (Wright and Andrew 1976).

If the trees selected for seed collection are too young, their characteristics may not indicate their later performance or quality. For pines in the Southern United States, trees that would have superior height and diameter at age 30 could not be identified with much certainty before age 20 or at the very least age 15 (Wakeley 1971).

Agroforestry

A strong appeal for mixed cropping and its social as well as physical benefits in the Tropics has been made by Igbozurique (1971): "Yield is not the only index of agricultural efficiency, but it is hardly debatable that a system which fares so well without the astounding technological material of Anglo-American agriculture, the vast manpower inputs of Oriental agriculture or the coercive sociology of Soviet agriculture is worthy of intensive study. The call is for unstinted research into mixed cropping." Research is needed on the synergistic and antagonistic interactions of crop species in mixtures and their sustainable yields (Duke 1981).

By one estimate (Bene and others 1976), more than half of all the land of the Tropics, although too dry, too steep, or too rocky to be classified as arable, was considered suitable for agroforestry. Although there are few hard data to support this contention, the field is a promising avenue for research (Alvim 1981).

Research in agroforestry requires an integrated approach and is much more complex than conventional field experimentation (Alvim 1981). Interactions between different species are usually site specific, making it difficult to generalize conclusions from isolated studies.

A better balance is needed between research on tree plantations and farm crops in the Tropics (Pelzer 1958). Most of the effort so far has concerned intensifying practice in plantations. Hill cropping has received little scientific attention. If agroforestry is to progress, there must be more research collaboration between foresters and agronomists.

Because agroforestry is commonly expected to replace (or mitigate) the problems of shifting cultivation in the Tropics, Kellogg (1963) suggested that research should begin with quantitative studies of existing systems of shifting cultivation. Many such studies have been done since his recommendation, but their significance is mostly local, and there undoubtedly remain many practices based on long experience that are still little known or understood by the scientific community. An early outline of such studies includes literally hundreds of avenues for research (Conklin 1963). Some of special interest include the following (Newton 1960; Watters 1968a, 1968b, 1968c):

- General considerations—climate, soils, biotic factors, cultural setting, trends

- Burning practices—timing

Table 9–6.—Pros and cons of tree provenance test designs in forestry research

Feature of the experiment	Fully random design	Randomized	
		Complete block	Latin square
Number of replications	Need not be the same for all species	The same for all species	The same for all species
Number of treatments (species and provenances) possible	Unlimited, except that a very large number may lead to much variability	If too many, the advantage of blocks may be lost	Effectively limited to 5 and 10; if less, the layout is intensive; if more, unwieldy
Laying out the trial	Easy	Fairly easy but the blocks are of fixed size and must be carefully made out according to the size	Design is fixed and little flexibility is possible
High variability between plots	No account can be taken of this	Can take care of variation in one or more directions, depending on layout of the blocks	Particularly good if variation is in two directions
Missing plots	No difficulty in analysis	Little difficulty but some loss of efficiency	May entail much loss of efficiency and complex analysis
Residual degrees of freedom	Maximum number available	Number reduced by number of blocks	Number reduced both for rows and columns
Differences in treatment	Whole area must be treated uniformly	Blocks may be treated differently	Whole area must be treated uniformly if two-way effectiveness is not to be reduced

Source: Wright and Andrew 1976.

- Cropping practices—timing, soil preparation, seed preparation, fencing, guarding, weeding, protection from animals, thinning, mulching, manuring, harvesting, storing of crops, secondary cropping
- Fallowing—necessity, preferred vegetation, time ratios, procedures, use of legumes, soil relationships
- Supplementary inorganic fertilizer potentials.

A shift in focus in genetics research is foreseen as a result of increasing attention to agroforestry (Burley 1980b). Contrasts with research on industrial plantations are apparent in the following new considerations:

- The need for a range of agricultural crops and managerial treatments in combination with the tree crop
- Comparisons of a wide range of tree products and uses
- Active communication between scientists and growers
- Testing and conservation of the local adaptation and race development that many agroforestry tree species have already achieved
- Recognition that interactions of tree genotypes with agricultural crops are equally important to those of tree provenances, but more difficult to identify.

Research priorities identified in a workshop in Sri Lanka (Shea and Carlsom 1986) are directed specifically at multipurpose tree species but are of much broader import. Their research objectives and high priority goals and activities are outlined below:

1. Selection, genetic improvement, and conservation of species
   A. Choice of species
   B. Tree breeding and vegetative propagation

2. Nursery, establishment, and tending techniques
   A. Seed collection methods
   B. Site selection methods
   C. Site preparation techniques
   D. Establishment techniques

3. Management systems
   A. Spacing, thinning, and rotation
   B. Water consumption
   C. Tree/crop interface
   D. Shelterbelts
   E. Irrigation systems
   F. Production economics

4. Pest management

5. Maintenance and improvement of soil productivity
   A. Culture and inoculation with N-fixing organisms
   B. Assessment of N-fixing species
   C. Field trials concerning the N cycle and organic matter
   D. Fertilizer experiments

6. Determination of social, economic, and environmental aspects

As scientific information concerning agroforestry possibilities accumulates, there should be a trend toward the testing of systems rather than merely practices.

Chapter 9 has brought together the thinking on tropical forestry research from a large number of sources under different circumstances. Many of the practices described differ for reasons not fully clarified. No intention exists to decide for the reader which of the alternatives described best suits any local need. The variety of experience is presented. It will be up to practitioners to retest and improve on the judgments to date.