PN-ABL-092
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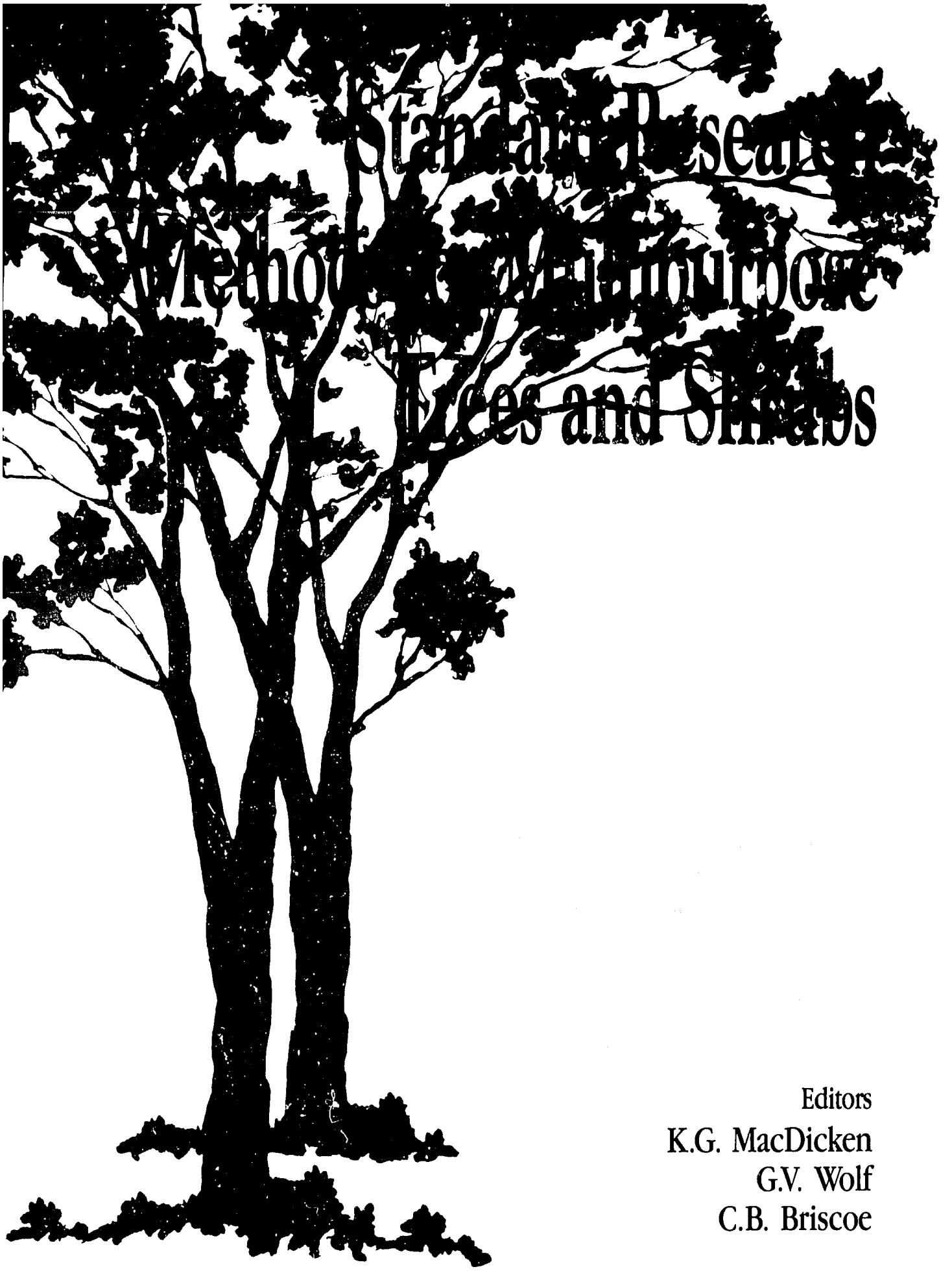
Standard Research Methods for Multipurpose Trees and Shrubs

Editors
K.G. MacDicken
G.V. Wolf
C.B. Briscoe



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Multipurpose Tree Species Network Research Series

This series includes papers, reports, manuals, and handbooks produced or supported by the Forestry/Fuelwood Research and Development Project (F/FRED). Publications in this series are available for distribution to MPTS network members and other selected individuals and institutions.

Cover art and illustrations: Design Consultants, Inc.

Library of Congress Cataloging-in-Publication Data

MacDicken, Kenneth G.
Standard research methods for multipurpose trees and shrubs / K.G. MacDicken, G.V. Wolf, C.B. Briscoe.
p. cm. -- (Multipurpose tree species network research series; manual no. 5)
A research study co-sponsored by the International Council for Research in Agroforestry (ICRAF) and the Winrock International Institute for Agricultural Development.
Includes bibliographical references (p.) and index.
ISBN 0-933595-54-9
1. Multipurpose trees--Research--Methodology. 2. Multipurpose shrubs--Research--Methodology. I. Wolf, G. V. (Gregor V.), 1958-. II. Briscoe, C. B. III. International Council for Research in Agroforestry. IV. Winrock International Institute for Agricultural Development. V. Title. VI. Series.
SB172.M33 1991
634.9'072--dc20 91-31053
CIP

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Contents

Preface 7

Acknowledgments 8

1.0 Introduction 9
- 1.1 MPTS Research Requirements 9
- 1.2 Need for Standard Methods 10
- 1.3 How to Use This Manual 11

2.0 Measurement Decisions: What? When? How? 13
- 2.1 Process of MPTS Research Design 13
  - 2.1.1 Goals and Objectives 13
  - 2.1.2 Identifying Specific Research Problems 15
  - 2.1.3 Hypotheses 16
  - 2.1.4 Objectives 17
- 2.2 Approach 18

3.0 Experiment Design 19
- 3.1 Range of Applicability 19
- 3.2 Site Selection 20
- 3.3 Experimental Design 21
- 3.4 Experiment Layout 23
- 3.5 Treatment Structure 25
- 3.6 Plot Structure 27
- 3.7 Management 29
- 3.8 Experimental Unit 29

4.0 Minimum Data Set 31

5.0 Non-Destructive Measurement Options 33
- 5.1 Accuracy and Precision 33
- 5.2 Measurements for Trees with Single Stems 35
  - 5.2.1 Height 35
  - 5.2.2 Diameter 38
  - 5.2.3 Crown Diameter 39
- 5.3 Multiple Stems 40
  - 5.3.1 Definition of Stems 40
  - 5.3.2 Height 41
  - 5.3.3 Diameter 41
- 5.4 Phenology 42
- 5.5 Assessment of Damage or Health 44

6.0 Destructive Sampling for Biomass Assessment 46
6.1 Introduction 46
6.2 Tree Selection for Destructive Sampling 46
6.3 Components 49
6.4 Moisture Content and Oven-Dry Weight 51
6.5 Volume and Density Measurements 53
6.6 Fodder and Green Manure 56

7.0 Related Measurements 59
7.1 Introduction 59
7.2 Other Products of Woody Perennials 59
7.3 Non-Woody Crop Yield 60
7.4 Animal Production 62

Appendices 65
A Symbols and Standard Abbreviations 66
Reminders 66
Standard Symbols 66
B Glossary of Terms 69
C Equipment for Measuring MPTS 75
Tools for Measuring Tree Height 75
Tools for Measuring Tree Diameter 75
Tools for Measuring Woody Biomass 78
D Useful Conversion Factors and Formulas 79
Moisture Content 81
Volume-Weight Conversions 82
Weight-Volume Conversions 82
E Developing Biomass Tables for MPTS 83
Planning a Weight Table 83
Field Sampling 83
Partitioning and Weighing 84
Analysis 84
F For Further Reading 85

Index 87

Figures

3.1	Hypothetical layout of a provenance trial with irregularly positioned blocks	24
5.1	Tree height using the percent scale and known horizontal distance	36
5.2	Measuring height (h) and length (l) of leaning tree	37
5.3	Measuring crown diameter	39
6.1	Displacement measurement of small- to medium-sized samples	55
7.1	Sampling intercrop yield (vertical view)	61
C.1	Using a clinometer	76
C.2	Using the diameter tape	77
D.1	Moisture content comparison	81

Tables

4.1	Recommended minimum data set and preferred data for MPTS field experiments	31
5.1	Log score for recording number of flowers or fruits per tree	43
5.2	Categories used to assess damage or health at tree level	45
6.1	Number of trees to sample in each plot	48
D.1	Conversion factors for SI and non-SI units	79
E.1	Most common equations for biomass types	84

Text Boxes

5.1	Methods for defining height	37
5.2	Methods for diameter measurement of MPTS with single stems	38
5.3	Methods for defining stems for measurement	40
5.4	Methods for diameter measurement of trees with multiple stems	41
5.5	Methods for quantitative evaluation of MPTS phenology	43
6.1	Methods for selecting sample trees for destructive biomass assessment	49
6.2	Volume determination using stem diameter and length measurements	54

Preface

Research on multiple uses of trees has been under way for decades, long before the terms *multipurpose tree species (MPTS)* and *agroforestry* were coined. Yet research on many aspects of MPTS still falls short of providing the information that farmers' require. Research methods, tools, and standards are too often those used by default from traditional forestry research. Forestry research has relied on standard approaches for measurements such as height and diameter for over 100 years. Many textbooks describe these methods in great detail. Yet traditional forestry approaches are not always appropriate for multipurpose trees and need to be modified or replaced by more suitable techniques.

Some of these traditional methods are appropriate for MPTS research but others are not. As a consequence, MPTS researchers often face the problem of trying to use inappropriate methods because standard ones have been unavailable. MPTS research has lacked well-accepted standards for such common problems as how to measure multiple-stemmed trees or partition foliage. The need for such methods has led to developing this manual, which seeks to provide standards based on years of experience with MPTS assessment in various internationally operating institutions.

We hope that *Standard Research Methods for Multipurpose Trees and Shrubs* will help field researchers better accomplish the tasks ahead in MPTS research and will facilitate communication between individuals and organizations who are interested in planning, conducting, or managing MPTS research.

K.G. MacDicken
G.V. Wolf
C.B. Briscoe

Acknowledgments

Standard Research Methods for Multipurpose Trees and Shrubs is in part the result of the combined efforts of many, particularly the following individuals who revised and improved an early draft at the MPTS and Shrubs Assessment Methods Workshop, which was held in Nakorn Pathom, Thailand, in May 1991.

Suree Bhumibhamon	MPTS Research Network, Kasetsart University
Doug Boland	International Centre for Research in Agroforestry (ICRAF)
C.B. Briscoe	Agroforestry Consultant, Winrock International Institute for Agricultural Development
Foster Cady	Winrock International Institute for Agricultural Development
Soren Moestrup	DANIDA Forest Seed Centre
Lars Graudal	DANIDA Forest Seed Centre
K.G. MacDicken	Winrock International Institute for Agricultural Development
Bunyarit Puriyakorn	Royal Forest Department, Thailand
James Roger	International Centre for Research in Agroforestry, Live Data
Julia Roetzer	Food and Agriculture Organization, Regional Office for Asia and the Pacific
Janet Stewart	Oxford Forestry Institute
Luis Ugalde	Centro Agronomico Tropical de Investigacion y Ensenanza (CATIE)
Rick Van Den Beldt	International Crops Research Institute for the Semi-Arid Tropics (ICRISAT)
G.V. Wolf	International Centre for Research in Agroforestry (ICRAF)

To C.B. Briscoe, K.G. MacDicken, J.L. Stewart and G.V. Wolf go a special thanks as portions of their previous writings were used as a basis for part of this manuscript. We would also like to thank Winrock International publications staff Norma Adams who edited, indexed, and directed development of the cover design and Rita Butler for proofreading and word processing. Finally, a sincere thanks to Doug Boland, Richard Coe, J.A. Maghembe, Julia Roetzer, James Roger, and Janet Stewart for their comments on the draft manuscript.

1.0 Introduction

MPTS can be defined as trees or shrubs grown to provide more than one significant product and/or service in the land-use systems they occupy. For small farms, this frequently means significant use of both wood and foliage from the same tree. Part of the confusion about whether a tree species is multipurpose exists because most can be grown for either multiple or single purposes. MPTS are managed to provide multiple products and services in two principal ways: 1) co-production of more than one product/service from the same tree simultaneously or sequentially and 2) using various management methods to produce different products/services from different trees of the same species.

For example, *Gliricidia sepium* grown in Central America or Southeast Asia is used simultaneously for fuel, fodder, and green manure in living fences. This typifies the co-production management described above. *Leucaena leucocephala*, on the other hand, managed for wood products on some trees and leaf meal on adjacent trees, typifies production of different products from different trees of the same species.

1.1 MPTS RESEARCH REQUIREMENTS

Many discussions have been held on research priorities for MPTS. These have resulted in lists of priority species, silviculture research topics, and tree improvement needs. Yet many of these research priorities focus on traditional plantation uses of MPTS rather than the needs of small-scale farmers. In some cases, there are no substantial differences in research needs since many practices used at the plantation scale are also applicable for small-farm production. However, the differences in research needs for trees managed for multiple uses are striking.

These differences can be seen in many research areas. For example, tree improvement research generally focuses on industrial needs for sawtimber. Yet trees for multipurpose use by farmers require evaluation for a range of tree products that may be more important than sawtimber. In the case of provenance evaluation of a fodder and fuelwood species, this means monitoring performance under realistic fodder and fuelwood management. In research designed to test

agroforestry combinations of MPTS with crops or livestock, it is critical to evaluate both MPTS production and the trees' effect on crop or livestock.

MPTS management for one product may affect output of other products.

Managing trees for multiple products from the same tree means that management optimized for one product affects the production of another product. For example, fodder yields generally increase with more frequent cutting, but wood yields decrease. Likewise, intensive use of tree flowers for food reduces the amount of seed available for other uses. This is important in such species as *Azadirachta indica* where both flowers and fruits are used.

These trade-offs are seldom evaluated in either forestry or agricultural research, yet they form the basis for decisions farmers must make regarding the planting and management of MPTS. It is a major area where research can contribute much to helping farmers increase their incomes and improve their life-styles.

1.2 NEED FOR STANDARD METHODS

Research is an investment whose full potential is rarely realized. This is often due to the lack of applicability or application of results from the experiment site to other sites. Lack of standard research methods for MPTS intensifies the problem, making it more difficult to understand and apply the methods of one researcher to the problems faced by others.

Even simple measurements can be made in several different ways.

One part of the problem is that the same measurements can be made in several different ways. For example, height can be measured either as the vertical distance from the ground to the apical bud of the main stem or along the axis of the main stem to the same point. When the tree is perfectly straight and vertical. the values for these two measurements are the same. When the tree is leaning or crooked, the value for the second measurement (stem length) is greater than the first (height). Even simple measurements such as these are frequently done in ways that produce different results.

Another part of the problem relates to reporting. Seldom do reports of research results provide enough detail to allow other researchers to interpret and reconstruct adequately the way the data was collected or to apply the results to other sites.

Field research on MPTS is frequently done in single-site experiments. The results of each experiment have a "recommendation domain" or an area to which they can be appropriately applied. If the experiment is conducted on soil type X and in climate type Y, then the recommendation domain has soil type X and climate type Y. Standard methods and the use of a standard minimum data set help ensure the reporting of enough information to allow interpretation and, in some cases, application of results to sites outside the recommendation domain.

1.3 HOW TO USE THIS MANUAL

Shaded text boxes provide suggestions for standard research methods.

Standard Research Methods for Multipurpose Trees and Shrubs is designed to serve as a reference and guide for those who wish to plan and conduct MPTS field research using standard methods. It is intended for use by research scientists and technicians with a sound background in agricultural or forestry research. Recommended standards and alternative approaches are provided for critical MPTS research decisions. These are presented in shaded text boxes and are further described in the text. The use of these recommended standards is encouraged unless there are strong reasons for not using them. Clearly, there will be cases in which the recommended standard is inappropriate. In these cases, the alternative(s) provided for each standard should be considered before other methods are used. Margin notes found throughout the text highlight or summarize important points made in the main body of the text.

In general, the greatest emphasis is on those aspects of research that may be unique to multipurpose trees and shrubs. As a result, a number of important research topics related to MPTS and agroforestry have been avoided. For example, the manual does not cover below-ground biomass measurements or yield assessment of intercropped herbaceous plant species.

The manual provides both a general introduction to decision-making and experimental design for MPTS research and a description of specific methods. Chapter 2.0 reviews the decisions required to plan research. Chapter 3.0 discusses important considerations for experimental design. Chapter 4.0 outlines two recommended minimum data sets for MPTS research. Chapter 5.0 describes recommended

standards and alternative methods for non-destructive measurements, and Chapter 6.0 describes those for destructive measurements. Finally, Chapter 7.0 briefly describes other rarely used measurements that should be considered.

2.0 Measurement Decisions: What? When? How?

Research: "investigation or experimentation aimed at the discovery and interpretation of facts, revision of accepted theories or laws in the light of new facts, or practical application of such new or revised theories or laws." (Webster's Ninth New Collegiate Dictionary)

Research requires carefully considered decisions. MPTS research does not differ from other forms of biological research in terms of process, but it clearly differs from traditional forestry or agricultural research in the methods used.

2.1 PROCESS OF MPTS RESEARCH DESIGN

MPTS research decisions are routinely made on goals, objectives, problems to be solved, hypotheses, methods, interpretation, and reporting. Some of these are determined consciously while others are not. For most of these decisions, researchers working on MPTS rely on precedents established by other researchers, such as the framing of a null hypothesis or the general outline of a journal paper. These conventions differ little between biological research fields because the steps involved are essentially the same--setting goals and objectives, defining a specific research problem, designing, implementing, monitoring, interpreting, and reporting.

2.1.1 Goals and Objectives

Lack of goals means progress cannot be measured.

Every serious researcher has a goal. Without goals, progress cannot be measured against a desired end, nor can the lack of progress be measured, potentially resulting in aimless wandering and the waste of precious resources.

The first and most critical decision in selecting a goal is identifying the potential end user of the research. Researchers often forget or neglect to identify clients' needs, resulting in information that, however interesting, fails to answer end users' important questions. Confusion over who the client is can prevent useful results from being produced, communicated, or used.

Knowing the client's needs is essential.

Once the clients have been identified, the next step--too often omitted in the past--is to discuss goals with them. It should be obvious and correct that the clients are the ultimate authority on their goals. They are, indeed, the ultimate authority, but most action organizations--including the small farmer--tend to think in terms of very general goals (e.g., survive, make a profit) or specific task-oriented goals (e.g., plant rice on 200 square meters tomorrow, harvest 1,000 cubic meters of lumber this month).

This means a researcher cannot simply walk up to the industrialist or small farmer, ask what his goals are, write down the answer, and walk away. The researcher must devote energy and often considerable time to determine real problems and researchable goals. Quite often, the biologist may find the support of a sociologist, economist, or anthropologist helpful or essential. Conversely, these other specialists may need to include the biologist while determining their own research goals.

Once a goal or set of goals has been tentatively identified, it must be reviewed and verified by the clients. Some clients can and will read a definition of goals prepared by the researcher and discuss them cogently. From others, extracting meaningful and helpful comments can be difficult. However difficult, agreement on goals is essential if research is to provide information useful to the clients. If the information is not useful, research degenerates into an expensive hobby for the educated elite.

Goals change and need regular review.

It is important that goals be reviewed at regular intervals, for goals change over time as conditions change. For example, an increase in market prices for fuelwood or a decrease in tree fodder prices may change the goal of the producer from both fodder and fuelwood to production of fuelwood alone. Similarly, the goals of small farmers may change radically if a new road is built with connections to new markets.

Once a set of general goals has been established (e.g., increasing fuelwood, fodder, and food production), specific goals and objectives need to be defined. Specific goals commonly restrict the scope of the general goal, often to a geographical or ecological zone. An example would be to increase fuelwood production in watershed X.

2.1.2 Identifying Specific Research Problems

Once specific goals have been set, associated problems must be identified and prioritized. A primary problem for the specific goal of increasing fuelwood in one watershed may be species selection. Various criteria must be considered, each of which is probably necessary but insufficient and some of which may be contradictory. Examples of criteria for species selection are:

- Site adaptability (including climate, soil, pests/symbionts)
- Social acceptability (taboos, appearance, tradition)
- Economic value (products, markets, increment rate)
- Acceptable levels of undesired effects (weediness, allelopathy/competition)
- Sustainability (perennial, coppice, nutrient cycling)

Any or all of the factors within each criterion may require informal or formal consultation, literature review, even preliminary or simultaneous field research. Social acceptability, in particular, tends to be uncertain and unpredictable for a specific area but just as important as biological adaptability.

Priority of products and services is usually:

1. Needed but not present on the farm (e.g., dry-season fodder)

2. Supplies an established but not yet satisfied cash market (e.g., jackfruit or durian)

3. Creates a new market by growing and marketing new crops, varieties, or products

4. Desired but not essential on the farm (e.g., fragrant blossoms, windbreaks)

Methods for comparing dissimilar outputs (e.g., timber and fodder or timber and fruit) are important in evaluating MPTS production, particularly when more than one species is included in an experiment. In many cases, the only meaningful way to evaluate multiple outputs is to use economic value rather than biological yield.

Once species have been chosen for trial, further information needs appear, along with related problems. Each problem for which the supply of knowledge is unavailable becomes a research need. Examples are:

- Supply and handling of seed
- Nursery/seeding/planting methods
- Spacing effects
- Field establishment, care, and management practices
- Harvesting and regeneration

A consideration too often ignored is the timing of food crop management, which almost invariably takes priority over tree management (i.e. crops are sown in the most favorable season; trees are planted before or after the crops).

2.1.3 Hypotheses

Hypothesis framing is often done unconsciously.

A hypothesis is a tentative assumption made in order to draw out and test its consequences. A hypothesis implies there is insufficient evidence to provide more than a tentative explanation.

To solve a problem, hypotheses are developed, although the process is often not identified as such. For example, if a client wants to grow a cash crop on a moderately steep hillside, a forest researcher may look at the hillside and think, "*Calliandra calothyrsus* would grow well here, produce good fuelwood and palatable fodder during the dry season, reduce erosion if planted in contour rows, not compete severely with the crop if pollarded regularly, and add nitrogen and improve soil structure if the pruned foliage is scattered between the rows." That is a hypothesis--a tentative assumption based on insufficient evidence. It depends on theory and specific knowledge of site and species characteristics combined with observation, and it requires verification.

Standing alone, the usefulness of a hypothesis is limited. If *Calliandra* is planted and fails to provide one or more of the products or services anticipated, the hypothesis is not proven, but *it is not disproved*. One successful trial proves it can be done. One or one thousand unsuccessful trials do not prove it cannot be done. History is full of failures followed by success. Dozens (and probably hundreds) of pine (*Pinus* spp.) trials in the tropics were failures until inoculation with mycorrhizal fungi became a standard practice.

A more useful hypothesis, with a greater chance of success, would be: *Calliandra*, *Leucaena* hybrid, *Gliricidia sepium*, and/or *Tephrosia candida* would grow well and provide useful goods and services.

Practical hypotheses are essential.

When research resources are limited, one of the important guidelines in selecting hypotheses for testing is practicality. For example, if the cost of a method for storing seed exceeds the value of the stored seed, there is probably no point in verifying the hypothesis that this seed can be stored for long periods. Practicality and cost effectiveness may be functions of time and may change. Practical hypotheses should be framed in terms of their future value to the research client. In this way, hypotheses can be useful tools in deciding what treatments are appropriate for experimentation.

Like every other stage in planning research, peer and client review are desirable in selecting hypotheses. Fellow scientists are more likely to offer useful technical suggestions; clients may be more useful as guides to practicality.

2.1.4 Objectives

The most crucial step in any research process is defining objectives. In many cases, these are invented after the experiment has been designed as an excuse for the desired research plan. Often they are no more than a restatement of the set of treatments. However, a well-considered set of objectives is essential for the development of a trouble-free research program.

Limited studies cannot yield general results.

The objective is a description of what the research is meant to accomplish, and the more specifically it is stated, the more probable it can be attained. "Determining the growth rate of MPTS" is a laudable but unrealistic objective. Determining the relative production of fodder by six (specified) MPTS on a specific site under a specified management regime can be done. Balancing the conflicting demands of specific conditions with general applicability is difficult. What is clear, however, is that a strongly limited study cannot yield general results. Too many studies in the past have been extrapolated beyond all reason by their authors, as well as by readers. The objective should always delimit the population being studied, and thus clarify the application of results.

The specification of the end product, such as the development of a new agroforestry technology or the introduction of an existing agroforestry technology into a new region, helps determine the knowledge gaps that need to be filled by field research.

Objectives are likely to suggest a whole set of knowledge gaps. Some of these can be answered from existing sources, such as a literature search, or by direct investigation, such as a rapid rural appraisal of farmers' knowledge of existing practices. As a last resort, field experimentation may be needed to fill some of these gaps. One area that will often require such trials is the applicability of a technology and its components, such as tree species and management practice, to a geographic region, in terms of both its physical and social attributes. Examples include such questions as "Do these tree species grow sufficiently well in this region?" or "Do farmers have the necessary labor available at the required time of the season to cope with this management-intensive species?"

Usually it will be safer to divide research questions between several smaller experiments, rather than attempt to answer them all in one cumbersome experiment.

2.2 APPROACH

The approach (the manner in which research is carried out) will of course be strongly determined by the specific objectives. A study with pan-tropical objectives must be carried out by a well-funded international organization or a network of cooperators with a mutual interest in the objective. Similarly, an objective involving a variety of disciplines will depend on active participation by a variety of specialists capable of defining a mutual objective and integrating procedures and analyses to their mutual satisfaction.

Conversely, an objective geographically and ecologically restricted and dealing with a single scientific discipline can be accomplished by a single technician. When such a limitation exists, having the plan reviewed at an early stage by a peer from another discipline may reveal considerations previously overlooked. Even when this is not the case, the "outsider" may suggest a procedure or theory to improve the usefulness and efficiency of the proposed study.

Even when no other improvement is obtained, clarifying the disciplinary jargon and explaining the terms and methods often will be a cost-effective use of interdisciplinary review.

3.0 Experiment Design

For good research design, remember the six Rs:

- **REASONS** for doing the experiment(s) should be defined
- **RESTRICTING** the number of study objectives
- **RANGE** of applicability of the research results should be defined
- **RANDOMIZING** treatments in each block and locating blocks to minimize site variation within blocks
- **REPLICATING** every treatment
- **RECORDING** everything planned and done

When designing a new field experiment, the selection of treatments starts with a problem that can be solved through field research. A "researchable" idea based on previous experimental and survey information and non-experimental field observations is formulated as a simple hypothesis or a series of sub-hypotheses. Goals and objectives are then set. From these, experimental treatments and design are selected. When choosing the treatment structure, it is essential to determine whether the results can answer the research questions.

3.1 RANGE OF APPLICABILITY

Objectives should determine the range of applicability for any study. For what type of farmer is the agroforestry technology designed? What geographic and climatic ranges are envisaged? For example, if the range is wide, such as all farmers in the highlands of East Africa, it will be necessary to experiment at several well-chosen sites in the highlands, as wide variation can be expected. If a narrow range of applicability is chosen, such as tea growing areas of the Kenyan highlands, then perhaps two sites will suffice. However, it will be impossible to apply the results from these two tea growing sites to all the highlands of East Africa since the range of variation in this broader region has not been sampled.

In most areas, one would expect to find large variation in seasonal growth patterns due to climate variation. Growth differences between drought-resistant and non-drought resistant species would likely change dramatically from dry to wet season. If the range of applicability is to cover the wide spectrum of climate from season to season, the trees must be monitored over several seasons. To evaluate the resistance to drought, trees should be planted yearly for several years since rainfall patterns are often not consistent from year to year.

3.2 SITE SELECTION

Test the full range of sites to which results will be applied.

The range of applicability needs to be based on known soil, socio-economic, and bio-climatic information. After the area and experimental framework have been defined, trials are carried out to cover the range of applicability. Invariably, the combined analysis of data will show an interaction between the treatments used in each experiment and the sites planted. In other words, the differences among treatments are not the same on all sites. In analyzing the results, it is usually necessary to characterize each trial site by measuring weather and soil variables (see Chapter 4.0).

Recommendations for sites on which the experiment is not planted are based on knowledge of differences between experimental treatments and how these differences vary among sites. A prediction model, estimated from a series of trial, soils, and weather data, is an objective and useful means of applying trial results to non-trial environments. Due to site-to-site variability, it is usually more difficult to predict absolute yields than treatment differences.

Site selection must be based on objectives, range of applicability, and site characteristics.

The number of sites selected within each target area depends on the precision needed in the estimated transfer model and the number of significant environmental gradients. If rainfall is the only gradient of primary importance, the area can be stratified into several subgroups of increasing levels of expected rainfall, based on long-term records, and sites selected from each subgroup. If rainfall and soil texture, for example, are the most important gradients, the area can be divided into subgroups, each one a different combination of rainfall and soil texture and sites selected within each stratum.

Unfortunately, access to desirable experimental sites is often limited by unavailability of land, lack of facilities, etc. In these cases, sites must be selected that most closely cover the range of the selected gradient. Where no suitable site is available, one should not conduct the trial as it is often a waste of research resources.

3.3 EXPERIMENTAL DESIGN

The precision of any experiment depends on the amount of variability in the experimental material, site, and management. It is good practice to limit this variability. For instance, use only good-quality seedlings, and do not use rare and atypical parts of the experimental site, such as near termite mounds or where large trees once grew. Standardize all management techniques. It may be better to test fewer treatments on only the more uniform parts of a site when the remaining area is highly variable.

Even when care is taken to limit site variability, some will remain. Precision of the design can be further improved by assigning plots into groups called *blocks* so that the variability within each block is small. Then the treatments are allocated to the plots within each block so that comparisons between the treatments are made within each block. In this way, the much larger variability among blocks does not affect the precision of the experiment. This is usually known as the *experimental design.*

The RCBD is well understood and generally recommended.

One often-used type of experimental design is the *randomized complete block design (RCBD)*, in which the number of plots within each block equals the number of treatments used in the experiment. For instance, in a provenance trial, the number of plots within each block is the same as the number of provenances in the trial. Each plot within a block is allocated one treatment.

The advantages of this design are that it is simple, well-understood, easy to interpret, and robust in that if one treatment fails, the other treatments can still be compared in a simple way. However, its main limitation in the assessment of MPTS is that, in testing many treatments (e.g., a screening trial), the number of plots within a block is large. This means that there often remains much within-block variability.

Designs that use fewer plots within a block than the number of treatments are known as *incomplete block designs*. These allow more flexibility in the choice of an appropriate number of plots to use within a block than does the RCBD. The use of incomplete block designs requires experience with these methods in order to allocate the

treatments to the plots and suitable computer software for the analysis. Unless such support is available, a randomized complete block design is recommended.

The precision of the experiment will depend on the extent to which the natural variation is controlled and on the number of replications used. Usually the number of replicates is the same for all treatments. However, in some cases one or more treatments, such as a control, may be replicated more often so that comparisons with the control are more precise than between pairs of non-control treatments.

Controlling variability increases precision.

Controlling the variability in the experiment is usually a more cost-effective way of improving precision than increasing the number of replicates. Precision is inversely related to the square root of the number of replicates. For example, cutting the width of the confidence interval in half requires four times as many replicates.

Choosing the number of replicates in any experiment requires that:

1. there be enough residual degrees of freedom to estimate the plot-to-plot variation from within an experiment (as a general rule, at least 10 degrees of freedom). In MPTS trials, this is usually not a problem as there are often many treatments, and 2 replicates will provide sufficient degrees of freedom. However, when there are only a few treatments, check this by writing out an analysis of variance table.

2. the number of replicates be chosen to give the required level of precision after controlling as much of the experimental variability as possible.

In multi-site experiments, 2 replicates at each site will usually suffice unless a separate analysis is desired for each site. In this case, choose the number of replicates as for a single-site experiment.

Select enough replication to provide required level of precision and allow for possible failure.

In experiments at a single site, 3 or 4 replicates are usually enough. For complicated designs, list the degrees of freedom for the analysis of variance to check that the residual degrees of freedom are at least 10. This implies that a RCBD with a single-factor treatment with 3 treatment levels needs 6 replicates, one with 4 levels needs 5 replicates, and 5 needs 4. For 6 to 10 treatment levels at least 3 replicates are needed, while for more than 10 treatment levels only 2 replicates are absolutely necessary.

It is often sensible to add further replication to allow for failures in certain plots or even for whole treatments. When small plots, such as single trees, are appropriate, it is possible (and desirable) to use more replicates.

When the experiment is designed to test performance of plantings done over more than one year, single replicates can be established in future years. In subsequent seasons, less replication is required as extra information is available from replicates planted in previous years.

3.4 EXPERIMENT LAYOUT

Planning the layout of the trials should be a high priority. One should carefully evaluate all obvious site variation when laying out an experiment. Blocks should be arranged so that the conditions within them are as uniform as possible. The more uniform the site, the less likely environmental variables will influence tree performance within the block. However, there may be hidden variations within the site. For this reason, good trial layout and design are essential to account for such site variation.

In many studies, the blocking system is implemented rigidly regardless of site characteristics. The use of randomized block designs results in blocking schemes where the number of plots per block is determined by the treatment structure (number of factor levels) rather than by the characteristics of the site. For a blocking scheme to reduce experimental variability effectively, the field layout must suit the unique characteristics of the site.

Establish blocks to minimize within-block variation.

On a fertility gradient, the block is usually rectangular with the long axis along the contour of equal fertility. On level, apparently homogeneous ground, conditions usually vary with distance in any direction, so a block is square.

An additional way to overcome site variation is to orient single-row plots with the rows running up and down the fertility gradient.

This ensures that higher fertility areas do not favor some species over others. In many cases, fertility gradients run up and down the slope on a hillside. In such cases, blocks run along the contour while plots run up and down the slope. However, when plots that involve hedges are planted on sloping land, plant them with hedges on the contour to minimize soil erosion. This overrides other considerations about fertility gradients.

Square plots must be kept square, but the blocks they form do not have to be positioned regularly across the land in order to minimize the variation within the blocks (see Figure 3.1).

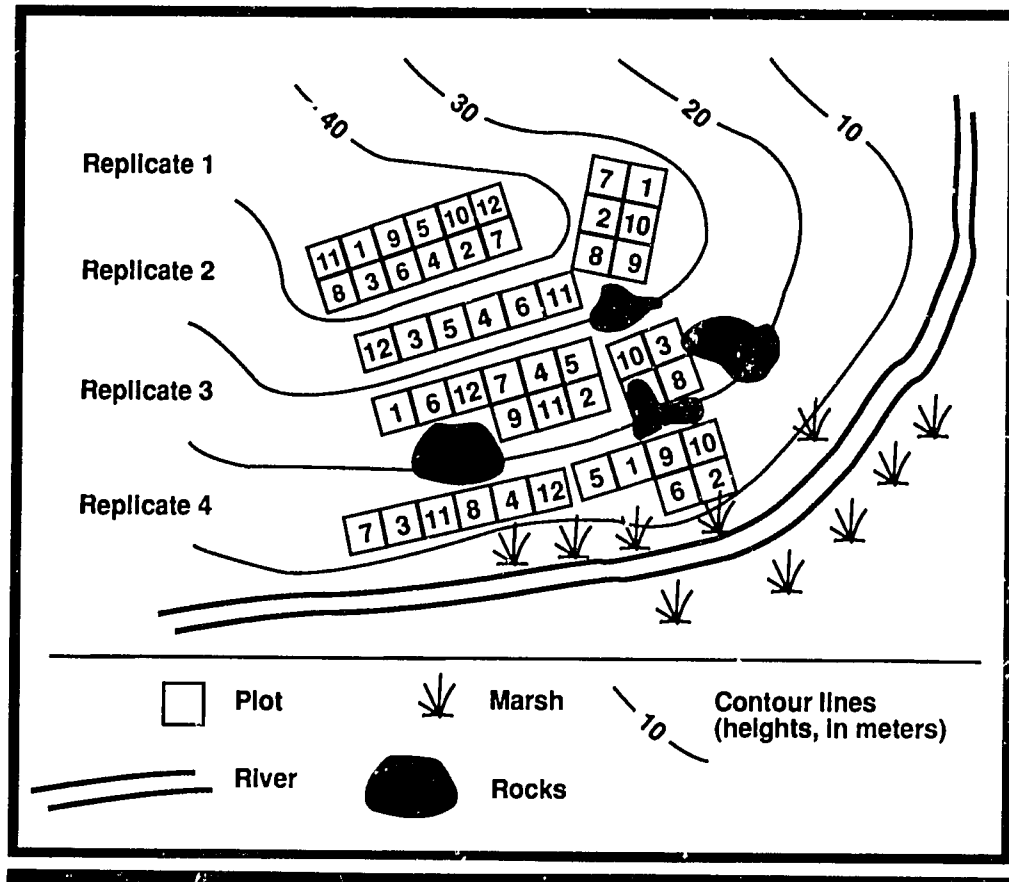

Figure 3.1. Hypothetical layout of a provenance trial with irregularly positioned blocks

On sites where the contours meander, adjoining plots are often not parallel. Often a wedge-shaped, non-experimental area is between the plots. Plant this with crops, ground cover, etc. so that each experimental plot is immersed in an environment similar to that found in the experiment.

When one treatment differs greatly from the others, much larger guard areas are needed than in cases where all the treatments are expected to impose similar levels of plant competition. A provenance

trial with a range of relatively similar provenances of a single species will need much smaller guard areas than will a species elimination trial where large differences between species are expected.

For row planting, this implies a minimum of 3 rows per plot (33% net usage excluding end guards) or 4 rows per plot (50% net usage). For block planting, this implies an absolute minimum of a net plot of 4 trees in a 4-by-4 block of 16 trees (25% net usage) up to, say, a net plot of 36 trees in a gross plot of 64 trees (56% net usage). Plots of 9-by-9 trees (60% net usage) provide a near optimum use of land for fast-growing, closely-spaced MPTS experiments designed for 4-6 year evaluations.

The size of the plot and guard areas will often depend on the planned duration of the study. If it is a screening for 12 or 18 months of growth, then the level of inter-tree competition may be limited and small plots desirable. However, there will often be pressure to extend such trials beyond the planned duration to see what happens. Avoid this.

3.5 TREATMENT STRUCTURE

Many unexpected events can occur over the life of tree experiments, some of which can affect experimental results. While unavoidable, their effects can be minimized by keeping the study simple through the use of single factors. In this manner, both the establishment and analysis are straightforward and robust. Even if grazing, fire, or other accidents occur in some plots, one can compare surviving treatments with the loss of only a proportional amount of precision.

Single factor experiments make trial establishment and analysis more robust.

Multiple-factor experiments (such as factorial experiments), although more complex, are usually capable of greater efficiency than a series of experiments that examine the effects of only one treatment factor. Analysis of multiple-factor trials makes it possible to study whether the factors interact when applied in combination on the same plot. Examples of this include species x management trials, or alleycropping where the spacing of both the hedgerow and the crop are part of the treatment structure. Successful application of multiple-factor experiments requires access to sufficient and timely agronomic and forestry inputs to ensure site homogeneity (e.g., weeding, watering, etc.). Analysis of such trials can involve an advanced level of statistical expertise that is not available everywhere.

When a treatment, such as management (e.g., spacing or cutting height) takes a range of possible values, the following rules are important:

- Choose a limited number of levels, usually 3 to 5; choose less if the shape of the response is known to be linear and more if the shape is unknown, but never more than 5 levels.

- Have 1 level at each end of the range of interest, but do not exceed the reasonable range unless an extreme level will provide a useful portion of the response surface.

- If the shape of the response curve is unknown, place the other 2 levels on either side of the anticipated turning point.

- Try to choose levels that are realistic and easily interpreted.

Only use control treatments where they answer useful questions.

In many experiments, it is useful to include a control treatment. This should reflect current practices or technologies and is compared with other experimental treatments to see if there is any gain. Examples of when to use controls include:

- *Genetic improvement.* In such trials, a provenance or cross from a previous cycle is included to check for any improvement.

- *Agroforestry experiments where crop yield is of paramount importance.* In such trials, inclusion of crop-only controls are imperative to see if the presence of trees influences (positively or negatively) crop yields. In areas of high heterogeneity, it is sometimes useful to include extra replication for the control treatment to ensure a reliable estimate of crop yields for current practice.

- *Agroforestry experiments where trees are expected to influence the site considerably.* In windbreak trials, for example, it is important to monitor micro-environment parameters like wind speed where no windbreak is present.

Crop-only controls in agroforestry trials are all too often laid out without sufficient border between them and other treatments. One should consider the above- and below-ground competition from neighboring tree/crop plots. When this problem is expected to be

When laying out control plots, consider competition from above and below ground.

extreme, locate the controls outside the experiment, well away from such effects. It is important to ensure that such control plots and the experiment site have similar soil and climate conditions. Take extra care in interpreting the precision of contrasts between such external controls and other properly randomized treatments.

At times controls are not advised. Laying out full controls in agroforestry experiments involves crop-only and tree-only controls, which can greatly increase the size, and therefore the cost, of the experiment. When it appears that basic tree/crop relationships are understood for a given agroforestry technology (through review of work done elsewhere or from results of preliminary trials), continued routine use of controls is questionable. The space occupied by controls could be better used to examine more treatments to fine-tune the technology to local conditions or to learn more about underlying processes. For instance, in a management trial of cutting height for hedgerow intercropping, including a crop-only control will not add any information to the trial.

3.6 PLOT STRUCTURE

Plot structure includes its net and gross size, the types of elements in it, such as the tree and the crop, and their relative configuration.

Plot shape should match the land-use specified by the objectives.

Configuration of the plot will generally be chosen to match the land-use system specified by the objectives of the experiment. For border plantings, species will usually be tested in lines. When testing species for tree-crop competition in hedgerow intercropping, a row of trees surrounded by the crop is suitable. When testing trees under competition, between and within rows, it is essential that the anticipated competition is duplicated in the arrangement of the plot. Single-tree plots can be used when low competition is expected.

Plot shape should be influenced by knowledge of soil gradients. If a gradient exists in one direction, it is sensible to use plots designed to maximize the variation within the plot and thus minimize the variation between plots. This might result in long, thin plots running up and down a slope, particularly when testing trees in rows. For some agroforestry practices, more important agronomic factors, such as arranging hedges along contours, will override these considerations. When testing trees in blocks where soil variability is patchy, square plots are useful.

Choice of plot size depends on several aspects. As the plot size is increased within a certain range, the variability for any plot mean or total will be reduced as the small fluctuations are averaged out. However, when the plots become too large, the site variation from plot to plot increases and the costs of establishing, maintaining, and monitoring the experiment will increase. In general, more replicates are recommended for smaller plots.

Generally, more smaller plots will give the experiment better precision as long as the plot represents the system being tested. Very small plots may be too small to provide a realistic environment for the treatment being tested. This is especially important for agroforestry plots where tree and crop are mixed. For example, large plots are often required when testing for competition between tree and crop in order to isolate effects from neighboring plots.

The following items suggest the use of larger plots; always consider these when choosing plot size:

- *Micro-variability*. If the micro-variability in the site is high, use larger plots. On the other hand, it is often easier to locate small plots in a way that avoids special areas like old termite mounds.

Apply the same level of management to all plots.

- *Size of the treatment difference*. When the effect of different treatment levels, such as species, is large, wider borders and guards will be required, suggesting the use of larger gross plots. If a control treatment (e.g., no hedgerow) is included that is expected to differ greatly from the other treatments, this may require the use of wide guards or borders between plots. The importance of differences between treatments will increase as the experiment continues. Rotation length is thus important, especially for some management treatments, such as pruning.

- *Extent of plot influence*. When the extent of the influence of the plot is large, use fewer larger plots. When underground competition for moisture is important, it is useful to think about the extent of the root system, e.g., how roots in hedgerow intercropping extend across the alleys. To some degree, this can be modified by management, such as pruning and thinning.

3.7 MANAGEMENT

Many small management activities require care to ensure that the same level of management is applied to all plots, unless variation in management is part of the treatment regime. Treat the net plot as an island within the sea of the surrounding land-use system. For instance, in trials where loppings from trees are used as mulch on the plot, spread the mulch from guard areas on the guard areas and the mulch from the net plot on the net plot. In many existing trials, the mulch from the gross plot is, in fact, spread evenly over the net plot, which is incorrect.

In trials with multiple species, manage nurseries so that seedlings are as similar in size and vigor as possible. Management may need to differ by species in order to produce uniform seedlings.

Variations in management, both within site and between sites, can obscure treatment differences. Care should be taken to ensure that the same type of field management is given to every plot, except in cases where management practices are also experimental treatments. If the trees are to be grown in clean weeded plots, then all of the plots need to be free of weeds. If irrigation is to be applied, then the same amounts of water need to be applied to every plot. If a management operation cannot be done to the entire experiment at one time, then it should be carried out using the blocking pattern so that management variation adds to block differences.

3.8 EXPERIMENTAL UNIT

In field trials, experimental treatments are allocated to experimental plots. A plot is the land area to which a treatment is applied (e.g., species, provenance, or a management treatment such as pruning).

Use plot-level variability--experimental error--to test differences between treatment means.

One may make measurements at the plot level by measuring the entire plot. If the plot is sub-sampled and a measurement recorded on the composite sample, the measurement is also said to be at the plot level. On the other hand, measurements are often made and recorded on sub-units of the plot, the most common example being when data are recorded for each individual tree within a plot.

When making measurements on several sub-units (i.e., individual trees) within a plot, a measure of variability can be made at both the tree and plot levels. The variability (within block) at the plot level is commonly called the *experimental error.*

Do not use the tree-to-tree variability within the plot, as calculated from an analysis of variance, for testing differences between treatment means. The standard errors for differences between treatment means must be based on the plot-to-plot variability (experimental error). Generally, the variance from tree to tree will be smaller than that from plot to plot. Using this, rather than the correct plot-to-plot variance, will lead to standard errors that are too small. This will lead to the conclusion that the experiment is more precise than it really is.

4.0 Minimum Data Set

In order to compare or interpret experimental results, there must be at least a minimum set of data on treatments and the environment in which the experiment is conducted. In many cases, researchers do not give enough information about their experiments to allow others to interpret the results. By defining a minimum data set (MDS) that adequately describes management, weather, and soil, researchers can more readily exchange and understand one another's results. Naturally, one should feel free to add measurements relevant to experimental objectives.

A minimum data set is essential for comparing or interpreting experimental results.

The MDS should include only those physical and biological variables necessary to make meaningful comparisons between data sets from different locations or studies on the same site. The MDS can also be used as a checklist of variables or descriptors for a particular experiment. Full understanding and interpretation of field experiment results may require additional information not included in the MDS (e.g., more detailed soils data for fertilizer or mulching experiments).

Table 4.1 describes the MDS for MPTS field experiments and suggests additional data. Criteria used in determining the MDS were the importance of information for data interpretation and the availability of equipment or facilities for generating the data. For some characteristics, multiple options (in italics) are given.

Table 4.1. Recommended minimum data set and preferred additional data for MPTS field experiments

MINIMUM DATA SET	PREFERRED ADDITIONAL DATA
PROJECT AND SITE DESCRIPTION	
Project name	Trial Site ID
Contact person	Local relief: *flat, hollow, slope, ridge top*
Local name of trial site	Surface soil color: *white, grey, yellow, orange, red, brown, black*
Address, State, Country	Subsurface soil color: *white, grey, yellow, orange, red, brown, black*
Latitude	Soil moisture at planting: *dry, damp, moist, wet, very wet*
Longitude	Soil moisture after planting (0-3 months): *dry, damp, moist, wet, very wet*
Elevation (m)	Sodicity measured in extractable sodium percentage (ESP): *non-sodic (ESP <15%), sodic (>15%)*
Slope: *flat or gentle (0-5°), intermediate (5-10°), steep (11-20°), very steep (21-40°), extremely steep (>40°)*	Mean minimum temperature of coldest month (°C)
Aspect: *N, S, E, W, level*	Mean maximum temperature of hottest month (°C)
Mean annual rainfall (mm)	
Rainfall regime: summer, winter, bimodal, uniform	
Maximum length of dry season (months <50 mm)	
Mean annual temperature (°C)	

Table 4.1. *Continued*

PROJECT AND SITE DESCRIPTION	
Frost: *annual, occasional, never*	Absolute minimum temperature (°C)
Surface soil texture: *sand, loam, clay*	Mean number of days of frost per year
Sub-soil texture: *sand, loam, clay*	Climatic classification system and description
Soil depth to impermeable layer: *<25 cm, 25-50 cm, 50-100 cm, >100 cm*	Soil drainage: *excessively well drained, well drained, impeded, waterlogged*
Surface soil pH (A horizon)	Average depth to water table: *<2 m, >2 m*
Sub-soil pH (B horizon)	Soil classification system and description
	Soil nutrient analysis
	Thickness of A, B, and C horizons
	Surface soil salinity: *low (<15 mS m^{-1}), medium (15-90), high (90-210), very high (>210)*
	Subsurface soil salinity: *low (<15 mS m^{-1}), medium (15-90), high (90-210), very high (>210)*

EXPERIMENT DESCRIPTION	
Objectives	Age of planting stock
Experiment design	Stock diameter at root collar (mm)
Number of replicates and number of plots/block	
Treatment factors and levels of each factor	
Plot dimensions and spatial arrangement (layout)	
Trial establishment and management:	
Date of planting	
Site preparation and planting method	
Stock height at planting (cm): *<30, 30-60, >60*	
Fertilizer and irrigation	
Inoculum	
Weed control	

PERFORMANCE DESCRIPTION FOR TREE COMPONENT	
Date of measurement	User-defined biomass (kg/tree)
Survival (%)	User-defined parameters
Height (m)	Health, pests and diseases
Stem length (m)	Phenology
Diameter(s) at 0.3 m	DBH at 1.3 m
Treatment means and standard errors of differences between the means	Coefficient of variation for the plot-to-plot residual variation

SEED SOURCE DESCRIPTION	
Species code	Nursery information
Provenance (name, state, country)	Scarification method
Latitude of seed origin	% germination
Longitude of seed origin	age of seed
Elevation (m) of seed origin	
Seed supplier name	
Seedlot identity number:	
(a) supplier's	
(b) local	

5.0 Non-Destructive Measurement Options for Multipurpose Trees

Remember:

- Research requires precision and accuracy. Long-term, cooperative research requires standard methodologies.
- Methods should conform to well-established global standards and terminology. To measure special products, try to follow the spirit of existing standards. Carefully document analytical methods, as well as measurement tools and techniques.
- Accurate measurements must be reproducible, especially in cooperative research conducted on multiple sites.

Estimating the yield of useful products is the ultimate aim.

The ultimate aim of mensuration is to determine the tree's yield of useful products. In industrial plantations, the product of interest is usually wood. In the case of MPTS, there may also be many important non-wood products, such as leaves, fruits, pods, and other tree parts. Measurement of MPTS products requires a mixture of methods taken from traditional forestry practices and agricultural research in addition to techniques unique to MPTS research.

This chapter describes recommended methods for non-destructive measurements commonly used in MPTS research. For critical measurement decisions, a recommended standard is suggested along with alternative approaches when the standard may be inappropriate.

5.1 ACCURACY AND PRECISION

The terms *accuracy* and *precision* are often misused. Precision refers to the exactness of measurement. Precision of measurement equals one-half the unit of measurement. That is, if measurements are made to the nearest centimeter (cm), precision is one-half cm. If measurements are made to the nearest meter (m), precision is one-half m.

Accuracy refers to correctness of measurement. It is determined by two factors: consistency and reality. If repeated measurements of the same object vary, they cannot all be accurate. With a vernier caliper, it is

possible to measure a tree's diameter at breast height (dbh) to 1/10 mm. But if the caliper is moved slightly, the new dbh measurement of the same tree will be different because of irregularities in stem roundness, bark thickness, and other variables. The precision is 1/10 mm divided by 2 = 1/20 mm, but as all the readings are not the same not all can be considered accurate. In such a case, the precision is illusory.

Relationship of measurement practice to reality is important.

The second factor is the relationship to reality. If one needs to measure dbh of a tree, breast height must be determined. This is often and reliably done with a stick cut to a length of 1.3 m. But if the base of the stick is sliced at an angle, the sharp point may slide through loose litter, sink into soft ground, sit exactly on hard ground, or rest on a raised root or stone. In such a case, only the measurements taken when the stick rests on hard ground can be accurate--and then only until the point wears down or breaks off.

Accidental or careless errors of measurement are not included in the above discussion of either accuracy or precision. Purely random errors tend to follow the rules of any random population. Positive and negative errors occur with equal frequency, and small errors occur more often than large ones. Thus, the errors tend to cancel out.

For a plot of many trees, the mean may or may not be accurate despite a number of random errors. For an individual tree (the basic unit of genotype selection), errors invariably produce wrong answers.

Preventing errors at every stage is essential.

Many errors, however, are not random in the technical sense. Foresters who fail to measure the location of dbh commonly estimate the location of 1.3 m too high in the morning and gradually lower as they tire during the day. These dbh measurements are too small on plots in the morning and too large on plots in the afternoon. These are not compensating errors. Similarly, if a forester swings the angle gauge around himself as he revolves to view the whole plot instead of correctly walking around the angle gauge, the measured basal area is consistently too large.

Regardless of precision, tests demonstrate that consistency is improved by recording to the completed unit, not to the nearest unit. For example, record both 1.2 and 1.8 as 1 and both 35.4 and 35.9 as 35.

5.2 MEASUREMENTS FOR TREES WITH SINGLE STEMS

5.2.1 Height

Even though tree height is generally referred to as "height," various height measurements are possible:

- *Total height (h).* This is the height value most often measured and refers to the vertical distance from the average ground line (on relatively level ground) to the apical bud, excluding leaves and terminal inflorescence extending beyond this point. On a slope, the most common reference is to the ground line on the uphill side of the tree.

  The h of a leaning or crooked tree is measured vertically, not along the slope of the stem, and so is always less than the length of any bole that is not both straight and vertical. The reason is practical, not theoretical. For trees too tall to be measured directly with measuring poles, total height can be determined directly by a hypsometer or by simple trigonometry (Figure 5.1).

- *Total length.* This is the length of the bole measured along the slope of the stem. For leaning trees, this value will always be greater than total height. The stem may be straightened up against the vertical rod or the rod may be laid along the leaning tree. This method gives total stem length rather than height (Figure 5.2).

Height and stem length measurements are not necessarily the same.

- *Commercial or merchantable length.* Because this varies with time and place, it must always be defined explicitly, usually in terms of minimum acceptable diameter. For example, if sawlogs are accepted to a minimum diameter of 25 cm, merchantable height equals the vertical distance from the ground line to a point on the bole with a diameter of 25 cm.

- *Length of clear bole.* This is the vertical height from ground to base of the live crown. When the primary concern is high-quality sawn timber, base of live crown is most often defined as the attachment point of the lowest branch of the continuous crown, without considering isolated or epicormic branches.

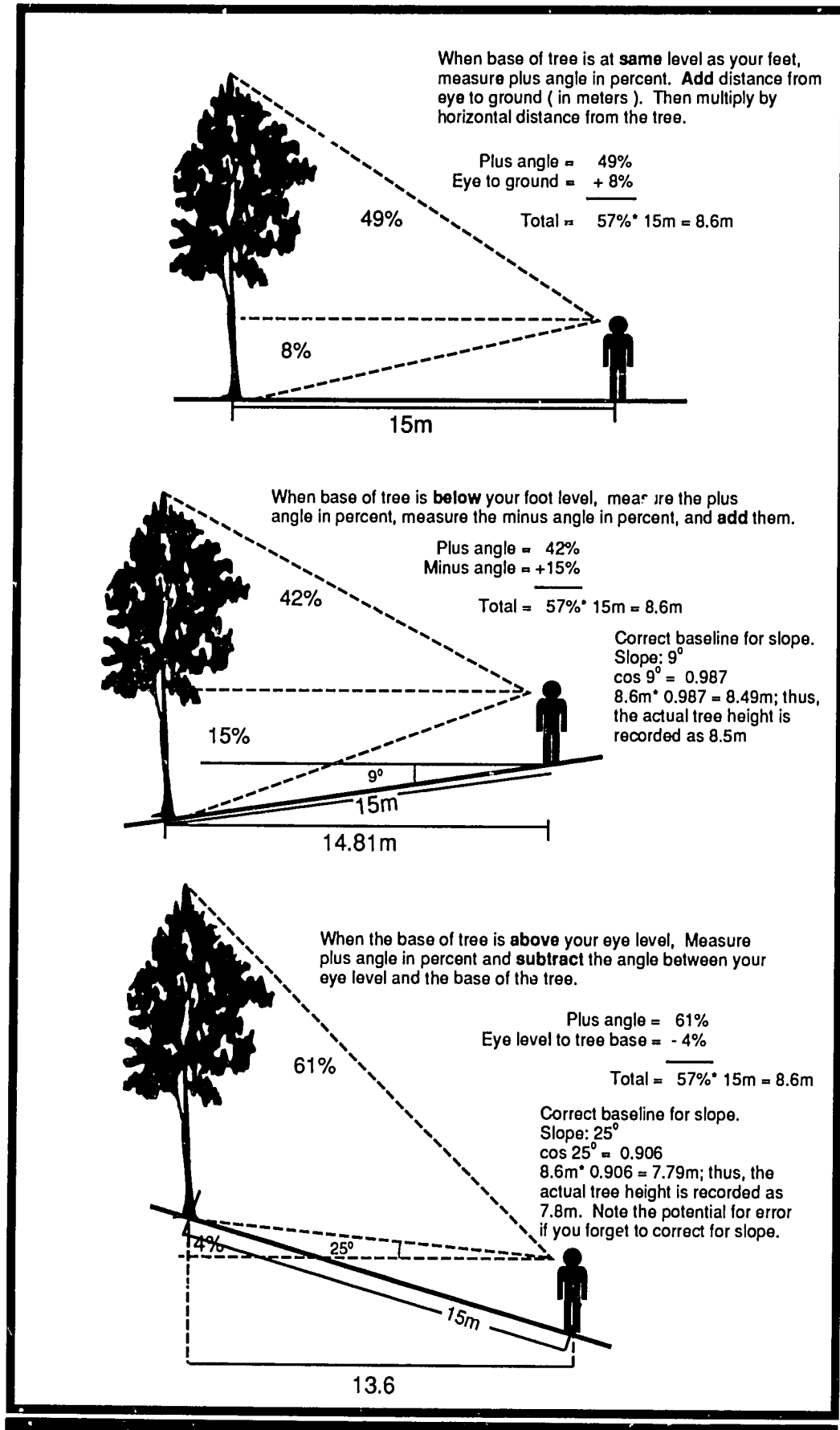

Figure 5.1. Tree height using the percent scale and known horizontal distance

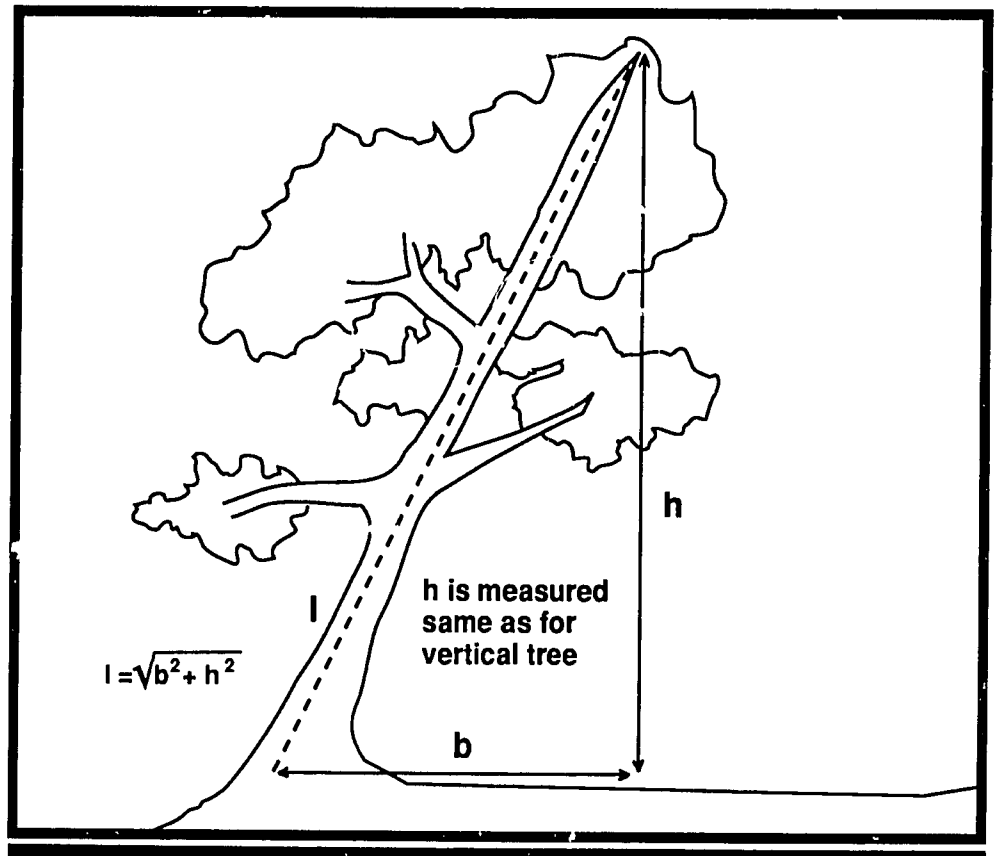

Figure 5.2. Measuring height (h) and length (l) of leaning tree

It is recommended that stem length of the longest stem be used for MPTS (Text Box 5.1).

5.1 Methods for defining height

Recommended standard: Total stem length from the ground to the highest (apical) growing point

Alternative #1: Total vertical height from the ground to the highest growing point

Alternative #2: Commercial/merchantable length to a specified minimum diameter (usually the minimum saleable size) or length of clear bole measured from the ground to the lowest branch of the continuous crown

Measure height or length to the nearest 0.1 m for trees of up to about 15 m, and to the meter above 15 m. These units are related to limits of accuracy more than utility. Even for accuracy, the precision is often false; nevertheless, they are the commonly accepted norms and should be adopted unless another unit is demonstrably superior.

5.2.2 Diameter

Diameter is measured as a step toward determining wood volume or biomass and as a measure of growth. The forester's traditional standard measurement of diameter is at breast height (dbh) or 1.3 m. However, this standard may not be useful for MPTS with short or many stems. In general, the higher the measuring point on multi-stemmed species, the greater the number of stems to be measured. Since most MPTS trials include trees with single stems and with multiple stems, it is important to have a measure of diameter that is useful for both stem forms.

The recommended standard point for measuring diameter for MPTS is 0.3 m (d_{30}) above the ground line, average or uphill side as specified (Text Box 5.2). It may be useful to use metal or plastic pegs to mark ground level for future reference on sloping land where erosion or changes in measuring position will make a difference in diameter measurement. If a knot or other abnormality occurs at 0.3 m, make two measurements (one above and one below the abnormality) and take the mean. Where accuracy or consistency is critical, measure height from the ground line with a scaled stick. Mark every point used with paint or some other identifier for future reference.

5.2 Methods for diameter measurement of MPTS with single stems

Recommended standard: Measure the stem at 0.3 m above the ground.

Alternative: Measure dbh at 1.3 m above the ground.

Diameter usually includes bark. In rare cases, diameter inside bark (d_{ib}) is required (i.e., where bark must be removed or has a separate economic value). Make inside bark measurements using a straight rule or bark gauge.

In the nursery, diameter is often measured at the root collar (d_{rc}). Because of changing obstructions and inequalities of ground surface, 5 cm above the soil level is preferred as a standard. Various calipers can be used to measure seedling diameter, but a homemade cutout gauge can be faster and cheaper. One should measure to the nearest 2 mm.

5.2.3 Crown Diameter

Tree crowns are usually irregular and, because of their size and position, present mensuration problems. Diameter of the crown (d_k) is also influenced by thinning and spacing, pruning, species, site quality, season, and age. It is perhaps the best single indicator of tree-to-tree competition, and can be used as a measure of shading and competition with other crops.

The crown is usually measured using a non-elastic tape, which is stretched along an axis from one edge of the crown to its opposite edge, passing through the center of the crown. The edge of a crown 5 to 20 m above ground can consistently be located by a person standing with shoulders parallel to the tape and nose positioned exactly below the crown edge (Figure 5.3). Consistency is nearly impossible when standing with shoulders perpendicular to the tape.

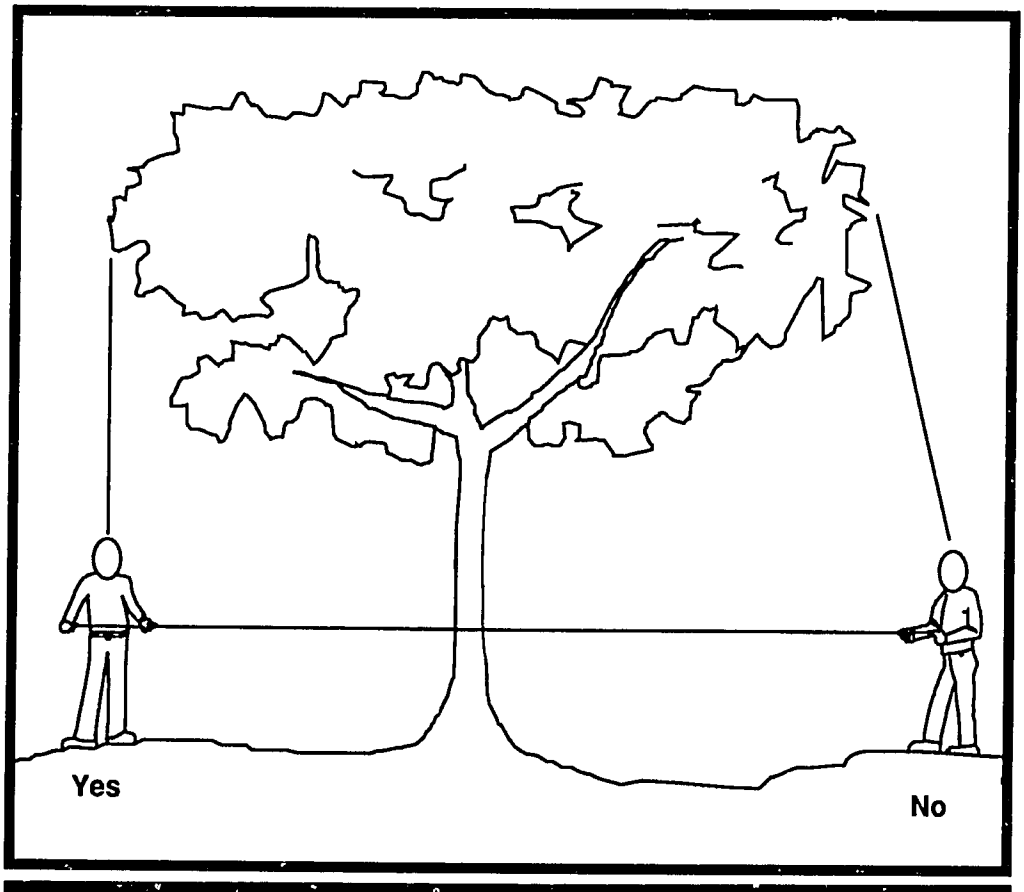

Figure 5.3. Measuring crown diameter

If the crown is regular in shape, measure along any two axes perpendicular to each other. If the crown shape is irregular, usually measure the longest and shortest axes, being sure to pass through the geographical center of the crown.

5.3 MULTIPLE STEMS

Multiple stems are a common problem in the measurement of MPTS. Since mensuration textbooks and research manuals have provided little guidance on this topic, no standards have been established, resulting in great differences attributable to methods of measuring growth and yield. Many studies are unnecessarily devalued by a failure to define, consistently measure, and report decisions on the handling of multiple-stemmed trees.

5.3.1 Definition of Stems

Defining stems is essential for many MPTS.

Anyone measuring a multi-stemmed tree is confronted with the problem of deciding what to measure. Defining what is and what is not a stem is often done inconsistently. Therefore, the first step in measuring multi-stemmed trees is to define what constitutes a stem.

The recommended standard is to define stems as originating in the zone 30 cm or less measured *along* the main stem; for multi-stemmed trees these must be at least one-half the diameter of the main bole at the point of attachment (Text Box 5.3). Any axis separating from the main bole more than 30 cm above the ground is considered a branch. Any axis separating from below 30 cm and less than half the diameter of the main bole is also considered a branch.

5.3 Methods for defining stems for measurement

Recommended standard: Those originating below 30 cm that are at least half the diameter of the main bole (all others should be considered branches)

Alternative: All material over 1 cm in diameter originating below 30 cm for most measurements

The advantage of this definition is that it uses a standard height (30 cm) as the upper limit of the stem definition zone and eliminates small diameter materials, which generally contribute little to total or woody biomass. The disadvantage is that potentially useful biomass is sometimes excluded for some species.

An alternative definition of stems is a fixed limit of 1 cm (all axes larger than 1 cm are considered stems). The advantage of this definition is that nearly all potentially useful biomass is included, allowing accurate comparisons between trees with single and multiple stems. The primary disadvantage is that it requires more labor for measurement and recording than the recommended standard and, for large trees, requires measurement of stems that contribute little to the estimated biomass.

5.3.2 Height

Measurement of total stem length to the highest growing point, but for the longest stem only, is recommended (see Figure 5.2, p. 37).

5.3.3 Diameter

Diameter measurements of multiple stems can be time-consuming and expensive for trees with many stems. For bushy plants, dbh is clearly inappropriate because many small stems may be at that height. Measurement higher up the stem is easier because stems are more clearly divided, but the number of stems increases as the measurement point is raised.

It is recommended that all of the stems (as defined above) be measured at 0.3 m above the root collar along the axis of the main stem (Text Box 5.4).

5.4 Methods for diameter measurement of trees with multiple stems

Recommended standard: Measure all stems at 0.3 m as defined above and combine with formula below.

Alternative #1: Measure the three largest stems at 0.3 m and combine their diameters with the formula below. This is easier, but may give less accurate prediction of biomass than the recommended standard.

The formula for combining stem diameters is:

$$d_{combined}=\sqrt{d_1^2+d_2^2+d_3^2+...+d_n^2}$$

5.4 PHENOLOGY

Phenology is the study of the seasonal timing (or periodicity) of the life events of an organism. Monitoring and describing MPTS phenology are important to understanding the basic biology of relatively poorly-understood species. Information on foliage growth, flowering, and fruiting is essential to tree improvement research and to an understanding of the seasonality of production, particularly for fodder.

In relation to MPTS assessment, the study of phenology has both qualitative and quantitative aspects.

The qualitative aspect considers the development stages of leaves, flowers, and fruits and concerns the reproductive cycle of the plant. Development stages often need to be monitored to obtain an appropriate picture of seasonal variation. Monitoring is, however, a relatively time-consuming process. It is recommended that this be done monthly at the plot level, recognizing that adjustments may be necessary to meet species requirements and resource constraints. Record an assessment of the average appearance of the plot. Some studies will require a higher monitoring intensity. Individual tree assessments give more information for those with the available time and resources.

The recommended standard scoring scales for a qualitative evaluation are:

Leaves

Leafless	N
Leaves flushing	I
Full leaf (young)	Y
Full leaf (mature)	M
Leaves falling	F

Flowers and Fruits

Live flowers or fertile fruits occurring? Yes cr No

If yes:		If no:	
Flower buds	B	Dead flowers	D
Open flowers	F	Infertile fruits	I
Immature fruits	G		
Mature fruits	M		
Dry empty fruits	D		

Record the presence of each stage for each plot. For example, if both immature and mature fruits are present in the plot, record 3,4.

The quantitative aspect considers the production of leaves, flowers, and fruits in relation to possible end uses as well as the reproductive capacity of the plants. Estimate variation in the production of flowers and fruits by applying a quantitative scoring approach (see Text Box 5.5).

5.5 Methods for quantitative evaluation of MPTS phenology

Recommended standard: Use a simple score of three levels for rating leaf, flower, and fruit production.

Alternative: Use a log score for quantifying flower and fruit production as described in Table 5.1.

The recommended three-level scale for quantitative scoring for phenology is as follows: light = 1, medium = 2, and heavy = 3. An alternative, more descriptive method for quantifying flower and fruit production uses a log score. Estimate the number of fruits or flowers per tree and record the appropriate log score (see Table 5.1). Verify and correct the log score by destructive sampling.

Table 5.1. Log score for recording number of flowers or fruits per tree

Avg. no. flowers or fruits	Log score	No. flowers or fruits
0	1	0
2	2	1-3
8	3	4-15
30	4	16-60
125	5	61-250
500	6	251-1,000
2,000	7	1,001-4,000
8,000	8	4,001-16,000

5.5 ASSESSMENT OF DAMAGE OR HEALTH

The condition of the tree and its susceptibility to adverse site conditions and attack by insects, disease, or animals are important indicators of its adaptation to the site. One can describe tree health by a simple coding system at either the individual tree or plot level. Plot-level assessments are often used rather than tree-level measurements of damage or health because they estimate damage at lower cost than that required for tree-level assessments.

It is recommended that damage and health be recorded at the plot level using the following international conventions for rating insect and disease problems (Rohrmoser 1984):

1 = no problems observed
3 = moderate attack--about half the plants show symptoms of medium severity or more than half show symptoms of light severity
5 = medium attack--all or nearly all plants show symptoms of disease or insect attack of medium severity
7 = heavy--all plants show symptoms of disease or insect attack of high severity (individual plants or plant parts are dying off)
9 = very heavy--the disease or insect attack causes large-scale dying off of plants or plant parts

The even-numbered values are reserved for "in-between" situations (e.g., if 5-30% of the plants in the observation plot are infected, the rating would be 2).

"Light severity" signifies that the symptoms of disease or insect attack occur only individually and are scattered on a plant. "Medium severity" indicates that healthy plant parts dominate the appearance of the plant. "High severity" indicates that the affected plant parts dominate the appearance of the plant.

As an alternative, assess damage/health at the individual tree level using the measures shown in Table 5.2.

Table 3.2. Categories used to assess damage or health at tree level

Type of damage		Parts of the tree affected		Severity of attack	
N	No Damage	S	Stems	1	Light
M	Tree Missing	B	Branches	2	Moderate
X	Wrong Species	F	Flowers/Fruits	3	Severe
I	Insect Damage	L	Leaves	0	Dead
D	Nutrient Deficiency	R	Roots		
P	Animal (physical)	W	Whole Tree		
H	Human (cutting)	C	Bark		
C	Cold/Frost				
F	Fire				
S	Water Stress				
L	Waterlogging				
W	Wind				
U	Unknown				
O	Other				

If there is no damage (N), i.e., the tree is normal and healthy, or if the tree is missing (M) or of the wrong species (X), leave the "parts of the affected tree" and "severity of attack" categories blank.

6.0 Destructive Sampling for Biomass Assessment

Measurements that cannot be taken without harvesting the tree or tree parts are called *destructive measurements*. Destructive sampling is required for the evaluation of many products from many MPTS, primarily because weight or quality of those products are important. In some cases, regression models can be developed to allow reliable estimates of product weight or quality, but destructive measurements must be used to provide the basic data from which the regression models are derived.

6.1 INTRODUCTION

Biomass from MPTS is the total weight, at a given time, of living trees per unit area and can be partitioned into above ground biomass (stem, foliage, flowers, etc.) and below ground biomass (roots, nodules, etc.). Biomass is usually expressed as oven-dry weight. The common procedure is to divide the tree into component parts and determine fresh weights in the field, then take small samples from each component for drying. Moisture contents can be determined from the fresh and dry weights of the samples. These measurements can then be used to calculate the total dry weights of the harvested components (see Appendix D, p. 81).

One can partition the tree into five basic components: stem, branches, foliage, fruit, and roots. Any of these may provide more than one product. For example, the stem can be used for commercial timber, pulp, fuel, poles, etc., and foliage for fodder, mulch, food, and other purposes. This section concentrates on selection and handling of components for biomass assessments. Specific quality aspects of products are discussed briefly in Chapter 7.0.

6.2 TREE SELECTION FOR DESTRUCTIVE SAMPLING

The most accurate assessment of biomass can be obtained by direct measurement of the whole experiment, i.e., by cutting and weighing every tree. This is often not possible, however, because of the time and labor required and because it may be preferable to maintain the stand for future observations.

It is, therefore, often necessary to select a sub-sample of trees for destructive (biomass) measurements. These are used to determine the relationship between biomass and non-destructive measures, such as cross-

sectional area, using regression analysis. A regression function is then used to predict the biomass of a larger population of standing trees.

Adequate sampling is critical for biomass studies.

Destructive biomass measurements are taken for various purposes, which relate to the allometric relationship between biomass and non-destructive measurements. One purpose is to predict biomass for "unsampled" trees in an experiment; other purposes may be to construct standard or local biomass tables for more general use or to use as dependent variables in environmental prediction models, etc.

Discussion in this manual is limited to sampling for prediction of biomass from unsampled trees in single-site experiments. In the case of multilocation experiments, the use of standard biomass tables or, when these do not exist, development of such tables is recommended (see Appendix E). For single-site experiments, one should sample at least 9 to 12 trees for each treatment; sample more if the trees are not too large or thorny. Also increase the sample size if the trees are clearly variable in form or if other sources of variability have been introduced (e.g., major soil differences).

Trees to be sampled can be selected either randomly or with stratification by size to ensure the whole size range is covered. (It is important not to use regression functions outside the range over which they have been modeled.) A stratified random sample is recommended, but requires more calculation (Table 6.1). If testing multiple species, each species should have its own regression.

The stratified method discussed here chooses trees from within each plot without reference to the size of trees in other plots or replicates (see Text Box 6.1). Selection of trees for destruction can then be done sequentially plot by plot and replicate by replicate.

Although random sampling is easier to do than using recommended stratified sampling, the random method is potentially dangerous because the selected trees may not cover the whole size range. When using random sampling, it is therefore recommended that *at least* 16 trees be sampled per treatment.

For both recommendations, estimate the biomass values for the remaining trees using the regression parameters (slope and intercept) based on all sampled trees within that single treatment (e.g., species).

Table 6.1. Number of trees to sample in each plot

Total sample size	Number of replicates																			
	2		3			4				5					6					
	Replication number																			
	1	2	1	2	3	1	2	3	4	1	2	3	4	5	1	2	3	4	5	6
9	6	3	3	3	3	3	0	3	3	3	0	3	0	3	3	0	3	0	3	0
12	6	6	3	6	3	3	3	3	3	3	3	0	3	3	3	3	3	0	3	0
15	6	9	6	3	6	3	6	3	3	3	3	3	3	3	3	3	3	0	3	3
18	9	9	6	6	6	3	6	6	3	3	3	6	3	3	3	3	3	3	3	3
21	9	12	6	9	6	6	3	6	6	3	6	3	6	3	3	3	6	3	3	3
24	12	12	9	6	9	6	6	6	6	3	6	6	6	3	3	6	3	3	6	3

Note: Numbers shown are totals for each plot. These numbers must be divided equally between the 3 size classes (e.g., a sample of 6 trees should include 2 from the "small," 2 from the "medium," and 2 from the "large" classes).

6.1. Methods for selecting sample trees for destructive biomass assessment

Recommended standard: Use a stratified random sample for each plot as follows:

1. Harvest trees and place all in ranked order by diameter at 0.3 m (estimated cross-sectional area for trees with multiple stems).

2. Delete smallest tree(s) from list until remaining total is divisible by 3 (e.g., if there are 16 trees in the plot, use the largest 15; if there are 15, use them all).

3. Divide remaining trees into 3 equal groups: "small," "medium," and "large."

4. Within each of these groups, randomly select 1, 2, 3, or 4 trees, according to Table 6.1.

5. Measure chosen trees.

Alternative: Use a random sample from each plot as follows:

1. Number of trees to be sampled in each plot = Total no. in sample per species/no. of replicates.

2. Select trees randomly in each plot.

6.3 COMPONENTS

The end use and economic value of MPTS products vary with many factors. Quality aspects and product-specific standards vary from region to region. Measuring biomass of components simplifies the task of considering local quality standards, size classes, etc. Use of biomass components allows the comparison of production from trees with different morphologies. To evaluate useful biomass yields in an experiment, separate harvested biomass components of interest into well-defined size classes and convert to dry weight. As it is impractical to oven-dry and

weigh the whole tree, select a representative sample of trees, take samples of components within each size class, and use these values to estimate biomass production of each component.

Define biomass components according to end use or research requirements.

In deciding how to partition biomass components, two approaches can be taken: 1) partition the tree according to the end use and market requirements for different sized products or 2) partition components to ease the biomass measurement of the species being assessed. Following are two examples of recommended size classes according to end use (*Gliricidia sepium*) and for ease of assessment (*Acacia tortilis*).

For *Gliricidia sepium* grown in Central America, it is relevant to separate foliage from the woody components because the foliage is used for fodder and then divide the woody components into diameter size classes based on local end use. Practical divisions then become less than 1 cm (partly used for fodder, partly left as residual), between 1 and 2.5 cm (used for domestic fuel) and above 2.5 cm, which is the lower diameter limit of commercial fuelwood used in this area. The class above 2.5 cm may be further sub-divided, depending on the precision of the biomass estimate required and the potential market value of larger diameter wood. Size classes of the woody components in this example would be:

leaves and twigs less than 1 cm
> 1 and ≤ 2.5 cm (thin branches)
> 2.5 cm (branches and stems for fuel)

Begin with plant parts that are most easily lost or change between harvest and weighing.

For *Acacia tortilis* grown in India, it is difficult and time-consuming to separate pods, leaves, and twigs from the minor branches, although it would be of interest. Therefore, estimate these tree parts by sub-sampling (see "Fodder and Green Manure," section 6.6). Here relevant size classes would be:

< 1 cm diameter (small branches, twigs, foliage, etc.)
> 1 cm and ≤ 5 cm (small branches for fuel)
> 5 cm and ≤ 10 cm (larger branches and stems for fuel and small timber)
> 10 cm (large branches and stem(s) for timber)

In many cases, the component yield, or the biomass in each size class, cannot be directly converted to the product of interest. Fodder is a good example, where the characteristics of palatable fodder vary with both tree and animal species. Fodder may include foliage, flowers, fruit, succulent bark, and twigs. However, the twigs for many species have already lignified at a diameter of 1 cm, depending on season, species, and age of the twig. Therefore, if greater detail is required, weigh separately the foliage, succulent material, flowers, and fruit.

The disadvantage of measuring product-specific yield is that the manner and extent of component utilization depends on such factors as animal browsing pressure, season of availability, etc. These factors vary greatly between regions and MPTS. Thus, direct comparison of MPTS product yields is far more difficult. A standard size class of harvested biomass is more easily compared, regardless of its end use, and correlation of biomass and local products can be determined by modeling of the relationship.

6.4 MOISTURE CONTENT AND OVEN-DRY WEIGHT

Moisture content can be defined in several ways.

Products like fodder, fuelwood, and pulpwood are frequently marketed by weight. Weight of wood or foliage in the field can be determined using portable weight scales for moderate or small quantities or by transporting large quantities to industrial platform scales, if available. However, weight is directly affected by moisture content, so moisture content is an important variable to define and determine carefully. For example, the term *dry weight* can mean air-dry weight, which varies with temperature and relative humidity or it may mean oven-dry weight, which is wood or other plant material dried to a constant weight in an oven. Oven-dry weight is strongly recommended where an appropriate oven is available.

The main advantages of oven-dry weight are that it is a measure that permits the reliable comparison of materials with greatly differing moisture contents and is a widely used means of reporting wood weight. The main disadvantage of oven-dry weight is that it is only practical for representative samples and that a suitable weighing balance and drying oven are necessary. Additional costs are incurred because of time spent transporting material and analyzing samples in the laboratory. (Appendix D provides additional detail on moisture content and conversions between wet- and dry-weight moisture content values.)

To determine the oven-dry weight of large quantities of wood, select a sample representative of all portions of the total biomass being sampled: this means the entire cross section or a pie-shaped section of every cross-sectional disk. Before weighing samples, be sure to remove all foreign material, such as soil clumps and small stones that may have been picked up during collection.

Weigh the sample fresh to determine the wet weight, and then dry to a constant weight. To convert sample wet weight to total oven-dry weight, use the following formula:

$$\frac{\textit{sample dry weight}}{\textit{sample wet weight}} \times \textit{total wet weight} = \textit{total oven-dry weight}$$

For example, if total wet weight is 100 kg, sample wet weight is 10 kg and sample dry weight is 6 kg, then total oven-dry weight = 60 kg:

$$\frac{6\ kg}{10\ kg} \times 100\ kg = 60\ kg$$

Drying samples to oven-dry weight is recommended.

A drying temperature of 50-103 °C is recommended for most samples depending on the objective. To preserve biomass samples for fodder quality or chemical analysis, dry the samples slowly, preferably at 50 °C. If the objective is to determine the oven-dry weight of woody biomass, 103 °C (or just above the boiling point of water) is recommended. Leafy biomass, litter, and twigs with a diameter of less than 1 cm normally reach their constant weight after 24 hours when dried at a temperature above 80 °C. Woody material with a diameter of more than 1 cm and less than 5 cm requires about 48 hours. Larger material will require even more time unless it is split into smaller pieces before drying. Weigh the oven-dry mass immediately after removing from the oven to avoid moisture absorption. Measure the green and oven-dry samples to a unit approximately 1% of the total sample. For example, if the sample weight is 1 kg, the precision of the measurement should be the nearest 10 grams (e.g., 1.00 kg).

Minimum sample sizes for moisture content may be as small as 100 g per sample for a bush or small tree, but must be progressively larger as tree size increases. To obtain adequate representation of variation within the tree, take wood samples from different parts of the tree, within each size category, and then mix to give a single overall moisture content value for that tree. In combining samples, take care to ensure each major part of the tree component to be measured is proportionally represented in the sample. For example, if moisture content is to be taken for a branch, then proportionally more samples should be taken for the larger diameter portion of the branch than for the smaller, less woody portion.

Accurate scales that permit the exact determination of green weight on location may not be available. If fresh weight is to be determined at another site, keep samples in airtight plastic bags from collection until weighing to prevent moisture loss until they can be weighed. The bagged samples must be kept out of direct sun to prevent development of mold. Refrigerate the samples if they cannot be analyzed immediately in the laboratory. Careless treatment of samples will cause unnecessary variability, especially when chemical analyses are to be done in the laboratory.

6.5 VOLUME AND DENSITY MEASUREMENTS

While biomass weight is the most useful measure for fuelwood and foliage products, volume is still widely used as a measure of wood production. Because of the irregular form of some MPTS, determining their wood volume is often more difficult and expensive than for sawtimber species.

The method of volume determination depends largely on product size. Volume of small wood products can be determined from gross measurements of stacked products. However, actual wood content of stacked products varies up to 40%, so stacked volumes are of little use for research.

The primary disadvantage of volume determination of medium or large stems is that volume cannot be easily measured directly without harvesting the tree. The estimates of volume vary in precision and accuracy, and the procedures used in volume calculation are not standardized. Lastly, volume and value may be poorly related.

Volume of all but small samples is generally calculated using diameter and length measurements. The intensity of measurement generally varies directly with the value of the product and inversely with the cost of labor. Recommended measurements for volume calculations are d at the top, middle, and base of the individual log or branch section; d_{ib} if the terminal cuts have been made; and d_{ob} if the stem is intact. The recommended standard for MPTS volume measurements is described in Text Box 6.2. This method applies to stems (or branches) and is the most accurate of the general volume formulae used for wood volume measurements. The most time-efficient and least error-prone way to apply this method is to measure sections of equal length (i.e., 1 or 2 m). This makes both measurement and calculation easier and less expensive.

The alternative method is less time-consuming in that it requires only one diameter measurement. It uses Huber's formula for volume calculations and should not be used with sections longer than 1 m to avoid excessively high errors.

In general, any number of diameter measurements can be made on the stem to determine volume. Usually, the more measurements made, the more precise and accurate is the volume calculated. In all cases, the basic problem of an asymmetrical stem remains, but this can be minimized by taking careful diameter measurements and using the recommended standard method with short (i.e., 1 m) sections for measurement. In any case, clearly record the exact procedures.

6.2 Volume determination using stem diameter and length measurements

Recommended standard: Measure diameter at the base, middle, and top of stem sections and convert to cross-sectional area using the following formula:

g (m^2) = $0.00007854d^2$, where g is the cross-sectional area in m^2 and d is diameter expressed in cm.

Use Newton's formula to calculate volume as follows:

$$volume(m^3) = Lx\frac{(g_b + 4g_m + g_t)}{6}$$

where: L = length of the section in cm
g_b = cross-sectional area at the base of the section
g_m = cross-sectional area at the middle of the section
g_t = cross-sectional area at the top of the section

Alternative: Measure diameter at the midpoint of a 1 m long stem or branch sections, convert this diameter to cross-sectional area as above, and use Huber's formula to determine volume:

$$volume(m^3) = L(g_m)$$

The displacement method can be used to determine green volume of small- to medium-sized samples. First, place on a scale a vessel containing sufficient water to cover the wood samples (and with enough freeboard to avoid overflow) and weigh. Next, place the wood sample in the water and, with a plunger, force all samples under water. While exerting enough force to hold the samples under water, reweigh (Figure 6.1). The weight of the vessel with water and submerged wood minus the weight of the vessel with water only (in g) equals the volume of wood (in cc). If the necessary equipment is not available, immerse small samples in a measuring cylinder (i.e., 1,000 ml) or when the sample has a regular form, measure the dimensions of the sample and calculate the volume.

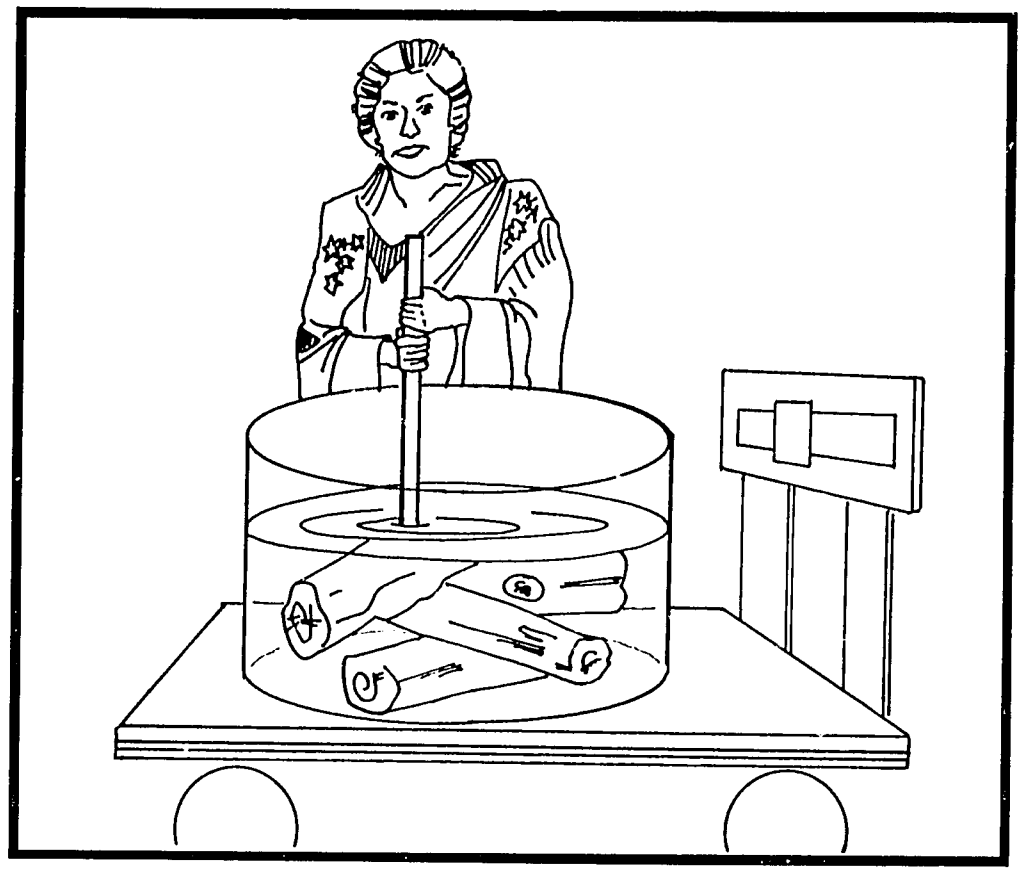

Figure 6.1. Displacement measurement of small- to medium-sized samples

Specific gravity is a useful measure of wood density that can be used to convert weight and volume measurements at different moisture contents. It is commonly defined as the ratio of the oven-dry weight of a sample (in g) to the green volume of the sample in cm^3. Specific gravity varies with:

- species and genotype
- age of tree
- rate of growth
- site
- position of sample in the tree
- percentage of sapwood, heartwood, or defects in the sample

Since specific gravity varies between trees and within tree, samples to determine specific gravity must be selected proportionately from throughout the usable, woody portion of the tree, preferably as disks containing complete cross-sections at the sampling point. Always remove bark before determining specific gravity.

Some products have specific size classifications for acceptability or several classifications of different values. Fence posts, house poles, and vegetable stakes are examples. Such products are not marketed by weight or volume, but by piece once they have satisfied the minimum dimensions required. Frequently, they are counted rather than measured.

6.6 FODDER AND GREEN MANURE

Sample to include leaves by different ages, position in the crown, and sun versus shade.

Fodder and green manure include foliage and, in many species, succulent bark, twigs, flowers, and fruit. For greater detail, weigh separately the foliage, succulent material, flowers, and fruit. For bushes or small trees, remove all foliage and succulent branches less than 1 cm diameter (or other specified limit) for fodder, and weigh fresh and dry. Fresh material can be weighed in the field with samples taken to the laboratory for oven drying and calculation of moisture content.

For fresh material, begin with plant parts that are most easily lost or change weight between harvest and weighing. Weigh flowers before the foliage is removed and weighed; complete this step before removing and weighing twigs, which precedes the weighing of branches, followed by stems. Complete the weighing of each tree before another is harvested.

For large trees, it is more efficient to weigh only samples. Because foliage structure and content vary with age and position, foliage samples must be drawn from systematically or randomly chosen positions throughout the crown.

For foliage quality analyses, any sampling scheme that draws representative leaves by age, sun versus shade, and by position in crown is satisfactory. The easiest is probably to use all leaves and succulent twigs of each chosen branch. Before removing any foliage, select a random sample of first-order branches (preferably 10 to 15 branches). Next, randomly select one sample, second-order branch from each first-order branch. Then, select one random branch from each succeeding lower

order in turn until reaching a twig with green leaves. Combine all green leaves and other acceptable fodder material into a well-mixed composite sample; transport in an airtight plastic bag. Document clearly the sampling scheme used.

Keep the foliage samples selected in the field cool for fodder analyses and then place in a drying oven at 50 ^{0}C upon return to the laboratory. Examine separately leaves, twigs, and fruits if so desired. Continue drying for at least 24 hours or until weight is constant.

The two most practical measures for evaluating the fodder value of MPTS are Dry Matter Digestibility (DMD) and Crude Protein (CP) content. Species with greater than 40% DMD and 10% CP deserve attention as potential fodder species. Additional useful measurements include chemical composition, e.g., P, K, Na, Ca, etc. Some leaf compounds may limit the usefulness of fodder values, e.g., presence of tannins, cyanins, etc. The most important measure of fodder value is weight gain or milk production by animals fed on leaf or pod material.

To allow comparison of fodder yields, record total fodder biomass per unit area over time, reported on an oven-dry weight basis. This should include information about the management regime used. Record species, season of harvest, position in the crown, cutting height, maturity of leaves, exposure, and other relevant considerations, such as the availability of fodder during extended dry periods, when reporting the laboratory results of the nutrient and chemical analyses. The interval between harvests may be the same for all treatments or may vary due to differences in growth. In either case, it must be accounted for in the analysis.

7.0 Related Measurements

7.1 INTRODUCTION

While Chapters 5.0 and 6.0 cover the main assessments required for MPTS, some additional related measurements are discussed briefly here. Many of these additional measurements are outside the range of experience of a typical forester, agroforester, or agriculturalist. Thus, it is advisable to consult experts and/or the specialized literature before attempting such assessments. (Note the need to consider the range of possible assessment issues and opportunities involved in MPTS research.)

7.2 OTHER PRODUCTS OF WOODY PERENNIALS

In MPTS elimination or testing trials, it is often useful to make either qualitative or quantitative assessments of non-traditional products of woody perennials. The purpose of these evaluations is usually to assess products that may increase the value or utility of a particular species. Some potential products from various plant parts include:

flowers--ornamental cut flowers, perfumes, chemicals (essential oils), honey/pollen

fruit--edible fruits for human or animal consumption, chemicals (tannins, dyes, etc.)

leaves--ornamental cut foliage, chemicals (alkaloids, insecticides, essential oils), building materials (e.g., palm leaves)

bark--fiber, chemicals (tannins, dyes)

wood--chemicals (essential oils), ornamental carvings (for tourist markets), resins, substrates for mushroom cultivation, etc.

tree wound or occluded products--gums, resins, rubber, fermented drinks

Obviously, one should undertake these assessments only if there is some good reason for doing so. For instance, if a species has attractive flowers or foliage and a potential market is envisaged, assessing the durability (vase-life) becomes important. Leaf essential oils can usually be

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detected by hand-crushing and smelling; here the main chemical component and quantity (usually obtained by steam distillation of samples) on a weight-for-weight basis are important to assess. Variables include wide plant-to-plant variation in particular components, i.e., chemotypes, so sample range is critical. For natural tannins, the yield, color, and ability to penetrate the pores in animal skin to make leather are important to assess. Here the hide powder test (percentage of tans versus non-tans in the tannin extract) is a useful assessment technique.

In all these cases and others, consult experts to learn about existing assessment techniques before attempting comparative assessments against known standards.

Distribution of extractives within a tree may require a stratified sampling system. All tissues containing the extractive of interest should be sampled by an unbiased, systematic scheme or a random one. Analyses of each sampling location within the tree offer the opportunity to determine internal distribution but are more expensive than a few analyses from a bulked sample.

7.3 NON-WOODY CROP YIELD

Report non-woody crop yield appropriately, using an adequately defined metric unit (usually kilograms or tons per metric unit of area). Mangoes or oranges, for example, would normally be reported in fresh weight per hectare, since dry weight is unrelated to crop value. Jackfruit (*Artocarpus heterophyllus*) or coconut (*Cocos nucifera*), however, could be reported in numbers of fruit (although fresh weight would still be preferable). Report copra, grain, fodder, hay, and other bulk products on a dry-weight basis. Grass increment is normally obtained by clipping grass, drying, then weighing. Carefully specify season, height of cut, and interval between cuts.

Plots to sample yields of crops should always include more than one tree or grain row, as yields vary consistently between trees and between rows. Yield per unit area should generally be measured relative to that of the whole plot, including the area with trees, and not just to the intercropped area.

If yield is to be analyzed in relation to tree proximity, stratify sample measurements by distance from tree, preferably from rectangular plots with the long axis perpendicular to a straight line connecting plot center to the

nearest tree (Figure 7.1). Such a series of plots permits regression analysis of the range from no tree effect to maximum tree effect. The configuration of such a series of plots may be modified to conform to local conditions, e.g., along and across contours and aspect. Individual plot size varies, as always, with the nature of the plot. Plots for measurement of rice or pasture grass yield, for example, can be substantially smaller than for maize (*Zea mays*) or pigeonpea (*Cajanus cajan*). The optimum combination of plot size/replications can be decided specifically only after experience with the crop.

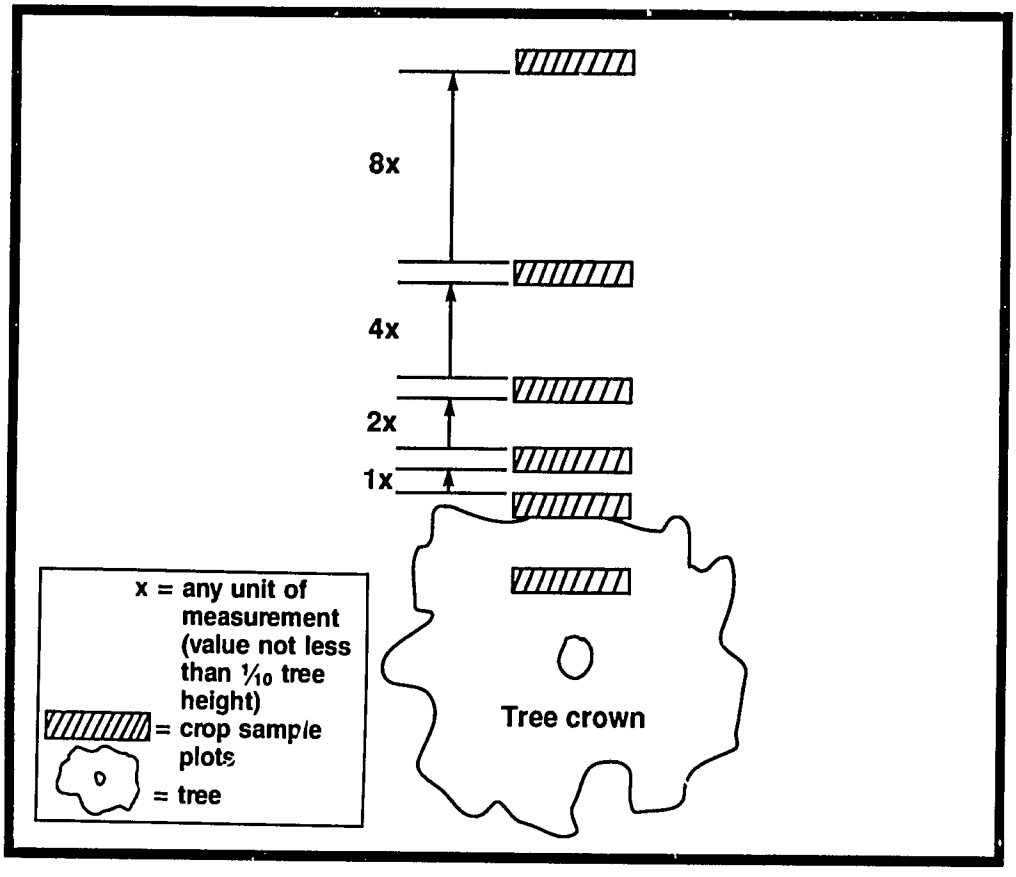

Figure 7.1. Sampling intercrop yield (vertical view)

For meaningful interpretation, crop sampling must include crops in the same field from throughout the complete range of interactions with [normally distance from] the trees. The significant information is rarely whether crops are affected by an adjacent tree, but how crop yield varies with distance from tree and how overall yield from the entire crop-and-tree system is affected.

For plantings with closely spaced trees, it is rare to find cropping areas free of tree influence.

For studies of alleycropping, orchards, shaded coffee/cocoa, or other closely-spaced trees, there is commonly no portion of the cropping area free of tree influence. In such cases, one may wish to determine the land equivalent ratio--i.e., the total amount of monocropped land required to produce the same crops produced on one hectare of mixed cropping. However, unless lengthy experiments are conducted on a large and uniform field, it is rarely possible to use monocrop yields as a realistic standard.

For biomass production comparisons, include crop and tree residues. Sugar cane leaves, suckers, and tops, for example, commonly contain as much dry matter as the cane harvested. Such residues are obvious "free" input as soil organic matter and minerals, erosion and runoff barriers, and weed suppressors. They are also potential sources of usable energy for crop drying, domestic fuel, electricity generation, and animal feed for traction, milk, and meat.

7.4 ANIMAL PRODUCTION

If animals are included in the system, they should also be included in yield measurements. However, animal-related measurements obviously differ greatly from tree measurements, and an animal scientist should be consulted before making them. The information given below is not meant to substitute for the help of an expert.

Animal production is a composite measurement calculated from:

- increased herd weight (reproduction rate, litter size, and birth weight of offspring and weight gains measured in kg),
- milk and fleece yields measured in kg, and
- survival.

Smallholders rarely weigh their animals, but the researcher can easily use a suspended balance to weigh small animals. Cattle and buffalo weights are difficult to measure directly without heavy and expensive equipment, although weight tapes are inexpensive and can be used to estimate animal weight by girth measurements at the heartgirth. Refinements such as carcass weight or grade are seldom available or necessary since first-sale receipts are usually related only to live weight.

Common substitutes for the desired measurements estimate:

- age from dentition,
- rate of reproduction and mortality from herd structure and farmer records or recall on herd entries and exits, and
- productivity from regular, periodic visits.

The substitutes are obviously less precise and are even more difficult to relate to nutrition and pasture conditions.

Differences between general farm management and bloodlines cause large between-farm variations. Herd size is commonly low, limiting the potential for on-farm replication.

However, supplementing grass and crop residues with nitrogen-rich fodder, obtainable from many trees, through a single dry season can contribute significantly to weight gain, animal units supported, reduced mortality, improved reproductive rate, age at selling, and age at first calving. In many cases, the magnitude of improvement will be visible to experienced farmers.

As with crops, supplementary information on domestic animals is essential. This includes species, breed, age, care, health, lactation, and whether working. Results are more replicable in a cut-and-carry system than when animals are on pasture. Fodder yield is also higher and more sustainable.

Appendices

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Appendix A
Symbols and Standard Abbreviations

REMINDERS

Use:

- The International System of Weights and Measures adopted in France in 1960 (see Appendix D).
- Only metric units.
- Lower-case characters for names of units, with the exception of "Celsius."
- Lower-case characters in metric prefixes, with the exception of "M" (Mega).
- Lower-case letters for direct measurements; for example, v = volume of one tree.
- Upper-case letters to indicate totals per unit area; for example, V = volume/ha.
- Subscripts following the unit name in the context of measurements such as diameter to indicate clearly where taken.
- The same symbols for both singular and plural forms of terms; for example, 1 mm and 21 mm.
- A period after the symbol *only* at the end of a sentence.
- A space to separate a number and symbol; for example, 21 cm, not 21cm.
- A blank space, not a period or comma, to separate three-digit groupings in large numbers; for example, 1 000 000, not 1,000,000 or 1.000.000.

STANDARD SYMBOLS

bh breast height. In the metric system, which is preferred, breast height is 1.30 m above the ground line. Specify any other value used; for example, bh = 1.37 m (4.5 ft).

c circumference or girth.

cai current (for most recent year) annual increment.

d diameter. Diameters of trees or parts of standing trees usually include bark. Diameters of logs from felled trees usually do not include bark.

d_{30} diameter at 30 cm above ground.

d_{ab} diameter above buttresses (non-standard term).

d_b diameter at the base (non-standard term).

dbh diameter at breast height.

d_{bhib} diameter at breast height inside bark.

d_{bhob} diameter at breast height outside bark.

d_{ib} diameter inside bark.

d_k diameter of the tree crown.

d_{ob} diameter outside bark.

d_{rc} diameter at root collar.

e spacing. This is usually given in meters or decimeters; for example, e = 1 x 2 m, or 10 x 20 dm. Within-row spacing is usually given first, followed by spacing between rows.

f form factor. This usually indicates the relationship of the volume of the main stem to the volume of a cylinder with a diameter equal to the diameter at breast height and height equal to a stated portion of tree height, expressed as a decimal portion or percentage.

g cross-sectional area of the tree stem(s).

G the sum of all the g's per hectare, unless another unit of area is specified.

h total tree height, unless otherwise specified.

h_{com} commercial height of a tree (height to top of usable logs).

h_{dom} mean height of all dominant trees.

i increment. This may be in any unit.

ib inside (without) bark.

k tree crown.

l total stem length.

mai mean annual increment.

n number of.

N total number per hectare or other specified unit of land area.

ob outside (including) bark.

pai periodic annual increment. Length of period should be specified.

rc root collar. Specify the height used.

t age in years (unless specified otherwise) from date of planting.

v volume of the individual tree or tree segment. Describe the unit referred to, such as merchantable stem, total stem, aerial (above ground), or total (stem + branches + roots).

V total volume per hectare.

Appendix B
Glossary of Terms

Accuracy: closeness of measurements, computations, or estimates to the true values

Agroforestry: land-use systems in which woody perennials (trees, shrubs, palms, bamboos) are deliberately grown on the same land-management unit as agricultural crops (woody or not) and/or animals, either in some form of spatial arrangement and/or in temporal sequence

Biomass: for MPTS, the total weight at a given time of living trees or tree parts per unit area

Border: region of a plot surrounding the measured part of the experimental plot. Usually has the same treatment applied as the net plot

Border rows: rows of plants surrounding an experimental plot, generally of the same experimenal treatment as the plants in the plot

Branch: woody portions of a tree other than the stem and roots. For MPTS measurements, an axis that diverges from the main stem more than 30 cm above the ground or that diverges at or less than 30 cm from the ground and has a diameter of less than half that of the main stem at the juncture

Caliper: instrument for determining tree and log diameters by measuring their rectangular projection on a straight graduated rule via two arms at right angles to the rule itself

Coefficient of variation: amount of variation as a percentage of the mean calculated by dividing the standard deviation by the mean and multiplying by 100. (In experiments, unless otherwise stated, the coefficient of variation will relate to the residual variation at the plot level adjusted for blocks and treatments.)

Coppice shoots: any shoot arising from an adventitious or dormant bud near the base of a woody plant that has been cut back

Coppicing: cutting trees close to ground level in order to produce coppice shoots

Co-variate: a baseline variable measured (often at the beginning of a study) to explain part of the variation in a measured response

Degrees of freedom: the number of independent comparisons that can be made between the items in a sample, usually the number of categories minus 1 (abbr. df)

Dendrometer: any instrument for measuring or estimating the diameters of tree stems or logs

Density: weight per unit volume. (For wood, the moisture content at the time of measurement should be specified.)

Destructive sampling: measurement of a sample that requires destruction of the organism (i.e., felling and cutting up of a tree) in order to measure the organism or a part thereof

Diameter at breast height: reference diameter of a tree at 1.3 meter height above ground line

Diameter tape: a tape measure specially graduated so that the diameter may be read directly when the tape is placed around a tree stem or log

Essential oils: volatile substances found in different parts of many plants, generally consisting of mixtures of hydrocarbons, alcohol, esters, aldehydes, and ketones

Experimental design: a set of rules for assigning treatments to experiment plots. (When all replications of each treatment are assigned to the plots completely at random [without restriction], the design is called a *completely randomized design*.)

Experimental error: the variability (within blocks) at the plot level

Foliage: the leafy biomass on the branches of a tree

Gross plot: the entire plot, including border region

Guard rows: region of an experimental site planted to protect the experimental plots from the effects of other plots or external factors such as wind. Usually has the same treatment applied to the guard region throughout the experiment. (See also *Border rows*.)

Height: vertical distance between the apical bud of a standing tree (even if this is a lateral shoot) and ground level

Heterogeneity: the property of one or more samples, which implies they are varied with respect to some or all of their traits

Homogeneity: the property of one or more samples, which implies they are similar with respect to some or all of their traits

Hypsometer: any instrument for measuring the heights of standing trees or their stems from observations taken at some distance

Incomplete block design: an experimental design in which each block contains fewer than a complete replication of the treatments. (If every treatment appears with every other treatment in the same block an equal number of times and the blocks are of equal size, the design is said to be *balanced*.)

Land equivalent ratio: the total land required using moncultures to give total production of the same crops equal to that of one hectare of mixed crop

Length: the measured distance of a tree or specified portion of a tree following the lean or curvature, not necessarily vertical or straight

Lopping: cutting off one of more branches of a tree, whether standing, felled, or fallen

Mean: the sum of all values divided by the number of values summed

Multipurpose tree species: tree species purposely grown to provide more than one significant product and/or service function in the land-use systems they occupy

Net plot: the portion of the plot where measurements are taken, excluding the border and guard regions

Network trial: a series of experiments with identical or similar treatment designs

Phenology: the study of the seasonal timing (or periodicity) of the life events of an organism

Plot: a precise area used for study and measurement

Pollarding: cutting back the crown of a tree to produce a close head of shoots beyond the reach of browsing livestock

Population: the aggregate of all units, finite or infinite, forming the subject of study

Precision of measurement: one-half the unit of measurement

Precision (statistical): the size of the standard error as a proportion of the mean

Product: outputs measurable both in quantity and quality

Pruning: the considered cutting away of superfluous growth (including roots) from any plant so as to improve its development, fruitfulness, etc.

Randomization: a specification of assigning treatments to the plots so that each treatment is equally likely to be assigned to any given plot

Randomized complete block design: experimental design in which the plots are arranged in subgroups or *blocks* so that the variability among plots within a block is minimized and the randomization is restricted so that every treatment occurs exactly once in each block

Replication: repetition of plots with the same treatment. (Replication should not be confused with samples or blocks [e.g., trees] within a plot.)

Site: area where trials or plots have been established

Specific gravity: as applied to wood, the ratio of the oven-dry weight of a sample to the weight of a volume of water equal to the volume of the sample at some specific moisture content, usually fresh

Sprouts: shoots growing out of the stump or roots

Standard deviation: the square root of the variance around the mean

Standard error of the difference of the mean: an estimate of the amount of error in using the difference between sample means to estimate the difference in population means

Standard error of the mean: an estimate of the amount of error in using the sample mean to estimate the population mean

Stem: an axis that diverges at or less than 30 cm above the ground and has a diameter more than half that of the main stem at the juncture

Stratification: a method of sampling from a population that classifies the population into several groups (strata) and then samples separately from within each strata. (By choosing appropriate sample sizes in each strata the overall sample can be made more efficient than a simple random sample.)

Treatment: generic term used in comparative trials to describe the effect of a procedure (agent or intervention). (Treatments can be physical, as with cutting managements, or definitional, as with species or planting dates; each type of treatment is commonly called a *treatment factor*.)

Treatment design: a structural arrangement of treatments. (A single factor treatment design will normally have 2 or more categorical states [e.g., species or management packages] or 3 to 5 quantitative levels [e.g., rates of fertilizer or planting density].)

Variable: a quantity able to assume different values (e.g., heights, diameters)

Variance: measure of variability that equals the total of the squared deviations of each observation from the arithmetical mean divided by one less than the total number of observations

Variate: a single observation or measurement

Yield: the quantity of a specified product or plant component harvested necessarily related to specified crops, trees, or animals on a particular area over a specified period of time

Appendix C
Equipment for Measuring MPTS

TOOLS FOR MEASURING TREE HEIGHT

Telescoping measuring rod. This is usually made of fiberglass and is capable of measuring tree heights up to 12-15 m. It can be read from eye level, making it easier and faster to use than fixed rods.

Fixed measuring pole. This is made of bamboo or roundwood and can be used on trees up to 6 m in height. Tape measures are attached to the pole or the pole can be marked in appropriate increments. Care must be taken to mark heights clearly on the pole so they can be read from the ground.

When either a telescoping or fixed measuring pole is used to measure height, always place the pole beside, rather than in front or in back of, the tree. This helps prevent differences in perspective, which can result in inaccurate measurements.

Hypsometer. A clinometer, Abney hand level, or other equipment for measuring tree heights from a distance used on those taller than 10-15 m in total height. (Vertical angles are measured to the growing point from a measured baseline [Figure C.1]; trigonometric principles are used to calculate the actual height.)

TOOLS FOR MEASURING TREE DIAMETER

Caliper. Diameter is often determined by 2 caliper measurements taken at right angles to each other, the mean calculated arithmetically from them ($(d_1 + d_2)/2$) and taken as the actual diameter. Caliper measurements may be either too large or too small with reference to the true mean, and tend to balance out. Because caliper measurements may fall anywhere on the tree circumference, they are not generally reproducible or well-adapted to repeated measurements of the same trees.

Diameter tape. This gives the diameter of a circle by using the formula $d = (circumference / \pi)$. Its results are more consistent than those of a caliper and it is easier to carry. Diameter tapes that convert circumference to diameter are convenient and help avoid conversion errors that can occur if a linear tape measure is used to measure circumference, which is then converted to diameter. Diameter tape measurements always have a positive bias except on trees that are perfectly circular at the point of measurement. (See Figure C.2.)

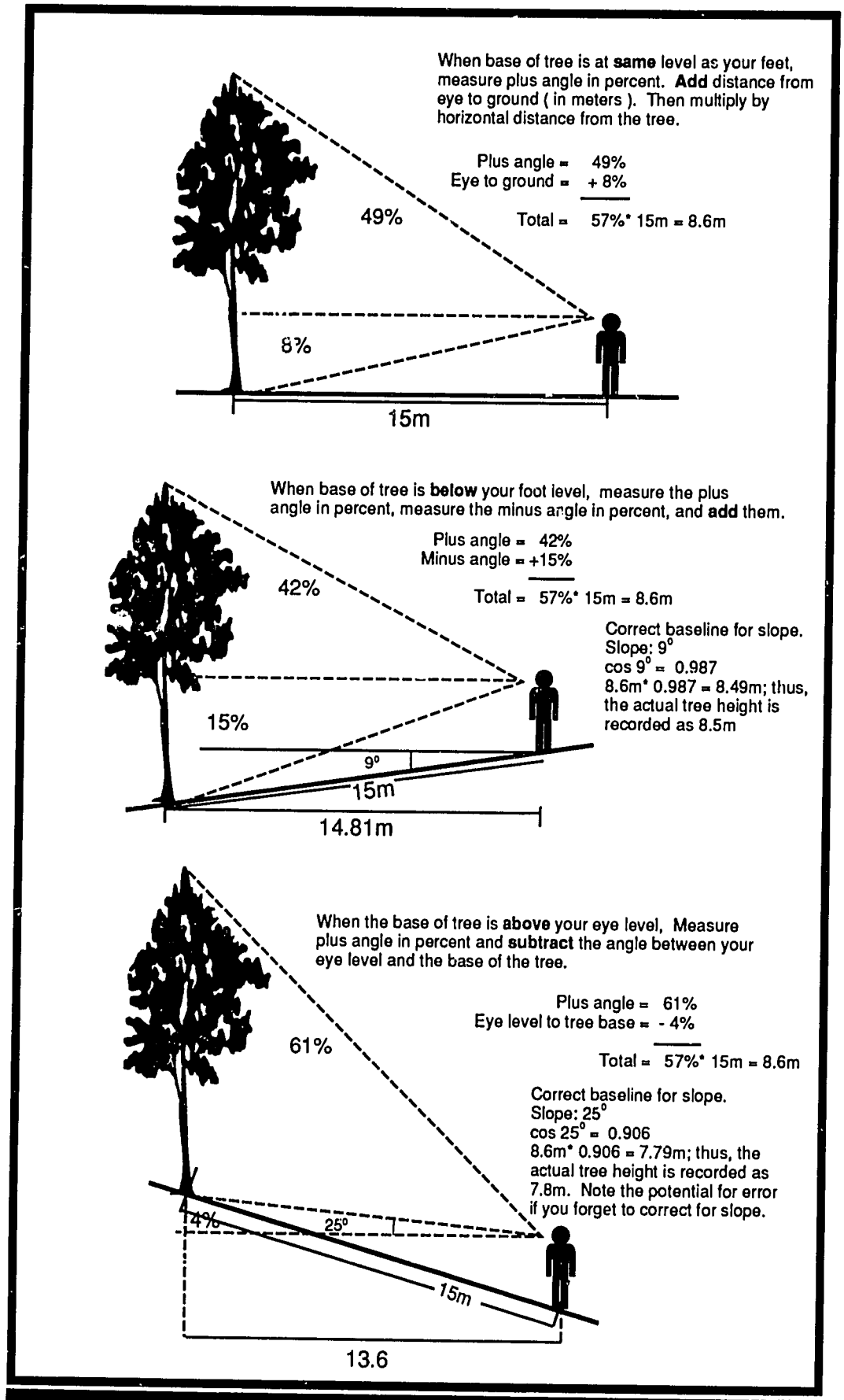

Figure C.1. Using a clinometer

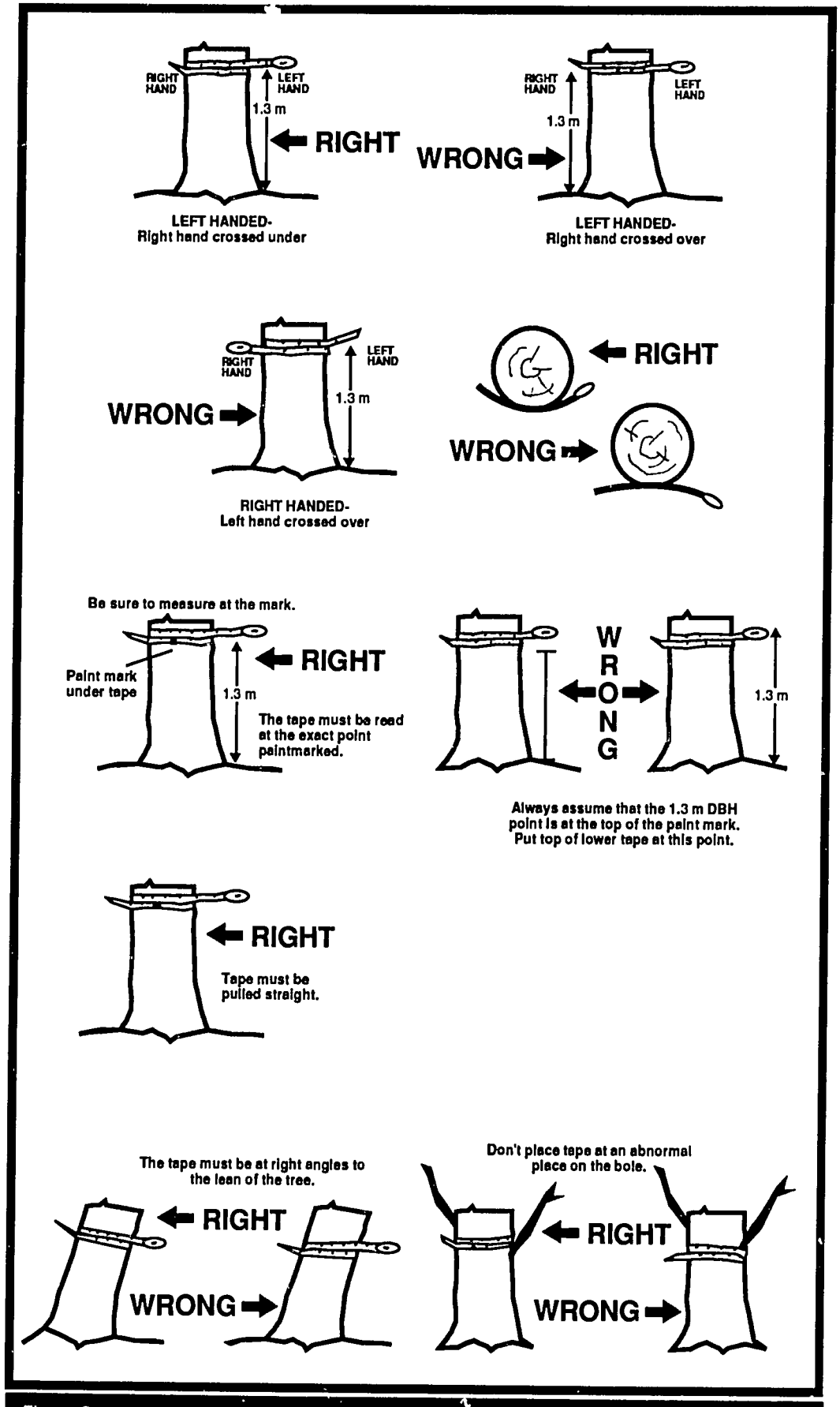

Figure C.2. Using the diameter tape

Linear tape measure. When diameter tapes are unavailable, flexible measuring tapes can be used to measure circumference (girth). Since diameter is a measure more commonly used and more easily visualized, circumference measurements should be converted to diameter for analysis and reporting purposes.

TOOLS FOR MEASURING WOODY BIOMASS

A typical rig for assessing total fresh weights in the field consists of a tripod with a set of scales suspended from the tripod apex. A bag sling to carry the woody material for weighing is then attached to the scales. Depending on the size of the MPTS biomass components, some suitable scales are 5 kg (20 g precision) or 50 kg (100 g precision). For weighing sub-samples of this material, 1 kg scales (with 1 g precision) are required if plastic bags are unavailable. For oven-dried material, laboratory balances with more precision are usually used.

Appendix D
Useful Conversion Factors and Formulas

Table D.1. Conversion factors for SI and non-SI units

SI unit to non-SI unit multiplier	SI unit	Non-SI unit	Non-SI unit to SI unit multiplier
		Length	
0.621	kilometer **km** (10^3m)	mile **mi**	1.609
1.094	meter **m**	yard **yd**	0.914
3.28	meter **m**	foot **ft**	0.304
1.0	micrometer μ **m**(10^{-6}m)	micron μ	1.0
3.94×10^{-2}	millimeter **mm** (10^{-3}m)	inch **in**	25.4
		Area	
2.47	hectare **ha**	acre	0.405
247	square kilometer **km**^{2}(10^3m)^2	acre	4.05×10^{-3}
0.386	square kilometer **km**^{2}(10^3m)^2	square mile **mi**^{2}	2.590
2.47×10^{-4}	square meter **m**^{2}	acre	4.05×10^3
10.76	square meter **m**^{2}	square foot **ft**^{2}	9.29×10^{-2}
1.55×10^{-3}	square millimeter **mm**^{2}(10^{-6}m)^2	square inch **in**^{2}	645
		Volume	
9.73×10^{-3}	cubic meter **m**^{3}	acre-inch	102.8
35.3	cubic meter **m**^{3}	cubic foot **ft**^{3}	2.83×10^{-2}
6.10×10^4	cubic meter **m**^{3}	cubic inch **in**^{3}	1.64×10^{-5}
2.84×10^{-2}	liter **L**(10^{-3}m^3)	bushel **bu**	35.24
1.057	liter **L**(10^{-3}m^3)	quart (liquid) **qt**	0.946
3.53×10^{-2}	liter **L**(10^{-3}m^3)	cubic foot **ft**^{3}	28.3
0.265	liter **L**(10^{-3}m^3)	gallon	3.78
0.220	liter **L**(10^{-3}m^3)	imperial gallon	4.546
33.78	liter **L**(10^{-3}m^3)	ounce (fluid) **oz**	2.96×10^{-2}
2.11	liter **L**(10^{-3}m^2)	pint (fluid) **pt**	0.473
		Mass	
2.20×10^{-3}	gram **g**(10^{-3}kg)	pound **lb**	454
3.52×10^{-2}	gram **g**(10^{-3}kg)	ounce (avdp) **oz**	28.4
2.205	kilogram **kg**	pound **lb**	0.454
0.01	kilogram **kg**	quintal (metric) **q**	100
1.10×10^{-3}	kilogram **kg**	short ton (2,000 lb) **ton**	907
1.102	megagram **Mg** (tonne)	ton (U.S.) **ton**	0.907
1.102	tonne **t**	ton (U.S.) **ton**	0.907

Table D.1. *(Continued)*

SI unit to non-SI unit multiplier	SI unit	Non-SI unit	Non-SI unit to SI unit multiplier
		Yield and Rate	
0.893	kilogram per hectare kg ha^{-1}	pound per acre lb $acre^{-1}$	1.12
0.107	liter per hectare L ha^{-1}	gallon per acre	9.35
0.220	liter per hectare L ha^{-1}	imperial gallon per acre	4.546
893	tonnes per hectare t ha^{-1}	pound per acre lb $acre^{-1}$	1.12×10^{-3}
893	megagram per hectare Mg ha^{-1}	pound per acre lb $acre^{-1}$	1.12×10^{-3}
0.446	megagram per hectare Mg ha^{-1}	ton (2,000 lb) per acre ton $acre^{-1}$	2.24
2.24	meter per second m s^{-1}	mile per hour	0.447
		Temperature	
1.00 (K-273)	Kelvin K	Celsius °C	1.00 (°C + 273)
(9/5 °C) + 32	Celsius °C	Fahrenheit °F	5/9(°F-32)
		Energy, Work, Quantity of Heat	
9.52×10^{-4}	joule J	British thermal unit Btu	1.05×10^{3}
0.239	joule J	calorie cal	4.19
10^{7}	joule J	erg	10^{-7}
0.735	joule J	foot-pound	1.36
2.387×10^{-5}	joule per square meter J m^{-2}	calorie per square centimeter (langley)	4.19×10^{4}
10^{5}	newton N	dyne	10^{-5}
1.43×10^{-3}	watt per square meter W m^{-2}	calorie per square centimeter minute (irradiance) cal cm^{-2} min^{-1}	698
		Concentrations	
1	centimole per kilogram cmol kg^{-1} (ion exchange capacity)	milliequivalent per 100 grams meq 100 g^{-1}	1
0.1	gram per kilogram g kg^{-1}	percent %	10
1	milligram per kilogram mg kg^{-1}	parts per million ppm	1
		Plant Nutrient Conversion	
	Elemental	*Oxide*	
2.29	P	P_2O_5	0.437
1.20	K	K_2O	0.830
1.39	Ca	CaO	0.715
1.66	Mg	MgO	0.602
0.160	N	Crude Protein	6.25

MOISTURE CONTENT

The two ways to express moisture content (MC) are wet or dry. The difference between the two is shown in Figure D.1.

$$MC\ (\%)\ wet = \frac{weight\ of\ water}{weight\ of\ dry\ sample + weight\ of\ water} \times 100$$

$$MC\ (\%)\ dry = \frac{weight\ of\ water}{weight\ of\ dry\ sample} \times 100$$

To convert MC from a dry to a wet basis:

$$MC\ (\%)\ wet = \frac{MC\ dry}{100 + MC\ dry} \times 100$$

$$MC\ (\%)\ dry = \frac{MC\ wet}{100 - MC\ wet} \times 100$$

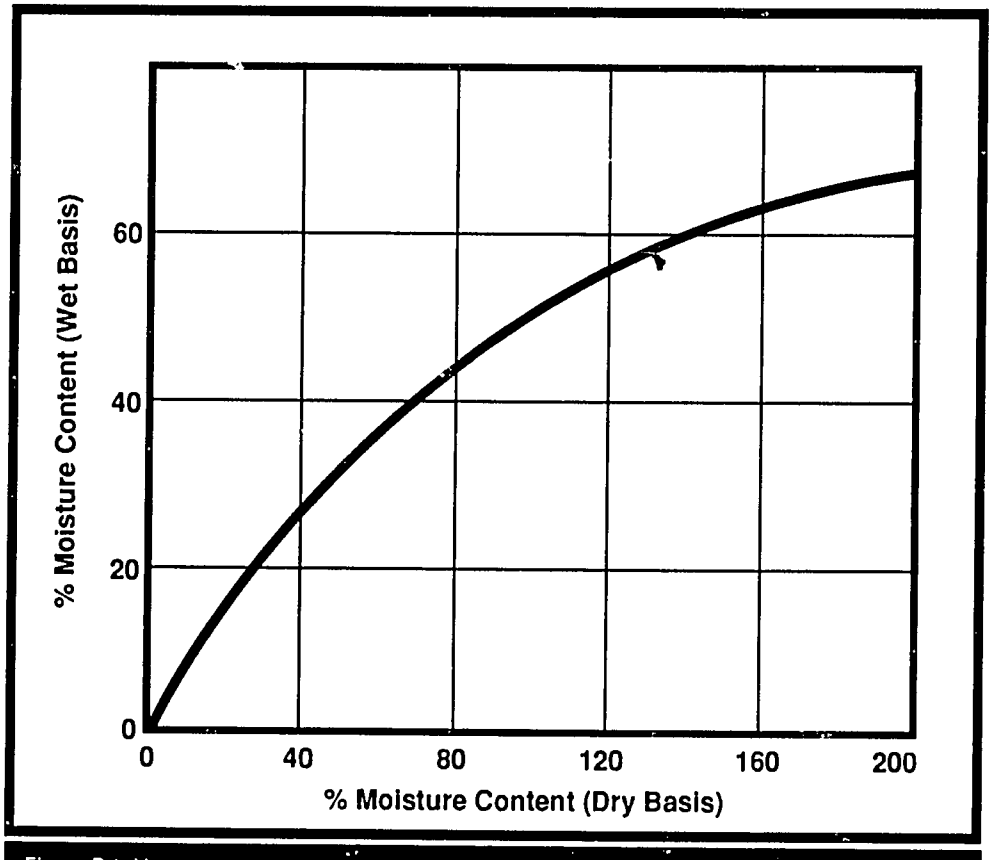

Figure D.1. Moisture content comparison

VOLUME-WEIGHT CONVERSIONS

Much of the data available on wood yields is expressed in units of volume, yet MPTS research often requires a measure of weight. Wood volumes can be converted into wood weights using density and moisture content. Wood density is usually expressed in terms of specific gravity, which is the weight of the oven-dry sample divided by the green volume of the sample:

$$\textit{specific gravity} = \frac{\textit{weight of oven-dry sample (g)}}{\textit{volume of green sample (cm}^3\textit{)}}$$

Methods for calculating specific gravity are found in section 6.5. To estimate the amount of oven-dry wood in a volume of green wood, use the following formula:

$$\textit{oven-dry weight (kg)} = \textit{green volume (m}^3\textit{) x specific gravity x 1,000}$$

WEIGHT-VOLUME CONVERSIONS

If the weight, moisture content, and specific gravity of wood are known, the volume of that wood can be calculated as follows:

$$\textit{kg (green)/m}^3 = \frac{\textit{sg x 1,000}}{1 - (MC_{wet})}$$

Once the density per m^3 is known, the green volume of wood can be calculated as follows:

$$\textit{wood volume (m}^3\textit{)} = \frac{\textit{kg of wood (green)}}{\textit{kg (green)/m}^3}$$

This method is sensitive to changes in either specific gravity or moisture content.

Appendix E
Developing Biomass Tables for MPTS

Tree biomass weight tables show the average weight of individual trees for one or more dimensions, usually diameter alone (for local tables) or diameter, along with height or length. The tables are constructed from data obtained in destructive sampling. Wood or foliage weight can be related to dbh, diameter at 0.3 m, and height through regression analysis. This appendix describes the process for developing standard biomass weight tables for important MPTS. The development of local weight tables is not recommended because of the limited application of such tables in relation to the amount of effort required to collect the data. The duplication of effort in producing such tables for important MPTS is another reason to avoid using local weight tables.

The primary disadvantage of using standard biomass tables is that, if within-species or between-site variability in the allometric relationships of height, diameter, and biomass is high, predictions made using values from the tables may be accurate for some sites and inaccurate for others.

PLANNING A WEIGHT TABLE

Critical decisions must be made before beginning to work on a weight table, including:

- Defining the range of tree or shrub dimensions to be covered by the table
- Defining the type(s) of biomass to be included in the table(s). (This may include stem wood, stem and branch wood, foliage, etc; one table will need to be developed for each biomass type.)
- Determining what measurements to use in relating biomass to a practical field measurement (e.g., d, dbh, or h)
- Defining size classes throughout the range of tree sizes

FIELD SAMPLING

A critical question is the number of trees necessary for a weight table for a given species. Estimates from many recent biomass studies suggest that 30-100 trees are enough for a regional table using stratified sampling of the population (see section 3.1). Sufficient evidence argues that, if sample trees are selected in equal or near-equal numbers in each size class, 30 trees for an individual tree biomass table are adequate. At least 30 well-selected trees should be used per species for individual tree biomass tables.

PARTITIONING AND WEIGHING

Each individual tree or shrub must be harvested; measured for diameter, length, and height; and divided into major components as defined during the planning stage. Length measurements are recommended, but if vertical height is to be included as an independent variable, the measurement must be taken before the tree is harvested. Individual components (e.g., stem, branches, leaves, etc.) should be divided into several size classes for convenience in handling and for sub-sampling. Sub-samples should be taken to determine moisture content, specific gravity, etc.

Techniques for weighing tree components depend largely on tree size and equipment availability. Care must be taken to separate trees and their parts. The best way to ensure this is to work on partitioning and weighing only one tree at a time.

ANALYSIS

Regression analysis should be done for each of the biomass types defined during the planning process. At least one complete set of equations and weight tables should include both diameter and height terms to allow use of the tables in as wide a range of environments as possible. (See Table E.1.)

Table E.1. Most common equations for biomass types

Biomass Type	Most Common Equation(s)*
Whole Tree	$B = b_0 + b_1D^2H$ $B = b_0 + b_1D$
Woody Biomass	$B = b_0 + b_1D^2H$
Branch, Foliage, or Crown Weight	$B = b_0 + b_1D^2$ $B = b_0 + b_1D$

* B = predicted total above-ground biomass, D = diameter (cm) at breast height (1.3 m), H = total height (m), b_0 and b_1 = regression parameters estimated from the data.

Results should be represented as both the regression equation and the table to allow the widest possible application of the work.

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Index

Acacia tortilis, 50
Accuracy
  and diameter measurement, 38
  and wood volume, 53
  defined, 33, 69
  limits of, 37
Agroforestry
  defined, 69
Analysis of variance, 22, 30
Animal(s)
  production, 62-63
  substitutes for, measurements, 63
  supplementary information on, 63
  weight gain, 63
Artocarpus heterophyllus, 60
Assessment of damage or health
  categories for, **Table 5.2** (45)
  international conventions for, 44
Azadirachta indica, 10

Biomass
  destructive sampling for, assessment, 46-57
  equations for, types, **Table E.1** (84)
  measuring, of components, 50-52
  MPTS, defined, 46, 69
  partitioning, 46, 50, 84
  production comparisons, 62
  selecting samples for, assessments, 46-49
  size classes, 50-51
  tables, 47, 83-84
  tools to measure woody, 78
Block(s). *See also* Site variability
  and fertility gradients, 23
  and provenance trials, 21
  and randomized designs, 23
  and within-block variation, 23
  differences and management variation, 29
  incomplete, design defined, 71
  irregularly positioned, **Fig. 3.1** (24)
  planting, 25
Border
  defined, 69
Branch
  defined, 40, 69
  taking moisture content for, 52
Briscoe, C.B., 7, 8, 85
Burley, J., 85

Cajanus cajan, 61
Caliper
  defined, 69
  measurements, 75
  to measure seedling diameter, 38
  use of vernier, 33-34
Calliandra calothyrsus, 16-17
Carter, E.J., 85
Client
  and goals, 14
  and range of applicability, 19
  and researchers, 14
  needs of, 13-14, 17
  review in research planning, 17
Clinometer. *See also* Hypsometer
  using, **Fig. C.1** (76)
Cocos nucifera, 60
Coefficient of variation
  defined, 69
Commercial length. *See* Height
Compendiums
  Kompendium fuer feldversuche, 85
Competition
  above- and below-ground, 27
  tree-crop, 27-28
Controls
  and agroforestry experiments, 26
  and genetic improvement, 26
  crop-only, 26-27
Conversion(s)
  factors, **Table D.1** (79-80)
  volume-weight, 82
  weight-volume, 82
Coppice shoots
  defined, 70

Previous Page Blank

Coppicing
defined, 70
Co-production management. *See* MPTS
Co-variate
defined, 70
Crown. *See also* Diameter
irregular, 39
live, defined, 35
regular, 39

Damage. *See* Assessment of damage or health
Degrees of freedom
and choosing number of replicates, 22
defined, 70
Density
defined, 70
Design
experimental, 21-23
research, reminders, 19
Diameter
at breast height, 34, 70
crown, 39; **Fig. 5.3** (39)
dendrometer for measuring, defined, 70
errors in locating, 34
formula for combining stems, 41
inside bark, 38
measurement at root collar, 38
measurement of, 38
measurement of multiple stems, 40-41
measurements to determine volume, 53
minimum acceptable, 35, 37
size classes, 50
tape defined, 70
tools for measuring, 75-78

End products
and partitioning biomass components, 50
specification of, 18
Error(s)
experimental, defined, 71
prevention of, 34, 53
Essential oils
defined, 70
Experimental design. *See also* Design, Layout
defined, 21, 70
incomplete block, defined, 21
on multiple sites, 22
on single sites, 22
randomized complete block, defined, 21
unit, 29-30

Experimental error
and standard errors for differences between treatment means, 30
defined, 29
Experiments
multiple-factor, 25
single-factor, 25

Fodder and green manure
comparison of, yield, 57
measures for evaluating, value, 57
weighing, 56
Foliage
defined, 71

Gauge
angle, 34
cutout, 38
Gliricidia sepium, 9, 17, 50
Goals. *See* Research
Guides
A guide to planning woodfuel production in rural communities, 85
Guia para la investigacion silvicultural de especies de uso multiple, 85

Handbooks
Wood handbook--Wood as an engineering material, 85
Health. *See* Assessment of damage or health
Height
defined, 71
measurement for multiple-stem tree, 41
measuring, of leaning tree, **Fig. 5.2** (37)
merchantable, 35
methods for defining, 37
of leaning tree, 35
tools for measuring, 75
total, measured using trigonometry, 35; **Fig. 5.1** (36)
total, measurements, 35
Huxley, P.A., 85
Hypothesis. *See also* Research
and experiment design, 19
and practicality testing, 17
defined, 16
examples of, 16-17
framing, 17

Hypsometer
defined, 71, 75
use of, to measure total height, 35

Land equivalent ratio
defined, 71
Layout
and site uniformity, 23
and site variation, 23
of control plots, 27
of provenance trial, **Fig. 3.1** (24)
Length
defined, 71
measurement of total, 35
measuring, of leaning tree, **Fig. 5.2** (37)
merchantable, 35
of clear bole defined, 35
Leucaena hybrid, 17
Leucaena leucocephala, 9
Lopping
defined, 72

MacDicken, Kenneth G., 85
Management. *See also* Plot(s)
nursery, in multiple species trials, 29
variations, 29
Manual(s)
A manual for species and provenance research with particular reference to the tropics, 85
Evaluation manual: International trial of Central American dry zone hardwood species, 85
Field trials manual for multipurpose tree species, 85
From seed to trial establishment, 85
how to use, 11
purpose, 11
MDS. *See* Minimum data set
Mean
defined, 72
Measurement(s). *See also* Diameter
animal production, 62-63
at plot level, 29
crown diameter, 39; **Fig. 5.3** (39)
destructive biomass, 47
destructive, defined, 46
diameter, for MPTS, 38
displacement, 54-55
equipment for MPTS, 75-78
errors, 34
fodder value, 57
height, methods, 10
inside bark, 38
non-destructive, options, 33-45
of multiple stems, 40-41
of special products, 33
of yield per unit area, 60
on sub-units of plot, 29
related, 59-63
Merchantable length. *See* Height
Methods. *See also* Research
Methodology for the exploration and assessment of MPTS, 85
Mimeos
Technical notes on MPT measurements, 85
Minimum data set
and preferred additional data, **Table 4.1** (31-32)
criteria used in determining, 31
recommended, **Table 4.1** (31-32)
use of, 11
variables included in, 31
Model(s)
prediction, 20, 47
regression, 46
Moisture content
and oven-dry weight, 51-52
comparison, **Fig. D.1** (81)
determining, 46
expression of, 81
formulas, 81
minimum sample sizes for, 52
MPTS. *See also* Biomass, Measurement(s), Minimum data set, Product(s), Research
and degrees of freedom, 22
and farmer decisions, 10
and minimum data set, 31; **Table 4.1** (31-32)
and randomized complete block design, 21
assessment techniques, 60
defined, 9, 72
evaluation of, outputs, 15
evaluation of, performance, 9-10
experiments designed for 4-to-6-year evaluations, 25
management for multiple products and services, 9
monitoring and describing, phenology, 42-43
non-destructive measurement options for, 33-45
priority of, products, 15
products, 33
research and traditional forestry, 13

MPTS (*Continued*)
research priorities, 9
volume and density, 53-56
Multipurpose tree species. *See* MPTS

Network trials
defined, 72
Non-destructive measurements
options, 33-35
reminders for, 33

Objectives. *See also* Research
and range of applicability, 19
Oven-dry weight
and recording total fodder biomass, 57
converting wet weight to total, 51
defined, 51
formula, 51, 82

Papers
Aspects of MPTS evaluations in the context of agroforestry technologies, 85
Measurement options for multipurpose trees, 85
Phenology
and log score, **Table 5.1** (43)
and MPTS assessment, 42-43
defined, 42, 72
recommended standard for quantitative evaluation, 43
recommended standard scoring scales, 42
Pinus spp., 16
Plot(s)
and level of management, 29
and micro-variability, 28
and provenance trials, 21
and sampling intercrop yield, 60-62; **Fig. 7.1** (61)
and site variation, 28
choosing, size, 28
defined, 29, 72
extent of, influence, 28
gross, defined, 71
level assessments of damage or health, 44
net, defined, 72
size, 25, 28
structure, 27-28
square, 24
tree-to-tree variability within, 30
within blocks, 21
Pollarding
defined, 72

Population
defined, 72
Precision
and amount of variability, 21-22
and biomass, 50
and number of replicates, 22
and number of sites selected, 20
and treatment structure, 25
and tree-to-tree variance, 30
and wood volume, 53
defined, 33, 72
effects of smaller plots on, 28
improvement of, 21
interpreting, 27
statistical, defined, 72
using caliper to measure, of diameter at breast height, 34
Problems. *See* Research
Product(s)
defined, 72
economic value of MPTS, 49
evaluation of, and destructive sampling, 46
measurement of MPTS, 33
non-wood, 33
other, of woody perennials, 59-60
reporting of, 60
size and wood volume, 53
wood, 33
Provenance trial. *See also* Block(s), Layout
single species, 25
Pruning
defined, 72

Randomization. *See also* Block(s), Experimental design, MPTS
defined, 72
Randomized complete block design. *See also* Experimental design
defined, 73
Range of applicability
and climate variation, 20
and seasonal variation, 20
Rapid rural appraisal. *See* Research
RCBD. *See* Experimental design, randomized complete block design
Recommendation domain. *See* Research
Replication
defined, 73

Research. *See also* Design, Treatment
approach, 18
defined, 13
defining, problem, 13
goals and objectives, 13-14, 18-19
hypotheses, 13, 16-17
interdisciplinary, 18
MPTS, design, 13-18
need for standard methods, 10
objectives and knowledge gaps, 18
objectives of, defined, 17
planning, 17
problems, 15-16
reporting, results, 10-11
Robinson, P.J., 85
Roger, J.H., 85
Rohrmoser, K., 85
Row(s)
border, defined, 69
guard, defined, 71
planting, 25

Salazar, R., 85
Salazar, Rodolfo, 85
Samples
combining, 52
drying, 52
heterogeneity of, defined, 71
homogeneity of, defined, 71
selecting , to determine specific gravity, 56
weighing foliage, 56
Sampling
components to estimate biomass production, 50
destructive, defined, 70
field, 83
for foliage quality analysis, 56
intercrop yield, **Fig. 7.1** (61)
methods for destructive biomass assessment, 49
random, 47
stratification, 47; **Table 6.1** (48)
Site
and environmental gradients, 20
and range of applicability, 20
and treatment variation, 20
characterization, 20
defined, 73
Site variability. *See also* Plot(s)
within blocks, 21
Species selection
criteria for, 15
elimination trials, 25, 59
information needs, 16
Specific gravity
as measure of wood density, 55
definition of, 55, 73
formula, 82
variation in, 55-56
Sprouts
defined, 73
Standard(s). *See also* Research
abbreviations, 66-68
alternatives for, 11
deviation defined, 73
error of the mean defined, 73
errors for differences between treatment means, 30
recommended, 11
symbols, 66-68
Stem(s)
defined, 40-41, 73
formula for combining, diameters, 41
methods for defining, for measurement, 40
multiple, measurements, 40-41
single, measurements, 35-39
Stewart, J.L., 85
Stratification. *See also* Sampling
defined, 73

Tape
diameter, defined, 70, 75
how to use, **Fig. C.2** (77)
used to measure crown diameter, 38; **Fig. 5.3** (39)
weight, 62
Tephrosia candida, 17
Tools
for measuring tree diameter, 75-78
for measuring tree height, 75
for measuring woody biomass, 78
Treatment(s)
and rules of range of possible values, 26
defined, 74
design defined, 74
differences and guard areas, 25
differences and management, 29
experimental, 29
interaction, 20
replication, 22-23

Treatment(s) (*Continued*)
selection, 19
size of, difference, 28
structure, 25-27
testing, 21
testing differences between, mean, 29-30
use of control, 26, 28
within blocks, 21
Tree(s). *See also* Assessment, Biomass, Diameter, Height, MPTS
and adverse site conditions, 44
and alleycropping, 62
and crops, 60-62
and standard errors, 30
and yield of useful products, 33
coding system for, health, 44
crowns, 39
growth differences of, and range of applicability, 20
height measurement, 10, 35-37
influence of, on site, 26
level, and measure of variability, 29
measurement of, with single stems, 35-39
multi-stemmed, measurements, 40-41
selection for destructive sampling, 46-49

U.S. Department of Agriculture, 85

Variable
defined, 74
Variance
defined, 74
Variate
defined, 74
Volume. *See* Wood volume

Weight(s). *See also* Moisture content
animal, 62-63
dry, 51
effects of moisture content on, 51
fodder, 50, 56
oven-dry, 46, 51-52
planning, tables, 83
scales for woody biomass, 78
Windbreak trials
and monitoring micro-environment parameters, 26
Wolf, G.V., 7, 8, 85
Wood, P.J., 85

Wood volume
determining, 53
determining, using displacement method, 54; **Fig. 6.1** (55)
formula, 82
recommended measurements for, calculations, 53-54
using Huber's formula, 53-54
using Newton's formula, 54

Yield
defined, 74
of non-woody crops, 60-62

Zea mays, 61

The Forestry/Fuelwood Research and Development Project (F/FRED) is designed to help scientists address the needs of small-scale farmers in the developing world for fuelwood and other tree products. It provides a network through which scientists exchange research plans, methods, and results on the production and use of trees that meet the household needs of small farms. These trees, in project terms, are multipurpose tree species (MPTS).

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Global Systems Research Staff and F/FRED Management Office
Winrock International
1611 N. Kent St., Suite 600
Arlington, VA 22209
USA

tel :703/525-9430
tx :248589 WIDC
fax :703/522-8758

F/FRED Coordinating Unit
c/o Faculty of Forestry
Kasetsart University
P.O. Box 1038
Kasetsart Post Office
Bangkok 10903, Thailand

tel :66-2/570-1977
tx :788/2134 WINROCK TH
fax :66-2/561-1041

ICRAF
ICRAF House, off Limuru Road
Gigiri, P.O. Box 30677
Nairobi, Kenya

tel :254-2/521450
tx :22048
fax :254-2/521001